# THE EFFECT OF KEY PROPERTIES ON THE THERMOMECHANICAL BEHAVIOR OF TORPEDO LADLE BRICKS USING FINITE ELEMENT ANALYSIS

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## ABSTRACT

The effect of some properties, *e.g.*, thermal expansion, thermal conductivity and hot mechanical behavior, on the thermomechanical behavior of $Al_2O_3$-SiC-C brick, typically used in torpedo ladles, is described. Computational modeling by finite element analysis (FEA) was applied in an attempt to better understanding the relative importance of each property for the development of refractories with enhanced spalling resistance and, then, longer service life. In spite of lots of evidences on the spalling, the key properties that drive this phenomenon remain to be investigated. In a first step, the simulations by FEA indicated that the failure criteria selected in this work are in accordance with the spalling mechanism proposed in the literature and with practical observations as well.In a second step, the effect of key properties on the thermomechanical behavior of $Al_2O_3$-SiC-C brick was simulated by FEA. It is proposed that the key properties to be controlled, among the investigated ones for the first step of the spalling mechanism, are the following: stress, thermal expansion, strain and thermal conductivity. The findings of the present investigation may be useful for developing refractories with enhanced spalling resistance and, then, longer service life.

Keywords: Torpedo ladle; refractories; spalling; mechanical properties; FEA.

## INTRODUCTION

Many efforts have been made on the development of torpedo ladle bricks. Fireclay and high alumina bricks were used in torpedo ladles in the past and, since then spalling has been evaluated[1].With the improvements of the chemical composition of the refractories and the use of $Al_2O_3$-SiC-C bricks, the thermomechanical behavior of this type of refractory has been investigated[1]. By simulating a complete cycle of a torpedo ladle lined with $Al_2O_3$-SiC-C bricks, these authors evaluated key aspects related to opening joint, however, their findings did not described the relevance of the refractory properties, for the development of a torpedo ladle brick with a better performance, to avoid or even minimize the spalling effect.

As it is difficult to analyze the thermomechanical behavior of constrained bricks under typical laboratory conditions, analysis by the finite element method (FEA) can be used as an important tool to predict the behavior of the material. The main challenge of FEA simulations applied to refractories is the selection of the correct failure criteria for it. There are some publications in which the Drucker-Prager yield criterion combined with a cut-off criterion has been assumed [2,3] which make the modeling applicable, but only to materials with the same behavior under compression and tension.

It is important to recognize that shear and compression data at high temperatures are not easily obtained and as the Drucker-Prager criterion was developed to granular materials, it seems to be the best choice for simulating the behavior of refractories. Nevertheless, in order to apply this criterion to some materials' parameters, such as the friction and cohesion angles, are required.

Based on visual observations, stress-strain curves and FEA simulations, Hirota *et al*. (1995)[4] have proposed a spalling mechanism for torpedo ladle bricks during operation, Figure 1. According to this mechanism spalling is a cyclic phenomenon. It will occur due to the increase of thermal stress on the bricks' hot face, stress which occurs as a result of the thermal gradient between the cold and the hot face of the refractory. In case of extreme stress the bricks' corners will chip and the cracks will advance horizontally along the hot surface; this zone will spall. Then, a new brick surface will be exposed and the phenomenon continues cyclically.

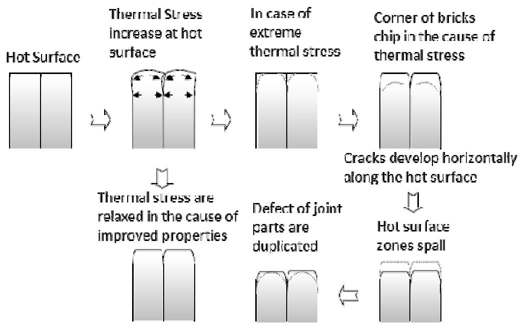


Fig 1: Schematic model of spalling mechanism (adapted from Hirota *et al*., 1995).

## EXPERIMENTAL

One typical $Al_2O_3$-SiC-C refractory brick (*i.e.*, 79% of brown fused alumina, 8% of silicon carbide, 8% of flake graphite, 3% of aluminum powder and 2% of silicon as antioxidants and phenolic resin as binder) was evaluated.

After curing at 200°C, 6h, the samples were characterized by thermal expansion. Heat treated samples (1400°C during 5h under reducing atmosphere) were characterized by stress-strain curves at different temperatures under compression. The thermal conductivity was obtained by standard values provided by Magnesita Refractories.

The FEA simulation was run using Ansys® Mechanical 14.0. In order to validate the data, the first step was to simulate the spalling mechanism as proposed by Hirota *et al*. (1995).Afterwards, different values of thermal expansion, stress and strain and thermal conductivity were inputted in the software to assess the key properties of the material in an attempt to enhance the spalling resistance.

Each stress-strain curve was divided in eight different strain dependent linear curves.As the typical high temperature stress-strain curve is non-linear, if only the modulus of elasticity is considered, the differences on the material's behavior with different strains would not be taken into account, thereby affecting the analysis of data.

