Corrosion of MgO-C Ladle Refractories

Industrial refractory brick were tested in the laboratory for their corrosion behavior at high temperatures under a protective atmosphere of argon or argon and carbon monoxide. A statistically designed set of experiments provided a polynomial equation of the model for corrosion.

S. Akkurt
Mechanical Engineering Dept., Izmir Institute of Technology, Urla, Izmir, Turkey

H.D. Leigh
Ceramic and Materials Engineering Dept., Clemson University, Clemson, S.C.

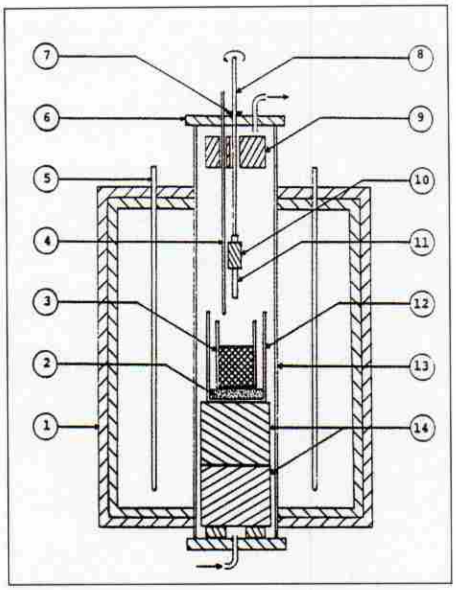
Magnesia–carbon (MgO-C) refractories are widely used in ladle refining furnaces because of their favorable properties—such as low wetting by corrosive steelmaking slags—chemical compatibility with basic slags and better thermal properties. Their service lives, however, are much shorter in ladles compared with basic oxygen furnace (BOF) use.

The development of higher-purity magnesia grains and a well-engineered microstructure have led to dramatic improvements in lining life. Resin-bonded magnesia–graphite refractories are composed of high-purity magnesia filler grains of various sizes, antioxidant metal powder and natural graphite flakes that are bonded by a phenolic resin.[1,2] The brick are cold-pressed into shape and are used in lining the slag lines of secondary steelmaking vessels as well as applications in other steel furnaces.

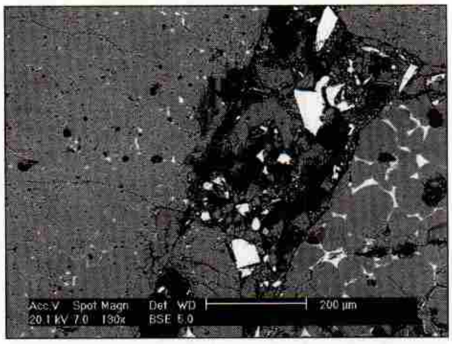
The molten slag is in contact with the refractory during the refining process, where temperatures >1650°C are common. Because the slag is floating over the steel melt in the furnace, local convection currents develop near the slag–refractory–steel–air intersection that leads to small-scale circulating flows that increase dissolution.[3]

The overall wear of a lining depends on chemical and physical considerations. The chemical potential between the refractories and the steelmaking slag determines the driving force to dissolve the refractory lining. The conditions of the slag include its chemistry, degree of saturation of magnesia, oxygen potential, temperature, temperature equilibrium and wetting characteristics between the slag and refractory.

The slag can be conditioned to decrease the potential for periclase dissolution by saturating it with magnesia. The refractory reaction with the slag can be decreased by decreasing its wettability. The use of large-flake graphite is a common method to achieve the low wetting characteristics. To retain the carbon to develop a ceramic bond and resist oxidation, metallic additions, known as antioxidants, are made to the refractory. Much work has been devoted to developing the proper chemical composition, size and distribution of these additives to improve their effectiveness.



Schematic of the experimental apparatus for corrosion tests.



SEM image of brick D. Bottom right periclase grain is a low-quality sinter with a high proportion of low-melting intergranular bond phase (IBP). Angular silicon and rounded aluminum antioxidant particles are visible in the middle portion. Dark elongated features are graphite flakes. Large periclase grain on the left is a higher-grade sinter with a lower proportion of IBP.

The intergranular phase associated with the high-magnesia periclase grains is of great importance to the performance equation.[4] The matrix phases of the refractory have finer grain sizes than the large aggregate, and attack of the matrix is preferential. This attack weakens the bonding of these aggregates and can cause large volume loss. The composition of this matrix phase is, therefore, important to the overall chemical attack of the steelmaking slag. Lee, Zhang and co-workers[5,6] have reported extensively on these corrosive reactions.

The physical attack of the lining results from charging of the furnace, thermally induced stress on the lining and visco-dynamic shear between the lining and the slag. The shear rate increases the erosive impact of slag on the refractory. Endell et al.[7] discussed these factors as early as 1939.

