

# THE EFFECT OF KEY ASPECTS ON THE THERMOMECHANICAL BEHAVIOUR OF TORPEDO LADLE BRICKS USING FINITE ELEMENT ANALYSIS

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## Abstract

In the current paper, the effect of some aspects, e.g., thermal expansion, thermal conductivity and hot mechanical behavior, on the thermomechanical behavior of Al<sub>2</sub>O<sub>3</sub>-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 variable for the development of refractories 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 breakage of the bricks' edges, it seems more reasonable to avoid spalling by hindering the formation of broken edges than by avoiding the phenomenon itself. The effect of key aspects on the thermomechanical behavior of Al<sub>2</sub>O<sub>3</sub>-SiC-C brick was simulated. The key variables to be controlled are the following: stress, thermal expansion, strain and thermal conductivity.

**Keywords:** FEM; Thermomechanical behavior; Torpedo ladle.

## O EFEITO DE ASPECTOS CHAVE NO COMPORTAMENTO TERMOMECANICO DE TIJOLOS PARA CARRO TORPEDO UTILIZANDO ANÁLISE POR ELEMENTOS FINITOS

## Resumo

No presente trabalho, descreve-se o efeito de alguns aspectos, tais como, expansão térmica, condutividade térmica e comportamento mecânico quente, no comportamento termomecânico do tijolo Al<sub>2</sub>O<sub>3</sub>-SiC-C, tipicamente usado em panelas de torpedo. Modelagem computacional por análise de elementos finitos (FEA) foi aplicada na tentativa de melhor compreender a importância relativa de cada variável para o desenvolvimento de refratários com maior resistência ao lascamento. As simulações da FEA indicaram que os critérios de falha selecionados neste trabalho estão de acordo com o mecanismo proposto na literatura e com as observações práticas. Como os valores de tensão foram sistematicamente mais altos após a quebra das bordas dos tijolos, parece mais razoável evitar a fragmentação impedindo a formação de bordas quebradas do que evitando o fenômeno em si. O efeito de aspectos-chave no comportamento termomecânico do tijolo Al<sub>2</sub>O<sub>3</sub>-SiC-C foi simulado. As principais variáveis a serem controladas são as seguintes: tensão, expansão térmica, deformação e condutividade térmica.

**Palavras-chave:** FEA; Comportamento termomecânico; Carro torpedo.

## I INTRODUCTION

Torpedo ladles are typically lined with alumina silicon carbide carbon refractories (Al<sub>2</sub>O<sub>3</sub>-SiC-C). These materials withstand a broad range of temperature and undergo severe thermal cycles during the campaign. As all bricks are assembled

in a restricted condition that retains the natural thermal expansion of the refractory, spalling effect may occur [1-3].

Many efforts have been made on the development of torpedo ladle bricks. Fireclay and high alumina bricks were

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used in torpedo ladles in the past and, since then spalling has been evaluated [4,5]. With the improvements of the chemical composition of the refractories and the use of  $\text{Al}_2\text{O}_3\text{-SiC-C}$  bricks, the thermomechanical behavior of this type of refractory has been investigated [1]. By simulating a complete cycle of a torpedo ladle lined with  $\text{Al}_2\text{O}_3\text{-SiC-C}$  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 [6-8], 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. Dahlem [9] have found these parameters at room temperature for two types of refractories (burnt magnesia and burnt magnesia spinel brick) using a method based on the application of uniaxial load on a

bar shaped specimen with an inclined notch in order to obtain, locally, a combination of shear and compressive stresses. The method required at least two specimen designs with different notch angles. From the maximum loads obtained on the laboratory tests it was possible to calculate mean values of cohesion and friction angle.

At this point it is important to comment that the parameters to be used during the simulation by FEA should be obtained at the operational temperature of torpedo ladle and using  $\text{Al}_2\text{O}_3\text{-SiC-C}$  refractories. Additionally, as this type of bricks exhibit a high oxidation level at high temperatures, some adjustments in the available method are mandatory.

Based on visual observations, stress-strain curves and FEA simulations, Hirota et al. [3] 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.

On the basis of this brief review, the purpose of the present work was (i) to evaluate the effect of some properties, such as thermal expansion, thermal conductivity and hot mechanical behavior (stress and strain curves), on the thermomechanical behavior of  $\text{Al}_2\text{O}_3\text{-SiC-C}$  refractories by means of FEA simulations and thus (ii) establishing their relative importance for the development of a torpedo ladle brick with enhanced spalling resistance.

