THERMO-MECHANICAL MODELING OF A STEEL LADLE USING THE PERIODIC LINEAR HOMOGENIZATION TECHNIQUE

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ABSTRACT

In the Steelmaking industry and in many others that involve the processing of molten metal, the metallurgical vessels can be lined with refractory bricks, with and without mortar. The design of these linings poses a complex problem, since the material itself is non linear regarding the mechanical behavior and the bricks/joints subsystem imposes considerable computational problems due to the large amount of interfaces between them. The Periodic Linear Homogenization (PLH) is a technique that allows the consideration of the expansion joints effect in the reduction of the stresses, providing a better estimation of the applicability of a given lining to the thermo-mechanical loads imposed by operational conditions. In this work, the PLH is coupled to a commercial Finite Element Analysis software and a complete steel ladle is simulated, considering the working, safety and insulating linings.

INTRODUCTION

In the refractories industry it is well known that the expansion allowance provided by joints is necessary to obtain stress levels that can be securely sustained by the materials, which usually have low mechanical resistance. In this context, the engineering calculations should, when possible, take into account this stress reducing effect, otherwise the calculation's accuracy is reduced, which can lead to misunderstandings of the product operational cycle.

The goal of this paper is to describe a numerical simulation technique used to improve the way to consider this effect, i.e., to obtain the joints status in large masonries composed of refractory bricks, subjected to high temperatures, and after calculate the stresses and strains. Different initial joint thicknesses were simulated for the wall and bottom linings, comparing the stresses obtained in the refractories and in the steel shell in each configuration.

MODELING OF REFRACTORY LININGS

The simulation of a complete refractory lining with several bricks using the Finite Elements method presents many difficulties, such as:

1. High computational cost due to the number of elements necessary to represent each brick and joint;
2. Convergence problems, related to material's behavior and contacts between bricks and joints.

To overcome these problems and be able to predict the adequacy of a refractory line to a given application, some authors have proposed methodologies to simplify the calculations and take at least qualitative conclusions.

POIRIER, GASSER and BOISSE [1] simulated a steel ladle considering the refractory as a linear elastic material, and the lining was represented by a continuous unit, i.e., not taking into account the joints between the bricks.

RUSSEL, HALLUM and CHEN [2] proposed a two-steps simulation, where a plane model of a horizontal cross section and an axissymmetric model of the vertical cross section of the ladle complement each other, and there is the possibility to impose frictional contacts between the bricks. The main problem to use an axyssimmetric simplification is that rarely the equipment has axial symmetry.

More recently, in an attempt to have numerical models that could join the best part of the two above cited methods, i.e., represent the full geometry of the equipment and also represent the reduction of stress levels due to expansion allowance, the Periodic Linear Homogenization technique was applied to refractory linings, as explained in the next section.

PERIODIC LINEAR HOMOGENIZATION TECHNIQUE

The Periodic Linear Homogenization (PLH) technique is used to allow the simulation of large assemblies of bricks containing joints with or without mortar. This is done by substituting the bricks and interfaces by an equivalent material containing the same elastic properties. This is done by imposing a strain energy density equality, and defining the equivalent materials constants with analytical and numerical techniques. More details about the mathematical framework can be found in [3]-[4]. As the thermal and/or mechanical loads are imposed in the structure, each element of the mesh is checked to see if the joints would be closed [5], changing the mechanical properties of the lining. Fig. 1 illustrates the four joint states in a flat masonry.

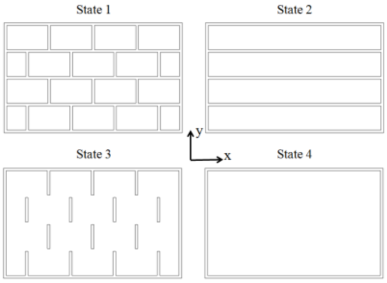

Fig. 1: Flat masonry joint states

In the PLH, two joint closure criteria are considered, being the brick deformation and brick sliding. These criteria are represented mathematically in each element integration point. Fig. 2 shows a schematic representation of the closure criteria.

