Thermal stress analysis method considering geometric effect of risers in sand mold casting process

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Abstract: Solidification and fluid flow analysis using computer simulation is a current common practice. There is also a high demand for thermal stress analysis in the casting process because casting engineers want to control the defects related to thermal stresses, such as large deformation and crack generation during casting. The riser system is an essential part of preventing the shrinkage defects in the casting process, and it has a great influence on thermal phenomena. The analysis domain is dramatically expanded by attaching the riser system to a casting product due to its large volume, and it makes FEM mesh generation difficult. However, it is difficult to study and solve the above proposed problem caused by riser system using traditional analysis methods which use single numerical method such as FEM or FDM. In this paper, some research information is presented on the effects of the riser system on thermal stress analysis using a FDM/FEM hybrid method in the casting process simulation. The results show the optimal conditions for stress analysis of the riser model in order to save computation time and memory resources.

Key words: thermal stress; sand mold casting; riser; numerical analysis; hybrid method; simulation

Computational methods such as the finite difference method (FDM) and the finite element method (FEM) have become very popular tools to rapidly, inexpensively and accurately solve various engineering problems. Especially in casting processes, computational methods can be efficiently used to predict the distributions of temperature, solidification time and residual stress. Casting processes involve complicated thermo-mechanical coupled phenomena such as heat transfer and stress components.

Tien et al [1] investigated the thermal stresses in casting processes and performed analytical thermal stress analysis using an elastic model during solidification. They studied simple geometrics such as plate and cylinder. Thomas [2, 3] performed extensive studies on stress analysis in casting. Riser system is an essential part of preventing shrinkage defects in the casting process and it has considerable influence on thermal phenomena such as temperature distribution, solidification time, shrinkage defects, and so on. However, the analysis of FEM model with riser is quite challenging from a computational point of view because it is difficult to generate finite element mesh in the model and the thermal stress analysis is very time-consuming due to a large riser volume. In order to overcome these challenges, this study used a hybrid numerical analysis method [4], which employs FDM for the heat transfer analysis and FEM for the thermal stress. Three models with different riser heights were used to investigate the influence of riser size in the analyses. As a result, this paper proposes a riser modeling concept for thermal stress analysis using FDM/FEM hybrid method.

1  Numerical analysis

1.1 FDM/FEM hybrid method

The flowchart illustrating the hybrid numerical analysis
method is shown in Fig. 1. It performs the heat transfer analysis during solidification by applying FDM. Field data such as temperature are converted for FEM analysis, which is applied for calculating the thermal stress distributions.

1.2 Thermal stress

The stress state during the casting process is defined by four different contributing factors: thermal effect, geometric effect, microstructure transformation stress, and mechanical constraint effect (contact between casting and mold). In this study, only the thermal and geometric effects are considered.

Figure 2 (a) shows the full model which consists of a riser, casting part and mold. Figure 2 (b) shows only the casting part without the riser. Heat transfer analysis is performed on FDM field [Fig. 2 (a)] and the temperature data is converted into FEM field [Fig. 2 (b)]. The thermal stress analysis is carried out on FEM field. Thus, the thermal effect and geometric effect induced due to the change in the geometry of the riser can be evaluated respectively. By maintaining the thermal effect at the same condition, it is easy to separate and analyze the role of the geometric effect on overall stress.

2 Numerical models

Figure 3 shows the test samples which are the typical riser types in sand mold casting process.

Thermal stress analysis was carried out for three cases of the top riser model shown in Fig. 4. The risers in the models are of different heights to investigate the geometric effects of the riser on thermal stress in casting process. Owing to the symmetry, quarter FEM model was used. The “Node #1–4” symbols are marked along the XX line for examining the stress results in detail.
The material for casting was CrMoSc1 (KSD 4101, 0.22 C, 0.9 Cr, 0.2 Mo) and the mold was silica sand. The pouring temperature was set to 1,500 °C and the initial temperature of mold was 25 °C. It was assumed that the sand mold will be shaken out at 26,000 s after pouring. The material properties shown in Table 1 for the analysis is derived from the material handbooks [5, 6].

