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Thermal Stress Analysis to Predict Locations of Defects in the Solidification Process for Large-Scale Cast Steel

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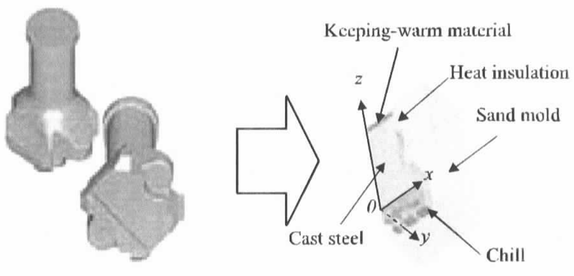
The large-scale cast steel has been used in broad fields of industries, such as power generation, construction, vessels, and automobiles. In the solidification process of a hummer used for press machine, for example, sinkage cavity and segregation can be predicted by performing non-steady state heat transfer analysis. However, uneven cooling rates at different regions of the large-scale cast steel generate thermal stresses, which cause solidification cracks, between the chills. For causing those cracks, thermal stress may be important; however, there have been few studies for this thermal stress analysis. In this study, a three dimensional thermal elasto-plastic stress analysis has been performed by using finite element method in connection with three dimensional non-steady state heat transfer analysis, including interaction between the temperature and stress field. The results provide further understanding of the observed solidification crack failure for large-scale cast steel.

Keywords: *Cast Steel, Solidification Cracks, Elastic-plastic Stress Method, Finite Element Method*

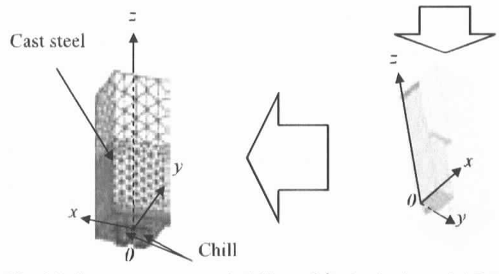
1 Introduction

The large-scale cast steel has been used in broad fields of industries, such as power generation, construction, vessels, and automobiles. Casting plans are usually made by experienced senior technicians without theory. Defects are found in the large-scale cast steel more often compared with in the small-scale. It is known that three types of defects appearing at large scale cast steel; they are called shrinkage cavity, segregation and cracks. Shrinkage cavity appears because of lack of molten steel. Segregation appears because of the specific weight difference of chemistry ingredients. Those defects can be predicted by performing non-steady state heat transfer analysis [1-2]; therefore, two types of defects can be eliminated by using chills and controlling solidification process. This is because such defects may be controlled by cast temperature to simulate the solidification processes in order to predict such defects.

However, crack-type defects cannot be predicted through heat transfer analysis. For cracks, thermal stress may be important. And cracks may be predicted by performing thermal elastic-plastic stress analysis by using FEM. Figure 1 (a) shows a hummer used for press machine, which manufactures bodies of automobiles. In this study, we will focus on predicting cracks for this hummer. And a three dimensional thermal elastic-plastic stress analysis has been performed by using finite element method in connection with three dimensional non-steady state heat transfer analysis, including interaction between the temperature and stress field [3]. Then, the thermal stress which may cause crack defects will be considered with varying the spacing of chills and chill shape.



(a) Hummer (b) Analysis model-1 (quarter)



(d) Mesh pattern at cast and chill (c) Analysis model-2 (quarter)

Figure 1: Research object

2 Method of calculation

Figure 1 (a) shows a hummer used for press machine, which manufactures bodies of automobiles. The hummer has dimensions about 2500mm × 2000mm × 3000mm and weighs about 30t. Figure 1 (b) shows examples of arrangement of chills. However, analysis model is too complicated, two chills model as shown in Fig.1 (d) will be considered. Then, the effect of location of chills upon the thermal stress is discussed.

2.1 ANALYSIS MODEL(ARRANGEMENT OF CHILLS)

Figure 2 shows mesh pattern of two chills FEM model. This analysis model includes five parts, heat insulation, keeping-warm material, cast steel, sand mold and two chills. Tetrahedral elements are mainly used; however hexahedral elements are used for the under-part of cast steel and the chills because temperature difference is larger than 1000℃. Figure 3 (a), (b) shows arrangement of chills and chill shape. In this study, two types of chills are considered. One is two cubic chills model (a^2 臂) and the other is two cylinder chills model (π? $d/2)^2$ 臂). The chill spacing is assumed as $l = 30mm, 70mm, \infty$. Figure 3 (c) (d) shows mesh divisions with $l = 70mm$. Fine mesh divisions are applied between two chills because high accuracy is required.

