Advanced Refractories for Iron and Steel Industries

RITWIK SARKAR

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Advanced Refractories for Iron and Steel Industries

This book covers details of specialized advanced refractories, their essentiality, their functions, the materials used, their properties, their degradation, and the possibilities for improvements. Elaborated details with various schematic figures and real-life photographs are included, with special focus on the iron and steel industries. It is based on different multi-national/international refractory organizations and their products correlating with fundamentals and concepts.

Features:

- Describes the design and types of refractory materials used in different industrial applications, along with their wear mechanisms.
- Focuses on specific applications during iron- and steelmaking.
- Includes numerous schematic diagrams with labelling and product photos with application areas.
- Reviews details of background, requirements from user industries, progress with time, materials used, compositions, and properties.
- Mentions failure mechanisms and pertinent improvements/modifications.

This book is aimed at graduate students, researchers, and professionals in refractory materials, pyro-metallurgy, and iron- and steelmaking.

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Dedicated to my
teachers, parents, and family

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About the Author

Ritwik Sarkar is a professor, Department of Ceramic Engineering, National Institute of Technology, Rourkela, India, since 2009. He has completed his graduation in ceramic technology from the University of Calcutta in 1993, post-graduation from Banaras Hindu University (BHU) in 1995, and a PhD degree from Jadavpur University in 2003, all from India. Prior to his current assignment, Dr Sarkar has worked as a general manager–technology, IFGL Refractories Ltd, India, in 2008–2009 and as a senior scientist in CSIR:CGCRI, India, in 2001–2008; in the Research and Consultancy Directorate, ACC Ltd, Thane, India, in 1999–2001; and in H&R Johnson (I) Ltd, Thane, in 1995. He was also a post-doctoral fellow at the Institute of Ceramic Components in Mechanical Engineering (IKKM), RWTH, Aachen, Germany, with DAAD (German Academic Exchange Service) Fellowship, in 2003–2004.

The current areas of research interest of Dr Sarkar include the development of refractory aggregates, unshaped and castable refractories, the use of nanoparticles and nanocarbon in refractories, magnesium aluminate spinel and spinel refractories, etc. A fellow of the Indian Institute of Ceramics and a life member of the Indian Ceramic Society, Dr Sarkar is the associate editor of the Transactions of the Indian Ceramic Society, a reviewer of many prestigious research journals, was the assistant editor of the IRMA (Indian Refractory Makers' Association) Journal, etc. Dr Sarkar has successfully completed many sponsored research projects, he has more than 200 research publications and nine patents to his credit. Dr Sarkar also appears in the list of the *World's Top 2% Scientists, prepared by Stanford University, United States, for consecutive years.*

Dr Sarkar has received the Gold Medal from BHU, Jawaharlal Nehru Memorial Fund's award, etc., for his academic excellence, and the Young Scientist Award, Ganpule Award, and Deokaran Award from the Indian Ceramic Society for his scientific and research contributions to ceramic science and engineering.

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Preface

Refractories are the backbone to any high-temperature process and industry, and the iron and steel industries are no exception. Refractories are closely associated with all the iron- and steelmaking processes, and their development, thus, contribute directly or indirectly to the human civilization. Since the start of the iron age (around 2,000 BC), iron has been produced by reducing iron ore in a furnace. In the early days, charcoal was mostly used as the reducing agent, and locally available clayey materials as the furnace refractory lining. The purpose of the lining was primarily to withstand the heat, along with the mechanical and chemical actions, of the process. Later, clay–charcoal mixture was also found to be used as refractory lining, especially in Europe, Japan, and China, for better performance and life. The first primitive blast furnace producing molten iron was developed in Europe in the 14th century, which was essentially changed with time for better performance, productivity, economy, and safety.

Major technological and industrial advancements post–Industrial Revolution (during the 18th and the 19th centuries) were found during and post–Second World War. The advancements were seen in all industrial sectors, including the iron and steel industries and refractory industries. Advancements that started for the iron and the steel industries during this period were the use of high temperature and high pressure in blast furnaces, the industrial use of oxygen blowing in open hearth and electric arc furnaces, top-blown oxygen converters, vacuum degassing of steel, continuous casting process, etc. Similarly, the major advancements that started for refractory industries were the incorporation of carbon in oxide systems, the initiation and use of MgO-C refractories, the start of the use of castables, the development and use of high-alumina cement, the use of cement in castables and monolithics, etc. Further advancements and improvements for the iron and steel and the refractory industries continued with time and are still going on for further betterment.

The iron and steel industries consume a huge amount of refractories, and more than two-thirds of the total refractories produced globally are being used only for iron- and steelmaking. These refractories are of different compositions and varieties, starting from acidic and basic to shaped and unshaped, oxides and non-oxides, fired and unfired, etc. Among all the different varieties of refractories, there are few specific refractories that are very special in nature and used only for a pinpointed specific application and only to perform a specific function. These functional refractories have become irreplaceable for those specific applications and functions and are of prime importance for iron- and steelmaking. But hardly any book or well-documented literature is available on these advanced refractories, and so this book, *Advanced Refractories for Iron and Steel Industries*, is an attempt to overcome the shortcomings in literature and provides a concise, compiled, documented knowledge and information on these advanced functional refractories used for the iron and steel industries.

Advanced refractories used for all the different primary shops of iron and steel industries, namely, ironmaking, steelmaking, and casting shops, are covered in the book. The first three chapters cover the advanced refractories for ironmaking, namely, ceramic cup for blast furnace, taphole clay, and trough refractory. The next four chapters cover advanced refractories for steelmaking and processing, namely, slag arrestor dart cone, taphole sleeve, porous plug, and slide gate refractory. The last three chapters cover the advanced refractories for continuous casting, namely, ladle shroud, monoblock stopper, and subentry nozzle. Various aspects of all these advanced refractories are covered in the book, including the possibilities for improvement of these advanced refractories that are already happening today and will still occur in the coming days.

At the end of the preface, I would like to record my sincere thanks and gratitude to all who have rendered suggestions and helped directly and indirectly in varieties of ways in making the book up-to-date and beneficial for the readers.

1 Ceramic Cup for Blast Furnace

1.1 INTRODUCTION

Iron is the fourth most abundant element on the Earth's crust and the most used metal on the planet. But iron is not available in its metallic form in nature; rather, it is available as various compounds in different minerals and ores. Other than iron-containing compounds (which are mostly the oxides), the ores also contain various other compounds which are unwanted and are impurities for the iron. Different impurities are present at different amounts in different ores, which are commonly referred to as "gangue" material. To produce pure iron, the gangue materials must be separated, first, from the iron source, and then the pure iron is to be extracted from its compounds. The process of getting pure iron from its ore commonly follows the pyro-metallurgy route, a high-temperature process. The high temperature is needed for the separation of gangue materials in liquid form by chemical reactions and further reduction of iron oxide (present in the ore) to convert it to pure elemental metallic iron in molten form.

The most common and widely used process of pyro-metallurgy for making iron is the blast furnace (BF) process, which uses an oxidation–reduction technique to extract elemental iron from its compounds and separate it out from the impurities present in the ore. As per the *Collins English Dictionary*, a *blast furnace* is "a large structure in which iron ore is heated under pressure so that it melts and pure iron metal separates out and can be collected." In detailed words, a BF is a vertical shaft (tower) type of high-temperature processing unit into which a blast of hot compressed air is introduced from the mid side wall, and the iron ore, with other reactants, enters from the top of the shaft, moves downwards through different sections at different temperatures, then reacts and finally produces the metallic iron and the slag (containing the gangue materials), both in molten state. The molten iron and slag are accumulated at the bottom of the furnace and collected intermittently through the opening (taphole) at the bottom wall. The BF is made up of various refractories that provide a safe and prolonged life to the furnace and allow the process to run in a continuous manner with optimum heat energy requirement to produce molten iron. The refractory lining of the BF is to protect the furnace shell from the high temperatures, and also from the chemical and abrasive actions of the moving charge and product materials inside the furnace.

The application environment of the refractories at different regions of a blast furnace varies widely due to the different pyro-metallurgical processes associated with various chemical reactions operating at different stages at different temperatures. Diverse physico-chemical conditions with various thermo-mechanical activities exist at different regions of the blast furnace that demand for different types and grades of

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refractories at different zones. Refractories used in different regions are to take care of all the thermo-mechanical and chemical activities to avoid damage due to them and to run the process continuously for years together. Again, to meet the ever-increasing demand of higher productivity, there is a trend of using large-capacity BFs that are subjected to further stringent operating conditions. To meet the demand for long service life under stringent operating conditions, a good combination of high-grade refractories is a must to ensure high productivity with smooth and continuous operation.

Among the different zones of the BF, the bottom and hearth portions are the most critical area for the refractories. With the BF being a high-temperature and high-pressure reactor, the bottom and hearth portions suffer due to severe high-temperature reactions, direct reduction reaction, melting, abrasion, erosion, corrosion from accumulated molten iron and slag, impact of frequent tapping, etc. Again, it is nearly impossible to repair or replace the hearth lining in an ongoing BF campaign, as it is not possible to reach that area without stopping the furnace and its production. Hence, it has been accepted that the life and service condition of the hearth refractory lining of a BF are the limiting factors to determine the service life of the blast furnace. Maintaining a safe hearth lining is the key link associated with the campaign life of the blast furnace. Prolonging the BF campaign is dependent on a long hearth service life that requires the systematic design and engineering of the hearth, the cooling system, and the monitoring arrangement, and the most vital part is proper refractory selection.

1.2 REFRACTORIES FOR BF HEARTH

The historical development of refractories shows that the controlled use of fire in the very early days of civilization was achieved by the use of locally available clays. These locally available clay-based refractories come under the classification of fireclay refractories. The blast furnace is also no exception, and all the refractories that are used in the BF in the very early days were clay-based. With the progress of time, BF application temperature has increased, the application environment for the refractories has become harsh, and gradually, fireclay-based refractories are being replaced by high-alumina refractories. As the application requirements for the hot face refractories in BF hearth are further critical from refractory points of view, high-alumina-based refractories have been in use for about a century or more. Mullite-containing high-alumina refractories were in the hot face for better corrosion resistance against silicate slags, backed by alumina refractories with high strength. As the demand for iron and steel has grown tremendously post–Second World War, large BFs with high productivity became common across the globe. This has also drastically affected the wear rate of hearth refractories, as the overall load of the furnace on the hearth and bottom refractories has increased along with the blast pressure. The major causes of degradation for hearth refractories are:

1. Alkali attack
2. Corrosion and dissolution of refractory by molten slag and iron
3. Wear and erosion of refractory due to moving molten iron and slag, especially during tapping
4. Penetration of liquid metal and slag within the refractory

As the attack on hearth refractories increases with the productivity and size of the furnace, the age-old conventional high-alumina-based refractories have failed to provide satisfactory service performance and life. Other than the aforementioned causes of degradation, high-alumina refractories also suffer from shrinkage during service due to further sintering and liquid-phase effect, often leading to serious breakouts. The average life of the hearth, and also of the blast furnace, was only in the range of 5 to 8 years.

The use of carbon refractories as dense blocks in the hearth and bottom portions of the BF produced a significant improvement in BF operation. The major function of the hearth is to hold the carbon-saturated molten iron along with the slag produced within the BF. Now, as the carbon blocks are made up of carbon only, they are difficult to dissolve into carbon-saturated molten iron (carburizing dissolution). Carbon has high thermal conductivity compared to conventional high-alumina refractories and effectively passes the heat of the hot face to the next refractory layer behind. Thus, it protects the hot face of the hearth from any strain generation due to thermal gradients. Also, the higher durability of the hearth refractories was obtained with carbon refractories due to its non-wetting character.

Carbon blocks were first applied in Europe and the United States in the middle of the 20th century and have been used ever since. For the continuous and stable operation of the BF, carbon blocks are in exclusive use for the hearth portion. The main advantages of carbon block in the hearth of the BF are as follows:

1. Stable up to very high temperatures in reducing atmosphere without any softening or melting
2. No polymorphism, no phase change, so volumetrically stable at all temperatures
3. Low thermal expansion, resulting in structural stability even at high temperatures
4. High thermal conductivity providing faster cooling and minimizing any thermal strain generation
5. High thermal conductivity and low thermal expansion providing excellent thermal shock resistance
6. Very high corrosion resistance against metal and slag due to non-wetting character
7. Good chemical compatibility with molten iron
8. High hot strength

The use of carbon blocks in the hearth and the bottom of BFs has significantly improved service condition, and the frequent breakouts that were common with high-alumina refractories are eliminated. Carbon has remained the preferred refractory in hearths for decades, as the life of the BF is significantly improved from 5–8 years to 10–15 years. But with time, the demand for metallic iron and steel has increased, requiring for a higher productivity and longer life expectancy of the BF. Thus, further improvement in hearth refractories has become a necessity, and people started looking for alternatives to only carbon refractories for the hot face of hearth applications. Numerous in-depth studies were also conducted, and the following are

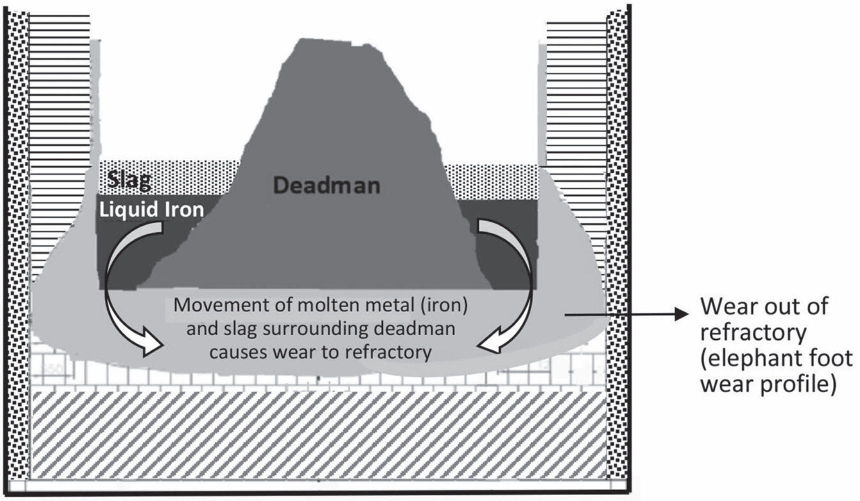

FIGURE 1.1 Formation of an "elephant's foot" wear profile in BF hearth carbon block refractories due to the movement of molten iron and slag in the presence of a deadman.

the shortcomings of carbon refractories in BF hearth applications, which further encouraged refractory technologists for improved alternatives:

1. Hearth refractory erosion due to metal penetration through the surface pores in carbon block under ferrostatic pressure resulting in the formation of a brittle layer and the removal of the refractory during metal movement
2. Wear at the junction of the hearth wall and bottom portion of BF due to high-temperature erosion and abrasion effect from the molten iron and slag flow during tapping and the formation of an elephant's foot wear profile, as shown in Figure 1.1
3. Dissolution of carbon in molten iron, depending on tapping temperature and carbon saturation level of the metal produced
4. Fracture and destruction of carbon block in the presence of alkalis, like K_2O, which is absorbed in carbon block, that reacts with impurity phases present in a carbon refractory, like alumina, silica, etc., forming low-melting and volume-expanding compounds like kalsilite ($KAlSiO_4$) and leucite ($KAlSi_2O_6$)
5. Penetration of zinc (coming from the iron ore and also from coke) in the refractory, oxidation of Zn, and the formation of $ZnAl_2O_4$ and $ZnSiO_3$ upon reaction with slag components and the impurities of carbon block refractories, resulting in the expansion, cracking, and destruction of the carbon blocks

1.3 DEADMAN AND HEARTH WEAR

A *deadman* is the formation of a solid porous mass in the hearth of the BF due to the accumulation of non-oxidized and unreacted coke mixed with molten iron and slag. Being porous in nature and primarily consisting of coke particles, the deadman is lighter in weight and commonly floats/partially floats on the accumulated liquid iron and slag in the hearth. Commonly, the size of the coke particles in the deadman is about 30–40% smaller than that of the original coke feed size, indicating that the incomplete oxidation of coke particles causes deadman formation. A complete understanding and full characterization of the deadman is difficult as the hearth is inaccessible and the prevailing conditions are complex.

Due to the formation of the deadman, the flow of molten mass during tapping is affected. Free space within the hearth is reduced due to the presence of the voluminous deadman, which appears as a truncated cone with its tip in the upwards direction. The flow of the molten mass within the hearth during tapping has to be peripheral, and a large turbulence occurs. This turbulent peripheral flow of molten iron and slag causes a tremendous erosion and abrasion effect on the refractory, especially at the junction between the bottom and the wall of the hearth. Thus, the hearth refractory gets severely affected (Figure 1.1).

In the earlier days, the deadman used to be considered as a stagnant column where coke particles move downwards with a much-reduced velocity and considered to have negligible effect on the ironmaking process. But with time this concept has changed, and nowadays, it is accepted that the deadman strongly affects the gas and liquid flow within the BF's lower part that influences the heat distribution and temperature profile within the hearth, the tapping of molten iron, and the wear rate of hearth refractory.

The deadman has a porous structure, having porosity of around 30–50% of its total volume. So with time, if the deadman grows and covers up the hearth volume, then only 30–50% of the hearth will be available for the liquid (molten iron and slag) to get accumulated. Further, the porous structure of the deadman is also filled with the accumulated molten iron and slag. Generally, the conical-shaped deadman is positioned with its base on the hearth bottom surface; it may sit on the hearth bottom or may partially or fully float on the molten mass. Iron has a much higher density than that of a coke-containing deadman and causes a buoyancy effect. The sitting position of the deadman gets severely affected due to the flow of molten iron and slag during tapping. Again, the flow pattern of molten iron and slag within the hearth gets affected strongly due to the presence of the deadman, especially during the tapping, and causes turbulence within the hearth. Different types of flow patterns of the liquid mass that may occur within the hearth due to different sitting positions of the deadman are shown in Figure 1.2. The resultant turbulence arising from these different types of flow patterns causes severe wear for the hearth refractories.

A partially floated deadman is commonly observed covering the central hearth position and allows a free annular zone at the edges of the hearth (junction between the hearth wall and the bottom) for the movement of the liquid iron and slag. Therefore, during the tapping process, the flow of molten iron along the circumference of the hearth gets minimal resistance. The position and formational placement of dead man restrict the direct flow of metal towards the taphole. The peripheral or circumferential flow of molten metal and slag causes wear and erosion of the refractory at the wall and bottom junction of the hearth. The wear profile moves

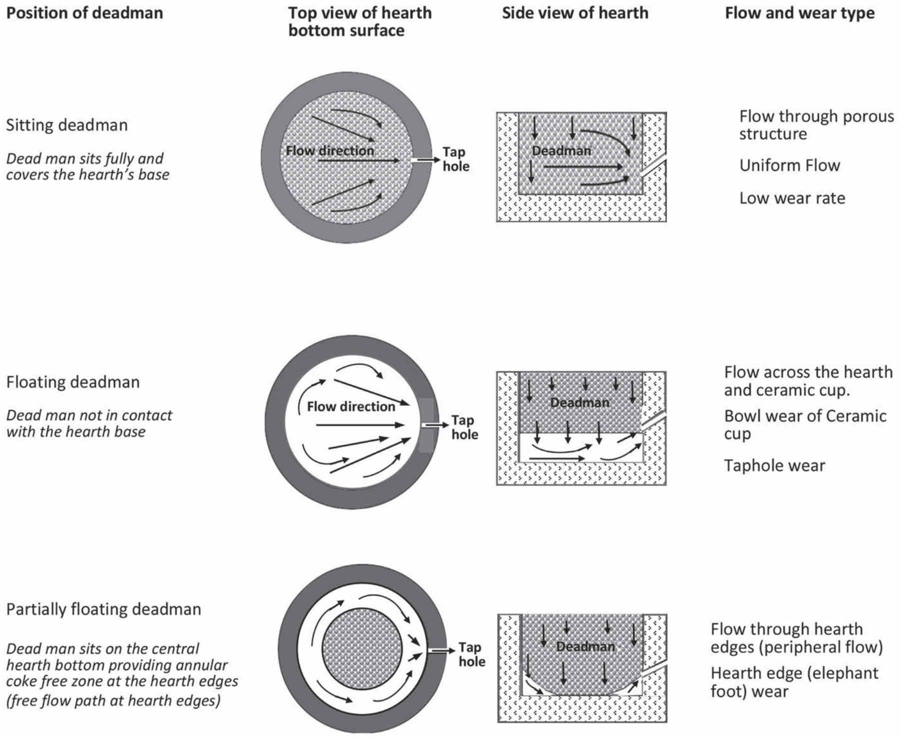

FIGURE 1.2 Effect of sitting positions of the deadman on the flow pattern of molten iron and slag and wear profile of the hearth.

downwards with time due to the gravitational effect of heavy molten iron. The wear pattern of the refractories has similarity to that of the "elephant foot" and is also named so (Figure 1.1). The wear-out effect enhances with time, and the remaining thickness of the carbon blocks becomes minimum and vulnerable to breakout and leakage of molten iron (Figure 1.3).

It has been found that the carbon blocks placed under the taphole or exactly opposite to the taphole are more severely affected. Shear stress is also excessively high at the corners of the hearth wall and at the bottom due to the circulatory flow of metal, aggravating the wear and erosion. Again, if deadman is floating on molten metal, then restriction to direct metal flow during tapping is reduced, which results in reduced circulatory flow and reduced wear at the junction of the hearth wall and the bottom. But this again increases the flow of metal through passage under the bottom surface of the deadman, causing an increase in temperature at the centre of the hearth bottom and also resulting in greater wear and erosion of the hearth bottom. This results in a "pan/bowl-shaped" wear profile. In reality, the hearth lining wear profile, whether elephant's foot–shaped or pan/bowl-shaped, is dependent on the size of the deadman formed, the floating state of the deadman, and its permeability distribution (nature of porous structure).

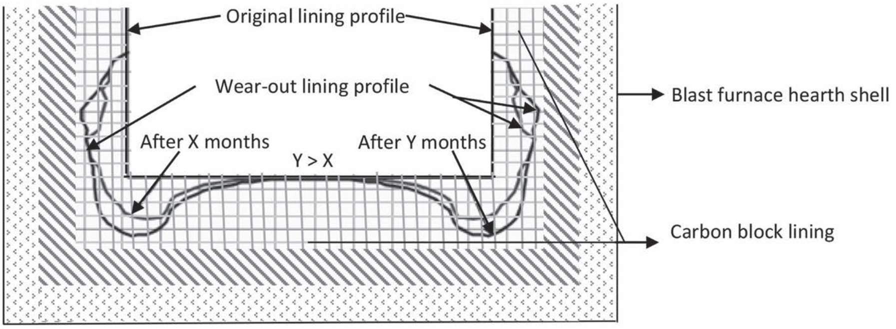

FIGURE 1.3 Changes in “elephant’s foot” wear profile of the hearth carbon block refractories with time.

Carbon blocks have become popular as hearth lining refractories are replacing the conventional alumina refractories due to improved corrosion resistance. The blocks are especially processed to produce a finer pore size (<1 μm diameter) within them to increase the resistance against corrosion and hot metal penetration. The sintered microporous carbon blocks are further densified by re-baking (for increased strength and wear/erosion resistance), and surface pore size is further reduced by tar impregnation under vacuum treatment with high applied pressure. All this processing is done to improve the quality of the carbon blocks, for better performance and an enhanced life of the hearth. But as the operating conditions of the hearth are becoming critical with time due to increased productivity, higher blast pressure and operating temperature, increased impurities in the ore, etc., carbon block refractories are getting eroded and wearing out fast as the life of the hearth increases. The excellence in corrosion resistance of carbon refractories is compromised due to their lower wear and erosion resistance.

1.4 CERAMIC CUP

The application of carbon blocks as BF hearth hot face refractory lining has improved the performance and life of alumina refractories but could not resulted in the desired performance and service life. The major damages observed for hearth carbon block refractories include the typical elephant’s foot–shaped wear/erosion and annular cracks on the side wall of the hearth. The junction between the hearth wall and the bottom is observed to be the area of major concern. The main reasons for such serious damage have been found to be the penetration of hot metal, thermal stress, oxidization of carbon (due to gases like CO_2 and H_2O), wear due to the peripheral flow of molten iron, and corrosion and erosion from molten iron, slag, zinc, alkalis like Na_2O, K_2O, etc. The initial attempts to improve hearth lining performance aimed to improve the quality of carbon refractory blocks, providing greater strength, lower pore size, greater thermal conductivity, etc. But such changes were found to result in marginal benefits. Significant improvement in the service performance and life of the hearth refractory, and also the BF as a whole, was only obtained after the introduction of the ceramic cup for the BF.

The ceramic cup for the blast furnace is an additional cup-shaped refractory lining in the hearth with insulating characteristics (low thermal conductivity) used on the hot surfaces of carbon blocks. The heat flow from the hearth is reduced from around 15 kW/m^2 to around 5 kW/m^2 with the use of ceramic cups, thus reducing the thermal effect on the carbon block refractory. The ceramic cup further resists abrasion and erosion of the liquid iron and slag and slows down the wear-out process of the hearth hot face lining. Due to its good thermal insulation property, the ceramic cup also reduces the total energy requirement and provides a stable, continuous blast furnace operation.

For blast furnace hearth operation, 1,150°C isotherm is considered as the internal liquid–solid interface within the hearth. It is the lowest temperature in the iron–carbon phase diagram where carbon-saturated iron can present in liquid form. So no liquid iron is present below 1,150°C in the BF system, and there will be no wear, corrosion, and erosion from liquid iron below this temperature. Again, the embrittlement temperature for carbon blocks is between 800 and 1,100°C, and the blocks will have a longer life if the operational temperature is below its embrittlement temperature range. The insulating character of the ceramic cup restricts heat conduction and controls the 1,150°C isotherm inside the ceramic cup itself. So there will be no corrosion and abrasion/erosion effect on the carbon blocks from liquid iron, as it would have solidified below 1,150°C and remains within the ceramic cup. Again, the cooling of the BF shell from outside and the high thermal conductivity of carbon blocks reduce the working temperature of the carbon blocks and protect them from the heat effect. Thus, the operational temperature of carbon blocks upon the use of the ceramic cup is significantly reduced, lower than the isotherm temperature and below the embrittlement temperature, resulting in a long campaign life for the carbon blocks, for the hearth, and as well as for the BF.

The use of the ceramic cup provides good protection for hearth refractories in the early periods after installation. But with time and use, due to the continuous chemical attack of molten iron and slag, along with other chemical constituents, erosion/abrasion effects, etc., the ceramic cup will corrode and wear out. Thus, during operation, the effect of protection of the ceramic cup for the hearth carbon blocks will reduce as the blast furnace life progresses. Now, with technological advancements, the quality of the ceramic cup has also improved significantly, and so the duration of the protection of hearth carbon blocks has also increased considerably with time. In the initial days, say, in the 1980s, when the ceramic cup was initially introduced in the BF hearth application, the service life of the cup was only for about 3–5 years, which has currently increased up to about 10 years due to the use of advanced refractory systems for ceramic cups. Further, the life of the hearth lining, as well as that of the BF, depends on the quality of the ceramic cup and the carbon block used. So for a long campaign life of the blast furnace, the carbon blocks used behind the ceramic cup need to be of high quality, like high strength (hot-pressed), high thermal conductivity, microporous/super microporous (very fine pore size) nature, etc.

Again, when in use, the ceramic cup is eroded/wears out with time due to the harsh application condition, but protection for the carbon blocks is continued. This is due to the formation of a skull that consists of the remnants of the ceramic cup mixed with slag and iron. This skull, a semi-solid layer on the inner walls of the hearth, continues to protect the hot face of the carbon blocks and allows the continuous operation of the blast furnace even after the wear-out of the solid/rigid ceramic cup. This type of skull acts as a hot face insulating layer on the carbon blocks, protecting from the heat impact and also from the abrasion and erosion effect due to the peripheral flow and movement of molten iron and slag. The formation of the stable skull and its prolonged stay at the hot face of the carbon blocks are dependent on the cooling rate and the thermal conductivity of the hearth lining. As long as the ceramic cup is present, without complete wearing out, a moderate cooling rate works well due to the good thermal insulation and erosion resistance of the ceramic cup. But with time, as the thickness of the ceramic cup decreases and finally it disappears to form the skull, the cooling intensity must be increased accordingly to match the higher heat effect and thermal conductivity of the carbon blocks (compared to that of the combination of the ceramic cup and the carbon block). Any lower cooling rate will lead to an unstable skull formation or skull removal and faster erosion of the carbon blocks, resulting in a reduced campaign life and even breakouts of blast furnace.

1.5 BLAST FURNACE HEARTH LINING WITH CERAMIC CUP

The refractory lining concept for modern blast furnaces has changed greatly with time, primarily to increase its service performance and life. The life of the hearth, as well as that of the blast furnace, has increased by more than five times within a century, and the conventional alumna-based lining has changed to multiple layers of lining with different types of refractories. The current refractory lining practice for the blast furnace hearth is based on the “heat transfer” and “heat insulation” concept. Heat transfer is achieved by the use of highly thermally conductive carbon blocks, and insulation is obtained by the use of the ceramic cup, which finally converts to a skull during use, protecting the carbon blocks by isolating them from molten iron and slag, thus providing a longer life.

The details of the modern-day blast furnace hearth lining (a layered lining structure) are schematically shown in Figure 1.4 and are described as follows from the outer side to the inner side of the hearth.

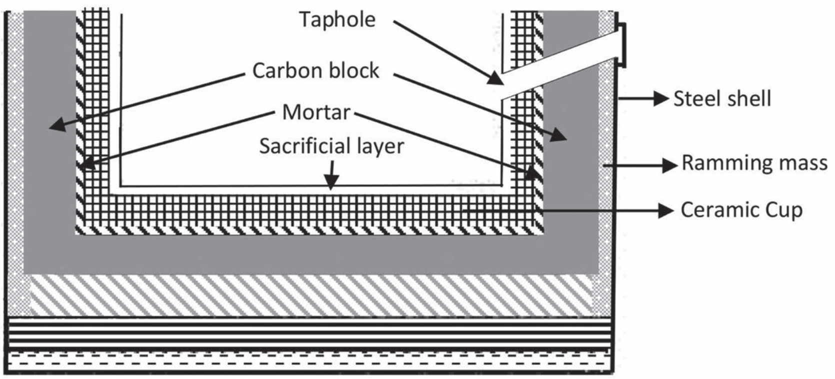

FIGURE 1.4 Details of the BF hearth lining – present scenario.

1. The external steel shell of the blast furnace, providing the basic structure and support.
2. The inner refractory lining is fixed with the shell by using a ramming mass having anchor support from the shell. As the inner lining is mostly carbon blocks, for compatibility, carbon-containing ramming masses are generally used. This ramming mass has the primary function of holding the carbon block, withstanding thermo-mechanical stresses, and also maintaining a good thermal contact between the hotter carbon blocks and the steel shell.
3. Next comes the carbon lining, generally made up of large-sized microporous carbon blocks. The primary characteristics of these blocks are high thermal conductivity and low pore size. High-strength, micropore/ultra-micropore-containing carbon blocks are important for application. The major role of the carbon block is to extract the heat from the inner wall (hot face) of the hearth to make it cooler. Fast cooling will solidify any molten mass that might have penetrated, thus nullifying any chance of leakage from molten iron, which can reach the outer steel shell. There are chances of carbon dissolution (from the block refractory) in iron, causing carbon loss (refractory wear), as the level of carbon saturation in molten iron varies. Hence, it is essential to develop a protective layer to reduce the contact of the carbon block with the molten iron.
4. A special unshaped refractory (acts as a mortar) is used in between the carbon blocks and the ceramic cup to provide stability in the structure and hold the ceramic cup in place on the carbon blocks.
5. The ceramic cup is used in front of the carbon blocks as an insulating layer to protect the carbon from wear/abrasion and erosion of the molten metal and slag flow, and also from the heat flux. The purpose of the ceramic cup is also to keep molten iron away from any contact with carbon blocks, as the carbon saturation of molten iron may not be achieved fully and rapid carbon loss may occur due to the dissolution of carbon within the molten iron in contact with the blocks. Further, due to its insulating character, the ceramic cup lowers the operation temperature of the carbon blocks below the critical temperature of 1,150°C isotherm, and also below embrittlement temperature. Thus, the ceramic cup protects the carbon blocks and helps attain a long service life.
6. In front of the ceramic cup, a low-quality refractory lining, commonly low-grade alumina/fireclay-based refractory, is used as a sacrificial layer to protect the ceramic cup and the carbon refractories from the initial thermal shock impact of the BF, and also from the chemical attack of the initial un-stabilized molten iron and slag.

1.6 TYPES OF CERAMIC CUPS

The function of the ceramic cup is primarily to create an erosion-resistant and chemically protective insulating layer to protect the microporous carbon blocks and to extend the service life of the hearth and the BF. In general, refractories are insulating in nature, but any common refractory cannot perform as well as the ceramic cup under the stringent environmental conditions of the BF hearth. Only a few refractory compositions have been tried and have gotten commercial success for such critical application. Also, with the progress of time, the demands for higher productivity and longer life have also modified the ceramic cup compositions. Brief details of the different refractory compositions that are successful and in commercial use as ceramic cup are described in what follows.

1.6.1 CORUNDUM MULLITE BRICK

Corundum mullite bricks, belonging to the high-alumina refractories family, contain two distinct major phases, corundum and mullite. These refractories exhibit various excellent properties, like high hot strength, high-temperature creep resistance, thermal shock resistance, chemical stability, resistance against hot metal and slag corrosion and erosion, etc. The corundum mullite composition, though developed during the early days of ceramic cup applications, is still in use and extends the service of blast furnaces.

Corundum mullite bricks are generally produced from high-purity raw materials, as impurities affect the properties drastically by low melting liquid phase formation. Mostly, these refractories are manufactured using pre-synthesized mullite as a component. Mullite grains and corundum powders or fused/sintered corundum grains with synthesized mullite powder are used as starting material, which are processed as per the conventional-shaped refractory manufacturing process, like dry mixing, green binder addition, mixing, pressing, drying, and firing. Firing temperature varies between 1,600 and 1,750°C, depending on purity, mullite content, and the type and quantity of impurities present. Some details of the corundum mullite bricks used in ceramic cup applications are provided in Table 1.1.

1.6.2 CORUNDUM–SILICON CARBIDE REFRACTORY

The use of the corundum-SiC-based composite refractory as a ceramic cup is also one of the initial developments. The main constituents for this refractory are brown

TABLE 1.1
Details of the Corundum Mullite Bricks Used for Ceramic Cup Application

Properties	**CM 80**	**CM 90**
Al_2O_3	80%	90%
SiO_2	18%	8%
Fe_2O_3, % ≤	0.5–0.6%	0.3–0.4%
Bulk density, g/cc	2.80–2.82	2.90–2.92
Apparent porosity, %	18–20	16–18
Cold crushing strength, MPa	80–90	110–110
Refractoriness under load (2 kg/cm^2), °C	1,650–1,680	1,700–1,710
Permanent linear change on reheating, %, at 1,500°C for 2 h	±0.2	±0.2

fused alumina as aggregate and matrix phase, and silicon carbide as matrix phase, along with metallic Si powder as antioxidant and little kaolin as additive. The conventional refractory making process with mould pressing and sintering is used to make the refractory, and the fired refractory is further machined before application. Corundum–silicon carbide refractories (also called brown corundum refractory) have excellent corrosion resistance against both acidic and basic slags, as well as against metals. They have high strength, low thermal expansion characteristics, good thermal conductivity, high thermal shock resistance, and excellent thermal stability even at high temperatures. These refractories are equally good both in the oxidizing and the reducing atmospheres, even at high temperatures. They are suitable for numerous BF applications, like ceramic cups, the bottom of the blast furnace, the tuyere and taphole region, etc. Some detailed information on the corundum–silicon carbide refractory is provided in Table 1.2.

1.6.3 PRECAST BLOCK OF CHROME–ALUMINA ULTRA-LOW CEMENT CASTABLE

Chrome-containing alumina castables have been used widely as precast blocks in ceramic cup applications. Chromia and alumina make complete solid solution at high temperatures and provide excellent resistance against corrosion, abrasion, and erosion, along with desirable properties, like high hot strength, high-temperature volume stability, and thermal shock resistance. A reduction in the number of joints present in the ceramic cup lining using precast blocks prepared from castables (initially low-cement-based and later changed to ultra-low-cement-containing compositions) is another added advantage in obtaining an improved precast block of chrome–alumina corrosion resistance and overall performance. Around 10 wt% of Cr_2O_3 is used in the castables, primarily to improve corrosion resistance.

TABLE 1.2
Details of the Corundum–Silicon Carbide Refractory Used for Ceramic Cup Application

Properties	CS-80
Al_2O_3 content, %	78–80
SiC content, %	8–15
Fe_2O_3 content, %	1–1.5
Bulk density, g/cc	2.9–2.95
Apparent porosity, %	14–16
Cold crushing strength, MPa	100–120
Refractoriness under load (2 kg/cm^2), °C	1,660–1,680
Permanent linear change on reheating, %, at 1,500°C for 3 h	0–0.2
Thermal expansion, %, up to 1,500°C	<0.8

The incorporation of Cr_2O_3 in high-alumina castables produces a complete solid solution with Al_2O_3 at high temperatures and limits the low melting eutectic formation. Generally, the presence of silica as impurity or as an additive in cement-bonded castable affects the high-temperature properties due to low melting phase formation with other impurities present in the system. The presence of Cr_2O_3 increases the viscosity of the glassy phase present in the matrix and thereby improves creep resistance. Thus, Cr_2O_3 improves the hot properties of alumina or alumina–silica systems by reducing the liquid phase in the system. It also improves the chemical inertness of the refractory, improving the corrosion resistance. Thus, the formation of $(Al, Cr)_2O_3$(ss) improves the overall performance of the refractory. This formed solid solution along with the mullite phase in the refractory forms an impermeable layer at the refractory–slag interface and improves the corrosion resistance. Thus, chrome–alumina refractory compositions improve the performance and service life of the ceramic cup.

1.6.4 SIALON-BONDED CORUNDUM REFRACTORY

SiAlONs are ceramic materials based on solid solutions of silicon nitride (Si_3N_4) where Si–N bonds are partly substituted by Al–N and Al–O bonds. They are high-temperature materials that show high hot strength, good thermal shock resistance, excellent resistance against wetting or corrosion by molten metals, high wear resistance, and low thermal expansion. Sialon-bonded alumina (corundum) refractories show much improved properties for ceramic cup applications compared to the other options, as described before.

The two major advantages of using sialon-bonded corundum refractories as ceramic cup are:

1. Increased corrosion resistance against alkalis (especially potassium), molten iron, and slag
2. Improved erosion resistance, especially against the liquid metal flow

Sialon-bonded corundum refractories show high hot strength and hardness, high-temperature creep resistance, good chemical stability, abrasion resistance, and excellent resistance against corrosion and erosion of alkali, zinc and slag attack, etc. These refractories show limited alkali penetration, even under microscopic study, and good dimensional stability, without any brittle layer formation (even in the presence of alkalis). They also show high oxidation resistance (in case of water leakage); high insulating character, leading to saving heat energy and coke requirement; and high dimensional stability in the presence of moisture, even at very high temperatures. All these advantages have made sialon-bonded alumina refractories the most suitable option for BF ceramic cup application. It provides the continuous and smooth operation of the BF, improved performance, reduced energy requirements (due to insulating character), and easy control of BF operation due to reduced cooling requirements, and thus prolongs the life of the BF.

Sialon-bonded corundum refractories are prepared from corundum aggregates (mostly fused alumina) with fine reactive alumina, silicon, and aluminium metal

TABLE 1.3
Details of the Different Sialon-Bonded Corundum Refractories Used for Ceramic Cup Application

	Characteristics	Ref 1	Ref 2	Ref 3
Oxide analysis	Al_2O_3 content, %	75–80	80–85	86–90
	SiO_2 content, %	18–22	11–15	8–12
Phase analysis	Corundum, %	72–78	78–82	85–90
	Beta-sialon, %	20–25	18–22	9–14
Physical properties	Bulk density, g/cc	3.22–3.25	3.18–3.22	3.25–3.30
	Apparent porosity, %	12–13	14–15	14–15
	Mean pore diameter, µm	<1	~2	~2
Mechanical properties	Crushing strength, 20°C, MPa	240–260	140–160	140–160
	Modulus of rupture, 20°C, MPa	18–22	12–15	12–15
Other properties	Refractoriness under load (2 kg/cm^2) in N_2 atmosphere, °C	>1,650	>1,680	>1,700
	Thermal conductivity, W/m·k	3.6–3.8	3.0–3.5	2.5–3.0

powders, and also additives in the fine fraction. The beta-sialon bond is developed by controlling the composition and processing parameters of, and the firing conditions in, the nitrogen atmosphere. The bonding (matrix) phase primarily contains the beta-sialon, $Si_{6-z}Al_zO_zN_{8-z}$, where $z = 3$. The amount of sialon bond present in the refractory is varied primarily by changing the amount of the addition of metallic silicon and aluminium powders and by controlling the processing conditions. The properties of the refractory vary significantly with the amount of sialon bond present in it. Refractories containing sialon in the range of 20–30% and about 65–75% corundum phase show improved properties and performance and last for about 10 years in ceramic cup applications, resulting in a BF service life of about 20 years or more. This type of sialon-bonded alumina refractories shows much improved corrosion resistance against molten iron, slag, alkalis, and carbon monoxide gas; abrasion resistance; oxidation resistance; creep resistance; etc. compared to lower-sialon-containing compositions. Some details of the different sialon-bonded corundum refractories are provided in Table 1.3.

1.7 SOME PROS AND CONS ON THE USE OF THE CERAMIC CUP

The ceramic cup withstands the chemical and abrasive forces of molten iron and slag and consequently slows down the erosion process and enhances the performance and life of the BF hearth. It is also expected that, because of its good thermal insulation property, the ceramic cup reduces heat loss of the hearth, thus reducing energy consumption and leading to a more stable operation. The ceramic cup provides good protection for the hearth in the initial periods, but with time, the ceramic cup will disappear due to erosion, and the benefits will disappear as well. After the ceramic cup has lost its structure, during the middle and later period of the hearth life, protection to the carbon blocks continues with the formation on the inner hearth walls of a skull, a semi-solid mass consisting of the remnants of the ceramic cup, slag, and the iron layer (partially solidified). This allows the normal operation of the blast furnace operation, and a long campaign life can be expected.

Generally, under normal service conditions, the ceramic cup survives for about 3 to 5 years. As the major service life of the hearth is to be continued with the same hearth lining, the carbon blocks used in the hearth need to have excellent properties, and high-grade super micropore or micropore carbon blocks are essential. The use of the ceramic cup also requires a greater extent of masonry work, demands a longer construction time, and is cost-intensive.

After the installation of the ceramic cup in the BF hearth, a moderate cooling intensity is sufficient due to good insulation and erosion resistance of the ceramic cup. But with time, as ceramic cup thickness is decreased, or it disappears, the cooling intensity needs to be enhanced to match the high thermal conductivity of the carbon brick. Otherwise, the porous carbon blocks will be eroded quickly due to the heat effect, leading to metal leakage and destruction. But in reality, it is difficult to identify the exact time from when higher cooling is necessary, as proper monitoring and lining thickness evaluation are difficult at the site.

The use of the ceramic cup in hearth applications actually provides a composite lining structure wherein the cup and the carbon blocks are the components. The ceramic cup acts as a protective layer on the carbon brick hot face. However, due to a wide variation in chemistry, the thermal expansion coefficient of the ceramic cup and carbon blocks varies widely, and expansion joints are the key for success of this composite structure. These joints need to be judiciously used with proper dimensions. Any smaller joint gap will lead to a huge strain due to thermal expansion, resulting in rapid cracking and destruction of the hearth refractory, and any excess gap may become a passageway for the infiltration of molten iron and slag and may cause severe damage to the lining structure due to chemical and alkali attacks.

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2 Taphole Clay

2.1 INTRODUCTION

The blast furnace route of ironmaking is the most successful commercial method for the high productivity of molten iron within the economy. The liquid iron produced inside the blast furnace by the carbothermal reduction of iron ores is tapped out intermittently after a specific time interval through the side opening(s)/hole(s) at the bottom (hearth) portion of the furnace called the taphole. The process of tapping out of molten iron from the blast furnace has changed significantly with the progress of time. The tapping sequence, tapping time, tapping schedule, number of tapholes, amount of metal tapped per tapping, use of separate tapholes for molten iron and for slag, etc. have changed with time and with technological upgradations. But for all its advancements and modifications, tapping is still done only through the tapholes placed at the bottom of the side wall.

The taphole is the heart and the lifeline of the blast furnace, as the desired product, molten iron, comes out through the taphole only. The main purpose of the taphole is to provide a means to draw the molten metal out of the furnace, to prevent excess storage, and to allow safe working of the blast furnace. As per the convenience, the taphole can be of different types; it can be used to drain out only metal (iron) or only slag or both the molten iron and the slag. The use of separate tapholes for metal and for slag allows slag-free tapping of metals and for easier treatment of the slag in the downstream for commercial use. But the use of separate tapholes causes difficulty in blast furnace design and operation and also makes the tapping process complicated. Combined metal and slag tapping is commonly practiced but is also associated with design challenge due to the different characteristics of molten slag and metal. With time, the size of the blast furnace has increased, to account for higher productivity, and that resulted in more number of tapholes and frequent tappings to tap out the huge amount of molten metal produced for operational convenience and safety. Globally, there are furnaces with production capacity of 10,000 t of hot metal per day, and generally, such big furnaces are equipped with 4–6 numbers of tapholes.

The tapping out of molten iron and slag is an intermittent process, and in the time period between two consecutive tappings, the taphole is filled with a special type of deformable refractory plastic mass named taphole clay (THC), or mud gun mass. It plays a very crucial role in drawing out molten iron from the blast furnace and to plug and open the taphole. The THC acts as a refractory lining for the taphole during the time gap between two consecutive tappings and performs all the duties of a refractory required for that application. Again, once there is sufficient accumulation of molten metal in the hearth, the same is tapped out by removing the taphole clay from its position by drilling. After the completion of the tapping process (once the accumulated stock of molten iron and slag inside the hearth is exhausted), the hole is again plugged in with a fresh batch of taphole clay mass. The taphole clay must seal

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any gap within the taphole and plug the opening properly to prevent any leakage of molten mass and flame from the hearth, and also any entry of cold ambient air from the outside environment that may cool down the furnace. The taphole clay needs to be strong enough to withstand the load of the accumulated molten iron and slag and the blast pressure (in the tune of 10 to 12 $kg \cdot cm^{-2}$) within the hearth. Plugged-in THC must not dislodge or de-plug from the taphole cavity. The critical functions that a THC performs are:

- Maintaining hearth lining and furnace integrity
- Controlling hearth temperature
- Preventing any leakage of molten iron and hot blast and the entry of cold air
- Regulating molten iron flow during the tapping operation
- Facilitating tapping operations and preventing accidents

2.2 TAPHOLE CLAY (THC)

The blast furnace *taphole clay* is a deformable semi-solid refractory mixture that consists of different refractory aggregates and fine additives and plasticizers. It is supplied by the refractory manufacturer in ready-to-use condition. Its primary function is to seal the taphole of a blast furnace properly after each tapping so that molten iron cannot leak out and the furnace does not cool down due to the loss of heat and/or because of the cold air entering into the blast furnace. The use of the taphole clay helps in the periodical and stable tapping from the blast furnace and also protects the hearth inner lining of the blast furnace near the taphole from the turbulence of the moving molten iron and slag during tapping. The THC needs to perform (seal the taphole) for the duration between two consecutive tapping operations. After each tapping, fresh taphole clay is introduced within the taphole, so it is used for a single cycle/heat only. The taphole clay has to comply with all the operating parameters of the blast furnace hearth and has to maintain a stable tapping time and taphole length, even under severe operational conditions, with high productivity (ton/cubic m/day). The plugged-in taphole clay also needs to be easily removable/drillable to open the taphole for each tapping operation.

Figure 2.1 shows the complete activity associated with the use of THC, starting from the drilling of the used clay in the hole, metal and slag tapping, and finally, taphole closure. Drilling is done to open the taphole and to start the tapping process. It is commonly done by hydraulic drill machines employing a hydraulic hammering technique. Once the drilling is through, the molten mass (mix of molten iron and slag) jumps out from the taphole and continues to flow out till the accumulated mass within the hearth is exhausted. Next, the taphole is to be plugged in using fresh THC mass using a special equipment, called the mud gun machine. A high reliability and robustness of the mud gun machine is required for the safety of the cast house and for smooth blast furnace operation. Once the THC is plugged in within the taphole, it starts setting, gets hard, and starts acting as a strong refractory lining within the taphole, sealing the hole completely and making it leak-proof. The THC stays within the taphole as plugged-in condition for a few hours till the next tapping sequence, as per the BF schedule.

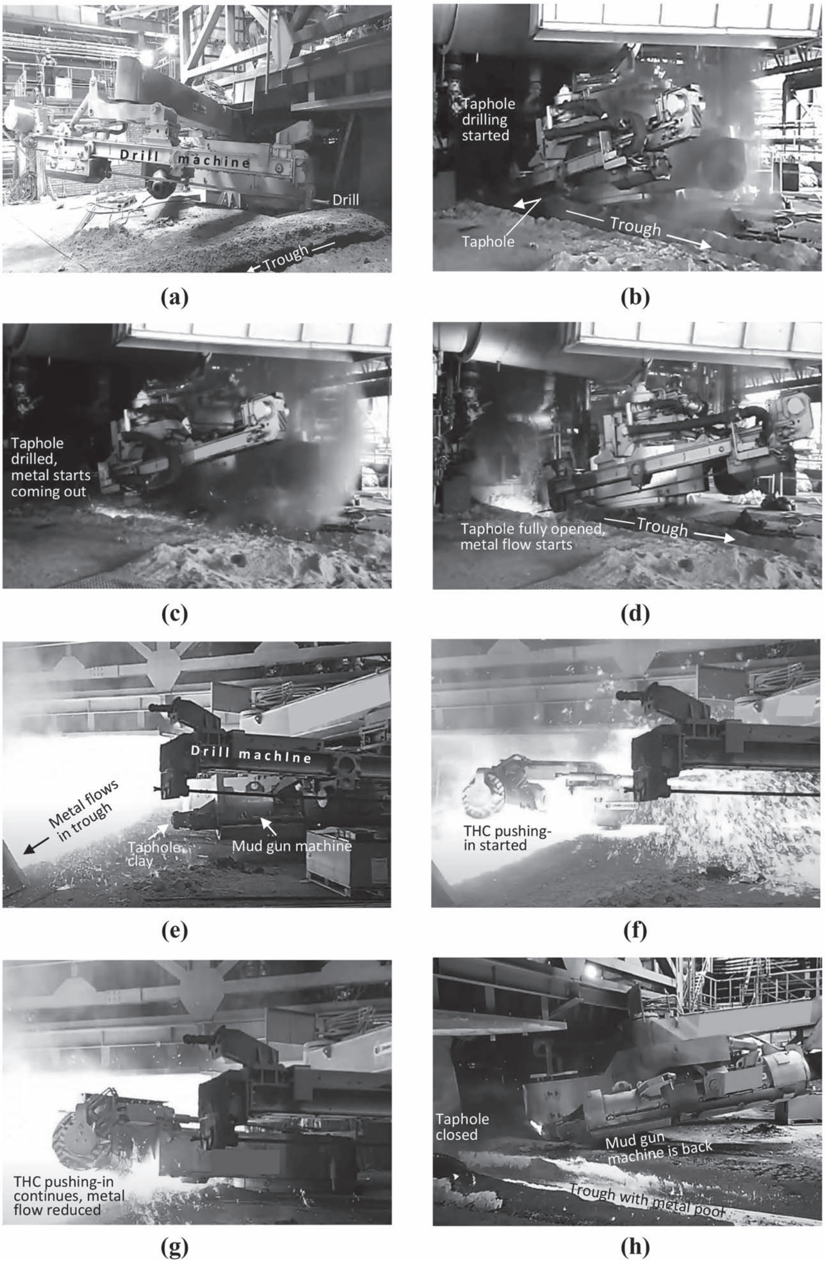

FIGURE 2.1 Complete cycle of taphole clay activity: (a) Drilling machine is ready. (b) Drilling of taphole going on. (c) Drilling completed; metal just started coming out. (d) Taphole is open, metal has started flowing in trough, and drilling machine is returning to rest position. (e) Metal flows through the trough, drilling machine is back to rest position, and mud gun machine is ready. (f) THC plugging in taphole has started. (g) THC pushing continues, metal flow reduced. (h) THC is plugged in, mud gun machine returning to rest position.

During the very early days of blast furnace ironmaking, before the invention and use of proper drilling and plugging-in machine for THC, the opening and closing of the taphole used to be done manually. Steel bars and rods were used in opening the taphole with manual hammerings, and the process was unsafe. For closing the hole, a small amount of clay mass used to be rammed in with the help of long steel bars, and the process used to be repeated a number of times till the complete filling in of the hole. It was very difficult to completely seal the hole against the hot blast pressure and the load of accumulated molten mass, causing the dripping of molten metal continuously and the leakage of hot air blast. Thus, the wastage of molten iron and heat was enormous. The intermittent stoppage of the BF and the regular loss of production were common features. The scenario has changed drastically, however, after the invention of the mud (clay) gun machine and the pneumatically operated drilling machine (initially operated by steam pressure during 1895 in the United States) and their commercial success in 1901, starting in Germany.

The role of the taphole clay has become more important with time for the blast furnace and cast house operation. It is no more a simple refractory mass for plugging in the taphole and for discharging molten iron and slag intermittently from the blast furnace; rather, it has to perform a lot more activities and is exposed to severe hearth conditions. The application has become more critical as the size of the blast furnace is increasing with time and the operational parameters are becoming stringent and harsh for the refractories.

2.3 MACHINERIES INVOLVED IN TAPHOLE CLAY APPLICATION

There are two major machines required for the proper functioning of the THC: One is the drilling machine, and the other one is the mud gun machine. Brief details of the machines are described in what follows, and details of their components are shown in Figures 2.2a and 2.2b, respectively.

2.3.1 DRILLING MACHINE

The drilling machine is used to open the blast furnace taphole by drilling the THC used previously within the taphole. For this purpose, long drill rods that are fixed to a drifter component are used. As per tapping schedule, when drilling is to be done (after sufficient accumulation of molten iron in the hearth), first, the drill rod is placed and adjusted as coaxial to the taphole by using slew arm and swivel body. Next, the latching system fixes the drill in its proper position. The drill rod is then pushed inside the taphole by the hydraulic feed motor and continuously drills the previously used THC mass, which is sintered and hard. The individual components of the drilling machine are marked in Figure 2.2a. It uses a combination of high-rotational drilling torque with a high striking rate and medium-impact energy on the plugged THC mass within the taphole. Once the full length of the taphole is drilled – commonly the depth is about a few meters – the metal will start coming out, and then the drill rod will be taken out from the taphole quickly and shifted away to avoid any damage from the outcoming molten mass and its turbulence. The head of the drilling rod containing the drill bits is shown in Figure 2.3a, and the tapping out of the molten mass from the taphole immediately after drilling is provided in Figure 2.3b.

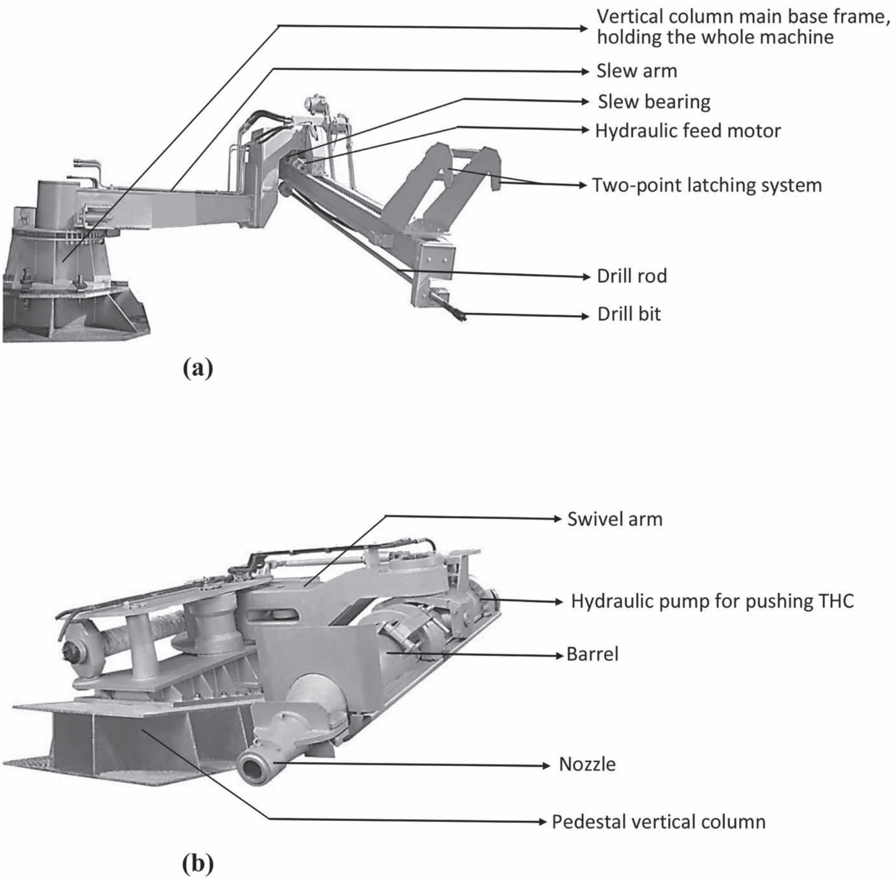

FIGURE 2.2 Machineries used for taphole clay application: (a) drilling machine and (b) mud gun machine.

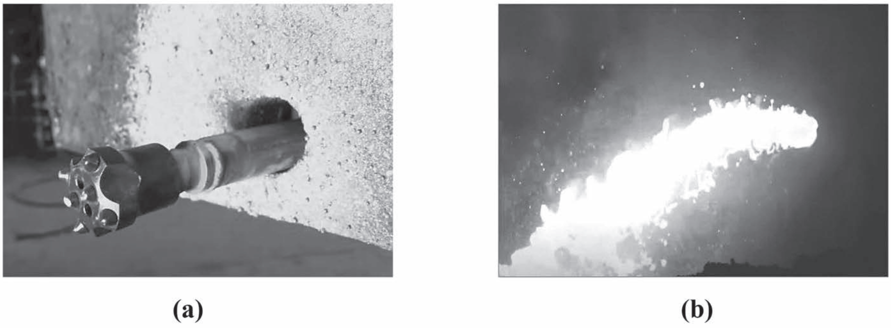

FIGURE 2.3 (a) Head of the drilling rod, featuring the drill bits. (b) Tapping out of the molten mass from the taphole immediately after drilling.

2.3.2 Mud Gun Machine

The mud gun machine is used to plug/push fresh THC inside the taphole to close the same after the metal tapping operation. The machine consists of a pedestal vertical column that holds the rest of the parts of the machine. A swivel arm is attached to the column for easy movement/proper placement of the machine during plugging in. A barrel is attached with the swivel arm that can store and carry the THC. The barrel is attached with a hydraulic pump which can push the THC using a piston head into the taphole through the nozzle of the machine. The individual components of the mud gun machine are marked in Figure 2.2b. The mud gun is basically an extruder machine that can generate a plugging pressure of 25–35 MPa. It can extrude a mass of up to 500 L and is capable of pushing the whole mass at the desired pressure in a single operation without any break. In the blast furnace operation sequence, once the tapping is completed, the nozzle of the mud gun machine (extruder) is placed at the taphole by the swivel action of the arm, and then it is aligned and clamped for fixing the position. Next, the hydraulic pump pushes the clay inside the taphole by the piston head through the nozzle opening. Sufficient pressure needs to be generated for pushing to overcome the hot air blast pressure inside the hearth and the taphole, and due to the semi-solid, highly viscous character of the THC. Once the plugging-in operation is completed, the swivel arm brings back the nozzle, barrel to the rest position, away from the taphole.

2.4 FUNCTIONS OF THE TAPHOLE CLAY

The taphole clay is one of the most critical refractories used in the blast furnace operation, and its proper functioning is essentially required for uniform and smooth ironmaking. The main functions of the taphole clay are mentioned in what follows.

1. To maintain a uniform taphole length after each tapping
2. To seal the taphole completely to make it leakage-proof against any molten mass and hot air blast, and to prevent any entry of cold air within the hearth during the period in between two consecutive tappings
3. To become hard, dense, and strong within the hearth in a short time post-plug-in to resist the blast pressure and the load of the accumulated molten mass
4. To be easily drillable for the opening of the taphole for the next tapping
5. To provide a smooth drilled surface after drilling operation so that the flow of molten mass during tapping is smooth, uniform, and steady, leading to hassle-free cast house operation
6. To protect the inner wall of the BF hearth (around the taphole) from the turbulence of molten iron and slag flow during tapping
7. Separation of hot metal and slag

2.5 REQUIREMENTS FROM THE THC REFRACTORY

THC is primarily required to completely seal the taphole for the time period in between two consecutive tappings and to open the taphole through drilling as per the tapping schedule, thus producing a stable and uniform molten metal delivery from the blast furnace to the cast house. After each tapping process, fresh THC is to be plugged in, and the same sealing performance is required till the next tapping schedule. For a smooth, safe, and hazardless tapping and cast house operation, the THC must possess the necessary refractory-specific properties, like high hot strength and excellent resistance against abrasion, erosion thermal shock, corrosion and penetration of molten slag and metal, etc. Further, it needs to have certain other properties, even when some appear contradicting to one another, as detailed in the following:

1. Uniform and smooth extrudability and flowability of the clay when pushed in to plug the taphole by the mud gun machine.
2. Easily deformable and pliable mass for smooth movement within the taphole without causing excessive pressure on the extruder motor.
3. Deformable enough to form the mushroom head (discussed in Chapter 2.6) after reaching the opposite side of the taphole (the inner wall of hearth), even at the hearth temperature.
4. Excellent adhesion of the fresh THC mass plugged in with old clay mass present inside the taphole and hearth inner wall, even after exposure to heat, for complete sealing of the taphole.
5. Curing within the taphole in a short time and becoming a hard, rigid mass without shrinkage (rather expansive character is desired), to ensure a tight, leak-proof sealing.
6. Hardening and strength development within the stipulated time to withstand the blast pressure and the load of the accumulated molten iron and slag within the hearth.
7. Compact and uniform texture attainment after curing inside the taphole.
8. Permeable enough for the release of various distillation gases and to prevent any “gas pressure” development within the blast furnace.
9. Easy drillability (by pneumatic/hydraulic drill machine) within the prefixed time period. Excessive hardening/strength development during curing may affect the drilling process, requiring longer time and causing an uneven drilled surface.
10. Smooth drilled surface, for a stable and controlled melt stream with a uniform flow rate and without any splash or spray, leading to smooth cast house operation.
11. Erosion, abrasion, and corrosion resistance of the drilled surface against the hot metal and slag during tapping, to protect the permanent hearth wall lining along the length of the taphole.
12. Drilled, exposed, and tapped surface of THC after tapping will act as a stable substrate for the fresh THC material plugged in, and both materials must adhere to/bond with each other for complete sealing, thus providing a stable taphole length.