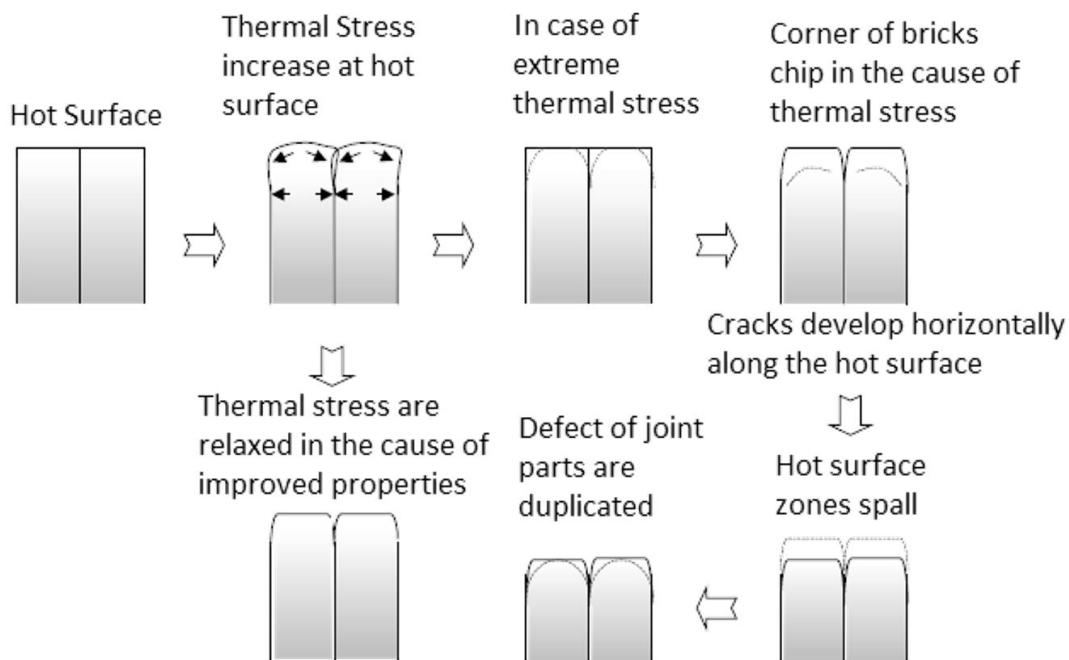


Figure 1. Schematic model of spalling mechanism (adapted from Hirota et al. [3]).

## 2 EXPERIMENTAL

### 2.1 Material and Properties

One typical  $\text{Al}_2\text{O}_3$ -SiC-C refractory brick (i.e., 79% (m/m) of brown fused alumina, 8% (m/m) of silicon carbide, 8% (m/m) of flake graphite, 3% (m/m) of aluminum powder and 2% (m/m) of silicon as antioxidants and phenolic resin as binder) was evaluated.

After curing at 200°C, 6 h, the samples were characterized by thermal expansion. Heat treated samples (1400°C during 5 h 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.

#### 2.1.1 Thermal Expansion

Thermal expansion curves were obtained using cylindrical samples with height of 50 mm and diameter of 35 mm, which were drilled in both faces to present a minimum parallelism of 0.05 mm. A MTS press (model 810) with specified capacity of  $15 \times 10^3$  kg was used for the thermal expansion measurement. The curves were determined by applying a uniaxial compression of 0.09 kN axis and alumina disks were placed between the specimens and the push-rod. The measurements were carried out with a heating rate of 5°C/min from room temperature up to 1400°C. In order to avoid oxidation, a continuous flow of argon gas was kept inside the test chamber through the measurements.

#### 2.1.2 Hot modulus of elasticity

Stress-strain curves were obtained by applying uniaxial compression over cylindrical samples with height of 50 mm and diameter of 25 mm, which were drilled in both faces to obtain a minimum parallelism of 0.05 mm, using the same equipment, as described above. The compressive load was applied parallel to the cylinder axis and alumina disks were placed between the specimens and the push-rod. Stress-strain tests were carried out at 800°C, 1000°C, 1200°C and 1400°C with a heating rate of 5°C/min. The load was applied after 10 min at the test temperature. The test was interrupted when the piece failed. In order to avoid oxidation, a continuous flow of argon gas was used inside the test chamber through the measurements.

#### 2.1.3 Thermal conductivity

The thermal conductivity of refractories is usually measured by the hot wire method [10, 11], but high conductivity and carbon oxidation may limit the applicability of this method for carbon-contained refractories. The thermal conductivity value used in this paper was collected from standard tables available at RHI Magnesita researcher center (Table 1).

### 2.2 Finite Element Analysis (FEA)

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. [3]. 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 exemplified in Figure 2. 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.

