Corrosion Mechanism and Wear Prediction of the Sole of an Electric Arc Furnace

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There are many alternatives for the refractory lining in the sole of an electric arc furnace that produces refined ferromanganese, Fe–Mn (80% with low carbon content, %C < 1.5). Empiric approaches have usually been used for the design. Even though they allowed increasing the number of tapping, they are not base in a quantitative prediction of the wearing from the knowledge of a corrosion mechanism.

This paper presents a quantitative prediction for the corrosion processes in two basic soles using the mathematical formulation of the Nodal Wear Model (NWM). In both cases, the equations that describe the corrosion are established and applied, according to the control mechanism of the corrosion, in each node of a Finite Element Model (FEM) grid of the refractory lining is in contact interface with the liquid ferroalloy.

When the sole formed by a magnesite castable refractory (with a minimum content of 95% periclase), the penetration of the molten phase through the open porosity of the refractory controls the corrosion. In the case of a dolomitic sole (75% MgO, 20% CaO, 0.60% SiO₂, 3.80% Fe₂O₃, Al₂O₃ < 0.30%), the corrosion rate is controlled by the diffusion of silicon, one of the active components of the refractory matrix, from each interfacial node in the sole to the molten phase.

KEY WORDS: wearing; electric arc furnace; ferromanganese; mathematical modeling.

1. Introduction

The solution of the corrosion problems in an electric arc furnace, like in most of the metallurgical reactors, has left overcoming through the repetition of trial and error tests. The basic knowledge of corrosion mechanisms is still very limited and does not allow to structure a specific analysis for each problem and thus to obtain qualitative and quantitative answers to scientific, technical and industrial problems.1–3)

The Nodal Wear Model NWM, has the objective to systematize a new line of knowledge and work in the corrosion of the refractory and ceramic materials in contact with corrosive fluids (metals, mattes and slags). Although the NWM has been initially developed in the study of corrosion profiles in a blast furnace,4–6) it constitutes in itself a new tool for the knowledge of mechanisms involved in the wear of materials and provides an appropriate way to solve all those similar problems that the Pyrometallurgical Processes outlines to the modern Materials Science.

The last years have shown a strong increase in the demand of ferritics products with very low carbon content. The ferroalloys that are needed to carry out the corresponding chemical adjustment in the secondary metallurgy have lower and lower carbon content specifications.

The classical procedure for the fabrication of low carbon ferromanganese is shown in Fig. 1. In a first step, the manganese oxide from the feed (pyrolusite, MnO₂) is reduced by a carbothermic reduction in an electric arc furnace. The

![Fig. 1. Flow sheet for the production of refined ferromanganese.](Image)
molten alloy produced has about mass 75% of Mn, and the carbon can reach up to 4%.

To reduce the carbon content (refined ferromanganese) an oxidizing slag (Fe₂O₃–MnO–SiO₂) is used to oxidize the dissolved carbon during the second step of the process:

\[ C(\text{dis.; Fe–Mn}) + MnO(\text{dis.; slag}) \rightarrow (CO(g) + Mn(\text{dis.; Fe–Mn})) \] ..........................(1)

At the same time, the presence of silicon in the metal helps to diminish the solubility of carbon in the ferromanganese alloy. The positive influence (positive interaction) of silicon on the activity of the carbon dissolved in this alloy makes that the maximum solubility of the carbon diminishes as the silicon concentration increases in the metal.

To adjust the final silicon content, the oxidizing slag could be enriched with manganese that is then reduced by a silicothermic reaction:

\[ 2MnO(\text{dis.; slag}) + Si(\text{dis.; Fe–Mn}) \rightarrow SiO₂(\text{dis.; slag}) + 2Mn(\text{dis.; Fe–Mn}) \] ..........................(2)

Even if a continuous feed is possible, the refining of the ferromanganese is a discontinuous operation. For the wear prediction, a time of three hours for the process was used in the calculation for the case of a magnesite sole and two and a half hours for the dolomite case.

2. The Nodal Wear Model

2.1. Fundamentals of the Mathematical Description

The resolution of the temperature field in the refractory lining of a furnace allows to know the temperature in the melt/refractory interface. To solve this mathematical problem in the steady state, two border conditions have to be chosen. The temperature on the shell and the heat transfer conditions between the melt and the refractory, represented by the convective heat transfer coefficient, are the simplest in this case. The first can be measured and the second calculated. With this data, the thermal conductivity of materials and using a Finite Element Model (FEM) resolution, the heat from the melt to the refractory lining can be determined and the temperatures in each node of the FEM grid are known. The specific temperature in the interface melt/refractory are called “nodal temperatures”.