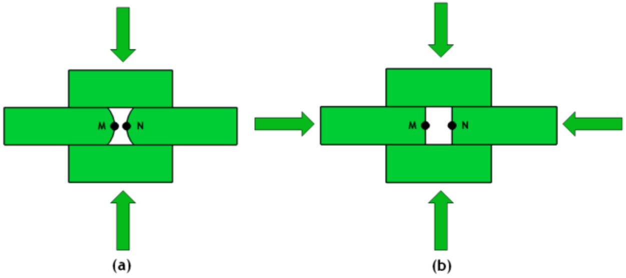

Fig. 2: Origins of joint closure. (a) Transverse brick deformation (Poisson's strain effect). (b) Normal brick deformation + brick sliding

Using this numerical simulation technique, GASSER, REKIK, BLOND and ANDREEV [6] studied the stresses in the shell of a steel ladle depending on the design of the bottom lining. In this work, temperature effects on properties were not considered, and the cylindrical refractory wall was not homogenized, i.e. the brick's mechanical properties were used. Latter, GASSER, BLOND, DANIEL and ANDREEV [8] improved this model, considering temperature dependent materials and using mortar joints in the cylindrical refractory wall. TEIXEIRA and GASSER [7] used the PLH to simulate the stresses in the cylindrical lining of a simplified steel ladle, containing only one wall refractory layer and considering the bottom lining as a monolithic material.

THE NUMERICAL MODEL

In this study a complete steel ladle was simulated. The refractory lining of this ladle contains a working layer, a backfill, and two safety layers. A ramming mix with approximated material properties was considered to fill the empty spaces between the safety layers and the bottom plate, and also between the working layer and the border plate. All the refractories of the working line (masonries with joints without mortar) were homogenized using the PLH technique, and the other linings were considered to be monolithic blocks. The brick size for the working layers is 160x100mm in the hot face, varying only in the thickness dimension. The general ladle dimensions and layer's thicknesses are represented in Fig. 3, in millimeters. This figure also shows the height of the slag in the model.

The ladle was considered to be held by the trunnions. To reduce the computational time, the steel shell was modeled using shell elements. The wall plate was considered to have a thickness of 25mm and the bottom plate a thickness of 30 mm. The refractories and the trunnion were modeled using solid elements. For simplicity, since the homogenization induces a considerable non linearity in the model, non linear contacts were used only between the working line of the bottom and of the wall, with friction coefficient of 0,2.

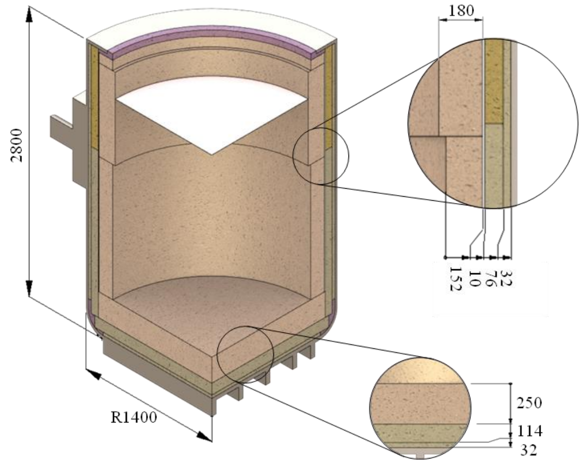

Fig. 3: Steel ladle model

A steady-state temperature load was applied at the ladle, as shown in Fig. 4. To calculate the temperature's field an internal temperature of 1600°C was applied, and in the steel shell a temperature varying convection coefficient and a radiation to ambient (ε = 0,85, ambient temperature = 35°C) were considered. It's important to notice that during operation a real steel ladle may not achieve the steady-state, so the joints closing may vary according to the time from operation beginning.