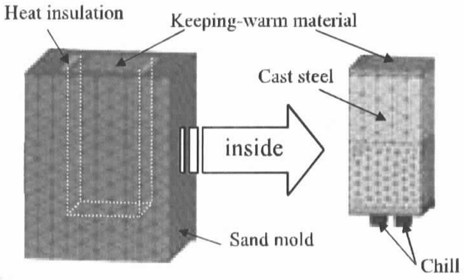
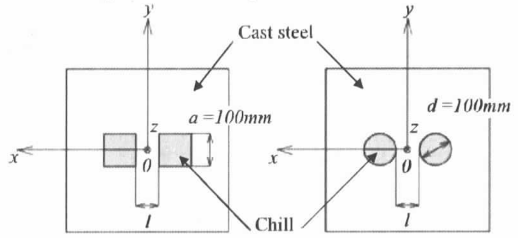
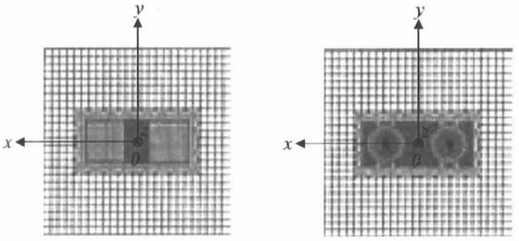


Figure 2: Mesh pattern of FEM model



(a) Cubic chills (b) Cylinder chills



(d) Cubic chills (l=70mm) (e) Cylinder chills (l=70mm)

Figure 3: Arrangement of chills

Table 1: Chemical compositions of cast steel (2Cr-Mo Alloy [wt%])

C	Si	Mn	P	S	Cu	Ni	Cr	Mo	V	Al
0.15	0.38	0.6	0.008	0.008	0.04	0.15	2.11	0.91	0.007	0.008

Table 2: Material properties for 2Cr-Mo, Silica sand, keeping-warm material, and heat insulation

Material	Cast steel (2Cr-Mo)	Chill (2Cr-Mo)	Sand mold (Silica sand)	Keeping-warm material	Heat insulation
Mass density [$\times 10^3$ kg/m^3]	7.85		1.7	0.15	1.1
Young's modulus [GPa]	*(1.225 × 10^3 ~ 205.8) (See Fig.4)	0.001			
Poisson's ratio	0.3	0			
Yield stress [MPa]	*(0.490 ~ 215.746) (See Fig.5)	0			
Coefficient of linear expansion [1/℃]	*(1.27 ~ 1.50) (See Fig.6)	0			
Thermal conductivity [$\times 10^{-2}$W/m]	*(2733.0 ~ 5191.0) (See Fig.7)		*(66.98 ~ 124.8) (See Fig.9)	8.4	41.9
Specific heat [J/kg·K]	*(460.47 ~ 1431.63) (See Fig.8)		964	922	1047
Heat transfer coefficient [W/m^2·K]	4144189.5(Cast steel-Chill, Heat insulation-Air) 418.605(Cast steel-Sand mold, Chill-Sand mold, Sand mold-Keeping-warm material, Sand mold-Heat insulation) 41.8605(Cast steel-Keeping-warm material, Cast steel-Heat insulation) 20.903025(Keeping-warm material, Heat insulation-Air) 4.18605(Cast steel-Heat insulation)				

* These are depending on temperature as shown in Fig.4-9.

2.2 MATERIAL PROPERTIES

Table 1 shows chemical compositions of cast steel. And Table 2 shows material properties for 2Cr-Mo, Silica sand, keeping-warm material, and heat insulation. The asterisk means material property depending on temperature. Material properties of cast steel are indicated in Fig.4-8 as function of temperature. Figure 9 shows thermal conductivity of sand mold [4].

2.3 BOUNDARY AND INITIAL CONDITIONS

Cast Steel is assumed to be filled in sand mold without delay. Initial temperature of cast steel is 1530℃. Initial temperature of keeping-warm material and atmosphere is 20℃ and others are 40℃. It is assumed that there is no-gap appearing between cast steel, chills, sand mold and others. And heat transfer coefficients are shown in Table 2. To consider the latent heat, the apparent capacity method is used. Then, the latent heat is including the specific heat of the material assuming that the latent heat is released uniformly between the liquids-solid range (1462℃ - 1503℃) [5]. For elastic-plastic analysis, the elastic material is assumed as perfect elastic material because work-harding effect is small at high temperature.