The effect of the different properties of THC on its performance is summarized in Table 2.1. Further, the correlation between the different characteristics that a THC must have and the requirements of the application site are discussed in what follows as per the chronological sequence during the application of the THC.

TABLE 2.1
Different Properties Required for Taphole Clay and Their Effect on Performance

Property	Effect on Performance
Deformability	Smooth emplacement and filling of the taphole; spreading, complete sealing of the taphole; better mushroom formation
Sinterability	Faster curing and hardening; strength development; better sealing
Corrosion resistance	Resistance to chemical action of molten metal and slag; maintaining taphole dimensions (diameter and length) and providing uniform flow of molten mass; protecting permanent refractory lining of hearth
Abrasion/wear resistance	Smooth and uniform surface and passage for molten mass movement; maintaining uniform taphole diameter and length; uniform and stable metal flow
Drillability	Smooth and easy drilling; smooth drilled surface of the THC for the easy and smooth movement of molten mass; uniform and stable liquid flow; no surge or splash or spray of molten mass; protection of permanent hearth lining
Bonding/adhesion	Bonding between exposed THC surface (that already faced tapping) and new THC freshly plugged in; complete sealing of taphole; proper curing and strength development

- THC must be well-deformable and workable (soft and plastic) during application so that it can be easily pushed in by the mud gun machine and the mass can smoothly move within the taphole cavity. At the same time, it must be sufficiently strong and hard, to remove any liquid (remnant molten iron and slag) present in the tapping passage (taphole) to plug the taphole to its required length.
- It must have high sinterability (but not prematurely within the mud gun) to attain strength and without any shrinkage (rather with little expansion) to ensure complete sealing (plug) of the taphole till the next tapping.
- It must plug in properly to ensure a safe taphole closure (no dislodging, failure, and self-opening) without damaging the permanent refractory lining of the hearth wall in the taphole area. This requires a good amount of taphole mass to be pushed in through the taphole in the pushing direction, and also good spreading of the mass in the perpendicular direction of pushing, for proper sealing within the taphole. Further, the THC must be deformable enough to spread and form a mushroom head once it reaches the inner side of the taphole during pushing in. Such spreading and mushroom head formation protect the permanent lining of the hearth wall around the taphole area from the turbulence of molten iron and slag flow, especially during tapping.
- The THC must be easily drillable even after sintering so that the drilling can be done smoothly, within an acceptable time, straight down the central line middle of the tapping channel, without much hindrance and deviation.

Also, any infiltration of molten metal and slag during plug-in condition due to the presence of any gap between the THC and the hearth wall may result in an excessively hard mass difficult to drill. Oxygen lancing may be required for such cases to open up the taphole.

- It must be strong and durable to withstand the penetration, corrosion, abrasion, and erosion effects of the flowing molten mass (iron and slag), so that the exposed surface of the THC on the taphole wall (lengthwise) can act as a protective annulus between the tapped molten stream and the permanent hearth lining of the taphole. This will extend the lifetime of the tapping channel refractory and the hearth life.
- The THC must have expansion behaviour for all the temperature ranges of its application. The THC is facing a highest temperature of above 1,500°C inside the hearth, whereas the outside shell temperature is about 300°C. Any shrinkage of the THC within this wide variation of application temperature range may result in a gap between the plugged-in THC and the taphole permanent refractory lining. This may cause bleeding (leakage of molten metal) and problem of self-opening of the taphole (de-plugging of THC).

2.6 FORMATION OF MUSHROOM

A stable and uniform tapping of the molten iron from the taphole is essential for smooth cast house and BF operation, and this is possible once a stable and optimum taphole length is maintained. Again, this can happen only when there is a stable mushroom head formation inside the blast furnace hearth. This is a special requirement from the THC to develop a mushroom head–like structure at the inner side of the taphole, on the inner wall of the hearth. The THC needs to spread around the inner wall of the taphole, adhering to the side walls. Fresh THC must have well adhesion/bonding with residual clay matrix, the drilled and exposed surfaces of the previous plug-in injections, present on the inner wall surface of the taphole along the taphole length. The deformability of the fresh THC pushed in within the taphole results in the formation of a mushroom head–like structure once it reaches the inner side of the taphole opening (hearth) under the blast pressure inside the hearth. This formation occurs on the inner hearth wall around the taphole opening. The fresh taphole clay needs to be soft and deformable, even at the hearth temperature, once it reaches the inner side of the hearth wall during plugging/pushing in post–tapping operation. The mechanism of mushroom formation is schematically shown in Figure 2.4.

The formation of the stable mushroom is very important for the blast furnace operation as it improves the plugging of the taphole and provides protection to the inner hearth wall around the taphole. Blast furnace campaigns are strongly dependent on the degree of wear of the hearth lining. The wear is enhanced mainly due to increased productivity, higher metal temperature, and changes in the fuel type (greater extent of pulverized coal addition than that of regular coke addition), zinc deposition, changes in the position of the deadman, etc. All these strongly affect the wear of the inner wall lining of the hearth and the opening of the taphole due to

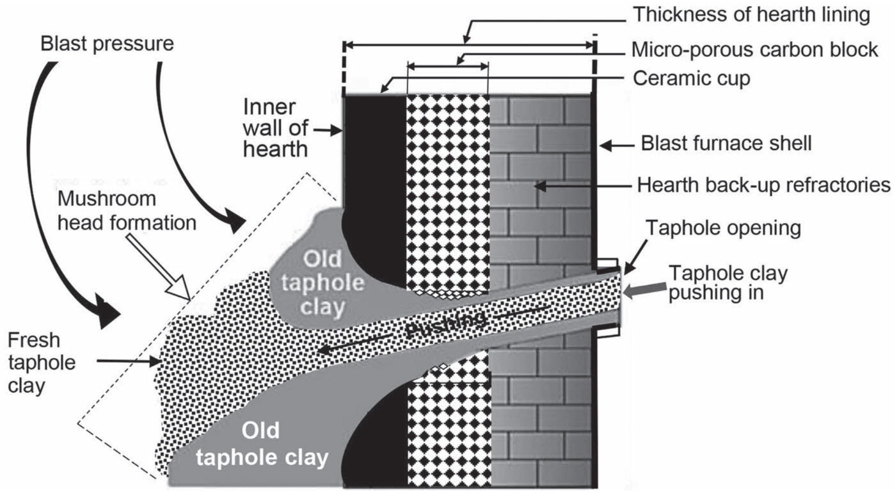

FIGURE 2.4 Mechanism of mushroom head formation inside the hearth of a blast furnace.

vigorous liquid movements and vortex formation during tapping. The wear on the hearth wall, especially around the taphole, can be restricted/reduced by the formation of the mushroom from THC. The formed mushroom is coaxial with the taphole axis, and the mushroom head spreads in all directions around the taphole opening, covering the hearth inner wall and protecting it against any type of wear, erosion, and de-plugging of the THC. The various physical and chemical factors on which the mushroom formation of the THC is dependent are the raw materials used and their granulometry, binder properties (high carbon-containing tar and resin system), viscosity and hot plasticity of the THC, deformability and curing properties of THC at hearth temperature, sinterability, strength development, etc.

Mushroom formation provides an extra protective layer on refractories over the hearth lining around the taphole and takes care about all the aggressive actions caused by the movement of molten iron and slag during tapping. Thus, it improves the performance and extends the service life of the hearth lining. Any damage in the hearth portion is difficult to repair in an operational (running) blast furnace, and so mushroom formation is essential in attaining a longer hearth life. For the desirable extent of mushroom formation, the THC needs to be:

- Sufficiently deformable upon reaching the inner side of the hearth while pushing in
- Adequately strong for the entire range of temperature of its operation to resist any de-plugging
- Adhered strongly with the permanent lining of the inner hearth wall to form a long and stable taphole length
- Strongly resistant to corrosion, abrasion, and erosion effects of the aggressive molten iron and slag movements, providing a long cast duration and uniform casting rate

Moreover, each blast furnace has its own operational practice. They have differences in raw materials used (composition of iron ore, ore-to-pellet ratio, reactivity of coke, etc.), differences in fuel (composition of coke and pulverised coal, their ratio, etc), differences in productivity, differences in inner volume and dimensions, differences in blast pressure and blast temperature, and differences in tapping sequence, THC pushing and drilling parameters, and many others associated with the ironmaking process. Thus, to obtain an optimised taphole performance and a smooth ironmaking practice, taphole clay formulation and application may need to be tailor-made for each furnace and its specific operational parameters.

2.7 CONSTITUENTS OF THC

The quality of the THC is very important for the functioning and performance of the blast furnace and the cast house. Further, the criticality of application for the THC is increasing with time due to the increase in the size of the blast furnace (for higher productivity, 10,000–12,000 t/day), the change in the composition of the metal and slag due to the gradual depletion of good-quality ores (raw materials), the increasing pressure on the taphole clay for productivity, the increased length of the taphole (4–5 m), etc. All these criticalities in application require a high-quality THC product for the uniform and smooth operation of the blast furnace. Furthermore, high-quality THC products also help in reducing the specific refractory consumption per ton of steel produced.

The taphole clay is a composite-natured refractory material containing smaller-sized aggregates (mostly alumina/alumina–silicate and coke), fines and matrix phase (clay/fine alumina), filler material (coke), binder (tar, pitch/resin), abrasive materials (silicon carbide), and some other special additives for specific property enhancement (metal powder, lubricant), among others. The selection of the raw materials and their amounts may vary according to the availability, cost, specific properties required, and application demands. For any refractory manufacturer, a fewer number of ingredients provides greater control on the processing, chemical composition, particle size, cost, and consistency in taphole clay quality. The chemical and granulometric compositions of the THC must be such that it can provide good sinterability to attain sufficient strength within a specific time period; deformability for smooth emplacement within the taphole and proper plug in; mushroom formation; swelling for proper sealing against any metal/flame leakage or cold air entry; the required resistance against corrosion, erosion, abrasion/wear; etc.

The taphole clay is manufactured in the refractory makers' units and supplied to the iron and steel industries as a plastic mass in ready-to-use condition. To retain the deformable plastic character, THC is generally wrapped in a cellophane/plastic sheet to avoid any loss in moisture or volatile matters. The plastic is removed only when the THC is to be applied and fed into the mud gun machine. Figure 2.5 shows the THC in a plastic-wrapped condition as supplied by refractory manufacturers.

2.7.1 AGGREGATES AND FINES

From the early days, the chemical and granular compositions of THC have seen various changes. From the major constituent (composition) point of view, the initial coke-based THC system changed to an alumina-based one, then shifted to silica-based

FIGURE 2.5 Plastic wrapped THC as supplied by the refractory manufacturers to iron and steel industries.

composition, and further modified to have an alumina-silica-based system containing coke and carbon. As on today, THC can be considered as an unshaped plastic refractory made up of alumina and alumina–silicate aggregates and fines with carbon (coke and graphite), bonded with organic binder, and also contains various other small components and property-enhancing additives. Among the various smaller components and additives, silica, zirconia, silicon carbide, kyanite, coke particles, carbon, metallic powders (like, Al, Si, Fe-Si alloy), etc. are important. The additives play multivarious roles in the performance of the THC, like improving abrasion, erosion, and corrosion resistance; enhancing compaction and strength; providing antioxidant property; lowering volatility; reducing shrinkage; improving extrudability and sinterability; etc. The roles of each of the components are summarized in Table 2.2.

The granulometric composition of the THC is also shifting towards a finer fraction due to the increased role of the matrix phase in the properties and performance, especially for extrudability, sinterability, and strength development. Commonly, in granulometry, a coarser size is present in the range of 1–3 mm and up to about 20 wt%. A finer matrix phase (below 45 μm) is present above 50 wt%. The use of ultrafine particles (less than 10 μm) has also become important for the matrix and overall property improvement, like improved compaction, better sinterability, greater sealing, higher strength, enhanced resistance against corrosion and abrasion. The presence of pure and finer silica (or alumina–silicate) particle is beneficial for the formation of mullite upon reaction with fine alumina present in the system at higher temperatures, resulting in improved corrosion resistance and expansion characteristics. This expansive nature is essentially required for better sealing characteristics and helps resist any de-plugging of the THC.

2.7.2 BINDER

Commonly, liquid binders are used for the THC that holds the different size fractions of various components together, especially at the green or unfired condition. The binders coat the refractory particles during mixing, making the mass flexible and

TABLE 2.2 Constituents of Taphole Clay and Their Role

Constituent	Form	Role
Fused alumina, calcined bauxite	Aggregate	Main aggregate; filling material; provides strength and resistance against abrasion, corrosion, wear
Clay	Smaller aggregate and fines	Deformability and extrudability (plasticity), sinterability, mullite formation, mushroom formation
Pyrophyllite	Smaller aggregate and fines	Deformability and extrudability, swelling, sealing
Silica, fine sand, fume silica	Smaller aggregate and fines	Mullite formation, expansion, sealing
Kyanite	Smaller aggregate and fines	Expansion/swelling character, sealing, mullite formation
Fine alumina	Fines	Sintering, strength, corrosion resistance, chemical and thermal stability
Zircon and zirconia	Smaller aggregate and fines	Special additive; resistance against corrosion, abrasion, and wear
Chromite	Smaller aggregate and fines	Special additive; resistance against corrosion and thermal shock
Coke	Fine aggregates and fines	Filler material; improves drilling; improves permeability
Carbon	Fines	Non-wetting property; resistance against corrosion and thermal shock; improves drillability and permeability
Silicon carbide	Fines	Abrasive; resistance against slag corrosion, abrasion, and thermal shock; reduces oxidation of carbon
Metallic powders	Fines	Antioxidant character, hot strength
Tar and resin	Liquid	Binder, deformability
Special oils	Liquid	Lubricant, smooth emplacement

uniform through the mix composition. The binders adjust the plasticity and serve to achieve the proper sintering properties of THC. Thus, the binders play a crucial role in the extrusion and emplacement of the THC and its overall property development. At the very early stages of THC development, the binders were clay-based materials that were used to develop the strength and deformability from the plastic nature of clay when mixed with water. Again, as the THCs are always in contact with molten mass, carbon has become an essential component due to its non-wetting character. But for carbon-containing compositions, the clay water system is not the suitable binder, as carbon does not disperse well in water due to its hydrophobic character, and also, clay may oxidize the carbon. To overcome these crises, organic liquids are used as binder for the THCs, replacing the clay-water system. Initially, coal tar/pitch was used as binder, up to about 20 wt%, in the THC mix, which was slowly replaced by phenolic resin (phenol formaldehyde) with time. Both the tar- and the resin-bonded systems have their own merits and demerits. So presently there are THC manufacturers who use tar or resin or a combination of these two as binder.

Tar-bonded THCs are excellent in achieving the desired taphole length and long cast duration. They also show better adhesion and bonding with the previously plugged in material (old THC), even at high temperatures. Thus, tar-bonded THCs produce a better leak-proof sealing for the taphole and make a consistent monolithic lining all through the taphole length, exhibiting uniform and better performances. But tar has the major drawback of environmental pollution. It releases various polycyclic aromatic hydrocarbons (PAHs) during use (heating), including the carcinogenic benzo(a) pyrene, and makes the cast house area unhealthy. Further, tar-bonded THCs are relatively hard and thermoplastic in nature. So to attain proper deformability and extrudability, these THCs need to be preheated (before extrusion/pushing in the taphole) within the mud gun barrel by gas burners, hot water, steam, or other heating systems. Further, as tar is thermoplastic in nature and not thermosetting, the tar-bonded THCs require some time to harden inside the taphole, and the strength development in the tar-bonded mass is relatively slow and time-consuming. As long as the setting and hardening occur in the THCs, there is a possibility that the plugged-in THC may be de-plugged due to the blast pressure coming out from the inside of the hearth. Hence, an external support is required to ensure the plugged-in condition, and the mud gun needs to remain at the pushing position (taphole mouth) for some time even after the completion of plugging in the THC. This external mechanical support to the plugged-in THC reduces the chances of any dislodging and/or self-opening. Further, due to a lack in strong C-C bonding, the tar-bonded THCs show relatively low strength even after hardening. Also, with the presence of a higher amount of volatile matter in tar, a greater extent of porosity is formed in tar-bonded THCs, resulting in faster, easier corrosion and wear-out.

On the other hand, resin-bonded systems are environment-friendly and have a shorter curing time (with a cross-linking agent). Commercially, phenolic resin, both novolac- and resol-type, is used as a binder for THCs. From the setting behaviour point of view, novolac is thermoplastic, and resol is thermosetting in nature, and so when the novolac resin is used in THC, hexa-methylene tetramine is used (around 10%) as a hardener. The use of resin binders results in a high carbonization yield at a higher temperature and produces higher strength. Resin also helps in the reduction in mud gun dwelling time without any heating and faster taphole turnaround. This faster curing also enhances the strength development and better performance of THC once plugged in. But faster curing also requires attention, as that may affect deformability and extrudability, causing difficulty in smooth pushing and plug-in. Faster curing may also affect the proper and desirable mushroom formation. Further, the greater extent of curing may produce a rigid and hard mass, causing difficulty in drilling (requiring more time to drill than the standard, around 15 min) for the next tapping. Again, prolonged storage of resin-bonded THC at hot environments (especially above 40°C) may cause detrimental performance due to its faster curing characteristics.

The use of a binder as a combination of tar and resin optimizes the properties of each system and has become popular too. To attain the desired consistent quality in THC, close control is required during the manufacturing process of THC, and the use of a combined binder system is practiced. Optimization in curing speed, strength development, mushroom formation, and drillability can be attained by using the combined binder system. Also, the THC composition may be monitored and minutely adjusted as per the special and specific application conditions to obtain an optimized performance.

2.8 DEGRADATION OF TAPHOLE CLAY AND POSSIBILITIES FOR IMPROVEMENT

Degradation in taphole clay and its wear rate are dependent on multiple parameters. Other than the quality and properties of the THC, the operational practices of the blast furnace, like, metal flow rate, tapping temperature, chemistry of hot metal and slag, blast pressure, etc., are very crucial for the performance and degradation of THC. Further, the porosity present in the cured-in clay mass and the associated crack formation are important for the wear of the refractory. For a good-quality, wear-resistant taphole clay, the setting and sinterability are important, and both of these need to be completed within the shortest possible time after pushing in within the taphole.

Commonly, the wear rate of THC (enlargement of taphole diameter) varies between 0.1 mm/min and 0.5 mm/min for large blast furnaces, which is again not linearly proportional to time. Important parameters that are directly affecting the degradation of the taphole clay are discussed in what follows.

2.8.1 Composition of Refractory

The composition of the THC is very important for the performance and service life of the refractory. An optimum amount of refractory aggregates of suitable-size fractions, fines, and fillers must be used with the proper quality and quantity of the binder, non-oxide components, and additives. Additives are again crucial for property development and performance. Among the additives, sintering aid, antioxidants, abrasion/wear-resistant materials, etc. are important. Each and every component and their optimum amount are important for the attainment of the desired properties and performance of the THC. Any deviation from the optimized condition may cause poor properties development, leading to a less dense, weak structure and faster wear-out; any oxidation of carbon and non-oxide components will produce a porous structure at high temperature, causing a degradation in hot strength, corrosion, abrasion, and wear; lesser abrasion and wear resistance of the refractory will cause faster wear rate and degradation; improper binder addition and its amount may result in weaker bonding and poor strength development, leading to faster wear and degradation, etc. Suitable binder addition for proper curing and desired sintering with strength development by the proper use of fines and additives are crucial from the THC composition point of view. To improve resistance against erosion, abrasion, and corrosion of the THC, the addition of zircon and zirconia in the composition is also common.

2.8.2 Volatile Matter and Moisture Content

The amounts of volatile matter and moisture present in the taphole clay affect the performance and durability of the refractory. A higher amount of these materials results in a porous structure of the refractory post-curing. This further leads to the oxidation of carbon and other non-oxide components present in the composition, causing a reduction in strength, poor corrosion and abrasion resistance, and a faster degradation of THC. The source of these components is mainly the liquid binder used for the refractory, and so the selection of a proper binder, its amount, and its composition is crucial for the wear and performance of the refractory.

2.8.3 Taphole Length and Mushroom Formation

Both of the parameters are important for a smooth tapping operation, a high metal productivity, and an extended life of the taphole. A uniform and consistent taphole length with stable mushroom formation is essentially required for proper sealing of the taphole, lowering the wear rate and trouble-free tapping process. They help in the proper fixation of the clay in the taphole, sealing without any leakage of any molten mass and hot air blast, providing excellent THC performance and extending BF life. The deformability of the THC even at hearth temperature, an expansive character over the whole application temperature range, sinterability, and strength development are important for the better performance of the THC.

2.8.4 Tapping Temperature and Casting Rate

Tapping temperature is very important for the viscosity and fluidity of molten metal and slag, and their erosion and corrosion behaviour. Any increase in metal/tapping temperature will drastically increase the wear rate of the clay, resulting in the enlargement of the taphole diameter and affecting the whole tapping operation.

Casting rate indicates the aggressiveness of the tapping process. A higher casting rate is commonly practised for greater productivity, causing greater wear and degradation of the taphole clay and lesser control on the tapping process.

2.8.5 Molten Metal and Slag Composition

Chemical constituents of molten iron and slag tapped out from the blast furnace directly affect the taphole clay chemically and wear the same. Impurities like silicon, titanium, manganese, etc. in molten iron drastically affect the refractory and wear out the THC faster. Similarly, a high silica or lime content in slag reacts with the refractory, causing faster corrosion, wear-out, and degradation of the clay.

2.8.6 Basicity of Slag

Basicity is commonly defined as the ratio of lime to silica and is dependent on the composition of the slag. Basicity determines the flow and chemical behaviour of the slag. A basicity between 0.67 and 1.1 is generally considered to be ideal for the blast furnace slag. A change in the basicity of the slag results in changes in chemical reactivity, its melting point, viscosity, etc., causing variations in the flow and corrosion behaviour and directly affecting the wear behaviour of the taphole clay.

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3 Trough Refractory

3.1 INTRODUCTION

The ironmaking technology is changing rapidly with time. The higher demand for steel has developed larger blast furnaces, with a phenomenal increase in productivity. In order to cope up with the higher productivity of the blast furnace, it is also essential to have higher and longer availability of the cast house. Once the molten iron and slag are out from the blast furnace through the taphole, it falls on a channel-type, refractory-lined structure, called the *main trough*, and flows down through it due to the downwards slope. The slag then gets separated at the skimmer block, and the molten iron continues to move along through a similar channel, called the *metal runner*, in the cast house towards the iron ladle or torpedo ladle. The ladle carries the molten iron to the steel melting shop for steelmaking and further processing. The complete trough system in the cast house consists of the main trough, iron runner, slag runner, skimmer block, and also tilting runner. The trough serves the function of providing passage for the molten iron and slag coming out from the blast furnace and guiding them to flow towards the respective runner and transport vessels.

The trough and the runners are important for the transportation, separation, and distribution of the liquid metal and slag while flowing down to the iron/torpedo ladle and slag pot, respectively. After leaving the taphole of the blast furnace, both molten metal and slag flow together through the ambient environment. The trough is designed in such a way that the molten metal and slag get separated from each other due to their density difference (metal being heavier flows at the bottom, and the slag floats on the metal), flowing as separate layers along the main trough. Next, the slag, flowing as the upper layer, is skimmed out and gets separated from the flowing bottom layer of molten iron and gets diverted by a solid refractory piece, called the *skimmer block*. The skimmer block is a dense single-piece huge refractory shape that closes the upper part of the flow channel in the main trough and allows flow only for the bottom layer below the block. So slag, flowing as the top layer, gets obstructed at the skimmer block and skims out from the mixed-flow stream, gets diverted to another opening, and flows down further through the slag runner, while molten iron, flowing as the bottom layer, can manage to pass through the bottom opening of the skimmer block and moves along through the metal runner. Thus, the flow of molten iron and slag gets completely separated, and further, they flow in separate channels in different directions and move to their respective vessels for shipment. The schematic details of molten mass flow in the main trough are shown in Figure 3.1. Further, Figure 3.2 shows a photograph of the main trough after tapping, showing the flow of molten mass in the main trough and the floating of the slag as the top layer (above the molten metal) during flow along the trough.

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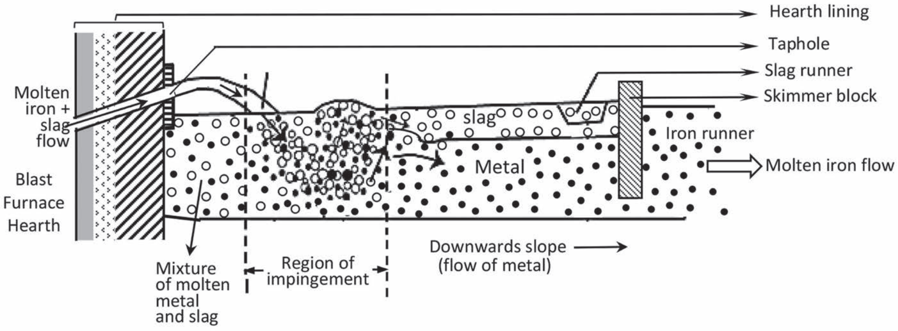

FIGURE 3.1 Schematic diagram of the trough with slag and metal flow and separation.

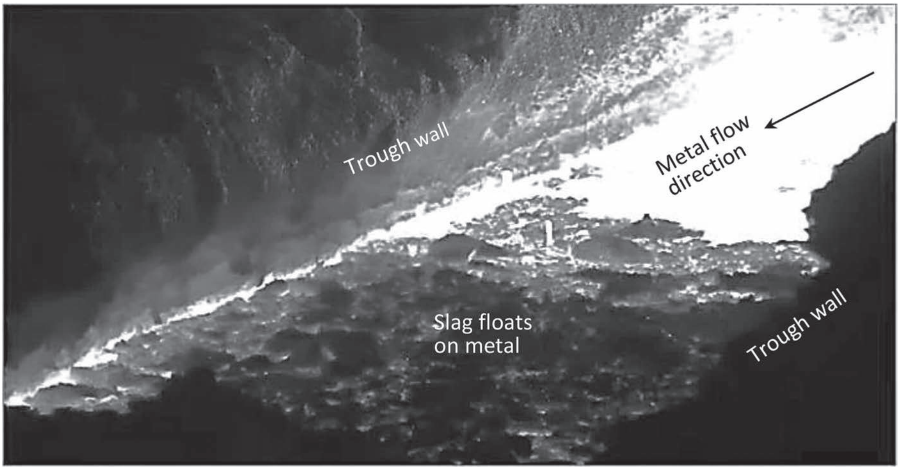

FIGURE 3.2 Photograph of main trough showing the floating of slag above the metal.

A long-performing trough with minimum repair and downtime is the demand of the day. A long-performing trough improves efficiency/productivity, reduces hot metal cost, and provides better working environment in the cast house area. The factors that primarily determine the campaign life of the trough are blast furnace operational parameters, geometry and design of the trough, composition and quality of the refractory used, and the erosion, corrosion, and abrasion of the refractory due to a flowing stream of molten metal and slag, among others. The degrading effects are more aggressive on the refractories in the impact area of the main trough. The primary aim of any blast furnace operation is to maximize the utilization of the trough by reducing the downtime. The major reason for the downtime of the trough is the repair and maintenance required for the working refractory lining of the trough. This requirement of repair and maintenance, nearly after each tapping, is primarily due to a high corrosion and erosion of refractory working lining due to the impact, flow, and chemical reaction of the flowing molten metal and slag.

Among the different parts of the trough system, the main trough (close to the blast furnace, where the molten iron and slag falls after tapping) plays the most critical and vital role for the cast house. The main trough alone consumes more than 50% of the total refractory required for the lining and repair for the total trough area. The wear-out of the working lining refractory from the main trough is primarily caused by the impact and turbulent flow of the mix of molten metal and slag.

3.2 BLAST FURNACE TROUGH

Form the available literature it is found that mostly small- and medium-sized blast furnaces were in use about a century ago with troughs having a higher downward slope for faster flow and lesser accumulation of molten metal in the trough. Low-cost aluminosilicate refractories in the form of unshaped ramming mass were commonly used as trough refractory, generally installed by manual ramming technique and bonded with tar. The blast furnaces mostly had single-taphole, and the campaign life for the troughs was also very low. Post–World War II, the demand for iron and steel has increased, and slowly people started moving towards large-sized blast furnaces. Large-sized blast furnaces came into commercial operation about 50 years back, and the concepts of a tapping system and the trough also changed slowly. For the trough, installation efficiency, lining life, cast house safety and cleanliness, etc. have improved significantly, with reduced maintenance and repair requirements.

The trough has prime importance in the cast house as the molten metal and slag run through it straight away just after tapping. The trough refractory lining is subjected to severe conditions of slag corrosion, FeO corrosion from metal, thermal/mechanical spalling, erosion caused by flowing molten metal and slag, impact and wear, oxidation, etc. Hence, the important requirements for the trough refractory are corrosion resistance to slag and metal, non-wetting nature to metal and slag, high hot strength, high thermal shock resistance, high abrasion and erosion resistance, etc. The main trough, located in between the taphole and the skimmer block, first comes in contact with the molten iron and slag after tapping and is the most severely affected portion of the total trough system. Just after tapping, the mix of molten iron and slag falls on the main trough and starts flowing downwards. The gravity difference separates them in different layers during the movement within the main trough (Figure 3.2). Slag, being lighter, flows down the trough as the upper layer – and the portion/zone of the trough in contact with the slag is called the *slag zone* – while the metal, due to its higher density value, flows through the lower region of the trough, which is called the *metal zone*. So the refractory requirements in these two zones are different. For an optimized performance and a longer life of the trough, attention is required for the zonal lining requirements. Again, the separating line between metal and slag zones on the trough refractory wall is commonly called the *metal line*, and that of the slag and open air is called the *slag line*. The refractories in contact with the metal line and the slag line are vulnerable to chemical attack as three different phases are present there, and so they require greater attention. For the slag line, the three phases are solid refractory, molten slag, and gaseous air, and for the metal line, these are solid refractory, molten metal, and molten slag.

3.3 DESIGN AND CONSTRUCTION OF THE TROUGH

The geometry, design, and construction of the main trough are important for the performance and life of the whole trough lining, and also for the cast house. The important parameters of the trough geometry are length and width of the trough, distance between the iron and slag overflow, skimmer opening dimensions, side wall angle, etc. Based on these parameters, three different types of trough designs are commonly used, and the designs are differentiated among them as per the slope of the bottom surface. The slope of the trough bottom controls the rate of flow of the molten mass through the trough and determines the life and performance of the trough. Figure 3.3 shows the three different trough designs schematically that are commonly used commercially.

3.3.1 Pooling Trough

The pooling trough is a specially designed trough wherein the molten metal is held like a pool within the main trough for a longer time. This is done by using a very minimum slope of the trough to reduce the complete drain-out of the molten metal from the main trough. This design is also known as non-drainable trough. The slope of the trough bottom used is in the range of 0.5 to 1.5% (Figure 3.3a). The metal pool present in the trough from the earlier tapping takes the impact of the fresh molten metal and slag stream when tapping is done again, thereby reducing the refractory erosion in the trough bottom to very minimum. Also, the liquid pool present in the trough protects the refractory lining from severe thermal shock during the initial period of tapping/casting and cooling. Large-sized blast furnaces commonly use this trough design for further advantages, like better slag–metal separation, faster movement of molten

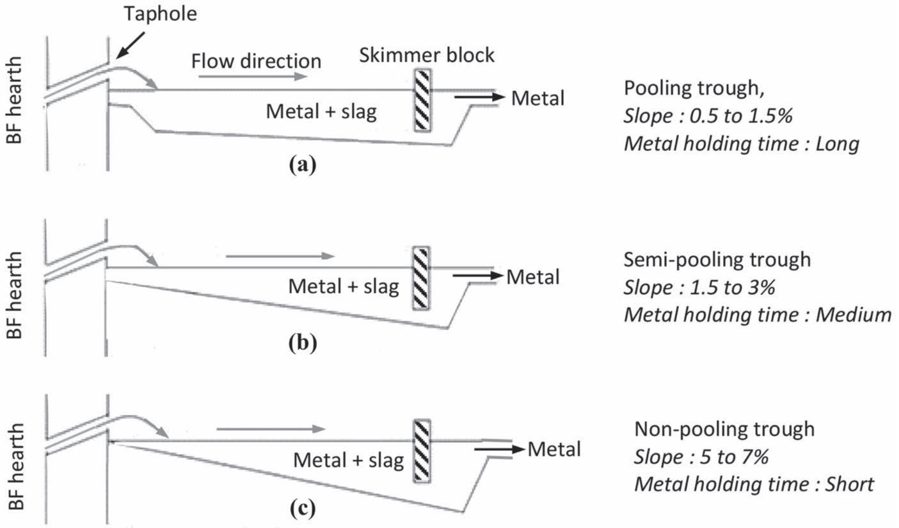

FIGURE 3.3 Schematic of different commercially used trough designs: (a) pooling trough, (b) semi-pooling trough, and (c) non-pooling trough.

stream, lesser maintenance and repair (leading to smooth cast house operation and greater productivity), etc. This design is also popular for furnaces with double taphole operation. Forced cooling arrangements are commonly used to reduce the heat effect on the working lining and to enhance the service life. However, due to the high velocity and turbulence of the molten stream from the larger casting volume for large BFs, the erosion effect on the trough side wall is severe. Generally, the pooling trough is completely drained out only for the inspection of the refractory lining. Most of the modern and large-sized BFs use this type of trough design.

3.3.2 Semi-Pooling Trough

Semi-pooling troughs have a relatively higher bottom slope in comparison to the pooling trough, in the range of 1.5 to 3% (Figure 3.3b). So the height/stock of the metal pool within the main trough, especially at the impact region, is low, causing a greater extent of wear for refractories at the bottom and walls in the impact area of the main trough. Thus, this type of trough design requires frequent check-ups for refractory maintenance and repair at the bottom and side walls during the intermediate time between two consecutive tappings. This trough design is commonly used for medium-sized blast furnaces and for single-taphole operation.

3.3.3 Non-Pooling Trough

The bottom slope of this type of trough is very high, in the range of 5–7% (Figure 3.3c). Molten stream coming out from the taphole directly strikes on the refractory of the trough bottom and flows down faster along the downward direction, causing a severe trough bottom erosion. This is relatively an old design for trough, and nearly all the BFs had had pooling trough about a century earlier. As the impact of the molten stream is much on the bottom and the slope is high to flow away the molten mass downstream, the side walls are not much affected. Inspection and patching repairs are very common and practiced almost after every casting/tapping. Also, as there is no protection of metal pool for the main trough working lining, both for bottom and side wall refractories at the impact region, they experience severe thermal shock. This design is commonly used for a small-size blast furnace with single-taphole operation.

3.4 EVOLUTION OF BLAST FURNACE TROUGH REFRACTORIES

The trough refractory lining is subject to slag oxidation and corrosion, FeO corrosion from metal, thermal/mechanical spalling and abrasion, and erosion and impact caused by molten metal and slag. Hence, the essential requirements of the trough refractory lining are to withstand all these conditions without much damage to the lining. Around the 1950s, refractories for the blast furnace troughs and runners were made up of clay and coke only, with tar used as the binder and manual ramming as application technique. A huge manpower and heavy labour were a common requirement due to the frequent repair and relining arising from poor service performance and life. With time, the trough lining has seen evolution in the type of refractories used. Initially used natural clay–based material, causing poor performance and shorter life, was replaced by an anhydrous clay–based ramming mass, which further modified into anhydrous-clay-SiC-based compositions. The use of anhydrous clay nullified the chance of damage caused by the dihydroxylation of clay at intermediate temperatures. SiC was introduced for better resistance against thermal shock, abrasion, impact, erosion, and corrosion. The properties of the lining were further improved by substituting the clay part with alumina, primarily to improve the high-temperature properties. During the 1960s and the 1970s, as large-capacity blast furnaces started coming into operation with modern ironmaking technology, with higher blast temperature and higher pressure, the troughs and runners suffered from the increased severity of the operational parameters. This has demanded for an improved lining material for the troughs and runners. The refractory was further modified to Al_2O_3-SiC-C-based ramming mixes, showing better resistance against corrosion, thermal spalling, and erosion.

The commercial development of high-alumina cement in the late 1960s and the availability of castable technology and products have significantly improved the quality, performance, and service life of the BF troughs since 1970s. An Al_2O_3-SiC-C-based ramming mass was replaced by Al_2O_3-SiC-C-based castables for faster and easier installation, with improved performances. Presently, large-capacity blast furnaces with high productivity and long campaign life have further increasd the blast temperature, tapping temperature, and furnace utilization factor. All these have imposed a stringent working environment for the troughs and runners. Parallelly, a large amount of work on monolithic refractories, especially castables, has been done all over the world for blast furnace trough, and many new compositions and installation methods have been developed. Due to multiple advantages, the ramming mass–based lining system has been replaced by the castable-based system with time. Further, it is important to note that the properties of the ramming mass and the castable for trough application, prepared from same raw materials and having the same composition, vary, especially from the porosity and pore size distribution points of view. Ramming mass lining shows inferior resistance against molten iron and slag penetration in comparison to castable lining and, hence, results in reduced lining life.

Further improvement and modernization of ironmaking and blast furnace technology in the last two to three decades has further modified the blast furnace operating parameters, and also the iron tapping temperature. Thus, the trough operating temperatre has also increased significantly with time. Slowly the cement-bonded castable system has been replaced by gel (silica sol) bonded castables for its multiple advantages. Changes in bonding system not only improve the hot strength and the corrosion properties but also enhance the flow characteristic and lining performances. Self-flowing castables are one further step towards improvement, improving the easeness of lining and saving time and energy for installation. Hot gunning mixes are also in use for trough repair, and maintenance for its ease of application at high temperatures and time and cost savings. Shotcreting and spray gunning techniques are also in use nowadays, providing greater convenience and easeness in installation. Figure 3.4 schematically shows the evolution of refractories for blast furnace trough application.

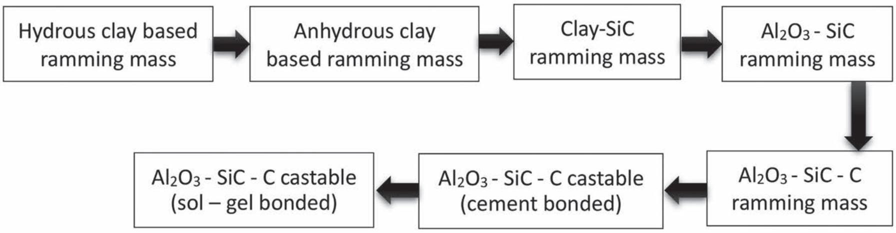

FIGURE 3.4 Schematic for evolution of different trough refractories.

3.5 THE BASICS OF TROUGH LINING

Though most of the study and discussion on the blast furnace trough lining are on the working lining only, the trough is made up of multiple layers of refractory lining, which is finally supported by a metallic structure/casing (or concrete support in a few cases). Each layer of refractory has certain specific functions to perform, and each one is required to have the characteristics accordingly. Working lining refractories that are in contact with the molten metal and slag suffer from the most aggressive conditions of molten mass flow and faces the most intense thermal loading. Frequent repair, maintenance, and also relining are common for this first layer. Next to the working lining, a permanent or safety refractory layer is used, which generally has service life in tens of times compared to that of the working lining. This permanent lining supports the loading effect of the working lining and compensates any working lining damage. Next, there is an insulating layer present between the permanent lining and the metallic shell/casing to prevent the heat from escaping and to protect the structure from the excessive heating effect. A schematic diagram for the complete trough refractory lining, with different zones and layers, is shown in Figure 3.5.

Among all the layers, attention is always at the working lining for its harsh application conditions, and the major improvements and developmental works occur mainly for the working lining refractories. The major properties required for the working lining of the trough are as follows:

1. Easy to install, with good workability and suitable hardening time that must match with the tapping/casting interval/sequence
2. Corrosion resistance (primarily against slag and FeO attack)
3. Non-wetting nature against metal and slag
4. Abrasion and erosion resistances, especially important for main trough (close to taphole) zone
5. High hot strength and impact resistance
6. Uniformly dense and strong structure even at application temperature
7. High-temperature volume stability
8. Thermal spalling resistance for heating and cooling effect due to periodic tapping
9. Oxidation resistance due to the presence of carbon and other non-oxide components exposed to ambient environment.

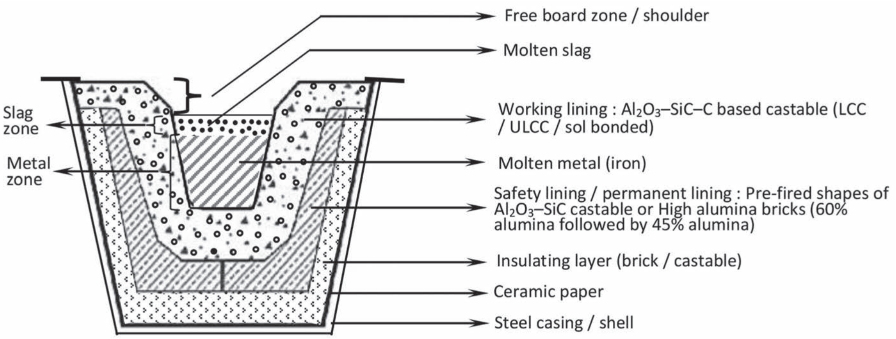

FIGURE 3.5 Schematic for different zones and layers for trough lining.

3.6 TROUGH REFRACTORY: ZONAL AND LAYERED LINING

The major function of the trough is accomplished by the hot face lining, made up of Al_2O_3-SiC-C-based castables. But even in the hot face, the trough is handling two different liquids, molten iron and slag. Both liquids have widely different characteristics, and so their effect on the refractory lining is also widely different. Hence, the zonal concept of lining, even for the working refractory lining, is essentially required to meet the different requirements in the metal and slag zones.

At the topmost portion of the trough, there is a free board zone or shoulder that is not in contact with any molten metal or slag. This free board zone is kept intentionally for safety and as a buffer zone and to protect the cast house from any flooding/overshooting condition of molten metal and slag. Next comes the slag zone, which is primarily facing the flowing blast furnace slag and has to withstand all the effects of the slag. The bottommost lining of the trough wall and trough bottom are in contact with the molten iron and is called the *metal zone*. This zone faces molten metal, much heavier than the refractory, and so the wear effect is also significantly higher. Hence, a stronger refractory is required, which is primarily attained by using a higher amount of alumina in the composition. Thus, the metal zone trough refractory needs to be denser and stronger, so a higher alumina content with lower non-oxides (which prevents bonding and sintering) is the prime feature for these refractories, whereas the slag is chemically active and corrodes the refractory strongly. Hence, corrosion-resistant non-oxide components, namely, graphite and silicon carbide, are added at a higher extent for the refractory used in the slag zone.

Again, the hot face lining requires support (especially mechanical support) from the back-up safety lining present next to the hot face working lining. Alumina bricks (between 50 and 70% Al_2O_3 containing) or low-density, low-conductive Al_2O_3 castables (70% Al_2O_3 containing) or pre-fired shapes of castables are mainly used in the backup or safety lining. The primary function of the back-up lining is to support the hot face lining from mechanical and thermal points of view. Conventional low-alumina-containing brick or castable in the safety lining commonly shows lower strength and corrosion resistance against flowing slag and results in lower lining life. Features of a good back-up and safety are mentioned in what follows.

1. High thermal conductivity, as higher heat dissipation freezes any penetrating liquid metal or slag very fast and restricts the chemical attack within narrow lining thickness.
2. Good resistance to oxidation.
3. High resistance to corrosion and penetration.
4. High mechanical strength to withstand the stresses at wrecking.
5. High thermal stability and thermal shock resistance.
6. Conversely the working lignin should be easily cleaned out before relining and should bear strains.

In case of any failure of the hot face (Al_2O_3-C-SiC castable) lining, the conventional back-up and safety lining is vulnerable against the corrosion and abrasion of the flowing molten metal and slag and may cause the complete break-out of the trough. To improve the performance of the safety lining, especially for the case of failure at the hot face lining, pre-fired castable shapes, blocks, or large-shaped products (called PCPF, *precast and pre-fired*) are used. Pre-fired castable shapes are similar in composition to the hot face castable with lower conductivity. The main advantages of using PCPF castable blocks are as follows:

1. Reduces the number of joints compared to brick lining, thus improving corrosion and abrasion resistance
2. No requirement of drying and strength development activity as essential for in situ castable lining
3. Nullifies the chance of crack formation (due to explosive spalling) compared to in situ castable lining
4. Higher hot strength
5. Presence of SiC (commonly more than 15%) improving corrosion resistance
6. Excellent thermal shock resistance
7. Key structure design (over-lapping construction) amongst the blocks to prevent penetration of molten metal and slag
8. Relatively low conductivity, helping in protecting heat and keeping the solidification temperature (isotherm) of the metal and slag within the working lining, preventing any infiltration

Behind the safety lining, a heat-insulating refractory is used to protect from the heat escaping from the system. Retaining the heat within the trough also helps prevent the molten metal from cooling down. It is also essential to retain the shell (steel casing) temperature at a low level to avoid any shell deformation, and so the insulating refractory is essential. Cooling facilities are also introduced to restrict any heating up of the steel shell. Different zones of trough and different layers of trough lining are shown schematically in Figure 3.5. Details of the different refractory lining materials used for trough are provided in Table 3.1.

TABLE 3.1
Details of Different Refractories Used in Blast Furnace Trough

Properties	Ramming Mass (Resin)	Metal Zone (Cement)	Slag Zone (Cement)	Sol-Gel Bonded	Pre-Fired Castable Shapes	Alumina Brick
Bulk density, g/cc, fired at 1,550°C	2.3–2.4	2.6–2.8	2.6–2.7	2.6–2.7	2.8–2.9	2.3–2.4
Cold crushing strength, MPa, at:						
110°C	16–18	35–40	30–32	30–35		
1,000°C	16–20	40–45	30–35	30–35		
1,550°C	22–25	50–60	45–50	60–70	65–75	70–80
Permanent linear change, max %, at:						
1,000°C		−0.1	−0.2	−0.1		
1,500°C	−0.1	−0.5	−0.5	0.2	−0.5	−0.6
Hot MOR, MPa, at 1,400°C	2–3	4–5	5–7	6–8	10–12	3–5
Chemical analysis, %:						
Al_2O_3	65–70	75–80	60–65	75–85	65–75	58–62
SiO_2	8–10	5–6	3–5	2.0–2.5	15–20	25–30
Fe_2O_3	1.0–1.5	0.8–1.2	0.8–1.0	1–2	0.8–1.0	1.5–2.5
CaO	0.6–1.0	1.5–2.0	1.5–2.0	0.2–0.5	1.0–1.2	0.4–0.8
SiC + C	16–20	12–15	25–30	15–20	10–12	Nil

3.7 THE CONSTITUENTS OF TROUGH REFRACTORY

The trough refractory needs to perform in the critical application area of the cast house and needs to possess various properties. Now, all the different critical properties cannot be attained by a single component of refractory; hence, the trough is lined with a composite type of refractory. The requirement of a wide variety of properties has led to trough lining materials made up of oxide, non-oxide composite system. Again, the fast and easy installation due to limited time availability for trough maintenance and repair in between two consecutive tapping schedules has made high-flowing (self-flowing/pumpable) castables the preferred lining material for the trough. Al_2O_3-SiC-C (ASC)-based monolithic refractories are the most preferred refractory composition for the blast furnace trough systems, including the main trough and slag/iron runner, for many years. Technological improvements in the last few decades have modified the trough lining from ramming mass to low-cement castable, from low-cement castables to ultra-low-cement castables, and further, to gel-bonded (no cement) castables. The desired properties, like hot strength, high thermal conductivity, high temperature abrasion and corrosion resistance, thermal shock resistance, etc. of ASC castables are the main reasons for its selection in such a critical application.

Alumina is the major constituent of the trough refractory, providing chemical inertness, hot strength and abrasion, wear, impact and erosion resistance, among others. The higher the alumina content, the better the high-temperature properties. The presence of carbon increases the resistance against corrosion due to its non-wetting character and thermal shock resistance for low thermal expansion and high thermal conductivity. Silicon carbide improves volume stability; increases resistance against wear, erosion, and abrasion; increases thermal conductivity; resists the slag attacks, etc. Also, the low wettability and lesser reactivity of silicon carbide significantly improve the corrosion resistance, and lower thermal expansion and higher thermal conductivity enhance the thermal spalling resistance of the trough refractory.

Further, the main non-oxide component of the trough refractory is carbon, and the primary source of carbon is graphite. Graphite (carbon) is primarily added to improve corrosion and thermal shock resistance, whereas silicon carbide is added for higher abrasion, corrosion, and thermal shock resistance. But the presence of these non-oxides in higher amounts affects the matrix properties of the castables (due to reduced wettability with water in the bonding system), resulting in reduced flow and other properties development. Hence, the optimal use of non-oxide components, as per the application requirements, is essential to obtain the desired performance and life of the trough.

Though carbon/graphite provides multiple advantages in the trough refractory system, it has the main drawback of high susceptibility to oxidation. Similarly, the other non-oxide component, SiC, also suffers from oxidation at relatively higher temperatures. Further, SiC inhibits the bond formation and sintering within the castable, and so the strength, both at ambient and elevated temperatures, decreases with increasing SiC content. To improve the oxidation resistances of the non-oxide components, metallic additives, like, metal powders of aluminum, silicon, etc., are added to the castable, which act as antioxidants. These metal powders have high oxidation potential and get oxidized to their respective oxides in the presence of any oxygen (oxidizing environment), preventing the oxidation of carbon or other non-oxide components. They also improve the hot strength of the trough refractory due to the formation of metal carbides (on reaction with carbon) at high temperatures, providing extra ceramic bonds (carbides) at high temperatures. The magnesium aluminate spinel is also incorporated in the Al_2O_3-SiC-C system primarily for its high corrosion and thermal shock resistance. Thus, the addition of the spinel improves the corrosion resistance, especially against FeO attack, for trough working lining in the meltal contact areas.

Commonly, the Al_2O_3-SiC-C castables are prepared by using corundum (Al_2O_3) aggregates, SiC (carborundum) grains and fines, microfine alumina powders, calcium aluminate cement as binder, fume silica as flow modifier, metallic additives as antioxidants, and a few other property-enhancing aditives. The castables are commonly processed by the conventional dry mixing route, supplied to the user iron industry as loose granular mass, and the same is mixed with water and cast at the site of application, as per requirement. Also, as the refractory cement contains lime and the trough castable contains alumina and silica, they react at high temperatures to form low-melting compounds in the CaO-Al_2O_3-SiO_2 system (anorthite and gehlenite) within the refractory, deteriorating all the high-temperature properties, especially hot strength and corrosion resistance. For this reason, slowly cement-bonded compositions are replaced by lime-free silica sol–bonded (colloidal bonding) castables, thus nullifying the chances of low melting phase formation and also improving flowability. Further, due to mullite formation within the castable at high temperatures, greater hot strength and corrosion resistance are also obtained.

3.8 ROLE OF DIFFERENT CONSTITUENTS IN TROUGH REFRACTORY

Trough castables are exposed to different wear mechanisms from the flowing mass of molten iron and slag. The penetration and corrosion of metal and slag into the lining and the erosion effect from the impact and flow of the molten stream cause severe wear of the refractory. The wear mechanism is further accelerated due to the extreme thermal gradient in the application affecting the service performance and life of the working lining. The formation of low-melting compounds in the working lining due to the reaction between the slag and the molten iron with the refractory constituents deteriorates the properties abruptly. Hence, the designing of the working lining refractory and the selection of its constituents are very important. A zonal lining concept has optimized the refractory performance as per the requirements of the metal and slag zones. However, for each of the zones, the judicious selection of the raw materials is important for the performance and service life of the lining. Details on the role of different constituents important for the trough zonal lining are described in what follows.

3.8.1 Role of Alumina

Alumina is the major constituent of the trough castable. Being a neutral oxide, alumina performs well in different chemical environments. The slag basicity (CaO/SiO_2 ratio) of the blast furnace slag varies in the range of 0.8 to 1.2, and alumina resists the corrosion well in the whole range. Alumina also provides all the different desired properties, like hot strength, thermal shock resistance, wear and erosion resistances, etc. For further improvement in the specific properties, like corrosion resistance, abrasion resistance, non-wetting character, various other constituents and additives are added with alumina in the trough refractory composition. With the increase in alumina content of the lining, the high temperature withstand ability and the mechanical properties increase. The common sources of alumina for making trough castable are tabular alumina, fused alumina, calcined bauxite, calcined alumina, reactive alumina, etc. Generally, high-pure and high-quality alumina sources are used for trough application to minimize the low melting phase formation from the impurities, considering the criticality of the application environment.

3.8.2 Role of Silicon Carbide

Silicon carbide is primarily introduced into the trough refractory composition (initially in the ramming mass) to enhance the thermo-mechanical properties and resistance against wear, corrosion, and thermal shock. Slag resistance of the castable significantly increases with the increase in the amount of silicon carbide due to its low wettability and low reactivity (strong covalent character). In Al_2O_3-SiC-C-based composition, SiC improves abrasion and erosion resistance for its high hardness, and also thermal shock resistance for its high thermal conductvity and relatively low thermal expansion chcracteristics. Thus, an increase in SiC content in the slag contact area improves the corrosion resistance and also the performance of the refractory lining. But an increase in SiC (non-oxide component) content in the refractory composition reduces the chances of sintering/direct bonding among oxide (mainly alumina) particles, thereby reducing the sintering, densification, and strength development of the refractory composition.

Like all other non-oxide compounds, SiC also suffers from oxidation during application in oxidizing environments, like the trough lining. Again, as per the availability of oxygen in the application environment, the oxidation behaviour of SiC varies. For most common applications, wherein the availability of oxygen is high, SiC oxidises from the lining surface and forms silica. [$SiC + O_2 (g) \rightarrow SiO_2 + CO (g)$]. The nascent form of reactive silica formed on the surface of the trough lining converts to highly viscous silica glass (liquid phase) at high temperatures and covers the surface of the refractory. This viscous layer of silica prevents further oxygen to come in contact with the unreacted SiC at high temperatures and prevents further oxidation, thus protecting the SiC from oxidation. This type of oxidation under high partial pressure of oxygen is called *passive oxidation*. However, at lower partial pressure of oxygen, gaseous silicon monoxide is formed instead of silica on reaction between SiC and less available oxygen [$SiC + O_2 (g) \rightarrow SiO (g) + CO (g)$]. Both the gaseous products formed escape from the surface of the refractory, and silica could not be formed on the refractory surface due to the less availability of oxygen. Thus, no protective layer is formed for the trough lining and oxidation continues, causing great damage to the refractory. This type of oxidation is termed *active oxidation*.

Further, during use in the working lining of the metal zone, SiC also gets oxidized from the oxide impurities present in the molten iron. It is found that the refractory wears out due to the oxidation of SiC from FeO and MnO [$SiC + 2FeO \rightarrow SiO_2 + 2Fe + C$]. This type of oxidation of SiC is the main cause of refractory wear in the metal zone. To avoid such kind of wear-out of the refractory, Al_2O_3-SiC-C castables with a lower SiC content are used for the metal zone, whereas the high SiC content in the refractory is used for the slag zone lining for its higher slag corrosion resistance. Thus, different castable compositions, with respect to SiC content, are used for the working lining of the slag and metal zones, respectively. It has also been found that the use of the broader distribution of SiC particles in the refractory composition results in a better corrosion resistance.

3.8.3 ROLE OF CARBON

Carbon provides multiple desired properties for the trough refractory. Mainly, graphite is used as the major source of carbon for the trough refractory. Though, many a time, the names *carbon* and *graphite* are synonymous, in actuality, graphite is one of the natural sources of carbon used for refractories. The use of crabon in refractories makes the composition composite in nature, as carbon does not react with oxides and makes no compound in the compositions. The incorporation of carbon, and the increase in its content, increases the thermal conductivity of the lining and also improves the resistance against corrosion and thermal shock. The use of graphite as the source of carbon has multiple benefits in trough refractories, mentioned in what follows:

1. It has no deformation, softening even at very high temperatures, and has high thermal stability in a non-oxidizing environment.
2. Non-wettable character against polar liquids, in particular, silicate slags.
3. Very high thermal conductivity due to the presence of an unpaired electron in a crystal structure.
4. Low thermal expansion due to strong bonding in the planar crystal structure.
5. Excellent thermal shock resistance.
6. Graphite has higher oxidation resistance among the different carbon sources due to its compact layered structure.
7. The flakiness of graphite provides a higher thermal conductivity, improving thermal spalling resistance further.

But the surface of graphite/carbon is hydrophobic in nature; graphite particles do not wet and disperse in water (polar liquid medium). Again, most of the castable bonding systems are based on an aqueous system (alumina cement or silica sol). Hence, the use of a higher amount of carbon in a trough castable will produce undispersed graphite in the composition that will lead to segregation of the composition. Due to its hydrophobic character, lighter graphite particles will separate out and float on the surface of the trough castable during mixing, without dispersing uniformly all through the composition, thus resulting in uneven and poor properties of the trough refractory. Hence, only a limited amount of graphite (commonly between 2 and 4 wt%) is used in the trough castable composition, which gets dispersed under the influence of other aggregates and fine particles present during mixing.

Though carbon/graphite incorporates multiple beneficial properties within the refractory, oxidation at application temperatures (even from 400°C) has limited its wide use and requires protective and preventive actions to save carbon. Once carbon is oxidized, it will form gaseous products and will leave the refractory, creating porosity and deleteriously affecting all other refractory properties.

The oxidation of carbon can occur in different ways, and the easiest way to understand oxidation is through gaseous oxidation. Gaseous oxidation is strong when hot refractories are exposed to the open atmosphere and are in contact with air, which directly reacts with the carbon to form its oxides. Also, gaseous oxidation occurs from the entrapped air/oxygen within the molten metal that got trapped during tapping, falling off the molten stream from the taphole to the trough. The entrapped gases reach the trough's hot face lining in the downstream of the trough and cause oxidation of the refractory. Oxidation from gasesous oxygen is commonly called *direct oxidation*. In the interval between two consecutive tappings, the trough is exposed to the open air in the cast house, and the refractories are highly susceptible to gaseous oxidation.

Oxidation may also occur by liquid phase, where the oxidizing components present in the slag or molten iron oxidize the carbon within the trough refractoy. Oxidation from liquid phase occurs mainly due to the presence of FeO and MnO.

This type of oxidation is called *indirect oxidation*. Interestingly, carbon also gets oxidized at high temperatures by the oxide components present in the trough lining itself. Though carbon-containing refractories are considered a composite refractory and the oxide components present are supposed to not have any reaction with carbon, still reactions occur at high temperatures and carbon gets oxidized. The oxidation of carbon degrades the properties drastically, and so proper attention is a must to restrict and reduce the oxidation of carbon.

3.8.4 ROLE OF THE SPINEL

The presence of FeO in the molten iron as impurity affects the refractory used in the metal zone of the main trough as it oxidizes the non-oxide components (like carbon and SiC) and degrades the refractory lining very fast. To improve the performance of the lining, especially to enhance resistance against FeO, a magnesium aluminate spinel is added to the metal zone trough refractory (castables). The magnesium aluminate spinel can absorb the FeO in its structure by forming a solid solution (accommodating Fe^{2+} ions in the vacant cation sites) and minimizing the deteriorating effect of FeO. Instead of a spinel, MgO is also used in the alumina-based castable composition, where it reacts with the fine alumina present in the matrix and form an in situ spinel within the castable at a high temperature during application. This in situ–formed nascent spinel is chemically more active in absorbing FeO, resulting in better performance. Further, the spinel does not get dissolved within the blast furnace slag, and so the slag cannot penetrate much within the spinel-containing trough castable. Thus, deterioration of the trough lining is significantly reduced. However, the in situ spinel formation is associated with a volumetric expansion that may affect the castable properties and performance. On the other hand, the use of pre-formed spinel in the castable composition shows high volumetric stability, nullifies any crisis of MgO hydration, and shows no expansive behaviour at high temperatures as that of in situ spinel-forming compositions. However, the presence of the spinel, whether in situ formed or preformed, has a negative effect on the trough lining as it accelerates the oxidation of SiC. Hence, the use of the spinel and SiC, and their amounts, needs to be judiciously adjusted for effective improvement in slag penetration and corrosion resistance of the trough castable.

3.8.5 EFFECT OF THE SPINEL ON SIC

The incorporation of the magnesium aluminate spinel improves the slag corrosion and penetration resistance of the Al_2O_3-SiC-C castable; however, it also enhances the oxidation of its non-oxide components, like C and SiC. The details of this oxidation mechanism are described in what follows.

1. The spinel decomposes in a reducing atmosphere, forming $Mg_{(g)}$ and $O_{(g)}$.

$$MgO.Al_2O_{3(s)} \rightarrow Mg_{(g)} + \frac{1}{2}O_{2(g)} + Al_2O_{3(s)}$$

2. The released oxygen upon the decomposition of the spinel reacts with the solid carbon to form $CO_{(g)}$.

$$C_{(s)} + \frac{1}{2}O_{2(g)} \rightarrow CO_{(g)}$$

3. The formed $CO_{(g)}$ reacts with SiC(s) and oxidizes SiC to form silicon monoxide [$SiO_{(g)}$].

$$SiC_{(s)} + CO_{(g)} \rightarrow SiO_{(g)} + 2C_{(s)}$$

4. The formed $SiO_{(g)}$ further reacts with $CO_{(g)}$ or $O_{2(g)}$, forming $SiO_{2(l).}$

$$SiO_{(g)} + CO_{(g)} \rightarrow SiO_{2(s)} + C_{(s)}$$

$$SiO_{(g)} + \frac{1}{2}O_{2(g)} \rightarrow SiO_{2(l)}$$

The partial pressure of $SiO_{(g)}$, formed from SiC, and that of $Mg_{(g)}$, formed from the spinel, affect the oxidation of SiC. $Mg_{(g)}$ produces the liquid phase at the surface of the aggregates and in the pores of the castable upon reaction with other matrix components and impurities present in the composition. This liquid phase dissolves the formed $SiO_{2(l)}$. Thus, the $SiO_{(g)}$ formed upon the decomposition of SiC is consumed by the liquid phase. This consumption of $SiO_{(g)}$ lowers its partial pressure. To maintain the equilibrium pressure of $SiO_{(g)}$, the decompoition of SiC continues. Thus, the presence of the spinel accelerates the oxidation and decomposition of silicon carbide.

3.8.6 Role of Cement and Its Content

A *binder* is an essential component of any refractory castable, as there is no shaping/compaction process involved during its manufacturing/processing. The binder bonds the material to retain the desired shape provided till sintering. Calcium aluminate cement is the common binder for refractory castables as it provides sufficient strength at low temperatures and helps in attaining sintering and strength at high temperatures. Particularly for Al_2O_3-SiC-C-based trough casstables, high-alumina cement is the common binder. These cement-bonded castables flow easily than the earlier-used ramming masses, making the installation process faster and easier; sinter well; and develop high strength upon sintering. Thus, installation becomes easier and the service performance and life of the trough are improved. But with the progress of time, the harmful effects of the presence of lime (coming from cement) in an alumina-based castable composition became known. At high temperatures, lime produces low-melting compounds upon reaction with alumina and other additives/impurities present in the castable composition and deteriorate the high-temperature properties, especially hot strength and corrosion resistance. For Al_2O_3-SiC-C-based trough castables, lime produces low-melting liquid phases in the CaO-Al_2O_3-SiO_2 system (namely, anorthite [$CaO.Al_2O_3.2SiO_2$] and gehlenite [$2CaO.Al_2O_3.SiO_2$]), drastically affecting the properties.