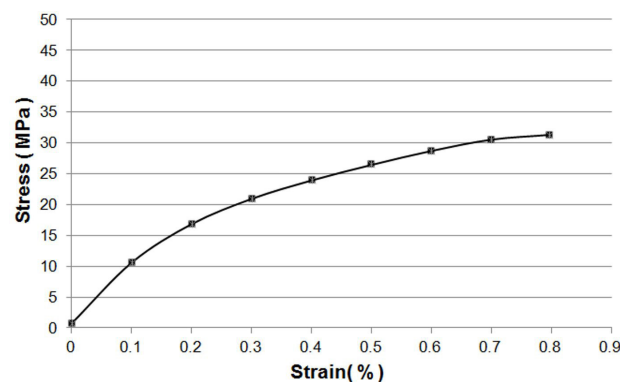
## 3 RESULTS AND DISCUSSION

### 3.1 Material Properties

Figure 3 shows the thermal expansion curve obtained for the  $\text{Al}_2\text{O}_3$ -SiC-C brick from the MTS dilatation test. It reveals a thermal expansion lesser than 1% under the investigated temperature range. Although this curve is non-linear, mainly at low temperatures due to the stress release generated by the binder as this is a after curing measurement, the data were fitted by a linear regression

**Table 1.** Thermal conductivity values for the standard composition

Temperature (°C)	Thermal Conductivity ( $\text{W}\cdot\text{m}^{-1}\cdot\text{C}^{-1}$ )
200	5.32
400	4.99
600	4.68
800	4.39
1000	4.11
1200	3.86
1400	3.62



**Figure 2.** Example of stress-strain curve divided in eight linear curves.

with intercept at (0,0) in order to find the thermal expansion coefficient as follows:  $6.84 \times 10^{-6} \text{ } ^\circ\text{C}^{-1}$ .

The static hot modulus of elasticity was calculated through stress-strain curves obtained at 800°C, 1000°C, 1200°C and 1400°C, as shown in Figure 4. In addition, each curve was divided in eight linear segments with their

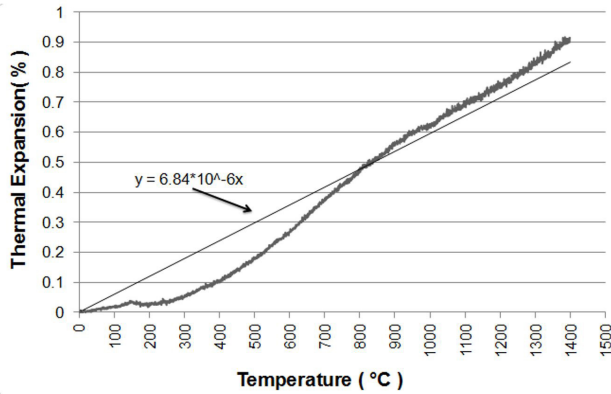


Figure 3. Thermal expansion curve and linear fitting.

corresponding slopes, which were used in the simulation at the corresponding temperatures. The measurements revealed that the maximum stress decreases as the temperature increases, likely as result of the plastic behavior with the temperature increase.

### 3.2 Finite Element Analysis (FEA)

#### 3.2.1 Failure criteria validation

Initially, the spalling mechanism proposed by Hirota et al. [3] 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. The temperature profile is shown in Figure 5. The FEA simulation reveals gradual temperature decay within well-defined temperature zones. Along the Y axis, the temperature dropped from 1450°C to 302°C, from

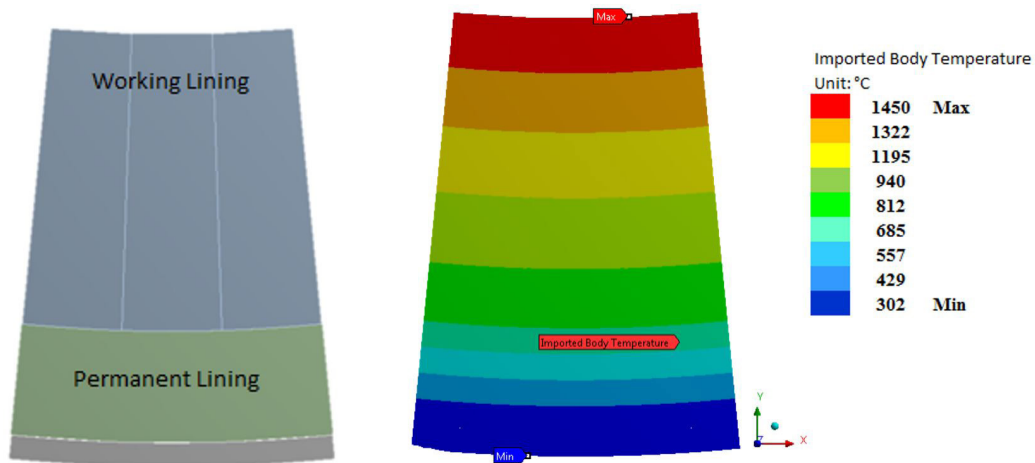


Figure 4. Stress-strain curves at different temperatures for the standard composition.

