Major determinant of service life in magnesia-graphite slagline refractory lining in secondary steelmaking ladle furnace

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Abstract. Magnesia-carbon (MgO-C) refractory bricks are used for slagline lining in secondary steelmaking to withstand the harsh basic slag and high temperature environment. In an operation using bottom purging ladle furnaces, preliminary study of residual bricks after lining failure shows less than 50 vol. % of the MgO-C bricks is typically used before the linings would fail. Slag basicity, high temperature oxidation and erosion are known as root causes of different degradation modes in this application. This work, presented in part herein, seeks to identify the dominant cause for this resource utilization inefficiency. Slag basicity excursions and thermal fluctuations versus service lives and residual thicknesses of each MgO-C brick after lining failure, were studied for five ladle linings. Optical and electron microscopy were also used in further post-mortem of the residual bricks. The operation data that showed thermal spikes above 1600 °C and acidic slags with basicity usually below the ideal of 1.67. Micrographs from the slag-refractory interfaces indicated effect of this operational extremes showing thermal shock cracking, slag penetration and evolution of phase due to the slag-refractory interactions. However, bricks evidencing these effects were not the most worn. Slag basicity attack and high temperature oxidations are diffusion controlled and did not proceed aggressively by themselves. Rather, least residual thicknesses were found in bricks from columns adjacent to the two purging gas entry points at the bottom of the ladle. Up to 86 % wear were obtained at such points, in contrast to 24 % for bricks farthest from this effect. Turbulence from the purging gas is thus responsible for localized and highest lining consumption rate that decimates lining life in these ladles. Without this purging turbulence, such as in induction stirring, it can be projected that the lining life can triple, with obvious economics and environmental advantages. While the MgO-C refractory is well able to withstand the chemical and thermal extremes of secondary steelmaking slag environment, bottom purging ladle furnace design deserves a review to improve refractory utilization.

1. Introduction

Secondary steelmaking ladle operations handling basic slags uses magnesia-carbon refractories for the slagline lining to withstand the process chemistry and temperature [1, 2]. Fluctuation in slag basicity and ladle operating temperatures are monitored and queried as underlying factors behind different wear mechanisms during slag-refractory interactions. When basicity is low, the slag behaves acidic to the lining, and magnesium oxide (MgO) can dissolve from refractory bricks into the slag. At high temperatures above 1400 °C, carbon within the refractory can reduce magnesia to magnesium [3]. Also, exposing refractory surface to the atmosphere at high temperature can cause direct oxidation of carbon.
in the refractory [3]. These factors can also synergise such that refractory linings continue to wear with each heat. After a set limiting residual thickness is obtained at any point in the lining, the whole lining is considered to have failed. This is to prevent slag or molten metal penetrating the backing safety lining.

However, slag basicity attack or the high temperature oxidations in this case are heterogeneous reactions. Slag viscosities is notably high, up to five poise at these temperatures, but can be orders of magnitude higher at just 100 °C lower temperature [4, 5]. The implication is that slag reaction with refractory interface will be diffusion controlled. Slag basicity and high temperature oxidation will therefore be self-limiting processes, and may not be the overriding factors responsible for refractory consumption rates seen in practice. Moreover, operations are supposed to monitor the slag basicity and operating temperatures so they do not exceed certain set values considered safe for the refractory linings. It follows that these factors may not be most decisive in determining the service lives of refractories.

In a secondary steelmaking operation, the slag line MgO-C refractory lining is projected to last a maximum of 85 heats, about 145 hours, while the alumina-magnesia-carbon barrel lining of the molten metal region serves about 165 heats though not commensurately thicker. Assessing residual bricks after breakout of the lining shows a sizeable resource waste, with less than 50% of total lining volume consumed by the time the lining has to be replaced. In the context of sustainable and efficient resource utilization, this should not be the norm. The refractory are actually chosen to withstand these extreme conditions, while operations also monitor and control temperatures and slag basicity below safe limits. It is interesting therefore to explore what factor is overriding in determination of the service life of the MgO-C slag lining in these operations. The work reported herein is to identify the most contributing factor to the limited life of the MgO-C slag-line refractory linings in this secondary steelmaking electric arc ladle furnaces. To minimize the length of the material herein, some of the results with brief discussions are presented.