However, the corrosion phenomenon modifies the geometry of the system, therefore, the thermal field before a \( \Delta t \) is not longer valid since a new distribution of temperature has left consolidating along the sole and in more general along the complete refractory lining of the furnace. The calculation of the new geometry is obtained applying to each of the nodes in the interface melt/refractory a corrosion equation. This equation (look Eqs. (5) and (13)), characterized according to the control mechanism of the wear process, it is phenomenologically or semi-empirically obtained. The temperature dependence of the parameters used for the specific corrosion equation considers the nodal temperature and the difference of temperature between the node and their adjacent nodes. 7 With this formulation, the corrosion rate in the node \( i \) expressed in units of length by unit of time is:

\[ v(\text{corrosion})_i = f(T_i, \Delta T_i) \]

The wear in each node is determined supposing that the temperature remains constant during the interval of time, \( \Delta t \):

\[ (\text{Wear})_i = v(\text{corrosion})_i \Delta t \]

As the geometry of the system has been modified, the new temperature field should be solved to obtain a new wear profile in the sole by means of an iterative process. If each iterative cycle takes place after a certain \( \Delta t \), the calculation process for the \( i \) node in the \( n \)th iteration is:

- Temperature in the \( i \) node by FEM: \( T_{i,n-1} \)
- Corrosion rate in the node \( i \):
  \[ v(\text{corrosion})_i = f(T_{i,n-1}, \Delta T_{i,n-1}) \]
- Wear during the \( \Delta t \) of the iteration \( n \) in the \( i \) node:
  \[ (\text{Wear})_i = v(\text{corrosion})_i \Delta t \]
- Definition of the new geometry and calculation of the new temperature field, \( T_i \), in the whole refractory lining, the sole of the furnace, and so the temperature of the interface melt/refractory is defined.

For two-dimensional problems, as those considered along this work, it is necessary to develop unidirectional equations of corrosion that allow the geometry correction of the refractory lining for a specific \( \Delta t \), that corresponds to the duration of the process for the production of refined ferromanganese.

2.2. Capillary Wear Mechanism

If the corrosion mechanism is controlled by the capillary penetration of the melt through the open porosity of the monolithic, the corrosion equation to consider in the NWM is deduced starting from the two following considerations (Fig. 2):

1) The work of the pressure (the height of the slag and of the metal on the node \( i \), \( e_r, e_m \)) is equal to the work due to interfacial phenomena during the penetration of the fluid into cylindrical capillaries of radius \( r \), an length, \( L_r \). In this case the depth reached by the melt fused in the node \( i \), \( l_r \), is:

\[ l_r = \frac{2(\rho_r g e_r + \rho_m g e_m + P_{\text{atm}})}{\gamma_{m/g} \cos \vartheta} \cdot r^2 \] ..........................(3)

Where \( \rho_r, \rho_m \) are respectively the nodal densities (function of \( T \)) of the slag and the metal; \( e_r, e_m \) the thickness of the slag and melt on the \( i \) node; \( r \) is the radius of the pores in the open porosity of the refractory; \( \gamma_{m/g} \) is the surface tension of the melt; \( P_{\text{atm}} \) the atmospheric pressure and \( \vartheta \) the contact angle between the melt and the sole refractory.

2) The time, \( t \), that the viscous fluid (remember Newton’s law, \( F = \mu \cdot \Delta v/\Delta x = \mu \cdot \Delta v/\Delta x/(\Delta t/\Delta x) \) or \( P = \mu/\Delta t \)) needs to travel the distance \( l_r \) is:

\[ t = \frac{\mu_i}{(\rho_r g e_r + \rho_m g e_m + P_{\text{atm}})} \] ..........................(4)

Where \( \mu_i \) is the nodal viscosity of the melt in the \( i \) node and \( (\rho_r g e_r + \rho_m g e_m + P_{\text{atm}}) \), is the nodal driving force of viscous flow.