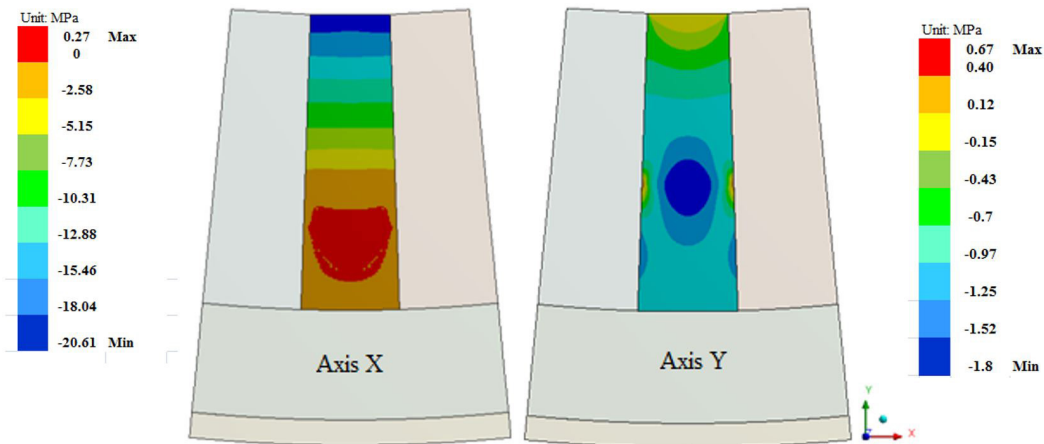


Figure 5. FEA simulation of the steady-state thermal gradient along the brick.

the brick hot face to shell, reaching 812°C by the end of the working lining.

Figure 6 shows the normal stress simulation along both X and Y axis. Higher compressive stress (-20.61 MPa) can be observed on the X axis and close to the bricks' hot face, rather than tensile stress on the Y axis (0.67 MPa). 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 7. 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 (-65.20 MPa). An increase on tensile stress can also be verified on Y axis (1.77 MPa). With regard to the shear stress, Figure 8, 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 [3].

As the failure criteria is in accordance with the schematic model (Figure 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.

### 3.2.2 Effect of relevant properties

The values simulated in the present work for the thermal expansion, thermal conductivity and hot mechanical behavior (stress strain curves) were selected according to practical observations for each property of the investigated material.

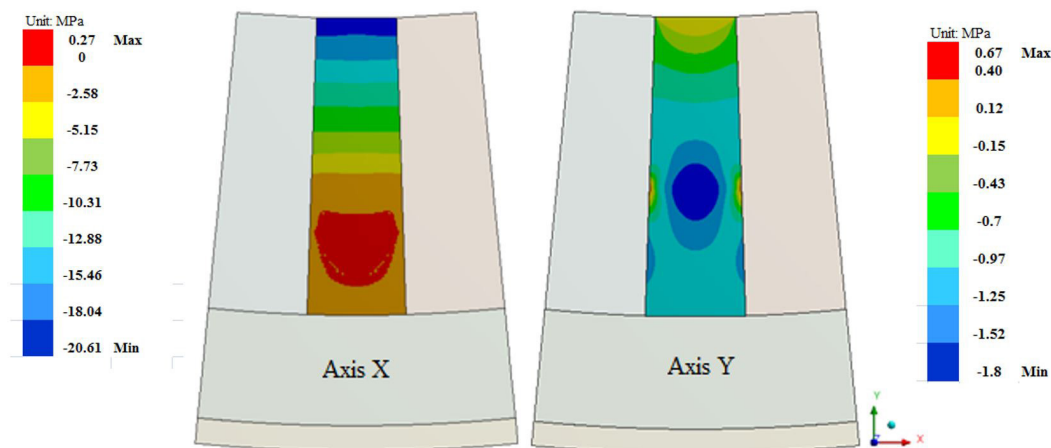


Figure 6. FEA simulation of the normal stress along the brick (X and Y axis).

