Thermomechanical Modelling for Refractory Lining of a Steel Ladle Lifted by Crane

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Numerical methods can be applied on metallurgical processes like engineering design of a steel ladle. In this study, the thermomechanical behaviour of refractory lining of a steel ladle which is lifted by a crane was investigated. To simulate this behaviour coupled heat transfer – structural analysis was made by using FEM (Finite-Elements-Method). For these calculations a two-dimensional, an axially symmetrical geometric model and a FE-model of a steel ladle with wear lining consisting of MgO-C brick in the slag zone and castable MgO-Al2O3-spinel in the working zone were created. Thermal stresses, hydrostatic pressure, gravity of molten steel and slag and refractory lining were used as boundary conditions. The results gained from the calculations showed that the maximum total displacements were observed at the bottom lining of the ladle.


Introduction

The rising demands on the secondary metallurgical processes in steel plants have resulted in an increased awareness of the importance of the steel ladle. When a steel ladle is to be replaced, a larger filling volume and a smaller dead weight (carrying capacity of cranes) of the new ladle are often considered as a means to increase the output of the steel plant. Other requirements are that the ladle must fit into the existing plant environment and that the operating costs should be reduced. To fulfill these demands it is necessary to develop new ladle concepts [1].

It is also possible to make metallurgical processes faster and easier by using numerical methods like FEM [2-4]. FE-analysis procedures have gained increasing importance in the solution of structural, heat transfer, field problems and more complex problems (e.g. coupled heat transfer – structural problems). Mathematical fundamentals can be found in references [5, 6]. The related parts of FEM are as follows.

Heat transfer analysis. In the study of FE-analysis of heat transfer problems it is instructive to first recall the differential and variational equations that govern the heat transfer conditions to be analysed. These equations provide the basis for the FE solution of a heat transfer problem. In the analysis of the heat transfer conditions, we assume that the material obeys Fourier’s law of heat conduction;

\[ q_x = -k_x \left( \frac{\partial T}{\partial x} \right) ; q_y = -k_y \left( \frac{\partial T}{\partial y} \right) ; q_z = -k_z \left( \frac{\partial T}{\partial z} \right) \]  

where \( q_x, q_y \) and \( q_z \) are the heat flows conducted per unit area, \( T \) is the temperature of the body, and \( k_x, k_y, k_z \) are the thermal conductivities corresponding to the principle axes \( x, y \) and \( z \). As the heat flow equilibrium in the interior of the body is a prerequisite, we thus obtain a steady state situation, where \( q^b \) is the rate of heat generated per unit volume. On the surfaces of the body the following conditions must be satisfied [6]:

\[ \frac{\partial q_x}{\partial x} [k_x (\partial T/\partial x)] + \frac{\partial q_y}{\partial y} [k_y (\partial T/\partial y)] + \frac{\partial q_z}{\partial z} [k_z (\partial T/\partial z)] = -q^b \]  

Axiallysymmetric stress analysis. The problem of stress distribution in axisymmetric solids under axisymmetric loading is of considerable practical interest. The mathematical problems presented are very similar to those of plane stress and plane strain as, once again, the situation is two dimensional. If \( r \) and \( z \) denote respectively the radial and axial coordinates of a node, with \( u \) and \( v \) being the corresponding displacements. The triangular element \( i, j, m \) is shown in figure 1 [5].

In plane stress or strain problems it was shown that internal work was associated with three strain components in the coordinate plane, the stress component normal to this plane not being involved due to zero values of either the stress or the strain [5].

In the axially symmetrical situation any radial displacements automatically induces a strain in the circumferential direction, and as the stresses in the direction are certainly non-zero, this fourth component of strain and of the associated stress has to be considered. Here lies the essential difference in the treatment of the axially symmetrical situation [5]. In an axially symmetrical deformation four non-zero strain components are possible [5]. Figure 2 illustrates and defines the strains and associated stresses:

\[ \varepsilon = [\varepsilon_r, \varepsilon_\theta, \gamma_{rz}] = \left[ \frac{\partial u}{\partial r}, \frac{\partial u}{\partial \theta} \right] w/r \left[ \partial u/\partial z + \partial v/\partial r \right] \]  

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Process metallurgy

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Pre-processing for FE-analysis of ladle lining

In this work, a model of a 120-t-steel ladle was used. This ladle has an axially symmetrical geometry [3, 4]. ANSYS FE-Software [7] was used in all of the models such as geometric (CAD), mesh generation (FE-model) and FE-analysis (CAE).

The steel ladle consists of wear-, safety-, isolation linings and steel cover as shown in figure 3a). The statistic information about the 2D FE-model and the parameters of the ladle are shown in figure 3b). Two different element types were used in the FE-model. One of them is the 2D, axially symmetrical-8-nodes, rectangular “Plane78” element type [7], which was used for the steady-state heat transfer analysis. The other one is a similar element with “Plane82” type [7], which was used for coupled structural analysis.