Table 1: Mechanical properties of CrMoSc1 steel

<table>
<thead>
<tr>
<th>Temp (°C)</th>
<th>Young modulus (Pa)</th>
<th>Poisson ratio</th>
<th>Expansion coefficient (K⁻¹)</th>
<th>Yield stress (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>221 × 10⁹</td>
<td>0.287</td>
<td>11.3 × 10⁶</td>
<td>274 × 10⁶</td>
</tr>
<tr>
<td>200</td>
<td>180 × 10⁹</td>
<td>0.292</td>
<td>13.1 × 10⁶</td>
<td>268 × 10⁶</td>
</tr>
<tr>
<td>400</td>
<td>151 × 10⁹</td>
<td>0.298</td>
<td>14.3 × 10⁶</td>
<td>262 × 10⁶</td>
</tr>
<tr>
<td>600</td>
<td>95 × 10⁹</td>
<td>0.308</td>
<td>14.8 × 10⁶</td>
<td>178 × 10⁶</td>
</tr>
<tr>
<td>800</td>
<td>60 × 10⁹</td>
<td>0.340</td>
<td>15.4 × 10⁶</td>
<td>57 × 10⁶</td>
</tr>
</tbody>
</table>

3 Results and discussion

The temperature values of heat transfer analysis during solidification are converted from FDM field to FEM. Since the temperature distributions of the FEM models with different riser heights are same, it is possible to investigate the geometric effect of the riser under the same thermal condition as mentioned in chapter 1.

Figure 6 shows Von-Mises stress distributions in the top riser model at 26,000 s after pouring. The maximum value of stress is about 316 MPa in all the three models.

For further investigation concerning the difference in stress values in the top riser models according to change in riser height, the XX stresses of the nodes along the XX direction line on symmetric plane are represented in Fig. 7. The largest difference occurs at the boundary position of the riser (Node #1) and the difference is decreased along the outward direction. The maximum difference between models with and without full riser height is about 65 MPa, but the difference between one-fourth height (25%) and full riser can be negligible [Fig. 7 (a)]. Figure 7 (b) shows the variation of YY stress in Node #1 over time during the casting process. The maximum difference is about 40 MPa.

Figure 8 shows Von-Mises stress distributions of the side riser model at 26,000 s after pouring. The maximum value of stress is about 155 MPa in the three models.
For further investigation concerning the difference in stress of the models without and with original riser, the YY stresses of the nodes along the YY line of the symmetric plane are represented in Fig. 9. The max. difference between models with and without full riser height is about 100 MPa, but the difference between one-fourth height and the full riser can be almost negligible [Fig. 9 (a)]. Figure 9 (b) shows the variation of stress at Node #2 over time during casting process.

The number of FEM elements and computational time of models are summarized in Tables 2 and 3.

4 Application

The present analysis method was applied on a real casting product (Fig. 10), which considered different riser heights.

Figure 11 shows the Von-Mises stress distributions at 26,000 s after pouring the real product. The maximum value of stress is about 400 MPa in all the three models. The numbers of FEM element of the models are 113,593; 96,980; and 95,021 with full, one-fourth height and without risers respectively. The Von-Mises stresses of nodes indicated by the black dotted circle in Fig. 11 are compared among themselves as in Fig. 12. The max difference between the models of full and one-fourth height is about 20 MPa, and this value is small considering the max stress of 400 MPa.
Fig. 9: Discrepancy in Von-Mises stress of side riser models

![Fig. 9: Discrepancy in Von-Mises stress of side riser models](image)

(a) Without riser  (b) With one-fourth height riser  (c) With original riser

Fig. 10: FEM models for a real casting product

![Fig. 10: FEM models for a real casting product](image)

Fig. 11: Von-Mises stress distributions at the end of casting process of real product

![Fig. 11: Von-Mises stress distributions at the end of casting process of real product](image)

(a) Without riser  (b) With one-fourth height riser  (c) With original riser
5 Conclusions

The paper presented the geometric effect of risers on the thermal stress in the casting process under the same thermal effect using the FDM/FEM hybrid method.

The study was performed on the top and side riser models with different riser heights. A relatively large difference in thermal stress was found between full riser and no riser models. However, no significant difference was found between the models of full and one-fourth height risers. Riser height in the model in which the risers are installed has negligible effect on thermal stress, so one-fourth height model is sufficient for thermal stress analysis instead of full height riser.

In conclusion, the reduction in computational time and memory resource was achieved by considering one-fourth height riser model with negligible analysis errors in the present FDM/FEM hybrid technique.

References