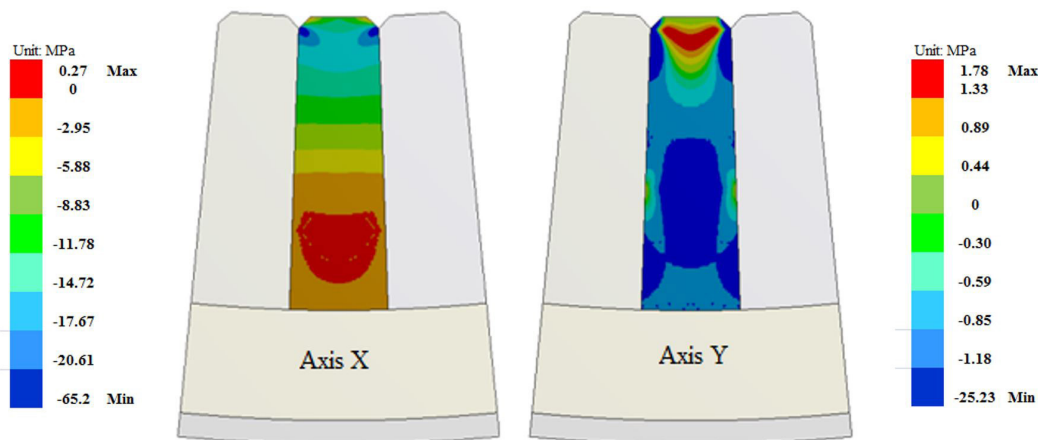
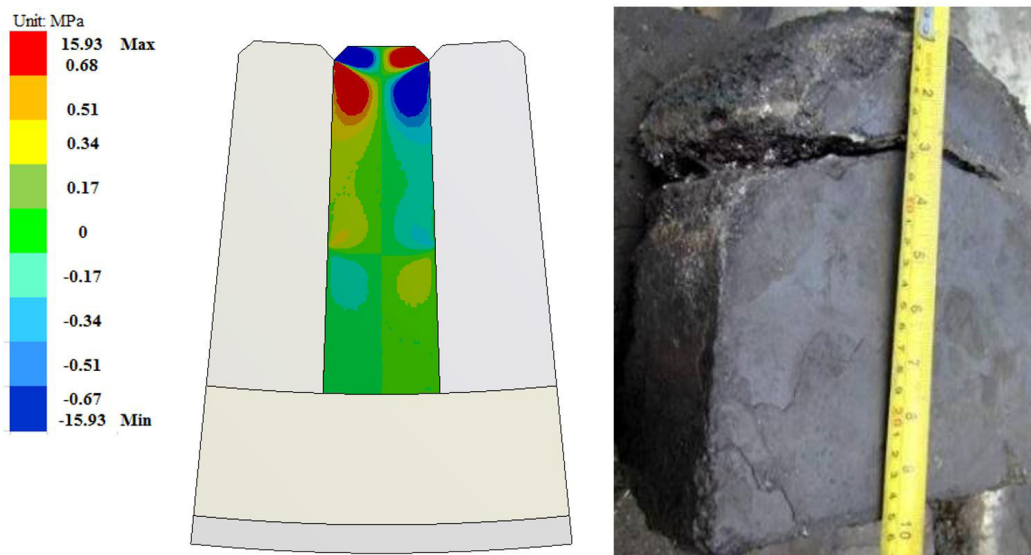


Figure 7. FEA simulation of the normal stress along the brick (X and Y axis) after broken edges.



**Figure 8.** 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.

### 3.2.2.1 Thermal expansion

Typical thermal expansion for the standard composition was 0.9% at 1400°C, with the thermal expansion coefficient equal to  $6.84 \times 10^{-6} \text{ } ^\circ\text{C}^{-1}$ . 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  $8.84 \times 10^{-6} \text{ } ^\circ\text{C}^{-1}$ ) and 0.7% (thermal expansion coefficient of  $5.84 \times 10^{-6} \text{ } ^\circ\text{C}^{-1}$ ). FEA results are presented in Table 2. It can be seen that when the thermal expansion decreased from 0.9 to 0.7% at 1400°C (Table 2), 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 (Table 2), 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, Table 3. The region without physical contact between the

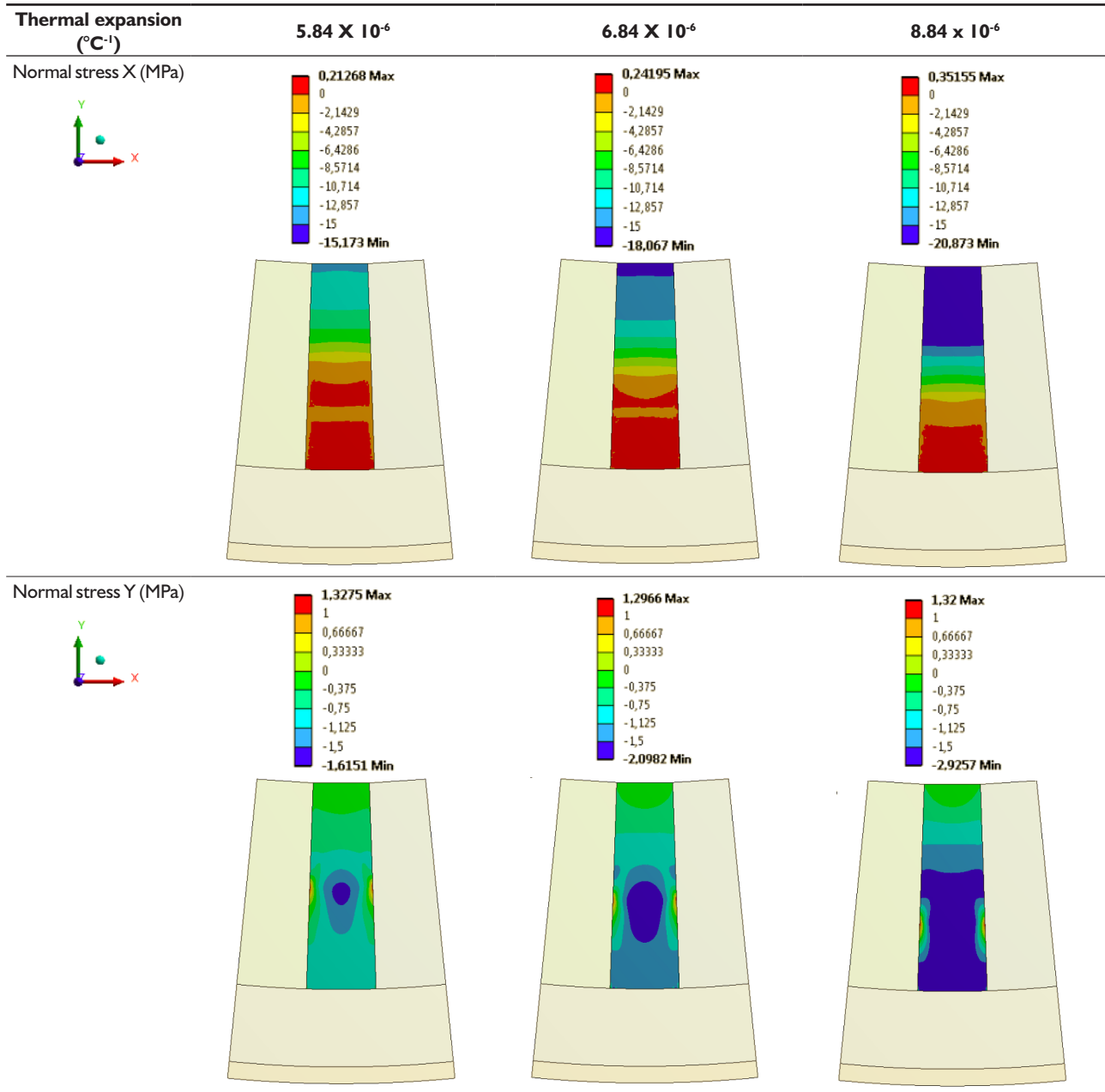
bricks, *i.e.* no contact pressure, became closer to the hot face in the case of low thermal expansion and, then, an infiltration of the molten metal between the joints during the torpedo car operation may become easier. In this case, it would be necessary to redefine the torpedo ladle project in order to avoid open joints.