2. Methodology

Slagline linings in five ladle furnaces designated Ladle A, B, C, D and E were studied in use and after service. These are 175 tons ladle furnaces’ slagline linings. Main feature of these ladle furnace are two purging plugs and a tapping hole all at the bottom. Bottom purging and tapping ladles furnaces are considered as industry standard in ladle metallurgy [6]. In these furnaces, the purging plugs for argon stirring are at 1 O’clock and 7 O’clock radial positions, while the tap hole is at 10 O’clock (Figure 1). The ladle uses combination lining concept for the working lining: the hot metal lining, for the floor and the lower side wall (the barrel), uses alumina-magnesia-carbon bricks; while the slagline (the upper side wall) uses a working lining of magnesia-carbon bricks. Behind these working linings are the safety lining. The slag line lining is projected to withstand 85 heats, while the barrel lining is projected to withstand a total of 165 heats. The second slagline campaign is for the balance of 80 heats of the barrel lining. Hence after maximum of 85 heats, the slag line is removed and relined, except the lining failed before that much heats. During use the lining is regularly scanned using thermal camera to detect hot spots indicative of the residual thicknesses. When any brick within the whole lining is worn down to 30 mm, the entire slag line is considered to have failed. It is broken out and relined. The life of lining is taken as the total number of heats endured before it failed. Of the five linings studied, B and D were first slagline campaign, while A, C and E were second.

Percentage compositions of the slag oxides CaO, SiO2, FeO, Al2O3, MgO and MnO were determined in the slag for every heat, and the slag basicity was determined for each heat from the data using equation 1 [7, 8]:

\[ \text{Basicity} = \frac{\text{CaO} + \text{MgO}}{(\text{SiO}2 + \text{Al}2\text{O}3 + \text{FeO} + \text{MnO})} \]  

(1)
MgO saturation in slag is relevant in this situation to avoid MgO leaching from the MgO-C lining, and MgO saturation which varies with basicity [9] can be ensured in operation. For a reference in this operation, the ideal operating basicity is chosen to be 1.67. The resulting data are tabulated and summarized in plots of basicity variations over all the heats for each lining, reference to the ideal basicity. To see effects of temperature extremes on the life of the lining, the ladle thermal history were studied over all the heats each lining served. The maximum process temperature recorded during each batch operation in the ladle for all the heats (85 maximum) during the entire campaign of a lining were summarised for each ladle. From these maximum temperatures during all heats of a lining, the highest and the least values were extracted and tabulated against the life of that lining. This data is finally summarised in a single plot for all the ladle linings studied. In the course of the operation, when in-situ measurements indicate any brick within the whole lining has 30 mm residual thickness or lower, the lining life is considered over. The whole lining is broken out. The residual thickness of all bricks are taken and tabulated according to their position in the ladle. Bricks with any distinct feature such as slag penetration, crack, discoloration and least residual thickness were selected for optical and electron microscopy studies to identify overriding mechanism the brick experienced.

3. Results and Discussion

3.1 Basicity Excursions versus MgO-C Refractory Lining Life

Figures 2(a) – 2(e) show the slag basicity excursions of the five linings during operation relative to the ideal operating basicity recommended for the slag-line refractory lining. The ideal operating basicity for these operations is set to 1.67, obtained from equation (1) based on an ideal slag composition of CaO 55 %, MgO 10 %, Al₂O₃ 35 % SiO₂ < 2 % and FeO + MnO < 2 % for the operation. This is within 1.52 – 1.88 which is the range of basicity allowable for MgO-C refractory. The figures show that most of the times the slags were relatively acidic, falling below the ideal basicity line for the operation, and also below the accepted range for MgO-C refractory. Lining E, for instance, experienced least basicity of 1.168 during its entire campaign (Figure 2(e)). Low basicity implies more acidic slag, with expected dissolution of MgO from the lining [10]. The more acidic, the more aggressive such slag is expected to be, and the shorter the lining life expected. It can be inferred that acid-base interaction and dissolution of MgO would underlie the degradation experience by the linings in all the instances, but this is not in accordance with the corresponding service lives recoded. In Figure 3, the
service lives of the five linings were plotted against the maximum and the minimum basicity experienced by each lining.

Figure 2. Basicity variations in slags over heats of the ladles furnaces studied — (a) Ladle A; (b) Ladle B; (c) Ladle C; (d) Ladle D; (e) Ladle E
Figure 3. Service life (total number of heats endured) versus range of basicity experienced by the linings.

It can be seen that none of the ladles experienced basicity higher than allowable for MgO-C refractory; all were rather low, that is, the slags were acidic. However, Ladle A which experienced the least basicity of 1.008, compared to all others, had a service life of 78 heats. This is the highest service life of the three second campaign linings in the study (Ladles A, C and E). Ladle E, falling three full heats behind Ladle A, experienced least basicity of 1.168, which implies, Ladle A experienced slightly more acidic slag, yet with higher service live than Ladle E. The obvious inference is that another factor, as this study will show, which is contributing to degradation and wear of the refractory is having more pronounced effect on the life of the linings.