Understanding the wear rate of a particular furnace lining depends on understanding the interaction between the chemical and physical conditions within a furnace during the processing. One way to achieve this is to conduct controlled experimental designs to determine the effects of chemical corrosion and physical erosion. These designed tests can be conducted within either laboratory or production furnaces.

Controlling conditions within a laboratory test, although difficult, is more easily achieved than within a production furnace. The results obtained from laboratory tests, however, cannot be quantitatively applied to a production furnace because of scale and gradient factors. Many attempts have been made to develop slag tests that predict refractory performance.[8,9] Most attempts have resulted in qualitative data with variability of 30, 50 and even 100% being common. The best attempts have been achieved through statistically designed and controlled experiments. One such laboratory study has resulted in unassigned variability (experimental error) as low as 5%.[10]

Experimental Models

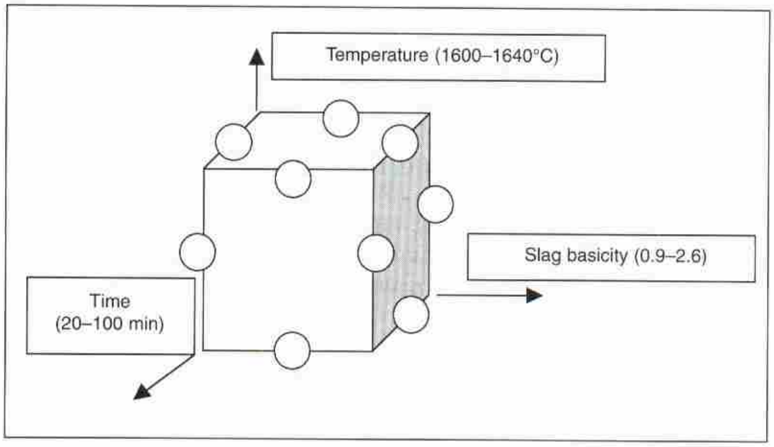
Prediction of refractory wear from slag tests and from production data is difficult. In the former case, the scale of the test and the dynamics are significantly different from those that occur in an actual production furnace. In both cases, statistically designed experimental plans rarely have been used, and low reproducibility of data is common.[5]

It is theoretically possible to produce a wear model based on laboratory tests and then to correlate that model to actual furnace practice by some type of regression technique. The precision that can be achieved by any wear model is directly related to the precision of the data used to develop that model. Obviously a larger number of replications is required to achieve greater precision.

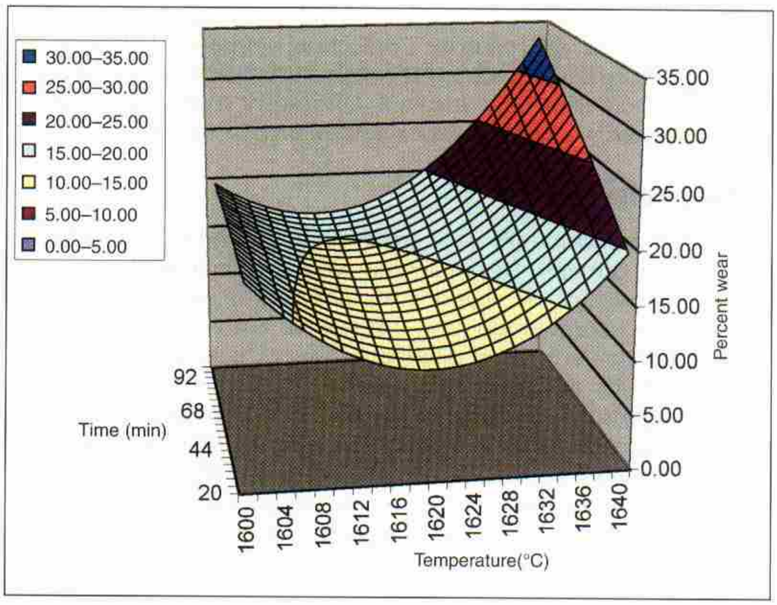
Models developed from either laboratory tests or data sets obtained from industrial operations require large data sets to allow precise predictions. Predictive models can be made from laboratory experiments provided the data are statistically significant and have a known and small variance.

Carbon-containing brick are protected from the corrosive action of slags mainly by their carbon component. Results from tests on these refractories are sensitive to premature carbon loss. The consequences of such should be considered when selecting and evaluating slag-testing methods.[10] Tests, such as a rotary slag test, have seen widespread acceptance among the refractory community because of their pragmatic approach.[8,9] The main disadvantages of these tests are poor control of temperature, atmosphere, reproducibility and time-consuming furnace construction.[8]

The test method used in this study, on the other hand, provides good reproducibility and quantitative measurement of refractory corrosion. Although some preliminary tests have been run under dynamic rotating conditions, the results



Design cube used in the Box–Behnken response surface experiments. Body-centered repicaltes are not shown.