With this two considerations, the rate of corrosions is obtained by dividing Eq. (3) by Eq. (4):

\[ v(\text{corrosion})_i = \frac{2(\rho_r g e_r + \rho_m g e_m + P_{\text{atm}})^2}{\gamma_{m/g} \cos \vartheta \mu_i} \cdot r^2 \] ..........................(5)
2.3. Chemical Wear Mechanism

When the open porosity of the refractory is small, the control mechanism for the wear process usually changes toward the dissolution of the main constituent of the refractory (where the most easily dissolution compounds could be found) to the melt. Usually, when the temperature is higher than 1000°C, the control stage of the process is the diffusion of the reaction products through the boundary layer in the melt. The diffusion mass flow of the attacked species $J_i$, could be calculated by the well known equation:

$$J_i = k_i \Delta C_i \left( \frac{\rho_i}{\rho_g} \right) \left( \frac{100}{\%cm} \right)$$ ..................................(6)

Where $k_i$ is the mass transfer coefficient, $\Delta C_i$ the difference of concentrations of the species that diffuses between the interface and the bulk of the melt. This equation can be transformed to represent this control mechanism in units of length by unit of time:

$$v_{\text{corrosion}} = k_i \Delta C_i \left( \frac{\rho_i}{\rho_g} \right) \left( \frac{100}{\%cm} \right) \left( \frac{\text{m}}{\text{s}} \right)$$ ..................................(7)

In this equation the difference of concentration $\Delta C_i$ should be expressed in mass percentage.

The corrosion equation that results from substituting the expression (8) in the Eq. (9) is:

$$v_{\text{corrosion}} = 0.332 \text{Re}^{1/2} \text{Sc}^{1/3} \left( \frac{D_i}{L} \right) \left( \frac{\rho_i}{\rho_g} \right) \left( \frac{100}{\%cm} \right)$$ ..................................(8)

Where $D_i$ is the diffusion coefficient of the attacked species; $L$ is the lineal characteristic dimension; Re, the Reynolds number and Sc the Schmidt number.

The corrosion equation that results from substituting the expression (8) in the Eq. (7) is:

$$v_{\text{corrosion}} = 0.332 \text{Re}^{1/2} \text{Sc}^{1/3} \left( \frac{D_i}{L} \right) \left( \frac{\rho_i}{\rho_g} \right) \left( \frac{100}{\%cm} \right)$$ ..................................(9)

To be able to use this corrosion equation it is necessary to know the movement of the melt in the interface with the refractory. The nodal velocity $\bar{v}_i$ used to calculate the Reynolds number is estimate from the two following considerations:

1) The flotation equation of particles with density, $\rho_p$, and size $D_p$ is:

$$\bar{v}_i = g \frac{D_p^2}{18 \mu} \left( \rho_m - \rho_p \right)$$ ......................(10)

2) The thickness for the velocity boundary layer, $\delta_v$, of a fluid that moves over a flat surface is:

$$\delta_v = 5.0 \left( \frac{\mu_i}{\bar{v}_i \rho_i} \right)^{1/2}$$ ......................(11)

For the system in analysis we can identify:

a) The characteristic lineal dimension, $L$, from Eq. (11) with $\delta_v$ ($L = \delta_v$).

b) The diameter of particles of Stokes equation, Eq. (10), with $\delta_v$ ($D_p = \delta_v$).

c) The difference ($\rho_m - \rho_p$) from Eq. (10) with $\Delta \rho_i$, difference between densities from $i$ node and its adjacent.

Then, the velocity of the melt in the $i$ node, $\bar{v}_i$:

$$\bar{v}_i = 6.98 \text{m} \cdot \text{s}^{-1} = 6.98 \text{m} \cdot \text{s}^{-1} \text{Re}^{1/2} \Delta \rho_i^{1/3}$$ ...............(12)

Substituting the Eq. (12) in the Eq. (9) we obtain the corrosion rate for every node in the melt/refractory interface, expressed in (m/s):

$$v_{\text{corrosion}} = 8.80 \cdot 10^{-3} L^{-1/2} \left( \frac{\Delta \rho_i}{\rho_i} \right)^{1/2} D_i \Delta(\%C) \left( \frac{\rho_i}{\rho_g} \right) \left( \frac{100}{\%cm} \right)$$ ..................................(13)

The difference of concentration of the species that diffuses, $\Delta(\%C)_i$, is expressed in mass percentage.
3. Experimental Results

The electric furnace used to carry out the refining operations is described in the Fig. 3. The letters B, D and E show the different distribution of dense refractories (refractory bricks produced by agglomeration and ceramic sinterization):

B: Sintered magnesite bricks.
D: Chrome–Magnesite bricks.
E: Sintered siliceous–aluminous bricks.