3.2 Impacts of Temperature Fluctuations on Lining Life

Figures 4(a) – 4(e) profile maximum temperatures reached during each heat over the life of the linings. From this data, the highest and the lowest of the maximum temperatures (endured by each lining during each heat over the life of the linings) were plotted against the life of each lining (Figure 5). Except on one heat where a spike of 1644 is seen in lining B (Figure 4(e)), and a dip down to 1571 during a heat in lining E (Figure 4(e)), the temperatures fluctuated mostly between 1575 and 1600 for all the heats and all the linings. This can be because some heats require a little superheat or deviations depending on the target cast item. As the operations typically seek to operate at 1590 °C, it can be said that the operating temperatures were largely under control.
Figure 4. Maximum temperatures experienced by each lining during each heat for the different ladles (a) Ladle A, (b) Ladle B, (c) Ladle C, (d) Ladle D, and (e) Ladle E, with ideal operating temperature line indicated at 1590 °C.

However, above 1400 °C, indirect oxidation of carbon within MgO-C refractory becomes thermodynamically favourable [3], allowing:

\[
\text{MgO}_{\text{(refractory)}} + \text{C}_{\text{(refractory)}} = \text{Mg}_{(g)} + \text{CO}_{(g)} \quad \Delta G^0_T = 646923 - 403.214T + 13.39T \ln T
\] (2)
At about 1590 °C (1863 K), the ∆G gives –108 kJ. Also the FeO content of the slag in principle can react with accessible carbon from the refractory as:

\[
\text{FeO}_{(\text{slag})} + C_{(\text{refractory})} = \text{Fe}_{(l)} + \text{CO}_{(g)} \quad \Delta G^0_T = 151125 - 151.105T
\]

Below 1400 °C, under direct exposure to the atmosphere, direct oxidation of carbon is also possible to give carbon dioxide. Considering these possibilities, various oxidations should be happening in the lining, to bring about the refractory degradations. Contrary to what can be expected, the lining in Ladle B with highest thermal spikes of 1644 °C lasted 84 heats, as can be seen in Figure 5. The lining in Ladle D which also lasted 84 heats had the least temperature peak of 1596 °C. Comparing Ladle C and Ladle E, which both had second slagline lining campaigns, both experience same maximum temperatures of 1599 °C, but differ in service lives by two heats. From this data, temperature too may not be having the overriding effect on the service lives of the lining.

![Figure 5](image.png)

**Figure 5.** Highest and lowest of maximum temperatures during heats over the service life of each lining against service lives for the different linings.

Though basicity and high temperature oxidations are prominently emphasised in the slag-refractory interactions, the foregoing inferences downplay these factors for aggressiveness in refractory wear and lining service lives. Fundamentally, rates of solid-liquid reactions are not chemically controlled, but diffusion controlled [11]. The chemical reactions deriving from basicity and high temperature oxidations at the slag-refractory interfaces will not proceed aggressively between the viscous fluid such as slag and the solid refractory. Further insight from the post-mortem studies of the residual bricks address is more conclusive.

### 3.3 Residual Thicknesses and Non-Uniform Wear of Bricks

The MgO-C bricks newly lined are 230 mm thick. Tables 1 show residual thicknesses map of bricks after breakout from their respective locations in Ladle B at the end of the service life of the lining. The columns in the table show radial positions 1 to 12 while the rows give layers 12 to 26 that makes up the slagline lining bricks. Hence, the data at column 10 row 22 in the table, for instance, refers to residual thickness of brick from radial column position 10 and layer 22, and this can be represented as C10L22 residual thickness for this discussion.
Studying Table 1, it is striking that the bricks did not wear uniformly. Highest residual thickness of 170 mm can be see at C6L21, and some other locations, indicating least wear of 60 mm (26%) relative to the new brick, while brick C7L19 has the least residual thickness of 35 mm, indicating wear of 195 mm (85%). Columns 7 and 8, and columns 1 and 2, show most bricks with least residual thicknesses, while columns 5, 6, 9 – 12 has no bricks below 80 mm.

Table 1. Residual thicknesses map of bricks from Lining B at corresponding layer and radial ladle positions.