Response surface plot of the effect of time and temperature on percent area loss in argon atmosphere.

presented here have been obtained under static conditions. The results obtained are consistent with observations cited in the literature.

The precise and quantitative results that have been achieved in large part are because of the planning and use of statistical experiment design. The objective is to develop a precise and reproducible refractory corrosion testing technique to allow the development of a predictive mathematical model for refractory corrosion as a function of furnace operation and slag practice.

Materials and Method

Slag corrosion tests were performed in a vertical tube furnace using a bath of slag melt as the corroding medium contained in a high-alumina crucible. A 1.4 × 1.4 × 7 cm refractory brick sample was half-immersed from the top and was kept as such for prescribed lengths of time. The testing geometry was similar to ASTM C-621. Description of the brick, slag, steel and experimental apparatus are given below. Steel was added to the crucible with the slag to provide a sharp slag–metal boundary during testing. The ratio of steel to slag was held constant.

Selected Properties of Tested Brick Sample

Property	Brick D
Chemical analysis (wt%)	
MgO	92.2
CaO	7.8
SiO_2	
Al_2O_3	
Fe_2O_3	
B_2O_3	
Bulk density (g/cm^3)	2.88–2.95
Apparent porosity (%)	
As-received	2.5–4.0
After coking†	8.5–10.0
Retained carbon (%)	9.2–9.8
Modulus of rupture (MOR) (MPa)	
As received	15.9–20.0
Coked (at 1370°C)	8.8–10.3
Cold crushing strength (MPa)	33.8–49.0
Thermal conductivity (W/(m·K))	
Linear thermal expansion (%)	
At 1100°C	1.6
At 1700°C	2.7

†At 1093°C for 10 h in a reducing atmosphere.

A commercially available resin-bonded MgO-C brick (coded as D) was tested in this project to understand its corrosion behavior in contact with a liquid secondary steelmaking slag at 1600–1640°C. The characterization of the brick is reported elsewhere.[10] Brick D contained silicon and aluminum as antioxidants. Crystallite size was in the range 30–120 µm.

Two types of magnesia grains were observed in the brick. The first grain had a higher average dihedral angle (>90°) than the second grain (17°). The glassy intergranular bond phase, therefore, was relatively higher in proportion in the second type of grain.

Semiquantitative EDS analysis of this bond phase showed its composition to range from monticellite ($CaO·MgO·SiO_2$ (CMS)) to merwinite ($3CaO·MgO·2SiO_2$ (C_3MS_2)). Aluminum and silicon antioxidants were identified in the brick using

SEM. Thin-section transmitted-light microscopy revealed the potential presence of monticellite in the unused brick.

Graphite flakes were on the average 50 μm thick and 200 μm long in polished section. Sieve analysis of air-burned brick indicated that the particle-size distribution modulus (n) was ~0.47 although this test may have given biased results because of potential reactions on heating the brick. Details of brick characteristics are given elsewhere.[10]

Three types of secondary refining slags were used for corrosion testing of brick. Their compositions were obtained from a local steel plant and had the following $CaO:SiO_2$ ratios: 0.9, 1.7 and 2.6. The latter is also called white slag, and it disintegrates on cooling because of the β–γ C_2S inversion at 675°C. The first type is an acid slag with a $CaO:SiO_2$ ratio of 0.9. The relative percentages of major slag components in the three systems CMS, CAS and CMSAF can be calculated for later thermodynamic evaluation. Because the temperatures in the furnace are high, equilibrium phase diagrams can be used in evaluation of refractory–slag systems.[11]

Slags with the above-mentioned chemistries were prepared in various proportions such that, at 1600°C, they would reach the desired chemistries and a weight of 30 g. Slag components were weighed in each run and placed in the reaction crucible, followed by the steel additions.

Chemical Analysis of Slags Used in This Study (ICP)

	Composition (wt%)		
Component	0.9 slag	1.7 slag	2.6 slag
CaO	37.36	52.33	41.06
SiO_2	42.28	30.73	15.86
MgO	2.14	10.50	15.71
Al_2O_3	12.18	2.39	21.16
Fe_2O_3	3.23	3.19	2.92
MnO	0.23	0.63	0.37
TiO_2	2.58	0.23	2.92
C/S ratio	0.88	1.70	2.59
Total	100.00	100.00	100.00
CMS total	81.78	93.56	72.63
CAS total	91.82	85.45	78.08
CMSAF total	97.19	99.14	96.71

The steel used in this study was a type-1018 steel. It was purchased in the form of round bars 2.54 cm in diameter and ~600 cm in length. The steel samples were cut to ~9 cm long pieces, washed with soap to clean the oil residue from milling and dried immediately. They were later ground on a sand belt to remove oxide layers and used as-such in slag corrosion experiments.