3 The Result of Thermal Stress between Two Chills

Since the yield stress of cast steel varies depending on temperature, we will focus on the parameter $\sigma_{eq}/\sigma_{yield}$, which is the equivalent stress normalized by the yielding stress. If $\sigma_{eq}/\sigma_{yield}$ = unity, cracks may appear. If $\sigma_{eq}/\sigma_{yield}$ is less than unity, cracks may not appear.

Figure 10 shows $\sigma_{eq}/\sigma_{yield}$ vs. time relation for spacing $l = 30mm$. Since the maximum stress σ_x appears at $z = 10mm$, z is fixed as $z = 10mm$. These figures indicate crack may appear because $\sigma_{eq}/\sigma_{yield}$ = unity. Figure 11 shows $\sigma_{eq}/\sigma_{yield}$ vs. time relation for spacing $l = 70mm$. For two cubic chills with $l = 70mm$, cracks may appear because $\sigma_{eq}/\sigma_{yield}$ =unity. However, for two cylinder chills with $l = 70mm$, cracks may not appear because $\sigma_{eq}/\sigma_{yield}$ is less than unity. Figure 12 shows $\sigma_{eq}/\sigma_{yield}$ vs. time relation for spacing $l = infinity$. For $l = infinity$, cracks may not appear in both cases because σ_{eq} is usually less than σ_{yield}. However, if the distance between two chills is too large, Shrinkage Cavity and Segregation may appear because cooling effect is not enough.

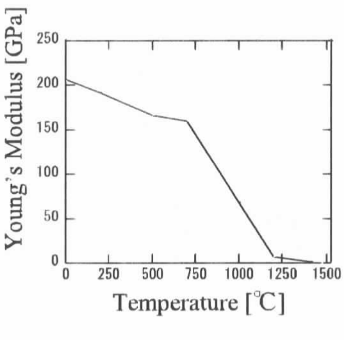


Figure 4: Young's Modulus of Cast Steel

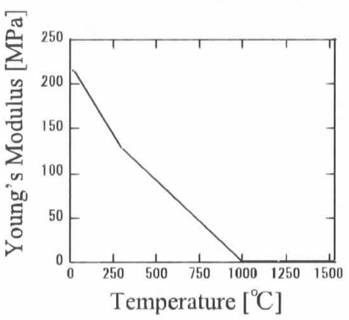


Figure 5: Yield Stress of Cast Steel

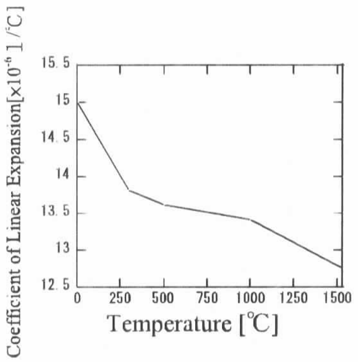


Figure 6: Coefficient of Linear Expansion of Cast Steel

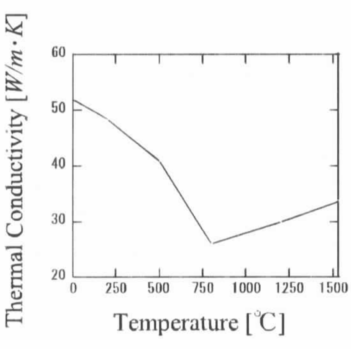


Figure 7: Thermal Conductivity of Cast Steel

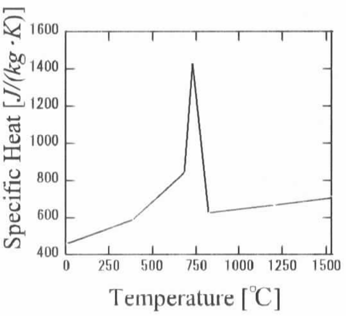


Figure 8: Specific Heat of Cast Steel

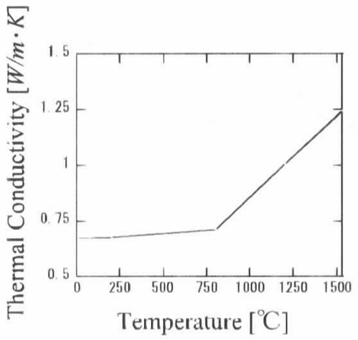


Figure 9: Thermal Conductivity of Sand Mold

4 Conclusions

(1) For spacing $l = 30mm$, cracks may appear in both cases.

(2) For spacing $l = 70mm$, cracks may appear for two cubic chills, but may not appear for two cylinder chills.

(3) For spacing $l = infinity$, cracks may not appear in both cases, but shrinkage cavity and segregation may appear.