To improve the hot properties of the castables, the amount of lime is to be reduced, which is implemented by two different approaches. Developmental work on refractory cement has produced cement with lower lime and higher alumina content, without affecting properties like flow and strength. The lime content in newly developed refractory cements has been reduced from ~35% to a range of 20–25%. The other approach is to use lesser amount of cement by modifying the castable constituents, their particle size distribution, the use of reactive fines, and the use of additives. Thus, the lime content of modified ultra-low-cement castables has been reduced to ~0.3 to 0.5 wt% from ~1.5 to 2 wt%. This reduced lime or cement content has improved packing density and reduced water demand, resulting in well compact high-strength castables with improved high-temperature properties. Thus, the application of these castables resulted in better performance and a longer service life for the trough.

3.8.7 Role of Silica Sol

The introduction of the silica sol as a binder in unshaped refractory, replacing cement, especially in castables, has brought significant improvements as it removes lime completely from the composition, minimizes the chances of low-melting compound formation, and so improves the properties and performances of the castables.

Silica sol is the stable dispersion of silica particles in a liquid medium, usually water, where the silica particles are electrostatically stabilized. The sol (colloidal) particles are small enough so that they do not settle down under gravity, but large enough such that they do not pass through a membrane (grossly, the size ranges between 10^{-6} and 10^{-9} m). When the sol is mixed with a castable composition, the SiO_2 particles cover the refractory particles/aggregates, and they get linked with one another by gelling and coagulation, causing the setting and hardening of the refractory mix, thus providing the initial green strength for the castable. The coagulation and linking of the silica particles form the siloxane bonding (Si-O-Si) in the three-dimensional network within the refractory mix and build up a network structure in all directions. Hence, a sol-gel bonded castable is basically a cement-free composition that develops initial strength through gelation (or coagulation) and forms a lime-free, high-temperature bond without the formation of low-melting phases. Also, as the sol-gel bonding does not involve any hydration reaction, there is no dihydroxylation process at high temperatures. Hence, there is no restriction on mixing and drying time and drying rate. Drying defects are minimal and nearly at the degradation of strength of the castable with an increase in temperature, etc., which are commonly observed for cement-bonded castables.

Further, upon firing, the sol-bonded castable produces the matrix phase, made up of the reaction products between the silica (gel) particles and reactive/finer components of the castable. The gel particles initiate the sintering and any reaction at a much lower temperature due to their high reactivity (coming from its nanometric particle size and extremely high surface area), resulting in enhanced sintering even at a significantly lower temperature. In particular, for silica sol in high-alumina castables, the matrix phase contains mullite, which is beneficial for higher hot strength due to in situ bond formation within the castable matrix at high temperatures, better chemical resistance (especially against silicate slags), and thermal shock resistance of the fired castable due to the presence of the mullite phase. Mullite is formed within the castable matrix below 1,200°C and remains stable even at high application temperatures.

The replacement of the calcium aluminate cement by silica sol in the trough castable composition results in higher flowability, faster and easier installation, reduced drying defects, greater productivity, and considerably improved performance and campaign life. The absence of low-melting compounds at the operating temperatures in the trough castable has improved the performance and service life of the trough lining significantly.

3.8.8 Role of Antioxidants

Refractories that are used in contact with molten metal and slag commonly contain carbon in the composition primarily to improve corrosion resistance due to the very high wetting angle (non-wetting character) of carbon against liquids. But the major crisis that carbon-containing refractories suffer is the oxidation of carbon or other non-oxide components present in the composition. The oxidized refractory becomes porous and loses structural integrity, and all the mechanical and chemical resistance properties deteriorate drastically. To protect the refractories from oxidation, special chemical additives are added that react with the incoming oxygen and convert to their respective oxides, thus consuming the incoming oxygen and preventing the oxidation of carbon and other non-oxide components. These additives are commonly called *antioxidants*. Metal powders like aluminium (Al) and silicon (Si) and carbides, like silicon carbide (SiC) and boron carbide (B_4C), are commonly used as antioxidants.

Aluminium and silicon metal powders are the most common antioxidants used for carbon-containing (and non-oxides-containing) refractories due to their effectiveness of protection and low cost. The Al metal powder present in the matrix of the castable gets oxidized upon increasing the temperature and forms a thin Al_2O_3 layer. Above 660°C, the melting point of aluminium, a thin Al_2O_3 layer is formed containing the liquid aluminium for a while until it breaks and releases the molten aluminium on the refractory surface. This released liquid aluminium reacts with C (present in the composition) to form Al_4C_3. Again, carbon may also get oxidized with an increase in temperature by the diffused air into the sample. Now, the formed Al_4C_3 reacts with CO and forms Al_2O_3. This in situ formation of the Al_2O_3 layer further protects the carbon particle by covering it and does not allow the incoming oxygen to be in contact with carbon. Thus, any oxygen ingress is consumed by the metallic Al powder, and carbon ultimately remains unaffected by oxidation in the matrix phase of the trough castable. Again, the formation of Al_4C_3 provides an extra bond for the refractory at high temperatures; thus, the hot strength of the refractory is also improved. The details of the reactions are given in the following:

$$4Al\ (s) + O_2 = 2Al_2O_3\ (s)$$

$$4Al\ (l) + 3C\ (s) = Al_4C_3\ (s)$$

$$Al_4C_3\ (s) + 6CO\ (g) = Al_2O_3\ (s) + 9C\ (s)$$

Though aluminium is highly beneficial and a common antioxidant for the trough castable, its amount needs to be judged properly, as an excess of aluminium metal may cause degradation in different ways. In the presence of free water (especially for cement-bonded castables), Al metal reacts with water to form a hydrogen gas [$2Al\ (s) + 6H_2O\ (l) = 2Al(OH)_3\ (s) + 3H_2\ (g)$] that evolves from the lining, causing surface cracks on the refractory and degrading the quality. Further, when the fire trough lining cools down to low temperatures, the formed Al_4C_3 reacts with the water vapour and expands enormously, forming cracks and reducing the service life. The formation of voluminous $Al(OH)_3$ and CH_4 (methane) gas [$Al_4C_3(s) + 12H_2O(g) = 3CH_4(g) + 4Al(OH)_3(s)$] causes the expansion and disintegration of the refractory lining.

When silicon metal powder is used as an antioxidant, it does not get oxidized like the Al metal powder; rather, it first reacts with the carbon particles present in the castable matrix at high temperatures, forming a silicon carbide. This formed SiC further reacts with CO or oxygen (from the incoming air) and forms gaseous silicon mono-oxide (SiO^{-2}), which is further oxidized to SiO_2 in the oxidizing environment. This in situ–formed thin silica layer covers the carbon or castable surface, preventing further oxidation. The reactions are shown thus:

$$Si\ (s) + C = SiC$$
$$SiC\ (s) + CO\ (g) = SiO\ (g) + 2C$$
$$2SiO\ (g) + O_2 = 2SiO_2\ (s)$$

The beneficial effect of the addition of SiC as antioxidant is also as per the preceding last two reactions. On the other hand, boron carbide acts differently as an antioxidant. It reacts with the incoming oxygen or CO and forms B_2O_3. This B_2O_3 is a low-melting oxide, and upon melting, the formed liquid coats the castable surface and protects the castable from oxidation. But the presence of the low-melting B_2O_3 liquid may affect the high-temperature properties of the castable, and so the amount of B_2O_3 formed or B_4C to be used in the castable composition must be critically judged. The associated chemical reactions are given as follows:

$$2B_4C(s) + 6O_2\ (g) = 4B_2O_3(l) + 2C\ (s)$$
$$B_4C(s) + 6CO(g) = B_2O_3(l) + 7C\ (s)$$

To protect the carbon or other non-oxide components of the trough castable, a single or a combination of antioxidants is used. For better protection against oxidation, generally, 2–6 wt% of antioxidants are used in castable compositions.

3.9 DEGRADATION OF TROUGH REFRACTORY AND POSSIBILITIES FOR IMPROVEMENT

The application environment for the trough refractory, especially for the main trough between the taphole and the skimmer block, is very harsh and critical. Both the molten metal and the slag fall from the taphole and flow together, with the slag separating as the upper layer above the molten iron. The primary function of the trough is to collect the molten iron and the slag from the blast furnace, then to separate them and transfer them to their respective runners to reach their respective transfer vessels. Any crisis or failure in the main trough will definitely affect the casting schedule, causing production loss (depends on repair time), and in extreme case may cause structure and property damage, fatality, etc.

The trough refractory lining is based on a zonal lining concept, and the ternary contact areas on the refractories where the three different phases are in contact (discussed in Chapter 3.2) are most vulnerable as they face the maximum number of components to react. The main influencing factors that affect the trough lining wear and control the degradation, performance, and service life of the trough are as follows:

1. Profile, pooling character, and dimensions of the main trough
2. Temperature, chemistry, and casting rate of the hot metal and the slag
3. Composition, constituents, and characteristics of the trough refractory
4. Drying and preheating schedules of trough of (castable) lining
5. Fluctuation in temperature and flow rate of the molten mass during operation
6. Basicity of the slag (ideal CaO/SiO_2 ratio is between 0.8 and 1.2)
7. Infiltration of liquid in the refractory (mostly in oxidized/decarburized porous layer)
8. Amount of FeO and MnO (also B_2O_3, if any) present in molten masses (FeO oxidizing the refractory components, MnO reducing slag viscosity and increasing corrosion [should be <1%], and B_2O_3 reducing slag viscosity and enhancing the dissolution and corrosion of the refractory)
9. Amount of alkali (Na_2O and K_2O) present (the greater extent of alkalis produces low-viscous and low-melting compounds, resulting in refractory corrosion – total alkali should be <1%)
10. Thermal properties of the refractory and trough cooling facilities (fast cooling required to freeze the penetrating liquid, restricting the freezing isotherm close to the hot face)

The refractories of the free board zone or shoulder portion are in contact with the air of the open atmosphere and primarily support the whole lining mechanically. This portion suffers from mechanical impact and oxidation. These refractories need to be mechanically strong and oxidation-resistant for better performance and life of the whole lining. The slag zone refractory primarily suffers from the chemical attacks of the moving slag and associated erosion and abrasion effects. The refractory degradation in the metal zone is primarily due to hot metal penetration. Other than the refractory composition used, the trough operating temperature, thermal gradients, and molten metal flow rates are the critical parameters affecting the degradation rate. The formation of FeO within the bulk metal affects the refractory chemically. Also, the refractory needs to withstand the impact of the metal falling to the bottom of the trough. The abrasion and erosion effects of the flowing metal, which has a density nearly double than that of the refractory, wear out the lining significantly. Factors that are critical for the degradation of the complete trough are listed zone-wise in Table 3.2. Some of the critical degrading factors are elaborately described as follows.

TABLE 3.2
Critical Factors for the Degradation of the Trough Refractory at Different Zones

Zone of Trough	Critical Factor
Shoulder/free board zone	Oxidation Mechanical impact
Slag zone	Slag corrosion and penetration Thermal spalling Abrasion Oxidation
Metal zone (wall and bottom)	Corrosion of FeO Abrasion Mechanical impact

3.9.1 MECHANO-CHEMICAL EFFECT OF MOLTEN IRON AND SLAG FLOW

The degradation of the refractories in the slag zone occurs mainly due to chemical reactions and the mechanical actions of the flowing liquid at high temperatures. Among the mechanical actions, impact due to the fall of molten iron and slag on the trough and the splashing effect post-impact are major degrading factors. Also, due to the flow of the liquid mass, both abrasion and erosion mechanisms are operating simultaneously. These actions will remove any loosely bonded part of the refractory and will wash away the dislodged refractory particles along with the flowing liquid mass.

Further, the dislodging of refractory grains from the lining occurs due to the combined effects of chemical reactions, followed by mechanical actions (washing away). Chemical attack/corrosion primarily occurs on the matrix phase of the refractory due to the presence of a greater extent of finer particles (higher surface area) and porosity in the matrix part. Along with the chemical reactions, the oxidation of carbon also occurs, resulting in the generation of further porosity and further penetration of the slag within the matrix phase. Thus, the matrix phase is invaded by corroding liquid, and the bonding within the matrix gets loosened. This causes the dislodging of the aggregates. So when a portion of the trough lining is corroded, the peripheral area and the bigger grains present nearby will be loosened and will be exposed to the corroding environment. Finally, the grains will be dislodged from their position by the abrading and eroding actions of the flowing liquid and will be washed/transported away by the liquids (metal/slag). Thus, the degradation and mass loss of the trough refractory lining will occur continuously.

There are primarily two different mechanisms involved in the chemical attacks of the molten iron on the trough refractory. They are (1) oxidation of iron and (2) its further reactions. Molten iron gets oxidized in the bulk to form FeO, and this formed FeO oxidizes the SiC and C of the refractory. The oxidation of carbon makes the refractory porous and weak, and the oxidation of SiC further produces low-melting silicate phases within the refractory, affecting the properties and causing degradation. The reactions involved with this mechanism are as follows:

$$\mathrm{FeO\ (l) + C(s) \rightarrow [Fe] + CO(g)}$$
$$\mathrm{SiC + 2FeO \rightarrow SiO_2 + 2Fe + C}$$

This indirect oxidation of the non-oxide components (C, SiC, etc.) may also occur due to the oxide components of the refractory or slag, causing similar degradation. Also, these components may get oxidized directly due to the presence of atmospheric air (oxygen), resulting in a similar degradation to the refractory.

The other mechanism for the chemical degradation of the trough refractories involves mass loss of the refractory due to the interfacial chemical reaction with the blast furnace slag. This loss is due to the dissolution of refractory constituents, mainly alumina and silica, in the molten blast furnace slag. FeO, free CaO, alkalis, etc. present in the slag react with the alumina–silicate fines present in the castable matrix and form low-melting compounds that get easily dissolved in the slag at the trough operating temperatures. Hence, slag composition is one of the key parameters for refractory corrosion and greatly influences the refractory dissolution and consequent degradation. It can be simply conferred that the higher silica and alumina content of the blast furnace slag will cause lesser dissolution of the refractory components and will reduce the refractory dissolution rate. Further, the higher flow rate of the liquid mass within the trough increases all the chemical reactions involved, causing the faster degradation of the trough lining. In reality, both mechanisms, namely, mass loss due to dissolution in the slag and interfacial chemical reactions, occur simultaneously and degrade the blast furnace trough refractory.

3.9.2 SLOPE OF THE TROUGH

The degradation of the refractory in the main trough is dependent on the slope/type of the trough. For a pooling trough having a very low slope, sol-bonded or low-cement castables provide excellent performance and service life. Commonly, the castable life for such applications reaches even more than 8 lakh tons of metal throughput in a single campaign, with one or two major repairs. The refractory wear is very less, and consumption rate is only about 0.8–1.2 kg per ton of hot metal passed, whereas in contrast, for the non-pooling trough with high slope, the refractory wear and the consumption rate of the refractory are high, and the durability of the working lining is very low. Frequent repair is common for the non-pooling trough design. The carbonaceous ramming mass is preferred over the castable for a quick and easy dig out of the affected and infiltrated area in the working lining and the immediate repair of the same by fresh ramming mass. The lesser the slope, the greater the time for the hot metal to remain in the main trough. This stored hot metal pool withstands the impact of the fresh-tapped metal falling on the trough, protecting the refractory from all types of mechanical and chemical actions, and also protecting from the thermal shocks. Figure 3.6 shows the variation of wear rate of the refractory in terms of micrometre thickness of the refractory wear per ton of hot metal throughput, against residence time, in second, for the main trough.

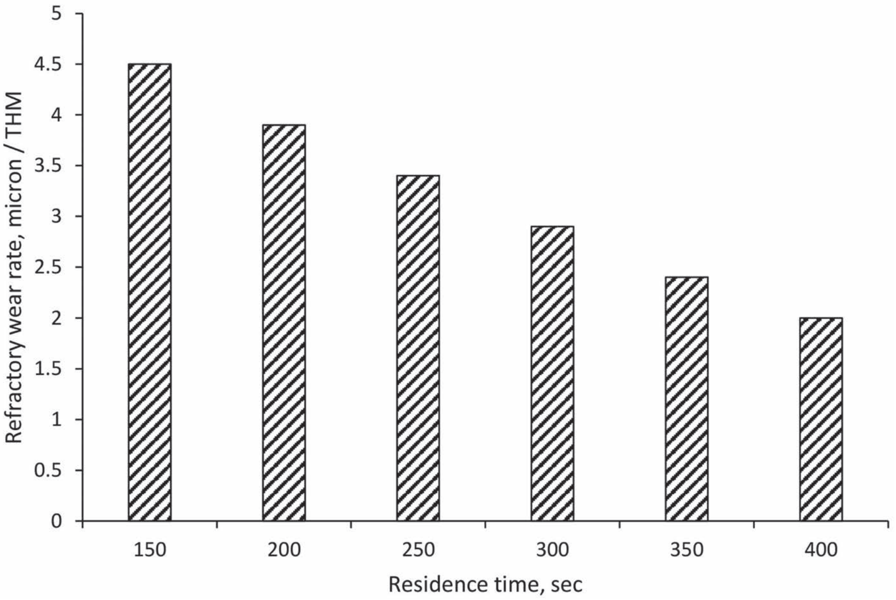

FIGURE 3.6 Wear-out rate of the trough working lining against residence time of liquid (metal + slag) in the trough.

3.9.3 INSTALLATION OF THE TROUGH REFRACTORY

The installation of the refractory lining is very important for its performance, and criticality increases when the installation is for an unshaped refractory (say, a castable). The importance of the composition and constituents of the trough refractory castable is elaborated in Chapters 3.7 and 3.8, but the desired properties can never be achieved if the refractory is not properly installed or the installation procedure/ schedule is not properly followed. Any deviation in installation practice may result in severe deterioration in the castable properties and its performance. Proper consistency of the castable applied in trough, irrespective of the zones, is very important for the uniform and required properties development, and the desired performance of the trough and lining life. Any inconsistency in the castable mix will degrade the quality and affect the performance of the trough. The amount of water to be added for mixing is very critical for the property development and performance of the lining. Any excess water that makes the mixing process easy and faster, showing better flow, may cause segregation and will degrade the quality drastically. Even 1% of excess water will cause an increase in porosity by ~3.5%, resulting in the degradation of strength by around 20% and an increase in penetration and corrosion by molten metal and slag at around 10%. Segregation will cause the separation of fines (as the fines will flow with the water), causing degradation in property. On the other hand, the use of a lesser amount of water will produce a thixotropic mass and will show poor flowability. Thus, excess vibration will be required for the filling and placement of the refractory, which may cause segregation and poor property development.

Again, for the complete trough refractory lining, irrespective of the zonal concept, the variations in metal level due to inconsistent flow, repeated commencement and cessation of tapping operation for molten metal and slag flow, changes in flow rate during tapping, variation in the specific location of jet impingement during tapping, etc. affect the refractory performance and degradation. All the variations also induce undue fluctuations in refractory temperature, causing severe thermal shock to the trough refractory. The improper and non-uniform preheating of the trough also affects the trough refractory and may cause severe thermal shock or failure due to the sudden temperature rise during tapping.

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4 Slag Arrestor Dart Cone

4.1 MAKING OF STEEL

Steel can be considered a purer form of iron, containing a little amount of carbon present as per its grade/quality (usually below 1%). It also contains impurities, like phosphorous, sulphur, silicon, etc., but significantly lower in amounts compared to that of pig iron produced in a blast furnace. The pig iron produced in a blast furnace contains around 94% iron (Fe) and about 4% of carbon, mostly present as iron carbide (cementite, Fe_3C) and other impurities. The carbide phase is hard and brittle in nature and makes the iron unsuitable for any structural application due to poor flexibility/malleability. To remove the detrimental brittle carbide phase from iron, carbon must be removed from the composition. This removal is done by burning off the carbon using oxygen in a reactor vessel called a converter. Thus, a converter converts the pig iron into steel.

In simple words, the steelmaking process involves the reduction of the carbon content of the pig iron by the oxidation of carbon and also a reduction in other impurities. The commercially successful bulk-scale steel production was first achieved by Sir Henry Bessemer in 1855, wherein air was used for the oxidation of carbon. The advantages of using pure oxygen instead of air in making steel were known since the time of invention of the Bessemer process, but the same could not be commercially implemented that time due to the commercial unavailability of a purer grade of oxygen. The first commercially successful steelmaking using purer oxygen instead of air was achieved in the late 1940s in two Austrian cities, Linz and Donawitz. Accordingly, the process of steelmaking using oxygen is termed the Linz–Donawitz (LD) process. As the chemistry of steelmaking in the LD process is basic in nature and oxygen is used for the removal (oxidation) of carbon, the process is commonly called the basic oxygen process, and the vessel/pot/furnace used for the same is called the basic oxygen furnace (BOF). As today, there are many other modern/technologically superior methods of steelmaking available, like the electric arc furnace, induction furnace, etc. However, due to higher productivity, faster processing, and low cost, the BOF method is the most used, common, and popular process. Presently, about 67% of global steel is produced by this process.

Typically, the basic oxygen furnace is a closed-bottom vertical steel shell vessel lined with refractory and capable of rotating around its horizontal axis. The movement is necessary for the charging of batch materials, sample collection from molten mass, and tapping out of produced steel and slag from the furnace. The furnace runs on a batch process, where each batch consists of about 70–75% molten pig iron from the blast furnace (containing around 4 wt% carbon), 25–30% scrap metal. Also, the batch contains calcined lime (or dolomite) and other fluxes. Used scrap has multiple roles in the steelmaking process. It primarily acts as a coolant and absorbs the enormous heat generated due to the oxidation of carbon and controls the molten steel

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temperature. It also helps in the productivity of steel and decreases CO_x gas generation. Lime or dolomite is used in the converter batch as flux material to promote the removal of impurities, especially the acidic ones, like silicates. Thus, it helps in making a purer and cleaner steel and also protects the basic refractory lining of the converter by increasing the slag basicity. Basic slag also helps remove phosphorus (P) and sulphur (S) from the liquid charge metal.

The batch materials are charged through the upper "open cone" mouth of the converter (BOF) in a tilted position. After batch charging, the converter is kept in a vertical position, and a water-cooled oxygen lance pipe is inserted through the open mouth into the converter to blow oxygen into the charge melt. The basic oxygen furnace requires no additional fuel, as the oxidation of carbon is exothermic in nature, producing a huge amount of heat that runs the steelmaking process. The oxygen is blown into the converter at supersonic velocities, with flow rates of 6–8 m^3/min/ton of charge at a pressure of 1–1.5 MPa for about 15–20 min. The vigorous oxidation process of carbon and other elemental impurities shoots the process temperature even up to 2,000°C. The oxidized products are either gaseous, like CO_2 (moves out with exhaust gas), or oxide liquids (like silicates) that form a waste liquid, called the slag. After the initial blowing, sample is collected from the molten bath, and steel chemistry is checked. As per the requirement of the desired steel composition, further oxygen blowing is done, and composition is further checked. Once the desired level of carbon and other impurities is reached, the lance pipe is taken out from the converter, the converter is tapped/emptied by rotating it to pour the formed steel into a ladle through a side opening called the taphole, and finally, the slag is discarded through the open mouth by tilting.

The steel thus produced is not suitable for many of the applications as the BOF steelmaking is mostly a decarburization process that primarily reduces the carbon content of the molten metal, but not much effective in reducing many other impurity elements present. Thus, to attain a desired steel composition, further metallurgical processes are required to be performed on the steel produced in BOF, which is commonly called secondary metallurgy, or secondary steelmaking. A variety of different unit processes are performed under this secondary metallurgy to attain the desired steel chemistry and final properties. Such unit processes are killing/deoxidation, desulfurization, degassing, dephosphorization, decarburization, alloying, etc. Once the desired composition and characteristics of steel are attained, the same is cast in the required/desired size and shape and solidified by cooling.

4.2 INTRODUCTION TO SLAG SEPARATION IN THE CONVERTER

The *slag* is an obvious, undesirable by-product generated in the iron- and steelmaking processes. Chemically, the *slag* is a silicate compound that also contains various other oxides. The formation of the slag is essentially required to clean the steel and separate the impurities present within the steel and associated with other accessory materials required in making steel. But the slag has an expensive and detrimental consequence on the steelmaking process and on steel properties. The inherent impurities present in iron ore are primarily separated during the ironmaking process by the formation of the slag. The externally attached impurities of the ore are also included in the slag. Some amount of ironmaking slag is carried over, even after slag separation by skimmer block, accompanied with pig iron to the converter. Further, some slag is formed during the steelmaking process due to the inherent and external impurities present in the calcined lime/dolomite and scrap metals. Thus, the total amount of slag present in a converter becomes huge. Due to the lower density value compared to that of molten iron/steel, the slag always floats and remains above the molten metal bath.

The presence of the slag in contact with steel for a prolonged time causes various deleterious effects. The converter slag contains various impurities, like phosphorous (originally present in iron ore), and if the slag remains in contact with the formed steel for a long duration, the phosphorus reverts back into the steel structure, degrading the quality of steel. The slag also causes substantial wear and corrosion to the refractory, damaging the refractory lining of all the steel processing units. Hence, the separation of the slag from steel is essential. Again, the separation of the slag post–converter operation demands for extra processing unit, time, and cost. Hence, the slag must be separated from the molten steel within the converter so that the tapped steel, post–converter operation, is free from impurities. Any slag present in steel after tapping from the converter can cause the following harmful effects:

1. Effect on steel quality and cleanliness as inclusion
2. Longer processing time
3. Difficulty in ladle desulphurization process
4. Clogging in steel processing units, like nozzles, shrouds, etc.

The demand for high-grade steel is increasing day by day, with the requirement of higher purity and cleanliness, and this has caused a continuous improvement in the quality of steel. To improve the quality and cleanliness of steel, it is important to separate the slag from steel during tapping from the converter, when both steel and slag are present in a highly fluid condition. To completely stop slag carry-over from the converter to the steel ladle, further processing steps are introduced in the converter post–steelmaking activity. The complete separation of slag from the molten steel during the tapping process of the converter has multiple benefits, as mentioned in what follows:

1. Reduces inclusions and improves the purity and cleanliness (quality) of molten steel
2. Reduces the chances of the return of phosphorus or other harmful impurities back to molten steel
3. Improves the alloy recovery rate
4. Reduces the slag sticking/clogging tendency in further steel processing steps
5. Prolongs the service life of the steelmaking refractories
6. Aids in smoother steel processing and casting operation

4.3 EARLIER TECHNIQUES FOR SLAG SEPARATION IN THE CONVERTER

During the steelmaking process in the converter, once the desired level of carbon in steel is achieved, further oxygen lancing is stopped, and the converter is tilted for tapping out the processed steel to the ladle for further processing and, finally, casting. The process of tapping is based on the bottom-pouring concept through an opening (called taphole) at the upper part of the side wall of the converter (that becomes the bottom upon tilting the converter). During bottom tapping, metal comes out first (due to a higher density), and once the molten steel is exhausted, the tapping process is stopped. The slag is retained within the converter and finally poured out through the open mouth of the converter into a slag pot (not through the taphole). In the early days, human experience and skill were used to identify the completion of metal tapping and to separate the slag from molten steel. On the basis of the visible characteristics of the flowing molten stream (colour, viscosity, and flow behaviour) coming out from the converter, people used to understand the completion of metal pouring and the start of the slag pouring activity. The moment the transition of metal pouring to slag pouring was identified, the tilted converter was placed upright, stopping any further flow of the molten mass and retaining the slag within the converter. But the accuracy level was completely dependent on human skill, and the whole activity used to be performed without much scientific/technical support. Hence, with the progress of time, this age-old skill-based technique for slag separation in converter is substituted by the use of the slag retaining ball, or slag ball, and further improved by the use of a refractory dart cone.

4.4 SLAG RETAINING BALL

The slag retaining ball (also called the slag ball/ball-shaped stopper/spherical stopper) is made up of a refractory-wrapped mass containing metal/iron as core. As the ball contains both refractory and metal, its density value lies between the density of a slag and that of molten steel, generally kept between 3.0 and 5.5 g/cc. So at high temperatures, when both the steel and the slag are in a molten state within the converter, the slag ball will float at the slag–steel interface. During the tapping of the converter, after about 75–80% completion of metal tapping, the slag ball is dropped inside the converter, on the top of the taphole, using a special tool holder that can enter into the converter through its open mouth. The slag ball dips through the slag layer and floats at the interface between the slag and the molten steel. When metal pouring is nearly completed, the vortex above the taphole (formed due to the flow of molten metal from a large pool inside the converter through the taphole with a much smaller diameter) pushes the ball floating at the slag–metal interface onto the taphole mouth. The moment that metal flow/tapping is completed, all liquid steel present in the converter is completely tapped out, the slag ball present at the interface between the molten steel and the slag layers sits exactly on the mouth of the taphole, thus blocking the taphole and preventing any molten slag from flowing out from the converter through the taphole. Figure 4.1 shows the slag ball and its working in the converter. The diameter of the slag ball is kept sufficiently large compared to that

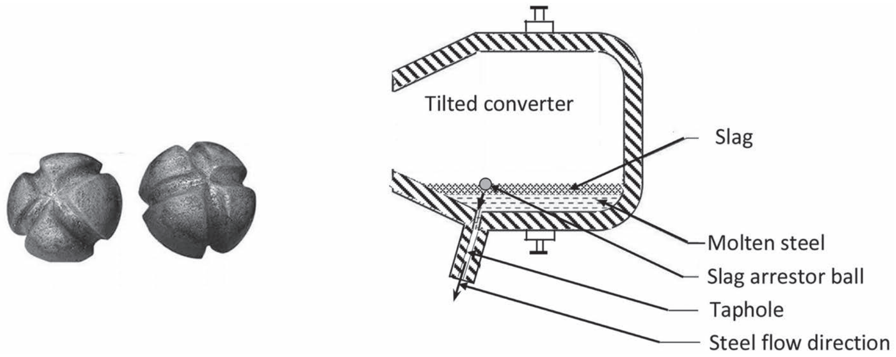

FIGURE 4.1 Slag arrestor ball and its functioning in the converter.

of the taphole diameter for better fitting of the slag ball on the taphole mouth and to accommodate any reduction in the size of the slag ball due to erosion and corrosion by molten slag and metal.

However, a large amount of residual molten steel generally remains within the converter at the time of closing the taphole mouth due to vortex push on the slag ball, resulting in the lower recovery rate of the molten metal. Another major disadvantage of the slag ball technique is that some of the slag is entrained by the swirl above the taphole and carried over to the steel ladle, making it difficult to obtain a completely slag-free steel tapping. Also, the proper positioning of the slag ball on the taphole mouth and the complete blockage of the taphole are not guaranteed, as the ball position may change due to the impact of the molten steel flow/moving slag. This situation is only marginally improved by using a hinged slag ball.

4.5 DART CONE AND ITS WORKING

The design and concept of the slag dart cone are an improvised version of the slag retaining ball to overcome the difficulties and drawbacks faced in the use of the slag ball. The refractory dart cone is commonly used nowadays to completely prevent any slag flow from the converter to the steel ladle. A large amount of molten slag is generated in the converter during the steelmaking process which must be separated from molten steel before/during tapping. These slag-separating darts are cone-shaped and specially designed refractory products made up of refractory and iron parts and have a density value between those of molten steel and slag, so that it can float at the interface between the liquid steel and slag layers in the converter. The dart cone resembles a gyroscope, where the centre of the gyroscope is made up of a cone-shaped refractory with a metallic guide rod along its vertical axis. It is primarily composed of two parts: (1) the dart head and (2) the dart rod (tail). The length of the dart rod generally varies between 1,000 and 1,800 mm, and the dart head diameter between 120 and 250 mm (depending on the size of the taphole of the converter). The details of the dart head, the complete dart cone, and its parts are shown in Figure 4.2.

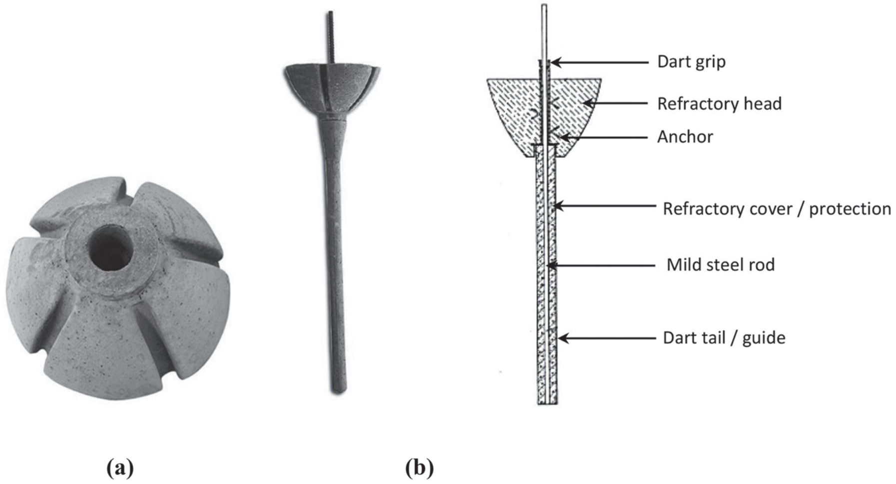

FIGURE 4.2 Slag arrestor dart cone: (a) refractory head and (b) parts of the dart cone.

For the tapping of steel from the converter, first, the converter is tilted to move the molten steel in it towards the taphole, located at the top side of the side wall of the converter. The molten steel, being heavier, remains at the bottom, and the molten slag floats above it. Hence, the molten steel will come out first through the taphole opening, and once the pouring of steel is completed, then only slag will come out. A steel ladle is kept just below the taphole to collect the molten steel, and after complete filling, the ladle carries the tapped molten steel to other works for further processing and, finally, casting. As the tapping process continues, the inclination (tilting) of the converter is increased so that more amount of liquid steel is shifted towards the taphole for pouring out. The diameter of the taphole is significantly smaller in comparison to the amount of total molten mass present in the converter and the available surface area of molten mass inside the converter. Due to the tilting condition and the continuous tapping through the smaller-sized taphole, the molten metal and slag rotate within the available space of the converter and form a vortex above the taphole with an axis coaxial with that of the taphole. Both molten steel and slag rotate, surrounding the vortex axis, with the slag as the top layer and the rotating molten steel as the bottom layer, getting tapped out through the taphole.

Once the metal tapping is nearly completed (steel ladle is nearly filled), with 75–80% of the molten steel tapped out, the slag arrestor dart cone is inserted into the converter with the help of a dart application (dispatching) machine. The machine holds the cone and helps it enter the converter through its open mouth. Figure 4.3 shows the entry of a dart cone in the converter using a dart cone application machine. The dispatching machine is calibrated in such a way that it will enter up to a fixed distance within the converter, vertically just above the taphole, and then release the dart cone so that the guiding tail rod of the dart cone is positioned towards the taphole mouth. Once free, the dart cone will fall, will pass through the slag layer, and will float at the interface between the molten steel and the slag due to a density factor, with the tail rod coaxial with that of the formed vortex and the taphole. On further progress of tapping, the tail

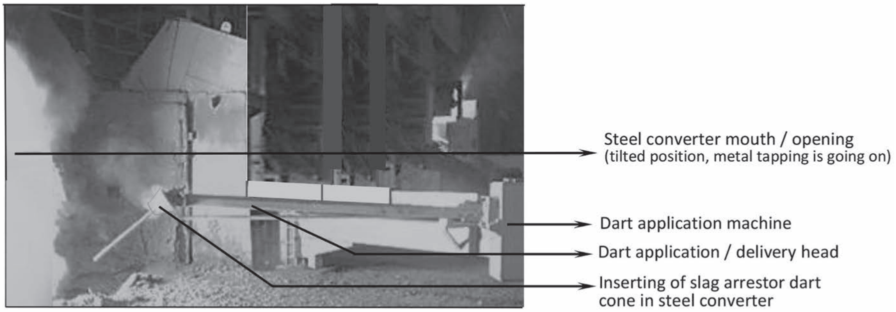

FIGURE 4.3 Insertion of the dart cone in a converter.

rod (at the lower part of the dart cone) will enter within the taphole to play a positioning role, so that the dart cone and its head can sit properly without displacement.

As tapping continues, the tail rod will further enter within the taphole, and there is lowering of the interface between the molten metal and the slag. So the dart head comes closer to the mouth of the taphole. The dart tail guides the dart head to move towards the opening or the mouth of the taphole even under the impact of the vortex and the flow of the molten mass. In addition, the downward movement of molten steel flow will make the dart stable at a position just above the taphole. When the molten steel is about to be completely drained out, the interface layer reaches the taphole mouth and the head of the floating dart cone at the interface will sit and set on the taphole mouth, thus closing the taphole completely and preventing any slag from flowing out of the converter to the ladle. Figure 4.4 schematically shows the complete working of a dart cone in the converter. Any little remnant steel present can flow out through the groove on the dart head. Thus, the flow of the molten mass from the converter to the steel ladle will stop completely.

Once there is discontinuity (stopping) of the flow of molten mass from the converter to the steel ladle, indicating the complete tapping out of molten steel, the converter is immediately made straight in an upright (vertical) position. So the slag present in the converter will immediately be shifted (fall) to the bottom of the converter from the taphole area. Thus, no slag is carried over to the steel ladle, and the slag is completely separated from the metal stream. However, the dart cone may also fall within the slag present at the converter bottom and mix up with the slag. So the dart cone is consumed in that single heat, and its life is only one heat.

4.6 ADVANTAGES OF THE DART CONE

The main advantages of using a slag arrestor dart cone over other methods are:

1. Improved slag blocking performance, producing clean steel
2. Increased steelmaking operation security
3. Better removal of remnant molten steel
4. Reduction in molten steel temperature loss
5. Reduced energy consumption

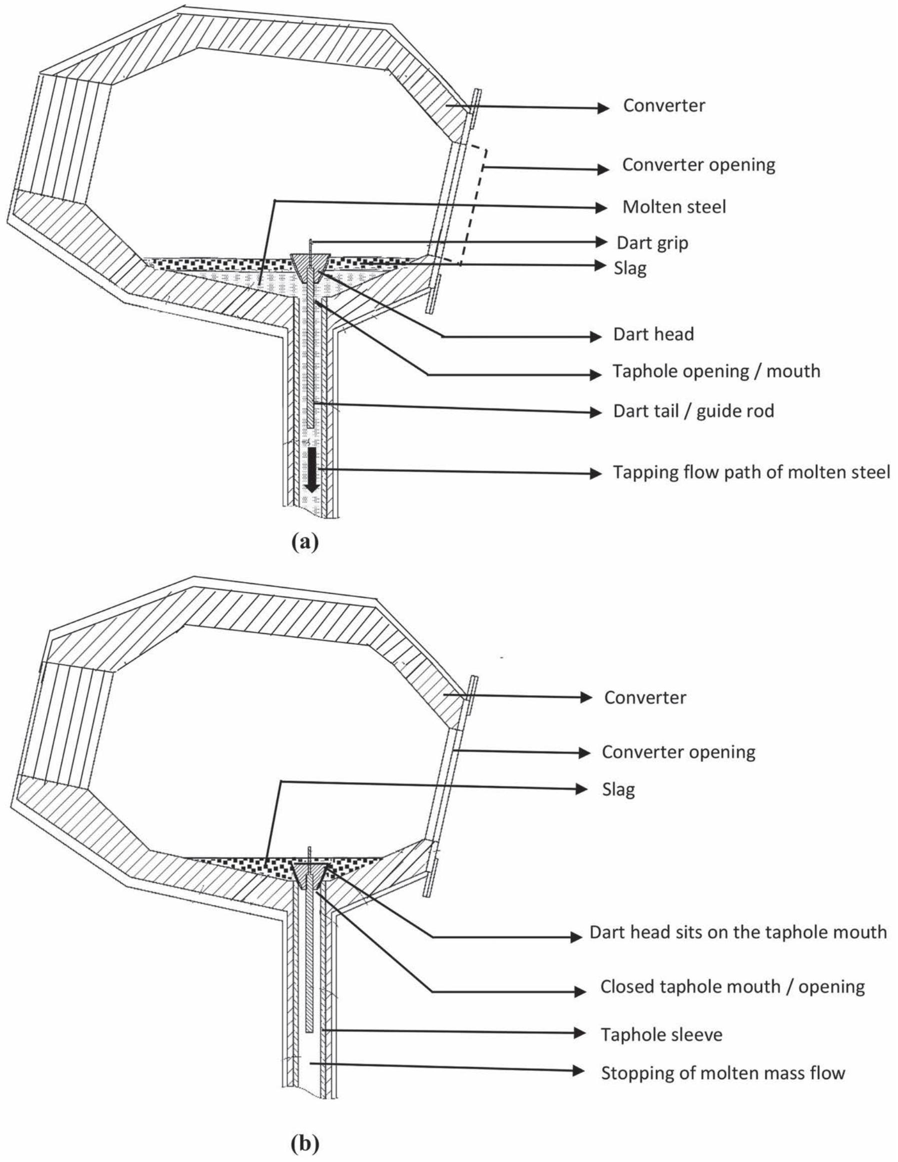

FIGURE 4.4 Schematic diagram for the working of the dart cone: (a) dart cone at the interface between the slag and the metal layer; (b) dart cone sitting at the taphole, preventing slag flow.

TABLE 4.1 Common Features of the Dart Cone

Features	Data
Total length	1,000–1,800 mm
The height of dart head	120–230 mm,
The diameter of dart head	120–350 mm (as per taphole diameter, dart diameter > taphole diameter)
Softening point	>1,750°C
Cold strength (compressive)	>20 MPa

4.7 PROPERTIES OF THE DART CONE REFRACTORY

Common features of the dart cone are described in what follows, and related data are provided in Table 4.1.

1. Compared to the slag stopping ball, the dart cone has higher density value. Specific gravity varies between 3.5 and 6.0.
2. The softening point of the refractory should be high (1,700°C or more) and should not soften during its use even in contact with molten steel and slag.
3. The refractory should have high thermal shock resistance; when the dart cone enters into the converter, it comes from an ambient (room temperature) environment and faces a temperature higher than that of the steel melting temperature, thus encountering a huge thermal shock.
4. The dart cone should have high strength for easy transportation and handling and also needs to withstand the impact of dropping during application.
5. It also needs to be strong to withstand the turbulence and erosion effects of molten steel and slag during the floating condition at the interface between molten steel and slag.
6. Dart cones need to have excellent corrosion resistance against molten steel and converter slag and should not have great dimensional loss during operation.

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5 Converter Taphole Sleeve

5.1 INTRODUCTION

The basic oxygen furnace (BOF) has the most important role in the making of steel. It converts the pig iron into steel by removing carbon using an oxygen purging process and so is commonly called as "converter." The working lining of the converter is made up of an MgO-C composition having different carbon contents and quality (purity) of MgO at different zones, depending on the severity of application conditions. These refractories must withstand high temperatures, have strength to withstand the harsh steel processing conditions, resist the corrosive action of the highly oxidized and basic slags, bear the impact, abrasion, and erosion effect of the processing during charging and blowing actions, must have high thermal shock resistances, etc. There are back-up and insulation refractory linings next to the working lining refractories whose working environments are less severe.

The steelmaking process is basically a decarburization process of molten iron. The removal of carbon is done by lancing oxygen into the molten iron at a high pressure for a certain time. Once the desired levels of carbon removal, steel composition, temperature, etc. are achieved during processing in the BOF, oxygen purging is stopped and the produced steel is tapped out through the converter taphole, mostly located at the junction between the barrel and the upper cone area of the converter. The converter is tilted to shift the molten steel from the bottom area to the barrel and then to pour it out through the taphole into a ladle placed on a transfer car below the converter taphole. The taphole area and the taphole refractory lining are different from that of the working lining of the converter, as the movement of molten steel and slag causes enormous wear, erosion, and corrosion. The opening of the long tube-shaped taphole in the inner side of the converter is facing the high-temperature and harsh environment of converter processing, while the outer side of the taphole is facing the ambient environment. This again causes tremendous thermal shock to the tube-shaped taphole refractory. Again, when tapping is done, the converter side of the taphole refractory suddenly comes in contact with the molten steel flow and faces all the high-temperature effects, including wear and erosion. Thus, the converter-side taphole refractory suddenly experiences a widely different application condition. During tapping, the hot face working lining of the taphole refractory wears out gradually due to abrasion, erosion, and chemical attack of molten steel flow and results in an increase in inner diameter. This increase in diameter increases the flow rate of molten steel, shortens the total tapping time, and produces a non-uniform flow of molten steel to the ladle. Also, this may cause a splash of molten steel and enhances the chances of slag entrapment, affecting steel quality. Hence, to protect the taphole and the refractory in contact with molten steel within the taphole, a special kind of refractory is used, called the "taphole sleeve" (THS). The location of the taphole and the taphole sleeve refractory in the converter is shown in Figure 5.1.

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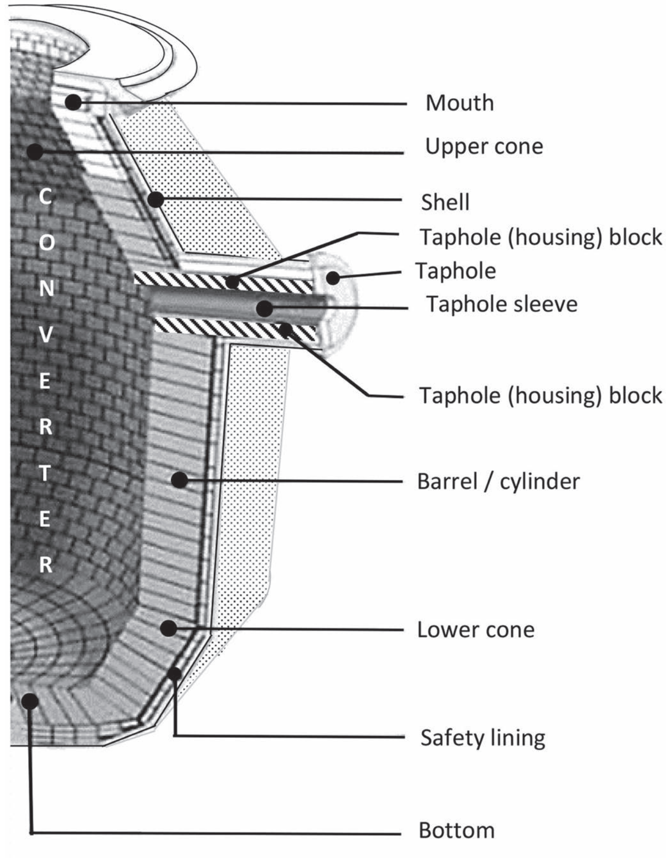


FIGURE 5.1 Taphole sleeve and other parts of the steel converter.

5.2 CONVERTER TAPHOLE REFRACTORY

The *taphole sleeve* (THS) is a long cylindrical-shaped refractory piece with a hole at the centre (Figure 5.2). It is used as a sleeve to protect the taphole of the converter. The THS refractory has to face the impact of molten steel flow and huge turbulence during the tapping process caused by the rotational movement of molten steel during tapping and vortex formation. These effects severely damage the hot face working lining of the THS. Thus, the refractory used to protect the taphole has to have the required properties to withstand the severe conditions associated with molten steel flow, as mentioned in what follows:

1. Abrasion and erosion at operating temperature due to steel flow
2. Oxidation of refractory by dissolved oxygen in liquid steel
3. Chemical action due to molten steel and slag present in the converter
4. Thermal and mechanical spalling due to an intermittent tapping process
5. Atmospheric oxidation during the interval between consecutive tappings

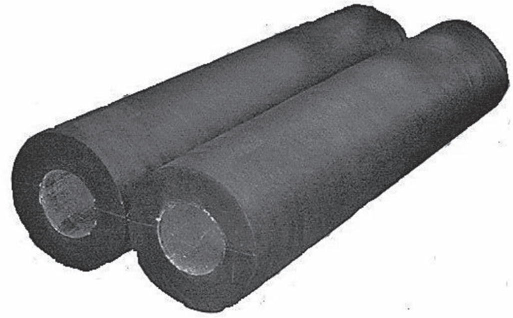
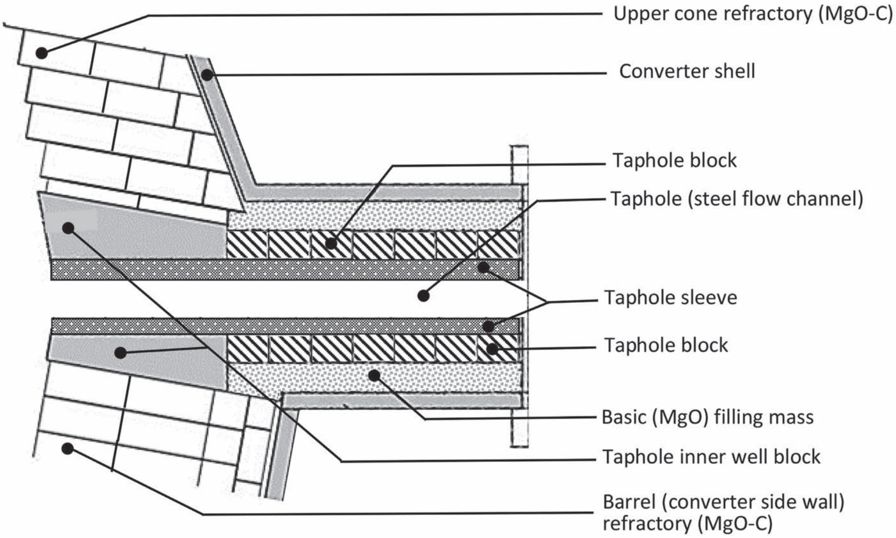


FIGURE 5.2 Photograph of commercially used taphole sleeve.

The application environment of the THS is similar to that of the converter hot face lining (barring the oxygen lancing effect). THS faces the same chemical environment and encounters the molten metal and slag of the same chemistry that are formed within the converter. Hence, the THS refractory requires very similar properties to that of the working lining of the converter. Generally, the THS is a resin-bonded, isostatically pressed refractory tube made up of a magnesia–carbon composition, mainly consisting of fused magnesia and carbon (~15%) with metallic additives. The refractory composition must have excellent resistance against corrosion and hot erosion, oxidation, and thermal shock. A carbon-enriched matrix is created in the refractory microstructure by post-impregnation of carbonaceous materials or special polymers to enhance the corrosion and hot abrasion resistance of the refractory. The taphole sleeve contributes effectively to increasing the productivity and efficiency of the converter by reducing converter downtime and minimizing average tapping time. Also, the use of a suitable basic gunning mass (preferably at hot condition) to fill up any gap/annular space formed during use around the sleeve refractory system, in comparison to the conventional slurry-pouring technique, results in further improvement in performance and life.

The hot face working lining of the THS, which is in contact with the molten steel, wears out faster due to the abrasion, erosion, and corrosion effects of the metal flow. Thus, the complete lining of the taphole is done with a zonal lining concept. The annular refractory tube (sleeve) takes care about all the aggressive actions of molten metal flow, and there is a separate outer ring covering to this annular inner portion that protects the inner sleeve/tube and supports the sleeve mechanically. The inner portion, facing the molten metal and all aggressive actions, is required to be of high quality and high purity and technically acts as the taphole sleeve. The outer-side refractory annular ring for this sleeve is called the taphole block (THB), which is not in contact with the molten metal, not facing the steel tapping temperature and any aggressive harsh environment of molten steel flow. So the block refractories are made up of a little inferior-quality material and have a longer life compared to that of the sleeve refractories. Application details of the taphole sleeve and taphole block are shown in Figure 5.3. Thus, a complete taphole refractory system primarily contains two different types of refractories, taphole sleeve and taphole block, and both the refractories are based on an MgO-C system. For the sleeves, MgO needs to be



FIGURES 5.3 Application details of the taphole sleeve (THS) and the taphole block (THB).

highly pure and have large grain sizes (fused quality) for better corrosion and wear resistance. Carbon also needs to be of high purity (low ash content), and the whole refractory needs to be denser and stronger compared to the block refractories, as the sleeve has to face the impact of the flow and the associated effects of molten steel. Table 5.1 provides some details of the composition and properties of the commercially used THS and THB refractories.

5.3 TYPES OF THS

Conventionally, the taphole sleeve looks like a long tube with the wall made up of a refractory. It plays a vital role in achieving a consistent steel flow with the desired flow rate for converter tapping. But with time, there are advancements and modifications in its shape and the design of the THS. For the last few decades, continuous modifications, improvements, and plant-specific optimization for the design of the THS have been done to improve the tapping performance and life of the THS. Depending upon the application criteria and converter tapping parameters, there are two major types of taphole sleeves that are in use commercially:

1. *Single-piece THS (monolithic type).* This is a long cylindrical refractory piece, the most conventional one, commonly more than a meter in length. A single piece helps in reducing wear-out of the refractory from the corrosion and erosion effects of molten metal flow. Also, they are easy to install. But as the refractory piece is long in dimension, the chances of having non-uniformity in the structure and properties are high, and if any portion of the refractory is damaged, then the whole sleeve needs to be replaced. The replacement for the complete sleeve requires a long time, and the converter

TABLE 5.1
Comparison between Taphole Sleeve (THS) and Taphole Block (THB) Refractory

	THS	THB
	Constituents (wt%)	
Al_2O_3	1–3	<1
Fe_2O_3	<1	<1
SiO_2	<1	<1
CaO	1–1.5	1.5–2
MgO	80–82 (Purity >97%)	82–85 (Purity >95%)
C	12–15	10–12
Antioxidant (Al, Si, SiC, etc.)	1–3	1–3
	Properties	
Bulk density, g/cc	2.85–2.95	3.0–3.1
Apparent porosity, %	3–4	4–5
Cold strength, MPa	45–55	40–45
Hot MOR, MPa	12–15	10–12

downtime will be high, affecting the productivity. The chances of damage due to abrasion, erosion, and corrosion wear are higher in the molten steel entry point of the sleeve (inner wall of the converter), and damage due to thermal shock is greater at the outer side/exit point of the molten steel from the converter.

2. *Segmented THS (sleeve blocks/bricks).* This type of sleeve is made up of a multiple number of small pieces joined together to make the complete and long sleeve. As the individual sleeve piece is much smaller in dimension compared to the single-piece sleeve, they are well dense and compacted and have uniform texture and properties. Uniform properties all through the sleeve length is difficult to attain for a single-piece, isostatically pressed product due to chances of material segregation during mould filling and pressing. Also, the thermal strain generated in a single-piece sleeve is huge due to the wide variation in temperature between the two opposite ends of the piece, whereas the strain for segmented pieces is small, as the variation in temperature for each segmented piece is marginal. Further, for the segmented pieces, a single-piece replacement is easier for the worn out or damaged portion without having to replace the complete sleeve. But as a number of pieces are joined together, each junction point is weak and vulnerable for any erosion, corrosion, and wear effect. Also, the replacement for any inner-positioned piece (not at the hot or cold face of the taphole) is difficult.

The efficiency and performance of tapping of molten steel from the converter and the filling of the steel teeming ladle depend on the design of the sleeve. The design is also important for the wear-out of the refractory, the installation and dismantling process, and the performance and service life of the sleeve. There are two types of THS design that are in wide commercial use:

1. *Uniform diameter.* In this THS design, the diameter of the sleeve remains uniform and constant all through the length of the sleeve. This design is a conventional one and may cause a widening up of the molten metal flow diameter while the ladle is poured.
2. *Iso-jet design.* The diameter of the iso-jet taphole sleeve decreases along its length. The molten steel enters the sleeve within the converter at a bigger opening diameter, and as it passes through the sleeve, the diameter decreases; at the exit end, the sleeve has the minimum diameter, causing a concentrated metal flow.

5.4 PARAMETERS AFFECTING THS PERFORMANCE

The refractory composition, processing conditions, and properties developed for the taphole sleeve are the primary factors for its service performance and life. Further, there are few operational parameters which are very critical for its performance and life. Such operational parameters are mentioned in what follows:

1. *Tapping temperature.* Any increase in tapping temperature drastically deteriorates the performance and life of the sleeve. An increase in temperature enhances the oxidation of the non-oxide components of the sleeve and also reduces the viscosity of the molten steel, thus increasing the wear and erosion effect on the sleeve refractory.
2. *Tapping time.* An increase in tapping time also deteriorates the sleeve refractory significantly, as the refractory is exposed to molten steel and high temperature for a prolonged time, causing greater oxidation and wear-out.
3. *Oxygen content in steel.* An increase in oxygen content deteriorates the quality of the refractory as it enhances the oxidation of the non-oxide components in the sleeve refractory, making it porous, weak, and vulnerable to abrasion, erosion, and corrosion.
4. *Chemistry of the flowing molten mass.* The composition of the molten mass is also important for the performance of the sleeve. The presence of any harmful impurity in molten steel or slag, even in very low amount (ppm level), causes damage to the refractory due to the high temperature and flow effect.

5.5 DEGRADATION OF TAPHOLE SLEEVE

Commonly, the degradation effect for a refractory is calculated from the remaining lining thickness after use. One can easily understand the extent of corrosion/wear-out of the refractory in such application. But for THS, the effect of degradation is generally considered from the time required for tapping. For each tapping, the amount of molten steel tapped is nearly equal, so when a new THS is installed, molten metal takes a longer time to pass through as the working surface is unaffected/non-corroded/un-abraded. The more the THS is used, the more the molten metal flow will corrode and abrade the THS working surface, causing a reduction in THS thickness and an increase in the inner diameter of the THS, causing a higher metal flow rate. So the tapping time from the same THS for the same amount of molten steel will be reduced after multiple numbers of tapping. Again, the duration of tapping is important for steel processing activity. For a long tapping time, the steel productivity will be less, and on the contrary, for a shorter tapping duration, it is difficult to mix the additives and alloying materials uniformly and fully within the steel ladle. Hence, tapping requires to be done in an optimum time duration.

The THS refractory majorly suffers from three different wear mechanisms of flowing molten steel stream, namely, oxidation, corrosion, and abrasion. The oxidation mainly occurs for carbon and other non-oxides present in the composition with the presence of oxides, like, FeO and MnO, in steel. The corrosion primarily occurs for the MgO fines and grains that are in contact with the impurities of steel and slag. Further, the extent of corrosion is also dependent on the amount of impurities present in the MgO itself. Wear-out of the refractory also occurs due to the flow of the molten steel at very high temperatures. The degradation of the refractory is accelerated due to the thermal and mechanical spalling effects for intermittent tapping operation and environmental oxidation (by gas phase).

The outer side of the THS, which is facing the outside open environment, suffers from thermal shock due to the sharp increase in temperature when the tapping starts. Also, mechanical spalling occurs as the heavy metal (molten steel with specific gravity ~7.9) passes suddenly through the sleeve during tapping, which otherwise has no load during the process of steelmaking in the converter. Further, the environmental oxidation of the non-oxide components of the THS refractory, especially for the matrix phase (finer particles), occurs during the interval between two consecutive tapping operations, during inspection, repair, and charging times, etc., affecting the properties of the THS. The use of metal powder antioxidants prevents oxidation, but they also degrade the refractory if the converter is cooled to room temperature for repair/maintenance (or for any requirement). Al metal powder present in the composition as antioxidant may crack and suffer disintegration due to hydration (from atmospheric moisture) of the formed aluminium carbide phase at very low temperatures. The THS composition needs to be optimized to withstand the harsh environment of application by the use of fused MgO (large crystal size) and its content, carbon content, type and amount of antioxidants used, extent of porosity generation, developed strength after coking, decarburized layer thickness, hot strength, etc.

Due to oxidation, the working surface of the THS becomes porous, mainly due to the removal of constituent carbon from the composition, and the decarburized layer is easily removed due to the turbulent metal flow during tapping, causing a thickness loss of the refractory at the hot face. So the mechanical properties of the refractory degrade gradually with the increase in oxidation or metal flow time. The oxidized refractory is also weak against corrosion, as the molten flowing mass can easily penetrate and corrode the porous refractory. In order to restrict or slow down the oxidation of carbon in the THS refractory, antioxidants, like metal powders (Al, Si, Al-Mg, etc.), or carbide (SiC, B_4C) additives must be added to the composition. The metal powders also improve the hot strength properties of the refractory by forming metal carbides that provide extra bonding at high temperatures. The formation of metal carbides also improves the abrasion resistance. For an improvement in corrosion resistance, the use of fused magnesia with a large crystal size is the primary requirement for the refractory, as the corrosion resistance of MgO-C compositions is found to be directly related to the content of fused magnesia and its crystal size.

5.6 OPPORTUNITIES FOR IMPROVEMENT

The steel industries are in demand for THS with excellent spalling resistance, longer tapping duration, and longer service life, to reduce the frequency of taphole repair and replacement activities. The replacement process of the THS is shown in Figure 5.4, and for complete replacement, the converter downtime is about 40 min (including 15–20 mins for drilling and about 10 mins for sintering post-replacement), which is again close to 1 heat/cycle time of the converter. To enhance the life of the THS and reduce the downtime of the converter, the quality of the THS refractory is improved by compositional adjustments, especially for the enhancements of thermal spalling and abrasion resistance. An improvement in bonding within the sleeve refractory and an increase in hot strength are achieved by using the proper type and amount of metallic additives, which also help in improving oxidation and abrasion resistance.

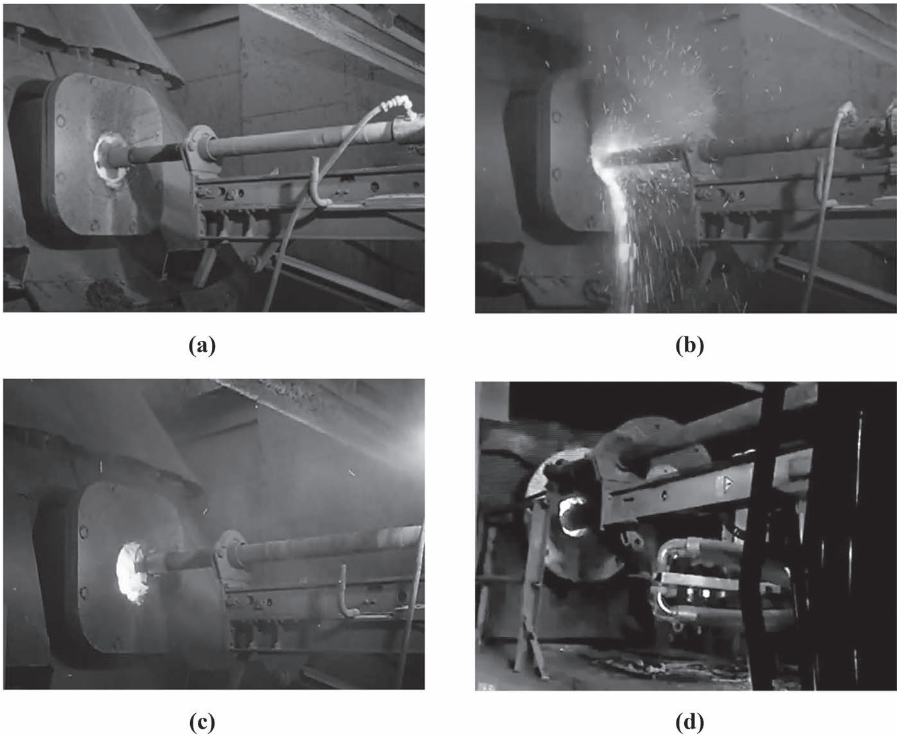

(a) (b) (c) (d)

FIGURE 5.4 Complete replacement process of the taphole sleeve: (a) initiation of drilling process; (b) drilling going on; (c) drilling completed, where old THS is dislodged, removed, and pushed inside the converter; (d) new THS being placed in.