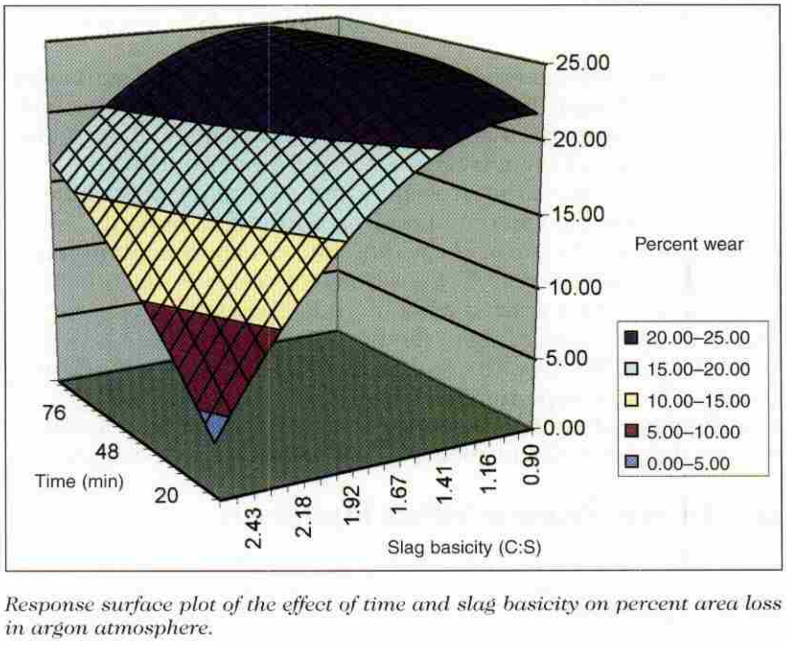
Experimental Setup

The experimental apparatus consisted of a mullite reaction tube mounted vertically in a resistance-heated furnace. The upper end-cap assembly allowed a specimen, which was attached to a 1.27 cm diameter steel shaft, to be raised, lowered and rotated via a small hole at the center of the end-cap. An airtight seal between the steel shaft and end-cap was maintained using a graphite ring.

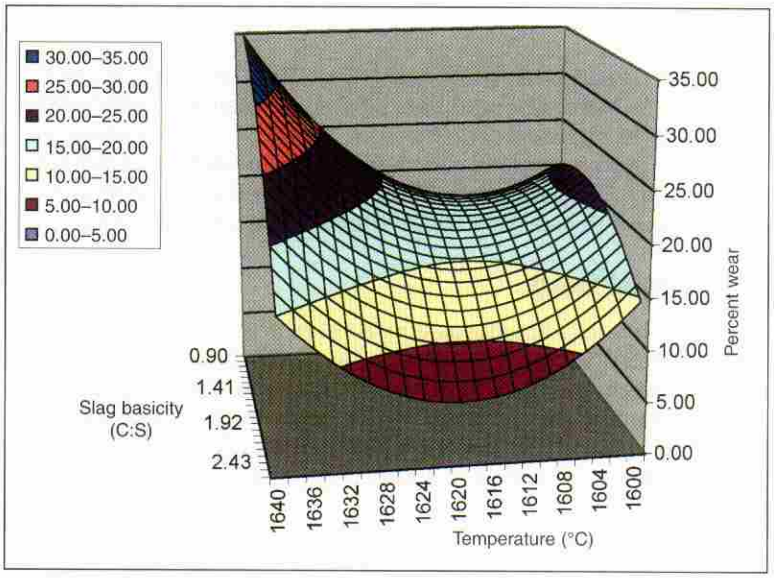
An argon or argon plus 5% carbon monoxide gas mixture entered through a port in the bottom end-cap and exited through the top end-cap. Square refractory specimens, 1.4 × 1.4 × 7 cm, were cut from larger brick and mounted in a calcium aluminate-cement-containing refractory castable. High-alumina crucibles, 5.5 cm outside diameter × 10 cm height, were used to contain the molten steel and slag. These crucibles were made in-house by slip casting and were satisfactorily impervious to the steel–slag melt. The safety crucibles were used to prevent spillage of liquid to the inner wall of the mullite reaction tube.

The apparatus was able to accommodate continuous operation of the simulated ladle furnace environment at 1640°C. A typical run began by loading slag and steel into the reaction crucible, securing all gas-line connections and heating at 320°C/h. The specimen then was lowered into the melt and held there half-immersed for 20–100 min.