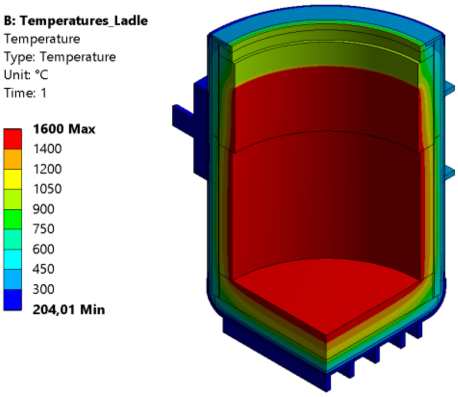

Fig. 4: Temperature distribution in the steel ladle.

As explained in [4], the orthotropic material's properties in the linear homogenization case should be defined for each joint state (Fig. 1), and updated according to the changing of state due to loading. For the present case, the cylindrical lining domain of calculation (DOC) was approximated by a flat DOC, and the material's properties determined as explained in [3]-[6].

Four different configurations were modeled: without joints, dry joints of 0.1mm, 0.3mm and 0.5mm. These joints can appear due to imperfections in the bricks surfaces in a way that, even if they are in initial contact during the assemblage of the lining, some thermal expansion can occur without meaningful stress generation.

All refractory materials were considered to have a Poisson's coefficient of 0,2. The evolution of Young's modulus with temperature for each material is shown in Fig. 5. As can be observed, the material used in the safety lining of the slag zone is much stiffer than the others, and the Young's modulus isn't available for all materials at the entire range of temperatures.

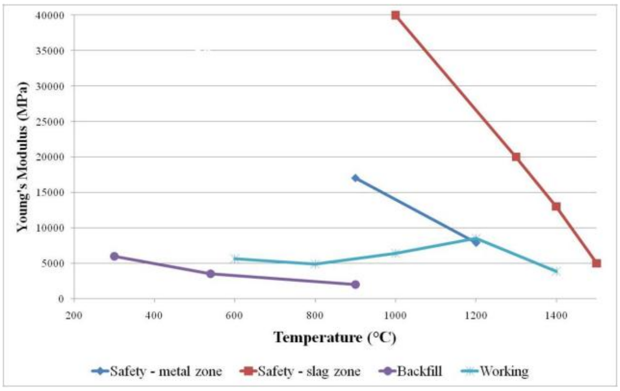

Fig. 5: Steel ladle model

RESULTS AND DISCUSSION

Fig. 6 shows the von Mises equivalent stresses in a vertical line of the steel shell, starting from the junction of the bottom plate with the wall plate. The configuration without joints presented the highest stress through all the height, achieving approximately 500 MPa in position zero. The stresses tend to lower until the region close to the trunnions bottom line, then increasing until the trunnions upper line. In the exact position of the reinforcement rings (A and B in Fig. 6), the stresses are the same for all configurations. The other simulated cases show the importance of the joints design in the shell equivalent stresses. In the case where the joints have 0,5mm, the stress at position zero is approximately 250 MPa, a reduction of 50%. Therefore, the refractories expansion allowance is an important parameter in the steel shell design.

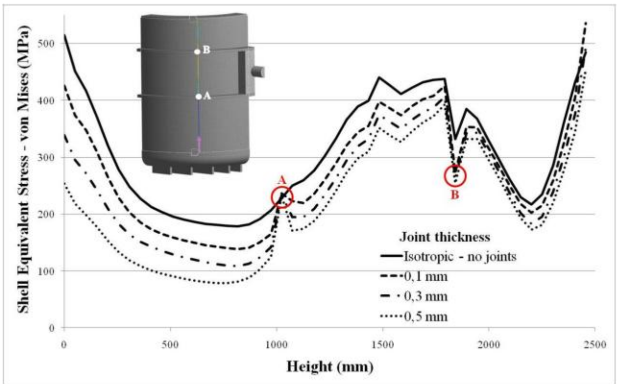

Fig. 6: Von Mises equivalent stress in a vertical line of the steel shell

At the bottom plate of the steel shell the same tendency of stress reduction with increase of joint thickness is observed, more influenced by the joints of the bottom lining. This can be observed in Fig. 7.