### 3.2.2.2 Thermal conductivity

The simulations by FEA were conducted using thermal conductivity values which are 15% higher and 15% lower than the typical values presented on Table 1. It has been found that along the Y axis the temperature dropped from 1450°C to 857°C from the brick hot face to the cold face of the working lining. By increasing the thermal conductivity by 15% (Table 4), the temperature dropped from 1450°C to 898°C by the end of the working lining, while by decreasing it by 15% the temperature dropped from 1450°C to 808°C by the end of the working lining.

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 MPa to 17.54 MPa) axis and lowers shear stress during the first step of the spalling mechanism (from 0.63 MPa to 0.58 MPa). 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

**Table 2.** FEA simulation of the effect of thermal expansion on the normal and shear stresses along the brick - first step of the spalling mechanism



stresses along the X axis increase to 18.30 MPa and shear stresses to 0.70 MPa.

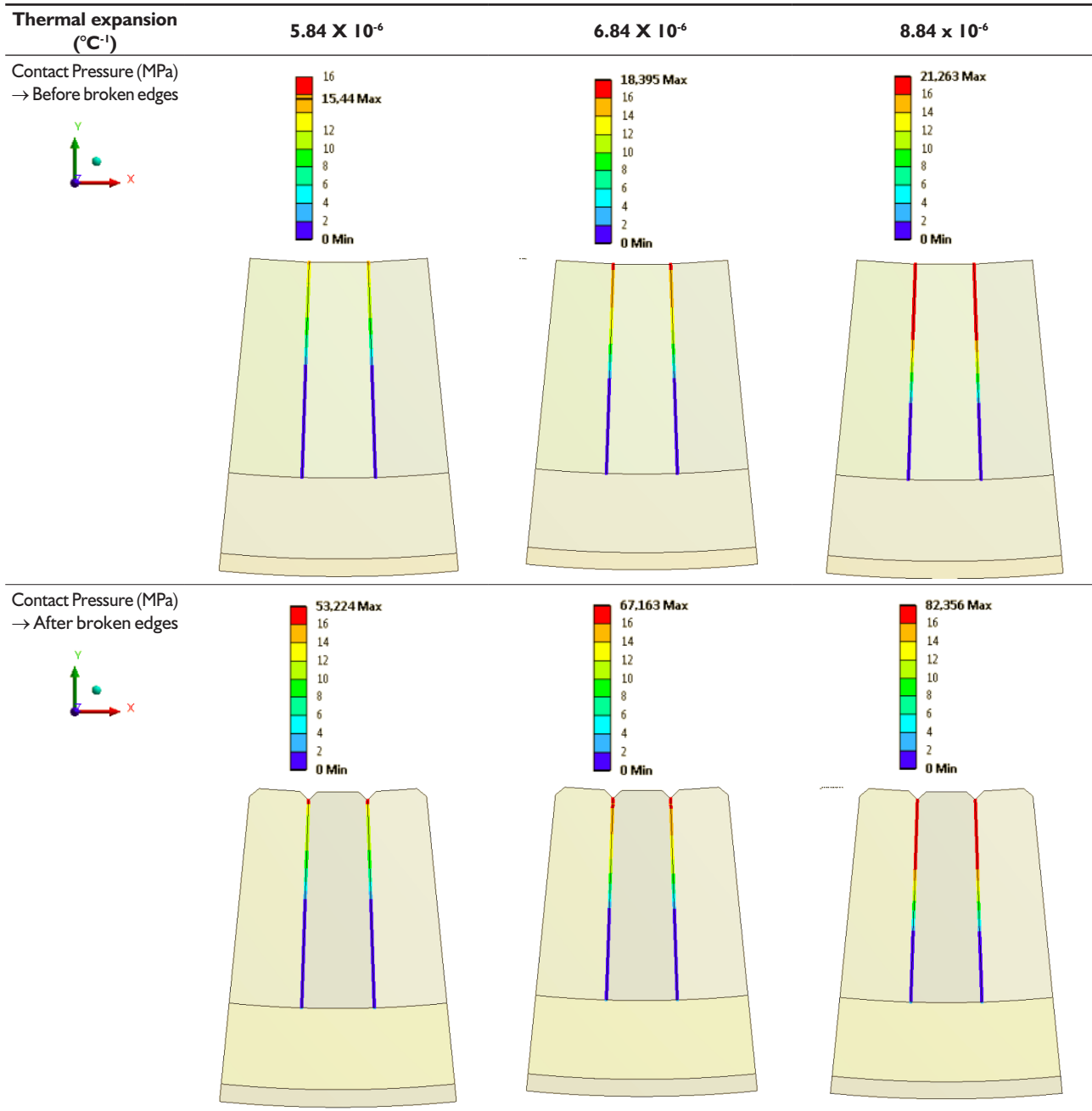
### 3.2.2.3 Hot mechanical behavior

- **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). For instance, Figure 9 shows the measured stress-strain curve at 1000 °C and those shifted by 20% in relation to the measured one.

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 MPa to 17.04 MPa on the X axis and from 2.10 MPa to 1.95 MPa on the Y axis) and shear stress (from 0.63 MPa to 0.58 MPa) 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

**Table 3.** FEA simulation of the contact pressure along the brick after varying the thermal expansion during both steps of the spalling mechanism



lower values for the maximum stresses and smaller areas with maximum stresses.

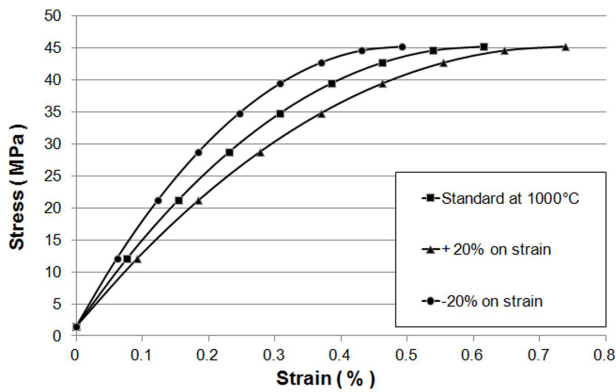
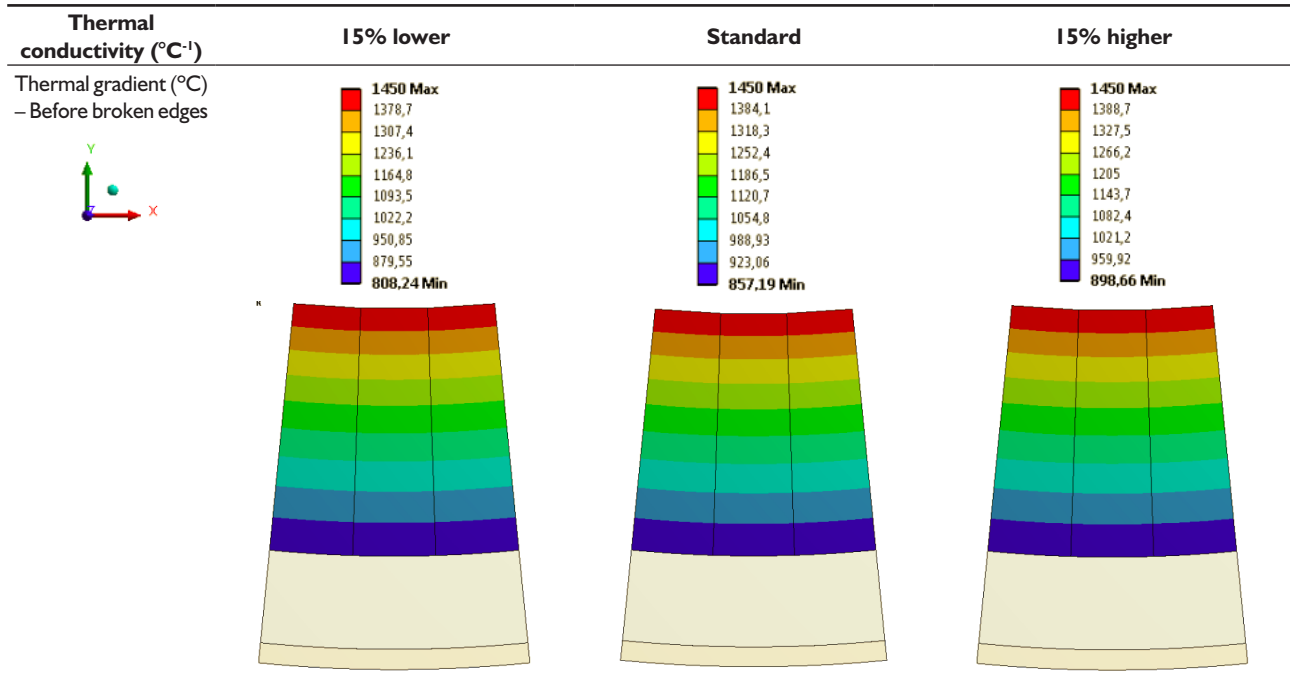
- **Stress**

