A THERMOMECHANICAL MODEL OF A FULL 3D STEEL LADLE USING HOMOGENIZATION TECHNIQUE

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ABSTRACT

A very common lining type in steel ladles is dry-joint refractory masonry. The presence of joints and their state (open or closed) affects the stiffness of the structure. Accordingly, the joint behavior needs to be accounted for implementing reliable thermomechanical models of refractory vessels. As these large-sized structures have many components, an approach that represents bricks as individual solids has a high computational cost and may lead to convergence problems. To work around this shortcoming, one may use an equivalent material model, replacing the bricks and joints of the structure. The present work uses this approach to model a full 3D solution of a steel ladle, including regions with different stiffness such as plug and well block. The numerical model also considers a detailed representation of steel shell. The evolution of joint state as a function of the thermal load applied and stresses are reported, bringing some insights for the design of steel-ladle masonry linings.

INTRODUCTION

Steel ladle linings are subject to severe operational conditions as, for example, high temperatures and abrasive environment[1]. These severe conditions may lead to cracking and premature end of the masonry life. The understanding and mitigation of thermomechanical issues, concerning steel ladles linings, is an industrial challenge, and this topic has been studied substantially in recent years[2-4].

Finite element simulations have been used by several authors[5-8] to predict the stresses, thermal expansion and to prevent the crack formation in refractory masonries. To represent the thermomechanical behavior, the analysis must consider the joints and their evolution as a function of the temperature. This phenomenon directly affects the stresses in different parts of the steel ladle, contributing to an overall decrease of the stress magnitude[6].

Two approaches are commonly used to model the thermomechanical behavior of refractory masonry: micro and macro-modeling. Micro-modeling concerns the representation of the bricks and joints, considering the interaction between them. This strategy has been used to describe local phenomena in the lining during the steel process. Although a good representation for local phenomena, micro-modeling has a high computational cost and convergence challenges for large structures. In this case, macro-modeling, which replaces the bricks and joints with an equivalent material, can be more adequate.

Using periodic homogenization, a macro-modelling approach is applied in this work to estimate an equivalent material, representing the joint and bricks' mechanical behavior. The equivalent material was applied to represent the wear lining in a full 3D steel ladle geometry, enabling the study of the evolution of joint state and the stresses. A comparison of two different refractory designs (with and without a 50-mm layer of a refractory mix between wear and permanent lining) for the bottom lining is also reported.

NUMERICAL MODEL

The periodic linear homogenization technique permits the implementation of the numerical analysis for large structures, containing bricks and joints with or without mortar. The present work studies a mortarless refractory lining (dry joints). The applied homogenization technique is based on the substitution of the bricks and joints by an equivalent material to represent the assembly global stiffness. For the sake of brevity, the numerical framework is not described herein. However, it is extensively explained in the literature[5-7].

In this numerical approach, horizontal and vertical joints (also known as bed and head joints) are considered. These joints may be open or closed, depending on the thermomechanical loads. Consequently, four joint states are possible[6].

a) All the joints are opened in both directions.
b) Horizontal joints are closed, and vertical joints are opened.
c) Horizontal joints are opened, and vertical joints are closed.
d) Horizontal and vertical joints are closed.

Fig. 1 illustrates the four joint states in a flat masonry.

In this study, the constitutive model for the bricks is considered as isotropic linear elastic. However, the distribution of joints' states may lead to orthotropic mechanical behavior in the equivalent material. Despite the use of a linear elastic material law, the constitutive behavior is non-linear, since the mechanical properties depend on the state of the joints, which can vary with time. The equivalent-material properties are evaluated imposing energy density equality in a simplified representative volume.

Fig. 1. a) section view and b) top view of the refractory lining and c) section view of the finite-element geometry.