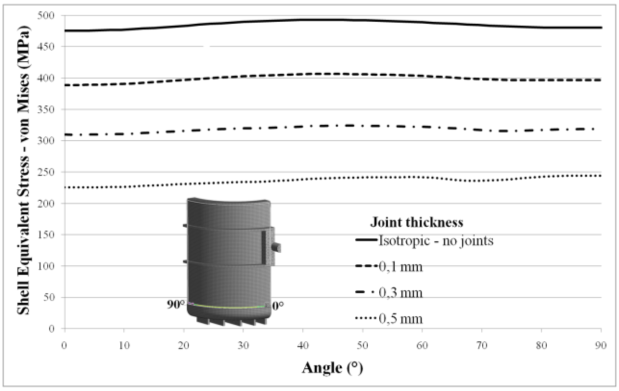

Fig. 7: Von Mises equivalent stress in a circumferential line of the steel shell (at the mid-height of the bottom lining).

Fig. 8 shows a circumferential stress plot comparing the cases with joints of 0,1mm and 0,5mm thickness, where it's possible to see that in the first case the entire hot face in contact with molten steel (below slag line) has stresses above -40 MPa, while in the latter case several regions present stresses between -30 and -40 MPa.

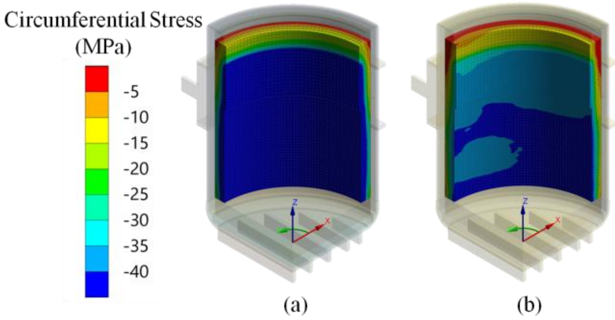

Fig. 8: Circumferential stresses in the refractory wall. (a) 0.1mm joints. (b) 0.5mm joints

To give a better idea on the stress reduction due to the increase of the joints, Fig. 9 shows the circumferential stress variation in the refractory wall thickness, in a line going from the hot face to the working line cold face, in the region near the trunnions. In this situation, the stress at the hot face in the case without joints is -61 MPa, decreasing in modulus to -30 MPa at the cold face. When using joints of 0,5mm, the stresses at the hot and cold faces are, respectively, -38 MPa and -13 MPa.

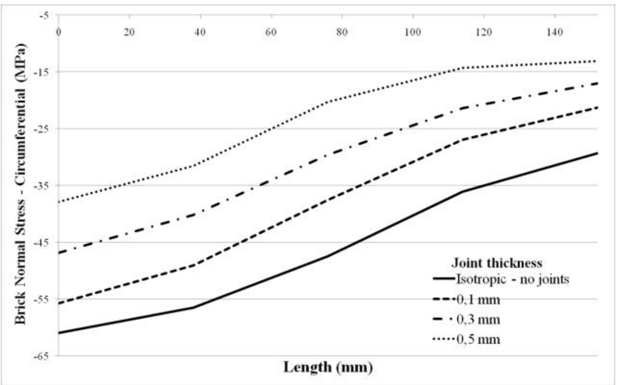

Fig. 9: Circumferential stress variation in the refractory wall thickness

At the bottom lining, the normal stresses in direction y can vary from -52 MPa in the hot face of the case without joints to -26 MPa in the case with joints of 0,5mm. Fig. 10 shows how the area affected by stresses above -35 MPa decrease significantly when increasing the joints and Fig. 11 shows the stresses distribution on the thickness of the bricks in the center of the bottom, from the hot face (0 mm) to the cold face (250 mm).