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 (from 800°C to 1400°C). For instance, Figure 10 shows the measured stress-strain curve at 1000 °C and those shifted by 20% in relation to the measured one.

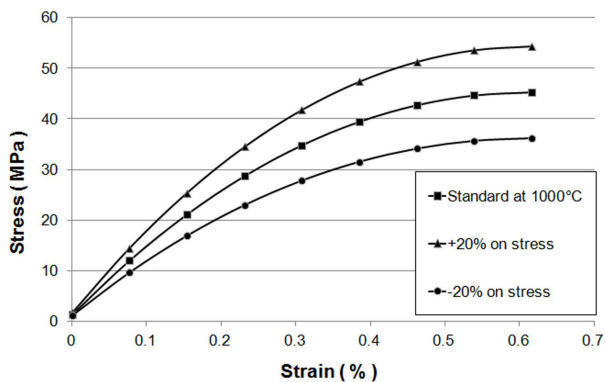
Again, it is important to recognize that an increase or decrease of stress by 20% does not correspond to a similar variation of the modulus of elasticity. In contrast to the simulations exhibited before when strain was varied, the simulation by FEA showed that higher normal stresses (from 18.07 MPa to 20.20 MPa on the X axis and from 2.10 MPa to 2.32 MPa on the Y axis) and shear stress (from 0.63 MPa to 0.80 MPa) 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



**Table 4.** FEA simulation of the steady-state thermal gradient along the brick with different thermal conductivities



**Figure 9.** Stress-strain curves at 1000°C: measured and shifted ones in relation to the strain values.



**Figure 10.** Stress-strain curves at 1000°C: measured and shifted ones in relation to the stress values.

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.

### 3.2.2.4 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 them without affect the others.

Table 5 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. This type of chemical/physical improvements on the refractory composition were already studied by different authors. Matsuo et al. [12] studied the influence of different kinds of alumina source on the physical properties and corrosion resistance of Al<sub>2</sub>O<sub>3</sub>-SiC-C refractories. Hayashi et al. [13] evaluated the influence of the expanded graphite in MgO-C refractories. The use of this type of raw material was responsible for a reduction on the crack length increasing the thermal shock resistance. The influence of the graphite content was studied by Hino [14] by using thermal shock tests in

**Table 5.** Stress variation (%) after changes in key properties

Property	Variation	Stress variation			How to avoid spalling	
		Normal stress on X (%)	Normal stress on Y (%)	Shear stress (%)		
<b>First step of the spalling mechanism - before broken edges</b>						
Thermal expansion	+33%	15.5	2.0	25.0	Increase carbon content.	
	-22%	-11.0	2.0	-11.0		
Thermal conductivity	+15%	-3.0	17.0	-9.0	Increase carbon content.	
	-15%	1.0	-3.0	11.0		
Hot mechanical behavior	Strain	+20%	-6.0	-20.0	Decrease carbon content, change granulometry design for an unpacked one.	
		-20%	2.0	13.0		8.5
	Stress	+20%	12.0	40.0		25.0
		-20%	-15.0	-23.0		-14.0

high temperature (1000°C and 1200°C) and fatigue tests. The increase on the graphite content was responsible for an improvement in both properties. The addition of different antioxidants can also influence the mechanical resistance of the refractories. According to Khezrabadi et al. [15] the formation of AlN when the aluminum powder is added on the refractory composition can increase the mechanical resistance of the final refractory due to the needle shape of this phase.

#### 4 CONCLUSION

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. The simulations showed that for the first step, stress seems to be the most sensitive aspect to affect the thermomechanical behavior of the brick, among the investigated ones. The highest and lowest effects on the normal stresses (X and Y axis) and shear stress were observed when the inputted stress value was varied by  $\pm 20\%$  at the investigated temperature range. As higher normal stresses and shear stress were found along the brick in case of positively shifted stress-strain curve, the probability of spalling occurs may rise. 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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