Industrial-grade argon (with 7 ppm oxygen and 14 ppm water)



Response surface plot of the effect of time and slag basicity on percent area loss in argon atmosphere.



Response surface plot of the effect of slag basicity and temperature on percent area loss in argon atmosphere.

Slag Batch Composition†

Component	Composition (wt%)		
	0.9 slag	1.7 slag	2.6 slag
Wollastonite	27.34	20.95	10.81
Sil-co-sil	0.76		
A16-SG	4.22	0.8	7.4
Magox-98	0.74	3.73	5.6
TiO_2	0.9	0.08	1.02
Fe_2O_3	1.02	1.03	0.98
MnO2	0.05	0.2	0.12
$Ca(OH)_2$		10.96	12.15
Total	35.03	37.75	38.08

†As formulated to produce 30 g of weight at test temperature.

Experimental Factors Used in Formulating Response Surface Experiments

Factor	Effect		
	Low	Medium	High
Time (min)	20	60	100
Temperature (°C)	1600	1620	1640
C:S ratio of slag	0.9	1.7	2.6

used in the tests was treated to remove its moisture and oxygen. Total gas flow rate was 1.62 L/min during the slag corrosion tests. Oxygen gettering was done by passing argon through a pack of copper turnings that was heated at 400°C. The oxygen partial pressure of the argon for the protection of carbon in the brick was $<10^{-15}$ atm ($<10^{-10}$ Pa). The oxygen partial pressure also was measured to be of the order of 10^{-15} atm, using an oxygen sensor (Bosch Co.). Carbon monoxide gas was reported to contain 25 ppm carbon dioxide.

Refractory specimens were photographed after the run, and they were mounted in polyester resin and sliced longitudinally using a low-speed diamond saw. The sliced refractory specimens were later polished and photographed to calculate the percent area loss in the cross section using an image analysis program. The results obtained using the image analyzer were satisfactory and reproducable.

Laboratory slag corrosion tests were planned using a statistical experiment design. The objective was to verify the previous tests on refractory corrosion and to present a mathematical model for corrosion kinetics on corrosion rate. The key in statistical experiment design is that it enables the researcher to obtain a maximum possible amount of information from a limited number of runs. Because of the difficulty of experimentation in high-temperature research, the statistical design is essential.

The investigation started with an initial series of 16 experiments designed according to the Box–Hunter screening experiment design. The objective was to identify the more important factors affecting experimental precision and refractory corrosion. The Box–Behnken response surface experimental design was used to analyze the effects of factors affecting corrosion.[12]

Box–Behnken Response Surface Experiments

The factor effects chosen were duration of slag exposure, temperature and C:S ratio of the slag. The response variable was percent area loss due to corrosion. These experiments were planned to serve as a tool for developing the mathematical model for corrosion of MgO-C refractories. An exact theoretical model is difficult to fit the real data in the process of corrosion of refractories in service.

Most models are developed based on plant data and suffer from poor reproduceability. Polynomial approximations are widely used in different areas and have proved valuable in modeling process data. The dependent variables can be mathematically formulated as follows:

$$y_1 = f_1(x_1, x_2, x_3, \ldots, x_p)$$

$$y_2 = f_2(x_1, x_2, x_3, \ldots, x_p)$$

The value of the dependent variable is affected differently at various combinations of independent variables. The resulting 3-D plot provides a visual response surface model, while the polynomial equation presents the complete model developed. The difference between the exact mathematical model and the polynomial model is that the polynomial model is valid only within the limits specified by the levels of the independent variables in the experiments.

A polynomial approximation interpolates well, but the quality of its extrapolation is unknown. In most cases, the polynomial actually closely approximates the exact model, and this is an important point to consider in this particular work. The polynomial also forms the basis for developing and fitting a theoretical model. The optimum value of the response surface does not necessarily have to be inside the limits studied.

The response surface experiments are designed in such a way as to keep the number of runs minimal and at the same time to maintain sufficient number of degrees of freedom for error. In the case of Box–Behnken experiment design, a subset of the full three-level factorial is used. When three factors at three levels are investigated, the total number of runs in the full-factorial is 27.

Minimum number of runs required from the design to achieve a response surface is 10. However, 15 runs, including three center-point replications and 12 at the edge centers of the design cube, are recommended. The three dimensions of the design cube correspond to the three independent factors investigated at three levels. The mid-point on each axis is the edge-center, and it corresponds to the middle value of one of the factors. Three experimental replicates are made using the median of each factor to provide estimates of experimental error. These replicates occur in the body-centered position of the cube.