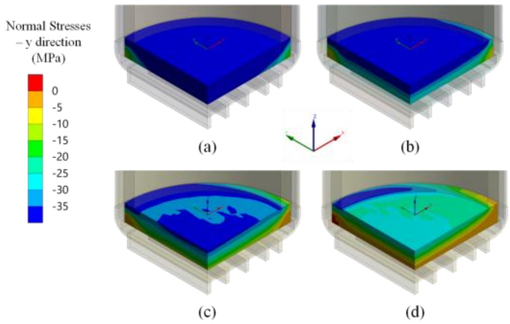

Fig. 10: Normal stress variation in the y direction in the refractory bottom. (a) Isotropic – no joints. (b) 0.1mm joints. (c) 0.3mm joints. (d) 0.5mm joints.

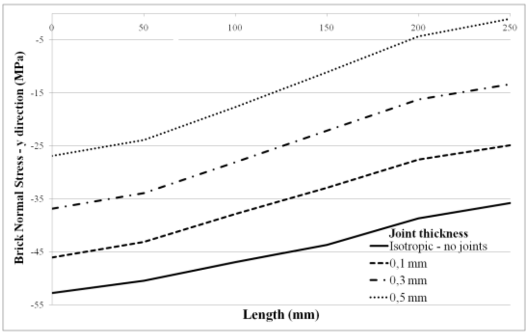

Fig. 11: Normal stress variation in the y direction in the center of refractory bottom.

Although there is an obvious and significant decrease in the stresses of the refractory and the shell when increasing the joints thickness, there is a limit for the maximum expansion allowance that can be used in a lining. Fig. 12 shows that for the case with joints of 0,5mm not all the joints are closed even with 100% of loading, i.e., in operation with the ladle at thermal steady-state. The designer must define a criterion saying how much of the joints should be closed through the lining thickness at each operational step and what the accepted stress values are, then performing the calculations using the PLH to dimension the joints.

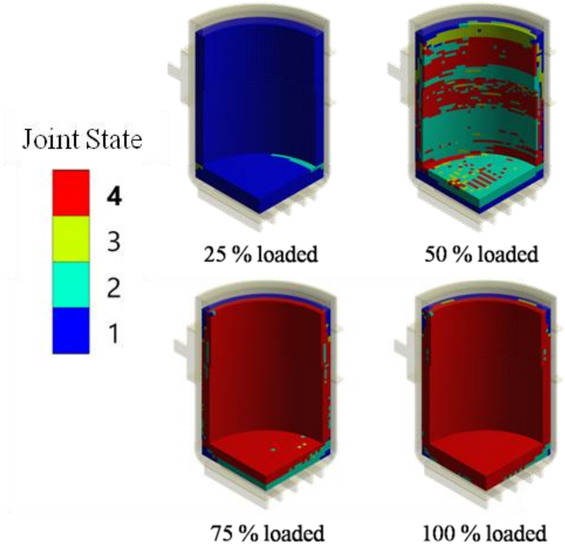

Fig. 12: Joint status in the steel ladle. Joint thickness: 0,5mm

CONCLUSIONS

In this paper, the Periodic Linear Homogenization was used to simulate a complete steel ladle in thermal steady-state, and the effect of increasing the joints thickness in the lining was studied.

The calculations showed that, when using the linear homogenization technique, it's possible to predict which joints will be closed and which ones will be open in consequence of the imposed loads, what significantly changes the magnitudes and the distributions of stresses in the lining. An important conclusion is that, although the increase of joints thickness has an obvious beneficial effect in the reduction of stresses in the refractory lining, it should be limited to guaranty that the joints will be closed when the ladle is loaded with melted steel.

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