| Layer | Post-production profile (mm) |
|-------|-----------------------------|
|       | 6   | 7   | 8   | 9   | 10  | 11  | 12  | 1   | 2   | 3   | 4   | 5   | 6   |
| 26    | 150 | 100 | 95  | 150 | 160 | 150 | 140 | 120 | 145 | 160 | 150 | 150 | 150 |
| 25    | 150 | 100 | 100 | 150 | 170 | 170 | 150 | 105 | 145 | 155 | 150 | 150 | 150 |
| 24    | 130 | 100 | 70  | 140 | 130 | 140 | 160 | 105 | 135 | 150 | 150 | 150 | 130 |
| 23    | 120 | 55  | 60  | 150 | 150 | 150 | 150 | 55  | 90  | 130 | 130 | 120 | 120 |
| 22    | 120 | 125 | 130 | 130 | 135 | 140 | 140 | 100 | 100 | 120 | 120 | 120 | 120 |
| 21    | 170 | 115 | 115 | 100 | 110 | 140 | 150 | 120 | 125 | 120 | 130 | 130 | 170 |
| 20    | 130 | 115 | 100 | 120 | 120 | 130 | 130 | 90  | 80  | 120 | 125 | 130 | 130 |
| 19    | 130 | 35  | 60  | 115 | 120 | 80  | 120 | 40  | 70  | 80  | 110 | 120 | 130 |
| 18    | 130 | 80  | 90  | 120 | 120 | 125 | 130 | 125 | 110 | 120 | 120 | 130 | 130 |
| 17    | 135 | 90  | 90  | 120 | 120 | 125 | 140 | 125 | 110 | 120 | 125 | 130 | 135 |
| 16    | 140 | 100 | 100 | 130 | 130 | 125 | 130 | 120 | 110 | 110 | 110 | 120 | 140 |
| 15    | 140 | 120 | 130 | 130 | 130 | 125 | 130 | 120 | 115 | 110 | 110 | 120 | 140 |
| 14    | 125 | 120 | 100 | 135 | 130 | 135 | 135 | 115 | 115 | 110 | 110 | 120 | 125 |
| 13    | 125 | 100 | 95  | 125 | 125 | 120 | 130 | 105 | 115 | 125 | 125 | 125 | 125 |
| 12    | 120 | 105 | 105 | 125 | 125 | 120 | 130 | 100 | 100 | 120 | 115 | 115 | 120 |

Residual thickness map obtained for bricks from the other four linings studied show similar non uniformity. For Ladle A, least thickness of 35 mm was found at C7L15, indicating again, the 7 O’clock column as most prone to highest wear. The other three linings, C, D and E studied, show worst wear at either the 1 O’Clock or 7 O’Clock radial position.

It stands out that the 1 and 7 O’clock positions in all the linings suffer the worst wear. From the ladle design, these are the locations of the purging plugs (Figure 1). It is obvious that the purging gas caused turbulent flow of the slag against the bricks in these locations. Any weakened brick in these columns experienced aggressive wear. The slag basicity and high temperature oxidation which affects the entire lining obviously caused moderate wear, as can be seen from locations far away from these purging areas. From Table 1, some columns far away have from these zones have least residual thickness up to 120 mm, thrice that at column 7. It can be projected that without the turbulent wear, such as induction stirring, the service life of the lining can easily triple.

3.4 Micrographs of last working surfaces of residual bricks

Figures 6(a) and 6(b) show optical and electron micrographs from the last working surface of some sample residual bricks. The images capture thermal shock cracking propagating from frozen slag on the surface of the refractory inward (Figure 6(a)). Figure 6(b) shows a secondary phase that evolved from the slag refractory interaction. Residual bricks from the 1 O’clock and the 7 O’clock locations did not retain such slag penetration, or show thermal shock cracks, graphite loss or residual magnesium from oxidation effects. Rather the last working surface is largely comparable in composition to the rest of brick. Since Figures 6(a) and 6(b) show that the generally expected effects of slag-refractory interactions did actually occur in these linings, it can be inferred that the turbulent wear at the 1 O’clock and 7
O’clock locations removed any such interaction effects leaving least residual thicknesses of the bricks. It follows that wear due to the uprising purging gas from the bottom purging holes in these ladle furnaces design, not the thermal or chemical extremes, was the highest determinant of service live of the lining. This result did not admit that corrosion is the main wear mechanism in this type of operation for MgO-C degradation as some other researchers prefer to conclude [12].

![Figure 6. Slag-refractory interphase from last working surface layer of residual bricks showing (a) thermal shock crack propagating from frozen slag into the brick, and (b) phases evolved as a result of slag-refractory interaction.](image)

4. Conclusion
Magnesia-graphite refractory slagline linings of 750 tons ladle furnaces in a secondary steel making operation were studied to determine the factor most critical to the service life of the lining. Temperature extremes and basicity fluctuations during the service life of the linings, map of residual thicknesses of bricks after breakout of the linings, and microstructures of slag-refractory interfaces from the last working surface of the residual bricks were studied. The results show that the refractories tolerated thermal spikes above 1600 OC and basicity excursions well below 1.67 ideal for the operations. Rather, the bottom purging design of the ladle, which caused localized slag turbulence, is most responsible in determining the life of the lining in service. Least residual thickness that decimated the life of the lining were obtained at lining positions closest to these purging positions. It was analysed that without this single effect, the life of the lining can triple. Magnesia-graphite refractory is well able to withstand the thermal and chemical extreme conditions of secondary steelmaking slag, but bottom purging in ladle furnaces design is the major challenge to the lining life.

5. References
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