Regression Coefficients for Percent Area Loss

Regression coefficients for percent wear	Type of atmosphere	
	Argon	Argon plus carbon monoxide
Constant	59675.900	30016.800
A (time)	–6.590	–1.750
B (temperature)	–70.630	–36.990
C (C:S ratio)	348.625	–183.669
AB	0.004053	0.001
AC	0.080	0.027
BC	–0.210	0.115
AA	-0.0003396	2.710
BB	0.020	0.011
CC	–5.465	–3.641

The potential response variables were percent area loss, slag line cut, depth of slag penetration, etc. In this project, the percent area loss of polished sections was used as the response variable. The experimental plan was used for the runs in treated argon atmosphere and in argon plus 5% carbon monoxide gas atmosphere. Therefore, two identical response surface experiment sets were run to compare the effect of atmosphere on corrosion.

The centerpoint of the C:S ratio was 1.7 instead of the arithmetic mid-point of 1.75. This was due to the fact that the original slag used in the steel plant was 1.70, and we wanted to use the original slag. Also, 15 run Box–Behnken experiments are known to be robust against such small changes in levels.

Corrosion Test Results

Analysis of variance (ANOVA) tables for argon and argon plus 5% carbon monoxide gas runs were obtained. The experiments done in argon plus 5% carbon monoxide gas atmosphere generally resulted in lower-percent wear numbers that were possibly affected by two main factors related to the addition of carbon monoxide: the lower oxygen partial pressure better protected the carbon, and the loss of magnesia through reaction with carbon was accelerated in the presence of carbon monoxide where oxygen partial pressure was lower.

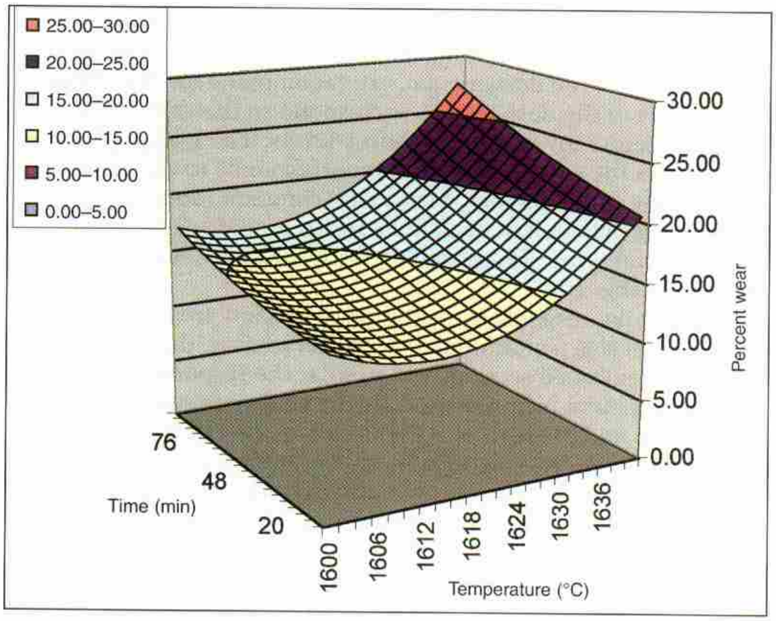
Direct loss of magnesia was observed in some of the argon plus 5% carbon monoxide gas runs. A white, needlelike, light-colored rim that formed around the tested brick during the corrosion test was analyzed using XRD and was found to be composed of magnesia crystals.

Percent wear (area loss) numbers are interchangeably used with the term "corrosion" based on the assumption that erosion

Regression Coefficients†

Effect	Argon			Argon plus carbon monoxide gas		
	Time–temperature plot	Temperature–slag basicity plot	Time–slag basicity plot	Time–temperature plot	Temperature– slag basicity plot	Time–slag basicity plot
Constant	59560.2	56853.6	15.92	31010.9	29693.8	18.68
A (time)	–6.46		0.03	–1.718		0.01
B (temperature)	–73.46	–70.73		–38.43	–36.66	
C (slag basicity)		353.51	10.02		–181.88	5.05
AB	0.00405			0.00107		
AC			0.084853			0.02706
BC		–0.21100			0.11540	
AA	–0.00015		–0.00076	0.00039		0.00005
BB	0.02266	0.02200		0.01191	0.01132	
CC	-	–5.40700	–6.39700		–3.68800	–4.12700

†Calculated by elimination of the third effect when calculating the polynomial equation for plotting the response surface.



Response surface plot of the effect of time and temperature on percent area loss in argon plus carbon monoxide atmosphere.