To improve the quality of the THS, and its performance, refractory manufacturers are continuously working on THS, and few of the measures implemented are mentioned in what follows.

1. *Use of optimized carbon content.* To obtain an improved corrosion and thermal shock resistance, many a times refractory makers introduce a greater amount of carbon in the composition. The higher amount of carbon will oxidize faster and in a greater extent by the atmospheric air and oxides present in the molten flowing mass. This will degrade the quality and performance of the THS. Also, the chances of the dissolution of carbon in the produced steel are higher, which will deteriorate the quality of steel too. Hence, optimization of the carbon content as per the application requirement is required to be judged properly.
2. *Use of finer (micro- and meso-phase) carbon.* The use of larger-sized carbon/graphite (flake) has the tendency to oxidize faster. Finer (micro) carbon acts as filler material, fills the gap between the aggregates efficiently, and reduces pore size to get a dense matrix. The dense matrix will have lesser space for ingress of oxygen and also reduces the penetration of any liquid, thus improving both oxidation and corrosion resistance. Again, meso-phase carbon provides an anisotropic and graphitizable coke structure on heating, which improves the resistance against oxidation, corrosion, and thermal shock.
3. *Modification in particle size distribution/granulometric composition.* The concept of particle size distribution/granulometric composition of a shaped refractory is based on the filling of voids/pores among the aggregates. The coarse- and medium-sized aggregates form the skeleton of the shape, and the finer ones fill the voids and the gaps. But the use of a greater extent of coarser-sized grains also creates voids with a larger size among them. These bigger voids enhance the chances of ingress of oxygen and penetration of liquids. Hence, the formulation may be modified by reducing the amount of the coarser size and increasing the amount of middle fraction(s). A reduction in pore size and total porosity helps improve the performance of the THS. Optimization in particle size distribution and high compaction are essentially required in obtaining a packed and dense structure of the THS.
4. *Use of nano-sized carbon.* The use of nano-sized carbon (as carbon black) by partially replacing the graphite content and by a reduction in the total carbon content of the THS composition results in an improvement in hot strength, oxidation resistance, and other properties. The presence of nano-sized carbon black produces a very close-packed matrix and improves compaction and strength. Also, nano-sized carbon forms faster and a greater extent of metal carbide phases upon reaction with the metallic antioxidants and improves bonding and strength properties. Further, the use of nano-sized carbon helps reduce the total carbon content, and increased compaction reduces the overall oxidation of the refractory. Also, the reduced amount of carbon in the refractory reduces the chances of carbon dissolution in the

produced steel (carburization). All these improvements lead to developing a low-carbon-containing refractory with improved properties.

5. *Use of greater amount of additives.* Property-enhancing additives, like antioxidants, improve the performance and service life of the THS. A greater extent of antioxidants produces a greater extent of bonding at high temperatures, providing oxidation resistance along with high hot strength and resistance against corrosion and abrasion.

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6 Porous Plug

6.1 INTRODUCTION

The introduction of a secondary steelmaking process incorporates efficient and effective processing that produces steel with desired purity, compositional optimization, uniformity in temperature, and final properties. Also, it optimizes the usage and availability of primary steelmaking reactors (namely, basic oxygen furnace and electric arc furnace) for smelting the steel. All the activities of secondary steelmaking processes, to obtain purer and quality steel, are allowed to utilize the limited extent of work, energy, resources, and time for higher productivity and economy.

A high-purity clean steel essentially demands for minimum inclusion, uniform composition and properties with desired phase constituents. The removal of inclusions, especially non-metallic inclusions (NMI), is a major concern to attain clean steel. Non-metallic inclusions, commonly ceramics, are typically made up of oxides, sulphides, etc. that remain as defects in the metal matrix and deteriorate the properties drastically. The level of tolerance allowed for these inclusions is very low to make a "clean steel." These non-metallic inclusions have many origins throughout the steelmaking processes, and generally, they are classified accordingly. Commonly, the exogenous inclusions come from the refractories in contact or entrapped slag, whereas the endogenous ones are the reaction products of the interactions among the steel constituents within the molten bath or inherent to the original raw materials. To obtain a clean steel, the level of inclusions (for both types) must be very low, and they must be separated and removed from the processed molten steel.

The secondary steelmaking process improves the quality of steel by removing the inclusions, making the steel uniform in composition, temperature, and properties, and also allows to adjust the concentration of the minor constituents by the addition of various alloying elements. Hence, mixing activity is essentially required to attain uniformity in the steel and distribution of alloying elements all through the molten bath. Again, the duration of the molten steel residing in a ladle depends on the casting sequence, availability of tundish, etc. In case of any long duration of steel residence in a ladle, there remains a high chance of heat loss through the open end of the ladle and fall in steel temperature. Further, the chance of a heat loss through the ladle wall increases with steel residence time in ladle. This results in a cooler zone of molten steel, especially at the top and the portions in contact with the ladle, whereas hotter steel remains at the centre of the ladle, as schematically shown in Figure 6.1. This zonal temperature difference within the steel bath affects the desired crystallization of different phase constituents after casting, leading to variation in the properties and performance of the final steel products. So the formation of the cooling zone (temperature gradient) within the steel bath of the ladle must be avoided, and the stirring of the molten steel is essential, especially for the long holding duration of molten steel in the ladle. The stirring of the molten steel within the ladle also ensures uniformity in steel quality from various aspects.

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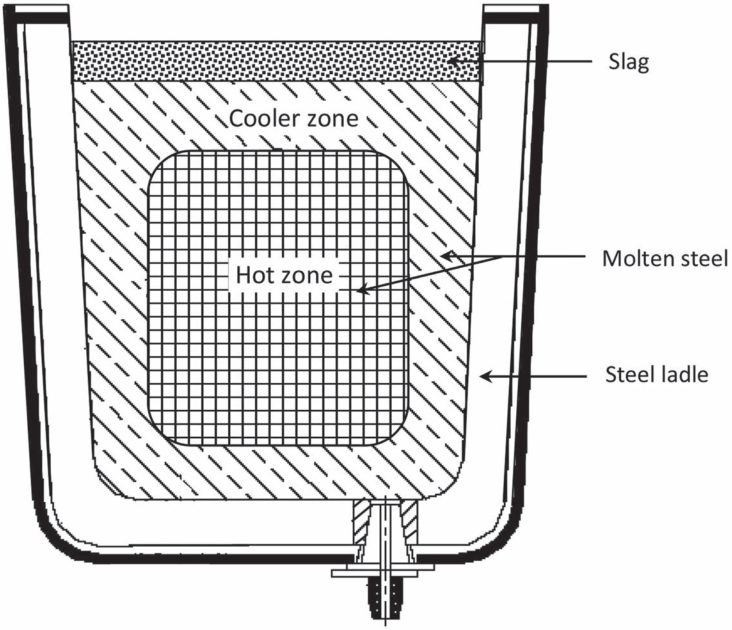

FIGURE 6.1 Cold and hot zones of the steel bath within the ladle.

The use of any mechanical stirrer for the mixing of molten steel within the ladle is just not feasible due to the high density and viscosity of molten steel and application temperature. The more feasible and easier way for the stirring of the molten steel bath is to introduce pressurized inert gas bubbles at the bottom of the steel bath. Inert gas will not react with the molten steel or with its alloying components and impurities and will cause vigorous movement of steel (stirring action) while moving upwards within the steel bath due to great density difference (buoyancy effect). Thus, the introduction of inert gases at the bottom of the steel bath will automatically force the bubble to move upwards, causing movement and stirring action within the steel bath. The greater the amount of gas bubbles and the higher the injecting/purging pressure of the bubbles, the greater will be the movement and turbulence of the bubbles, and the greater will be the stirring/mixing action within the steel ladle. Stirring of molten steel in the ladle can also be carried out by the use of electromagnetic stirring, but the process is yet to be commercially successful.

Purging of inert gas bubbles in steel ladles has started commercially since the 1970s and has also seen multiple modifications and improvements. The advantages of the introduction of inert gas bubbles at the bottom of the molten steel bath within the ladle are mentioned here:

1. It helps in attaining uniformity in temperature and chemical composition of the entire molten steel pool within the ladle.
2. It improves the fluidity of molten steel, especially helpful when the casting temperature decreases.

3. It reduces non-metallic inclusions by pushing them up, towards the slag region; two different mechanisms may be involved for such activity: attaching the inclusion particle to the gas bubble's surface or (b) by a plain kinetic mechanism of pushing upward due to the movement of the bubbles.
4. It reduces the absorbed gaseous inclusions, like oxygen, hydrogen, and nitrogen, in the steel bath by agglomerating and coalescing with the inclusion gas bubbles, making bigger-sized combined bubbles and generating a greater buoyant force for faster upwards movement and removal.
5. It helps in stirring and mixing of any additive (desulfurization, dephosphorization agents) and alloying elements for their uniform distribution. The stirring process also enhances the rate of all the chemical reactions occurring within the steel ladle.

6.2 TOP AND BOTTOM PURGING

The introduction of inert gas at the bottom of the steel bath in a ladle can be attained by two different mechanisms, namely, top purging and bottom purging. In top purging, inert gas is introduced by inserting a refractory-lined lance pipe from the top open end of the ladle. The lance needs to be long enough to reach the bottom of the steel ladle after passing through the slag layer and molten steel bath and should have the channel at its centre to carry the inert gas till the bottom and then purge the same within the steel bath. On the other hand, for bottom purging, the same phenomena can be achieved by placing an appropriate gas-permeable refractory plug (called porous plug) installed at the bottom of the steel ladle and pushing the inert gas through the plug. Schematic diagrams for the operation of both the systems are shown in Figure 6.2. However, in comparison to the plug, the performance and life of the lance are inferior, primarily due to economy, efficiency, wear effects, and difficulties in installation and operation.

In the bottom purging system, the inert gas moves from the bottom side to the top surface of the porous plug through a porous network structure and comes out from the top surface to enter into the molten steel bath within the ladle. The inert gas bubbles move upwards and push the inclusions in the upward direction (by physical pushing or by attaching the inclusion with the gas bubbles). Thus, the inclusions move to the slag zone, present as the top layer in the steel ladle above the molten steel, and the steel becomes clean. Due to the movement of the gas bubbles, the molten steel also moves upward under the thrust of the bubble movement and makes a circulatory movement within the steel ladle. Thus, the molten steel within the ladle moves on under the impact of the gas bubbles' movement, and stirring continues, resulting in uniformity in molten steel batch. But this circulatory movement also causes back pressure of molten steel at the bottom of the steel ladle, causing abrading effect on the ladle wall and bottom. The upward movement of the gas bubbles also affects the steel–slag interface layer and may expose the molten steel to the open environment (molten steel is usually covered by the slag layer at the top side) by removing the slag cover due to high purging gas pressure. Such a condition is commonly called a slag eye/open eye formation. This may result in the oxidation of the exposed molten steel. These effects of inert gas purging through a porous plug from the bottom of the steel ladle are schematically shown in Figure 6.3.

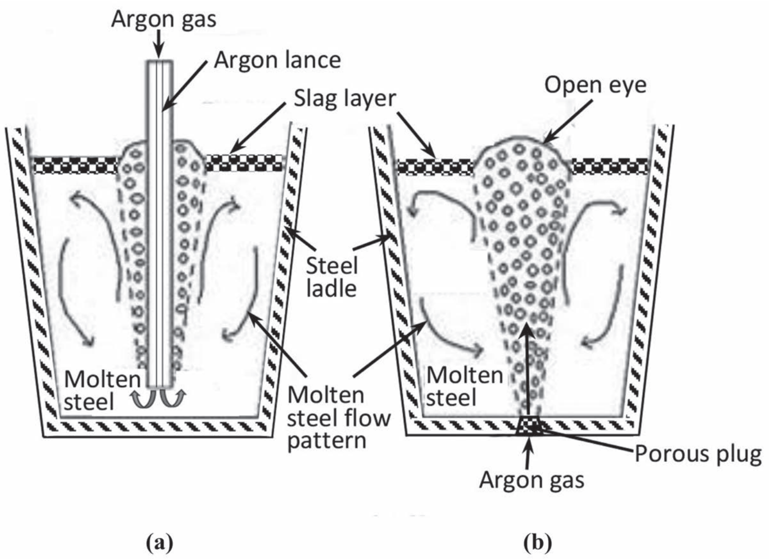

FIGURE 6.2 Inert gas purging in a steel ladle: (a) top purging (argon lance), and (b) bottom purging (porous plug).

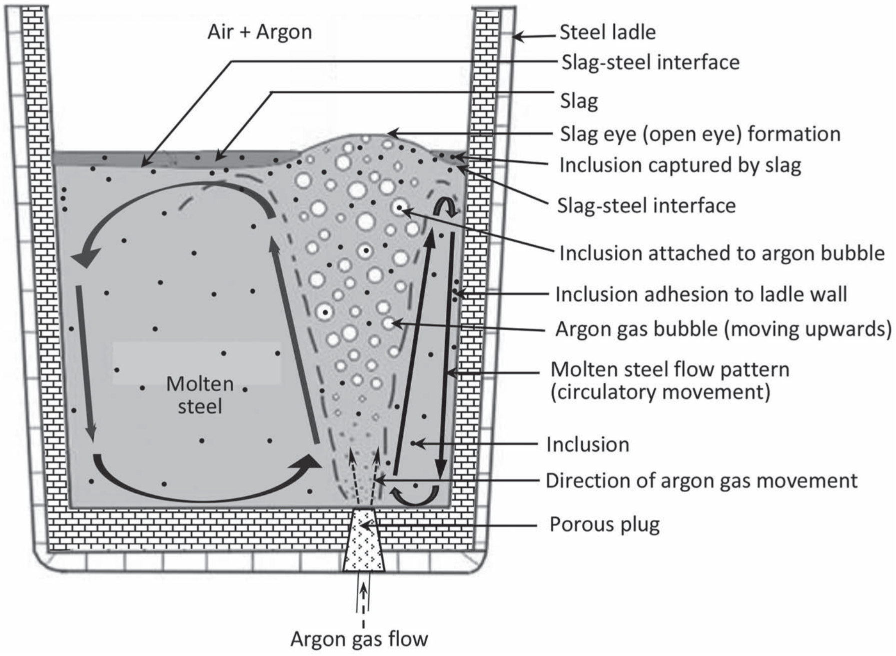

FIGURE 6.3 Effect of argon gas purging through the porous plug on the steel bath in the ladle.

Operational practices are different in different steel manufacturing units. Commonly, gas purging porous plugs are attached at the ladle bottom, and inert gas is purged by using an auto coupler arrangement. The moment the ladle is placed on the transfer car to carry the molten steel from converter to casting site, the inert gas supply will start automatically by the coupled arrangement. Among the different inert gases available, argon (Ar) is preferred for purging and rinsing of molten steel due to its inertness, extremely low solubility in molten steel, and relatively easy availability. The lance mechanism of gas purging (top purging) is also used at specific purging stations as an extra backup means for bath stirring if the plug fails or upon the requirement of excess purging as per steel processing demands.

6.3 POROUS PLUG OR PURGING PLUG

The *porous plug*, or purging plug, is a porous refractory piece installed at the bottom lining of the steel ladle that enables the inert gas to be introduced into the ladle and to create a stirring action within the molten metal bath. Typically, the porous plug is a truncated cone-shaped porous refractory body which is assembled within a steel or iron jacket connected to a gas inlet pipe. The jacketed porous plug is fitted into an opening at the bottom of the ladle, through which inert gas is injected/purged into the molten steel bath. The porous plug can be considered as a *breathable refractory* through which inert gas can pass from one end (bottom) surface to the other (top), but not the liquid metal in reverse direction. It primarily acts as a gas diffuser to the molten steel bath. The use of a porous plug provides the flexibility of introducing inert gas into the steel bath within the ladle at any of the following positions, which is not possible by using a top purging (lance) system:

1. During tapping from converter
2. During transport of molten steel–filled ladle from steel melting shop to casting shop
3. During operation under vacuum treatment or ladle furnace
4. At rinsing stations
5. During casting

The pore structure arrangement within the plug actually allows and controls the gas flow from the bottom end of the plug to its top surface. Though it allows purging of the inert gas into the molten steel bath due to gas pressure, it restricts any possibility of molten metal penetration through the plug. The plugs need to have proper gas permeability and the ability to transfer large quantities of gas with the desired bubble size. Also, the porous plug has to have high hot strength, good thermal stability, and excellent resistance against erosion, wear, abrasion, corrosion, and thermal shock. The complete porous plug refractory assembly, located at the steel ladle bottom, consists of various parts, namely, the porous plug (refractory); the metallic sleeve, within which the plugs fits; the well block, containing the complete system; clamp; and the tie-down system. Sleeves provide stability to the plug, and refractory mortar is used for fixing the plug refractory with the metallic sleeve/jacket. The mortar also acts as a cushion to compensate/accommodate any expansion of the plug at high temperatures. For effective inert gas purging, the optimum size of gas bubbles, amount of gas purged, gas flow rate, etc. are important technological parameters. All such parameters are controlled by the installed porous plug and its porous network structure.

Inert gas purging time through the porous plug generally varies between 60 and 90 min per heat, with variable flow rates, which again depends on operational requirements. Presently, plug performance is above 95%, and the service life of a good plug refractory is around 2,000–2,500 min for an average steel holding time of 2.5–3 h. The performance of the porous plug is dependent on the type of the plug used and also on the quality and properties of the refractory material. They are also equally dependent on various operational parameters and practices, as mentioned in what follows.

1. *Turnaround time.* A longer turnaround time means prolonged contact of the plug refractory with the molten steel and slag, resulting in the choking of the porous channels (reduced opening) of the plug and poor performance.
2. *Holding time and idle time.* A higher holding time reduces the life of the porous plug, especially for a longer duration with idle plug condition (without purging), as the chance of metal infiltration through the plug top surface is increased.
3. *Steel/tapping temperature.* The temperature of the molten steel bath and its tapping temperature are important for the performance of the porous plug. A reduction in temperature causes chilling effect and skull formation on the top surface of the plug, reducing the opening of the plug and its performance. The peeling/cracking of the plug top surface also occurs in the next purging. This causes high fluctuation in inert gas flow rate during purging. Again, an increased steel/tapping temperature reduces the molten steel viscosity, leading to a greater metal penetration in the plug, causing higher wear, erosion, abrasion, and corrosion of the plug top surface.

Though the purging of inert gas provides multiple benefits, it causes higher refractory wear at the ladle bottom due to back attack of the molten steel flow, resulting in a shorter campaign life. Extensive purging and the use of a greater volume of inert gas lead to a higher bath turbulence that further enhances the wear rate of the ladle side walls. The position and the number of plugs at the ladle bottom are also important for the efficiency of the purging activity and affects the wear rate of the refractory, both at the ladle bottom and the side walls.

6.4 INERT GAS BUBBLE AND PURGING

Structurally, the porous network within the plug acts as an individual capillary system, and the inert gas passing through the pore channels comes out as bubble from the open (top) surface of the plug and enters into the molten steel bath in the ladle. Primarily, there are three different stages of this bubble formation, namely:

1. Nucleation of the bubble
2. Growth of the formed bubble
3. Detachment of the bubble from the porous plug top surface to the liquid steel

The formation of bubbles within the molten steel bath is primarily dependent on the amount of gas introduced and its flow rate. This bubble nucleation stage is mainly governed by the pressure difference between the inside and the outside of the bubble's curved surface that forms the boundary layer between the inert gas and the molten steel (Laplace pressure effect). Due to the greater pressure of the incoming purging gas from the plug refractory, the bubble grows and finally attains a maximum size, beyond which the detachment occurs. The detachment of the bubbles is almost instantaneous at relatively low gas flow rates, but a jetting stream of gas flow occurs at higher flow rates. A lesser amount of inert gas at low pressure produces small and single individual gas bubbles, as the governing factor is only the surface tension effect. An increased amount of gas will result in an increase in the individual bubble size, and upon further increase, the individual bubble will agglomerate/merge to form the jet stream. The porous network structure of the plug also governs the transition from individual bubble to jet stream. As per the application requirements of steel processing conditions, different types of porous plugs are used to attain different bubble conditions of the inert gas during purging.

From the steel processing point of view, the amount of inert gas purged, its flow rate, and the formed bubbles are important. For common activities, like purifying of steel, separation and removal of oxide (non-metallic) inclusions, reduction in absorbed gaseous impurity in steel, inclusion shape control, etc., the flow rate is maintained at a lower level, in the range of 50–150 L/min. The size of the bubble remains small with less-vigorous stirring, and this low flow rate avoids any exposure of the liquid steel to the atmosphere by opening the slag layer (slag eye formation). But for the requirements of a higher extent of mixing/homogenizing of liquid steel (uniformity in composition and temperature) or the mixing of additives like alloying agents, deoxidizing additives, etc., the flow rate is increased to the range of 150–800 L/min. Further, for pushing away of the slag, processing like desulphurization, etc., high thrust is required, which is attained by increasing the gas flow rate up to 2,000 L/min. A greater flow rate develops bigger-sized bubbles and initiates the jetting stream of the inert gas.

Also, at higher gas pressures, the gas thrust opens up the slag layer present at the top of the molten steel bath (open eye formation), causing an exposure of the molten steel to an open-air environment, thus increasing the chances of oxidation. Once the gas bubble is detached from the porous plug surface, it moves upwards due to buoyant forces. The size of the bubble may change due to numerous parameters depending on the steel processing conditions, like viscosity and temperature of the molten steel, gas pressure, surface tensions, bubble inertia, gas momentum, etc. All these parameters are important for the behaviour of the bubble formed and its movement through the molten steel bath.

It is important to note that the surface between the inert gas bubble and molten steel acts as a deposit/sink for the gaseous impurities and oxide (non-metallic) inclusions present in molten steel. The greater surface area (smaller size) and the slower movement of the bubble provide a longer time for the interaction of the inert gas with the inclusions and increase the possibility of removal of inclusions, producing cleaner steel.

6.5 TYPES OF POROUS PLUGS

The porous plugs need to withstand different conditions of chemical, mechanical, and thermal environments as per the application requirements. They have been in use for a long time in purging inert gas to clean the molten steel. The functioning and design of the porous plugs and their application environments have changed considerably with time. To meet the requirements of a changing operational environment and the growing demand of the steel industry, different types of porous plugs are developed. As per the design/concept of the pore structure/porous channel used to purge the inert gas, porous plugs are majorly classified as:

1. Non-directional porous plug
2. Directional porous plug

The initially developed porous plugs were highly porous, sintered products having non-directional porosity and a permeable structure. These products produced a high opening rate but allowed only a small amount of gas flow from one end to the other due to its non-directional pore structure. The inert gas enters within the plug at the bottom surface, gets multiple channels/passages to move on under gas pressure in all directions due to the non-directional porosity present in the refractory. So the net amount of gas reached and its pressure at the opposite end (top surface) are low. The entered gas loses its direction of flow due to non-directional porosity and may even oppose the gas flow, but due to the porous structure and high porosity, the refractory wears out very fast from the corrosion and abrasion/erosion effects of molten steel and slag. Thus, the service life of the plug with non-directional porosity is very poor.

The plug refractory is modified with a directional porous network having slit or slot porous channels that enhance the gas flow in the desired direction. These modified plugs are called directional plugs. As the directional plug refractory contains very narrow porous channels for gas flow in a dense refractory structure, the corrosion, abrasion wear effects are considerably low compared to that of the non-directional plugs. So the service life is enhanced considerably. Further developments produced segmented porous plugs with directional pore channel, which provide high gas flows, high opening rates, and further increased lifetime. The directional porous plugs showed excellent performance in handling a huge gas volume and higher flow rates but perform less satisfactorily at low flow rates. Further developments have resulted in a hybrid porous plug which is a combined form of directional and non-directional pore structure concepts. Hybrid plugs show excellent performance and optimal bubble formation with high opening rates both at low as well as high flow rates. These hybrid plugs, widely acceptable for technical reasons, can easily operate at a wide range of gas flow rates, both for purifying and homogenizing requirements. All these types of porous plugs are described in detail in the following.

6.5.1 NON-DIRECTIONAL POROUS PLUG

The development of the porous plug has started with this type of refractory piece wherein the pressed and fired refractory piece to be used as plug is made by designing the granular composition in such a way that increases the interconnected porosity and permeability. This feature allows inert gas to pass through the refractory piece placed at the bottom of the steel ladle and generate gas bubbles to homogenize the molten steel and to capture and remove non-metallic and gaseous inclusions from molten steel. As the distribution of porosity within the refractory is random, no specific directional arrangement is made; hence, they are called non-directional porous plugs. These plugs are also called dispersion-type or diffusion-type porous/purging plug. Figure 6.4 represents a commercial non-directional porous plug.

The pore characteristics of the plug affect the inert gas bubble formed, their size, the rate of inert gas flow, and gas velocity when flowing out of the plug and entering into molten steel bath. Again, the pore characteristics of the non-directional porous plug depend on the size of the different grain fractions used, the amount and size of the pore formers (commonly burnable materials), etc. in making the refractory and also on the manufacturing technique. Non-directional porous plugs perform better at lower gas flow rates, and the rate can be controlled easily. The non-directional porosity produces a large number of smaller sized bubbles, which is most suitable for the soft bubbling of inert gas required for the purifying of steel. The higher flow rates of inert gas are difficult to achieve due to the non-directional nature of the pores. Again, at higher flow rates, the wear-out effect of the top surface of the plug will be high due to a higher back pressure effect (highly porous refractory having low strength and wear resistance), causing a significantly low life. The low life of the plug requires a frequent plug change that adversely affects the productivity, manpower requirement, and economy.

The refractory part of the non-directional porous plug (porous, gas-permeable segment) is made up of alumina, magnesia, alumina–spinel, alumina–chromite, magnesia–chromite, etc. compositions with porosity in the range of 25–40%. The

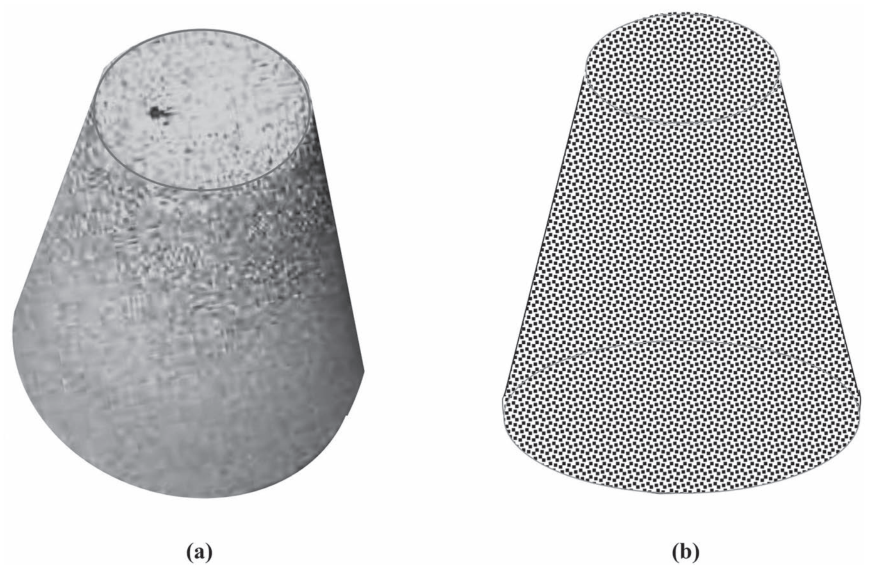
(a) (b)

FIGURE 6.4 Non-directional porous plug: (a) commercial product, and (b) schematic.

porosity is generated within the plug refractory by suitably selecting the grain fractions and the organic burnout materials (carbon-containing ones). The organic materials need to be low-temperature burn-out ones to generate porosity without leaving any residue. However, in reality, the developed porosity within the plug refractory is not uniformly distributed throughout the plug; rather, it is higher in the central portion of the plug and lower towards the outer inclined surface. The non-uniform distribution of porosity is difficult to avoid as the shaping of the conical-shaped plug is commonly done by uniaxial pressing process.

In application, during the plug idle time (when the purging operation is stopped), the molten steel and slag from the ladle can infiltrate into the non-directional porous structure of the plug through the top surface and can penetrate into the deep areas of the plug through the open pores network structure. Thus, the plug is easily penetrated and gets corroded by the molten steel and slag. Also, a dense layer is formed on the working surface of the plug, containing the penetrated molten mass that has a different characteristic compared to the rest of the plug refractory. This layer may be peeled/spalled off the surface while cleaning of plug post metal casting and de-slagging. Or the layer will be separated out from the top part of the plug upon restart of the purging action in the next heat of the ladle, thus causing the wear of the plug. Furthermore, the plug cleaning activity with oxygen lancing to remove the surface deposition at the top surface in between two consecutive castings, also wears out the plug (due to excessive heat) as the plug is highly porous and low in strength, affecting the service life.

6.5.2 Slot Plug (Containing Porous Channel/Slit)

The highly porous and permeable structure of the non-directional porous plug has a weak refractory structure, especially from the mechanical and corrosion resistance points of view. The plugs wear out faster due to poor strength and easy penetration of the molten metal and slag. To improve plug performance, the concept of creating a passage for inert gas within the plug refractory is modified. The improved porous plugs are made up of a dense refractory mass having designed/fabricated porous channels/slits, with a very small width that will allow the inert gas to pass through, but the molten steel and slag will not enter in the thin channels due to a restriction from minimum droplet diameter. The channels within the plug are present, from its bottom surface to the top (steel contact) surface, making the flow of inert gas completely directional. So the slot plugs have a directional porous network structure and can be called directional plug. The porous channels are designed and customized as per the application site requirements, considering factors like grade of steel, processing time, capacity of ladle, steel temperature, ferrostatic pressure of the liquid steel bath in ladle, etc. As today the slot plug is the most widely used purging plug, the results in the best purging effect within the steel bath of ladle and also provides low wear rate, long service life, safety, stability, performance, and productivity.

The porous channels through which the inert gas is purged are straight slits and are arranged in such geometric configuration so that the porous plug can meet the purging requirements as per the application criteria. The number and dimensions (width and thickness) of the slits may vary in the plug to optimize the amount of inert gas purged, gas flow rate, conditions of molten steel (temperature and viscosity), total purging time, and also as per process requirements. A huge amount of gas can be purged at high flow rates using this directional porous plug to meet the requirements for the chemical and thermal homogenization of molten steel, pushing away of the slag, etc., which is difficult to achieve with the non-directional porous plugs.

The development of the slot plug with directional porosity using slits has surmounted the most serious disadvantages of the non-directional plugs related to service lifetime. Slot plugs are generally made up of an alumina-based dense castable system, mostly in combination with spinel, and has arranged porous channels/slits for gas flow. An alumina–chrome system is also used for improved corrosion resistance. Porous channels are developed within the dense castable by using organic/plastic (Teflon) strips/tapes that get burnt out during the heat treatment process of the plug. Lubricated metallic/steel strips are also used instead of plastic strips, which are removed from the cast green body post–demoulding stage. The slits/channels remain unaffected during drying and firing/sintering of the plug and remain fully permeable. Figure 6.5 shows a slot plug containing the slits made by using steel strips at the green conditions. As the

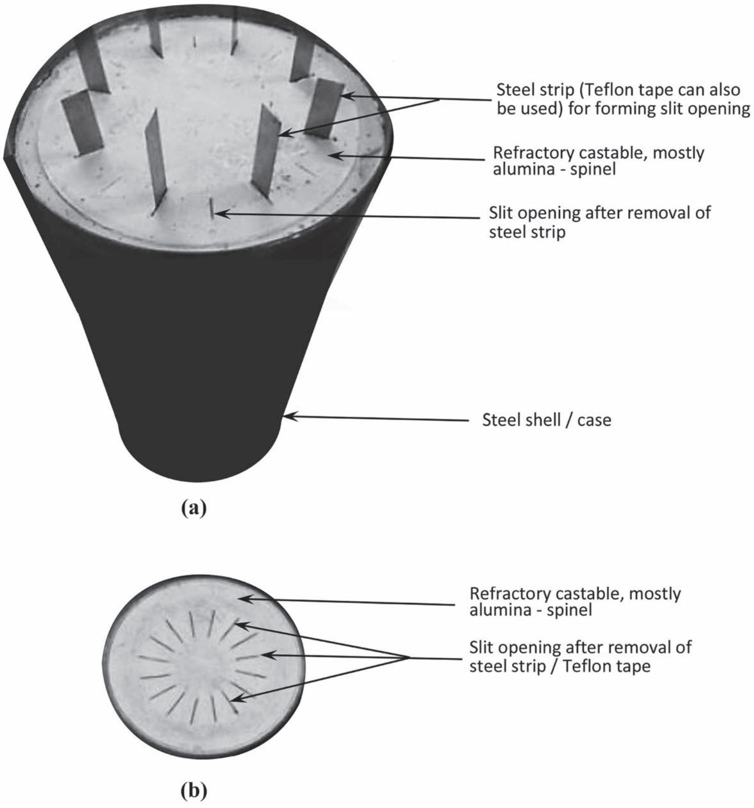

FIGURE 6.5 Slot plug: (a) containing the steel strips during manufacturing (green shape); (b) slits on the top surface after manufacturing.

slot plugs are prepared from castables, they can be provided with any critical shape and dimensions, which are not limited due to any processing step or equipment capability as is restricted for non-directional porous plugs (for pressing limitations). A dense castable for the slot plug provides a homogenous and compact microstructure throughout the plug, resulting in excellent properties, performance, and service life. Some details of the commonly used castable for making the slot plug are provided in Table 6.1.

The castable composition, slit dimensions, numbers of slits present, arrangement of slits, etc. all affect the gas purging capability, performance, and service life of the slot porous plug. A higher slit dimension will enhance the gas flow rate, which also increases the back pressure, causing greater erosion, wear, and chances of metal and slag penetration and may result in early failure of the plug. Due to the risk of penetration, the opening rates of slot plugs are not as high as those of non-directional plugs. Again, slot plugs show an excellent performance at high flow rates of inert gasses and mostly used for general metallurgical processes, like homogenizing the steel. At low flow rates, slot plugs are difficult to control, and a separate flow control equipment (mass flow controllers) may be required to control the inert gas flow rates for soft purging. This behaviour, in combination with a relatively small number of bubbles generated by the slot plug, makes them less preferable for soft bubbling (low-purging-rate) conditions.

6.5.3 SEGMENT PLUG

This type of porous plug also contains directional channel porosity, wherein the porous channels are present as a central blowing unit, formed by arranging highly dense ceramic plates. Pressed and fired highly dense plates made up of alumina, corundum–mullite, alumina–zirconia, alumina–chromia, and alumina–chromia–zirconia

TABLE 6.1
Properties of Castable Commonly Used for Making a Porous Plug

Properties	**Castable Details**
Spinel content (%)	10–15
Chemical analysis (wt%)	
Al_2O_3	90–92
SiO_2	0.1
MgO	3.0–5.0
CaO	1.5–1.8
Fe_2O_3	0.1–0.2
Properties, after firing at 1,600°C	
Bulk density ($g.cm^{-3}$)	3.15–3.20
Apparent porosity (%)	12.0–14.0
Cold crushing strength (MPa)	>120
Flexural strength (MPa)	>40
Permanent linear change (%)	0.18–0.22
Thermal shock resistance, heating 1,200°C – air quenching	>20 cycles

compositions are used. Chromia and zirconia are added to alumina-based refractory compositions (>90 wt%) primarily to improve the strength, thermal stability, and resistance against corrosion and wear. These plates are designed in such a way that a groove between them, of thickness 0.2 to 0.3 mm, will be formed when they are stacked over one another. The groove thickness may be varied during the fabrication of the plates, as per the purging process requirements, like argon flow rate, viscosity of liquid steel, etc. The stacking arrangement of these plates creates the gap/slit within them, and a multiple number (4 to 8) of plates are stacked to create multiple channels at the central position of the plug, as shown in Figure 6.6. This

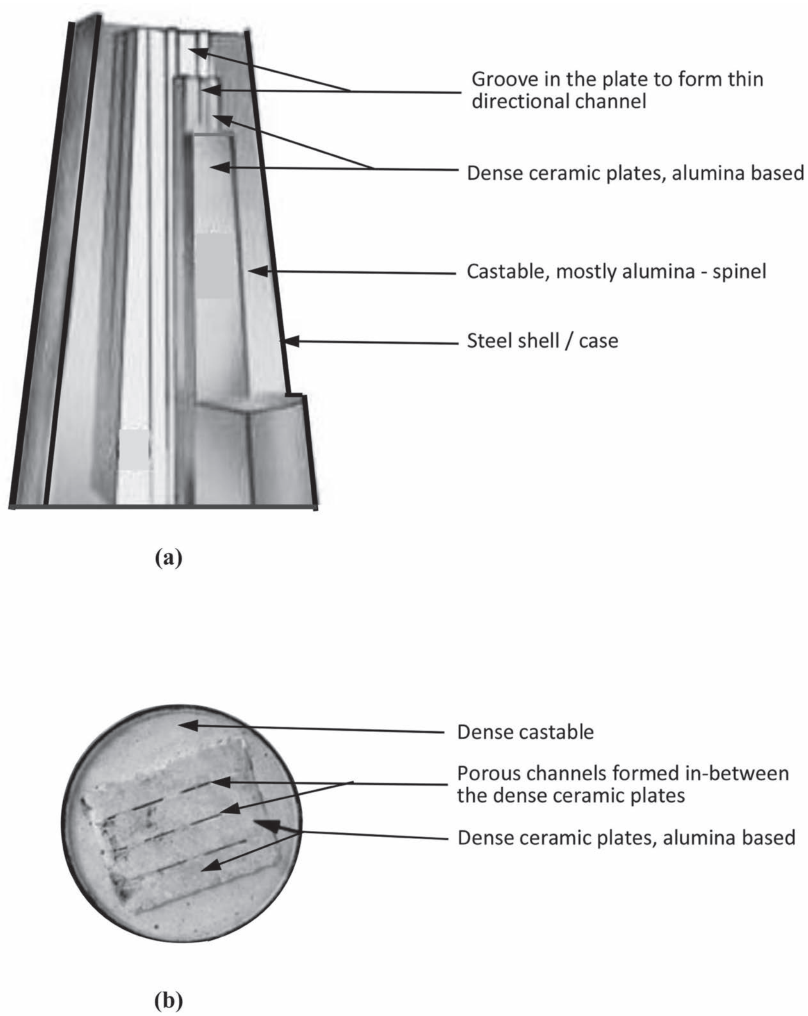

FIGURE 6.6 Segment plug: (a) stacking arrangement of sintered alumina plates (forming porous channels); (b) view of the porous channels on the top surface.

stacked arrangement of sintered plates is surrounded by low-cement, high-strength, and dense castable, mostly made up of alumina–spinel composition. The complete assembly of the refractory materials (plates and castable) is then encased in a stainless steel case/jacket.

A strong and dense refractory structure, both for the sintered plates and the castable within the plug refractory, resists the mechanical and chemical attack of the molten steel and slag, resulting in improved performance and longer service life of the segment plug. The main advantages of this segment porous plug are:

1. High purging rate
2. Easily adjustable gas flow
3. Easy cleaning (higher resistance to oxygen lance cleaning due to dense structure)
4. Low wear rate due to the use of high, dense, strong ceramic plates
5. Higher availability of gas channels that can provide a uniform and regular bubble pattern
6. Better plug life

6.5.4 PLUG CONTAINING RECRYSTALLIZED ALUMINA (RCA) TUBES

Directional channels for inert gas flow through the porous plug are also attained by the use of dense alumina tubes containing narrow channels/slits. Highly sintered *re-crystallized alumina* (RCA) tubes are prepared from high-pure-alumina and porous channels, or slits are fabricated within the tube by using burnable organic tape/slits while making the dense cylindrical alumina shapes. The tubes are fired at very high temperatures, with prolonged dwell time for the recrystallization process of alumina, to attain very high density, strength, and very low porosity. Organic tapes will burn out during the firing, and straight directional channels are produced in place of the tapes which remain as slits retaining the dimensions even after sintering. These tubes contain about 99.7% of alumina and have bulk density above 3.8 g/cc, with apparent porosity close to 3.5%. Multiple numbers of these RCA tubes are used in making the porous plug, mostly placed in a wider area, distributed throughout the plug cross section (not arranged only at the central portion), and then the rest of the portion of the porous plug is cast with a highly dense castable of alumina–spinel composition. The plug refractory, dense castable shape containing the RCA tubes, is heat treated for the desired property development. Figure 6.7 shows the details of an RCA tube containing the plug. The main advantages of RCA tube containing plugs are:

1. Modified slot profile for distributed gas flow
2. High purging rate
3. Low wear due to the use of dense castable and sintered recrystallized alumina tubes
4. Long service life

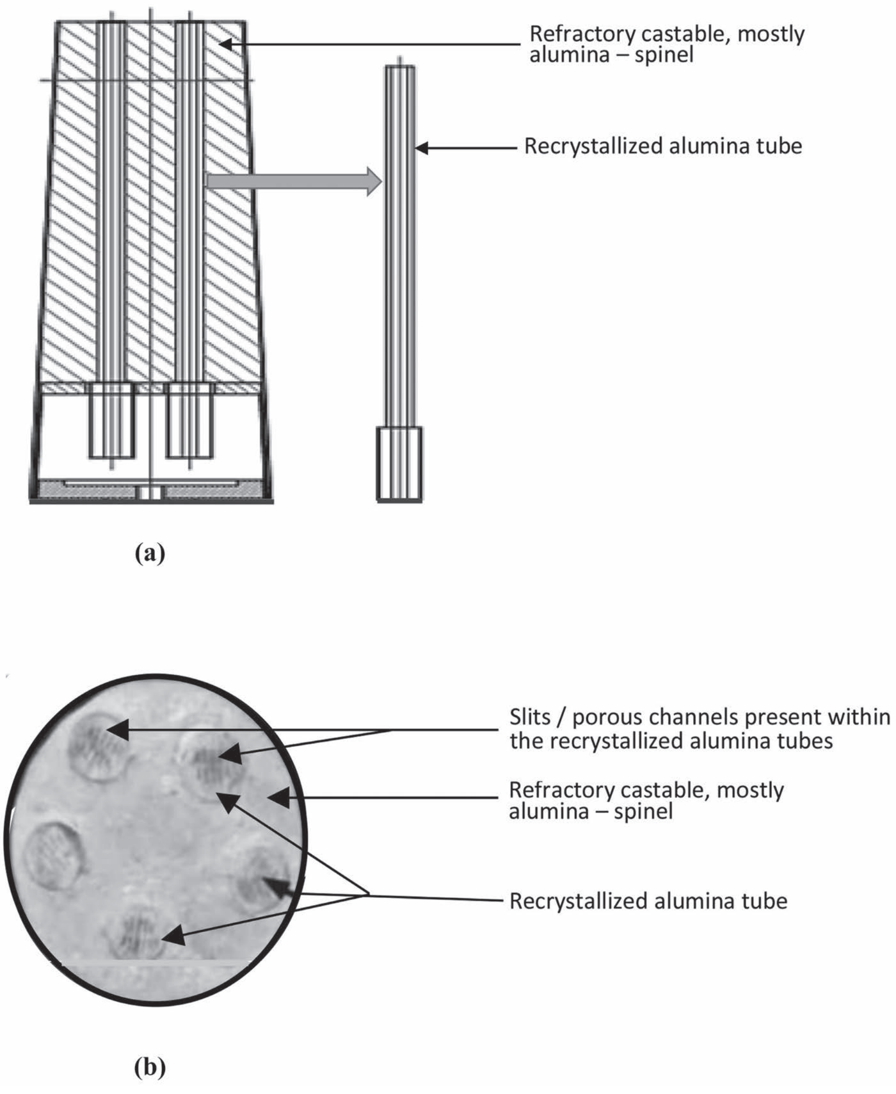

FIGURE 6.7 Recrystallized Alumina (RCA) Tube containing a porous plug: (a) schematic drawing of vertical cut cross section; (b) top surface of the actual plug.

6.5.5 HYBRID PLUG

A hybrid porous plug is a multi-component system that uses the benefits of both the non-directional and directional porosity and is manufactured by both the pressing and the casting techniques. Hybrid plugs are made with various cross sections to optimize the purging activity as per the application requirements. Commonly, the non-directional porous refractory is placed at the central portion, and the directional porous channels/slits are placed towards the periphery of the circular cross section. Hybrid plugs, having the combination of random (non-directional) and directional porosity, are suitable for both the low as well as high gas flow rates and also have excellent initial opening rate for inert gas purging.

At very low flow rates, the inert gas passes through the non-directional porous segment of the plug as the directional openings are nearly closed due to infiltration of molten steel (which cannot be removed at low gas pressure). Thus, optimum soft bubbling conditions can be achieved, as per application requirements. When higher gas flow rates are required, the blockage due to an infiltrated steel in the directional slit/porous channels are opened up due to the higher gas pressure, and high purging rates can be achieved mainly through the slit openings. Thus, the higher stirring of the steel bath within the ladle for the homogenization of steel temperature and compositions along with alloy mixing can be achieved easily. Both the high and low purging requirements are met by the hybrid plugs easily and efficiently, which was not possible with conventional plug designs having either non-directional or directional porosities. Further, due to reduced wear, as the same plug optimizes both the operations, the life of the plug is also increased, improving the economy of the purging process.

Commonly, the hybrid plug consists of two separate refractory pieces for the purging activity, namely, a pyramid-shaped porous part and the surrounding castable with directional slits. The porous part, containing non-directional porosity, is mostly made up of a high-alumina composition using coarse-grained granulometry and sintered at high temperatures. The surrounding outer castable portion is mostly made up of spinel-containing, low-cement, high-alumina dense castable. The dense and strong castable part provides high resistance against corrosion, abrasion, and erosion. The directional channels or slit openings are introduced by the use of organic tapes within the castable part of the plug. The organic tapes are placed in such a way that directional channels will form around the non-directional porous part and be distributed uniformly within the surrounding castable portion only. Figure 6.8 shows the details of a hybrid plug.

The hybrid plugs, at any cross section, contain both the porous and the dense structures, containing both directional and non-directional porosity, and so maintain their hybrid porous character even after wear-out of the top part of the plug due to prolonged use. They work well in both the requirements of liquid metal homogeneity and cleanliness for their hybrid character. The advantages of the hybrid plugs are listed as follows.

1. Adjustable gas flow
2. Good control on inert gas flow rate both at low and high purging pressure
3. Low wear rates, resulting in longer service life and process economy
4. Operation-friendly
5. Easy switching between low and high gas flow rates

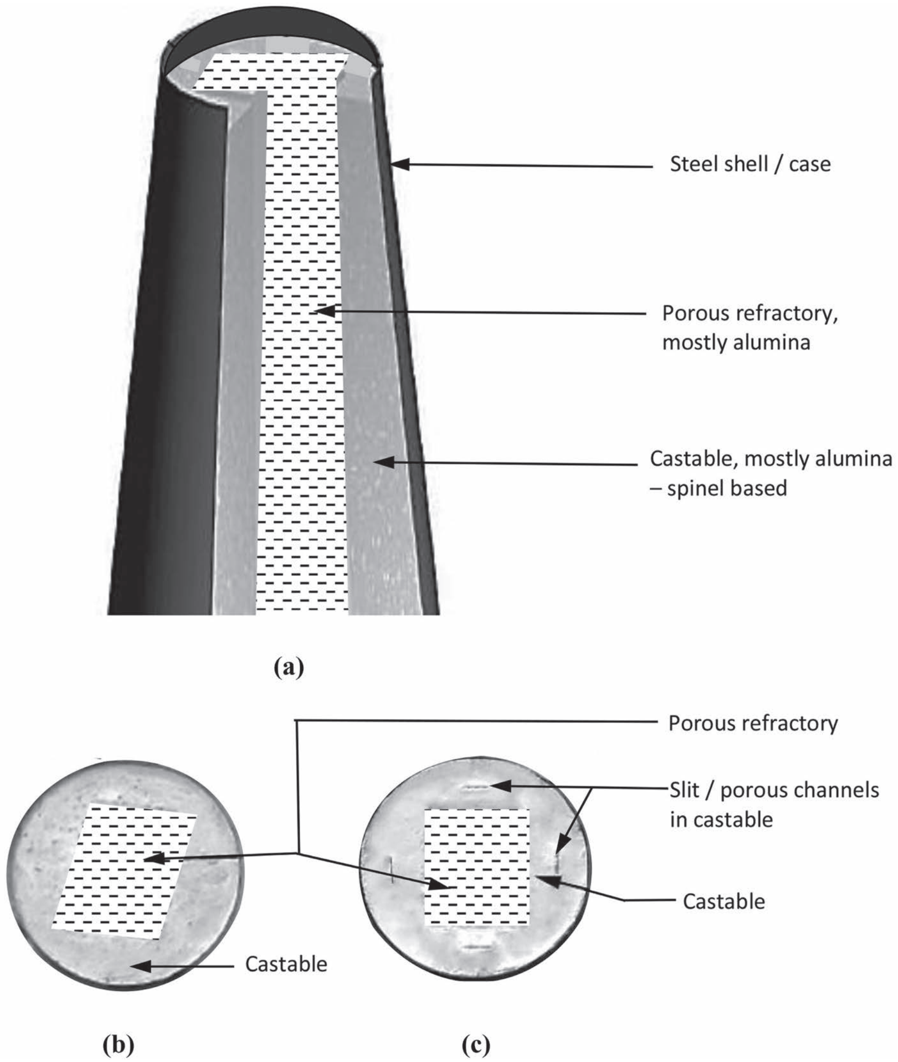

FIGURE 6.8 Schematic figure of the hybrid porous plug: (a) vertical-cut cross section; (b) top surface of hybrid plug with no slit; (c) top surface of hybrid plug with slits.

6.6 SAFETY OR SECURITY DEVICE

A *safety* or *security device*, also called a wear indicator, is an essential component in porous plug refractories for the safety of the plant, the personnel working in the surrounding area, and also the performance and life of the plug. If the plug refractory is significantly worn out, then the liquid metal can make a puncture and leak out from the bottom of the ladle, causing a disaster. Therefore, whether a plug has sufficient remaining height or its major portion is worn out, it has to be judged by the ladle man/ladle cleaning person/refractory operator. The judgement/decision has to be taken

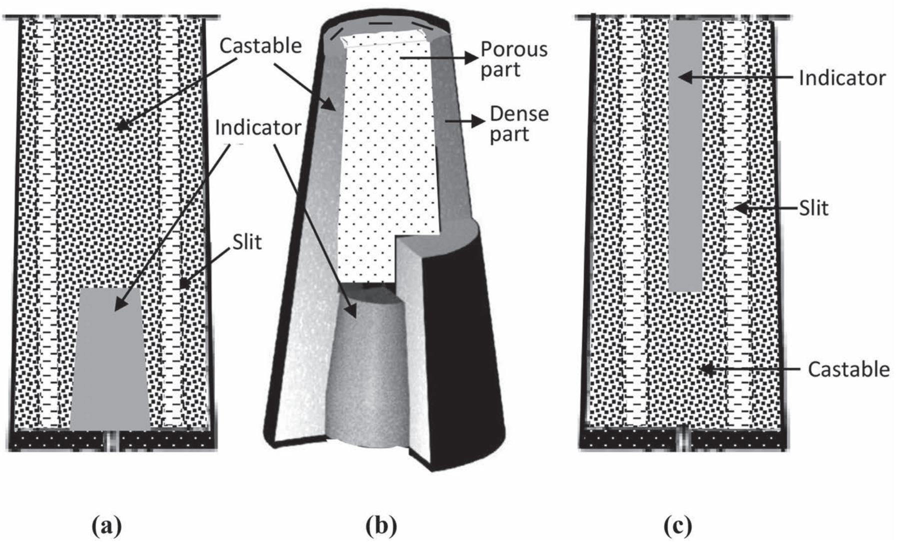

FIGURE 6.9 Schematic figure of different wear indicators in the porous plug: (a) appearing-type indicator in a slot plug; (b) appearing-type indicator in a hybrid plug; (c) disappearing-type indicator in a slot plug.

only by visual observation of the plug area from the open end of the empty ladle when the ladle is hot (mostly during cleaning of the plug by oxygen lancing). It is difficult for any person to understand the wear-out and to get the idea of the remaining thickness of the plug at such a hot environment. Hence, a safety or security device is incorporated within the plug (having similar wear-out behaviour as that of the plug refractory) that gives an indication of the remaining thickness of the plug during use. The device/indicator has to be visibly different in nature than that of the surrounding hot refractories so that it can be distinctly identified even at high temperatures. There are two major types of wear indicators that are commercially successful, namely, appearing type and disappearing type. The appearing-type indicator is not visible initially or at the early stages of porous plug use, but upon prolonged use, when the plug refractory wears out significantly, the indicator becomes visible, indicating the need for an immediate change of the plug for safe operation. On the other hand, the disappearing-type indicator is visible from the very beginning of the use of the plug, but when it disappears upon prolonged use, the plug needs to be changed. Figure 6.9 schematically represents both types of indicator in a porous plug.

The most common type of safety device or wear indicator is an appearing-type one, made up of a porous high-alumina (>95% Al_2O_3) refractory material having a square cross section (say, 40 mm × 40 mm). This sintered porous alumina body is placed at the centre of the bottom surface of the porous plug and has a height/thickness equivalent to the minimum thickness of the plug when that is to be replaced (say, 120 mm with safety). When a new plug is placed, the wear-out is minimum; the porous alumina indicator is covered with the plug refractory and will not be visible from the top surface. But on continuous run, and after several heats of use, due to wear-out, if the height/thickness of the porous plug reaches the level of the porous alumina indicator (at 120 mm from the base), then the porous refractory will be visible from the top end of the ladle during cleaning/inspection activity. As the indicator is porous in nature, it will appear as a dark portion when observed from the top open side of the ladle, not as bright as that of the surrounding hot, dense plug refractories. So when the indicator is visible, the remaining height of the purge plug is minimum, and it has to be replaced with a new one immediately.

Another concept for the appearing-type wear indicator is based on using a refractory material with a higher thermal conductivity in place of porous alumina. The highly thermally conductive material (say, an SiC) is placed at the bottom side of the plug in the same way as that of the porous alumina indicator. Upon continuous use and wear-out of the plug, when the height of the plug reaches that of the indicator piece, the indicator will be visible and will look darker from the top end of the ladle. Due to the higher thermal conductivity of the indicator piece, it will cool faster (as it is exposed to open environment) compared to the surrounding hot plug refractories (having poor conductivity). So the indicator will appear dark and can be easily identified.

There is also a disappearing-type wear indicator commercially used in the porous plugs. In this case, commonly, a steel rod/pin is placed on the top face of the plug, which remains up to a safe height of the plug. So initially, during use, the indicator is visible as a dark portion due to the faster cooling of the steel rod in comparison to the surrounding plug refractory. Upon continuous use, the plug will wear out, and the indicator steel rod/pin will also be worn out along with the plug refractory. After prolonged use and wear, once the remaining thickness of the plug reaches the safe height, the complete steel rod will wear out and will disappear during the inspection of the ladle. So once the pin disappears, it indicates that the minimum thickness of the plug is reached and the plug needs to be changed. Generally, this steel pin is made up of a special alloy material and does not melt or wear out faster compared to that of the plug refractory material. Thus, the indication of wear-out of the plug is understood by the appearance or disappearance of the indicator and the requirement for the replacement of the plug as the minimum remnant height is reached.

6.7 PROPERTIES REQUIRED FOR POROUS PLUG REFRACTORY

The proper functioning of a porous plug is essential for the purging of inert gas into the steel bath within the steel ladle at a desired flow rate as per the process requirement. It ensures the steel quality, cleanliness, uniformity in temperature and composition of steel, alloy distribution, and many other quality parameters of steel. For proper functioning, the porous plug refractory needs to be a very high-temperature-withstanding material and has to maintain certain other qualities, which are described in what follows:

1. *Gas permeability.* The permeability of gas is the most important criteria for the functioning of the porous plug. The plug has to perform well both at the low and high gas pressures and needs to handle low and huge gas volume, as per the application demand. A higher flow rate of purging will obviously produce greater stirring within the molten steel bath and will be directly proportional to stirring efficiency. This higher stirring is required for a good mixing that results

in uniformity in temperature and composition of the steel bath, and also for the uniform distribution and mixing of additives and alloying elements.

2. *Corrosion resistance.* The top surface of the plug is in constant contact with the molten mass, steel or slag, and needs to have high resistance against corrosion by them. Corrosion becomes severe as the purging effect causes stirring in the steel bath and fresh liquid comes in contact with the plug with a strong back pressure effect. Highly dense (low-porosity) refractory is required to withstand such effects, and non-directional, porosity-contacting plug (having higher porosity) are weak against the attack. Slot plugs are made up of dense castable, segmented, and alumina tube–containing plugs are made up of very dense alumina plates/tubes and dense castable; thus, these plugs show improved corrosion and wear resistances. To increase the corrosion resistance further, Cr_2O_3 is added to the alumina-based compositions. The addition of fine Cr_2O_3 powder produces an alumina–chrome solid solution and a chrome-containing glassy phase at high temperatures. These phases react with the molten steel and slag, increase the viscosity of the liquid by absorbing the iron oxide and manganese oxide from molten steel/slag, produce a dense spinel layer on the plug's top/working surface, and thus, further improve the corrosion resistance.

   Other than corrosion, the refractory also needs to be resistant against infiltration, and low open porosity is essential for the same. Molten steel may infiltrate through the available surface pores/channels and enter within the refractory. The infiltrated liquid will solidify due to the cooling effect from cold purging gas and will increase in volume. This expansion will cause cracking in the refractory, leading to failure. Hence, a dense and strong refractory structure with narrow porous channels is required to improve its infiltration and corrosion resistance.

3. *Wear resistance.* When argon is purged for stirring of the molten steel bath within the ladle, the molten metal moves within the ladle in circulatory paths (as shown in Figure 6.3), and the movement/turbulence is dependent on the purging pressure used. The upward movement of the inert gas bubbles/jet forces the metal to move up, which upon reaching the top (slag layer) reverses and flows downward along the ladle side wall and impacts on the ladle bottom. This effect of impact (back pressure) is also exerted on the top/working surface of the porous plug. This causes erosion of the refractory at the ladle bottom, including the porous plug. Further, after the transfer of molten steel to tundish and the removal of the slag, the ladle is cleaned for the removal of any residual/remnant steel or slag, which may get solidified due to cooling and may choke the plug for next use.

   Cleaning is done by oxygen blowing/lancing to melt the solidified steel and slag adhered (also sometimes solidified) on the working surface of the porous plug and remove them by using lancing pressure. This cleaning process uses oxygen gas at very high speed that generates an extremely high temperature, causing severe erosion, wear, and damage to the top surface of the porous plug. Again, for high-argon purging flow rate, the refractory needs to have excellent erosion resistance. Hence, the porous plug requires excellent high-temperature abrasion, wear, and erosion resistance.

4. *Thermal shock resistance*. The temperature of the porous plug increases suddenly and abruptly when the molten steel is tapped into the ladle from the converter, causing thermal shock to the plug. Again, during the argon purging process, the working surface of the plug is at the steel melting temperature, and the cold argon gas passes through it, thus also causing huge thermal shock for the plug refractory. Further, with the progress of time, steel tapping and casting temperatures are increasing day by day, demanding for greater thermal shock resistance for the plug. Hence, the plug refractory needs to be very strong against thermal gradient and thermal shock. The use of additives, like the spinel, in the porous plug refractory composition helps improve thermal shock resistance.
5. *Hot strength*. The porous plug refractory has to withstand the ferrostatic pressure generated from the height of the molten steel bath in the steel ladle, as also faced by the other refractories present at the ladle bottom. The refractory composition used for making the plug has to bear the load constantly along with the erosion and abrasion effects due to the flow of steel. Non-directional porosity-containing plugs are basically porous refractory and have lower-strength values, causing inferior performance and significantly lower life. Directional porosity/porous channel–containing plugs are made up of dense castables or have highly dense sintered alumina parts, providing considerably higher hot strength and service life. The refractory compositions also need to be highly volume-stable, even at application temperatures, to retain the strength properties.
6. *Operational friendliness*. The working environment for the porous plug is extremely harsh. Hence, the installation, repair, replacement, and other activities for the plug need to be easy, friendly, safe, and reliable. The life of the ladle lining is multiple times greater than that of the plug, so the plug refractories need to be replaced multiple times for each lining of the ladle. The time required for plug replacement increases the downtime of the ladle, affecting the productivity and economy. All these aspects need to be considered for the selection of the type and composition of the porous plug and for obtaining the optimum performance and service life.

6.8 DEGRADATION OF THE POROUS PLUG

The application environment for the porous plug is harsh and severe. This has resulted in considerably lower service life for the plug compared to the rest of the corresponding steel ladle bottom refractories. This is even after taking all the different precautionary measures to protect the porous plug. The main influencing factors for the degradation and wear of the porous plug are as follows:

1. Chemistry, viscosity, and temperature of steel
2. Inert gas purging conditions, like purging pressure, flow rate, volume of purged gas, purging time, frequency of operation, etc.
3. Total holding time of steel per cast
4. Refractory type and design of the plug
5. Cleaning practice, post–metal casting and de-slagging operation
6. Ladle circulation frequency

These factors act on the porous plug refractory simultaneously during operation, affecting the performance and degrading the quality and life significantly. The degradation of the plug refractory occurs through different pathways or mechanisms based on these factors, and the mechanisms act simultaneously on the refractory. Details of the porous plug degradation mechanisms are described in what follows.

6.8.1 WEAR-OUT DUE TO METAL FLOW AND BACK PRESSURE

The introduction of inert gas into the molten steel bath of the ladle through a porous plug placed at the bottom of the ladle causes huge metal movement within the ladle. This movement of molten steel and the back pressure generated due to its circulatory movement within the steel ladle wear out the top surface of the porous plug. The circulatory-type flow of molten steel continues with the upward movement of the inert gas flow during purging. The back (reverse) movement of molten metal from the top to the bottom of the ladle due to the circulatory movement impacts on the top surface of the plug, the generating point of inert gas bubbles/purging. This continuous flow and back pressure of molten steel causes constant abrasion and erosion that result in wear of the top surface of the plug. The wear-out effect is strong as the turbulent molten steel is much heavier than the plug refractory. The effect gets stronger when the metal movement and back pressure are enhanced due to the higher flow rate of gas purging, thus causing a drastic degradation of the porous plug.