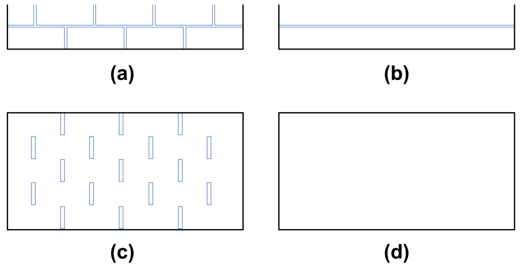
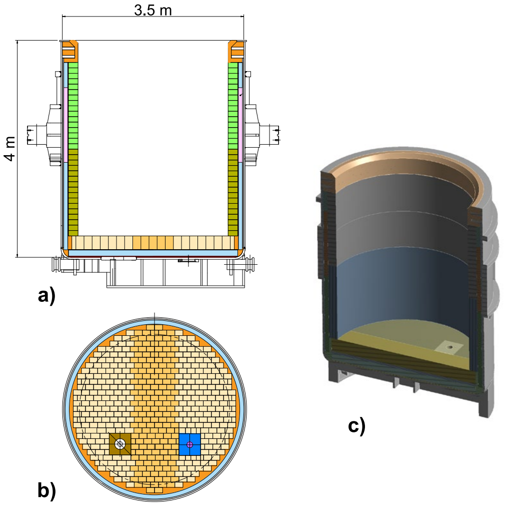

(a) (b)
(c) (d)

Fig. 2. masonry joint states[4,5]

In this work, the finite element model concerns a full 3D steel ladle geometry (see Fig. 2). The mechanical behavior of the wear lining was described using the homogenized equivalent material. The other regions were represented by a linear elastic material model.



To estimate the temperature field, a steady-state analysis was carried out. A prescribed temperature (1600°C) was applied on the surface in contact with molten steel. In the other regions, convection and radiation conditions were considered following the literature[9]. It is worth noting that a normal operation of steel ladle may not reach a steady state. The obtained temperature field is shown in Fig. 3.

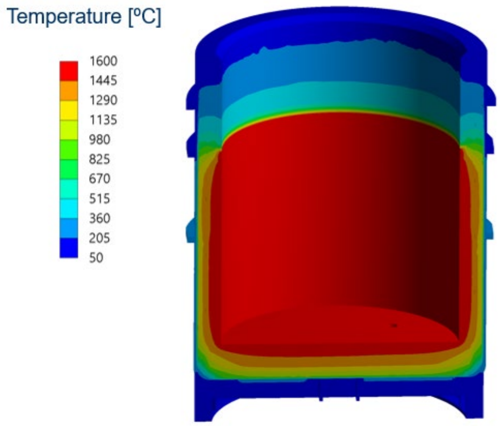


Fig. 3. temperature field in the steel ladle

A structural simulation is performed, importing the temperature field obtained in the steady-state analysis. The ladle is assumed to be supported by its trunnions and a prescribed displacement was applied to represent this condition. The gravity was considered, using an acceleration of 9.81 m/s². The molten-steel hydrostatic pressure was also considered, estimated by a molten-steel density of 7000 kg/m³. No sliding or separation between the refractories and the steel shell is allowed.

The refractory material and steel properties (Young's modulus, Poisson's ratio, coefficient of thermal expansion, conductivity, and specific heat) were obtained from the literature[5-7] and RHI Magnesita internal database. The parameters for the equivalent material were obtained using the approach described in Nguyen et al.[5] and Teixeira et al.[6]

To investigate the influence of changes in refractory design, a case with a refractory mix layer of 50 mm was also carried out. Fig. 4 shows the lining in the reference case and the case with an additional layer of refractory mix.

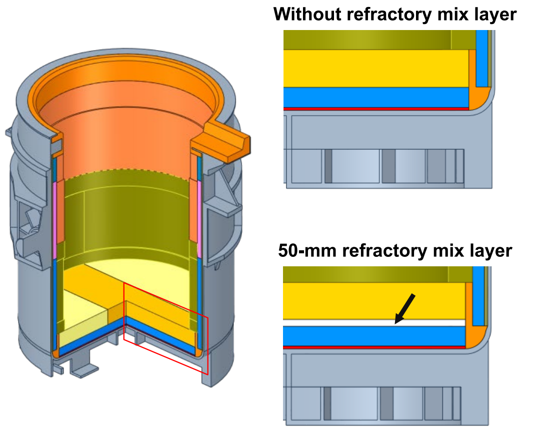


Fig. 4. studied ladle bottom linings

A submodel of the region between the purging plug and the well block (see Fig. 2b) was implemented to better understand how the loss of compression, described later in this manuscript, may influence during cooling. A transient step was added to estimate the temperature and displacements during cooling. The heat exchange of ladle internal surfaces in this step was represented by a convection and radiation condition[9].

In this submodel, the bricks were represented as solids, considering the joints between them, which can be viewed as a micro-modeling approach described earlier in this manuscript. Fig. 5 shows the boundary conditions (prescribed displacements) imported from the previous simulation. The temperature field was also imported.