A and C are monolithic refractories where the geometric form was obtained by manual or automatic compaction:

A: Magnesite castable refractory.
C: Aluminous castable refractory.

The initial refractory in use was a magnesite castable sole, with high MgO content (mass% MgO > 95%), section A, Fig. 3. The average duration for the sole was only 19 tappings, that represent a corrosion rate of 0.52 cm·h⁻¹. When the thickness of the sole arrived to the level of the security refractory, magnesite sintered refractory, section B in Fig. 3, the furnace was turn off and cooled for the reinstatement with a new sole.⁸–¹⁰

Even the thermal level of the molten refined ferromanganese, 1 598 K (1 325°C), is far from those of a liquid carbon steel, 1 873 K (1 600°C), the corrosion rate of 3.70 · 10⁻² cm·h⁻¹ reported by Wolfram and collaborates from Voest–Alpine for an electric furnace of direct current show an extremely high difference with the 0.52 cm·h⁻¹ for the electric furnace used for the refining of the ferromanganese.¹¹

Nevertheless, it is necessary to remark the differences in the thermal condition during the solidification between those alloys. The interval of solidification for a carbon steel is 20°C and for the refined ferromanganese is 205°C (the solidification starts at 1 180°C and ends at 975°C). This value has been determined by means of differential thermal analysis (Shimadzu DTA-50) for a refined ferromanganese with the following chemical composition in mass%: Mn = 80%, C = 1.4%, Si = 0.80%, P = 0.15%, and mass balance for iron. Also from the DTA data, the practical solidification temperature, from which the material has a rigid behavior, was determined at 1 100°C.

![Diagram of the electric furnace](image)

**Position coordinates in meters**

| Point | X coordinate | Y coordinate | Point | X coordinate | Y coordinate |
|-------|--------------|--------------|-------|--------------|--------------|
| 1     | 0            | 0            | 25    | -0.25        | -0.25        |
| 2     | 1.572        | 0.349        | 26    | -0.25        | -0.542       |
| 3     | 1.7          | 0.58         | 27    | -0.75        | -0.229       |
| 4     | 2            | 0.58         | 28    | -0.75        | -0.479       |
| 5     | 2            | 0.68         | 29    | -0.75        | -0.529       |
| 6     | 2.12         | 0.68         | 30    | -1.25        | -0.099       |
| 7     | 2.235        | 0.68         | 31    | -1.25        | -0.349       |
| 8     | 2.12         | 1.63         | 32    | -1.25        | -0.399       |
| 9     | 2.35         | 1.63         | 33    | -1.572       | -0.349       |
| 10    | 2.35         | 0.68         | 34    | -1.7         | 0.58         |
| 11    | 2            | 0.149        | 35    | -2           | 0.149        |
| 12    | 2.235        | -0.099       | 36    | -2           | 0.58         |
| 13    | 2.35         | -0.07        | 37    | -2           | 0.68         |
| 14    | 2.35         | -0.12        | 38    | -2.12        | 0.68         |
| 15    | 1.25         | -0.099       | 39    | -2.235       | 0.68         |
| 16    | 1.25         | -0.349       | 40    | -2.35        | 0.68         |
| 17    | 1.25         | -0.399       | 41    | -2.235       | -0.099       |
| 18    | 0.75         | -0.229       | 42    | -2.35        | -0.07        |
| 19    | 0.75         | -0.479       | 43    | -2.35        | -0.12        |
| 20    | 0.75         | -0.529       | 44    | -2.35        | 1.03         |
| 21    | 0.25         | -0.292       | 45    | -2.12        | 1.03         |
| 22    | 0.25         | -0.542       | 46    | 0            | -0.6         |
| 23    | 0.25         | -0.592       |

Fig. 3. Detail of the electric furnace used in the fabrication of refined ferromanganese.
3.1. Calculation of the Convective Heat Transfer Coefficient between the Melt and the Refractory

The application of the NWM, requires the knowledge of the nodal temperatures in the melt/refractory interface. One of the border conditions fixed to solve the heat transfer problem is the temperature or heat flux in the shell. The second is the heat transfer condition between the sole and the melt, which is determinate by means of the calculation of the convective heat transfer coefficient among the liquid ferroalloy and the sole.