6.8.2 PEELING OF TOP SURFACE

During tapping of molten steel from the converter, steel falls to the bottom of the steel ladle (on the impact pad area) at temperatures above 1,600°C and also comes in contact with the top surface of the plug. The molten steel enters into the plug through the surface pores and can infiltrate if the purging pressure of inert gas is low in the plug. This infiltration may also occur during the idle condition (not purging while the ladle holds molten steel) of the porous plug. The infiltrated molten steel gets solidified within the plug due to the continuous contact with the cold inert gas passing through and also due to ambient temperature at the ladle bottom surface. Thus, the upper portion of the plug, infiltrated by metal, has different properties (due to the presence of solidified steel) than the unaffected portion of the plug. This results in stress development and subsequent cracking/peeling of the infiltrated portion. Peeling also occurs at the infiltrated portion due to the solidification of molten steel and the associated expansion. Further, due to infiltration, the porous channel of the plug is blocked, and the purging activity will be reduced/hampered. The purging pressure is increased to get rid of the obstacle/blockage in the purging porous channels, causing peeling/chipping of the top infiltrated surface.

6.8.3 CRACKING DUE TO THERMAL SHOCK

The top surface of the plug remains in contact with molten steel, at a temperature above 1,600°C, whereas the opposite surface of the plug is facing a much lower temperature, close to ambient environment. Again, the porous channels continuously carry the cold inert gas entering into the porous plug from ambient temperature.

Hence, there remains a huge temperature difference within the plug refractory. This causes very high thermal stresses within the porous plug refractory during its operation, which causes thermal shock effects. Further, the top surface of the plug experiences a sudden surge in temperature when the tapping of molten steel starts from the converter, causing a sudden thermal shock to the plug. Also, when the ladle becomes empty after the bottom pouring of molten steel and the removal of slag, the plug temperature falls drastically, resulting in a huge thermal shock to the plug refractory. These thermal shock effects cause cracking and peeling and even the rupture of the porous plug.

6.8.4 Corrosion from Molten Mass and Cleaning Activity

The top surface of the porous plug refractory is in a continuous contact with the molten steel since the metal is poured in from the converter, and also in contact with the slag after the bottom pouring of molten steel until slag removal. Impurities and oxides (like FeO) present in molten steel and the slag components react with the top surface of the plug refractory, causing corrosion. Again, once the ladle is emptied after slag disposal, the ladle gets cooled immediately, causing the solidification of any remnant steel and slag present at the bottom of the ladle. To remove the solidified remnant steel and slag from the top surface of the plug for the next purging activity, high-pressure oxygen lancing (up to 20 bar) is done to melt the remnant solidified steel and slag and to remove them from the plug top surface by impact. This lancing activity produces temperature even up to 2,000°C, and large amounts of iron oxides may be produced due to the oxidation of the steel present on the top surface of the plug. This formed iron oxide gets infiltrated within the plug refractory under the lancing pressure and is very harmful for the refractory from a corrosion point of view. Further, due to oxygen lancing, the temperature of the plug top surface shoots up, affecting the porous plug due to thermal shock, and causes cracking at the top surface. Hence, during the cleaning activity, along with the removal of the solidified steel and slag, the layer of the top surface of the plug (few millimetres to centimetres in thickness) also gets removed. Thus, the top surface of the plug corrodes and wears out continuously with the cleaning process, and the height or thickness of the plug gets reduced.

6.9 POSSIBILITIES FOR IMPROVEMENT

The performance and life of the porous plug refractory is dependent upon multiple degrading factors, as discussed earlier in the chapter. To overcome many of the degrading factors, multiple modifications and improvements have already been incorporated into porous plugs, and many others are in the process of incorporation. A few of such modifications and improvements are detailed in what follows.

6.9.1 Improvements against Peeling and Cracking

The peeling and cracking of the porous plug can be improved by optimizing the refractory composition and porous character of the refractory. The reduction in total porosity and surface pores of the plug, by changing from non-directional plug to slot or other directional dense plug, significantly reduces liquid infiltration and improves corrosion, cracking, and peeling resistance. The dense structure of the directional plugs enhances its strength significantly, providing increased resistance against abrasion, erosion, and wear effects for metal movement and back pressure effect. Also, due to the dense structure of the segment plug, plug with RCA tubes, etc., better infiltration resistance and reduced peeling effect are observed. An improvement in thermal shock resistance can be achieved by increasing the strength and hot strength properties of the plug using a dense compact structure, thus reducing the chances of peeling and cracks.

6.9.2 IMPROVEMENTS AGAINST CORROSION

Improvement in corrosion resistance can be achieved by the proper selection of the refractory composition and dense structure. The presence of silica in the composition needs to be avoided to nullify/minimize the formation of low-melting compounds (mostly calcium aluminosilicates, namely, anorthite [$CaO.Al_2O_3.2SiO_2$] and gehlenite [$2CaO.Al_2O_3.SiO_2$]) within the refractory that degrade the hot strength and resistance against corrosion and penetration. The use of *magnesium aluminate spinel* positively influences the properties of the plug, especially corrosion and penetration resistance. The spinel has a large number of cation vacancies in its structure and can absorb various cations in these vacant sites by making a solid solution with the harmful impurity oxides of those cations. Thus, it reduces the free presence of many harmful ions (or oxides) in the molten metal and the slag, reducing corrosion or penetration effect, and thus improves the performance and life of the plug. The spinel also improves corrosion resistance from a wettability point of view. The spinel has a contact angle of around 110° with molten steel, whereas pure alumina has around 90°. The higher contact angle reduces the contact surface of wetting of the refractory against molten steel and thus improves corrosion and penetration resistance. The in situ formation of the spinel in the plug refractory composition is beneficial as the nascent spinel is chemically active, resulting in better corrosion resistance. But the volumetric expansion associated with spinel formation may induce stress in the refractory upon the sudden increase in temperature, when the plug comes in contact with molten steel. This stress may lead to cracking and structural failure of the plug. To prevent such failures, a preformed spinel is commonly added to an alumina-based refractory composition for making the plug. Further, the optimization of the pore size and its distribution is important for the infiltration of liquid within the porous plug. Control on pore size distribution and overall reduction in pore size of the plug refractory are incorporated with precise control and adjustment in particle sizes used and their distribution of the castable.

6.9.3 IMPROVEMENTS AGAINST INFILTRATION

Metal infiltration in a porous plug may start when it comes into contact with molten steel during the tapping out of the converter. For slot plugs (containing porous slits in the refractory castable), the low and unstable flow rate of inert gas influences the penetration of the liquid infiltration. The unstable flow will also cause an unstable back pressure on the plug, affecting the infiltration and influencing the wear properties. An increase in the flow rate to form a stable gas flow will automatically improve the situation. Also, an increase in the contact angle of the plug by incorporating the spinel in the composition improves the non-wetting character and the reduction in pore size of the castable. These, in turn, improve the resistance against infiltration, penetration, and corrosion.

6.9.4 IMPROVEMENTS RELATED TO CLEANING

Oxygen lancing is a common practice to clean the top surface of the porous plug post–metal and slag removal for reliability in inert gas purging in the next cycle. It removes any metal and slag skull formed over the plug due to cooling after emptying the ladle. But the activity is harmful for plug wear-out and also for the operator who performs the cleaning process (as the operator is exposed to the heat of radiation from the hot ladle). The activity needs precision as it may damage the ladle bottom refractories, the ladle wall due to the bending of the lance pipe inside the hot ladle, etc. Hence, the oxygen lancing activity has many negative effects and needs to be used only when it is essential. A refractory composition without any low-melting-phase formation, commonly achieved by removing the silica part from the composition, reduces plug damage upon oxygen lancing. Again, the use of the spinel in the plug refractory composition improves resistance against oxygen lancing and thermal spalling. The laying over time of molten steel and slag, and their subsequent solidification when the ladle is empty, can be minimized by increasing the argon gas flow rate through the porous plug at the end of the metal casting process. This can minimize the requirements of the cleaning process by oxygen lancing and the damage associated with it.

6.9.5 IMPROVEMENTS RELATED TO OPERATIONAL PARAMETERS

Steel plant operational parameters also affect the life and performances of the porous plug, and optimization in certain such parameters improves the functioning of the porous plug. A frequent variation in purging pressure during the operation of the plug may affect plug performance as the same produces fluctuations in back pressure, resulting in wear-out of the plug top surface. Similarly, a sudden fall in purging pressure may lead to increased chances of metal infiltration within the plug top surface. Steel temperature is also important, as the lower temperature of steel casting may cause chilling action of the liquid steel, leading to increased skull formation on the top surface of the plug. Again, prolonged tapping time increases the risk of metal penetration and associated corrosion and the wear of the refractory. Similarly, longer holding time of molten steel in the ladle, especially without purging (idle plug) condition, and longer ladle turnaround time increase the risk of metal penetration within the plug. Hence, all these steel plant/process-related parameters need to be optimized to attain the desired/optimized performance and life from the porous plug.

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7 Slide Gate Refractory

7.1 INTRODUCTION

Slide gate refractories are a special type of valve or gate refractories containing multiple plates that can slide over one another to control the flow of molten steel flowing from the steel ladle to the tundish, and also from the tundish to the casting mould, in a continuous casting process. However, the use of slide gate refractories between the steel ladle and the tundish is common and widely employed by steel manufacturers. The basic difference between these two applications of slide gate refractories is the number of plates used. There are two sliding plates for the slide gate refractory system between the ladle and the tundish, whereas mostly three plates are used for applications between the tundish and casting moulds. The control mechanism for the three-plate system is relatively complex, and so it is less popular. Advanced countries with better automation systems and control are well equipped with three plates of slide gate refractories.

The two plates used for the slide gate refractory to control the flow of molten metal from ladle to tundish are named the top plate and the bottom plate, each having a bore/hole through their thickness and are positioned over each other during application. The top plate is fixed at the ladle bottom, and the bottom plate is free and can slide along the flat surface (lower side) of the top plate. The plates can be arranged in such a way that their boreholes can be (1) aligned coaxially to obtain a complete opening between the plates, providing an unobstructed free path for any flowing stream passing through the holes; (2) moved away from the coaxial position partially so that the effective opening is reduced, thereby resulting in reduced flow rate; and (3) placed in a completely non-aligned condition, thus causing no opening between the plates and thereby stopping the flow completely. During operation, the change in position/alignment of the holes of the two sliding plates is done continuously by the movement of the bottom plate along the fixed top plate in a precise and controlled manner. The change in the position of the plates changes the extent of the opening formed by the position of the holes in the plates and thus regulates the flow rate of the molten steel passing through the plates. This sliding movement of the bottom plate is performed by mechanically pushing it from one side using a bell crank pushing mechanism attached separately at the outer side of the steel ladle wall.

The critical properties for the refractories used for making slide gate refractory plates are corrosion resistance, thermal shock resistance, resistance against abrasion and erosion, and hot strength. Again, as the operating conditions and steel chemistry vary among the different steel manufacturers, the specific refractory composition and properties for the plates need to be optimized as per the particular steel plant's requirements to attain the desired performance and service life.

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7.2 HISTORY AND BACKGROUND

The concept of controlling the flow of molten metal by using the sliding gate valve system was originally conceptualized by David D. Lewis, Pennsylvania, United States, who filed a patent in November 1884 that describes the basic concept and details of the operating system. The patent was granted in 1885 with US Patent No. 311,902. There were some more patents similarly filed and granted in the United States on similar types of systems, but the application of such a control device for molten steel flow in steelmaking units was not possible during that period due to the non-availability of a suitable refractory material and the industrial applicability of such a concept.

In the early days, after the steelmaking process, the molten steel is transferred to steel ladles, and casting into the mould used to be done by bottom pouring technique. To control the flow of molten steel from ladle to casting mould (mostly ingot mould), stopper rod arrangements were used. The stopper rod is a long solid refractory rod that enters through the open top end of the ladle, passing through the molten slag layer and the molten steel bath, and reaches the pouring hole at the bottom of the ladle, where it sits close to the flow of molten steel. Once the stopper rod is lifted vertically, an opening is formed at the bottom hole mouth of the ladle, and molten steel flows out of the ladle through the gap/opening. The major difficulty was to precisely control the vertical movement of the stopper rod passing through the molten metal pool within the ladle due to the turbulence and impact of the flowing molten steel. Thus, control on borehole opening area was also difficult. Further, corrosion of the rod at the slag layer (top part of the ladle) and the wear, abrasion, erosion, and corrosion especially at the tip portion (bottom-most) of the rod due to the aggressive flow of liquid steel and the associated vortex formation were the serious drawbacks of the system.

It took a long time for the successful development of a feasible and industrially acceptable design for the slide gate refractory system to formulate a suitable refractory composition for such application and assembling the whole system to control the steel pouring activity. It was only in 1961 when Benteler Steel Works in Paderborn, Germany, successfully implemented a trial of the slide gate system in a 22 t steel ladle in collaboration with the refractory supplier Stoecker & Kunz, Germany. After the successful trial and implementation of the slide gate refractory system, by 1964 Benteler Steel Ltd converted all their steel ladles from the conventional stopper rod system to the slide gate refractory system due to its multiple benefits. During that time, this new system was highly attractive for its operation-friendly push-button flow rate control mechanism without stream flaring; the simple procedure of assembling the slide gate refractory components, which can be done in a separate workstation; its higher reliability and great control on molten steel flow; etc. There was no restriction on ladle preheating, and also on the use of the ladle slide gate system. Slowly the use of the slide gate system has gained popularity across the globe, and about nine steel manufacturing units in the USA had converted to the slide gate valve system by 1970. In Japan, the first use of the slide gate valve system was in 1968 for a steel ladle of 50 t capacity. Also, during this period, the steel casting process has started converting from ingot casting to the continuous casting technique globally due to user-friendliness and a smooth and trouble-free casting process. Similarly, the use of the slide gate valve system also got momentum for its better operational control on molten metal flow. As today, nearly all steel ladles used for the continuous casting process are attached with slide gate refractories to control the metal flow from ladle to tundish.

The benefits of the slide gate refractory system in controlling the flow of molten steel over the stopper rod control system are as follows:

1. Control on the flow of steel moving out from the ladle is faster and greater.
2. The amount of refractory required for the flow control system is significantly reduced.
3. Only the surface of the bore/hole area of the slide gate plates is in contact with the molten steel.
4. Wear-out of the flow control refractory due to erosion, corrosion, etc. and its effects on the quality of the cast steel are minimal.
5. Liquid steel can be held in the ladle for a prolonged time, and the ladle can be used in a greater number of heats/cycles as wear-out of flow control refractory is minimal.
6. The sliding of the plates to control the flow of molten steel is operated from outside the ladle, and the molten steel pool present within the ladle has no influence on it.
7. The slide gate refractory system increases ladle availability and productivity as ladle downtime is reduced.

The slide gate refractory system controls the flow of molten steel from the ladle to the tundish. A steel ladle carries the molten steel from the steel melting shop (converter) to the casting shop (tundish), and multiple processing is performed on the molten steel present in it. These processes, namely, alloying, decarburization, desulphurization, dephosphorization, degassing, etc., are done primarily to improve the purity, quality, and properties of the steel. The names of the processes grossly indicate the operations that are performed in each one. Further, to improve purity and cleanliness, various killing processes and treatments are performed on the molten steel in the ladle. Killing and treatment processes change the chemistry of steel, which, in turn, affects the refractories in contact. Hence, these two processes are important for the functioning and performances of the steel contact refractories. Some details of the killing and treatment processes are described in what follows.

7.3 KILLING AND TREATMENT PROCESSES OF STEEL

Steel producers are under tremendous pressure from the steel user industries and from market competition to produce steel with high purity (low inclusions) and smaller-sized (and controlled) inclusions, and its distribution, stringent reproducibility conditions, etc. The chemistry of steel has become very important, and the type and amount of the inclusions present are very crucial in determining the quality, performance, and selection of steel. Among the different types of inclusions, non-metallic inclusions are of great threat for the properties and performance of steel. The non-metallic inclusions are chemical entities consisting of one or more non-metallic elements which are present in molten steel and alloys like separated phases. Non-metallic inclusions in steel have a negative impact on the mechanical properties of steel and cause serious threats, like brittleness, a variety of crack formation, inhomogeneity, reduced toughness, lower resistances against corrosion and fatigue, etc. Steel manufacturers pay special attention to eliminating (or at least reducing/controlling) these inclusions to achieve the desired properties in the final cast steel products. Table 7.1 summarizes the effect of different impurity elements present in steel on its property.

TABLE 7.1
Effect on the Properties of Steel of Different Impurity Elements Present

Impurity Element	Properties Affected
Sulphur (S) (as sulphide inclusion)	• Ductility, Charpy impact value, anisotropy • Formability (elongation, reduction of area and bendability) • Cold forge-ability, drawability • Low-temperature toughness • Fatigue strength • Weldability
Oxygen (O) (as oxide inclusions)	• Gaseous inclusion • Fatigue strength • Anisotropy • Bending • Toughness • Internal soundness
Carbon (C) (as solid solution, settled dispersion, pearlite and cementite phases, carbide precipitates)	• Solid solubility (enhanced), hardenability • Strain aging (enhanced), ductility (lowered) • Dispersion (enhanced) • Precipitation, grain refining (enhanced), toughness (enhanced) • Embrittlement by inter-granular precipitation • Deep drawing • Electromagnetic properties
Nitrogen (N) (as solid solution, settled dispersion, nitride precipitates)	• Solid solubility (enhanced), hardenability • Strain aging (enhanced), ductility (lowered) • Dispersion (enhanced) • Precipitation, grain refining (enhanced), toughness (enhanced) • Embrittlement by inter-granular precipitation • Weldability
Phosphorus (P) (as solid solution)	• Solid solubility (enhanced), hardenability (enhanced) • Temper brittleness • Separation, secondary work embrittlement • Weldability • Toughness
Hydrogen (H) (gaseous inclusion)	• Internal soundness

Control on the inclusion in terms of their amount, size, and composition can produce steel with high quality. The control on the formation of non-metallic inclusions and the identification of their constituent phases are of extreme importance to produce clean steel. Commercially available common steel products contain different types of non-metallic inclusions up to a certain extent, which may be in parts per million (ppm) level. The presence of these non-metallic inclusions in the final steel products depends on different factors, like grade of steel, the manufacturing process, secondary metallurgical treatments, killing and purification processes, casting techniques, etc. In reality, the term "clean steel" is a relative one, since a very high-purity steel with only 1 ppm inclusion, each of oxygen and sulphide, contains 10^9–10^{12} non-metallic inclusions per ton. Hence, from the viewpoint of complete "cleanliness," all steel is "dirty."

To increase the cleanliness and quality of steel, steel manufacturers have introduced multiple complex processes that can reduce the inclusion level. Significant progress has been made to control the concentration of the elements, like, C, H, N, O, P, S, which are commonly present in the range of a few ppm to several tens of ppm. For example, the vacuum treatment of steel in industrial conditions can produce liquid steel with C content <20 ppm. Similarly, the sulphur levels for HIC (hydrogen-induced cracking) resistant steel or oxygen levels for bearing-grade steel can be reduced to a few ppm. These reductions in the inclusion content have significantly improved the operating performance and life of steel products. But the extra processes involved in producing clean and high-quality steel cause a great impact on refractories. Steel cleanliness and its purity requirements have made the selection of refractories more stringent and critical, and high-quality refractories are to be used as per the specific application requirements.

In the primary steelmaking process, molten iron (mainly from the blast furnace) is converted to steel in the converter/BOF by the removal of carbon (entrapped in the iron structure). High-pressure oxygen is used to oxidize the carbon present in iron. This oxidation process is exothermic in nature and generates a huge amount of heat. About 70% of the global steel is produced by this converter/BOF route, converting the entrapped carbon to its oxides (CO and CO_2), and also the iron to its carbon lean state, called steel. But in doing so, the oxygen gas gets dissolved in steel. This dissolved oxygen can react with the remnant (unreacted/un-oxidized) carbon present in steel, forming the oxides in the later stages of processing, and may generate blow holes, porosity in steel, formation of iron oxides, etc., resulting in deterioration in steel properties. Hence, the level of dissolved oxygen in steel needs to be reduced. The deoxidation of steel is done by the external addition of strong oxide formers (deoxidizing agents), like Al, Si metals in steel ladles that react with the dissolved oxygen, forming respective oxides (like Al_2O_3, SiO_2, etc). Ferro-silicon alloys, ferro-manganese alloys, calcium silicide, etc. are also used for the same purpose, forming the oxides Fe_2O_3, SiO_2, MnO, MnO_2, etc. The process of removing the dissolved oxygen from molten steel is called the "killing process," and the resultant steel is called "killed steel" (like Al killed steel, Si killed steel, etc).

The oxides formed due to the killing process remain in the solid state (oxides have a high melting point, above steel processing temperatures), have density lower than that of steel, get separated from molten steel, and move (float) upward towards the slag layer due to density differences. But the formed oxides are very small in size, and the upward movement is very slow (due to lower buoyant forces), causing the entrapment of these formed oxides in steel as non-metallic inclusions. The presence of oxides in steel is measured as oxide cleanliness, which is dependent on the thermodynamic stability of the oxides, processing techniques, heat treatment temperature and time, etc. Among the various oxide inclusions of steel, alumina and silica are the most common, especially present in Al and Si killed steels, respectively. The total oxygen level in these killed steels is generally below 20 ppm. However, in special cases, like in medium- or high-carbon steels (example: bearing steels), the oxygen level is maintained below 5 ppm. Oxide inclusions present in molten steel mainly originate from two sources:

1. Deoxidation products (endogenous or micro inclusions)
2. Re-oxidation products (exogenous or macro inclusions)

The production of clean steel depends upon the extent of the removal of these oxide inclusions, which can be achieved by further processing/treatments of molten steel post–killing operation. Among the various post-killing processes of molten steel, Ca treatments are very common and popular worldwide to remove oxide inclusions. Calcium has a greater affinity for oxygen than most of the metallic elements and is common for the treatment processes. The main objective of Ca treatments is to control most of the non-metallic inclusions, by modifying and converting the oxides to Ca-containing compounds. These formed Ca-containing compounds (containing Al_2O_3, SiO_2, Fe_2O_3, etc.) are low-melting ones, get separated from molten steel easily due to their immiscibility character, and float above the molten steel bath due to their low-density values. Thus, these compounds (impurity oxides formed) mix up with the slag. Ca treatment (addition) in steel is also beneficial for refining; desulphurization, and control of shape, size, and distribution of the non-metallic inclusions. Ca does not get dissolved in steel and does not make any alloy as it has very low solubility in steel. The chemicals that are commonly added to molten steel for Ca treatments are Ca-Si, Ca-Fe, Al-Ca-Fe, pure calcium wire, etc.

In the Ca treatment process, Ca first converts to CaO and further reacts with the oxide inclusions present in steel, forming various low-melting binary and ternary compounds (like Ca-aluminates, Ca-silicates, Ca-aluminosilicates, etc.). These calcium-containing compounds are mostly present in liquid phase at steel processing temperatures, contrary to the solid particles of various oxide inclusions. The formed liquid phases, unlike oxide inclusions, get separated from molten steel faster (due to lower density and immiscibility), do not stick to the refractories in contact, and also do not affect the flow characteristics of molten steel.

The incorporation of Ca treatment in steel manufacturing ensures control on the non-metallic inclusions and improves the flow/castability. The selection of the particular Ca compound (say, Ca-Si, Ca-Fe, etc.) for the treatment of the killed steel depends on the permissible limit (concentration) of Ca, Si, Al, etc. in the final steel product. The formed Ca-containing liquid compounds are globular in shape because of the surface tension effect, and the change in inclusion morphology helps in easier separation and removal of inclusions from molten steel. Upon the introduction of Ca-containing compounds (alloy) deep into the molten steel bath, the following series of reactions are expected to occur in varying extents for Al killed steels, containing alumina as inclusion.

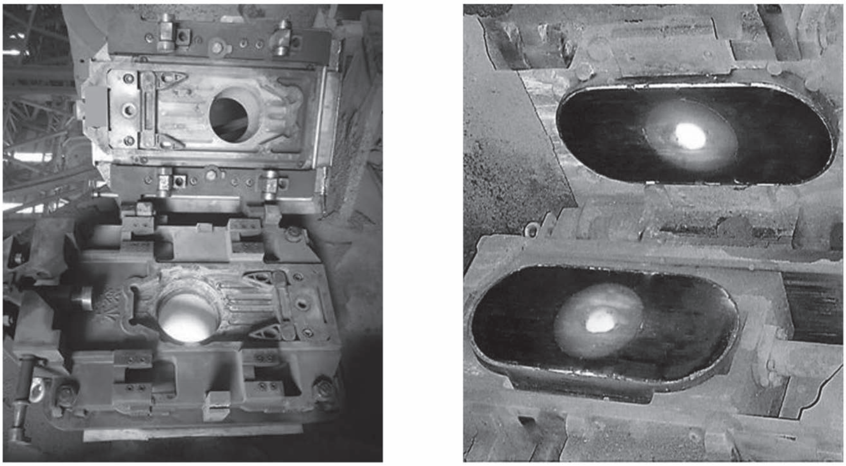
$$Ca + O = CaO$$
$$Ca + S = CaS$$
$$Ca + (x + 1/3)\ Al_2O_3 = CaOx\ Al_2O_3 + 2/3[Al]$$

A similar type of reaction also occurs for other killing agents, like Si, and low-melting Ca-silicate phases are formed and get separated from the liquid steel, producing cleaner, purer, and high-quality steel.

7.4 THE SLIDE GATE REFRACTORY SYSTEM

As per the sequence and requirements of casting in the casting shop of a steel plant, the processed (after killing and treatments) steel is taken out from the ladle to the tundish by bottom pouring technique. Control on the molten steel flow, coming out from the steel ladle, is achieved by the sliding action of the two refractory plates and the alignment of their boreholes only. But for better functioning, greater control on steel flow, and long life of the refractory plates, the complete slide gate system has a few more components. The other components used are the well block, ladle nozzle, ladle plate, collector nozzle, frame sled, pressure plate, pressure springs and bolts, and the drive system for the sliding movement. The frame is fixed to the bottom of the ladle and serves to hold and align the refractory top plate, exactly matching with the ladle opening/hole present at the bottom. It also acts as a horizontal guide system and provides support for the whole attachment containing the plates. The movable lower/bottom plate slides within the frame. The position of the slide gate plates at the ladle bottom is shown in Figure 7.1. The vertical support required to hold both plates tightly together is obtained by fixing the plates in the grooves of the frame. Elaborative details of the total slide gate system, including the metallic support components and mechanical pushing arrangements for sliding action, are shown in Figure 7.2. The individual refractories that make the complete slide gate refractory system are separately shown in Figure 7.3.

For a uniform and optimized wear pattern of the ladle bottom refractories, different types of refractories are used at the ladle bottom, especially around the bottom hole of the ladle. When the molten metal comes out through the bottom hole of the ladle, a vortex is formed in the ladle bottom around the exit hole, and the vortex remains as long as metal pouring continues (full tapping time). This vortex causes a huge movement in the molten steel, causing a greater wear for the refractories at the ladle bottom close to the hole. Thus, the ladle bottom refractories around the exit hole have a greater wear effect and lower service life. Refractories used for this highly wear-prone areas require greater attention than the other parts of the ladle bottom refractories, and a separate refractory block is used so that the same can be replaced easily and separately as and when required due to wear. This separate refractory block is termed the well block, which has a central hole coaxial with the ladle bottom hole for the flow of molten steel. Again, as vortex formation and higher



(a) (b)

FIGURE 7.1 Position of slide gate at ladle bottom: (a) empty cavity (without the plates); (b) plates in position.

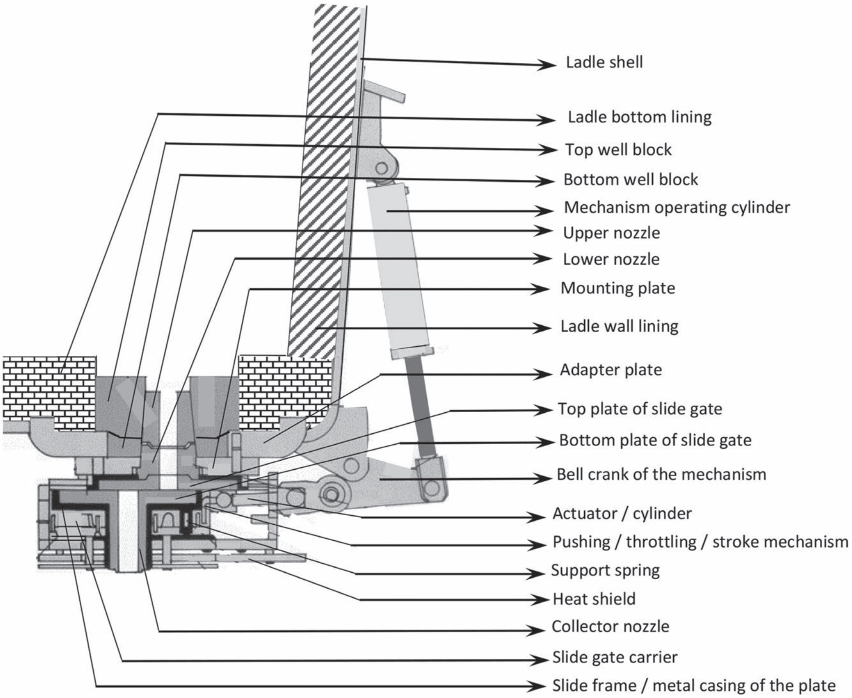


FIGURE 7.2 Details of the slide gate refractory system, including the metallic support components and pushing arrangements for sliding action.

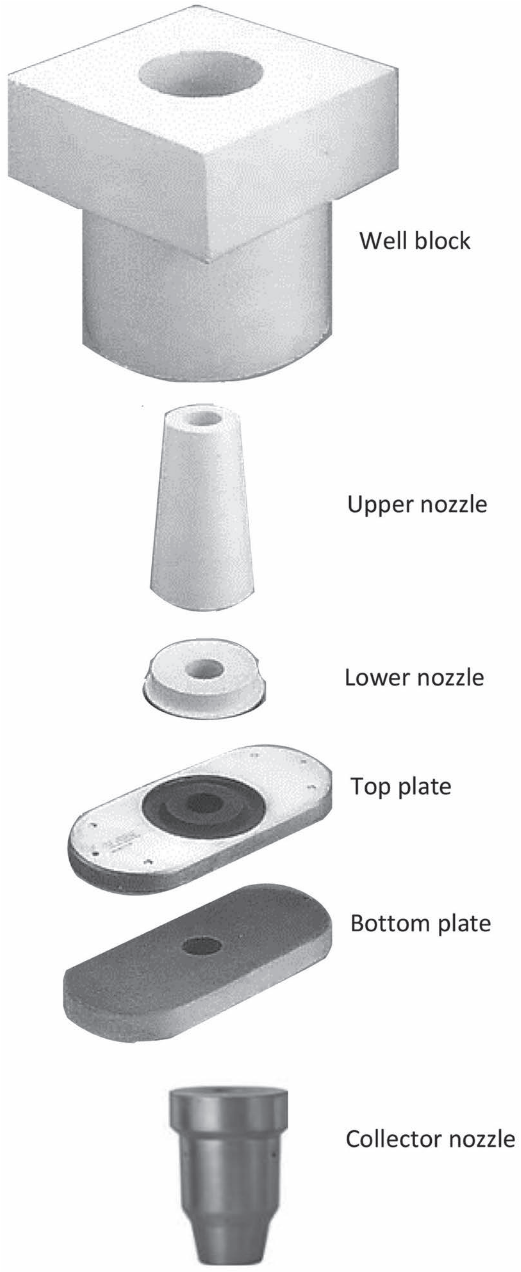


FIGURE 7.3 Complete slide gate refractory system showing all the individual refractory components.

wear occur at the top surface of the well block, the top part of the well block wears out faster and greater and results in lower life. So in many applications, the well block is divided into two parts, the top well block and the bottom well block, and only the top well block can be replaced separately as per the wear pattern.

Again, due to the flow of molten steel during the bottom pouring activity through the hole of the well block, the rate of wear and abrasion due to flow is very high at the metal contact area of the hole passage (side wall of the hole). Thus, the life of this particular area of the well block (metal contact area, vertical wall of the hole) is much lower than the rest portion of the well block. To protect the same, a special annular cylindrical refractory piece (tube-shaped) is used, coaxial with the bottom hole of the ladle, called the ladle nozzle. The nozzle fits into the hole of the well block and is made fixed using a high-temperature mortar. Further, the upper part of the ladle nozzle faces the major impact, thrust, wear, and whirling action (vortex) of the molten metal flow and gets worn out faster compared to the lower portion of the nozzle. Hence, the ladle nozzle is again divided into two parts: (1) the upper nozzle, which takes up the major wearing action of the metal flow, and (2) the lower nozzle, which faces a relatively lower wear effect and carries the molten steel to the slide gate plate. The upper nozzle is required to be changed frequently compared to the lower nozzle due to the higher extent of wear. The lower nozzle is fixed with the top slide gate plate and makes the top plate fixed with the ladle bottom refractories. Below the top plate, the sliding bottom plate is attached, which is encased in a separate attachment. Support springs are used to push the bottom plate upward for intimate contact with the sliding surface of the top plate, allowing no gap between the plates, to prevent any molten steel penetration and any ingress of air/oxygen. The movement/sliding of the bottom plate is controlled by an actuator connected with a bell crank mechanism, which is supported externally, and the whole pushing mechanism is fixed at the outer ladle wall. Molten metal passes through the holes of the plates and then moves to the collector nozzle, usually made fixed with the bottom plate, matching the hole coaxially. The collector nozzle transfers the molten metal to the ladle shroud, held mechanically at the bottom (exit port) of the collector nozzle, which further carries the molten metal to the tundish. All the rest of the components are mostly non-refractory metallic parts required to support the refractory system and in fixing and the movement of the bottom plate.

7.5 FUNCTIONING OF SLIDE GATE PLATES

Today, the slide gate refractory is the most commonly used device to control the flow of molten steel from ladle to tundish in the continuous-casting steelmaking process. The function of the slide gate valve, that is, the control mechanism (the gate action), is actually done by a set of two separate refractory plates. The plates are made up of a composite refractory composition having holes of the same diameter. The plates face each other and can also slide over each other. As per the position of the plates in the assembly, the upper plate is called the top plate, and the lower one is the bottom plate. The bottom plate is free, is moveable, and slides underneath the top plate, which is fixed at the ladle bottom. The movement (sliding) of the bottom plate and the matching of the boreholes of the two plates control the functions of the slide gate refractories, as shown in Figure 7.4.

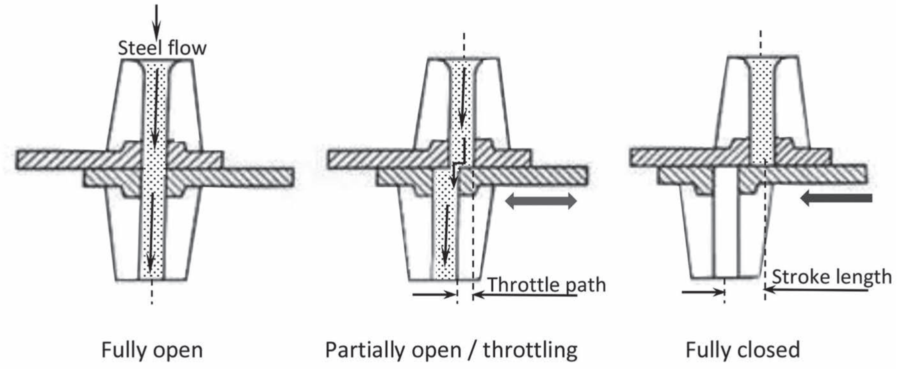


FIGURE 7.4 Operation of slide gate plates and the position of the boreholes.

As per the positions of the plates, when the boreholes of the plates are exactly matching and have a coaxial position, the plates are in fully open position, and the molten steel can pass through at its maximum flow rate. This flow of steel is controlled by "throttling" the lower plate, done by the marginal *to-and-fro* movement (sliding) of the bottom plate to partially close the opening (Figure 7.4a). Thus, a portion (length) of the bottom plate is used to partially close (reduce) the opening of the hole. The portion/length of the sliding surface of the bottom plate that is used to reduce the opening (also in contact with the molten steel) when it is under the throttling process is called the "throttle path" (Figure 7.4b). The continuous throttling process (little to-and-fro movement) of the bottom plate also prevents the sticking tendency of the plates due to any penetration of molten steel during flow along the sliding surface and solidification of the same. Thus, by the throttling process, the opening of the borehole is constantly controlled, along with the flow rate of the molten steel.

Again, when the boreholes are wide apart, the gate valve is completely closed, and there is no flow of metal (Figure 7.4c). The molten metal is present at the borehole of the top plate but gets obstructed at the sliding surface of the bottom plate. Thus, a portion (length) of the bottom plate sliding surface is wet by (in contact with) molten metal between the position of complete opening and that of complete closing of the gate (boreholes). This length of molten steel contact (wet) area is called "stroke length." It is the max length/distance that the bottom plate can slide/move to during operation. During operation of the slide gate refractory (flow of molten steel from ladle to tundish), commonly the holes are in a partially open position, and the bottom plate is under constant *to-and-fro* throttling movement. Thus, it controls the flow of molten steel and avoids any sticking and solidification of the liquid steel at the sliding surfaces of the plates. The movement of the bottom plate is controlled by a push–pull mechanism operated by a hydraulic system attached separately at the ladle outside wall (shell).

At the end of the tapping, when the ladle is nearing an empty condition, the ferrostatic pressure of steel (height of the molten steel bath) is very less, and the flow rate of molten steel drops drastically. In such a situation, the bore opening is made maximum to allow an unrestricted flow of metal so that a maximum possible flow rate of metal from ladle to tundish can be attained. This will help maintain a nearly uniform flow rate of molten steel all through the tapping process. Thus, the bottom plate actually controls the flow of molten steel by its sliding movement and throttling process. It also has to withstand the ferrostatic pressure from the height of the molten steel bath in the ladle. Hence, the sliding surface of the bottom plate is under a huge load and the severe actions of a flowing metal stream in terms of corrosion, erosion, abrasion, impact, etc. These degrading actions are extremely severe, especially for the throttle path region, and extends up to the region of stroke length.

7.6 PROPERTY REQUIREMENT FOR SLIDE GATE PLATES

The basic purpose of the slide gate refractory is to control and streamline the flow of molten steel during its transfer from the teeming ladle to the tundish, mostly in a continuous casting process. Among all the different components of the slide gate refractory system, the slide gate plates face the most challenging and harsh environment and need to have excellent properties and stringent quality check-up. The major characteristics required for the slide gate plates to meet the challenges in the application are as follows.

1. High strength at elevated temperatures to withstand the load of the steel bath present in the ladle (ferrostatic load)
2. Resistance to corrosion against molten steel (including inclusions present) and slag
3. Resistance to wear and erosion against a flowing stream of molten steel and slag
4. Very high resistance against thermal shock and high thermal conductivity
5. High dimensional stability and low thermal expansion at operating temperature
6. Low apparent porosity, with smaller pore size
7. Defect-free, smooth-surface finish for the sliding surfaces

Other than the preceding refractory-specific criteria, operational parameters also strongly affect the performance and life of the slide gate plate refractory. These parameters are operating temperature, type of steel, chemistry of steel and slag, molten steel flow rate, extent of opening of the plates, throttling parameters, metal holding time, secondary steelmaking processes involved, total casting time, frequency of ladle use, etc.

7.7 REFRACTORY COMPOSITIONS FOR THE SLIDE GATE PLATE

The time gap between theoretical conceptualization and practical (commercial) use of the slide gate refractory is about a century. This long time was required to develop the suitable refractory composition for such a stringent application and the commercial manufacturing process for the plates. The refractory compositions used in making a slide gate refractory are primarily responsible for its performance and life. Several research works had been carried out to develop the correct refractory material and to judge the suitability. Still, developmental works are going on for further betterment, as per the feedback from the application sites and demands from user industries. The type and quality of the refractory to be used for slide gate plate application for a particular plant are specific to that plant's various operational parameters. Hence, the type and quality of the refractory to be used for the slide gate plate are plant-specific and may vary from one application site to another, as the process conditions and parameters may vary as well. There are few common and basic refractory properties that are essential for a material to be used for the slide gate plate, which are hot strength; corrosion resistance to slag and steel; thermal shock resistance; resistance against impact, abrasion, and wear; low porosity; volume stability; etc. A refractory composition may be selected for slide gate plate application if it satisfies all the properties required for a particular site of application. Again, as steel quality is changing with time and moving towards higher purity, new steel processing technologies with further stringent operational parameters are being employed that demand for high-performing refractories and a prolonged service life. This has resulted in the continuous upgradation of the slide gate plate refractories through the modifications in their basic compositions and the use of additives.

Since the wide commercial exploitation of slide gate refractory about 60 years back, the composition of the slide gate plate refractory has been improvised continuously as per the application requirements and modernization of steelmaking technology. Various refractory compositions have been commercially used to optimize the property requirements as per application requirements and modified further for better performance and life. Among all the different parts of the slide gate refractory system, plate refractories have gotten the most attention due to their extremely critical application conditions. Brief details of the different refractory compositions that have been used commercially to make the slide gate plates are described in what follows.

7.7.1 ALUMINA PLATE

The refractory composition to be used for the slide gate plate must meet the requirements of the application environment, specifically for hot strength and resistance against corrosion, thermal shock, abrasion, and erosion. The commercial success of the slide gate refractory has started with high-purity and high-dense sintered alumina plates. Alumina was initially selected as the refractory material for slide gate plate applications in the 1960s due to its excellent properties, like hot strength, hardness and wear resistance, chemical inertness, volume stability at high temperatures, and thermal shock resistance. Some details of commercially used alumina plates are provided in Table 7.2. The continuous demand for longer life from the plates and the requirements for the processing of ultra-pure steel involving various killing operations (to remove dissolved oxygen) and chemical treatments (to improve the purity of steel), particularly in the last two to three decades, have forced the refractory technologist to look for improved refractory compositions suitable to meet the demands. Under the stringent application environment, the performance of the sintered alumina plates was not remarkable, and life was only about 1–2 heats. Accordingly,

TABLE 7.2
Details of the Commercially Successful Alumina and Alumina–Carbon Plates

	Al_2O_3 Plate 1	Al_2O_3 Plate 2	Al_2O_3–C Plate 1	Al_2O_3–C Plate 2	Al_2O_3–C Plate 3
		Constituents			
Al_2O_3	85–88	92–95	78–80	70–75	82–85
MgO	0.05	0.05			
SiO_2	10–12	4–6	10–12	12–15	
Fixed carbon			8–10	12–15	8–10
Antioxidant			1–4	1–4	1–4
		Properties			
Bulk density (g/cc)	2.95–3.0	3.15–3.2	2.9–2.95	2.8–2.85	2.9–2.95
Apparent porosity (%)	12–14	12–14	10–12	8–10	8–10
Cold strength (MPa)	120–140	180–200	140–150	120–140	140–150
Hot MOR @ 1,400°C (MPa)	18–20	20–22	20–22	15–18	18–20

newer refractory compositions and combinations have been developed and used as slide gate plates with excellent tailor-made properties, thus opening up newer horizons for the refractory field.

7.7.2 ALUMINA–CARBON PLATE

Though the oxides (like alumina) are the first candidate for slide gate plate application, the requirements of greater chemical resistance (against molten steel, slag, and impurities of steel) and higher thermal shock resistance have shifted the plate refractory compositions towards carbon-bonded and carbon-containing ones. The introduction of carbon in oxide refractory imparts high thermal conductivity, low coefficient of thermal expansion, and non-wetting characteristics in the composite composition, providing greater resistance against corrosion and thermal shock. As the desired performance and service life is not obtained from the sintered alumina plates, carbon was introduced with alumina, initially as a bonding material (organic binder like tar, pitch). Later, carbon became a component in the composition, mostly used as graphite, when a higher amount of carbon is planned to be incorporated for its multiple beneficial effects. A higher amount of carbon cannot be incorporated by the bonding materials alone, as the binders contain a limited amount of fixed carbon (<50%) and the bonding materials can be used only up to certain percentages of the refractory composition. The incorporation of carbon produces a composite refractory, as carbon does not react with the oxide components, and all the characteristics/benefits of carbon can be retained in the developed composite refractory. Further, the use of a wide range of additives, like antioxidants (metal powders), property-enhancing additives (like ZrO_2, SiC), etc., makes the refractory a multi-component system containing various ceramic phases at high temperatures. Different components and phases contribute to the properties of the composite refractory and its performance. Hence, Al_2O_3–C refractories perform much better and improve resistance against corrosion, thermal shock, and thermomechanical properties compared to the originally used alumina plates, even for long sequences, under extreme application environments. The amount of carbon and the type and amount of the additives to be used in the plate refractory may vary as per the requirements, depending on the severity of the application site.

The alumina carbon compositions for slide gate plates are generally made up of white tabular alumina, white fused alumina, graphite, and various additives. Graphite is used as the primary source of carbon due to its higher oxidation resistance among all the different carbon sources, a non-wetting character that improves the corrosion resistance, and flakiness, which improves the thermal conductivity and thermal shock resistance of the refractory. Moreover, graphite, as a carbon source, does not show any softening character at steel plant operating temperatures. From a microstructural point of view, graphite has a plate-like layered structure, with no bonding in its crystallographic "z" direction. So the graphite layers can slide over one another easily and provide better slideability for the slide gate plate application. Thus, the addition of graphite results in better performance and longer life of the plate refractory. Al_2O_3–C slide gate plates show 4–5 heats of service life compared to the 1–2 heats of the sintered Al_2O_3 plates. Some details of the alumina–carbon plate compositions and properties are provided in Table 7.2.

Carbon (graphite) is hydrophobic in nature; hence, water-based binders are not used in mixing these plate compositions, as carbon will get separated, causing segregation in the composition. So organic binders, commonly phenolic resin, are used for the mixing of Al_2O_3–C slide gate plates. Phenolic resin is beneficial as it has a higher fixed carbon content, greater bonding strength, lesser toxic gas generation, better compatibility with graphite and alumina (oxides), etc. During curing, around 200°C, it polymerizes to a three-dimensional isotropic interlocking network structure and provides strength to the refractory plate. But at elevated temperatures, isotropic glassy carbon is formed from the fixed carbon of the resin and results in a brittle character with deterioration of the properties. Catalysts like nickel, cobalt, boron, etc. graphitize the amorphous carbon formed from resin at high temperature and further enhance the properties of the plates.

But the presence of carbon/graphite makes the plate susceptible to oxidation above 400°C, and during application, the slide gate plates are exposed to temperatures above 1,600°C. If the carbon is oxidized, it goes out of the refractory structure as gaseous CO or CO_2 form, and the refractory becomes highly porous and wettable. Porosity reduces all the different mechanical properties and allows molten metal and slag to penetrate within the refractory structure easily. This will degrade the quality drastically, and finally, the molten mass will completely wash out the refractories. Chemical additives, like antioxidants, are used to control/prevent the oxidation of carbon, which react with the incoming oxygen and convert to oxides, thus protecting the carbon from penetrating oxygen. Among the antioxidants, metallic Al and Si powders are commonly used in the industry due to their high affinity for oxygen, better protection against oxidation, relatively low costs, and acceptable performances. The formation of various non-oxide ceramic phases, such as Al_4C_3, TiC_3Al_2, AlN, and SiC, as per the addition of antioxidant, provides high thermal conductivity and low thermal expansion for the refractories. The formation of Al_4C_3, SiC, and AlN in situ ceramic phases within the Al metal powder containing the Al_2O_3–C plate composition at high temperatures also enhances the strength both at room and elevated temperatures. Further, microstructural modifications also occur due to the formation of in situ ceramic phases. The formation of SiC whiskers with high aspect ratio within the microstructure of the Si metal powder–containing plate refractory composition improves the mechanical properties significantly.

To improve the quality and performance of the plates further, various additions are used in the plate refractory composition, like how SiC is added to Al_2O_3–C plates to improve wear resistance, thermal conductivity, oxidation resistance, thermal shock resistance, etc. Mullite is also added in certain plate compositions, especially to improve the resistance against corrosion and thermal shock. Improvements in alumina–carbon plates are also achieved by thus:

- Graphitization of the fixed carbon of resin binder by using special additives (Ni catalyst), avoiding the formation of amorphous carbon, which enhances mechanical properties and thermal shock resistance
- Formation of a greater extent of in situ ceramic phases, like Al_4C_3, AlN, and SiC, and non-metallic oxides, like SiAlON, for reinforcement of the refractory and improved strength
- Use of microcrystalline graphite replacing flake graphite to improve hot strength and thermal shock resistance
- Incorporation of nano-sized carbon and the use of other non-oxide components to reduce the graphite/total carbon content in the refractory composition, thereby improving the oxidation resistance and strength.

7.7.2.1 Problems with Alumina-Based Plates

The demand for high-quality steel has increased with time, and among them, high-purity (minimum inclusion), low-carbon steels are in great demand for their improved properties. The introduction of various purification processes to produce low-carbon, purer, and cleaner steel has resulted in the changes in steel chemistry, inclusion level, process parameter, etc. These have demanded for advanced technologies and precise steelmaking parameters, along with high-quality refractories. For the production of low- and ultra-low-carbon-containing steels, the use of conventional alumina–carbon plates is not ideal because of the increased risk of diffusion and dissolution of carbon into liquid steel, affecting its properties.

Again, the alumina-based slide gate plates degrade during use, which depends on the steel grades, steel and slag chemistry, processing involved, casting parameters, etc. Further, alumina-based plates are not chemically very stable against Ca-treated steel (secondary metallurgy), which has a higher level of Ca content in steel composition. Also, alumina is not the ideal refractory for applications where iron oxide concentration is high. Alumina reacts with CaO (formed upon the oxidation of increased Ca content of steel post–Ca treatment) and forms Ca-aluminate phases. The Ca-aluminates form low-melting liquid phases upon reaction with the impurities present in the refractory and steel, and also when it is in contact with iron oxide at steelmaking temperatures. The liquid phases corrode the refractory and wear out/wash out faster. The liquid-forming temperature gets further reduced in the presence of other inclusions present in the plate composition, like silica. The formed low-melting phases reduce the viscosity of the melt and increase the kinetics of corrosion and wear, and also the degradation. To avoid the deterioration in pure alumina-based systems, mullite-bonded, high-alumina refractories were introduced and became one of the most used plate materials during the early stages. The incorporation of fused zirconia–mullite aggregates in alumina-based compositions has also improved the quality of the alumina-based plates due to an increased resistance against corrosion, abrasion, and wear. However, the presence of silica in mullite-containing compositions (acidic in nature) restricts the application of such plates for steel and slag high in CaO or iron oxide content. Few reports also revealed better performances for the silica-free alumina carbon plates against Ca-treated steel, but such benefits were not obtained in commercial applications.

7.7.3 Basic Plates (MgO, MgO-C)

Contrary to alumina, magnesia (MgO) does not form any low-melting liquid phase upon contact with calcia (CaO), even at steelmaking temperatures, due to its similar chemical nature. Magnesia forms a partial solid solution with calcia, and these two highly basic oxides do not react with each other, as observed in the CaO-MgO phase diagram. Again, for iron oxide, magnesia forms a completely solid solution with ferrous oxide and also can accommodate a large quantity of ferric oxide in its structure, forming a partial solid solution before forming any liquid phase at higher temperatures. Thus, the formation of any low-melting compound and the chances of any degrading effect are less probable for MgO-based slide gate plates in the presence of CaO or iron oxide. Hence, the chemical stability of magnesia in a Ca-rich environment makes it a preferable candidate than the conventional alumina-based compositions in slide gate plate applications. Also, magnesia-based plates show better performance for high-oxygen-containing steel. But in comparison to alumina, magnesia has high thermal expansion, high modulus of elasticity, and relatively low strength, resulting in susceptibility to thermal stresses and crack formation under thermal fluctuations, leading to an increased chance of cracking and failure during use. Hence, it is a common practice to use magnesia-based compositions for smaller-sized slide gate plates so that the cumulative effect (due to size) of thermal stress on strength or thermal shock property will be less, whereas alumina-based compositions are preferred for bigger-sized plates, where magnesia-based systems perform poorly.

To improve the hot strength of magnesia-based plates, zirconia is commonly added to the composition, which also improves the corrosion resistance. The formation of Mg or Ca zirconate phases as solid solution at high temperatures results in an optimized matrix properties and an increase in the liquid formation temperature, thus improving hot strength. To improve the quality of magnesia-based plates further, carbon is commonly added to the composition as component along with antioxidants and other additives. The magnesia carbon plates act as composite refractory and result in excellent corrosion resistance, even against high-Ca-containing (Ca-treated) steel. The presence of carbon also imparts multiple benefits, and these compositions perform better and provide longer life for the plates.

Slide gate plates are used in an extremely severe condition with high temperatures and heavy load and face the turbulent molten steel flow. The presence or formation of any liquid phase in the plate refractory will drastically deteriorate the quality of the plate refractory, its performance, and its life. To minimize any such deterioration, basic plates are a must for Ca-treated steel for better chemical compatibility. Other than the magnesia- and magnesia-carbon-based composition, magnesia spinel–based slide gate plates are also important, showing an improved thermal spalling resistance and corrosion resistance. A significant improvement in operational performance and life is obtained for the basic composition compared to that of the alumina plates. Service life is found to be increased by 40% against Ca-treated steel. The improved performance and longer life of slide gate plates are also reported in many of the studies using silica-free alumina-carbon refractories. Details of the compositions and properties of different basic plates are provided in Table 7.3.

7.7.4 ZIRCONIA-CONTAINING PLATES

For all the different refractory compositions of slide gate plates, abrasion is a common and major degrading factor. Molten steel flowing at a very high rate and under a huge ferrostatic pressure (due to the height of the molten steel bath in the ladle) abrades the surface of the plates, especially at the borehole area of the bottom plate, causing the fast wearing out and degradation of the metal contact portion (borehole) and an increase in bore diameter. Thus, the increased hole diameter increases the flow rate in an uncontrolled manner. This increase in borehole diameter will further increase with the number of heats (use). Hence, the plate needs to be replaced frequently. To minimize such a degradation and avoid the frequent replacement of plates, highly wear- and corrosion-resistant plate refractory composition is essential. To improve the abrasion and corrosion resistance, the addition of zirconia in the composition is common practice. Even in the presence of high Ca (or CaO), zirconia reacts with it, forming the calcium zirconate ($CaZrO_3$) phase, a high-temperature melting compound, and thus restricts the deterioration of the plate. Further, for high-manganese-containing steel, alumina-based

TABLE 7.3 Details of Different Basic Plates

	Basic (MgO)	MgO-C	MgO-Spinel-C	Spinel-C
		Constituents		
Al_2O_3	4	8	16–18	80–82
MgO	94–95	82–85	75–80	16–18
SiO_2	0.05			
ZrO_2	1.0			
CaO	1.5–2	1–1.5	1–1.5	<0.5
Fixed carbon		5	5	4
		Properties		
Bulk density (g/cc)	2.95–3.0	2.9–2.95	2.95–3.0	3.0–3.05
Apparent porosity (%)	13.5	3	4	5
Cold strength (MPa)	100–120	120–150	90–100	150–160
HMOR @ 1,400°C (MPa)	8–10	10–12	8–10	15–16

plates form galaxite ($MnAl_2O_4$, melting point 1,520°C) and low-melting compounds in the presence of impurities like SiO_2. Such compounds and low-melting phases are not formed in the presence of zirconia, and so the zirconia-based compositions result in much improved performance and life against steel-containing Mn. The introduction of zirconia in the plate composition and its amount increase the resistances of the plate against wear and corrosion. Pure zirconia plates show excellent properties, especially mechanical, and also resistance against wear, abrasion erosion, and corrosion, but suffer from properties like thermal shock, etc. Also, very high zirconia-containing compositions are not economical and have phase stabilization challenges.

The use of zirconia carbon compositions has reduced the technical difficulty for the plates, but the economy is negatively affected in comparison to the obtained benefits and life of the plates. Alumina-zirconia-carbon-based compositions are also successful and improve the performance and life of the plates. However, the economy and corrosion resistance against Ca-treated steel, Mn-containing steel, etc. are not that great. To reduce the wear-out (both mechanical and chemical) of the plates, especially in the bore area, high-sintered zirconia inserts are used to provide reinforcements in the highly affected areas, thus improving the overall quality and performance of the slide gate plates. Zirconia inserts are also used up to the stroke length area to protect the complete metal contact surface of the bottom plate against corrosion and mechanical wear-out. The rest of the portions of the plate, those that are never in contact with molten metal or slag, are made up of conventional compositions (like alumina carbon), primarily to provide strength and thermal shock resistance. Different types of zirconia inserts containing slide gate plates are shown in Figure 7.5. The high pure zirconia present in the inserts takes care of all the

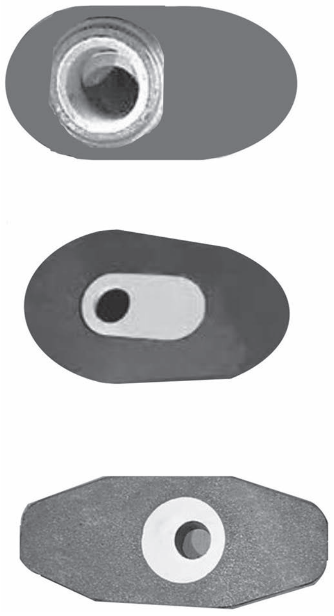


FIGURE 7.5 Different types of zirconia inserts used in slide gate plates.

TABLE 7.4
Details of Different Zirconia-Containing Plates and Zirconia Insert

	Al_2O_3–ZrO_2	Al_2O_3–ZrO_2-C Plate 1	Al_2O_3–ZrO_2-C Plate 2	ZrO_2 Insert
		Contents		
Al_2O_3	82–85	65–70	80–85	
MgO	0.05			
SiO_2	10.5	10		
ZrO_2	7–8	8–10	8–10	96–87
CaO	0.3	0.4	0.4	3–4
Fixed carbon		10–12	7–8	
		Properties		
Bulk density (g/cc)	3.1–3.15	3.0–3.05	3.2–3.25	4.5–4.6
Apparent porosity (%)	12–15	8–10	7–8	8–10
Cold strength (MPa)	140–160	120–130	140–160	220–250
HMOR @ 1,400°C (MPa)	20–25	15–18	18–22	32–35

corrosive and abrasive actions of the flowing molten steel stream. Thus, the cost of the plates is not excessively high in comparison to the improvements attained in terms of performance and life. These inserts are mostly MgO-doped, partially stabilized zirconia, which also provides good resistance against thermal shock. Table 7.4 compares the composition and properties of different zirconia-containing slide gate plates that are successful and being used commercially.

7.8 SELECTION CRITERIA FOR SLIDE GATE PLATE

The type of slide gate refractory, especially the plates, to be used for a particular application depends on a few factors of the steel plant's operating conditions. Some of the basic guidelines in selecting plate refractory compositions are mentioned in the following, and final selection is done with judicious consideration of all these factors along with the performance, life, and economy of the plates for such application.

7.8.1 Steel and Slag Chemistry

The refractory composition for the slide gate plate must be compatible with the chemistry of the steel (including inclusions) being processed and that of the associated slag. Any mismatch among them and the reaction of any component of the plate refractory with the elements present in molten steel (even inclusions) and slag may lead to serious problems for the plates due to chemical attack, leading to the deterioration of the plate and its failure. Any chemical interaction of the plate with the molten steel or slag under extreme mechanical and thermal conditions will cause drastic deterioration of the plate. Hence, the plate refractory must be chemically compatible with the molten steel and slag.

7.8.2 Size of the Plate (Stroke Length)

The size of the slide gate plate (or the stroke length) is an important parameter in the selection of the type and quality of the slide gate plate refractory. Normally, magnesia-based basic compositions are highly suitable for smaller plates, but for bigger-sized plates, alumina-based compositions perform better. Magnesia-based compositions are avoided in favour of making bigger-sized plates (longer stroke length), as magnesia has higher thermal expansion properties. For bigger-sized plates, the thermal stress (and associated strain) generated in magnesia-based compositions due to the higher thermal expansion at high temperatures may be higher than the strength of the plate, leading to cracks and failures. However, for smaller-sized plates, the extent of total stress (and strain) generated is lower due to its smaller size, which the basic plate can withstand. Hence, for bigger-sized plates, alumina-based compositions are preferred as alumina has a lower thermal expansion property, generating lower thermal strain even at high temperatures with bigger size. Further, alumina has a higher strength compared to magnesia-based compositions. Thus, alumina plates can withstand the higher thermal strain generated in bigger-sized plates and perform better without failure. Thus, the size of the plate is decisive in the selection of the refractory composition for the plates.

7.8.3 Bonding within the Refractory Plate

The bonding system used in the refractory composition of the plate also controls the plate properties and its performance. During application, the slide gate plates encounter a severe throttling process and high-temperature erosion and abrasion. The severity and criticality of application vary from one site to another. Hence, the type of refractory composition for the plate application needs to be selected as per the conditions prevailing in the specific application site. Slide gate plates used for billet and ingot casting encounter severe throttling and abrasion in comparison to that of the bloom and slab casting applications. So strongly bonded plates are essential for the billet and ingot casting compared to the other applications. Different types of bonding systems are used for different types of slide gate plate compositions to obtain the required properties as per the application site. The common bond systems used are as follows:

- *Carbon bond.* This is the most conventional bonding system, requiring a carbonaceous bonding material and a suitable firing schedule to develop the bond within the refractory composition and the necessary properties development.
- *Ceramic bond.* It is the most stable bonding system developed in situ during solid-state sintering at high temperature. Commonly, the plates are fired before use to develop the ceramic bond and desired properties.
- *Metal bond.* It is one of the advanced bonding systems for refractories, requiring a suitable heat treatment process depending on the specific metal powder used to develop nascent in situ ceramic phase formation for the bonding.
- *Lightly burnt metal bond.* This is also an advanced bonding system with a specifically designed firing process wherein prior heating of material helps develop strong bonding within the refractory.

7.8.4 Calcium Content in Steel

The calcium concentration in the steel may vary depending on the purification steps involved in the secondary steelmaking process. An increased concentration of calcium affects the quality, performance, and life of the refractory tremendously. Hence, the selection of refractory composition for slide gate plate depends on the Ca content of steel for a specific application site. Basic (MgO-based) plates are preferred against high-Ca-containing steel compared to alumina-based compositions, as alumina reacts easily with the calcium present in steel and gets corroded rapidly.

From the preceding discussion, it can be concluded that alumina-based (Al_2O_3, Al_2O_3-C) plates (silica-free/very minimum silica content) are suitable for plates with bigger size/longer stroke length application and with low Ca content (<10 ppm) of steel. These types of plate are suitable for low-carbon steel (mild steel), stainless steel, high-silicon steel (for electrical applications), etc. Again, for a high level of Ca content (>35 ppm) in steel, basic plates (MgO, MgO-C) perform well, especially when they are smaller in size (stroke length <150 mm). Basic plates work well in high-Ca-containing steel, low-carbon steel, manganese-containing steel (work-hardening steel, important for mining industries). But the larger size of the basic plate produces a huge strain within the plate due to the higher thermal expansion and causes failure. Plates of spinel-containing systems, like spinel-carbon, spinel-MgO-carbon, etc., work well for a medium range of Ca content in steel (up to 30 ppm) and provide good thermal shock resistance due to the presence of spinel. These plates are suitable for low-carbon- and manganese-containing steel also. Zirconia-based plates work well against high-Ca-containing steel and can be used for low-carbon-, high-Ca-, high-Si-containing steel. In many a cases, the composite concept of slide gate plates is used to optimize the properties required. Also, zirconia is used as an insert around the borehole of the plates to take care of the criticality of the steel contact conditions. Hence, optimization and customization of the refractory composition for the slide gate plates are done to meet the requirements of specific application sites and to obtain optimized performance and life.