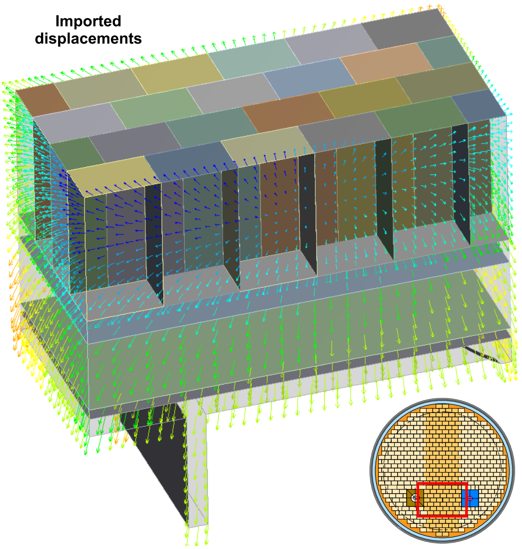


Fig. 5. Prescribed displacement applied in the submodel for the bottom region of the ladle

RESULTS AND DISCUSSION

The thermomechanical analysis was performed, providing variables as the displacement, stress fields, and state of the joints. Fig. 6 shows the displacement field in a cross-section of the steel ladle, magnified 3000 times to highlight the deformation modes in the geometry. One may note the bending in the bottom which is a consequence of the temperature gradient in this region. The region of the cylinder has a barrel-like expansion, with higher displacement values in the region between the bottom and sidewalls, because of the reinforcement ribs over the circumference at the trunnion's height.

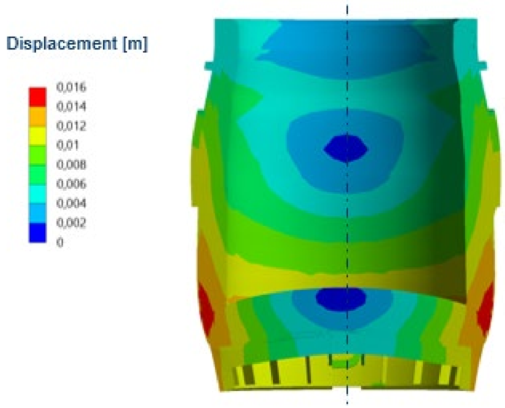


Figure 6: displacement field in the steel ladle

The periodic homogenization technique provides us the joint state as internal variable of the finite element model. One may observe the progressive closure of horizontal and vertical joints in the geometry with increasing temperature (Fig. 7). For the studied case, the joints closure occurs differently depending on the region of the steel ladle. As expected, hotter regions rapidly close their joints. One may also note that vertical joints of the bricks close first. This may be explained by the ratio between the thickness of the joints, which are equal for both directions, and the different height and width dimensions of the bricks (see Fig. 5).

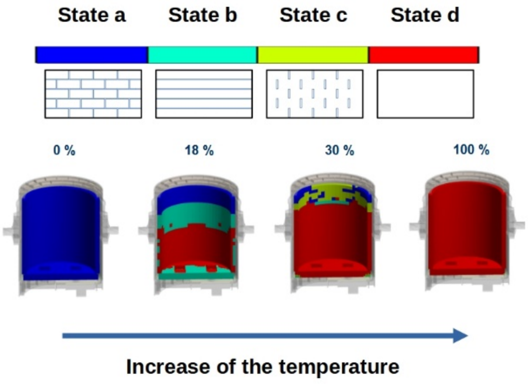


Fig. 7. progressive closure of bed and head joints

The joint closure will change the stiffness of the ladle regions when the thermal load is applied. Along with unequal expansion of the ladle parts, the progressive joint closure contributes to an anisotropic and heterogenous stress field. Fig. 8 shows the stress field in x and z direction for the center part of the bottom (region between purging plug and well block). It can be observed that, in general, the stresses in the x direction are higher than in the z direction, as a consequence of the head joints closing first.