## RESULTS AND DISCUSSION

Initially, the spalling mechanism proposed by Hirota *et al.* (1995) was simulated in order to validate the failure criteria used in the current work. To obtain the thermal gradient along the material under steady-state condition the hot face brick temperature was set up to 1450°C.

Figure 2 shows the normal stress simulation along both X and Y axis. Higher compressive stress (-20.61MPa) can be observed on the X axis and close to the bricks' hot face, rather than tensile stress on the Y axis (0.67MPa). Considering that the compressive stress, which is larger than the tensile stress, is large enough to break the bricks' corners a new scenario can be simulated, as shown in Figure 3. After broken edges the normal stress on X and Y axis changes. As a larger contact surface area between bricks was replaced by a smaller one, compressive stresses became concentrated closer to the brick hot face on axis X (-65.20MPa). An increase on tensile stress can also be verified on Y axis (1.77MPa). With regard to the shear stress, Figure 4, it is concentrate close to the hot face showing that spalling will occur over this region, as observed in the industrial operation and in accordance with the mechanism proposed in the literatura (Hirota *et al.*, 1995).

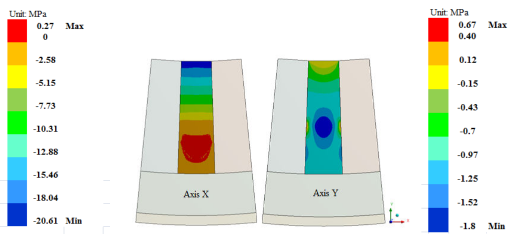


Fig.2: FEA simulation of the normal stress along the brick (X and Y axis).

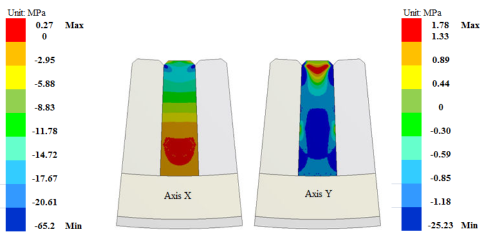


Fig.3: FEA simulation of the normal stress along the brick (X and Y axis) after broken edges.

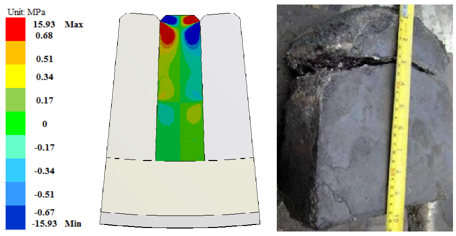


Fig.4: FEA simulation of the shear stress along the brick (X and Y axis) after broken edges and a photograph of brick after being removed from a torpedo ladle.

As the failure criteria is in accordance with the schematic model (Fig. 1) and practical observations this criteria will be used to better understanding and quantitatively assessment on the effect of the key properties on the thermomechanical behavior of the selected brick.

In summary, the computational modeling by FEA revealed that the stress values were systematically higher after bricks' broken edges than before it. Thus, it seems to be a better choice to avoid spalling by hindering the formation of broken edges (first step of the spalling mechanism) than by avoiding the spalling itself (second step of the spalling mechanism). Due to its relevance this paper will focus on the first step of spalling.

### Thermal expansion

Typical thermal expansion for the standard composition was 0.9% at 1400°C, with the thermal expansion coefficient equal to 6.84 X $10^{-6}$ $^{\circ}C^{-1}$. In order to analyze the effect of such property on the thermomechanical behavior of the selected brick at 1400°C, two different coefficient values were simulated by FEA, as follows: expansion of 1.2% (thermal expansion coefficient of 8.84 x $10^{-6}$ $^{\circ}C^{-1}$) and 0.7% (thermal expansion coefficient of 5.84 X $10^{-6}$ $^{\circ}C^{-1}$). When the thermal expansion decreased from 0.9 to 0.7% at 1400°C, there was a diminution of the magnitude of the compression on the axis X and shear stresses, close to the brick hot face, stress that causes the break of the brick's edges (first step on the spalling mechanism), as previously discussed. On the other hand, when the thermal expansion increased from 0.9 to 1.2% at 1400°C, an increase of the magnitude of the compression on the axis X and shear stresses can be observed, which is certainly a risky to the material stability.

The decrease of the thermal expansion of the investigated brick seems to be an adequate method to minimize the stress on the bricks and, therefore, avoid spalling. Nevertheless, it is very important to make a deeper analysis of the effect of this property. A significant decrease of the thermal expansion can be sufficient to create open joints between the bricks during both steps of the spalling mechanism, which in turn may lead to a severe wear of the refractories used in the torpedo ladle. The simulations by FEA have confirmed that the contact pressure between the bricks decreases when the thermal expansion decreases.The region without physical contact between the bricks, *i.e.* no contact pressure, became closer to the hot face in the case of low thermal expansion and, then, an infiltration of the molten metal between the joints during the torpedo car operation may became easier. In this case, it would be necessary to redefine the torpedo ladle project in order to avoid open joints.