7.9 DEGRADATION OF SLIDE GATE PLATES AND POSSIBILITIES FOR IMPROVEMENTS

Among the different applications of refractories, slide gate plates face one of the most stringent conditions during use. It is not only any specific condition of temperature or pressure or chemical environment that the plates need to withstand; the plates that are only a few centimetres thick also have to withstand all the different stringent application conditions prevailing in the application site. The common application conditions that a slide gate plate faces are outlined in what follows:

1. Application temperature is commonly between 1,600 and 1,700°C (liquid steel temperature).
2. Ferrostatic load may be up to 400 t (ladle capacity).
3. Chemistry and quality of steel may vary depending on the grade of steel (carbon content), addition of alloying elements, killing conditions, treatment process, and permissible inclusion level (to achieve the desired purity/grade of steel).

4. Slag composition may also vary depending on the source of iron ore, fluxing materials, killing and treatment processes, alloying compounds, etc.
5. Properties of slag, especially viscosity, corrosiveness, flow behaviour, etc., may change according to its composition, temperature, and other processing parameters.
6. Flow behaviour of metal and associated abrasion, erosion, and wear effects.
7. Opening and throttling conditions of the plates during application.
8. Wide temperature distribution and thermal conditions within the plate.
9. Prolonged time of casting (ladle discharge).
10. Oxidation of the non-oxide components (carbon and other non-oxide additives).
11. Adhesion/sticking of metal and slag with the sliding surfaces and further solidification, affecting throttling process, chipping and peeling of plate surface, and closing of the plates, etc.

The aforementioned application conditions can be broadly classified in a few property-specific degradation factors for the refractory plates, which are described in detail in the following with possible remedies. However, it is important to note that all the following degrading factors act simultaneously, not singly, or as standalone basis, and the combined effect is much pronounced. Also, certain degrading factors enhance degradation by other mechanisms and enhance the deterioration of the slide gate refractory drastically. Table 7.5 lists out some of the degradations that are observed for slide gate plates during their applications and the basic reason for such degradations.

7.9.1 CORROSION

It is the major and foremost parameter for the degradation and deterioration of slide gate plates. The corrosive environment for the slide gate plates has become very stringent as steel manufacturers are introducing newer processing techniques and purification methods to produce cleaner steel.

The introduction of Ca treatment post–killing process to produce clean steel increases the Ca content of molten steel. This Ca present in steel reacts with the Al_2O_3-based slide

TABLE 7.5
Degradations Observed in Slide Gate Plates and Their Reasons

Effects Observed during Operation	Reason of Wear
Increase in bore diameter	Molten metal flow
Wear-out of the sliding surfaces in the stroke area	
Wear-out/chipping/erosion of bore edge	
Chipping out of sliding surfaces	Thermal shock/temperature gradient
Radial cracks	
Breaking out/chipping of bore edge	
Peeling of the sliding surfaces in stroke area	Sticking of metal on sliding surface
Reduction in bore diameter/clogging	Alumina build-up at bore

gate plates upon contact with the molten steel, forming low-melting Ca-aluminate compounds, and wears out the portion of the refractory. The presence of a higher level of Ca in steel has forced refractory makers to replace alumina-based refractories with basic refractories. But even with the use of basic (MgO-based) refractories, the basic oxide gets dissolved by the more basic component CaO (as thermodynamic stability of CaO is greater than that of MgO). This leads to a transfer of magnesia from the slide gate plate towards the inclusion (steel), whose MgO content increases at the expense of the refractory. Thus, for improved performance and life of the slide gate plates, the amount of the treatment additives (Ca-Si or Ca-Fe) needs to be judiciously added (to control the Ca content in molten steel) as per the oxygen level in steel and Al killing process used.

The processes involved in improving the purity/cleanliness of steel adversely affect the quality of the slide gate plates. The deteriorations are also found to be higher for certain steel grades, like high-manganese steel or Ca-treated steel. The selection of slide gate plates for a particular grade of steel and its cleanliness depends primarily on the chemical interactions of the refractories with molten steel and slag. It is common to find undesirable elements in the liquid steel, mainly as inclusions coming from the impurities of iron source or even from the refractories, like C from alumina-graphite, Ti from bauxite, etc. The chemical compatibility of the plate refractory composition with the molten steel, its inclusions, slag, etc., is important in maintaining the quality of steel as well as the performance and life of the refractory. The raw materials and constituents used in making the plate, their mineralogical/phase compositions, the impurities present in the plate refractory, the chemistry of the molten steel and slag, its operating temperature, the process conditions, etc. are important for the reactions involved and the degradation of the refractory.

The type and amount of Ca-containing, low-melting compounds formed depend on multiple factors, like grade of steel, extent of the killing process, amount of oxide (like alumina, silica, etc.) inclusions present, extent of Ca treatment (amount of Ca-Si, Ca-Fe addition) involved, etc. The size of the oxide inclusions formed during the killing process also influences the formation of low-melting phases.

Smaller-sized oxide inclusions readily convert to calcium compounds (mostly in molten state) in comparison to the larger ones due to surface area effect. However, as per thermodynamics, if sulphur or oxygen or both are present in the molten steel at moderate levels, calcium will react with oxygen or sulphur until the contents of these inclusions (S or O) are very low, lesser than 2 ppm. These nascent Ca compounds (CaO or CaS), upon reaction with other inclusions, also produce low-melting and low-viscosity compounds, which are highly corrosive to refractories. These low-viscosity liquids present with molten steel enter into the refractory structure through the surface pores, get solidified, and cause cracking. Thus, they reduce the hot strength and corrode (also wash out) the refractory. This results in rapid degradation in the quality of the slide gate plates. Again, lime in association with silica and titania forms further low-melting liquids which are highly dreadful for the refractories. Hence, Ca-treated steel affects the performance and life of the slide gate plates with greater severity. The higher the level of Ca content in the steel, the more dangerous it will be for the refractories.

Moreover, when the slide gate plates are exposed to stainless steel or Ca-treated steel, the deterioration increases drastically if any silica is present in the refractory composition (even as impurity), primarily due to mismatch in chemical compatibility (acid–base combination). Hence, any silica- or mullite-containing plates are not suitable for flow control of these steel grades. An alumina-zirconia (A-Z) plate or basic plate (MgO based) performs better depending on the Ca content in steel. MgO-based plates match with the chemistry of molten steel and slag, whereas in the A–Z plate, the presence of zirconia improves the corrosion resistance, thus providing better performance and service life. Further, A-Z plates have a well-dispersed monoclinic zirconia phase within the corundum grains that produces an expansion discontinuity around 1,000°C, generating micro cracks and decreasing the elasticity of the refractory, thus, in turn, increasing thermal shock resistance.

7.9.2 DISSOLUTION

Among the different refractory components used for making slide gate plates, carbon is the only component that gets dissolved in steel. The sources of carbon are residual carbon from organic binders and free carbon (like graphite) used for making the refractory. The dissolution of carbon from the refractory in steel affects the quality of steel significantly and makes the refractory porous, weak, and vulnerable to degradation under the flow of molten steel. Similarly, the oxide components of the refractory also get reacted and get dissolved in slag, which is again dependent on the composition of the plate and the slag. Degradation and wear-out of the refractory are often controlled by a direct dissolution mechanism of slag. The chemical exchanges involved in dissolution are controlled by a boundary layer at the slag (liquid)–refractory (solid) interface. However, the contact between the slide gate plates and the slag is not very common and desirable for steel processing and refractory performances. Steelmaking slag is retained within the converter by the dart cone, and any slag formed/present within the steel ladle is not allowed to be transferred to the tundish through the slide gate plates, to maintain steel quality. However, still, if any slag comes in contact with the plate refractory, the driving force for the dissolution of refractory components is the gradient of chemical potential, usually the composition gradient. The elementary steps that govern the dissolution process are:

1. Thermo-chemical reaction at the refractory/slag interface
2. Diffusion of species due to chemical potential (gradient)

When the dissolution mechanism involves the precipitation (formation) of a new phase at the interface layer, the wear rate decreases with time, as the new phase restricts the movement/diffusion of the species. The dissolution–precipitation mechanism alters the refractory microstructure due to the formation of these new phases at the interface region. The texture of the formed phases and the shape and habit of the crystals formed at the refractory–slag interface indicate that they are precipitated slowly from a liquid phase. The slag–refractory reactions show the gradual disappearance of the refractory lining and a re-oxidation of the liquid steel, leading to an increase in solid non-metallic inclusions.

Refractory oxides like Al_2O_3, MgO, and CaO in pure phase are stable when they are in contact with the elements/inclusions present in steel, like Mn, Al, Si, and C. But these oxides are unstable and vulnerable in the presence of Ca in the molten steel. Further, oxide components like, SiO_2, and Cr_2O_3, if present in the refractory, react with many of the elements present in steel. Mn present in steel reacts with the silica of the refractory and forms molten metallic silicon (melting point 1,410°C) at the steel processing temperatures ($2Mn + SiO_2 \rightarrow 2MnO + Si$). The reaction product MnO, instead of forming a protective layer on the refractory surface, reacts further with the silica present in the refractory, forming low-melting silicates (like rhodonite, $MnSiO_3$, melting point 1,250°C). These reaction products are easily carried out by the flowing molten steel, and degradation of the refractory continues. Thus, the presence of silica in the refractory (even in the form of a compound, like mullite, or as impurity) is highly vulnerable in contact with steel-containing Mn as alloying agent or inclusion.

7.9.3 HOT STRENGTH

Slide gate plates, especially the bottom plate, are under tremendous mechanical thrust during operation. When the plates are in closed condition, during the transportation of molten steel from the steel melting shop to the casting shop, and during the waiting period before casting, when no metal flows out of the ladle, the bottom plate has to withstand the complete load of the molten steel bath (ferrostatic load, depends on the height of the metal bath and also the slag layer) in the ladle. Once the metal casting starts, molten steel flows out through the boreholes of the plates, the height of metal starts decreasing, and ferrostatic load starts getting reduced. But with the flow of the metal, the throttling process of the plates also starts, mainly to maintain uniformity in molten steel flow with casting time and avoidance of any sticking of the plates. Again, as the casting time progresses, the height of the molten steel bath decreases, and the ferrostatic load also decreases; thus, the flow rate gets reduced. Hence, the opening of the plates needs to be adjusted to maintain the near-uniform flow of steel. So at the beginning of metal casting, the opening between the plates is not full, and the bottom plate is placed in such a way that it closes some portion of the opening, thus reducing the full flow. With the progress of casting, the opening of the plates is increased to accommodate the effect of reduced ferrostatic pressure and to maintain a similar flow rate. Thus, the bottom plate is under tremendous impact of flowing metal due to partial closing and also under severe abrasion and wear effect at the edges of the bore for the molten steel flow. Moreover, the bottom plate is under constant throttling action during operation. Hence, the plate has to be very strong against all the mechanical actions of flowing liquid steel. Now, as the plates are operating at steel processing temperature, in the range of 1,600 to 1,650°C, the hot strength of the plates has to be very high to bear all these mechanical actions.

The slide gate plates are made up of different components, and the presence of impurities, even in a minute amount, is common. Though the raw materials used in making the plates are a highly pure one, still minute amounts of impurities are effective in reducing the high-temperature properties of the plate refractory. This may cause a degradation in strength of the plates at the steel processing temperatures and may lead to failure of the plates under extreme application conditions. Hence, the plate composition has to be a very pure one; there should not be any minute formation of liquid phase that may cause little grain sliding or deformation of the plate and failure of the plates. Accordingly, the constituents of the plate refractory are to be selected, and the impurity type and amount need to be adjusted. Also, the processing of the plates has to be foolproof to avoid any formation (or presence) of minute crack in the plate. Any such flaw under such a highly strained application will cause disruption and failure of the plates.

7.9.4 THERMAL SHOCK

Among the different applications of refractories, the application environment for slide gate plates is one of the most stringent and critical from a thermal gradient point of view. The bore area of the plates is in contact with the liquid steel and is at a temperature between 1,600 and 1,650°C, whereas the outer side of the plates, that is, in contact with the metallic shell/cover, is exposed to an ambient condition (temperature). Hence, there is a tremendous thermal gradient between the outer side and the bore/hole part of the slide gate plates which results in a huge thermal stress within the plate. All the plates have to withstand the thermal stress during operation, and any minor crack developed due to the strain generated from this thermal stress in the plate during operation poses a great threat. The extension and propagation of the crack that occur under thermal stress lead to the failure of the plate and to safety threats. A huge ferrostatic load and the tremendous impact of flowing molten metal stream also enhance the chances of failure, especially for the bottom plate. The formation of crack also increases the air inspiration within the plate, leading to oxidation and deterioration of the plates.

Radial cracks (through the thickness) in the plates are common for thermal shocks. Thermal stresses are generated within the plate during the preheating of the ladle and during the steel casting operation. These stresses result in strain within the plate refractory. The resultant strain will generate cracks once it exceeds the strength limit of the refractory. As the refractories are hard, rigid, and brittle in nature, any crack generated due to thermal strain will propagate under the thermal gradient through the whole plate, leading to catastrophic failure. Cracks in the plates may also be developed due to the frictional forces between the plates (generated due to the throttling process during operation), the removal of any refractory particle due to sliding action, the oxidation of carbon from the sliding surface, etc., which finally lead to failure of the plates. The formation of cracks due to the thermo-mechanical effect and its extension can be controlled by encasing the slide gate plates within a steel casing.

Among the various oxides that are used in making the slide gate plates, magnesia has the highest thermal expansion values. Hence, the thermal strain generated due to the temperature difference between the outer part of the plate and the bore area is huge for magnesia plates. Thus, magnesia-based plates are more vulnerable under similar thermal gradients compared to alumina-based compositions. Mullite and spinel have further lower thermal expansion values compared to alumina, hence resulting in improved properties against thermal shock. Further, the incorporation of carbon in the plate composition significantly changes the thermal shock behaviour. Carbon (mainly incorporated as graphite) has a very low thermal expansion behaviour, with high thermal conductivity. These two properties in combination result in improved thermal shock resistance for the carbon-containing slide gate plates.

7.9.5 OXIDATION

Carbon has become an integral component for the slide gate plate due to its multiple advantages. But the oxidation of carbon, and that of any non-oxide component present in the composition, is a major degrading factor for the slide gate plates. Oxidation results in the formation of porosity within the refractory and primarily affects all the mechanical properties and corrosion resistance. The oxidation of carbon may occur in two ways, namely, (1) direct oxidation and (2) indirect oxidation. Direct oxidation occurs below 1,400°C (starts even at 400°C), when carbon is oxidized directly by the gaseous oxygen from the atmosphere.

$$2C\ (S) + O_2\ (g) = 2CO\ (g)$$

Indirect oxidation occurs generally above 1,400°C, where carbon is oxidized by the oxide components present in the refractory composition or the surroundings (mainly FeO). The common reaction product, CO (g), escapes through the porous structure of the refractory.

$$C\ (S) + MgO\ (S) = Mg\ (g) + CO\ (g)\ \text{(mainly for basic plates)}$$
$$C\ (S) + FeO\ (l) = Fe\ (l) + CO\ (g)$$

For both types of oxidation, the space occupied by carbon becomes void, and the refractory becomes porous, becomes weak, and gets corroded easily. The carbon present on the surface of the plate may get oxidized due to indirect oxidation by the molten steel when it comes in contact with molten steel during the throttling process and the closing position of the gate. This causes carbon loss from the sliding surfaces of the plate, enhancing the porosity and roughness of the surface and leading to poor strength, greater wear, abrasion, and corrosion. To improve the oxidation resistance of the plate compositions, the addition of antioxidants is usually done. Also, the steel encasing of the plates improves the oxidation resistance against direct oxidation.

Metal powders, such as Si and Al (having high oxidation potential), and carbides, such as SiC and B_4C, are used primarily as antioxidants to prevent the oxidation of the plates. Metal powders or carbides react with incoming oxygen, get oxidized, and thus consume oxygen (potential threat to carbon). Formed oxides also cover the carbon and other non-oxide components from contact with any incoming oxygen and further improve the oxidation resistance. Moreover, the metal powders react with the carbon present within the refractory at high temperatures and form metal carbides that provide extra bond within the refractory and improve the hot strength of the plates. In situ formation of Al_4C_3 crystals and SiC whiskers, upon the addition of metallic Al and Si powders, respectively, are responsible for the increases in the hot strength of the plates. The oxide and carbide phases that are formed in situ within the plate matrix upon the addition of antioxidants reduce the pores and voids present in the plate and further reduce the ingress of oxygen or corrosive liquids and thus improve the performance and life of the slide gate plates.

Again, for high-oxygen-containing steel, oxygen present in the steel is a threat to the plate refractory. It was reported that the addition of SiC(s), B_4C(s), and ZrC(s) provides excellent antioxidant character and prevents oxidation of carbon till 1,530°, 1,570°, and 1,600°C, respectively. On the contrary, the in situ–formed Al_4C_3 phase formed upon the addition of metallic aluminium powder can prevent oxidation even up to 1,900°C. The high reactivity of the nascent-formed carbide phases show the greater benefit for the plate refractory.

7.9.6 Wear and Abrasion

The wear and abrasion of slide gate plates vary mainly with the type of refractory composition used, developed strength, properties of the plates, steel quality and inclusions present, application and operational parameters, etc. The major reasons for the mechanical wear-out of the slide gate plates are grade of steel, flow pattern of molten steel, clogging of metal on plate surface, chipping off from the plate surface (due to thermal shock, throttling, impact of flow, etc.), alumina build-up, etc. Abrasion and wear-out of the sliding surface of the plates occur due to frictional forces between the plates under constant throttling process during operation, even though the plates are polished to certain minimum roughness. Different wearing mechanisms of the plates operate simultaneously and increase with the increase in temperature. Further, the wearing-out effect due to mechanical actions enhances the degrading effects of corrosion due to the generation of rough and fresh surfaces, and the overall degradation is increased by many folds and becomes devastating.

Improved bonding within the plate, an increase in strength, the use of components/additives with high abrasion resistance (like SiC, ZrO_2, etc.), proper preheating, etc. are important to improve the abrasion and wear resistance of the plates. Again, among the operational parameters, control on process, steel flow rate, flow pattern, casting sequence, throttling conditions, etc. are also important.

7.9.7 Metal Penetration and Sticking at Sliding Surface

During casting, the flow of molten steel through the boreholes is restricted to control the flow rate by partial closing of the hole and throttling process. As the flowing molten steel strikes on the throttle path portion of the sliding surface of the bottom plate, there are chances that metal may penetrate in between the two sliding surfaces during throttling. If the metal penetrates through the sliding surface, it will cool down fast and get solidified in between the sliding surfaces of the plates. This will fix both the sliding surfaces (as well as both the plates) as the solidified steel sticks with both of them. Thus, both the sliding activity and throttling process will be restricted. Hence, a higher throttling/sliding pressure is necessary. Complete sticking may also completely stop the sliding/throttling action and may lead to cracking and failure of the plates under the higher sliding pressure. The risk of metal sticking and plate failure increases with the increase in the number of heat (use), as the sliding surface becomes rough (less smooth). A higher abrasion resistance; an absolutely flat and smooth sliding surface; a controlled throttling process; higher resistance against abrasion, wear, and oxidation; etc. are the requirements for improving the resistance against metal penetration and sticking of the sliding surfaces. Commonly, Al_2O_3-C- or Al_2O_3-ZrO_2-C-based plates are used to reduce the metal sticking problem.

Figure 7.6 schematically shows the different degradation effects that are observed on the bottom plate due to different degradation mechanisms. Sometimes it is difficult to identify the exact cause of degradation or the exact cause of failure for a slide gate plate, as multiple factors are involved simultaneously. A plate may

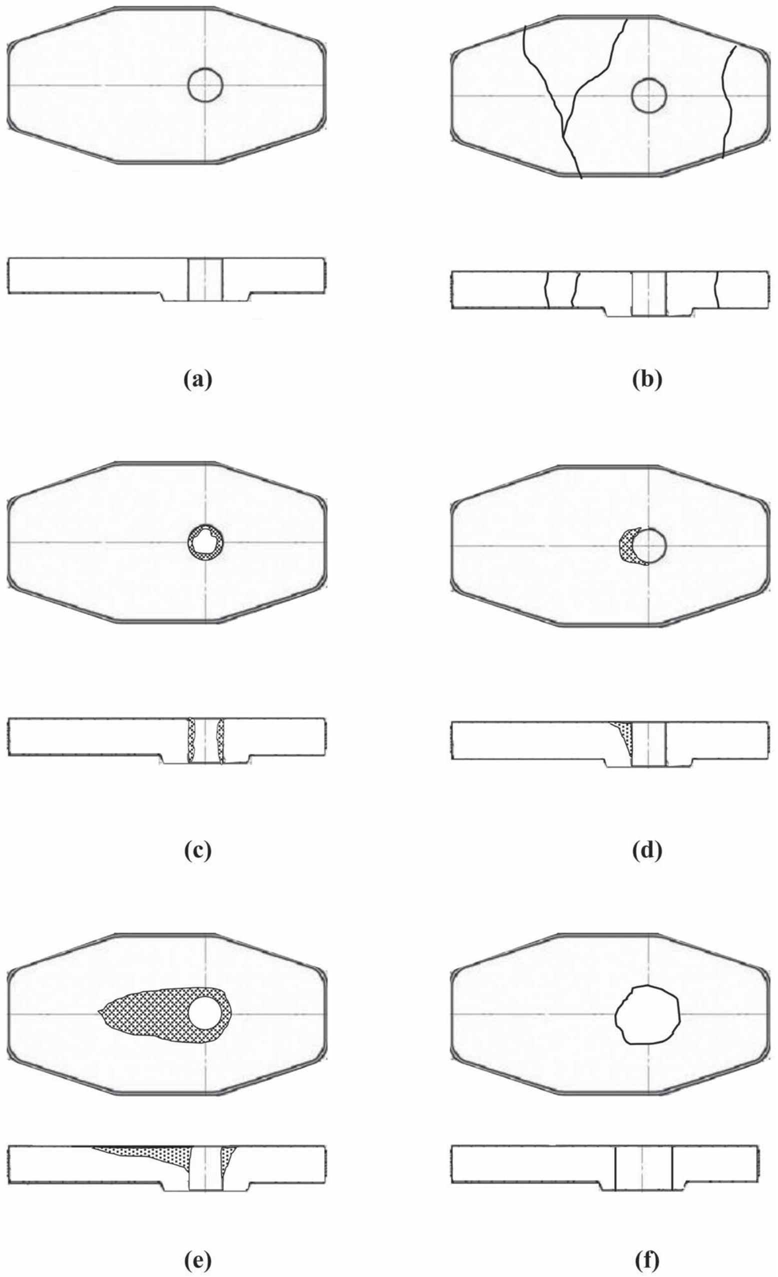


FIGURE 7.6 Schematic figure of a slide gate plate having different degradation effects: (a) original/unaffected plate; (b) effect of thermal shock; (c) clogging/deposition on bore wall; (d) chipping out, wear of bore due to throttling; (e) corrosion, erosion, wear-out along the stroke length, including the throttling effect; (f) wear and abrasion of the bore wall.

be discarded due to the enlargement of bore/hole diameter, which may be due to multiple factors:

1. Corrosion of the plates upon reaction with slag/inclusions present in steel
2. Formation of low-melting compounds and washing out of the portion
3. Weakening of bore or edges due to oxidation at the bore area (due to the presence of oxygen in steel)
4. Breaking out of the bore area refractory due to mechanical factors, like impact, abrasion, etc.
5. Chipping of the bore area due to thermal shock
6. Removal of bore contact refractory, along with the alumina build-ups, under the impact of flowing liquid steel
7. Excessive cleaning of the borehole by oxygen lancing post–steel tapping at the ladle pit, etc.

Hence, for the precise understanding of the degradation of the plates, root cause analysis and post-mortem study correlating with other steel processing and operational parameters are important, along with knowledge on refractory quality and properties, steel and slag chemistries, idea on inclusions present in steel even in ppm level, details of operating parameters, etc. All these will help narrow down the degrading factors and pinpoint the exact reason for failure. Accordingly, the necessary corrective measures, modifications, and improvements in the slide gate plates can be incorporated to overcome the failure.

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8 Ladle Shroud

8.1 CASTING OF STEEL: INGOT AND CONTINUOUS CASTING

The conversion of iron to steel (commonly called primary steelmaking) is done in a converter or a basic oxygen furnace. The formed steel is further processed for the removal of impurities and inclusions (to produce high-purity, high-quality clean steel) or for making alloys by different techniques, called secondary steelmaking. Once the desired composition (including impurity level) and properties of steel are attained by different steel processing techniques, the molten steel is then cast and solidified. Casting is the process of pouring the liquid metal into moulds to provide a specific shape and further cooled to solidify. Certainly, the faster process of casting improves productivity. For steelmaking industries, two different types of casting processes are available, namely, ingot casting and continuous casting.

Ingot casting is a batch process of creating solid ingot shapes from processed molten steel. The molten steel is poured into an ingot mould, which then cools down and solidifies within the mould and finally, the solidified ingot shape is obtained by dismantling the mould. It was the only possibility for the casting of steel for more than 100 years, till the introduction and widespread use of the continuous casting process in the 1960s. Commonly, refractory-lined cast-iron moulds of various cross sections (like square, round, etc.) and dimensions were used for ingot casting as per the requirements of the end user. During the very early days, the pouring of molten steel from a ladle was done by the top pouring technique, which later was modified to bottom pouring for multiple benefits, like a reduction in cast defects, improved cast surface finish, increased mould life, etc. Refractories involved for ingot casting were generally fireclay, high-alumina, and bauxite-based ones.

The continuous casting process is a later-developed technique wherein the molten steel is cast continuously, even up to an infinite dimension in length. Sir Henry Bessemer has proposed the concept of continuous casting of steel in 1846 and also received a patent in 1857 for continuous casting molten metal using two counter-rotating rollers. But to make the concept commercially viable and successful, it took more than a hundred years. That, too, the first successful continuous casting technique, has started for non-ferrous metals in the 1930s. The first pilot plant for continuous casting of steel was established in Germany in 1943, and by the 1970s, the process became known worldwide. Slowly popularity was gained, and in today's world, about 95% of total steel produced is cast through the continuous casting process.

In continuous casting, the liquid steel is cast through a special mould and then solidified to semi-finished shapes and dimensions (similar to ingot casting). Commercially, three major shapes are made by steel manufacturers, namely, billet, bloom, and slab. The billet shape has a square (rarely round) cross section, with the dimension of one side up to 150 mm. The bloom shape has a square/rectangular

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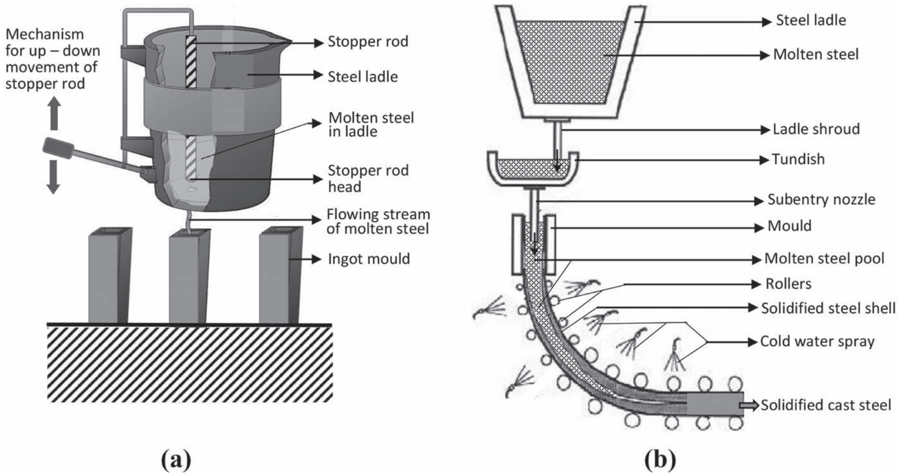

FIGURE 8.1 Schematic diagrams of the casting of steel: (a) ingot casting; (b) continuous casting.

cross section having a side dimension bigger than billet's and up to 300 mm, whereas the slab shape has a flat rectangular cross section with width around 800–1,200 mm and thickness around 150–250 mm. These semi-finished shapes are further processed to get the desired finished commercial products in the finishing mills. The major advantages of the continuous casting process are listed in what follows:

1. Direct casting to finished product shapes possible
2. Increased productivity, increased efficiency, and reduced labour requirements
3. Nearly no material loss, improved yield, economic process
4. Improved and consistent quality of steel, with minimum casting defects
5. Increase in energy efficiency and a reduction in operational costs
6. Operation-friendly and environment-friendly (reduced pollution) compared to ingot casting
7. Greater control on casting due to higher automation

However, it also has a few drawbacks, like huge capital investment and less flexibility in the process. So continuous casting may not be suitable for any special steel quality and for the requirements of a lesser quantity of steel. Schematic diagrams for both the ingot and continuous casting process are provided in Figure 8.1.

8.2 TUNDISH AND CONTINUOUS CASTING REFRACTORY

In the continuous casting process, molten steel is cast continuously. The source/reservoir of molten steel also needs to supply the molten steel continuously and so has to have an infinite amount of steel in stock. But after steelmaking, the molten steel is stored in a ladle and cast from the ladle, which has limited capacity. So to make the continuous casting process feasible, another buffer stock reservoir/holding bath of molten steel is introduced in between the steel ladle and the casting mould, called the tundish. The *tundish* is the last vessel in the steelmaking process, before the solidification of steel through the continuous casting mould. So it is important to feed the desired quality of molten steel to tundish in terms of composition, temperature, and cleanliness.

The tundish, a refractory line vessel, acts as a reservoir of molten steel to feed the casting moulds continuously even during the period when the stock of molten steel is exhausted in one ladle and casting is switched over from another ladle. Thus, it plays a major role in continuous casting as a buffer stock of molten steel to run the casting process uninterruptedly. The tundish has multiple layered refractory linings, and at present times, it is mostly lined with unshaped refractories. The hot face is lined with basic spray mass or dry vibratable mass, backed by the permanent lining of a high-alumina castable and followed by insulating refractories. Other than acting as buffer stock of molten steel before casting, the tundish also performs various activities, like the following:

1. Reduces the turbulence of molten steel flow to mould
2. Helps in the regulation/control of the metal feed to the moulds
3. Helps in the separation of non-metallic (oxide) inclusions and the further cleaning of steel
4. Improves thermal and chemical homogenization of steel
5. Helps maintain a steady height of molten steel (also a uniform ferrostatic pressure) flowing to the mould, thus keeping the steel flow rate constant
6. Provides steady and stable molten steel flow patterns to the mould

To facilitate the continuous casting process through the tundish, a few special refractories are also introduced with time. Among them, the ladle shroud and subentry nozzle (or subentry shroud) are refractory tubes that are used for the guided transfer of molten steel from the steel ladle to tundish and from tundish to casting mould, respectively. Another refractory item, called the monoblock stopper, or stopper rod, has been introduced to control the flow of molten steel from tundish to mould. Highly automated advanced steel plants (and countries) use three plate-based slide gate refractories for this flow control, which is not very common and simple too.

All these refractories are essentially required for the continuous casting of steel and are commonly called continuous casting refractories (CCR). Different types of refractories that are commonly used for the continuous casting of steel, starting from the steel ladle to the casting mould, including the continuous casting refractories, are shown schematically in Figure 8.2. As the CCRs are in intimate contact with molten steel during application, they contain carbon (for non-wetting character) as one of the components and appear black in colour, so these refractories are also called black refractories. All these refractories are strongly resistant to corrosion, thermal shock, abrasion, and wear and have high thermal and volume stability and high hot strength, etc. These refractories are composite in nature, commonly containing at least one oxide (like Al_2O_3, MgO, ZrO_2, etc.) and carbon, with multiple numbers of

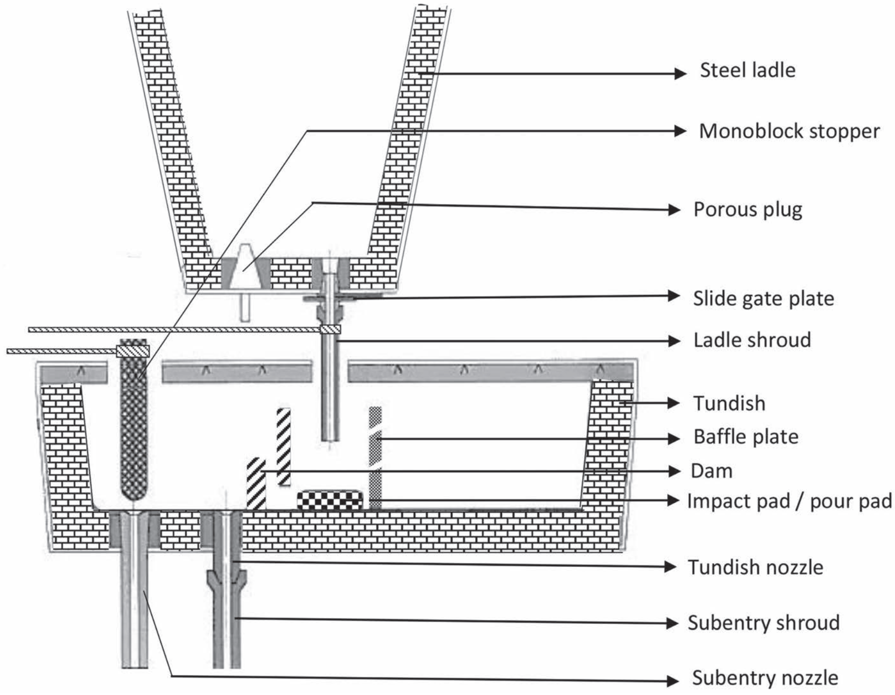

FIGURE 8.2 Different types of refractories especially required for continuous casting of steel.

property-enhancing additives. The different advantages of using carbon in all these refractories are as follows:

1. High refractoriness, no softening, no low-melting phase formation
2. Very low thermal expansion, providing excellent volume stability even at high temperatures
3. Very high thermal conductivity; transfers heat easily and minimizes any thermal gradient and thermal strain
4. Low thermal expansion and high thermal conductivity, resulting in excellent thermal shock resistance.
5. Carbon molecules have strong covalent bonding, do not react easily (other than oxidation), and so carbon does not wet by liquids. This non-wetting character provides excellent corrosion resistance against molten metal and slag.
6. Graphite, the major carbon source, has a low modulus of elasticity, so it accommodates strain without much deformation, thus reducing the discontinuous wear due to strain/crack. Also, a low elastic modulus makes the refractory less rigid, deformable and, in turn, improves spalling resistances.

In general, all the CCRs are cured/tempered (products, not fired/sintered) to avoid any oxidation of carbon. Again, to develop the required strength at high temperatures, resistance against corrosion and abrasion, and the development of other important properties within the refractory, different steps are incorporated. Namely, compositional adjustment, the addition of additives for in situ high-temperature bond formation (like metal powder antioxidants), control on granulometry, reduction in pore size, greater and uniform compaction (use of isostatic pressing), use of highly fixed carbon-containing resin and use of a catalyst (to graphitize the nascent fixed carbon developed from resin), etc. Hence, refractory compositions, processing, etc. of all the CCRs are important for the properties development, performance, and service life.

8.3 INTRODUCTION TO LADLE SHROUD AND ITS FUNCTION

The worldwide steel production is nearing about 2000 million tons and more than 95% of the steel is being cast through the continuous casting process. The continuous casting (CC) process is highly successful mainly due to its high efficiency, productivity, and cost-effectiveness. In the continuous casting process, the ladle shroud is an essential refractory component, appearing like a cylindrical-shaped refractory tube used for feeding molten steel from a ladle to a tundish. The main purposes of a ladle shroud are listed in what follows:

1. To shroud (covered) the transfer of molten steel from the ladle to tundish
2. To minimize the chances of heat loss
3. To prevent oxidation of the molten steel
4. To restrict any nitrogen pickup by molten steel up on exposure to open atmosphere
5. To avoid any splashing of molten metal and reduce turbulence during transfer
6. To maintain laminar flow of the molten steel in tundish and a reduction in slag trapping in molten steel.

These benefits have helped steel manufacturers use the ladle shroud and contribute in improving the quality of steel. Also, it helps attain the desired properties in the cast steel products by ensuring the laminar flow of the molten steel within the tundish, reducing in the entrapment of slag within steel and producing cleaner steel. The performance of the continuous casting process is closely related to the flow behaviour of molten steel within tundish, and the ladle shroud has control on the characteristics of the flow of molten steel stream in the tundish. The turbulence kinetic energy of flowing molten steel stream within the ladle shroud is high, and this turbulent behaviour is controlled/reduced within the tundish during the transfer of molten steel through the ladle shroud. Hence, the ladle shroud plays an important role in controlling the flow within the tundish and also on the total casting process.

8.4 BACKGROUND AND INITIAL DEVELOPMENTS

The continuous casting process for steelmaking has become popular since the 1970s. During the early days, crisis of re-oxidation and increased gaseous inclusion in the molten stream of steel were also observed while flowing from the ladle to the tundish, thus affecting steel quality. Techniques like high-speed cine-photography and improvised, still photography were used for critical observation of the flowing stream. Rough (non-uniform), irregular, discontinuous, teeming steel stream with splashing was also reported to have caused uneven turbulence within the molten steel pool in the tundish. Studies confirmed that the prime factors for such disturbances in flowing stream were the flow pattern of molten steel within the ladle, height of the teeming stream, stream turbulence, viscosity, surface tension of the molten steel, etc. The final steel products were found to be defective due to air pickup, re-oxidation, and even slag entrapment. To avoid these difficulties, the shrouded pouring of molten steel from ladle to tundish was planned, and the water model experiments produced calm and confined flowing stream with much reduced turbulence in the tundish.

During the initial developments for the shrouded flow of molten steel from ladle to tundish, two different approaches were tried by steel technologists. One is shrouding by inert gas only (mostly argon) to fully cover the flowing molten steel stream to avoid any contact of molten steel with ambient air. The second one is shrouding by the use of a refractory pipe (ladle shroud) that isolates the molten steel completely from the outside environment, and submerged transfer of molten steel within the metal pool of the tundish. Argon gas shrouding was effective in controlling the flow behaviour and restricting the re-oxidation and gaseous entrapment of molten steel, but the process was not user-friendly, not economic, and has possibilities of argon pickup by steel. Further, if the ladle slag is carried over with the teeming molten steel stream, the shrouding gas stream may emulsify the slag within the molten steel, causing serious slag inclusion problem. These issues have made the only gas shrouding option unpopular and finally discarded.

On the other hand, the refractory ladle shroud envelops the molten steel stream in a straight flow channel. After the initial developments, during the early days, the commercial ladle shrouds were about 4 to 6 ft long, made up of fused silica-based refractory compositions. During application, the top end of the shroud was held mechanically at the bottom of the ladle (collector) nozzle, and the bottom end was submerged into the molten steel pool within the tundish. From the initial studies itself, the use of ladle shroud was highly successful, especially in reducing the re-oxidation and gaseous entrapments of steel and controlling the turbulence effect significantly. The surface quality of the cast steel was far superior to that of non-shrouded steel transfer, and the average oxygen content was reduced considerably.

The ladle shroud is also known as shrouding pipe, pouring tube, or long nozzle due to its shape, appearance, and function. Though it appears as a simple refractory tube/pipe, in the whole continuous casting process, it plays an important role in the overall casting process and quality of steel. The ladle shroud has been developed to shield the molten teeming stream of steel from atmospheric effect/contamination and a guided movement for flow from steel ladle to tundish. The introduction of ladle shroud has helped overcome the difficulties during the initial days of the continuous casting process, like re-oxidation and air pickup of molten steel, macro inclusions affecting the cast steel quality. The bowl- or cup-shaped upper end of the ladle shroud is held externally at the exit port of the collector nozzle (Figure 8.3). The lower part of the collector nozzle enters/sits at the open end of the shroud cup, which is positioned and held by a mechanical arrangement called manipulator (Figure 8.4). During operation, the shroud (which is held and fixed at the bottom of the collector

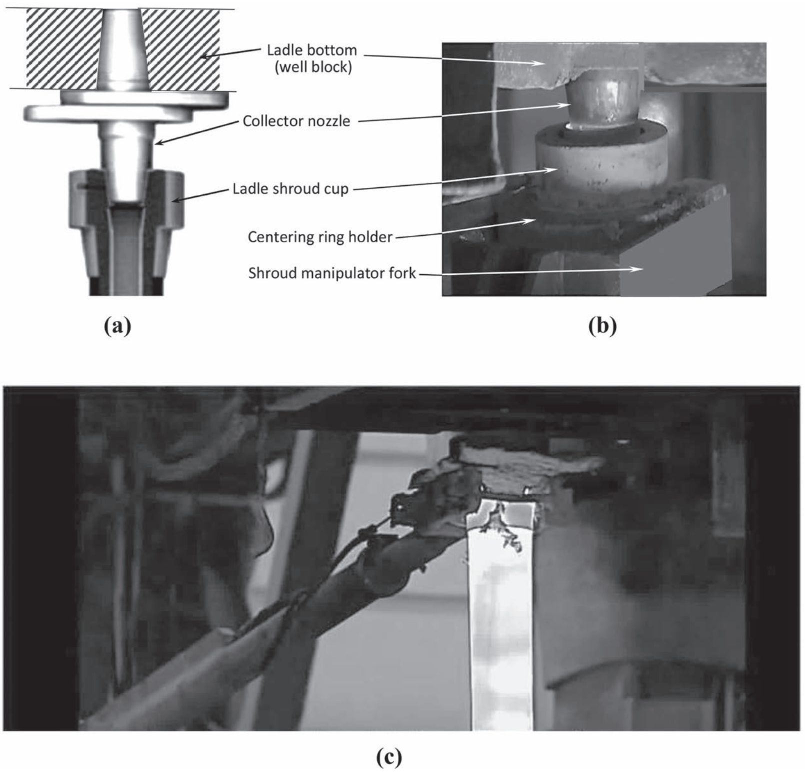

FIGURE 8.3 Joining of ladle shroud cup portion with the collector nozzle of slide gate refractory: (a) schematic figure; (b) actual product in cold condition; (c) actual product during operation.

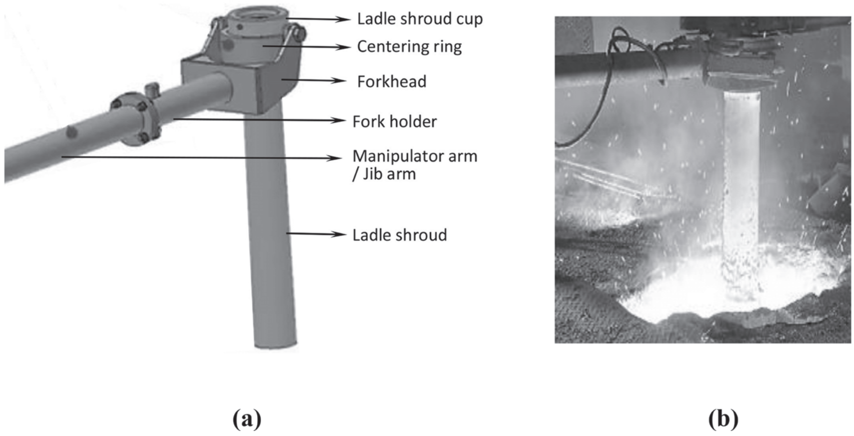

FIGURE 8.4 Manipulator holding the ladle shroud: (a) schematic drawing; (b) actual products during operation.

nozzle externally) is moved/vibrated by a hydraulic mechanism connected through the manipulator. In some special cases, argon gas is injected through the gas port in the upper end (cup) of the shroud for better shrouding effect and producing cleaner steel. Molten steel stream with injected argon gas moves downwards and enters the molten steel bath in the tundish, where the argon gas bubbles rise due to buoyancy effect and come out from the top surface opening of the tundish.

8.5 COMPOSITIONS AND ZONES OF LADLE SHROUD

Fused silica–based ladle shrouds were initially tried to achieve higher thermal shock resistance for its extremely low thermal expansion property. However, during use, these ladle shrouds were found to be acceptable, but not great. These shrouds have an average life of 2 to 2.5 heats. Fused silica has a lower thermal conductivity value (also important for thermal shock resistance), does not have good mechanical properties, and is chemically weak against basic steelmaking conditions. So fused silica–based shrouds could not perform for a longer period of time. As the refractory for the ladle shroud requires high thermal shock resistance along with excellent mechanical and chemical properties, alumina-based compositions in combination with graphite (carbon) and some amount of fused silica were tried next. The presence of graphite is important for excellent corrosion and thermal shock resistance. Corrosion resistance has also been improved by controlling the grain size distribution, the Al_2O_3-to-SiO_2 ratio, and the oxides-to-graphite ratio in the composition.

With the progress of time, cleaner and high-purity steels are in demand, which makes the steelmaking process highly basic in nature. Also, processes like killing, Ca treatment, etc. are also incorporated. So the presence of acidic silica as component in ladle shroud composition has been removed completely by many manufacturers. Also, corrosion resistance is improved by using phenolic resin, replacing the conventional pitch binder. Resin-bonded ladle shrouds show various advantages, like dense texture, smaller pore size, higher oxidation resistance, higher bonding strength, and excellent corrosion resistance. To prevent the oxidation behaviour of carbon, metallic powder additives (mainly Al and Si metal powders) are added along with the batch constituents during mixing. This also improves the hot strength of the shroud due to the formation of in situ ceramic phases (metallic carbides) at high temperatures.

Again, during operation, the ladle shrouds are exposed to the open atmosphere while containing molten steel stream inside (with temperature above 1,600°C) it. So the carbon present at the outer (air contact) surface is highly prone to oxidize even in the presence of metallic additive antioxidants. To prevent the oxidation, a special coating, containing an oxygen inhibitor, is used on the outer surface of the shroud. This coating consists of silica, which fuses during the preheating process, coats the refractory, and acts as a barrier between the shroud (graphite/carbon) and air (oxygen). Also, to insulate the shroud (reduce the temperature gradient between the inner and the outer surfaces) and to reduce heat loss through the walls during use, the shroud is wrapped with ceramic fibre/paper, which also improves the thermal spalling resistance. These improvised ladle shrouds, along with an upgraded alumina-graphite composition, structural design, and coating, improve the performance and service life of the shrouds significantly.

Conventionally, the ladle shroud has two zones, namely, cup and body. The uppermost portion of the shroud that is held fixed to the collector nozzle of the slide gate refractory at the ladle bottom is the cup. The primary function of the cup is to collect the molten steel and to pass the same downwards through the body of the shroud. Proper fixing of the cup with the collector nozzle is very important, as there is no fixture or arrangement to fix them and completely close (seal) the junction. Any air ingress through the joint between these two will lead to severe multiple crises, leading to the poor quality of cast steel. The cup portion faces primarily the mechanical impact of the molten metal flow and requires very high strength and resistance against erosion, corrosion, impact, etc. Refractories in the cup portion are also required to withstand the effects of the oxygen cleaning required to remove the steel skull developed below the collector nozzle. The standard ladle shroud has a cup composition with alumina content around 50%, silica between 15 and 20%, and carbon between 25 and 30%. To enhance erosion and impact resistance, zirconia is commonly added to the composition up to about 5%.

The rest of the part of the shroud other than the cup is commonly called the body. It is the tube/pipe portion that carries the molten metal downwards to the tundish smoothly without much turbulence. It is a major part of a shroud, and the functions of the shroud are actually performed by the body. The body needs to be resistant against the erosion and corrosion effects of the molten steel flow and, most importantly, must resist the thermal shocks. It faces the greatest temperature gradient, contains molten steel (at ~1,600°C) within it while facing the ambient environment on the outer surface.

The standard ladle shroud has a body composition of alumina around 50%, silica between 10 and 15%, and carbon in the range of 30 to 35%. For an improved thermal shock resistance, the body composition is modified with alumina content between 45 and 50%, silica between 18 and 20%, and carbon between 25 and 30%. Again, for high-performing shrouds, the standard composition is modified to high-alumina ones, with alumina content between 60 and 65%, silica between 5 and 7%, and carbon in the range of 25 to 30%. To improve the performance and enhance the service life of the shrouds, the use of the zonal lining concept is also practiced. Like, to enhance the mechanical properties of the shrouds, the cup lining is made by refractory composition different to that of the shroud body portion, where thermal shock resistance is more important. Again, for improved corrosion resistance of the shroud, particularly for the zone that is in contact with the tundish slag/tundish powder, the composition is modified by removing the silica completely and making the lining with alumina-graphite or Al_2O_3-MgO system.

8.6 TYPES OF LADLE SHROUD

The conventional tube-shaped ladle shroud has been modified from multiple aspects with time for the betterment, and at present, different types of shrouds are being used commercially and successfully. The classifications of the ladle shrouds based on various aspects are detailed in what follows.

8.6.1 CLASSIFICATION AS PER DESIGN/SHAPE

The most common and widely used ladle shroud appears to be a simple tube with straight inner bore and having a wider dimension at the top end. This *conventional Y-shaped ladle shroud* (Figure 8.5a) has the advantage of a concentric flow of molten steel from the ladle to the tundish. These conventional shrouds are gradually replaced by new types and designed products for better performance and service life. The next improved design and commercially successful ladle shrouds have an enlarged bore diameter at the exit end, exactly opposite to that of the conventionally designed shrouds. These modified shrouds have outperformed the conventional ones, primarily due to better control on flow of molten steel. The modified ladle shroud with gradually enlarged diameter along the length is called the *reverse tapered shroud* (Figure 8.5b). The increased bore diameter along the flow direction reduces the backfire of molten steel during flow, and also the turbulence within the tundish. Further modified design of the ladle shroud has an increased diameter at the exit end, having a divergent chamber and a straight end with a larger diameter. This type of ladle shroud is called *bell-shaped/trumpet-shaped ladle shroud* (Figure 8.5c). This bell-shaped shroud helps reduce the backfire of molten steel during flow, minimizes inclusion entrapment, ensures a smooth flow of molten steel, and reduces turbulence.

The improved design ladle shrouds are reported to be beneficial from both a steel quality and a productivity point of view. They help reduce nozzle clogging, nullify the chance of flowbacks during ladle changeover, and thus improve the efficiency and productivity of the casting process, and help improve the flow behaviour of molten steel within the tundish, decrease the chances of slag entrapment, and improve

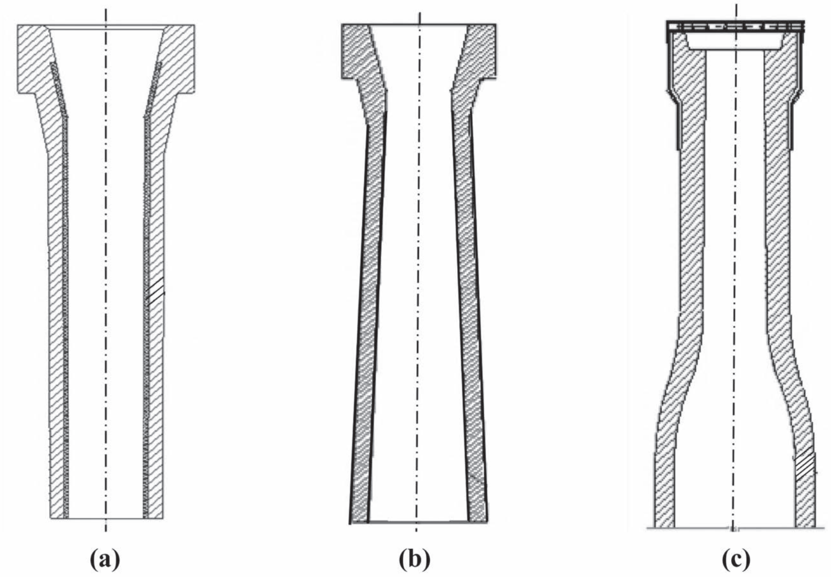

FIGURE 8.5 Different designs of the ladle shroud: (a) conventional/standard (Y-shaped); (b) reverse tapered; (c) bell/trumpet-shaped.

the quality of the cast steel. The greater diameter at the outlet end of the shroud significantly reduces the jet velocity of molten steel while it enters into the tundish. This reduces the turbulence, both in the ladle shroud and in the pouring zone of the tundish, which, in turn, reduces the erosion of the refractory. A reduction in turbulence also improves the flow behaviour of molten steel within the tundish, decreases the chances of slag entrapment, and overall gives improvement in the quality of steel.

8.6.2 As per the Connection with the Collector Nozzle

During application, the ladle shroud is externally held exactly at the bottom of the collector nozzle by a mechanical support system, called the manipulator. The dimensions of the collector nozzle and the shroud cup are maintained in such a way that the nozzle enters and fits exactly in the cup portion. The shroud is held by the centring ring of the manipulator just below the cup portion. The centring ring is placed in a forkhead which is connected to the fork holder. This, again, is connected to the manipulator arm/jib arm, which is connected with the main support system operated by a hydraulic or pneumatic mechanism (Figure 8.4). The whole manipulator system allows the shroud to move up and down, slew, rotate, etc. and helps it press and fit against the collector nozzle. It is important for the flow of steel that the shroud fit perfectly at the collector nozzle, with the proper sealing of the joint. This joining between the collector nozzle and the shroud cup is important for the functioning of the shroud, which is mainly done by two different connection mechanisms.

8.6.2.1 Standard/Conical Connection

Both the collector nozzle and the cup part of the ladle shroud are in conical contour, and the collector nozzle exactly fits in the conical-shaped contour of the inner side of the cup of the shroud (Figure 8.6a). The outer conical contour of the collector nozzle exactly matches with the inner conical contour of the cup part of the shroud. Due to the conical-shaped connection, a larger area of the surface gets coupled at the junction between the two refractory components, which helps in a better coupled movement of the shroud with the collector nozzle (slide gate bottom plate) and ensures good sealing. However, the forces for coupling act as tensile forces on the cup and any ceramic or refractory that is weak in tension. This causes a limitation for such connection, and typically, the conical coupling is used for lower coupling forces, commonly below 250 kg.

8.6.2.2 Butt Connection

This connection between the collector nozzle and the ladle shroud cup portion is done through a flat resting surface after the conical contour. It is difficult for a complete matching and coupling between the two mating surfaces of the collector nozzle and the shroud cup in a conical connection. Coupling becomes further difficult at high temperatures due to the thermal expansion effect and compositional differences. These difficulties in coupling are improved in case of a butt connection, where the flat bottom face of the collector nozzle sits on the flat step-like contour at the inner side of the cup portion of the shroud (Figure 8.6b). A high coupling force

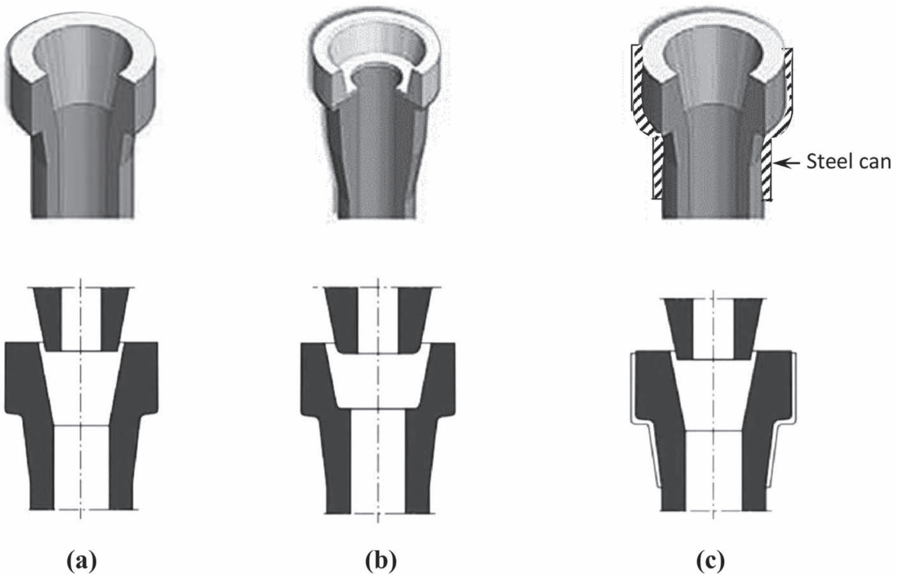

FIGURE 8.6 Different designs of ladle shroud cups: (a) standard/cone design; (b) butt design; (c) metallic supported.

can be applied during operation, as both connecting components rest on each other through a flat surface and works under compression.

8.6.3 AS PER FLANGE DESIGN AND METALLIC CAN

During operation, the ladle shroud is held by the centring ring or support ring of the manipulator arm at the flange portion (junction between the cup portion and the main body), below the cup region. The force to hold the shroud tightly at the bottom of the collector nozzle is transferred by the centring ring to the flange portion of the ladle shroud. Hence, the design of the flange region of the shroud is important for holding the complete shroud and for a smooth, continuous casting operation. The flange portion of the shroud can have different designs to hold the complete shroud and to accommodate the mechanical stresses developed due to the flow of metal. The initially designed and conventionally used design of the flange, which appears *T-shaped*, called the *T flange* (Figure 8.7a), is still in use but has certain limitations. At high coupling forces (>250 kg), the sharp corner of the design (T shape) causes crack and failure of the shroud. The design is modified by the *Y-shaped flange* (Figure 8.7b), wherein the sharp corner is avoided and the load is distributed along the flange length. Hence, a higher coupling load can be used, and the design holds the shroud strongly and seals the gap (between the collector nozzle and the shroud cup) better. This Y-type flange is essential for ladles with higher capacity, as higher forces are required for positioning and holding the shroud. But for the Y-shaped flange, the centring ring has to hold the shroud at a conical (angular) surface, which causes operational difficulty. To optimize the conditions for shroud holding and the application of a higher coupling force, a mixed design of the flange has been

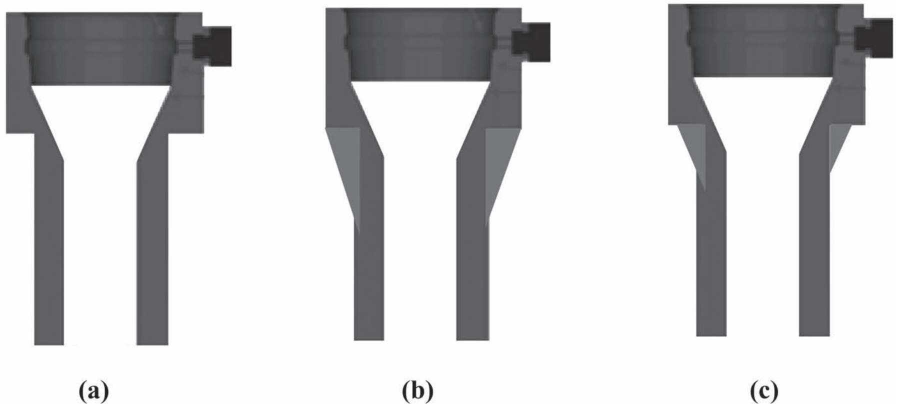

FIGURE 8.7 Different flange designs of the ladle shroud: (a) T-shaped; (b) Y-shaped; and (c) T-Y-shaped.

introduced, wherein both the T and Y designs are clubbed together, the *T-Y-shaped flange* (Figure 8.7c). The selection of the type of flange to be used at a particular casting process depends upon the operational parameters and conditions prevailing in the steel casting shop.

As the whole ladle shroud is held mechanically at the flange portion by the manipulator, the flange portion has to bear the whole weight of the shroud. Further, during operation, the impact of metal flow, thrust, mechanical effects and turbulence of flow, etc. is also added. Due to these effects, there are high chances that the refractory at the flange portion will crack/collapse during operation. To support the whole shroud, the flange region is mechanically reinforced/supported by using a metallic can (fitted and fixed at the outer wall of the shroud by mortars) to cover the complete cup and flange portion (Figure 8.6c). This metallic can helps distribute the mechanical stress over the whole can-covered region, reduces the stress concentration at the manipulator-held flange area, and protects the shroud from mechanical failure.

8.7 DEGRADATION OF THE LADLE SHROUD

In the continuous casting process, molten steel coming from the steel ladle passes through the slide gate plates, then flows down through the collector nozzle to the top part (cup) of the ladle shroud. It flows down inside the shroud under the gravitational force and comes out through the free opening at the bottom side of the shroud immersed within the molten steel pool in tundish. This flow of molten steel and the application environment affect the performance of the ladle shroud refractory and degrade it from multiple aspects, as detailed in what follows.

8.7.1 BREAKAGE

The ladle shroud is mechanically held from outside by the manipulator at the cup portion of the shroud, whereas the rest of the part is free and unsupported. Moreover, the bottom part of the shroud is free, submerged inside the molten steel bath of the tundish, and faces the impact and turbulence of the molten steel flow and its turbulence within the tundish during casting. Further, the shroud is also under the mechanical impact of the slide gate plates' throttling movement and the down-flowing molten steel stream that cause continuous impact, vibration, jerking, and extreme mechanical stresses. Again, all these different mechanical stresses are acting at different directions on the shroud and at extremely high temperature during use. Also, the flow of the molten metal stream causes corrosion, impact, wear, abrasion, erosion, etc. on the inner surface (refractory) of the shroud. The shroud also experiences extreme thermal gradient during use. Thus, breakage of the ladle shroud under these different mechanical stresses due to crack formation is one of the most common failures. Commonly, the breakage occurs at the junction between the rigidly held portion and the free-hanging portion (joining portion of the cup and the body, called the cup breakage) that is just below the portion where the centring ring is holding the shroud. Vertical cracks along the body are also common, which are primarily due to thermal shock. Shrouds also fail at its lower part (bottom portion) under mechanical stresses due to the multidirectional flow of molten steel (downwards within the shroud, and at different directions on the outer face wholly submerged in the metal pool within the tundish). A reduction in the chances of breakage failure can be attained by attaining a higher strength and better compaction of the shroud, by preheating the shroud before use and also by coking (firing in reducing atmosphere) of the shrouds during its manufacturing stage.

8.7.2 EROSION

The upper part of the shroud also suffers from local erosion due to drift flow, the throttling of the slide gate plates, and also the closing of the plates at the end of the ladle casting. This local erosion causes the removal of the refractory at the upper part, which may cause suction of air through the joint between the collector nozzle and the cup part. To prevent any air ingress, proper sealing at the upper joint of the ladle shroud is necessary for an improved performance and life. Again, during application, the shroud is under constant vibration as per process requirement to avoid any sticking of molten steel, for better flow and casting. The vibration is detrimental for the bottom part of the shroud, submerged in molten steel bath in the tundish, due to the different directional flow of molten steel within the shroud and within the tundish.

8.7.3 CLOGGING/BUILD-UP

Commonly, the ladle shroud is made up of an alumina-based composition that increases the chances of alumina build-up on the inner wall, especially for the Al killed steel. Any build-up or clogging in the steel contact inner wall of the shroud reduces the opening of the shroud, reducing the flow of molten steel, affecting the molten steel flow pattern, causing turbulence within the tundish, and finally, affecting the cast behaviour of molten steel. The chemical affinity of the fine free alumina particles present in molten steel (generated due to the Al killing process) towards the alumina present in the ladle shroud refractory composition (as major component) is the cause of the build-up and clogging.