Materials properties

Chemical properties of refractory types for the ladle lining are given in table 1a) – c). The material model was created according to the physical properties which are the temperature dependent heat transfer coefficients (kxx) and thermal expansion coefficients (α). Elastic modulus (E) and Poisson’s ratio (ν) were also taken as the parameters that represent the materials properties, figures 4a) - c). In this study, FE-calculation was carried out in two steps. First was the steady-state heat transfer calculation and second was the coupled structural calculation.

Heat transfer calculation

The solution of this heat transfer problem depends on Fourier’s differential equation (equation (2)) for full and steady-state situation of the steel ladle. For the calculation the boundary conditions should be defined. The ladle is full with molten steel and under this condition the inner temperature is considered as 1550°C. Figure 5 exhibits the temperature distribution for the steady-state case. Due to the lack of isolation and the high thermal conductivity of the MgO-C brick in the slag zone the heat is transferred more rapidly than in the working zone.

<table>
<thead>
<tr>
<th>Wear lining in slag zone</th>
<th>MgO</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>Fe₂O₃</th>
<th>CaO</th>
</tr>
</thead>
<tbody>
<tr>
<td>%15C-MgO</td>
<td>98.04</td>
<td>0.63</td>
<td>0.48</td>
<td>0.46</td>
<td>0.31</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Wear lining in working zone</th>
<th>Tabulare Alumina</th>
<th>MgO-Al₂O₃-Spinel</th>
<th>Reactive Alumina</th>
<th>Cement</th>
<th>Dispersant</th>
</tr>
</thead>
<tbody>
<tr>
<td>MgO-Al₂O₃-Spinel castable</td>
<td>43.0</td>
<td>44.0</td>
<td>8.0</td>
<td>5.0</td>
<td>0.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Safety lining</th>
<th>High alumina bricks</th>
<th>Al₂O₃</th>
<th>Fe₂O₃</th>
<th>TiO₂</th>
<th>Na₂O+K₂O</th>
<th>CaO+MgO</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>42-46</td>
<td>1.5-2.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td></td>
</tr>
</tbody>
</table>

"Figure 1. Element of an axially symmetrical solid material [5]."

"Figure 2. Strains and stresses involved in the analysis of axially symmetrical loadings [5]."
Figure 3a). 2D-axially symmetrical geometric model of a ladle with refractory lining.

b). 2D-axially symmetrical FE-model of a ladle and related statistic information.

Figure 4. Physical properties of refractory materials [3-4, 8-14]:
a) Thermal conductivity,
b) Thermal expansion,
c) E-Modul.
Structural calculation of the steel ladle lifted by a crane

The important part of the study was the calculation of stresses and strains in the refractory lining of an axially symmetrical 120-t-steel ladle while lifted by a crane. All the loads and related boundary conditions are simulated in figure 6.

The results obtained by the heat transfer analysis were used to determine the thermal boundary conditions for the coupled structural analysis. Thermomechanical stresses and strains on the refractory wall of the ladle, after the ladle was lifted by a crane, had to be taken into account as additional boundary conditions in the coupled structural analysis. For this analysis, the same FE-basis model, figure 3b), was used, but the element types switched to "Plane83".

As the ladle is lifted, the simulated mechanical loads are shown in figure 6. The additional forces acting on the crucible were considered under axisymmetric rule such as the hydrostatic pressure of molten metal and slag, the dead weights of the refractory lining and of the liquid metal as lifted. Under these boundary conditions, coupled structural analysis was solved.

The results of structural analysis can be seen in figure 7. Deformation and nodal displacements of the ladle lining and thermal stresses would be more effective if the ladle were set on the ground. In this situation the maximum displacements should be observed on the upper side of the slag zone refractory lining [4, 5]. When the ladle is lifted by a crane, the maximum displacements are observed at the bottom of the ladle lining, figure 7. As the crane chain wraps the ladle, the direction of the thermal expansion and the intensity decrease. Comparison of the displacements in the slag zone, working zone and bottom lining are given in table 2.

Conclusions

Higher ladle capacity can be realized by larger filling volume and smaller dead weight (carrying capacity of cranes). In the last years 400-t-steel ladles have been produced [1]. The engineering design and construction are very important for the production of the ladles.

Table 2. Comparison of total displacements, directions and intensities in the refractory wall.

<table>
<thead>
<tr>
<th>Lining in</th>
<th>Total nodal displacements in radial and vertical directions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slag zone</td>
<td>(0.16x10^-3 m.)</td>
</tr>
<tr>
<td>Working zone</td>
<td>(~0.16x10^-3 m.)</td>
</tr>
<tr>
<td>Bottom lining</td>
<td>(~0.02-0.18 m. increases to centre)</td>
</tr>
</tbody>
</table>

←, ↓ less intensive; ←←←←, ↓↓↓↓ intensive
In the reference [1], a 3D-steel ladle model was used. A 3D-modelling is more difficult than a 2D-modelling. For ladle design and construction a 2D-axially symmetrical model can be used easily and effectively for different refractory types, loading and boundary conditions. All variations can be investigated more rapidly and more economically until ideal design is reached.

Figure 6. Simulation of axially symmetrical loads and boundary conditions in a ladle while lifted by crane.

Figure 7. Distribution of deformations and nodal displacements on refractory wall.
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References