From the data of the differential thermal analysis of the ferroalloy and the duration of the MgO monolithic sole (19 tappings) we can apply the classic penetration theory to calculate the wear in each of the 19 tappings. The result should correspond to the evolution of the 1 100°C isotherm (rigid behavior of the ferroalloy). This isotherm is obtained by the resolution of the thermal problem using FEM (the software was COSMOS2.5). The evolution (penetration) of the isotherm is function of the value that reaches the convective heat transfer coefficient, \( h \), between the melt and the sole, Fig. 4. The problem is solved when the value of \( h \) used in the calculation adjusts, after 19 tappings, the residual thickness of the MgO sole with a tolerance of 5 mm. The point measured was the central part of the sole, where the maximum wear takes place and the value obtained for the convective heat transfer coefficient is 18 W·m\(^{-2}\)·K\(^{-1}\). This value constitutes a fundamental reference for all the simulations.

3.2. Capillary Wear Model

The magnesite castable sole does not have any type of organic, hydraulic or chemical bonding that could block the capillary infiltration of the alloy, implying that the wear mechanism is controlled by the penetration of the alloy through the open porosity as shown in Fig. 2.

Experimentally, the wear in the central node was measured (point 1 (0, 0) Fig. 3) and consequently, with the operation and tapping time, the corrosion rate of the sole (Fig. 5).

Solving the thermal problem using FEM with 18 W·m\(^{-2}\)·K\(^{-1}\) for the value of the convective heat transfer coefficient between the melt and the sole, the central node reach 1 280°C for the first tapping. The viscosity of the ferroalloy for that temperature was estimated in 8.2 \( \times \) 10\(^5\) Pa·s that allows to apply Eq. (5) since all the parameters are well known.

- Surface Tension of the ferroalloy\(^{12,13}\): 1.0 N·m\(^{-1}\). Although in the bibliography does not exist a value for the specific ferroalloy of this study, the values are known for the pure metals: Fe and Mn. As the same behavior between Cr and Fe, where the surface tension of Fe diminishes with chromium addition, it is assumed that for the manganese the surface tension diminishes due to the presence of 20% Fe.
- Slag density\(^{13}\): 3 200 kg·m\(^{-3}\), constant for the calculation.
- Ferromanganese density\(^{12,13}\): \( \rho (\text{Fe–Mn80\%})=7 125 - 3.22 \times 10^4 \ T^2 + 0.0151 \ T^3 - 0.265 \ T + 1.63 \)

Fig. 5. Experimental variation of corrosion rate for the magnesite monolithic refractory (MgO\(>\)95%) in the central node, point 1 (0, 0), Fig. 3.
Contact angle of the ferromanganese in the refractory: \( \theta = 30^\circ \).

Average of thermal conductivity of refractory materials in the sole (A, B, C, regions Fig. 3): \( \lambda = 5.0 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1} \).

Average size of porous in the central zone: 10 \( \mu \text{m} \).

Height of slag in the central node: 0.18 m.

Height of the melt (ferromanganese) in the central node: 0.34 m.

Corrosion rate in the central node, Fig. 5: 1.61 cm \cdot h^{-1} (4.47 \times 10^{-6} \text{ m} \cdot \text{s}^{-1}).

Repeating the calculation for each tapping in the central node of the sole (Fig. 3), we obtain a set of values for the viscosity that adjust the hypothesis of the infiltration according to the nodal temperature (i.e., for the 19th tapping, a temperature of 1119°C is in agreement to a viscosity of 4.3 \times 10^7 \text{ Pa} \cdot \text{s}). In definitive, the whole process leads to the validation of the wear control step by capillary, that allows to obtain the magnitude of the wear for all the nodes of the interface melt/refractory by means of a relation between nodal temperature and viscosity (Fig. 6).

Table 1 shows the viscosity calculated by the NWM at 1119°C and 1280°C as well as those for a rigid solid, 975°C, and a viscous flow or solid creep, 1100°C. The viscosity for the ferroalloy at 1400°C was estimated from those of a manganese melt and the Fe–C system (there are not reported in the literature a specific value for the ferroalloy used in this study).