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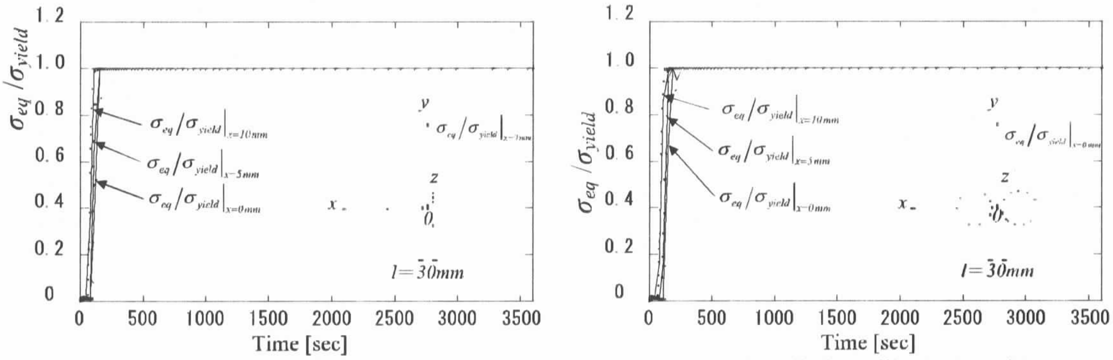
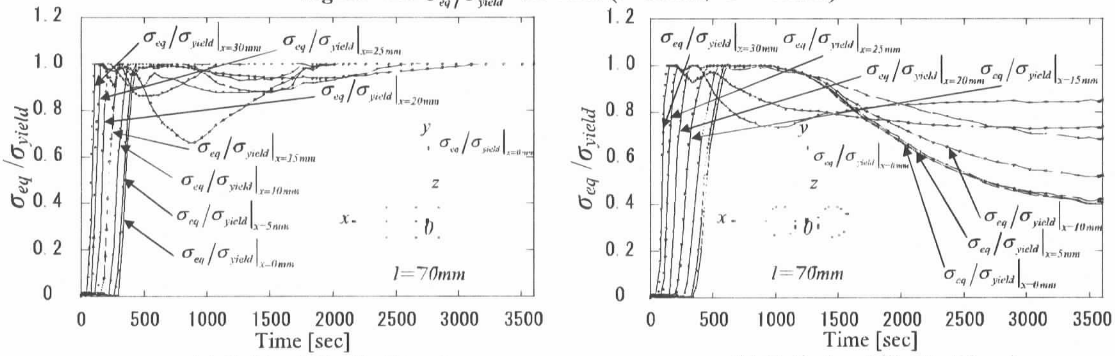


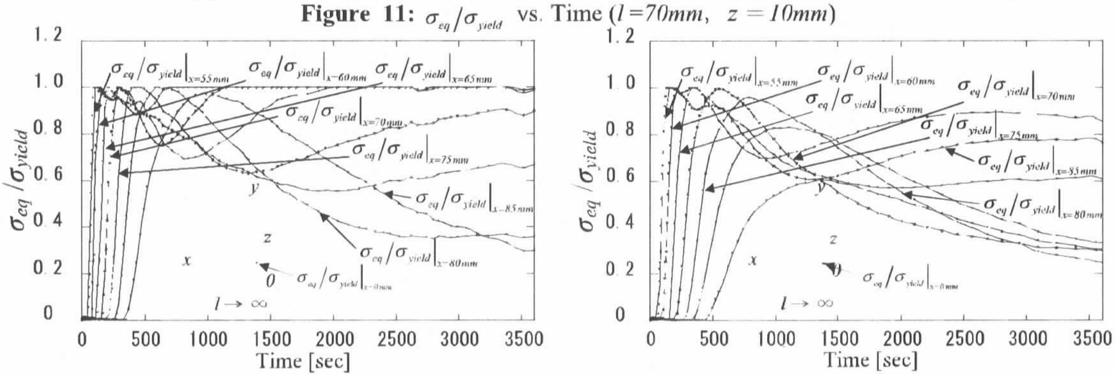
(a) Cubic chills (l =*30mm*) (b) Cylinder chills (l =*30mm*)

Figure 10: $\sigma_{eq}/\sigma_{yield}$ vs. Time (l=*30mm*, z = *10mm*)



(a) Cubic chills (l =*70mm*) (b) Cylinder chills (l =*70mm*)

Figure 11: $\sigma_{eq}/\sigma_{yield}$ vs. Time (l=*70mm*, z = *10mm*)



(a) Cubic chills ($l \to \infty$) (b) Cylinder chills ($l \to \infty$)

Figure 12: $\sigma_{eq}/\sigma_{yield}$ vs. Time ($l \to \infty$, z = *10mm*)