### Thermal conductivity

The simulations by FEA were conducted using thermal conductivity values which are 15% higher and 15% lower than the typical values.
It is expected that the variation of the thermal conductivity affects the contact pressure between the bricks. As a higher temperature implies in a higher brick expansion, if the thermal conductivity is larger than a standard value the region with no contact pressure between bricks shifts down to the brick cold face. Thus, the contact area between bricks become larger and, consequently, the stresses are better distributed through the material. It results in a lower compression stress along the X (from 18.07 to 17.54MPa) axis and lowers shear stress during the first step of the spalling mechanism (from 0.63 to 0.58MPa). An opposite scenario was observed when the thermal conductivity has been decreased, that is, the contact area between the bricks became smaller causing a stress concentration. Compression stresses along the X axis increase to 18.30MPa and shear stresses to 0.70MPa.

**Hot mechanical behavior**
**Strain**
In order to evaluate the effect of strain on the spalling effect, the measured stress-strain curve was modified. Each strain value was varied by ±20% at the investigated temperature range (800-1400°C).
Firstly, it is important to recognize that an increase or decrease of strain by 20% does not correspond to a similar variation of the modulus of elasticity. The simulation by FEA showed that lower normal stresses (from 18.07 to 17.04MPa on the X axis and from 2.10 to 1.95MPa on the Y axis) and shear stress (from 0.63MPa to 0.58MPa) were found along the brick in case of positively shifted stress-strain curve . It is simple to realize that under similar stress condition, a brick will be more flexible at the temperature range if its measured strain is higher. Such material absorbs better the stresses developed between bricks, thereby resulting in lower values for the maximum stresses and smaller areas with maximum stresses.
**Stress**
In order to evaluate the effect of stress on the spalling behavior, the measured stress-strain curve was modified as well, as earlier described. Thus, each stress value was varied by ±20% at the investigated temperature range (800-1400°C).
Again, it is important to recognize that an increase or decrease of stress by 20% does not correspond to a similar variation of the modulus of elasticity. In contrast to the simulations exhibited before when strain was varied, the simulation by FEA showed that higher normal stresses (from 18.07 to 20.20MPa on the X axis and from 2.10 to 2.32MPa on the Y axis) and shear stress (from 0.63MPa to 0.80MPa) were found along the brick in case of positively shifted stress-strain curve for the first step of the spalling mechanism. It is simple to realize that under similar strain condition, a brick will be more rigid at the temperature range if its measured stress is higher. Such material does not absorb the stresses developed between bricks, thereby resulting in higher values for the maximum stresses and larger areas with maximum stresses.

**Possible alternatives to avoid spalling**
As observed on the FEA simulation results there are some important aspects on the development of a new refractory to be considered in order to avoid the spalling *e.g.* reduce thermal expansion, increase thermal conductivity, increase strain or decrease stress. Although these properties are all connected and is not possible to modify one of then without affect the others.
Table 1 presents an overview of how stress is affected by the variation on the individual properties evaluated on this paper. Some important aspects on the refractory development can be taken in account in order to produce a material with enhanced spalling resistance likely carbon content, granulometry and alumina source.

| Property | | Variation | Shear stress (%) | How to avoid spalling |
|---|---|---|---|---|
| Thermal expansion | | +33% | 25.0 | Increase carbon content. |
| | | -22% | -11.0 | |
| Thermal conductivity | | +15% | -9.0 | Increase carbon content. |
| | | -15% | 11.0 | |
| Hot mechanical behavior | Strain | +20% | -10.0 | Decrease carbon content, change granulometry design for an unpacked one. |
| | | -20% | 8.5 | |
| | Stress | +20% | 25.0 | Increase carbon content, use a denser alumina source. |

Table 1: Stress variation (%) after changes in key properties.

**CONCLUSIONS**
In this work, computational modeling by FEA was applied to validate a yield criterion of $Al_2O_3$-SiC-C brick, typically used in torpedo ladles, in order to confirm a mechanism proposed in the literature and visual observations. Additionally, the method was also applied to evaluate, in a qualitative way, the effect of the properties thermal expansion, thermal conductivity, stress and strain, on the thermomechanical behavior of this refractory, in an attempt to develop products with enhanced spalling resistance.
The simulations by FEA indicated that the failure criteria selected in this work are in accordance with the spalling mechanism proposed in the literature and with practical observations. As the stress values were systematically higher after the break of the bricks' edges, it seems more reasonable to avoid spalling by hindering the formation of broken edges (first step of the spalling mechanism) than by avoiding the phenomenon itself (second step of the spalling mechanism).
On the basis of the simulations by FEA, it has been proposed that the key aspects to be controlled, among the investigated ones for the first step of the spalling mechanism, are the following: stress, thermal expansion, strain and thermal conductivity. It is important to recognize that all of the evaluated properties are connected and is not possible to change one without affect the others.

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