3.3. Simulation for New Design

With the analytic equation adjusted by the measurements of the corrosion profile one can simulate the results of the following new conditions:

1. Changes in the thermal conductivity for the materials in regions B, C, D and E, Fig. 3:
   a) Region B changes from sintered magnesite \( (\lambda = 11.0 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}) \) to magnesia–carbon graphite refractory \( (\lambda = 25 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}) \).
   b) Regions B, C and D, using a magnesia–carbon graphite refractory \( (\lambda = 25 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}) \).

2. Changes in the conditions of external refrigeration for the shell of the furnace:
   - Air forced convection: \( h = 10–100 \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-1} \).
   - Water forced convection: \( h = 50–3000 \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-1} \).

The results for the corrosion profile with conditions 1 a) are shown in Fig. 7 and for conditions 1 b) in Fig. 8.

For metals as steel, with very narrow interval of solidification, it is easier to carry out the thermal design of the sole furnace to facilitate the formation of a "cold sole": a solidified layer of the metal on the refractory. In the case of this study, with a ferromanganese liquid alloy that has an interval of solidification ten times wider, it is difficult to get a
“cold sole” only by using high thermal conductivity materials. It is necessary to combine this with the use of refrigerated panels.

3.4. Chemical Wear Model

When the sole is made by a castable dolomitic sole, with a very little average size of particles (less than 100 μm) and very low content of impurities: (75% MgO, 20% CaO, 0.60% SiO₂, 3.80% Fe₂O₃, 0.30% Al₂O₃, others: 0.30%), the formation of liquid reactive phases is facilitated at low temperature. Even of being a not conformed material, the open porosity is very low and the mechanism of corrosion
is conditioned to the dissolution of the matrix constituent (magnesium, calcium, aluminum and iron silicates) in the melt. In this case the constituent of the refractory that is corroded by the melt is the SiO₂ by the reactions:

\[
\text{SiO}_2 \text{ (dis; matrix)} \rightarrow \text{Si (dis; Fe–Mn)} + 2\text{MnO}_2 \text{ (dis; slag)} \quad \ldots \quad (14)
\]

\[
\text{SiO}_2 \text{ (dis; matrix)} \rightarrow \text{Si (dis; Fe–Mn)} + 2\text{CO (g)} \quad \ldots \quad (15)
\]

It was shown experimentally that the substitution of the castable magnesite sole (material A, Fig. 3) by a dolomitic sole increase the number of tapping to about 45. The corrosion rate is in this case 0.27 cm · h⁻¹ (the wearing of the 30 cm of the sole is achieved in 45 operations of two and a half hour each), that is still far from 3.70 · 10⁻² cm · h⁻¹ in the case of the sole of an electric arc furnace in the production of carbon steel.

The progression of the wear in the central node (point 1, 0, 0) Fig. 3) expressed in meters is a function of the number of tappings, \(N\). The equation that represents this relation is:

\[
\text{(Wear; m)}_{\text{central node}} = -4.723 \cdot 10^{-3}N^2 + 8.792 \cdot 10^{-3}N \\
\]

(16)

In the same way to the case of the wear by infiltration, the resolution of the thermal problem using FEM (with the border condition for the convective heat transfer coefficient 18 W · m⁻² · K⁻¹) establishes a relation among the temperature of the central node, point 1 (0, 0) Fig. 3, and the number of tapping. This relation represents the effect of the geometry change by the successive corrosion profiles of the sole in the temperature, Fig. 9, curve A:

\[
T_i(\text{central node, K}) = -1.08 \cdot 10^{-2}N^2 - 3.1625N + 1556 \\
\]

(17)

Applying Eq. (13) in the central node with the dolomitic sole, the corrosion rate, expressed in m · s⁻¹ is:

\[
v(\text{corrosion}) = 7.65 \cdot 10^{-5}\left(\frac{9.0}{\rho_i}\right)^{1/6}D_S^{2/3}(S_i^z - S_i^0)\rho_i \\
\]

where:

- 9.0 kg · m⁻³ is the difference of average densities between the central node and their adjacent during the 45 tapings.
- 7.65 · 10⁻⁵ is a constant that includes the value of 8.80 · 10⁻³ from Eq. (13), the value of the global density of the refractory, 2 100 kg · m⁻³, the lineal characteristic dimension for the furnace, \(L\), 1.20 m (average between the sole radio, 1.88 m, and height of melt, 0.52 m, during ferromanganese production) and the mass 5% of the matrix constituent in the dolomitic sole.
- \(D_S = 4.50 \cdot 10^{-7}\exp(-4.626/T(K))\) m² · s⁻¹. This values correspond to the approximation from the Fe–Si (0, 0–4.0%) system to the ferromanganese alloy.²
- Density of the ferromanganese¹²,¹³: \(\rho_i = 7125 – 0.8393 \times T(K)\) kg · m⁻³.
- \(S_i^z\), maximum (thermodynamic equilibrium in the reactions (14), (15)) silicon content in the melt in mass%.

In the Eq. (18) all the parameters are known except \(S_i^z\). Assuming the chemical wear model one can adjust a relationship among \(S_i^z\) and temperature that adjust the rate of wear in the central node. We obtained the relationship:

\[
S_i^z = 32000 \exp\left(-\frac{2644}{T(K)} - 8.20\right) \quad \ldots \quad (19)
\]

With the corrosion equation adjusted from the experimental data one can simulate different situations to improve the behavior of the material used in the sole. For example, if the temperature of the central node (point 1 (0, 0) in Fig. 3) follows the variation given by curve B, Fig. 9, the average rate of corrosion is 0.12 cm/h that represent 100 tapings. To obtain this profile, likeness to the case of the capillary wear model, the following actions could be carried out:

![Fig. 9. Temperature of the central node of the sole (point 1 (0, 0) Fig. 3) for different number. Curve A: experimental profile (45 tapping). Curve B: simulated profile (100 tapping).](image-url)
a) Increasing the thermal conductivity of the materials that compose the security lining: regions B, D and C. 

b) Increasing the external refrigeration conditions (air and water): forced convection of air or watering. 

c) Using both mechanisms simultaneously. 

Certainly this type of simulations does not consider any other possibility of wearing that the chemical attack of the matrix constituent, aluminum, iron, calcium or magnesium silicates by the ferromanganese. Nevertheless it is necessary to remark that in some occasions abrupt changes in the thermal conditions of the furnace, or inadequate operational practices will produce a quick wear, therefore the calculated values will always give a value that represents the maximum resistance condition. 

Finally, it is interesting to analyze the influence in the model of the mass percent of the matrix constituent in the refractory, 5% for the value of the constant in Eq. (18). It was verified that during the thermal stabilization in a dilatometer Adamel DI-24, the matrix constituent could rise up to mass 15%. In this way it is possible to increase the duration of the sole if a systematic and regular maintenance is achieve to increase the matrix content, before each tapping and mainly, previously to the first tapping after the installation of the sole. Nevertheless, it is necessary to consider that the variation in the physical chemistry properties of the sole can increase the value of $\text{Si}^+$ in the Eq. (19) increasing the speed of corrosion (Eq. (20)).

4. Conclusions

The application of the Nodal Wear Model, NWM, was done for the sole of an electric arc furnace that produces ferromanganese. Two situation were considered, with an specific corrosion control for each one:

- Capillary wear model for a magnesite sole.
- Chemical wear model for a dolomitic sole.

In the capillary wear model the corrosion rate is controlled by the viscosity of the ferromanganese and its capacity to infiltrate the open porosity of the sole. 

In the chemical wear model the rate is controlled by the diffusion of silicon from the refractory interface to the ferromanganese. 

The NWM, is an analysis technique that allows to quantify the processes and mechanisms of wear in refractory materials. It can also be used as an instrument of great effectiveness in the construction and design of furnaces. 

Knowing the control mechanism of the corrosion, the NWM allows to simulate the effect of many new conditions: changes in material qualities, dimensions and distribution in the lining, refrigeration systems, etc. 

In hot zones, the NWM, could be use for the study of changing the heat transfer conditions, using cooling plates or addressing the heat flow toward cold areas 

Finally, the NWM, could be a very versatile tool for the calculation of physical properties (viscosity, Eq. (5)), thermodynamics properties (Eq. (19)) and transport properties (thickness of the boundary layer, Eq. (11)) as well as in the analysis of the laboratory test (finger test) with the purpose of obtaining the pertinent corrosion equations. 

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