This alumina build-up can be prevented by using a mullite-containing (having silica) composition for the inner layer of the shroud composition, which produces viscous alumina-silicate phases with the deposited (built-up) alumina at the steel processing temperatures. Thus, the build-up formation can be easily eased out along with the flow of the steel. Also, the build-up tendency can be reduced by using an inner lining with a basic refractory (like CaO-MgO), which will form low-melting phases with the built-up alumina particles and will be washed away easily along with the flowing molten steel. Further, the introduction of argon purging along the inner wall of the shroud prevents the contact between the free alumina particles present in molten steel and the shroud's inner wall lining, thus restricting the deposition of alumina and any clogging tendency.

8.7.4 CORROSION

The degradation of the shroud due to chemical wear-out in contact with molten steel is dependent on steel chemistry and steel grades. Steel compositions containing high oxygen, calcium, silicon, etc. are more corrosive for the shroud refractory. High-oxygen-containing steel has a higher oxygen potential, causing the oxidation of the carbon of the refractory. High-Ca-containing steel reacts with the alumina present in the shroud refractory forming low-melting calcium aluminate phases and wash the refractory out along with the flow of the molten steel. The inner layer of the ladle shroud in contact with the molten steel needs to be strong to withstand corrosive effects. Like, for high-Ca-containing steel, the inner layer of the shroud (steel contact refractory) should be basic in nature, like the MgO-based or MgO-CaO-based ones. Avoiding the use of alumina-based compositions will reduce/nullify the low-melting-phase formation and washing away of the layer. Also, the outer layer of the bottom portion of the shroud (precisely the top part of the submerged portion) is highly prone to corrode by the tundish slag and the tundish cover powder. Special attention is required for this zone, and using a corrosion-resistant slag band refractory is commonly practiced to resist degradation.

8.7.5 OXIDATION

The chance of air infiltration in the shroud cup portion through the joint between the cup and the collector nozzle is high during throttling and closing of the plate after each heat. This may cause local oxidation and loss of the refractory in the cup portion, degrading the shroud. Hence, proper sealing, use of gasket, argon purging, etc. need to be properly functional. Also, oxidation occurs at the shroud outer surface (above the submerged portion within the tundish) due to the exposure of the refractory to the open environment during operation (at high temperatures). This can be prevented by using an oxidation-resistant special coating/glaze that protects the shroud from direct contact with air in the open environment.

8.7.6 GRADE OF STEEL

The degradation of the ladle shroud is also dependent on the grade/type of steel being produced/cast. Wear rate is higher for certain grades of steel, depending on the minor constituents present in the steel chemistry. Like, high-oxygen-containing steel degrades the shroud faster due to the oxidation of the refractory (containing carbon) in contact with molten steel; high-Mn-containing steel reacts fast with refractory oxides; etc. The compositional adjustments of the inner layer of the shroud as per the steel grades improve the performance of the shroud.

8.7.7 Sticking

The upper part/cup portion of the shroud may stick to the collector nozzle if the molten metal can enter in any gap between them and gets solidified due to cooling from ambient air/environment. Such sticking will not allow the free movement and vibration of the shroud and will lead to cracks and breakage of the cup portion during operation (due to vibration) or during ladle changeover. Proper sealing between the shroud cup and he collector nozzle is necessary to avoid such failures.

8.7.8 Carbon Dissolution

The presence of carbon in the metal contact surface of the ladle shroud refractory may lead to carbon pickup by steel, leading to a serious crisis in steel quality. Also, this leads to the removal of carbon from the refractory, leading to a porous structure, poor properties (especially hot strength and corrosion), and catastrophic failure of the refractory. Shroud inner lining composition without carbon can avoid such degradation.

8.8 TECHNOLOGICAL IMPROVEMENTS AND FURTHER POSSIBILITIES

Technological improvements of the ladle shroud resolve many of the challenges that it faces during use. In the initial days, the ladle shrouds were made up of fused silica and had an average service life between 2 and 2.5 heats. The main challenges that the initial shrouds faced were maximizing the shrouding effect, reducing the damage from thermal shock, and exploring multiple functions that would ease the continuous casting operation. Initial improvements were primarily targeted to improve the performance and service life of the shroud. The basic composition has been shifted from the fused silica–based system to an alumina–carbon system, providing significantly improved corrosion and thermal shock resistance. Improvements were also achieved with the introduction of suitable antioxidants, a change in structural design, the implementation of zonal lining, with the graded lining concept along the thickness, etc. These modifications and improvements have enhanced the reliability and performance of the shroud and increased its life for more than 10 heats. Some of the technological improvements that have been successful in improving the performance of the ladle shroud are detailed in the following.

8.8.1 Argon Gas Purging

As the metal flows down from the ladle to the tundish, there remains a pressure gradient due to the downwards flow of molten steel. The upper part of the shroud is present at a lower pressure than that of the bottom part. This Venturi effect, due to the flowing steel stream inside the ladle shroud, causes an air ingress through the junction between the collector nozzle and the shroud cup portion, which leads to reoxidation of the molten metal and nitrogen pickup. Rigid fixing of the shroud at the collector nozzle is not possible to accommodate various processing requirements, so design modifications have been attempted to restrict the air ingress, but none was found to be foolproof. A minute opening at the junction crevices between the collector nozzle and the ladle shroud remains the challenge in achieving a seamless sealing that can protect the metal stream fully.

In the design modification of the ladle shroud, an argon-purging arrangement has been incorporated at the top part of the shroud. Argon gas is introduced (purged/injected) at the cup portion of the shroud through an opening at the outer side wall of the ladle shroud. The argon gas comes in contact with the flowing molten steel through the openings at the inner wall of the shroud cup portion. The inject pressure of purged argon gas compensates the negative pressure inside the shroud due to the downwards flow of molten steel. The injected argon gas covers the metal stream and creates an argon seal around the junction (cup–collector nozzle) to push away any air ingress within the shroud. Thus, the air ingress is restricted during the steel flow. The purged argon gas shields the metal stream, moves downwards with the molten steel through the ladle shroud, and gets transferred to the metal pool in the tundish. Due to the buoyant forces in the tundish, argon gas (as bubbles) moves upwards and reaches the upper surface of the molten steel pool in the tundish and finally moves out to the open environment. Hence, in the modern continuous casting process, the use of both refractory shroud (mechanical shrouding) and argon purging (gas shrouding) is in practice to improve the shrouding performance, productivity, quality of cast steel, and service life of the shroud refractory.

The different benefits of argon purging in the ladle shroud are listed in what follows:

1. It compensates the negative pressure generated due to the downwards flow of molten steel inside the shroud, thus restricting any air ingress tendency.
2. It creates a sealing with an argon barrier at the cup–collector nozzle junction to prevent any air infiltration.
3. It completely covers/shields the flowing metal stream, nullifying any chance of oxidation, nitrogen pickup, etc. Figure 8.8 shows a comparison of nitrogen pickup by molten steel under different flowing conditions in the ladle shroud and the effectiveness of argon purging/shielding.
4. It helps eliminate impurities in the tundish by floatation while rising to the tundish top surface after being transferred to the tundish, along with the steel stream through ladle shroud.
5. It influences the multiphase flow.

The effectiveness of argon purging depends on various factors, namely, the size of the argon bubble, the trajectories of the bubbles, the argon gas purging pressure and volume, the mode of argon purging, etc. Smaller-sized bubbles are more efficient in the removal of inclusions, whereas bigger-sized ones reduce the collision efficiency

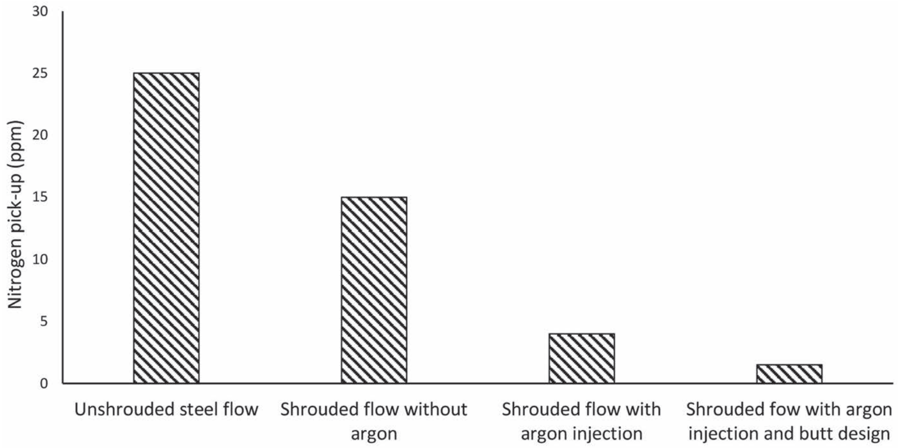

FIGURE 8.8 Comparison of nitrogen pickup by molten steel under different transfer conditions from ladle to tundish.

within the shroud due to the coalescence of the bubbles. Again, the size of the bubble is dependent on the gas inlet diameter, the characteristics of the molten steel, the flow rates of argon gas and molten steel, etc. A high flow rate of molten steel with a lower flow of argon gas produces smaller-sized bubbles, whereas the low speed of molten steel at a high flow rate of argon gas produces bigger-sized bubbles. The rapid downwards flow of molten steel within the shroud generates high shear rates with turbulent kinetic energy that helps in forming smaller bubbles.

The introduction of argon purging in the ladle shroud also affects the behaviour of the slag present in the tundish. The molten steel stream containing the argon bubbles flows down vertically through the ladle shroud to the tundish, and the argon bubbles, after reaching the molten metal pool within the tundish, float upwards (reverse direction) due to the buoyancy effect within the tundish. This sweeps off the slag layer at the top of the tundish bath, leading to a tundish eye formation, exposing the molten metal to the open atmosphere. An increase in argon purge volume increases the area of the tundish open eye and increases the chances of metal re-oxidation and cooling. Again, the bigger-sized argon bubbles cause a greater extent of slag open eye and increase the chances of molten steel oxidation. But relatively finer bubbles produce a smoother flow and reduce the impact of the reverse flow (upwards direction) and the chances of tundish eye formation.

The higher flow rate of molten steel within the ladle shroud again produces a higher pressure difference between the inlet and the outlet of the ladle shroud that increases the chances of air ingress through the joining between the shroud cup and the collector nozzle. Again, due to the demand for higher productivity, commonly a higher casting speed is used, resulting in a greater pressure difference. Thus, an improved argon purging system is essential to accommodate the greater pressure difference between the top and the bottom parts of the ladle shroud and for better prevention of air ingress.

Argon injection/purging of the ladle shrouds can be done by different modes/ways, and the shrouds are also classified as per the techniques of the introduction of argon gas to it. Commonly, the argon gas enters into the cup from outside through a tube connected to the inner channel, and the gas will be purged uniformly from all the sides of the inner wall of the circular-shaped cup portion, preventing any air ingress through the junction. In the "groove-type shroud" (Figure 8.9a), there is a continuous groove on the inner surface of the shroud cup, and the groove is connected to a tube that allows the argon gas to enter inside the shroud cup from outside. A uniform and continuous argon purging occurs all through the inner surface of the cup, preventing any chance of air ingress through the junction. In the "slotted/slit-type shroud" (Figure 8.9b), argon gas is purged through multiple slots present on the inner surface of the cup, which are again connected to a channel within the cup, and the channel is connected to the argon gas source. Further, to introduce the argon gas uniformly and in a continued manner through the slots from all sides of the shroud cup to the molten steel stream, a special porous refractory piece is used at the inner side of the cup, called "porous inserts" (Figure 8.9c). The insert passes the incoming argon gas (from outside) uniformly through it to the cup–collector nozzle meeting surface, where it covers the outer side of the metal stream within the shroud. These porous inserts have an apparent porosity between 20 and 22% and generally contain 60–65% alumina, 5–7% silica, and 20–25% carbon. To improve the mechanical property and wear resistance of the inserts, about 10% zirconia is also added to the composition. Argon gas can also be introduced from the top of the shroud cup at the junction between the cup and the nozzle, as "top purging" (Figure 8.9d). Argon gas purged through the top purging technique covers/shrouds the metal stream better within the shroud, as only argon gas is available at the junction between the shroud cup and the collector nozzle, and only argon gas ingress will occur to compensate for the pressure difference caused by the Venturi effect arising from the molten steel flow through the shroud.

8.8.2 GASKET AND SEAL INCORPORATION

The prevention of air ingress through the junction between the collector nozzle and the shroud cup can be further improved by the use of a sealing gasket. The sealing

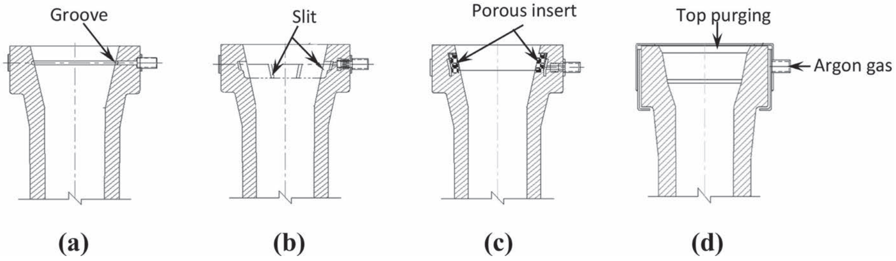

FIGURE 8.9 Different designs of argon purging through the cup portion of the ladle shroud: (a) groove-type; (b) slit-type; (c) porous insert; (d) top purging.

is done both along the mating surfaces of the two parts and also at the bottom of the collector nozzle if butt fitment is used. This type of sealing is also effective in preventing any air/nitrogen ingress and pickup by the flowing molten steel. Generally, a *gasket* is an annular-shaped refractory product that has some extent of cushioning (compressibility) effect for the perfect sealing of the gap at the mating surface. In many cases, the use of both the argon injection and the sealing gaskets is practiced for better prevention of air ingress.

The gasket materials need to withstand a temperature of at least 1,300°C and should have low heat capacity, high flexibility to provide cushioning effect, long service life, etc. Commonly, the gaskets are made up of high-alumina ceramic fibres. Different types of gaskets are used for sealing the joint and in controlling the limit of nitrogen pickup. For common ceramic fibre gaskets, the nitrogen pickup is below 15 ppm, whereas the use of gummy gaskets reduces the maximum level of pickup to 10 ppm, and for vacuum-pressed gasket, the maximum limit is only up to 5 ppm.

8.8.3 REFRACTORY BAND IN SLAG ZONE

The ladle shroud transfers the molten steel to the tundish as submerged condition in the molten steel bath of the tundish. Hence, a portion of the shroud outer wall is in contact with the tundish slag (tundish covering powder), floating above the metal pool in the tundish. This slag contact portion of the shroud is highly prone to corrosion. In the early days, once it was found that the limiting factor for the service life of the shroud is corrosion by the tundish slag/cover powders, the thickness of the shroud in the slag contact area was increased. It was expected that the slag will corrode at the same rate and the increased thickness would lead to an increase in life significantly, but such a modification did not result in the desired improvements and caused other operational difficulties. Hence, special attention has been given to the refractory composition of the slag contact portion, especially for the outer surface of the shroud, to have greater corrosion and erosion resistance against the slag. A slag zone refractory band containing zirconia as a major component (75–80 wt%) with carbon (15–20 wt%) is used for such an area where the tundish slag (cover powder) is in contact and the slag is relatively acidic in nature. But for the basic-natured tundish slag and the tundish covering powder, the slag zone of the shroud is modified to a magnesia carbon–based composition (MgO between 60 and 65 wt%, and carbon between 28 and 32 wt%) that results in improved performance. ZrO_2 is also added as an additive for further improvement in performance and service life. The use of ZrO_2 in the slag band improves not only the corrosion resistance but also the wear and abrasion resistance of the refractory.

8.8.4 CARBON-FREE INNER LINING

The carbon-free inner lining of the ladle shroud is primarily used to restrict the clogging and build-up formation within the shroud (as discussed in Chapter 8.7.3), and mainly mullite (silica-containing) or CaO-MgO-based refractory compositions are used for this purpose. This carbon-free lining also helps in improving the thermal shock resistance of the shroud. To improve the thermal shock resistance of the shroud refractory, the temperature gradient of the refractory wall needs to be reduced. This is achieved by decarburizing (oxidizing) a substantial thickness (~20%) of the shroud inner wall. The inner wall is allowed to oxidize in a controlled manner or is made up of refractory composition without carbon (only oxide composition). For the carbon-free (oxide) compositions, the lining is based on alumina–magnesia (spinel type) or alumina–silica systems. This oxide inner layer acts as a heat insulator, reduces the amount of heat from the molten steel stream to pass through and reach the main body composition (alumina-carbon-based) of the shroud (Figure 8.10), thus reducing the thermal stress at the point of contact and reducing the temperature gradient for the shroud wall (alumina–carbon refractory). The use of the carbon-free inner wall lining can reduce thermal stress up to about 40%, improving thermal spalling resistance. The inner oxide lining also improves the erosion and wear resistance of the shroud due to better sintering and greater strength development, resulting in improved performance and longer life. A carbon-free insulating inner lining allows the ladle shroud to operate in cold start condition, avoiding any preheating requirement, thus improving productivity and the economy. The carbon-free inner lining also helps in processing ultra-low-carbon steel as it nullifies any chances of carbon pickup by the flowing molten steel stream. Also, the shrouds perform better in processing high-oxygen-containing steel, as the lining has no carbon to get oxidized that deteriorates the properties drastically.

Figure 8.11 shows a schematic of the ladle shroud which is modified and improvised with all the possible improvements. Also, Table 8.1 and Table 8.2 provide the refractory compositions of the different zones of modified/improvised ladle shrouds and their properties.

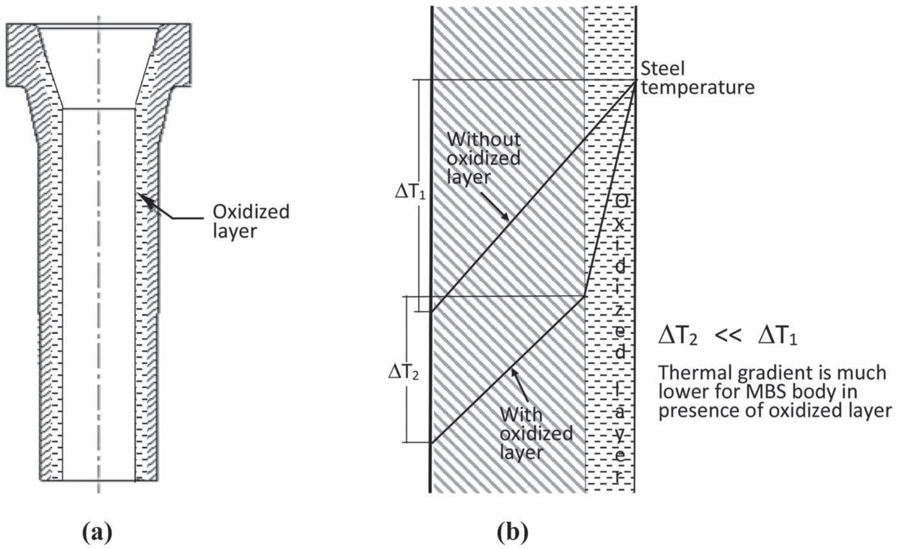

FIGURE 8.10 Carbon-free (oxidized) inner layer of the ladle shroud: (a) schematic of the shroud; (b) temperature gradient across the shroud wall.

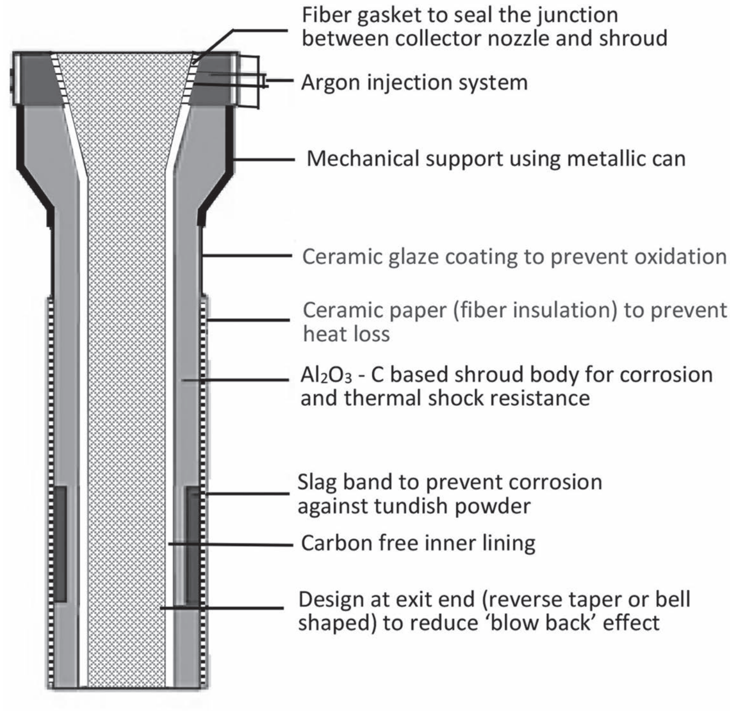

FIGURE 8.11 Schematic diagram of the ladle shroud improvised with multiple technological improvements.

TABLE 8.1
Some Details of the Refractory Compositions and Their Properties of Cup Area and Slag Zone of Modified Ladle Shrouds

Characteristics	**Cup Area**		**Slag Line**	
Chemical Analysis (%)	**Type 1**	**Type 2**	**Type 1**	**Type 2**
SiO_2	18–20	6–8		
Al_2O_3	48–50	60–65		
CaO			2–3	3–4
MgO			65–70	
ZrO_2		4–5		70–75
C	25–30	20–25	28–30	16–18
		Properties		
BD, g/cc	2.4–2.5	2.6–2.65	2.3–2.35	3.4–3.5
AP, %	14–16	14–15	16–18	15–18
MOR, MPa	12–13	11–12	12–15	10–12
CCS, MPa	25–28	28–30	26–28	22–24
Speciality	Standard	High hot strength	Basic tundish cover	Acidic tundish cover

TABLE 8.2
Some Details of the Refractory Compositions and Their Properties of Body Portion of Modified Ladle Shrouds

Characteristics	**Body**			
Chemical Analysis (%)	**Type 1**	**Type 2**	**Type 3**	**Type 4**
SiO_2	12–14	5–6	18–20	15–18
Al_2O_3	52–55	60–65	45–50	42–46
C	32–35	28–30	28–30	35–40
	Properties			
BD, g/cc	2.3–2.4	2.4–2.5	2.3–2.4	2.2–2.3
AP, %	14–16	14–16	14–16	15–18
MOR, MPa	10–12	12–14	10–12	10–11
CCS, MPa	24–26	28–30	26–28	20–22
Speciality	Standard	High-performance	Thermal shock–resistant	Reusable

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9 Monoblock Stopper

9.1 INTRODUCTION AND FUNCTIONS OF THE MONOBLOCK STOPPER (MBS)

In the continuous casting process, the molten steel flows down from the tundish to the continuous casting mould through the nozzle placed at the bottom opening of the tundish. The flow of molten steel needs to be controlled during the movement while exiting the tundish, and there are two different mechanisms that can be used to control the flow of molten steel. Many of the steel manufacturers use a tundish slide gate valve system, very similar in function to that of the slide gate refractories used at the bottom of the steel ladle. But it consists of a three-plate system, compared to the two-plate system used as a ladle slide gate valve. In a three-plate system, the moving plate is the middle one, which is placed in between two stationary plates. The bottom plate is made fixed and stationary as it is connected with the subentry shroud (SES), discussed in next chapter, and movement of the plate will cause an equal movement of the SES that will affect the flow pattern of molten steel within the mould, and also the casting performance and cast steel quality. The slide gate system to control the flow of molten steel from tundish to mould is comparatively smaller, simple, and safe but is also associated with the following multiple drawbacks.

1. It requires a relatively clean steel (processed through secondary steelmaking) to cast, as any clogging or alumina deposition will choke/reduce the bore opening, affecting the metal flow rate, and will result in strand closure. The removal of the deposition is also difficult for this slide gate system.
2. The erosion of the slide plate bore walls may lead to a loss in control of metal flow and also affect the closure of the casting sequence.
3. Any vortex formation at the tundish nozzle due to metal flow (through the nozzle) is difficult to control.
4. For high casting rates at low metal level in the tundish, there are chances of slag entrapment in cast steel. Slag may pass through the slide gate plates and can even reach inside the mould, resulting in breakouts.
5. The system has multiple openings due to the movement of the middle plate, which is a threat for air ingress and oxidation.
6. The system is relatively cost-intensive and requires mechanism support and automation.

The other option to control the flow of molten steel from tundish to mould, avoiding the slide gate system, is to use a monoblock stopper or a stopper rod. The monoblock stopper is a long solid refractory rod that can sit at the open exit end of the tundish bottom hole/at the opening mouth of the subentry nozzle or the tundish nozzle. These refractories are primarily used for the continuous casting of steel and foundry industries or auto-pour

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applications. During use, the rods are hung from one side above the tundish, and the other end is dipped within the molten metal pool of the tundish. The dipped end of the stopper rod is kept within the tundish just above the nozzle opening. The gap between the stopper head and the nozzle opening controls the flow of molten metal from tundish to mould. By the vertical movement (up and down) of the stopper rod, the gap can be increased or decreased, which will change the flow rate of the molten steel moving towards the mould. No gap (when the rod sits completely at the opening of the nozzle) will result in complete closure of the opening and the stoppage of metal flow.

The main functions of the monoblock stopper are:

1. Controlling the flow of molten metal from tundish to mould
2. Prolonging (control on) casting time for better productivity and efficiency
3. Smooth, easy, and clean closing of a casting sequence

9.2 ZONES OF MBS

The monoblock stopper, though appears as a solid refractory rod, has multiple zones having individual roles and functions to perform in controlling the flow of molten steel. The zones that are common to all the MBSs are discussed here. There are also some improvements and modifications going on with time for better performance and service life, which will be discussed separately.

9.2.1 Fixing Unit

The fixing unit is located at the top of the stopper rod, and its main function is to hold the whole monoblock stopper in a hanging condition. The upward-and-downward movement of the stopper rod is also performed through this unit. The fixing unit also provides the provision for the entry of inert gas through the stopper rod if there is the requirement of injection of gas into the molten metal stream. The fixing unit commonly contains a metallic component that enters into the refractory solid rod through an opening at the upper end and provides the mechanical support for hanging and up–down movement of the entire stopper rod. The fixation of this metallic arrangement with the stopper rod is done primarily by placing an insert (Figure 9.1a) within the stopper itself or by cross-pin arrangement (Figure 9.1b). The fixation of the component needs to be airtight to prevent any air ingress through it. This insert may be a metallic or ceramic type. Commonly, a steel nut with a standard thread is placed in the upper part of the stopper rod during its making, which is used to fix the mechanical arrangement for hanging with the stopper rod tightly by screw-driven method. The cross-pin method uses a simple metallic pin that transversely passes through the refractory walls, and also through the metallic part of the mechanical arrangement that has entered within the stopper rod. There is also a mortar fixing system for the stopper rod, where the MBS is fixed with the holding arrangement by means of a mortar and hangs from the mechanical arrangement by mortar fixation. The vertical movement of the stopper rod, essentially required for the opening and closing of the nozzle and in controlling the flow of molten steel, is controlled through this fixing unit only.

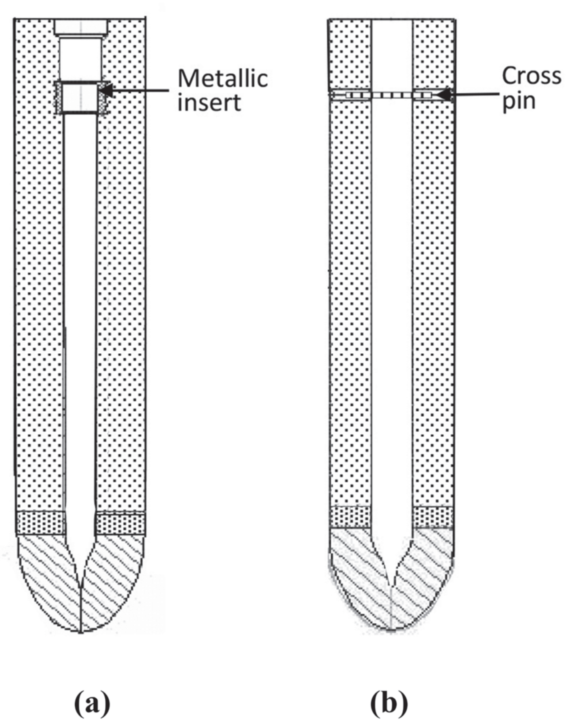

FIGURE 9.1 Mechanism for fixation of the monoblock stopper, with the mechanical arrangement for hanging: (a) insert system; (b) cross-pin arrangement.

9.2.2 BODY

The major portion of the MBS comes under the zone called the body. Originally, MBS was developed with the body composition only, and later, with the progress of time, the stopper rod was divided into different zones as per specific function and requirements during applications. Accordingly, the refractories of different zones got modified to meet the specific requirements. The body needs to have a uniform dense structure to attain a uniform and high strength. Part of the body portion remains above the molten steel level in the tundish, and the rest is dipped into the molten steel bath of the tundish. The dipped portion of the refractory is in constant contact with the molten metal and thus needs to be non-wetting in nature, and so carbon (and non-oxide components) is a must in its composition. So the body is required to have high oxidation resistance to prevent any carbon loss. Again, the stopper rod has vertical movements to regulate the exit flow of molten steel from the tundish, so the middle portion of the body sometimes remains dipped in molten metal and slag and also sometimes goes above the molten liquid layer. Thus, the middle portion of the stopper rod refractory is facing the very high temperature of the molten slag and metal when dipped in the liquid and again faces the open environment when it comes out during vertical up movement. This up-and-down movement of the stopper rod causes severe thermal shock to the hanging refractory rod, and the refractory requires a very thermal shock resistance, especially for the body portion.

9.2.3 TIP/NOSE

The role of the tip/nose portion of the monoblock stopper is most critical for the control of the flow of molten steel to the mould. Mostly, the nose portion needs to maintain a specific gap with the nozzle mouth at the tundish bottom, which again varies from time to time as per flow requirements to allow the flow of molten metal with a desired flow rate. Again, at times, the nose portion also needs to completely close/seal the nozzle opening, thus completely stopping the flow of metal to the mould. Hence, during application, the tip/nose portion is facing the impact of the flow of metal and has to withstand the mechanical impact and wear abrasion from the flowing metal. Again, the chemistry of the molten steel strongly affects the tip/nose portion, and the constituent refractory needs to be highly corrosion-resistant. The wear-out rate of this tip/nose portion governs the performance and life of the monoblock stopper. For a uniform and desired flow rate of the molten metal, a highly accurate tip/nose profile of the stopper rod is important. Also, the tip profile needs to be maintained during use. Any change in the tip/nose profile (due to wear/corrosion) will affect the flow behaviour and flow rate of molten metal, and also, the complete sealing of the nozzle opening (complete stopping of the metal flow) may not be possible. Hence, the tip/nose refractory needs to be highly resistant against the wear, abrasion, and corrosion effect of molten metal flow so that the profile remains unaffected.

Commonly, three major profile designs (geometry) of tip/nose portion are in use, namely, hemispherical (rounded), pointed, and conical (combination of the first two). Figure 9.2 shows the schematic diagrams of all the three tip/nose profiles. The selection of a specific nose/tip profile is dependent on the flow rate, flow behaviour, and casting requirements of the molten steel. To obtain a specific flow rate of the molten steel, the required vertical uplift (stroke distance) of the stopper rod is different for a different tip profile. It is more for the pointed-shaped one than that of the round/hemispherical one. For better understanding of the same, a comparison among the molten steel flow rates through different tip profiles/designs against the corresponding vertical lift of the monoblock stopper is shown in Figure 9.3.

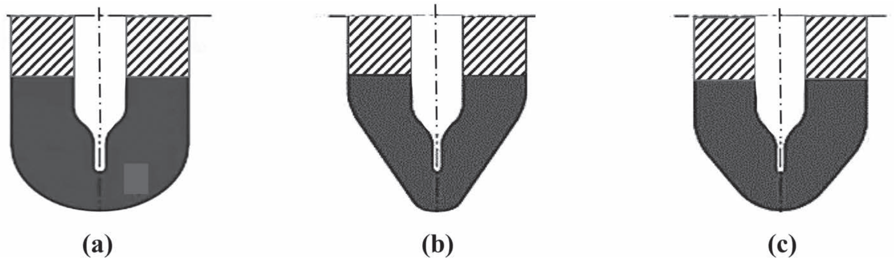

FIGURE 9.2 Different profile design/geometry of tip/nose portion of the monoblock stopper: (a) hemispherical (rounded); (b) pointed; and (c) conical (combination of rounded and pointed).

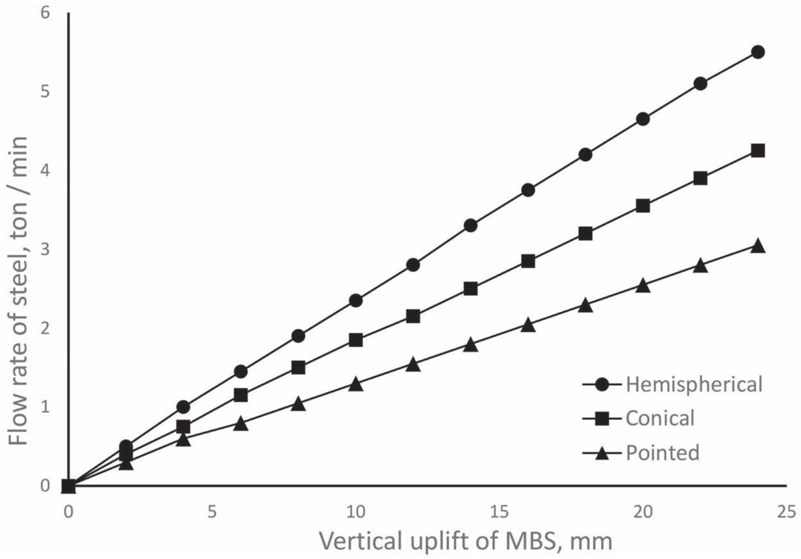

FIGURE 9.3 Comparison of molten steel flow rate through different tip profiles against the extent of vertical lift of the monoblock stopper.

9.3 REFRACTORY COMPOSITIONS FOR MBS

Originally, the monoblock stopper was developed with a uniform refractory composition all through its length and was planned only for the on–off flow of molten steel from the tundish. The requirement of precise control on the flow rate of steel was soon in demand using the same stopper rods. It was also immediately realized that the performance and life of the stopper depend mainly on the property requirements at different zones of the stopper rod. Hence, to meet the different types of properties required at different zones, the zonal lining concept came into application. The prime attention for the zonal lining was on the tip/nose area for its application criticality. The performance and life of the nose area were improved by changing the refractory composition to improve the wear, erosion, and corrosion resistance. In the present day, commonly monoblock stoppers have two major refractory compositions – one for the body, which consists of the major part of the stopper rod, and the other one for the tip/nose area.

The refractory used for the body of a monoblock stopper requires a uniform, dense structure with high strength even at high temperatures; abrasion, wear, and erosion resistance for the dipped part due to the movement of metal within the tundish; high thermal shock resistance; etc. Also, corrosion resistance against the tundish slag (tundish covering powder) is important primarily for the middle portion of the stopper, which is in contact with the slag layer. Further, high hot strength, strong oxidation resistance, and thermal shock resistance are essential for the upper part of the stopper rod. Generally, carbon-bonded alumina–carbon (graphite) compositions with different additives are used for the body composition.

The composition varies with certain special requirements. Commonly, the standard MBS body contains 50–55% alumina, 10–15% silica, 25–30% carbon, and some additives, namely, antioxidants, etc. For applications requiring higher wear and erosion resistance in the body, softer graphite and silica are reduced with an increase in alumina content and the introduction of zirconia in the composition. For the wear abrasion–resistant products, alumina varies between 65 and 70%, silica around 5%, carbon in the range of 20 to 25%, and zirconia around 5% (depending on the erosion rate). For applications requiring high thermal shock resistance, the extent of graphite content in the MBS body is increased, and mullite formation is allowed to be enhanced within the composition. For applications, the composition of the body contains alumina between 40 and 45%, silica between 15 and 20%, and graphite around 30 to 35%.

The nose/tip area is the most critical for the functioning of the MBS. Any minor degradation/wear-out drastically affects the performance and life of the MBS, and also the casting process, which may pre-terminate the casting sequence. For the most common and conventional MBSs, the tip area is also made up of an alumina–carbon composition containing 65–70% alumina, 5–10% silica, and 20–25% carbon. For applications requiring high abrasion and wear resistance, the alumina content in the tip portion is commonly increased compared to that of the conventional composition; the tip area contains about 80% alumina, around 5% silica, and 15% carbon. Also, in special cases, to improve the abrasion resistance of the tip area, zirconia is introduced about 5% in the conventional composition by reducing the alumina content.

The monoblock stoppers used for casting high-Ca-containing steel (processed through Ca treatment) get easily corroded if the tips are made of alumina-based compositions due to the formation of low-melting Ca–aluminate phases and get washed out along with the molten metal. Thus, the profile of the tip changes drastically, and the life of the MBS reduces drastically. For such applications, the alumina-based composition is commonly replaced by spinel- or magnesia-based compositions for better chemical compatibility. For high-Ca-containing steel, the tip area of the MBS is made up of compositions with 55–60% alumina, 15–20% magnesia, and about 20% carbon (spinel-based composition), or with magnesia between 65 and 70%, alumina around 5%, and carbon in the range of 20 to 25%. For applications with severe erosion and chemical attack, if the alumina- or magnesia-based compositions do not perform well in the tip/nose area, zirconia-based compositions are also used containing about 75–80% calcia-stabilized zirconia and about 15–20% carbon.

In few special cases, a separate slag zone/slag band refractory is used as the outer layer of the middle portion of the stopper rod (that is in contact with the tundish slag/powder) having a different composition, primarily to improve the corrosion resistance of that specific zone (slag contact area). For the reinforcement of the slag contact area, zirconia–carbon or magnesia–carbon compositions are used to enhance the corrosion resistance against basic and acidic slags, respectively. Magnesia-based composition is also important for silicon killed steel with high MnO- and FeO-containing slag. Some details of the compositions and properties of the refractories used for the body and nose/tip region of the MBS are provided in Table 9.1.

TABLE 9.1
Details of the Different Compositions and Their Properties Used for the MBS Body and Nose

	Body			**Nose/Tip Area**		
	Chemical Composition, %					
	Type 1	Type 2	Type 3	Type 1	Type 2	Type 3
SiO_2	12–15	6–8	15–18	5–8	2–4	
Al_2O_3	50–55	60–65	45–50	65–70	80–85	
MgO						70–75
ZrO_2		4–6				
C + SiC + LOI	30–32	20–25	35–40	22–25	14–16	18–20
	Properties					
Bulk density, g/cc	2.4–2.5	2.7–2.75	2.25–2.3	2.5–2.6	2.8–2.9	2.5–2.55
Apparent porosity, %	14–16	12–15	16–18	15–18	15–18	16–20
Cold strength, MPa	22–24	25–28	22–24	25–28	28–30	22–24
Cold MOR, MPa	10–12	12–14	9–10	10–12	12–14	10–11
Speciality	Standard	Erosion-resistant	Thermal shock–resistant	Standard	High-performance	Ca-treated steel

9.4 DEGRADATIONS OF THE MBS

The MBS is one of the most critical refractory products that directly affect the performance and duration of the continuous casting process. The monoblock stopper works in conjunction with the submerged entry nozzle or tundish nozzle to control the flow of molten steel during casting. The proper functioning of the MBS provides a uniform and uninterrupted flow of steel to the mould and the stability of the continuous casting process. The failure of the MBS can be considered one of the major reasons for the premature termination of casting.

Even in cases where the monoblock stopper is not completely failed, like for the case of change in dimensional profile, especially for the tip region, the uncontrolled flow of the molten steel will occur with leakage of the molten steel when the nozzle is completely closed by the MBS. These may lead to serious concern for the whole steel casting process and may lead to accidents or huge economic losses. Different types of degradation and failure at different portions of the MBS that affect the casting process are described in detail in what follows.

9.4.1 FAILURE AT THE TIP/NOSE REGION

The nose/tip (also called the head) is the key part of the monoblock stopper as it works in conjunction with the nozzle within the tundish to control the flow of metal and needs to have excellent strength and resistance against wear, both mechanical and chemical. In most of the standard MBS, the tip composition (generally alumina–carbon, magnesia–carbon, spinel–carbon, zirconia–carbon, etc.) commonly contains a lower carbon content compared to that of the body composition for improved mechanical (strength and wear) properties. But still, the major failure and rejection of the MBS occur due to the degradation of the tip/nose region, and the major degrading factors of the tip region are described in the following.

9.4.1.1 Erosion and Wear

Failures of MBS mostly occur due to wear-out of the tip/nose region caused by the impact and movement of the flowing molten steel. High-speed movement of the heavy molten steel causes an impact on the tip refractory, and also the turbulence formed at the nozzle mouth causes abrasion and erosion effects, resulting in a depression wear (concave shape) in the tip profile. The height of the stopper rod is lowered to fit the tip on the nozzle mouth, as the tip contour is eroded out and washed away. The extra lowering in the height indicates that the stopper is not able to control the flow effectively and not able to close the nozzle mouth properly when the pouring needs to be stopped. This causes instability and irregularity in molten steel flow to the mould, affecting the casting sequence and the cast steel quality.

Further, the vertical movement of the MBS to increase/decrease the nozzle opening aggravates the situation due to the relative movement and reversal of the same, causing greater erosion and wear. Also, the surface pores present in the tip/nose refractory allow the penetration of the liquid metal within the refractory matrix (dependent on the pore size and minimum droplet size of the molten metal and slag), which can gradually leach out the finer and loose particles of the refractory and cause a greater extent of wear. The oxidation of carbon particles during preheating also enhances the surface pore formation and degradation of the carbon bond of the matrix, resulting in porous and weak texture and easy erosion.

This excessive wear-out effect is primarily caused by three different mechanisms, namely, physical wear, carbon oxidation, and chemical reactions. The wear-out is also dependent on the grade of steel (chemistry) being cast, and so the refractory composition for the tip/nose region needs to be selected as per the grade of steel. Like for Al killed steel, alumina-carbon-based composition works well, but for Ca-treated steel, a higher Ca (CaO) content causes a reaction with the alumina, forming low-melting calcium aluminate compounds and easy wear-out of the tip refractory. Hence, magnesia-carbon-based compositions are suitable for the tip region against Ca-treated steel. For complex casting environments and steel containing multiple elements (as inclusion or alloying agents), zirconia–carbon compositions work well under extreme mechanical and chemical conditions.

To improve the mechanical wear and erosion resistance, especially at the tip/nose region, uniform dense structure is aimed by using finer particle sizes of the refractory and higher amounts of antioxidants. Ultra-dense matrix is targeted by the finer particles using isostatic pressing, and also by firing (coking) with lower elastic modulus. The formation of in situ ceramic bonds at high temperatures due to the use of antioxidants further improves the bonding, strength, and thermo-mechanical properties that, in turn, improve the resistance against abrasion and wear.

9.4.1.2 Corrosion

Chemical compatibility of the tip/nose refractory composition with the chemistry of molten steel is very important for the performance of MBS and the casting process. An increase in the demand for clean steel has introduced different secondary steelmaking processes, like killing (Al killed steel, Si killed steel, etc.), treatment (Ca-Si, Ca-Fe treatment, etc.). Each of the processes has had an impact on steel quality and on changes in steel chemistry, even in ppm (parts per million) level. The effect is found to be stronger for the steel processed through Ca treatment. A minor increase in calcium level (even at 10 ppm) in steel drastically affects the refractory in the tip region. The commonly used alumina-based refractory gets corroded due to the formation of low-melting calcium aluminate phases. The formation of these aluminates is also enhanced due to the prevailing high temperature (~1,600°C) of steel, and the formed aluminates are washed away due to impact and flow of the molten steel. The presence of any other impurity in steel, like silicon, manganese, vanadium, phosphorus, etc., even in ppm level, further deteriorates the situation and increases the corrosion rate. Thus, loss of the refractory occurs from the surface of the tip/nose region of the stopper rod, causing change in the profile of the tip portion and affecting the metal flow behaviour and casting performance (sequence). It is very important to choose the proper refractory composition, especially for the tip portion, to meet the required chemical compatibility as per the steel chemistry (casting strand). The major modification that has occurred on this tip region is the introduction of the basic refractory, replacing the conventional alumina-based compositions. For low to moderate Ca-containing steel, spinel- or magnesia-based tip compositions work well. An increased level of Ca content (>30 ppm) demands for high-MgO-containing compositions. But for very high-Ca-containing (~100 ppm) steel, zirconia carbon–based compositions suit better for the tip. The tip/nose composition may need to be customized as per the steel chemistry and other processing parameters to get an optimum MBS life, casting sequence, performance, and cast quality.

9.4.1.3 Sticking of the Tip

The MBS tip/nose is always in contact with molten steel passing through the nozzle, and the inclusions present in steel react with the components and impurities of the tip refractory (or with the glaze coating), forming low-melting compounds on the tip surface. These formed low-melting compounds may cause sticking of the tip portion at the nozzle mouth opening/SEN seat during complete closure of casting. The liquid phases formed on the surface of the tip/nose may also react with the nozzle mouth/SEN seat refractory compositions and can cause a firm bonding between the tip and the nozzle mouth. Thus, the sticking of the tip at the nozzle opening affects the vertical movement of the MBS, requiring a higher force, and may result in cracking/chipping of the tip portion, a change in tip profile, and even the complete breakage/failure of the tip and the MBS. Thus, sticking of the tip will affect the flow of molten steel through the nozzle, leading to an uncontrolled metal flow and degradation in casting performance.

9.4.2 Failure of the Body

Next to the tip failure of MBS, the major failure occurs due to the body portion. The body portion fails due to multiple reasons, as described in what follows.

9.4.2.1 Transverse Failure or Breakage

The monoblock stopper body has a rod-like structure with little tapering and has high aspect ratio (length: diameter). The long heavy refractory product is fixed at and hanging from the top part using a metallic/ceramic nut or cross-pin arrangement. During application, the MBS has an up–down movement, and the free bottom part suffers mechanical impact and turbulence from the flow of the molten steel within the tundish. The MBS body has a uniform composition all throughout, mostly made up of an alumina–carbon composition. To obtain a highly compact, uniform, dense structure all through the MBS length, isostatic pressing is used. The vertical movement of the MBS to control the flow of molten steel is along its axial direction, but the impact and turbulence of molten steel flow are in the transverse direction and cause transverse fracture of the rod. The transverse fracture occurs mainly due to mechanical and thermal stresses and is accelerated by corrosive actions. Commonly, the transverse fracture occurs in the middle of the length and close to the slag region.

The mechanical failure of monoblock stoppers also occurs due to crack formation in the refractory. There may be a number of reasons for such failure, like fixing the end problem due to misalignment, loose and defective fixing of the stopper, misalignment of the stopper rod, bent product, misalignment of the tip with the body (manufacturing defect), incorrect nose design and dimension, sudden uncontrolled turbulence from metal flow, etc. The performance of the service life of the MBS is dependent not only on the refractory composition and its quality but also highly on steel casting parameters, process conditions, operational issues, etc.

9.4.2.2 Corrosion

Commonly, the monoblock stopper body is made up of an alumina–carbon composition, and the composition works well with most of the steel grades. But the portion of the body present in contact with the tundish slag/covering powder faces multiple difficulties. A little amount of slag is allowed to be present in the tundish (that floats above the molten steel pool), primarily acting as a protective layer for the top surface of the molten metal to prevent the oxidation of the metal, nitrogen pickup, heat loss, and cooling. The uncontrolled cooling of molten steel affects the desired crystallographic phase formation within the cast steel and its desired properties development. This slag layer, being lighter than the molten steel and immiscible, remains always on the above of the molten metal pool and does not affect much of the steel casting process and steel quality.

But the slag strongly affects the MBS, which passes through it during operation. Slag, being a low-density, low-viscosity liquid, can easily penetrate through the open pores in the MBS body, affecting the matrix by reacting with the refractory components and loosening it out. Thus, the MBS body portion that is in contact with the slag layer wears out faster, and the slag contact refractory portion becomes weak and vulnerable to failure. Further, the tundish slag contains various non-metallic impurities, like SiO_2, FeO, MnO, CaO, etc., that can corrode the alumina-based compositions, reducing thickness and accelerating the failure.

9.4.2.3 Thermal Shock

During operation, the lower part of the MBS remains dipped within the molten steel bath of the tundish, and the upper part remains above the tundish slag layer. The single-piece stopper rod is present at the liquid steel temperature within the molten steel bath and also at the ambient environment above the slag layer (the undipped portion). Further, some portion of the body of the MBS is at the junction of the open atmosphere and the liquid mass (steel/slag), which also changes the position within a range due to vertical movement of the MBS. These cause extreme thermal gradient for the MBS body, and it suffers a huge thermal shock.

Further, when molten steel is poured into the empty tundish from the ladle, the stopper rod suddenly experiences the molten steel temperature causing a huge thermal shock, which may lead to cracking. To reduce the temperature gradient during metal pouring in the tundish, the stopper rods are generally preheated. However, a longer preheating time and higher preheating temperatures may cause oxidation of the stopper rod, making the rod porous and structurally weak, resulting in failure.

Again, different compositions are used for the lining of the different zones of the MBS. The thermal expansion mismatch among the different compositions may lead to further strain at the junctions during high-temperature gradients and may lead to the separation of the portions, breakage, and failure. Commonly, the tip portion, when it is of magnesia–carbon composition, gets separated and falls off at high-temperature gradients due to the higher thermal expansion of magnesia. The judicious selection of composition to reduce the thermal expansion mismatch and proper preheating are required to reduce failure. Generally, the MBS body composition is made up of a refractory to withstand thermal shock, but it still suffers failure due to thermal shock. A uniform dense structure, the development of high strength within the body composition, a composition to withstand thermal shock, strong fixture with the mechanical arrangement for vertical movement, etc. are essential for a better performance of the MBS.

9.4.3 Failure at the Connectors

During operation, the monoblock stopper is held by the manipulator arm and is hanging through the connector, which can be a metallic or ceramic nut/insert, cross-pin arrangement, metal wire plug, etc. This connector plays an important role in the continuous casting process as it controls the height of the MBS, the opening of the nozzle mouth by vertical movement of the MBS, and accordingly, control of the flow of molten steel from tundish to mould. Any failure of the connector will lead to the complete failure of the stopper rod and stoppage of the casting process. Softening of metal part, cracking, and mechanical failure of the ceramic components of the connector are the common problems observed during application.

9.5 TECHNOLOGICAL IMPROVEMENTS AND FUTURE POSSIBILITIES

The conventional monoblock stopper has been upgraded with time for the betterment of its performance and life. Various technological modifications and upgradations that have been incorporated in the MBS have produced improved performance and longer duration of casting sequence. Some of the technological improvements that are successfully implemented in the commercial level are detailed as follows.

9.5.1 ARGON INJECTION FACILITY (POROUS PLUG)

It is commonly experienced in the existing process of continuous casting of steel that the tube refractories (namely, subentry nozzle, ladle shroud, etc.) suffer from the problem of clogging/build-up formation, especially for the killed steels (Al killed, Al-Si killed). This leads to blockage in the molten steel flow path, which leads to a non-uniform metal flow rate, decreased productivity, increased cost, degraded steel quality, and low machine availability. This clogging usually takes place due to the deposition of solid inclusions on the inner wall of the tube refractory, primarily alumina, or CaO-Al_2O_3 or CaS in case of Ca-treated steel (details are described in Section 8.7.3 Chapter 1z0). An improved steelmaking practice can reduce the inclusions in the molten steel, and also the nozzle clogging, but re-oxidation of metallic aluminium (for Al killed steel) is difficult to control. To remove or reduce the formation of clogging in the inner surface of the subentry nozzle, one of the most effective and commonly used techniques is to purge inert argon gas through the MBS tip/nose. The injected argon gas forms a thin layer along the inner wall of the nozzle refractory surface and thereby restricts contact of the steel and its inclusions with the refractory inner wall surface and thus reduces the deposition/build-up formation. It also flushes out any deposition of inclusion that occurred on the inner wall due to the impact from high gas injection pressure. Injecting argon gas through MBS also helps in promoting the floatation of inclusions in the mould (making purer steel) and in increasing the casting sequence duration.

Argon gas from an external supply is introduced through the top end of the MBS refractory and passes along the length through a central axial passage (made intentionally by placing a metallic pin during MBS manufacturing). The argon gas comes out through an opening placed centrally at the tip/nose and moves downwards along with the flow of molten steel. The gas inlet point in the MBS must be an airtight one so that no air aspiration can occur; otherwise, the quality of steel will deteriorate. Commonly, argon gas is injected into the downward-moving liquid steel stream through a single hole placed at the stopper tip (Figure 9.4a), which increases the pressure downwards and removes or reduces the formation of any build-up or clogging in the inner wall of the casting nozzle (SEN).

This argon gas injection may also cause a back pressure which is unstable and generally increases with casting sequence time. Downwards-moving argon gas coming out from the tip hole of the MBS loses its pressure and direction within the throttling gap as it is the lowest-pressure region in the flowing mass. This causes pressure and velocity variations within the gap and ultimately results in non-uniform gas distribution in the downward stream. This results in variation in argon flow rate that may lead to surface defects in the final cast products. This argon gas pressure fluctuation causes the back pressure in upwards direction and also affects MBS functioning. So a higher argon gas pressure is commonly practiced to overcome the back pressure effect. Another major reason for the increase in argon injection pressure is to clear any blockage in the argon purging channel within the MBS that may occur due to an ingress of molten steel in the argon passage due to back pressure effect. This molten steel ingress within the MBS (argon axial passage) also occurs due to argon pressure fluctuations at the stopper tip.

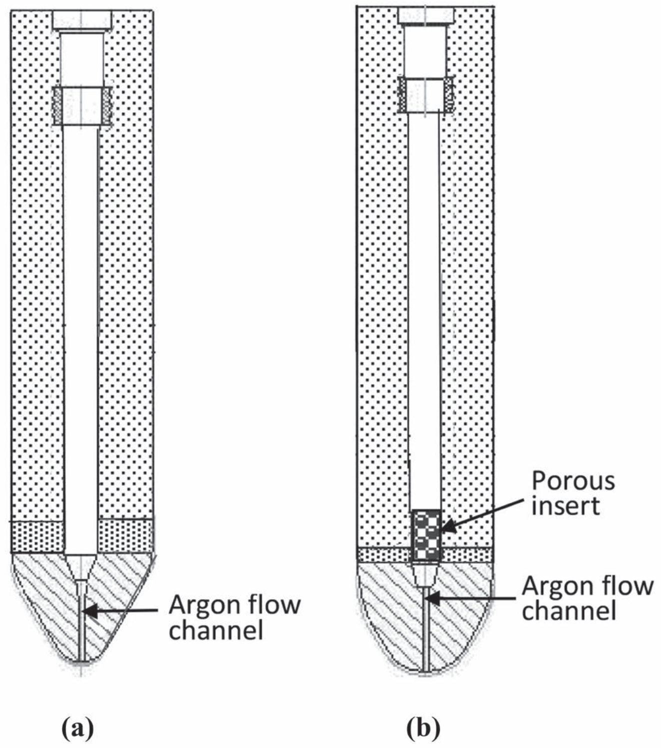

FIGURE 9.4 Argon flow channel inside the monoblock stopper: (a) single hole at stopper tip; (b) use of porous insert.

Again, the increased argon pressure may also cause abrupt and unexpected splashes of metal from the mould. To avoid all these negative effects, ceramic porous inserts are placed at the bottom end of the argon passage channel within the MBS (Figure 9.4b). These inserts are fixed within the inner refractory wall of the argon passage within the MBS by mortar to withstand the impact of back pressure. Also, the fixed porous inserts restrict any entry of molten metal within the passage, preventing any blockage to the flow of argon. The use of the porous inserts allows for a controlled injection of the argon gas through the monoblock stopper without abrupt or unexpected increase in pressure level and without any splashes of metal from the mould. It is also observed that the distribution of injected Ar gas within the molten metal stream in the nozzle can also be improved by modifying the single-hole exit port at the tip of the MBS to multiple holes' argon gas opening holes in the tip region. This modification helps in the increase in purging gas volume and its better distribution. Further modification in the purging gas opening at the tip portion by using a ring/circular-shaped slot has been reported to improve the quality of purging and better casting process and to improve cast steel quality. The ring-shaped slot has an annular gap of a submillimetre width and is less susceptible to pressure fluctuations and instabilities in Ar gas purging, resulting in uniform and homogeneous Ar gas distribution in the metal stream and improved casting process with better steel quality.

9.5.2 SLAG ZONE REFRACTORY

The conventional monoblock stoppers show noticeable wear in the slag contact areas of the body during use. Exceeding a certain amount of wear in diameter makes the MBS vulnerable and break at the slag line, causing an emergency situation. A study showed that for an MBS with about 130 mm outer diameter, the refractory wall is around 40–42 mm thick, and a slag wear of 15 mm or more makes the MBS vulnerable to break. So a wear in the slag line limits the life of the MBS, even though the stopper is perfect at other zones. To reduce the effect of corrosion and enhance the service life of the MBS, extra reinforcement is done for the slag contact areas of the MBS. Initial modification was to introduce a projected slag zone area – that is, the refractory wall is thicker for the slag zone using the same body composition; thus, the MBS looks thicker/projected at the slag zone area (Figure 9.5a). It was expected that the MBS will get a longer service life as the slag corrosion to reach the vulnerable thickness will take a longer time for the greater thickness of the refractory wall. But in reality, the improvements were not so great.

Also, attempts were made with the incorporation of better corrosion-resistant refractory composition in the slag contact area, as a slag band refractory, which resulted in a much-reduced corrosion effect. For highly corrosive tundish slag environments, the slag contact zone of the MBS is made up of higher slag corrosion–resistant compositions, like spinel–carbon, zirconium–carbon, etc. Refractory selection for the slag contact area of the MBS is critical and must be compatible with the composition of the slag (tundish powder). For example, steel having higher Mn inclusion produces higher MnO-containing tundish slag composition, and so refractories containing SiO_2, SiC, and only Si as antioxidant are to be avoided in the slag contact area to restrict the formation of highly corrosive and low-melting Mn-silicate phases. Commonly, a zirconia–carbon mix with ZrO_2 content in the range of 75–80% and carbon and non-oxides around 20% is used as the slag band. Only the outer lining of the MBS that is in contact with the tundish slag is lined with the corrosion-resistant composition (Figure 9.5b); thus, chemical degradation of the MBS is reduced, which, in turn, reduces the failure of the MBS due to slag corrosion.

9.5.3 OXIDATION-RESISTANT GLAZE COATING

Carbon plays an important role in the functioning and performance of the MBS. Due to its non-wetting nature, it provides excellent corrosion resistance to the refractory and lower thermal expansion, high thermal conductivity, and low elastic modulus of carbon, providing excellent thermal shock resistance. But the carbon present in the MBS body may oxidize during operation at high temperatures as it is exposed to the open environment, causing a porous and weak structure and failure of the MBS.

Before application, the MBS is first preheated up to 1,200°C to reduce the thermal gradient and thermal shock when it comes in contact with the molten steel (~1,600°C) during use in the tundish. Generally, the preheating is done in an enclosed chamber with ambient environment, and the carbon-containing stopper rod is exposed to an oxidizing atmosphere at high temperatures, leading to the oxidation of carbon. Also, during application, the upper part of the stopper rod (non-dipped portion, which remains above the level of the molten steel and slag) is exposed to the open air at high temperatures and is prone to oxidation.

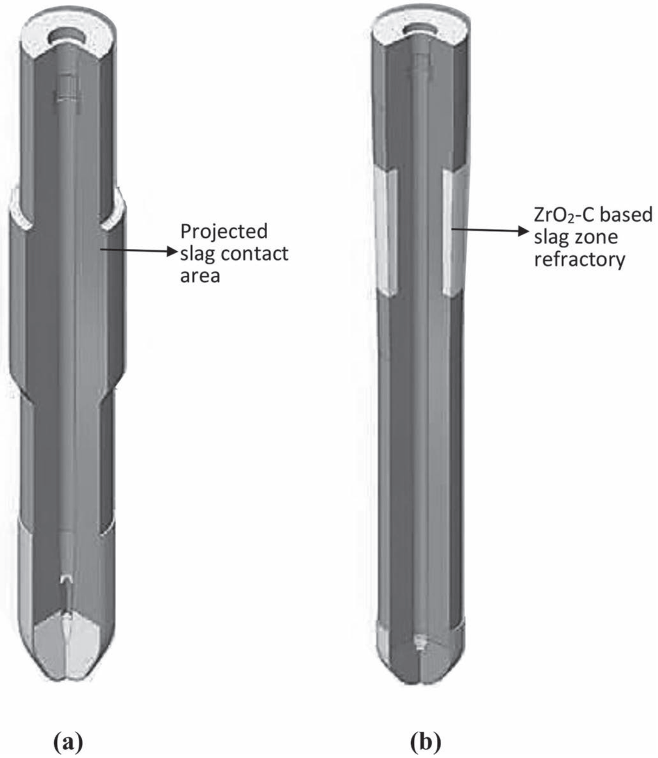

FIGURE 9.5 Improvement in slag corrosion resistance of the monoblock stopper by (a) projected slag zone area (thicker wall) and the (b) use of slag band at the outer surface in contact with the slag.

To prevent any kind of oxidation (for carbon or other non-oxide refractory components), antioxidants are used in the refractory composition. Further, the outer surface of the whole MBS is also coated with a high-temperature glaze that provides a protective coating for the MBS and prevents any contact of oxygen (present in the air) with the MBS. Proper thickness of the glaze is important, as a thin glaze may not protect well against oxidation and a thick glaze may cause defects, like crawling, glaze cracking, peeling off, blister formation, balling effect, etc., leading to improper coating. The glaze composition is made in such a way that it can mature in the preheating stage (~1,000°C) only, and it can have sufficient viscosity so that it does not fall out from the stopper rod surface even during application at steel processing temperatures. In some cases, the glaze firing is also done by the refractory manufacturers before supplying to the steel plants for use.

9.5.4 ANTI-STICK LAYER AT THE TIP

The sticking of the tip/nose portion of the MBS at the nozzle mouth/seat area of the SEN, resulting in the breakage of the tip or loosening of the tip profile, is a common failure for MBS. Minute contents of impurities in steel are difficult to remove/

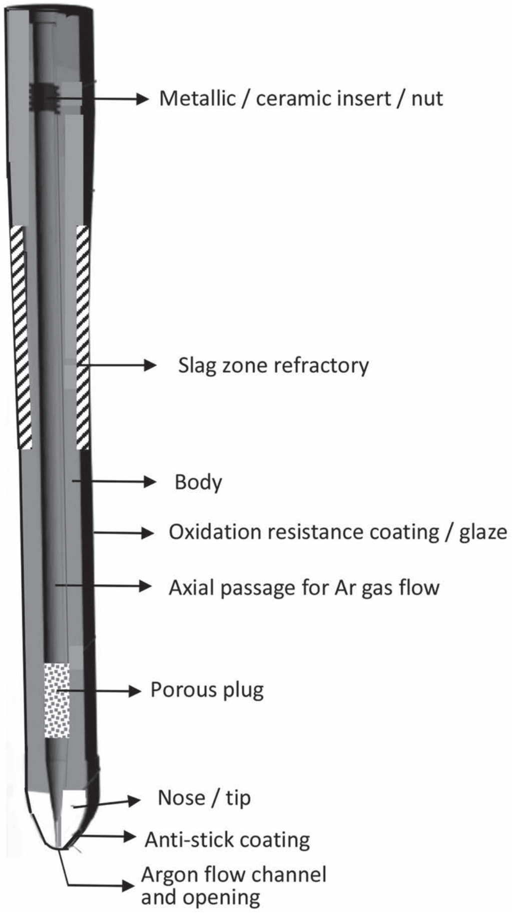

FIGURE 9.6 Schematic diagram of a monoblock stopper improvised as per various technological improvements.

control, which may cause the low-melting-phase formation at the tip surface upon reaction with the tip refractory components and, finally, sticking of the tip. To prevent the sticking, a special coating is used only at the tip portion of the MBS to protect the tip refractory from any reaction with steel impurities.

