Damage of slag-impregnated refractory in steel ladles, influence of interstitial pressure

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Abstract. The origin of spalling in a slag-impregnated bauxite lining of a steel ladle is examined. To study this phenomenon, a multi-physical coupling scheme is proposed. This work then focuses on the role that can be played by the interstitial pressure of molten slag. The main material and thermal loading parameters, which influence the pressure fluctuations, are identified and their influence is analyzed.

Introduction

In steel ladles, the inner layer of composite refractory linings is in contact with steel during metallurgical treatments, and with slag during casting. Bauxite bricks used for this wear lining are partially impregnated by slag. In the wetted area, cracks have been observed in a zone located a few centimeters from the hot face (figure 2). Cracks appear, run parallel to the hot face and cause "structural spalling" [1]. The principal consequences are the pollution of the steel bath and the premature wear of the refractory linings.

This work focuses on the damage origin of spalling which is studied in the framework of a multi-physical coupling scheme. First, this coupling scheme is introduced. Then, the role of the interstitial pressure of liquid slag is investigated. The influences of thermal and hydraulic diffusivities and the frequency of manufacturing cycles on the maximum pressure are examined.

Coupling scheme

Spalling in the Slag-Impregnated Zone (SIZ) results from degradations caused by highly complex interactions between refractory corrosion, stresses induced by thermal and mechanical loading and mineralogical phase transformations in the material. Several mechanisms may initiate damage, for example:

1. in SIZ, slag chemically reacts with bauxite at high temperature and leads to phase(s) transformation(s). It induces a volume change and modifications of mechanical properties of the material that can initiate a crack.
2. impregnation can be stopped by the solidification of the oxides. It leads to a significant change in material properties that can cause micro-crack initiation located at the impregnation front.
3. the liquid slag in SIZ, trapped in micro voids, can generate a pressure due to temperature fluctuations in the brick.

These phenomena can be analyzed in the framework of the coupling scheme summarized in Fig. 1.

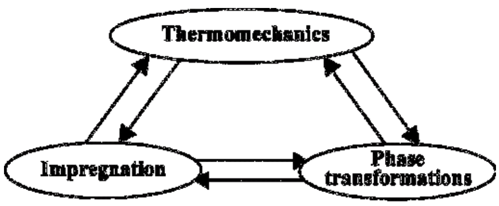

Fig. 1 : Coupling scheme

All interactions are not of equal importance. To our knowledge, no attention has been paid to the coupling between impregnation and the thermomechanical behavior. This coupling is developed herein to quantify the role of liquid slag pressure.

Influence of interstitial pressure

The steel-making process leads to a series of high and low temperature stages (i.e., full or empty vessels). The molten slag in the refractory open porosity (typically 15-20%) produces an interstitial pressure that fluctuates which space and time and induces stresses in the refractory lining. To model this phenomenon, only the SIZ is studied.

The SIZ is represented by a porous medium: the brick constitutes the skeleton and the molten slag the saturating liquid phase. For the sake of simplicity, chemical interactions between slag and refractory are not considered. Because of the ladle geometry, the problem is reduced to a one-dimensional description on a brick scale. Figure 2 shows the hypothesis adopted to establish a simplified analytical model.

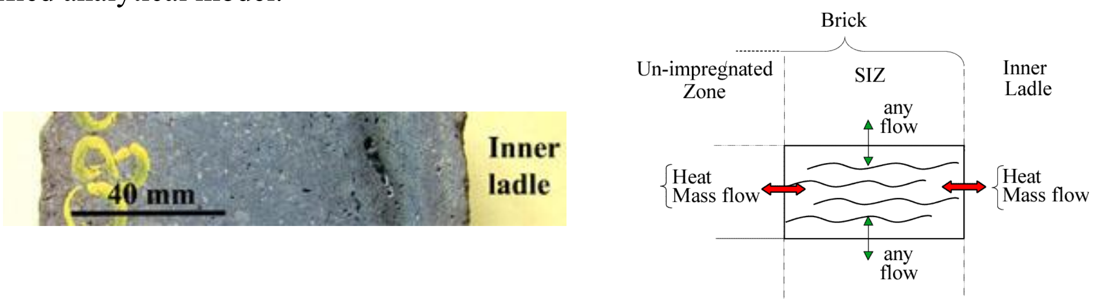

Fig. 2 : One-dimensional model on a brick scale

Principal notations:

$\underline{\underline{\sigma}}$, $\underline{\underline{\varepsilon}}$	stress, strain tensor
p, T, ϕ	pressure, temperature, porosity
b, M	Biot coefficient, modulus
D_T	thermal diffusivity
k	hydraulic conductivity
m	variation in fluid mass content
ρ, K	bulk density, compressibility
λ, μ	Lamé coefficient

Meaning of the subscript:

i	for initial
o	for drained characteristics
	anything for undrained characteristics
fl, s	for fluid, skeleton characteristics

Miscellaneous :

$a = (1-\nu_o) / (1+\nu_o)$

$\theta = T(x,t) - T_i(x)$

$P = P(x,t) - P_i(x)$

Because of lack of information on the high temperature behavior of the bauxite (from 1000 to 1600°C), the skeleton is assumed to be isotropic and thermoelastic. The associated constitutive equations are given by [2]:

$$\underline{\underline{\sigma}} = \underline{\underline{\sigma_i}} + \lambda\,(Tr\,\underline{\underline{\varepsilon}})\,\underline{\underline{I}} + 2\,\mu\,\underline{\underline{\varepsilon}} - b(p-p_i)\,\underline{\underline{I}} - 3\alpha_o K_o\,(T-T_i)\,\underline{\underline{I}} \tag{1}$$

$$p = p_i + M\,(-\,b\;Tr\,\underline{\underline{\varepsilon}} + m\,/\,\rho_{fl}) + 3\alpha_m M\,(T-T_i) \tag{2}$$