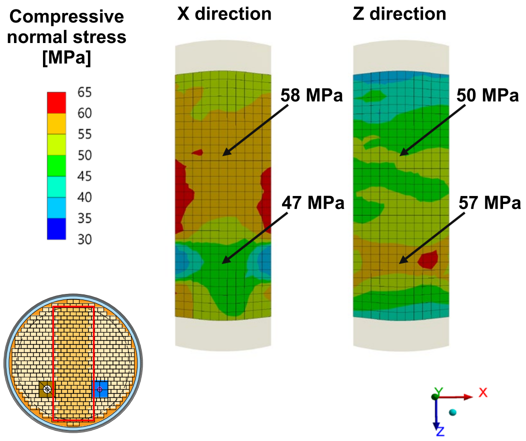


Fig. 8. compressive normal stresses in x and z directions

Moreover, the region between the purging plug and well block has lower stresses in the x-direction. Low compression stresses may be dangerous for the next step of the process, idle time of the ladle. During this step, the surface which was in contact with hot molten steel is now cooled by air convection. The temperature may be lower on the surface than in the inner regions. If the brick does not have a certain amount of compression stresses, this phenomenon may result in tensile stresses in the brick's hot face, facilitating the formation of cracks in this region.

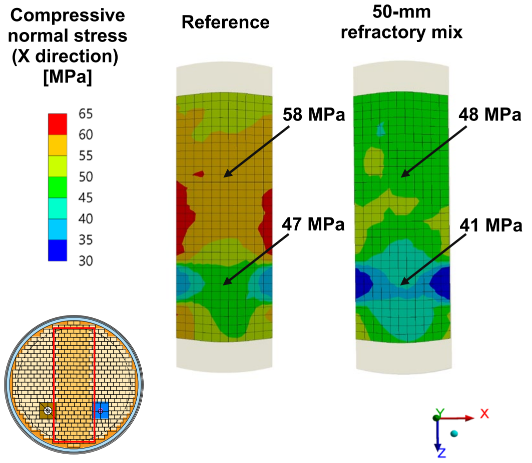
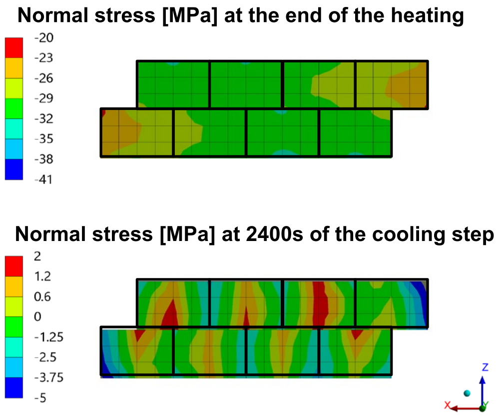


Fig. 9. compression of the cases with and without refractory mix layer

A comparison between refractory designs (with and without mix at the ladle bottom lining) was carried out. Fig. 9 shows the stress field for both cases. One may note that the additional mix layer reduces the compressive normal stresses, mainly, in the region between well block and purging plug. The stress field in the identified critical region was further investigated using a submodel, also considering a cooling step. The case, with an additional 50-mm refractory mix layer between permanent and wear lining, was analyzed. Fig. 10 shows the stress field for the inner bricks of the domain for two different times (end of heating and 2400s after cooling has started).


Normal stress [MPa] at the end of the heating

Normal stress [MPa] at 2400s of the cooling step

Fig. 10. Normal stresses (X direction) at the end of the heating and 2400s after the cooling is started

The decrease of temperature may induce tensile stresses at the hot face and compressive stresses inside the brick[10]. Cracks at the critical region identified by the numerical model are commonly observed in steel ladles, which is evidence of this cracking mechanism.

CONCLUSIONS

A thermomechanical model of the steel ladle was carried out. The joint closure as a function of the applied thermal load was presented, as well as its effect on the stress field obtained. In the wear-lining bricks, the absolute normal stresses are greater in the direction perpendicular to the vertical joints of the brick, because of the joints closing first in this region.

The reference case was compared with an alternative configuration, where a thicker layer of the refractory mix was added between wear and permanent lining. The outcome of this comparison was that, with a thicker layer of mix, the compressive stresses in the bottom region were reduced. These lower compression stresses may facilitate tensile stresses during the cooling steps of the steel processing.

To further investigate the consequences of the loss of compression in the next step (cooling), a submodel of the critical region was implemented, considering the bricks as individual solids and the joints between them. This finite element model revealed tensile stress in the middle of the bricks' hot face, which is compatible with crack formation usually observed. Therefore, the thermomechanical model adopted in this study is a good representation of the mechanical behavior in the ladle refractory masonry, and it is a powerful tool to compare different refractory design concepts.

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