Experimental Conditions and the Results of Response Surface Experiments

Experiment No.	CO amount (%)	Time (min)	Temperature (°C)	C:S ratio of slag	Area loss (%)
1	0	100	1640	1.7	41.22
2	0	100	1600	1.7	20.08
3	0	20	1640	1.7	22.82
4	0	20	1600	1.7	14.65
5	0	100	1620	0.9	15.23
6	0	100	1620	2.6	10.85
7	0	20	1620	0.9	18.89
8	0	20	1620	2.6	2.97
9	0	60	1640	0.9	32.34
10	0	60	1640	2.6	10.57
11	0	60	1600	0.9	24.83
12	0	60	1600	2.6	17.41
13*	0	60	1620	1.7	16.18
14*	0	60	1620	1.7	18.99
15*	0	60	1620	1.7	14.26
16	0.05	100	1640	1.7	30.87
17	0.05	100	1600	1.7	18.85
18	0.05	20	1640	1.7	21.14
19	0.05	20	1600	1.7	12.55
20	0.05	100	1620	0.9	19.2
21	0.05	100	1620	2.6	10.73
22	0.05	20	1620	0.9	18.43
23	0.05	20	1620	2.6	6.28
24	0.05	60	1640	0.9	12.55
25	0.05	60	1640	2.6	15.47
26	0.05	60	1600	0.9	24.03
27	0.05	60	1600	2.6	3.98
28*	0.05	60	1620	1.7	16.65
29*	0.05	60	1620	1.7	15.25
30*	0.05	60	1620	1.7	15.67

was not a major factor in this study because of the static nature of the test method. Erosion is definitely not completely ruled out, but the corrosion term was used for the sake of terminology.

The ANOVA table shows that the wear was much affected by the C:S ratio of the slag and, to a smaller extent, on the time and temperature of the test when an argon atmosphere was used. The only significant interaction term was the interaction of temperature by itself. This means that the impact of temperature is nonlinear. For the case of argon and carbon monoxide atmosphere, time, temperature and slag basicity were strongly significant, including again the temperature–temperature interaction term.

The R-squared value, which is an indication of the quality of the fit of the model, was 0.95 in the latter case. This was encouraging, because the reliability of the test method used was of major concern. The addition of carbon monoxide considerably improved this value from 0.85 to 0.95. Improvement in the model by carbon monoxide additions suggested that oxidation of carbon during the testing had a major influence on the calculated area loss.

Loss of carbon by oxidation weakens the refractory matrix and exposes more refractory matrix to slag attack. The loss of carbon, therefore, causes increased attack and higher variability through mechanisms of increased and variable wettability. Decreased structural integrity of the refractory matrix promotes refractory material loss.

Response surface plots were obtained from the polynomial model using the regression coefficients. The polynomial model equation has the general form

$$Z = K + x_1A + x_2B + x_3C + x_1x_2AB + x_1x_3AC + x_2x_3BC + x_1^2AA + x_2^2BB + x_3^2CC \qquad (1)$$

where K is a constant, Z the percent area loss in refractory, x_1 the time (in minutes), x_2 the temperature (in degrees Celsius), x_3 the C:S ratio, AB the interaction coefficient between time and temperature, AC the interaction coefficient between time and C:S ratio, BC the interaction coefficient between temperature and C:S ratio, AA the interaction coefficient between time and time, BB the interaction coefficient between temperature and temperature and CC the interaction coefficient between C:S ratio and C:S ratio.

When the response surface is plotted, for example, for time and temperature, in argon, the slag basicity is eliminated from the polynomial equation and the remaining factors are used:

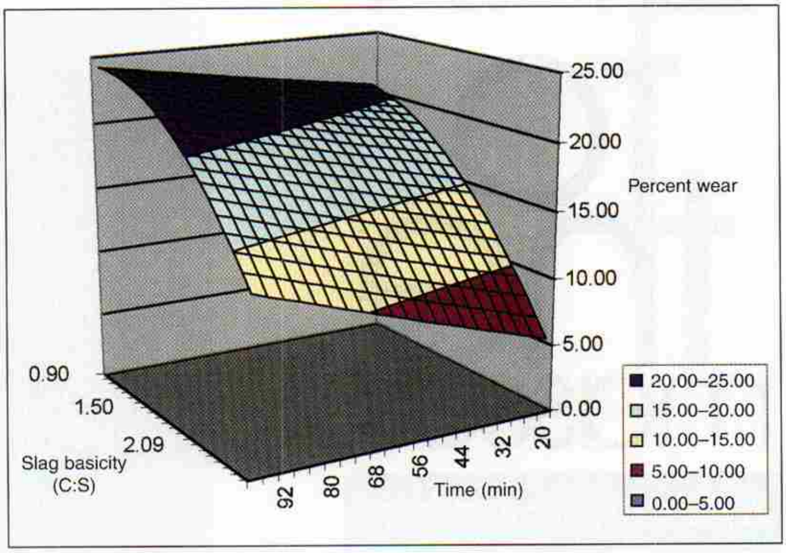
$$Z = K + x_1A + x_2B + x_1x_2AB + x_1^2AA + x_2^2BB \qquad (2)$$

where, for example, $A = -6.4604$.