Figure 9.6 shows a schematic diagram of the monoblock stopper rod which is modified and improvised with all the different possible technological improvements.

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10 Submerged Entry Nozzle

10.1 INTRODUCTION

The *submerged entry nozzle*, or *subentry nozzle* (SEN), is a tube-shaped refractory nozzle essential to the transfer of liquid steel from the tundish to the casting mould. It is the last refractory item used in steelmaking through the continuous casting process. SEN is important for the completely covered/shrouded transfer of molten steel without any contact with the ambient air until solidification. SEN acts as a long nozzle piece; entering within the tundish, it collects the molten steel from the tundish bottom and transfers the same to the molten metal pool within the casting mould. The bottom part of the SEN remains immersed completely within the metal pool and ensures the smooth transfer of molten steel. As the bottom part of the refractory nozzle is always immersed in the molten steel bath in the mould, the product is called the *submerged entry nozzle*. Unlike the ladle shroud, which has a simple cylindrical design with a single opening at the entry and exit points (flat surfaces of the cylinder), the submerged entry nozzle generally possesses multiple exit holes, commonly two or four, at the bottom side walls (called the discharge hole). The number and dimensions of the discharge holes are dependent on the desired steel flow rate, flow pattern within the mould, molten steel properties, and other steel casting parameters.

10.2 CONTINUOUS CASTING MOULD AND MOULD POWDER/FLUX

In the continuous casting process, liquid steel is given the desired shape by solidification through casting moulds. Moulds play an important role on the cast steel shape, size, and quality. The primary purpose of the continuous casting mould is to freeze the liquid steel to form a solid shell resistant to withstand the pressure of the liquid metallic core and contain the liquid phase at the entry of the water-sprayed cooling zone. The formed shell needs to be strong enough to retain the liquid steel inside the formed shape and to be dragged vertically down along the mould wall without forming any defect or crack. The freezing/solidification of molten steel has to be very fast, as the cast speed is high and liquid steel has a very limited residence time within the mould. Rapid cooling requires rapid heat transfer, and so a very high-heat-conductive material is essential for making the mould.

Copper, having very high thermal conductivity and excellent thermal erosion character with wide industrial applicability, is the most widely used continuous casting mould material. However, copper has a much lower melting point (1,085°C) compared to that of steel casting temperature (>1,500°C). Hence, the heat extracted by the copper mould from the molten steel (for its solidification) needs to be immediately shifted (taken

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away) to cool down the mould and retain its solid, stable form. Hence, the continuous water cooling of the mould is essential and very important to take out the heat from the copper mould surface for the casting process. The water-cooled copper moulds have an open-ended box structure with an inner lining (channels) for water cooling. They are commonly fabricated from highly pure copper alloy. As the molten steel shrinks upon solidification, mostly the moulds are a little conical in shape, and the mould walls are a little curved (convex or concave type). Such design of the walls further improves the heat transfer rate and uniformity, which, in turn, improves the quality of the cast products. As per the different product shapes, like blooms, billets, round beam blanks, slabs, and thin slabs, the casting moulds have different shapes and dimensions.

Due to the downwards flow of steel, there is a relative motion between the solid shell of steel formed upon cooling and the mould wall. To reduce the wear effect on the surface wall of the copper mould due to this relative movement, the mould surface is generally coated with wear-resistant Ni and/or Cr coating. Oscillation/vibration of the mould is also done to avoid any sticking and reduction in wear by reducing the continuous contact between the steel shell and the mould wall. Further, to reduce the continuous friction on the mould wall due to the downward flow of molten steel and the smooth, easy movement of the formed, solidified steel shell, some sort of lubrication is required between these contact surfaces. Lubrication also nullifies the chance of sticking of the solidified shell on the mould wall. A thin film of lubricating liquid is interposed within the molten steel and mould wall surfaces to avoid any direct contact between them (liquid steel, or steel shell, and mould surface). For the purpose of lubrication, mould powder/casting powder/mould flux is added on the top open surface of the mould. The mould powder melts around 1,100°C, forms a molten liquid layer above the molten steel bath within the mould, and protects the steel from atmospheric oxidation, nitrogen pickup, and heat loss. It also helps in absorbing inclusions from molten steel, both non-metallic and gaseous inclusions, and in improving the purity of cast steel. Mould powder is added periodically to the top surface of the steel pool within the mould, which sinters, melts, and floats above the molten steel bath in the mould (as protective layer) due to the density difference. The molten mould powder is drawn towards the downward direction due to the flow of molten steel, which remains on the surface of the steel and enters into the gap/partition line between the steel shell formed and the copper mould. The liquid mould powder moves downwards along with the formed steel shell and eases its downwards movement along the mould wall surface. Thus, the molten mould powder acts as a lubricant, restricts the contact between the molten steel and the mould surfaces, and helps in heat transfer from liquid steel to mould uniformly. The effect of using mould powder and the casting conditions of the continuous casting mould are schematically shown in Figure 10.1.

The mould powder/flux is a type of synthetic slag containing various oxide and non-oxide components to impart a variety of properties required for the steel casting process. As it needs to be a low-melting material, there are components that help fuse the powder at low temperatures, like a glass former, namely, SiO_2, B_2O_3, Fe_2O_3, etc.; to reduce the fusion temperature, various alkali and basic components are added, namely, Na_2O, K_2O, Li_2O, CaO, MgO, etc. It also contains a fluidizing component (especially for lubrication), like F (used as CaF_2), MnO, etc., and a melting control component, like C, etc. Commonly, the basicity of the liquid mould flux

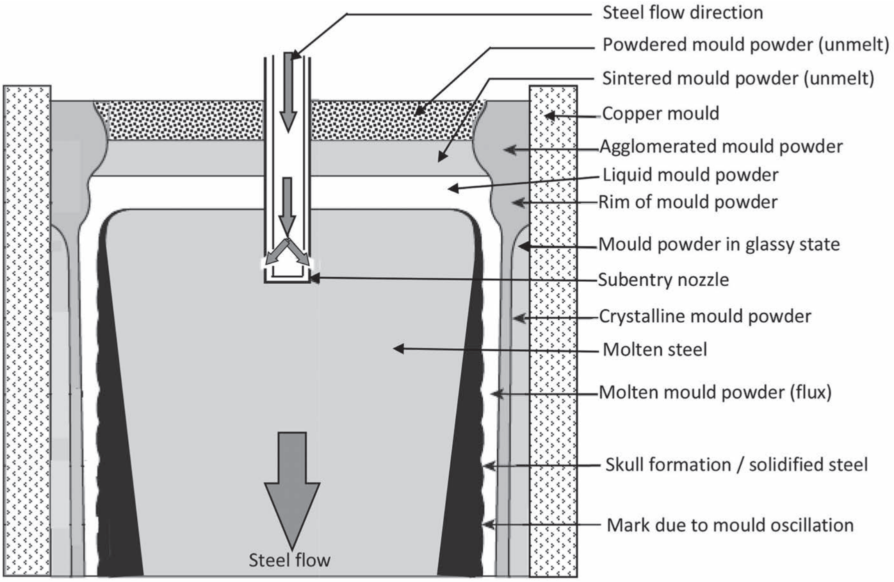

FIGURE 10.1 Schematic diagram of the steel casting mould with the mould powder/flux.

is maintained between 0.7 and 1.3 by controlling the lime–silica ratio. The viscosity of the molten mould powder is important for its performance and primarily dependent on the composition and its constituents. A sharp decrease in viscosity of the mould powder liquid is required at the casting temperature (above 1,500°C) so that it can easily coat the semisolid steel completely within the mould. This will help prevent the oxidation of steel and provide lubrication against the mould wall. Some details of the mould powder are provided in Table 10.1.

Fluorides are important for the performance of mould powder as they significantly lower the melting temperature and the viscosity. They also help in heat transfer from the molten steel to the mould. Due to the low-melting and low-viscous character (imparted by the fluorides), the molten mould powder gets easily and completely separated from the molten steel, minimizes the chances of slag entrapment in steel, and further entraps and absorbs inclusions present in molten steel, producing a cleaner steel. However, the presence of fluorides in the mould flux causes certain disadvantages too. In the presence of silica (major component in mould powder, acts as glass former), it forms gaseous SiF_4 [$2CaF_2$ (Slag) + SiO_2 (Slag) $\rightarrow$ SiF_4 (g) + 2CaO (Slag)], causing environmental threats and health hazards. Also, on contact with water (used for cooling of steel post-casting), it forms a highly corrosive HF gas [CaF_2 (Slag) + H_2O $\rightarrow$ 2HF (g) + CaO (Slag)], causing a corrosion problem to cast steel, casting components, and health hazards. Further, fluorine-containing, low-viscous mould powder liquid is highly corrosive to most refractories and corrodes the refractories tremendously present in contact with the molten mould powder. So technologists are trying to develop a casting powder without fluorine to avoid such disadvantages and having similar properties required for steel casting.

TABLE 10.1
Composition and Properties of Commercially Used Mould Powders

Chemical Composition	
SiO_2	30–40
Al_2O_3	2–8
Fe_2O_3	0.5–2
CaO	30–45
MgO	1–5
Na_2O	3–8
K_2O	1–5
F (mostly added as CaF_2)	5–12
C	6–15
MnO	0–2
Li_2O	0–2
Sieve Analysis (Micron) (%)	
>400	20–28
>125	>90
>63	>95
Properties	
Loose bulk density (g/cc)	0.7–0.9
Softening temperature (°C)	1,120–1,180
Melting range (°C)	1,200–1,250
Flowing temperature (°C)	1,240–1,280
Viscosity at 1,300°C (cP)	120–250
Viscosity at 1,600°C (cP)	0.5–0.8

10.3 FUNCTIONS OF THE SUBENTRY NOZZLE (SEN)

The major functions of SEN are as follows:

1. Smooth and shrouded transfer of molten steel from tundish to mould for casting
2. Prevention of oxidation of steel and any nitrogen picked up from the surrounding environment during transfer
3. Easy movement of molten steel within the mould and during casting, with no turbulence and splashing
4. Reduction in heat loss of molten steel to surrounding environment
5. Provision of a controlled flow pattern of molten steel within the mould, thus reducing the chances of mould powder entrapment in steel
6. An aid in the entrapment and floating up of the non-metallic inclusions present in molten steel, thus improving steel purity

10.4 SUBENTRY NOZZLE AND SUBENTRY SHROUD

The *submerged entry nozzle* is a single-piece refractory item that serves the purpose of a nozzle, to collect molten steel from the tundish bottom, and also acts as a shrouding tube to transfer the collected steel to the metal pool of the continuous casting mould. Any damage or degradation in the nozzle part or in the shroud tube part requires the complete change of the whole SEN, affecting productivity and the economy. To make the process easier, many a times, the nozzle part and the shroud tube are made as two separate refractory items, where the shroud is mechanically held at the bottom end of the tundish nozzle. These two separate refractory items are called tundish nozzle and submerged entry shroud (SES). From a functional point of view, SES reassembles with the ladle shroud. The replacement of SES is easier and can be done manually (also automatically) during the casting process, making its use convenient and easier, especially for billet, bloom, and slab casting.

Advanced continuous steel casting processes use slide gate plates to control the flow of molten steel from tundish to mould, replacing the stopper rod, and SES is essential for such systems. SES fits to the collector nozzle of the slide gate refractory for metal transfer purposes. SES also works well in stopper rod applications, where the tundish nozzle and the stopper rod arrangement control the flow rate. The junction between the nozzle and the SES may be a standard conical joint or a butt fit joint. For the proper sealing of the joint and to avoid any air ingress, ceramic gaskets are used to ensure airtight connections. The use of SES in conjunction with the tundish nozzle is an alternative to submerged entry nozzles.

10.5 REFRACTORY COMPOSITIONS AND ZONES OF SUBENTRY NOZZLE

During the initial developments of SEN, resistance against thermal shock, corrosion, and abrasion was considered as the primary requirement. The developmental activity for SEN was started with fused SiO_2-based compositions. With the progress of time, various drawbacks of fused silica for SEN application have been exposed, like poor chemical compatibility with basic steelmaking process (basicity of slag and steel), high corrosion even in the minor presence of manganese in steel (due to low-melting Mn-silicates formation), etc. So with the progress of the continuous casting process, the fused silica–based nozzles are gradually replaced by alumina-carbon-based compositions. The presence of carbon (graphite) in the refractory increases the thermal conductivity and reduces the thermal expansion properties, thereby improving the thermal shock resistance. Moreover, graphite (the source of carbon) is a soft material with low elastic modulus and imparts deformability within the composition compared to the oxide constituents, like alumina, and so also improves spalling resistance. It also improves corrosion resistance due to its non-wetting character. But on the contrary, the presence and increasing amount of carbon in the refractory composition reduce the strength, abrasion, and erosion resistance. Hence, the composition of the SEN and the constituents used to obtain the composition are important to achieve the desired performance and service life.

Further, with the progress of time, it has been identified that different portions/zones of SEN are exposed to different degrading activities as per the conditions prevailing in that particular area for continuous casting. Hence, the properties required for different zones of SEN are different. As per the application-specific zonal requirements, the SEN is primarily divided into four major zones. Details of the zones, the properties required at different zones, the major degrading factors acting on the refractory at different zones, and the refractory compositions used at different zones are discussed in what follows. The different zones of a SEN are schematically shown in Figure 10.2.

10.5.1 SEAT

Seat is that specific zone of the SEN that allows it to sit and properly fit within the tundish bottom. In other words, a *seat* is the upper part of the SEN that collects the molten steel to transport the same towards the mould. Seat has to work in conjunction

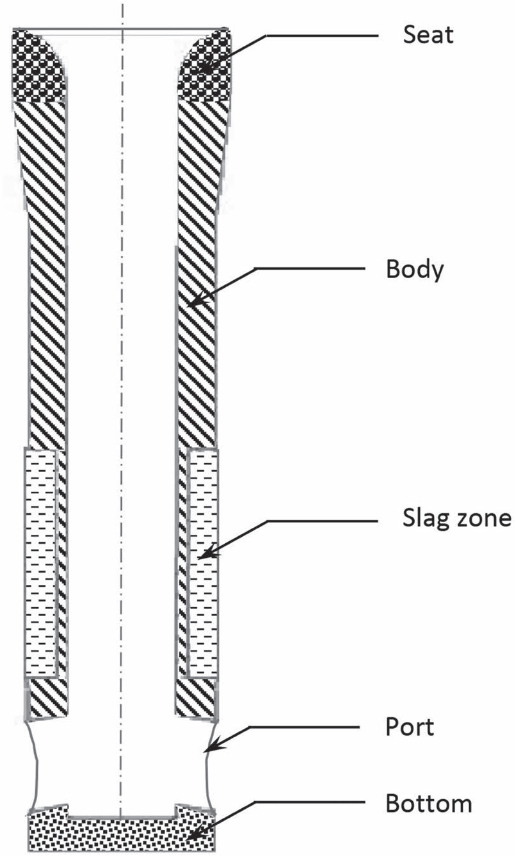

FIGURE 10.2 Schematics of SEN showing different zones of the subentry nozzle.

with the tip/nose portion of the monoblock stopper (MBS) to control the flow of molten steel for casting. The design/contour of the inner surface of the seat area has to match with the outer surface contour of the nose/tip of MBS for perfect sealing and flow control of liquid steel. The refractory of the seat area is in deep and prolonged contact with the molten steel and also has to withstand the effect of vortex formation due to the flow of molten steel within the tundish. Thus, the refractory used in the seat area faces severity in degradation from the multiple actions of the steel flow. The refractory composition needs to be corrosion-resistant against steel chemistry, wear- and abrasion-resistant against the molten steel flow and vortex formation. Primarily, the refractories are based on an alumina–carbon system containing little silica for mullite formation. Again, to produce clean steel, many of the steel compositions are processed through various secondary steelmaking processes, like Al killing and Ca treatment. Thus, the Ca content in steel (even in ppm level) becomes high. Hence, to resist the Ca attack on the refractory, basic MgO-based compositions are becoming popular, replacing the conventional alumina-carbon-based ones. Table 10.2 provides some refractory compositions and their properties that are important for the seat area.

10.5.2 BODY

The *body* of the SEN is its major portion. This zone performs the main activity of shrouded transfer of molten steel from tundish to mould without any splashing or much turbulence and preventing heat loss, oxidation, and nitrogen pickup for the steel. The tube-shaped body portion has to bear all the abrasive and corrosive actions of the

TABLE 10.2
Major Constituents and Properties of Refractory Compositions Used for the SEN Seat Area

	Chemical Composition, %			
	Type 1	**Type 2**	**Type 3**	**Type 4**
SiO_2	5–7	3–5	4–6	
Al_2O_3	65–70	65–70	80–85	
MgO				70–75
ZrO_2		4–6		
C + antioxidant + LOI	22–25	20–22	10–12	15–25
	Properties			
Bulk density, g/cc	2.5–2.55	2.55–2.6	2.8–2.9	2.4–2.5
Apparent porosity, %	15–18	15–18	10–12	14–16
Cold strength, MPa	25–28	28–30	40–45	22–26
Cold MOR, MPa	10–12	10–12	16–18	10–12
Speciality	Standard	Corrosion- and abrasion-resistant	Corrosion-, abrasion-, and oxidation-resistant	Resistant to in steel with Ca >30 ppm

molten metal flow in its inner wall and also has a huge thermal gradient between its inner and outer walls. Again, it has to bear the impact of molten steel flow and prevent any crack or damage formation that may lead to failure of the SEN. So the refractory composition for the body portion needs to be resistant against abrasion, erosion, wear, and corrosion of the molten steel flow and also has to be strong against thermal shock. To attain the required properties, the body composition is mainly based on an alumina–carbon system with some silica content, aiming to form mullite for better thermal shock resistance. Carbon content varies in the compositions for different application sites as per the corrosiveness of the steel, thermal gradients prevailing, and clogging/alumna build-up tendency (discussed in detail later). Zirconia is also added in certain compositions to boost up the erosion, abrasion, and wear resistance. In a few special cases (like the presence of Mn in steel), silica is avoided and SiC is used to enhance the thermal shock resistance. Table 10.3 provides information on refractory compositions and their common properties that are important for the body of the SEN.

10.5.3 SLAG BAND

Slag for SEN means the layer (mostly molten) of mould powder/flux. It is intentionally introduced on the top open part of the mould for lubrication of molten steel flow with the mould wall, and also to cover the liquid steel pool in the mould, preventing oxidation, heat loss, and nitrogen pickup (discussed in Chapter 10.2). The mould powder is very aggressive in the corrosion of refractories, as it has a very low melting point, has very low viscosity at the steel casting temperature, and contains a huge amount of fluorides in the composition. During the initial developments and use of

TABLE 10.3
Major Constituents and Properties of Refractory Compositions Used for the SEN Body

	Chemical Composition, %				
	Type 1	**Type 2**	**Type 3**	**Type 4**	**Type 5**
SiO_2	10–15	3–5	15–17		20–25
Al_2O_3	50–55	65–70	40–45	60–65	25–30
ZrO_2		4–6			28–32
SiC + Si				5–10	
C + antioxidant + LOI	30–35	20–22	35–40	25–30	15–18
	Properties				
Bulk density, g/cc	2.3–2.35	2.55–2.6	2.2–2.3	2.4–2.45	2.7–2.8
Apparent porosity, %	15–18	15–18	18–20	15–18	14–16
Cold strength, MPa	20–25	28–30	20–22	25–28	24–26
Cold MOR, MPa	10–15	15–18	8–10	12–14	10–12
Speciality	Standard	Corrosion- and abrasion-resistant	Thermal shock–resistant	Thermal shock–resistant (no mullite)	Stainless steel casting

SEN, there was no separate lining/band/sleeve for the slag zone. The same body composition was used from the bottom of the seat to the port (exit end of liquid steel) region of the SEN. These types of SENs had a very low life due to the huge corrosion in the mould powder contact region, and the failures were mostly due to the slag zone corrosion. Hence, special attention for corrosion resistance was required for the slag contact area only, and that, too, only for the outer surface of SEN. Such requirements are not there at the inner wall. Research and development activities have modified the design of the SEN, and a separate refractory band/sleeve is introduced at the slag contact outer wall, having excellent slag corrosion resistance. Most of the slag band refractories are based on a zirconia–carbon composition wherein the chemical inertness of zirconia is utilized to improve the corrosion resistance. Also, the compactness/densification of this slag band refractory is important as the mould flux is low-viscous and highly fluidic at the steel casting temperature and can easily penetrate in the refractory structure through the pores and corrode/damage the refractory. Table 10.4 provides some refractory compositions and their basic properties that are commonly used for the slag band of SEN.

10.5.4 BOTTOM

The portion of SEN that is completely immersed in the molten steel pool within the mould is the bottom. This part is important and critical as it contains the port(s). *Ports* are the exit hole for the molten steel from SEN to the molten steel pool within

TABLE 10.4
Major Constituents and Properties of Refractory Compositions Used for SEN Slag Band and Bottom

	Chemical Composition, %					
	Slag Band				**Bottom**	
	Type 1	**Type 2**	**Type 3**	**Type 4**	**Type 1**	**Type 2**
SiO_2	4–6				3–5	4–6
Al_2O_3	60–65				65–70	80–85
MgO		3–4	2.5–3	3.5–4		
ZrO_2		75–80	65–70	80–85		
C + LOI	25–30	12–15	22–25	10–12	25–28	10–12
	Properties					
Bulk density, g/cc	2.5–2.55	3.7–3.75	3.25–3.3	3.75–3.8	2.5–2.6	2.8–2.9
Apparent porosity, %	14–16	12–15	12–15	14–16	15–18	15–18
Cold strength, MPa	22–24	28–30	24–26	30–32	25–28	40–45
Cold MOR, MPa	10–12	12–14	12–14	12–15	10–12	16–18
Speciality	Standard	Resistant to corrosion	Resistant to thermal shock and corrosion	High performance	Standard	High strength

the mould. The position, number, and design of the ports control the flow behaviour of the liquid steel and also control the casting process and performance. For conventional billet and/or bloom caster, SEN with a single-hole port is conventional and commonly used. The port is located exactly at the opposite side of the seat. As the molten steel flows in the downward direction, the turbulence intensity at the steel–mould powder interface (which is at the upper top surface of the molten steel bath in the mould [Figure 10.1]) is low. This results in lower temperature at the mould powder–liquid steel interface, resulting in lesser activity of lubrication by the mould powder and segregation defect in steel. This also increases the chances of refractory and non-metallic inclusions/impurities in the cast steel products. However, for bigger cross section of the cast products (bigger-sized bloom or slab), SENs with two or four ports are used, located at the bottom of the SEN side wall. The greater number of ports at the SEN side wall results in a turbulent flow of the liquid steel during entrance into the metal pool within the mould, which causes higher and better temperature distribution at the mould powder–liquid steel interface and better casting performance with improved cast quality. Now, the higher the number of ports, the greater the criticality of the SEN bottom portion. The bottom portion needs to withstand the greater mechanical actions (impact, erosion, wear, abrasion) of the flowing molten steel and chemical attack from the steel chemistry. Again, with the increase in number of ports in SEN, the refractory wall is reduced at the bottom zone, so the refractory used needs to be very strong to withstand all the mechanical actions associated with metal flow. Commonly, high-strength refractory compositions with high wear and abrasion resistance are preferred, and high-alumina compositions with carbon are used. Table 10.4 provides some refractory compositions and their basic properties for the bottom portion of SEN.

10.6 DEGRADATION OF SEN

SEN is a critical refractory item for the whole continuous casting process, and any difficulty faced by SEN will seriously affect the casting process. Though plenty of modifications have occurred for SEN with time, still, due to the harsh and critical application environment, it degrades fast, sometimes prematurely and suddenly, affecting the whole continuous casting process. The major reasons for the degradation of SEN are listed here and discussed in what follows.

- Cracking and failure
- Degradation of the inner lining
- Corrosion by mould powder
- Clogging/build-up formation within SEN

10.6.1 Cracking and Failure

SEN is a long refractory product having high aspect ratio (length to diameter). Further, during application, SEN faces immense mechanical stresses at the inner wall due to the flow of molten steel, which is present at a very high temperature, whereas the outer surface of the SEN above the slag band is facing the ambient industrial environment. Hence, the refractory has to withstand an enormous extent of both thermal and mechanical stresses simultaneously. Mechanical effects from the steel flow, like impact, abrasion, and erosion, are simultaneously acting along with further stresses generated due to thermal gradient in the thin-walled refractory. If, at any point, the combined effect of the stresses is greater than the strength of the refractory, then it will crack. Hence, compaction and strength development within the SEN refractory, along with compositional adjustment to reduce the thermal strain, are important for the performance and life of the SEN.

10.6.2 DEGRADATION OF INNER LINING

The degradation of the inner lining of SEN primarily occurs due to mechanical actions aroused from the flow of the molten steel and also due to the chemical actions of the molten steel chemistry. Flowing molten steel abrades the inner surface of SEN, and the wear-out effect depends on the turbulence and flow rate of molten steel. At higher rate, the effect of wear-out is more due to the greater extent of impact and abrasion of molten metal. Further, the wear-out effect is not linear with flow rate but exponential. For higher productivity, higher flow rate is commonly practiced, compromising with the wear effect of the SEN. A higher flow rate also impacts the bottom part of the SEN and may cause bottom failure. It also enhances the turbulence within the mould, causing greater mechanical stresses on the free bottom part of the SEN, submerged in the metal pool within the mould. The chances of inclusion floating are also less for a higher flow rate (casting rate), which increases the chances of entrapment of inclusions within steel and degradation in the cast steel quality.

Again, the chemistry of molten steel, its inclusions, and its additives chemically affects the SEN refractory. Alumina, commonly the main component of SEN, reacts with the inclusion/additives of molten steel, causing wear-out of the lining. High-calcium, high-oxygen, and Mn-containing steel causes significant damage to the inner lining of the SEN. Calcium reacts with alumina, forming low-melting Ca aluminates which are washed away by the flowing steel. The presence of high oxygen causes direct oxidation of carbon and damages the lining. Further, carbon also gets oxidized due to the presence of FeO, MnO in steel (as inclusions), making the lining porous and weak.

$$\mathrm{FeO} + \mathrm{C} = \mathrm{Fe} + \mathrm{CO}$$
$$\mathrm{MnO} + \mathrm{C} = \mathrm{Mn} + \mathrm{CO}$$

Moreover, any air ingress through the joints/crack/gap due to the pressure difference between the seat (top) and port (bottom) portion of SEN may oxidize the carbon present in the SEN refractory. Air ingress may also cause oxidation of steel and nitrogen pick-up. Purging of Ar gas is a possible remedy to prevent such air ingress and deterioration. Again, if the SEN composition contains fused silica to improve thermal shock resistance (reducing graphite content) without affecting the mechanical properties, then the fused silica may crystallize to cristobalite phase at steel casting temperatures and may further react with the carbon present in the composition. The reaction products, namely, silicon monoxide and CO, both are in gaseous state and escape from the refractory, causing a porous and weak refractory structure, leading to fast erosion and wear-out.

$$\text{Fused silica} \rightarrow \text{SiO}_2\ \text{(cristobalite) (at T > 1,300°C)}$$
$$\text{SiO}_2\ \text{(cristobalite)} + \text{C} = \text{SiO (g)} + \text{CO (g)}$$

10.6.3 CORROSION BY MOULD POWDER

A subentry nozzle (or shroud) delivers the molten steel within the molten steel bath/pool of the casting mould. It remains submerged within the metal pool after passing through the layer of molten mould powder floating on the molten steel bath within the casting mould. Thus, the outer surface of the middle and the lower parts of the SEN are in direct and constant contact with the molten mould powder during operation. The low-melting, low-viscous, and highly corrosive fluorine-containing mould powder causes severe corrosion in the contact area of the refractory that is the outer surface of the SEN. The thickness of the mould powder contact area of SEN decreases sharply with casting time due to corrosion and becomes a serious threat to the casting process and operational safety. The bottom portion of the SEN, below the corroded line, may fall off, leading to breakage and failure of the SEN. The corrosive effect of the mould powder is much stronger and aggressive than corrosion by the molten steel at the inner wall of the SEN (primarily due to steel chemistry). Figure 10.3 shows a photograph of SEN which is rejected due to corrosion by the molten mould powder.

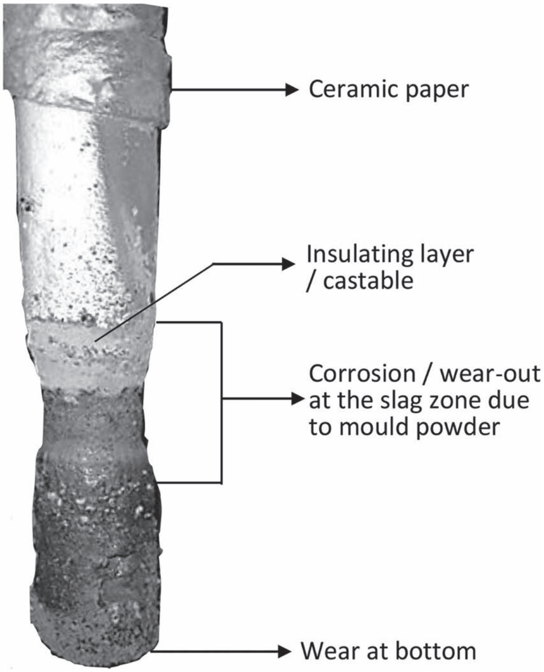

FIGURE 10.3 Photograph of mould powder/flux-corroded SEN.

The mould powder is highly corrosive for refractories as it contains multiple alkalis (Na_2O, K_2O, Li_2O) and alkaline–earth oxides (CaO, MgO) in the composition along with a high amount of fluoride (CaF_2), used for lowering the viscosity of the mould flux. The main body composition of SEN (Al_2O_3-C) performs poorly against mould flux and fails catastrophically, resulting in very low service life.

10.6.4 CLOGGING/BUILD-UP FORMATION WITHIN SEN

The quality of casting of steel is dependent on the flow rate and the flow pattern of molten steel coming out through the SEN. Any obstacle in the path of the flowing liquid steel will reduce the flow rate and affect the flow pattern, finally affecting the casting process and cast quality. Clogging or build-up formation is a solid or semi-solid obstacle that develops on the inner wall of the SEN, affecting the liquid steel flow dynamics, reducing the steel flow rate, changing the flow pattern in the mould, and finally, affecting the casting of steel. There can be four different types of clogging, each from a different origin, as detailed in the following.

1. *Agglomeration of deoxidation products.* It consists of deoxidation products, like alumina, titania, zirconia, etc., commonly observed with the same composition in the mould with a typical size of 1–20 μm. These deoxidation products sinter/agglomerate together to form a network, which causes the clogging with or without the incorporation of solidified steel.
2. *Solidified steel build-up.* Molten steel may solidify within the nozzle due to excessive heat loss of lesser heating (superheat), causing the deposition at the SEN inner wall and clogging.
3. *Deposition of complex oxides.* Clogs close to the port area are found to be a mixture of deoxidation products and mould powder. Also, clogs with Ca-bearing compounds and deoxidation products are observed for Ca-treated steel.
4. *Build-up of reaction products.* Clogging is also found to be made up of deoxidation products due to the reaction between the deoxidant and air/oxygen (from air ingress or generated due to reactions within steel). These are commonly observed as a layer/deposited film instead of a deposited agglomerate.

However, the clogging/build-up formation is majorly found to be made up of alumina and commonly termed alumina clogging or alumina build-up.

The formation of alumina build-up/clogging is a complex phenomenon wherein a network alumina forms on the inner wall of the SEN that grows into a clog/obstacle by further accumulation of alumina or other non-metallic inclusions, and even molten steel droplets. Alumina is commonly present as inclusion in the liquid steel, especially for the Al killed steel due to the reaction between the dissolved oxygen in steel and the added deoxidizers (Al metal). In situ–formed nascent nanosized alumina particles in flowing molten steel sometimes fail to reach the slag layer for lesser-buoyant forces (due to its finer size) and the requirement of longer time to float to reach the slag layer. These alumina particles are carried away by the movement of the liquid steel. Oxide particles also form due to the oxidation of molten steel during transfer within the SEN, which also helps in forming the clogging. Alumina impurities in molten steel may also come from the steel contact refractories due to wear-out by the flowing steel. The inclusion grows by further deposition/accumulation of inclusions suspended in liquid steel (including alumina) and even by liquid steel, layer by layer. The impurity inclusion thus formed and grown remains suspended and moves along with the flowing molten steel.

This suspended inclusion within the flowing molten steel gets adhered to the SEN inner wall surface, giving rise to a mesh-like configuration. Since the flow velocity of the molten steel decreases closer to the inner wall (due to frictional force), inclusions move downward slowly at the boundary layer, and the velocity is almost nil at the interface with the refractory. So the inclusions reaching near the interface do not flow downward and remain in contact with the refractory, causing build-up. The adhered mesh-like alumina network structure acts as a nucleation site, and it facilitates the further accumulation of suspended inclusions and other impurities from steel. Thus, the adhered inclusion on the SEN inner wall continuously grows with time (steel flow), and the aggregation of alumina inclusion converts to "build-up" formation and clogging. Further, surface roughness of the refractory wall helps fix and hold the inclusion in a better way. Any wear-out of the refractory inner wall acts as an incubation point for the inclusion and the clogging cluster to grow. Also, the oxidation of carbon from the inner wall and any carbon picked up by molten steel cause surface irregularities and help adhere the inclusion on the wall. The rapid cooling of molten steel due to the high thermal conductivity of the SEN wall may also cause the solidification of steel in contact with the wall and may also lead to the build-up of obstacles. The temperature gradient of the molten steel (lower temperature towards the wall) also acts as a driving force for the adhesion of the inclusions.

The most common clogging on the SEN inner wall is due to alumina. Two major types of alumina clogging are observed, namely, *build-up alumina* and *network alumina*. In build-up alumina, the chemical and structural similarities of the suspended alumina particles in molten steel with the alumina present in the SEN inner wall refractory lining cause affinity for the suspended particles to stick and adhere on the refractory alumina particles, thus resulting in the alumina build-up on the inner wall and clogging. Also, the network of alumina may be formed on the inner wall of the SEN due to a chemical reaction. Interfacial chemical reactions between the refractory and the molten steel may occur due to the release of oxidizing gases from the refractory by carbo-thermic reaction between the refractory's components. Then, these gases react with the molten steel, resulting in the formation of oxide phases. Al metal present in steel as deoxidant may get oxidised by gaseous oxides in the SEN inner wall vicinity as per the following:

$$\mathrm{SiO_2\ (s) + C\ (s)\ [present\ in\ SEN\ refractory] \rightarrow SiO\ (g) + CO\ (g)}$$
$$\mathrm{3SiO\ (g) + 2Al \rightarrow 3Si + Al_2O_3}$$
$$\mathrm{3CO\ (g) + 2Al \rightarrow 3C + Al_2O_3}$$

Though the inclusion primarily consists of alumina, with varying steel grades and processing conditions, the build-up obstacle also contains iron aluminate (due to the reaction

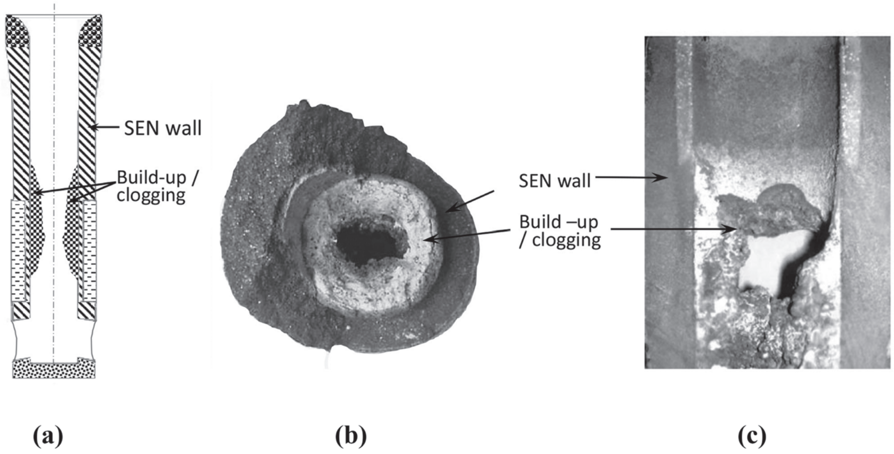

FIGURE 10.4 Photograph of clogging in SEN: (a) schematic figure; (b) broken piece of clogged SEN; (c) vertical cross section of clogged SEN.

between alumina and oxidized steel), calcium aluminate (commonly found in Al-killed and Ca-treated steel), CaO-Al_2O_3-CaS (seen in high sulphur-containing, calcium-treated Al-killed steels), Al_2O_3 and Ti oxides (Ti-treated Al-killed steel), MgO-Al_2O_3, solid steel (due to rapid heat transfer through SEN wall), etc. The grown inclusion clog/build-up reduces the flow path of steel and hampers the flow pattern, thus greatly affecting the steel casting and steel quality. The clogging is a major reason for SEN failure and rejection and also affects the costing process and quality of cast products. Figure 10.4 shows the schematic formation of clogging on the SEN inner wall with the photographs of the broken piece and cross section of SEN that is rejected due to clogging.

10.7 TECHNOLOGICAL IMPROVEMENTS AND FUTURE POSSIBILITIES

Developmental work is going on continuously in the field of refractories, and more prominently for the refractories used in the iron and steel industries. Any improvement in the performance and service life of the refractories will, in turn, improve the productivity and working environments for the user industries. In the same line, the refractory technologists are trying to improve the quality and life of the SENs by overcoming the degrading factors to provide uninterrupted and long steel casting sequences. Some of the technological improvements that have already been incorporated and are under implementation for the improvement in performance of SEN are detailed in what follows.

10.7.1 Improvement in Corrosion Resistance of the Slag Band

The improvement in the corrosion resistance of the mould powder contact area of the SEN is achieved by using a special corrosion resistant refractory band in the slag (mould powder) contact zone. Details of the refractory compositions for such application are provided in Table 10.4 and discussed in Chapter 10.5.3. The ZrO_2-C mix is selected for the SEN slag line for its high corrosion and dissolution resistances against mould flux. Commonly, for commercial applications, CaO- or MgO-doped partially stabilised zirconia is used for the optimization of performance along with economy (in comparison to Y_2O_3 or CeO_2 doping, which makes the zirconia costly). However, for a very high level of Na_2O and K_2O content in mould flux, the zirconia–carbon mix also suffer from corrosion. Further, the amount of ZrO_2 in the zirconia carbon composition is important for the performance and life of the SEN. Corrosion resistance of the mix is significantly high for mixes containing above 60% of zirconia; however, the mix suffers from thermal shock when zirconia is above 80%. So to optimize the properties and performance. about 70–80% zirconia content is used for the slag band refractory. Also, it has been observed that fine grained ZrO_2 particles have a higher dissolution rate in highly corrosive molten mould powder, causing penetration of the liquid in the slag band refractory during long run. To restrict such dissolution and degradation of SEN, ZrO_2 is used as aggregates with high purity.

10.7.2 PREVENTION OF CLOGGING/BUILD-UP FORMATION

The most common cause for the failure and rejection of a SEN during use is the clogging/build up formation in its inner wall. For smooth steel casting it is essential to prevent the formation of clogging/build-up. Any such formation within SEN affects the molten steel flow rate and flow profile and finally affects the casting performance and steel quality. Once clogged, the SEN needs to be replaced immediately by a fresh one and this replacement affects the refractory cost, casting sequence, productivity, etc. The prevention of any clogging formation in SEN improves the durability of SEN, stable production of steel, improvement in steel quality, reduced downtime, better productivity, lesser waste generation, better energy efficiency, etc.

Prevention/reduction in clogging can be substantially achieved by reducing the suspended oxide particles (non-metallic inclusions), in the steel; that is by improving the steel cleanliness. The incorporation of ladle refining practice (like vacuum degassing processes), prevention of oxidation of liquid steel during transfers (leak proof metal transfer facility from ladle to tundish and tundish to mould), covering of tundish surface, prevention of slag carryover, restricting slag (mould powder) entrapment in steel, etc essentially improve the steel cleanliness that in turn reduces the chances of clogging/build-up formation. Also, certain simple modifications in SEN composition, design, incorporation of argon gas purging, etc can reduce and restrict the clogging/build-up formation. Different technological improvements and measures that are/can be introduced in SEN to reduce the chances of clogging/build-up formation are detailed in the following.

10.7.2.1 Compositional Adjustment

Inclusion network formed within liquid steel sticks to the refractory wall (primarily due to the reduced flow at the boundary layer with chemical/compositional similarity and surface roughness of SEN inner wall) results in clogging. Hence, modification in refractory composition, especially for inner wall (smooth and non-similar to inclusion chemistry), will reduce the sticking/adherence tendency of the inclusion network, and thus will reduce/nullify the chances of clogging/build-up formation. This modification for the inner wall lining can be achieved by using different refractory compositions for the inner wall of SEN, as detailed in what follows.

10.7.2.1.1 Carbon-Free Composition

Conventionally, carbon is a preferred component for refractories that are in contact with the molten metal due to its non-wetting character. But carbon present in contact with molten steel (like the inner wall of SEN) may get dissolved in molten steel (carbon goes to the interstitial void of the iron structure, forming a solid solution) or oxidized (by molten steel inclusions/refractory components) and gets removed from the lining. Thus, the inner wall refractory lining of SEN becomes porous and rough, which helps in firm clogging/build-up formation. Furthermore, the oxidizing reaction of the carbon component in the SEN inner lining (commonly Al_2O_3-C composition) causes a subsurface tension gradient within the molten steel. This subsurface tension gradient becomes the driving force for the adhesion of inclusions on the inner wall.

The carbon-free composition for the SEN inner wall lining nullifies the chances for carbon dissolution and oxidation. Hence, there is no degradation of surface roughness and smooth inner wall surface is maintained. Chemical reaction of the inner wall refractory with the steel inclusions and the wear-out effects are reduced due to the absence of softer carbon in the composition. Also, the subsurface tension gradient can be suppressed by carbon-free lining restricting the adhesion of inclusions on the SEN inner wall. Further, the absence of carbon in the inner wall lining will reduce the thermal conductivity of the SEN greatly. This will nullify any rapid cooling of steel, deposition of solid steel and inclusion adhesion tendency on the inner wall. Thus inclusion network sticking to the inner wall and build up formation are greatly suppressed, improving the performance of the SEN. Flux containing carbon free lining was found to be further beneficial in restricting the clogging formation even under severe clogging conditions and without any argon purging support (discussed later). A carbon-free composition also reduces the carbon pick-up of steel and improves the steel quality. Commonly, carbon-free SEN inner wall compositions are based on an alumina-silica system. Figure 10.5 shows the use of carbon-free composition in the inner wall of the SEN both as schematic diagram and in actual product.

Again, many of the carbon-free compositions and the SEN products are processed as per the conventional processing technique, using resin as the binder. The fixed carbon coming from resin after curing will result in similar effects as that of the refractory lining containing carbon as component, but with reduced extent. Hence, resin-bonded, carbon-free refractory lining has only a reduced tendency for clogging/build-up formation; it does not nullify completely. To get the complete advantage of carbon-free composition against clogging/build-up formation, the resin binder also needs to be replaced by inorganic binder.

Other than the reduction in clogging/build-up tendency, carbon-free lining also reduces the heat loss and improves the thermal shock resistance of the SEN. Further, the carbon free inner lining also provides multiple benefits, as mentioned earlier.

1. It provides strong and stable SEN inner lining, no soft/weak character due to absence of graphite/carbon and no porosity generation due to carbon removal.

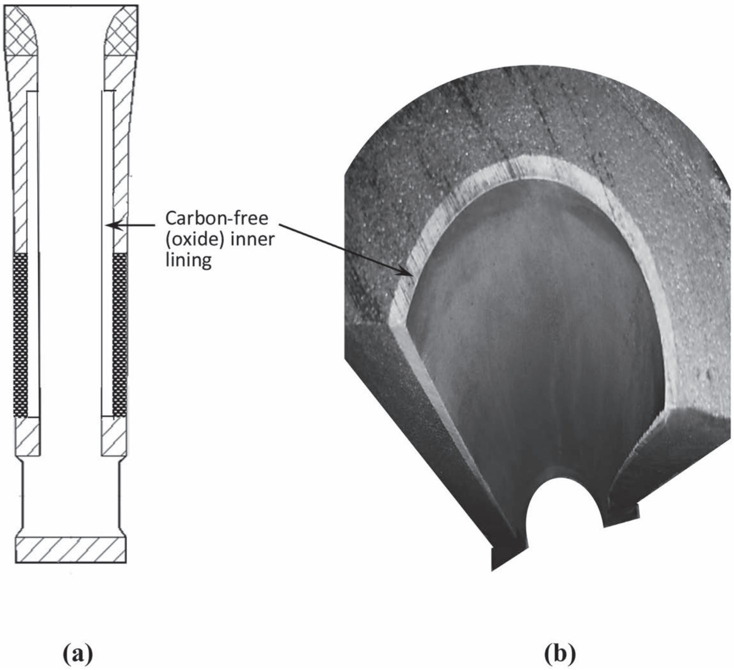

FIGURE 10.5 Carbon-free oxidized layer at the inner wall of the SEN: (a) schematic diagram; (b) actual SEN (vertical cross section).

2. It shows high corrosion resistance against high oxygen containing steels.
3. No formation of SiO (g) and CO (g) that may react with the dissolved Al present in liquid steel to form alumina, resulting in clogging.

10.7.2.1.2 Lime (CaO)–Containing Composition

Sticking/adherence of the inclusion network on the SEN inner wall can also be prevented by making the inner wall surface wettable. Whenever an inclusion network (alumina) comes in contact with the refractory wall, the wet surface will not allow the inclusion to stick/adhere on the refractory, and under the action of flowing molten steel, the inclusion will get dislodged and moved away along with the flowing steel. This wettable refractory surface is developed by using lime bearing composition that will react with the inclusion (like, Al_2O_3) present in steel and form wet (fused) Ca-aluminate compounds on the inner wall surface. The inclusion will easily be washed away by the moving steel from the inner wall without any adhesion or sticking. Thus, the wettable surface will prevent any clogging o build-up formation.

The common refractory systems used for such type of linings are $CaO\text{-}ZrO_2\text{-}C$, CaO-MgO-C, etc. Though the lime bearing inner wall composition performs well against any clogging/build up formation it may be reactive against some special steel grades (as per the composition/inclusions of molten steel) and may result in low corrosion resistance against certain grades of steel. Hence, suitability of the lining against the specific grade/chemistry of steel needs to be checked before application.

10.7.2.1.3 Spinel-Based System

The magnesium aluminate spinel is also used as the refractory composition for the SEN inner lining with a special coating material that forms liquidus and wets the inner lining of SEN during steel casting process. Inclusions of molten steel cannot adhere on the inner wall due to the wetness (liquidus phase present) and casting will occur without build up formation. This technique can widely be used for various grades of steel and provides better service performance and life for the SEN. However, matching of the coating composition with the spinel based refractory system is essential for the desired amount of liquidus formation and wetting of the SEN inner surface otherwise excess liquid formation may occur which can corrode and damage the refractory.

10.7.2.2 Argon Purging System

Argon gas purging inside the SEN is an effective means to reduce/restrict the clogging/build-up formation and improvement in overall performance of the SEN. Purging of Ar gas within SEN improves the clogging resistance due to the following reasons.

1) Formation of a film of argon gas on the SEN inner wall, thus preventing any contact of molten steel and its inclusions with the SEN inner wall refractory.
2) Formed argon film restricts any chemical reaction of the refractory components with the molten steel and its inclusions and gases (if any),
3) Ar gas can directly hit the inclusion or any deposit on the wall and remove it out from the SEN inner wall,
4) Ar gas increases the turbulence of the flowing molten steel within the SEN that forces any deposit or inclusion out from the SEN wall
5) It prevents any air ingress through the joints of SEN due to higher purging pressure (compensating any pressure drop at the seat portion due to downwards steel flow) thus reduces the chances of any oxidation and nitrogen pick up of molten steel.
6) It increases the chance of inclusion floatation within SEN, thereby improves steel cleanliness.

The purging of argon gas can be done through the nose/tip opening of the monoblock stopper (as discussed in chapter 9.5.1) or more effectively through the inner wall of the SEN using porous inserts or controlled openings. Various designs for purging Ar gas through SEN is shown in Figure 10.6. Argon purging along the inner wall of the body portion restricts any build up along the inner wall. Purging through the inner side of the seat portion helps to form an argon shield on the downward moving molten steel and prevents sticking/adherence of inclusion on the inner wall. Purging at the port portion and bottom restricts any clogging/build up formation at the port and makes uninterrupted molten steel flow and uniform and steady casting. Tailoring and modification of Ar gas flow is essential depending on the steel flow rate, deposition rate and chances of deposition. A typical argon gas purging/injection rate of 5 litres/minute of is commonly practiced for SEN and that varies between 2 to 20 l/min depending on the process requirements.

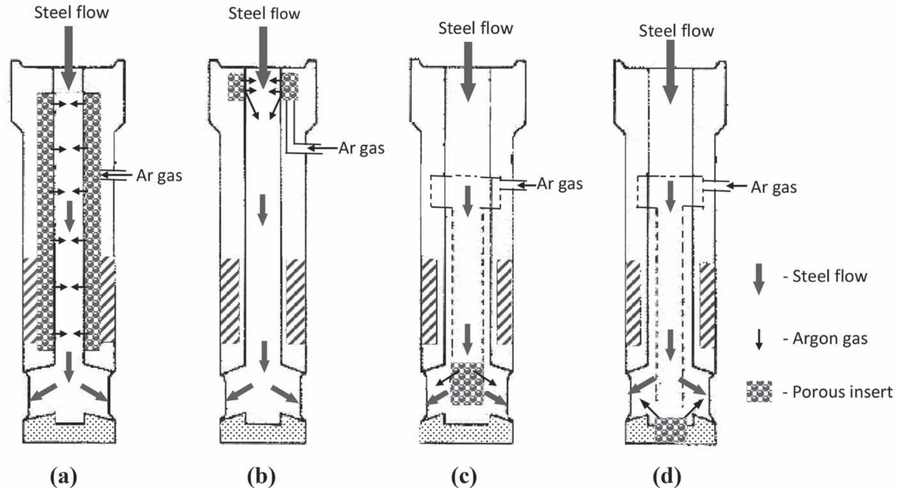

FIGURE 10.6 Different argon purging systems through SEN, A) standard, B) top injection/injection through seat, C) port wall injection and D) bottom injection

Argon purging does have certain negative features too on the casting process, like it increases certain steel defects; possibilities of Ar gas entrapment by the sloid steel shell; weakening of SEN due to presence of porous inserts/channels and cracking due to back pressure, thermal shock, etc.

10.7.2.3 Design/Geometry Modification of SEN

Modification in geometry, design, and shape of the SEN improves the performance and life and also reduces the clogging problem. Modification in SEN design is most effective against clogging formed mainly due to stagnant/reduce flow of molten steel at the inner wall of SEN. Different modifications in SEN design have been incorporated to restrict the clogging and to get uniform and uninterrupted molten steel flow are mentioned below.

10.7.2.3.1 Increase in Bore Diameter

The use of an oversized nozzle bore improves the clogging resistance as contact between molten steel and SEN wall is reduced. It is found that the gradual increase in bore diameter from the seat area to the bottom part of the SEN reduces the clogging considerably. Also, the exit velocity of molten steel (coming out of the SEN port) gets reduced, resulting in less turbulence of steel flow at the mould entry time. This also reduces the chances of turbulence of molten steel within the mould and minimizes the chances of mould powder entrapment in molten steel. SEN with sudden increased diameter at the lower end is termed as “trumpet” SEN, which produces straight and shallow flow of molten steel, ideal for bloom and billet caster with reduced defects. But the lower flow rate and the lower turbulence of molten steel in the mould may reduce the effectiveness of the mould powder/flux for lubrication.

10.7.2.3.2 Number of SEN Port

In bloom or billet casters, single-port SENs (outlet port is at the bottom end) are commonly used for simplicity. But in single-port design, the molten steel flows directly in a downward direction, from SEN to mould, resulting in much reduced turbulence within the SEN. Hence, there will be minimal effect of turbulence to remove any build-up formation at the SEN inner wall. Further, as the molten steel flows downwards directly within the mould, the turbulence effect at the steel–mould powder interface (at the top face of the mould) is significantly low. This again reduces the temperature at the steel–mould powder interface, causing freezing (less melting) of mould powder and increase in the chances of centre segregation defects in steel. Hence, the use of two or four ports at the SEN side wall (especially for bigger blooms, >250 mm diameter/square side) is beneficial for better steel casting process. Ports at the side wall increase the turbulence of molten steel within the SEN (closed bottom end restricts the direct downward flow of molten steel to the mould, thus causes turbulence within SEN) and also in the casting mould, which helps in the reduction of clogging within SEN and a better performance of the mould powder, resulting in improvement in cast steel quality.

10.7.2.3.3 SEN Port Design

The shape of the SEN outlet port is also important for steel casting. It has been observed that turbulence intensity at mould powder–steel interface is lower for rectangular/angular-shaped ports compared to that of oval/roundish-shaped ones. Hence, for the angular port, chances of mould powder freezing are high due to the lower temperature at the interface (lesser turbulence), which also increases the chances of inclusion and centre segregation defects in steel.

Further, in conventional SEN port design, both the upper and lower walls of the port have a downward slope, aiming for a better flow out of the molten steel from SEN to mould. However, such a design causes a greater extent of steel flow separation and flow stagnation at the walls of the port, allowing time for deposition/build-up formation at the port wall. The design modification of the port wall, by making a downward slope for the upper wall of the port and an upward slope for the lower wall of the port, has shown to reduce the crisis. This modified design of the port reduces/minimizes the travel path gap among the different steel flow paths and thus reduces the flow separation. Figure 10.7 shows the modification in the port design in

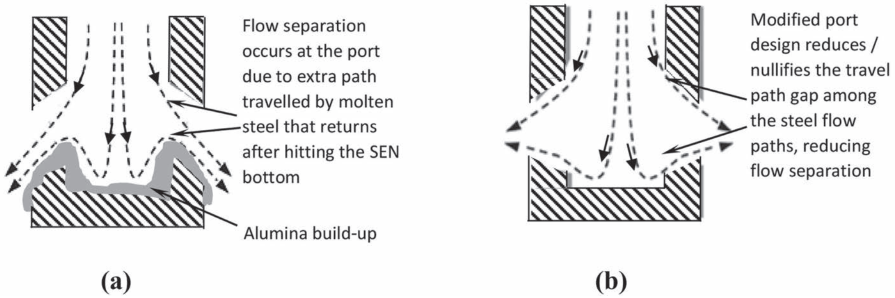

FIGURE 10.7 Modification in SEN port design to minimize the flow path gap of molten steel to reduce clogging.

SEN that reduces the molten steel flow path gap and also the clogging. A modified port wall design has reduced/nullified the stagnation of molten steel flow at the port, producing an evenly discharged molten steel flow through the ports, with minimum clogging on the port walls, resulting in uniform and defect-free casting.

10.7.2.3.4 Design Modification in SEN Inner Wall

Commonly, the SEN inner wall has a straight, smooth surface for easy downwards flow of molten steel. Modification in the design of the SEN inner wall surface affects the flow pattern and turbulence in molten steel stream. Providing protrusions on the inner wall or internal annular steps (5–10 mm each) at the mid-height portion of SEN reduces the build-up/clogging tendency. This also reduces the impact/impingement effect of molten steel flow on the SEN inner wall. The design also reduces any bias of flow entering into the mould. The annular step design minimizes the formation of a boundary layer at the junction between the molten steel and the inner wall of the refractory within the SEN and thus minimizes the build-up formation and clogging tendencies, which are otherwise strong due to the presence of a boundary layer in conventional SEN.

10.7.3 COATING ON SEN

10.7.3.1 Glaze Coating

The SEN body has an inner wall temperature equal to that of the liquid steel in contact, whereas the outer surface is facing the open ambient environment. Due to the presence of carbon in the refractory composition (used primarily to improve the corrosion and thermal shock resistances), heat is transferred from the inner side to the outer side of the SEN wall. Thus, the carbon present in the outer wall refractory is at a high temperature and exposed to the open (oxidizing) environment, thus getting oxidized. Primarily, to prevent the oxidation, antioxidants are added in the composition, and further, the SEN is coated with a glaze (having low maturing temperature, ~600°C, and high application temperature, ~1,500°C) that covers the outer surface of SEN to restrict the oxygen/air to be in contact with the outer wall (carbon in the composition) and prevents oxidation.

10.7.3.2 Insulating Coating

The high thermal conductivity of carbon-containing SEN body composition transfers the heat from the inner side to the outer side of the SEN wall, thus cooling the liquid steel rapidly that is in contact with the SEN inner wall. This increases the chances of scrap/solidified steel formation that builds up and grows on the SEN inner wall. An increase in the insulating characteristics of the SEN wall by providing insulating coating, ceramic papers, etc. on the outer wall of the SEN (externally) reduces the heat loss, thus minimizes the freezing tendency of steel in contact with the wall and improves the clogging resistance. The use of insulating coating also improves the thermal shock resistance, as the temperature gradient between the inner and the outer side of the SEN refractory wall is reduced. Also, proper preheating of SEN prior to use and localized heating at the positions of clogging also improve the clogging resistance. A coating of insulating castable on the SEN outer surface or wrapping the outer surface by ceramic papers improves the performance and service life

FIGURE 10.8 Subentry nozzle coated with insulating castable.

of the SEN. Figure 10.8 shows the photograph of a SEN that is coated with insulating castable. Again, as the insulating coating improves the thermal shock resistance of the SEN, it allows the use of SEN without preheating, technically called *cold start SEN*. Cold start SENs are especially important when a running SEN needs to be replaced during casting operation. They reduce the preheating time and cost.

10.7.4 Quick Changing/Tube Changing Device (QCD/TCD)

In the continuous casting process, to maintain the correct flow of molten steel from tundish to mould, the SEN is required to be replaced or exchanged once its life is over, due to its wear-out, erosion, cracking, clogging, and blockage (impeding the flow pattern in the mould), etc. For long casting sequences, where casting from multiple ladles is done continuously, the SEN replacement needs to be done quickly and safely in order to maintain the uninterrupted flow of molten steel, casting sequence (without considerably lowering the casting speed), quality of the cast product, and to protect personnel and plant machineries. For this purpose, a special quick changer/tube changing device (QCD/TCD) is installed at the bottom of the tundish that allows the replacement of the SEN with a marginal reduction (around 25%) in casting speed. The QCD actually uses the submerged entry shrouds (SES) rather than the SENs. The benefits for using such a device in a continuous casting process are as follows:

1. Replacement of SES without affecting the uninterrupted casting sequence
2. No lifting of tundish from its casting position for the replacement
3. Better scheduling of casting sequence

4. Higher caster productivity
5. Reduction in tundish skull formation
6. Reduction in biased flow and downward turbulence of molten steel in the mould, and also in back draft flow or suction flow
7. Improvement in casting flexibility and shop floor safety
8. No effect of SES replacement on cast steel grade and quality
9. Reduction in the number of tundish requirements and savings in the tundish refractory cost
10. Nearly no aborted casting due to SEN failure, and thus improving overall efficiency and the economy

Before the introduction of the QCD system, manual nozzle exchange used to be done. In manual replacement, first, the monoblock stopper (MBS) closes the nozzle opening and then the changeover used to be done by lifting the preheated SEN with the help of the holder, and the worn-out or clogged nozzle was replaced by the new one. Nozzle changing for the slide gate flow control system used to take place exactly in the same manner; slide gate throttling was almost in closed position, casting speed was reduced to minimum (~ 0.2 m/min), and the strand was operated in cast interruption mode. The total time required for nozzle changeover used to be around 3 mins.

The introduction of the QCD system extended the casting duration, providing higher productivity and reduction in operational cost. QCD also helps nullify/reduce the generation of low-quality cast products, as the casting speed is maintained above the minimum level, even during the changeover time (which is not possible for the case of SEN without a QCD system). In the QCD system, a tundish nozzle and subentry shroud (SES) are used (not SEN), and both are connected to each other through a cassette system. The special type of tundish nozzle used has a flat bottom side, whereas the SES has a flat tundish shroud plate at its top part (Figure 10.9). The

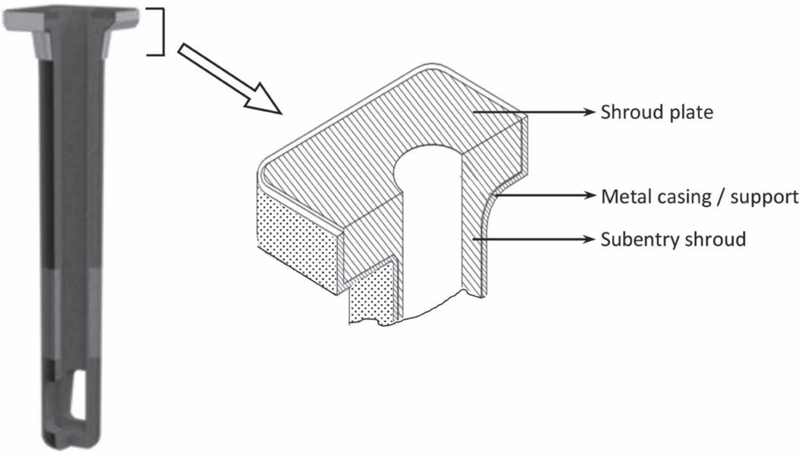

FIGURE 10.9 Subentry shroud for TCD application: (a) actual photograph; (b) schematic showing the flat shroud plate.

flat bottom of the tundish nozzle and the flat shroud plate are connected through the cassette and are in a closed, airtight contact condition during the casting sequence. When the SES in use is worn out/needs replacement, the new, preheated SES is loaded in the cassette mechanism and slowly immersed into the molten steel without lifting the tundish. The stopper is closed momentarily, with reduced casting speed; the new SES is pushed in the cassette to the casting position. It further pushes out the worn-out nozzle outside of the mechanism. Both hydraulic and pneumatic drive options can be used for moving the new SES in the cassette channel, pushing out the old one. Once the new SES is fully positioned, the stopper is opened again, and the casting speed is made to a normal value.

The use of the QCD system can reduce the requirement of tundish by about 60% per year, and the overall cost of tundish refractory by more than 40%. TCD also greatly reduces the flying tundish breakouts and strand closures due to SEN failure, like breakage, clogging, etc.

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