The conservation laws (momentum, mass flow and heat diffusion), boundary and initial conditions and the above constitutive equations form a closed set. Dufour effect is neglected, therefore the heat diffusion equation is uncoupled. The Soret effect is also neglected. Only the case of a traction-free surface is considered. The use of the Navier–Stokes equation for the skeleton and the fluid diffusion equation leads to the following differential equation for fluid pressure:

$$\frac{\partial^2 P}{\partial x^2} - \frac{1}{D_H}\frac{\partial P}{\partial t} = \frac{\delta_v D_T}{k}\frac{\partial^2 \theta}{\partial x^2} \tag{3}$$

where D_H is the hydraulic diffusivity and δ_v is the coefficient of relative bulk variation pore / fluid:

$$D_H = k\left(\frac{1}{M} + \frac{b^2}{3aK_o}\right)^{-1} \quad \text{and} \quad \delta_v = \alpha_o\left\lfloor b\left(\frac{1}{a} - 3\right) + 3\right\rfloor - 3\left[(1-\Phi)\alpha_s - \Phi\alpha_{fl}\right] \ . \tag{4}$$

The expression of δ_v shows that there are two sources of bulk variation: the differential pore / fluid dilatation and the poroelastic coupling.

Numerical simulations are performed by using the finite element code Abaqus-5.8 with drained boundary conditions ($P=0$ at the two ends) and intrinsic permeability of $1.8\text{x}10^{-16}$ m^2. For the considered application, a positive pressure appears during heating (Fig. 3). Consequently, it is the critical stage for the thermal cycle. The maximum interstitial pressure P_{max} is located a few centimeter from the hot face.

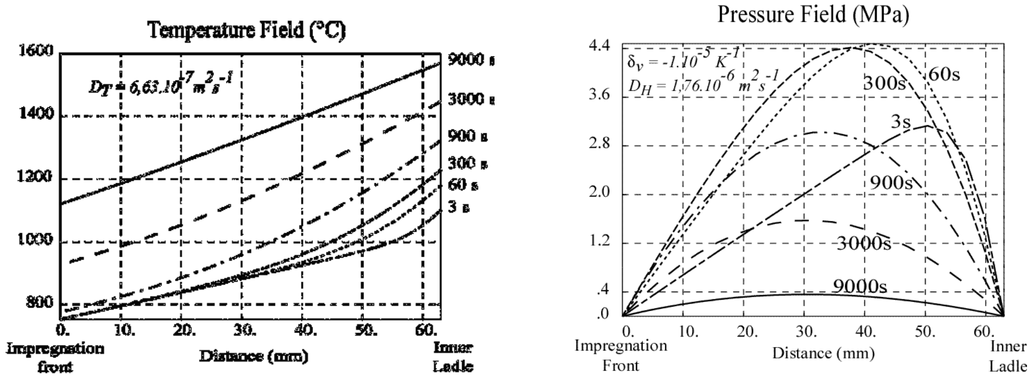

Fig. 3: Thermal and pressure space-time field

A reference pressure P_{nd} , which corresponds approximately to the case of a refractory with a very low hydraulic difusivity, can be derived in the undrained case ($m=0$, see Eqn. (2)):

$$P_{nd} = -\delta_v\left(\frac{1}{M} + \frac{b^2}{3aK_o}\right)^{-1}\theta_{\max} \ , \tag{5}$$

where θ_{max} is the amplitude of thermal loading at the hot face. The study of the case of a one-dimensional half space submitted to a harmonic surface temperature allows us to establish an analytical expression for an upper bound of the maximum dimensionless pressure. This bound only depends on the diffusivity ratio (Fig. 4) and its location is mainly dependent on the inverse of the square root frequency of thermal loading [3].

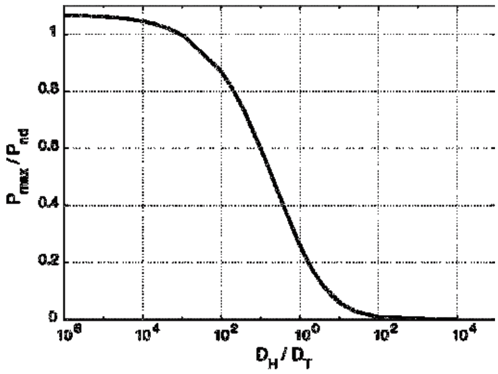

Fig. 4: Maximum dimensionless pressure versus diffusivity ratio [3]

By assuming that deformation is only possible in the thickness direction with a traction free hot face, it can be shown that the tensile normal stress of the skeleton (effective stress) in the thickness is proportional to the interstitial pressure. This tensile stress could be responsible for crack initiation parallel to the hot face.

Conclusion

The maximum interstitial pressure of molten slag due to thermal loading depends on thermal amplitude and diffusivity ratios. Consequently, the role of interstitial pressure in an impregnation-spalling phenomenon needs to be considered for low permeability and/or high thermal amplitudes (i.e., low ladle rotation). In such a case, pressure induces stresses in the brick that must be added to the classical thermal stresses. Furthermore, the location of the maximum pressure is close to those of micro cracks observed in bricks.

Because of the elastic skeleton behavior, this approach probably gives an upper estimate. At the present time, high temperature tests are carried out to identify a more realistic skeleton behavior. This identification will also be used to account for the influence of the non-linear thermomechanical behavior in an impregnation-spalling phenomenon. In a second analysis, phase transformations due to chemical reactions between slag and refractory will be identified. Lastly, their mechanical influences will be estimated.

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