The resulting plot shows a dramatically steep ascent in the vicinity of high temperature and longer holding times. This fact long has been recognized by refractory specialists and metallurgists. However, what has been done in this project was the quantization of the response surface behavior of slag–refractory interactions at a uniform well-controlled temperature and a well-controlled atmosphere.

The combined effect of time and temperature is clear from the graph. The decrease at the middle temperature range is interesting. This effect can be explained by some mechanism that becomes active in this temperature range. For example, the loss of magnesia through reaction with carbon has been reported to activate in a similar temperature range.[13]

The plot of the effects of time and slag basicity shows a dramatic increase in wear as the C:S ratio decreases. This effect of time on wear is more pronounced at a high C:S ratio. The effects of C:S ratio and temperature on the wear, as in the previous case, shows a minimum in the wear rate that occurs at ~1620°C. The wear increases from this temperature and accelerates as the C:S ratio decreases. The combined effect of high temperature and low C:S ratio produces a dramatic increase in corrosion. The plot shows an increase in wear linearly with time and nonlinearly with temperature.



Response surface plot of the effect of time and slag basicity on percent area loss in argon plus carbon monoxide atmosphere.

The plots for time and temperature when carbon monoxide is introduced to the atmosphere indicates a less significant time effect at high temperatures. The overall wear is decreased in all cases and the effect of slag basicity becomes nonlinear and convex, while the effect of time remains linear. As in the previous case, the C:S ratio is nonlinear when carbon monoxide is introduced and all wear is decreased compared to testing in argon alone.

All these cases show dramatically the importance to the retention of carbon during testing. The effects of low C:S ratio are dramatically increased if the carbon in the refractory is removed prematurely by testing atmospheres containing relatively high oxygen partial pressures.

Conclusions

The goal of this research was to investigate the corrosion of magnesia–graphite ladle refractories used in slag lines of secondary steelmaking vessels via the use of a laboratory slag test and a statistically designed set of experiments. Wear of these refractories is a major expense; therefore, a reproducible, reliable and quantitative model to explain the corrosion process is beneficial.

To achieve this goal, a test method has been developed and a statistically designed set of experiments has been used to develop a polynomial model of corrosion. This can enable steelmakers to predict reliably the consequences of the use of different types of slags. This simple test can be used for comparison of various brick types without variability introduced

Analysis of Variance Table for Percent Area Loss for Argon and Argon plus 5% Carbon Monoxide Atmospheres

Effect	Sum of squares	DF	Mean square	F-ratio	P-value
Argon test atmosphere/R squared = 0.85 (0.59) †					
A (time)	98.35	1	98.35	2.86	0.15
B (temperature)	112.35	1	112.35	3.27	0.13
C (C:S ratio)	306.16	1	306.16	8.91	0.03
AB	42.06	1	42.06	1.22	0.31
AC	33.30	1	33.30	0.97	0.38
BC	51.48	1	51.48	1.50	0.28
AA	1.09	1	1.09	0.03	0.86
BB	283.28	1	283.28	8.24	0.03
CC	57.56	1	57.56	1.68	0.25
Total error	171.80	5	34.36		
Total (corrected)	1181.06	14			
Argon plus 5 vol% carbon monoxide test atmosphere/R squared = 0.95 (0.86)†					
A (time)	56.45	1	56.45	7.78	0.004
B (temperature)	159.67	1	159.67	21.99	0.005
C (C:S ratio)	349.40	1	349.40	48.13	0.001
AB	2.94	1	2.94	0.40	0.559
AC	3.38	1	3.38	0.47	0.532
BC	15.40	1	15.40	2.12	0.205
AA	0.69	1	0.69	0.10	0.773
BB	76.83	1	76.83	10.58	0.023
CC	25.55	1	25.55	3.52	0.120
Total error	36.30	5	7.26		
Total (corrected)	733.73	14			

†Numbers in parentheses represent the value corrected for DF.

by uncontrolled thermal gradient effect during slag testing.

The following conclusions were obtained from this research:

- A reproducible slag test was developed to evaluate static slag corrosion of carbon-containing ladle brick.
- Quantitative results were obtained for the brick under the well-defined conditions of temperature, time, slag chemistry and atmosphere.
- A mathematical model was developed to define the corrosion of a commercial magnesia–graphite refractory brick under the defined conditions. The model quantitatively predicted the increased corrosion as time, temperature and oxygen partial pressure in the atmosphere increased and as slag basicity decreased. It should be possible to expand this model to include effects of slag viscosity and erosion by minor modifications to the test to include sample rotation.
- The degree of slag attack was related to the rate of carbon loss. ■

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Editor's Note

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