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Three-Dimensional Surface Heat Transfer Coefficient and Thermal Stress Analysis for Ceramics Tube Dipping into Molten Metal

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Abstract. The low pressure die casting machine has been used in industries because of its low-cost and high efficiency precision forming technique. In the low pressure die casting process is that the permanent die and filling systems are placed over the furnace containing the molten alloy. The filling of the cavity is obtained by forcing the molten metal, by means of a pressurized gas, to rise into a ceramic tube, which connects the die to the furnace. The ceramics tube, called stalk, has high temperature resistance and high corrosion resistance. However, attention should be paid to the thermal stress when the ceramics tube is dipped into the molten metal. It is important to reduce the risk of fracture that may happen due to the thermal stresses. To calculate the thermal stress, it is necessary to know the surface heat transfer coefficient when the ceramics tube dips into the molten metal. In this paper, therefore, the three-dimensional thermo-fluid analysis is performed to calculate surface heat transfer coefficient correctly. The finite element method is applied to calculate the thermal stresses when the tube is dipped into the crucible with varying dipping speeds and dipping directions. It is found that the thermal stress can be reduced by dipping slowly when the tube is dipped into the molten metal.

Introduction

Ceramic tube called stalk has been used in the low pressure die casting machine LPDC [1]. Ceramics tube has high temperature resistance and high corrosion resistance. Previously, the tube was made of cast iron which resulted in spoiling the quality of the product due to the partial melting of molten metal. Therefore, ceramics tube was introduced to improve the life time of tube. However, there is still low reliability of ceramics mainly due to low fracture toughness.

The ceramic tube plays a critical function in the LPDC [2] because it receives the molten metal with high temperature from the crucible. However, attention should be paid to the thermal stress when the ceramics tube is dipped into the molten metal. It is important to reduce the risk of fracture because of low fracture toughness of ceramics. In this paper the finite volume method three-dimensional model is applied to calculate surface heat transfer coefficient. Then, the finite element method is applied to calculate the thermal stresses when the ceramics tube is dipped into the crucible with varying dipping speeds and dipping directions. Figure 1 shows the model of ceramics tube for simple model.

Analytical Conditions

In low pressure die casting machine in Fig. 1, the ceramics tube is 170mm in diameter and 1300mm in length. Temperature of the molten aluminum is assumed as 750^{o}C, and the initial temperature of the ceramics tube is assumed as 20^{o}C. The physical properties of molten aluminum at 750 ^{0}C (1023K) [3] and the properties of ceramics called sialon [3] are used for the ceramics tube. Axi-symmetric model will be used for vertical tube with a total of 19500 elements and 20816 nodes as shown in Fig. 2. Three-dimensional model will be used for horizontal tube with a total of 15000 elements and 18786 nodes as shown in Fig. 2. Here, 4-node quadrilateral elements will be employed for FEM analysis.

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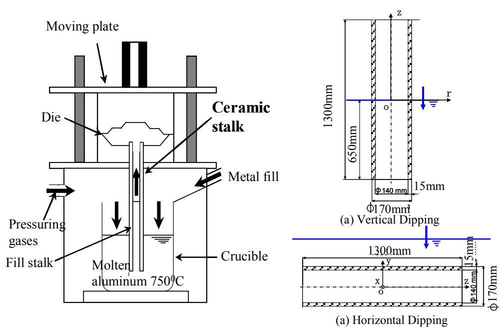
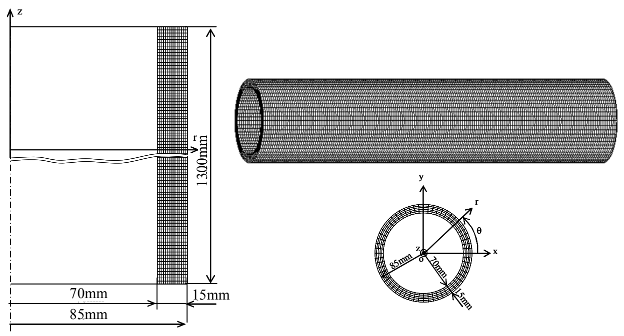


Fig. 1 Schema of the low pressure die casting (LPDC) machine (Note that LPDC is sometimes called "low pressure casting" in Japan)



(a) Vertical tube (b) Horizontal tube

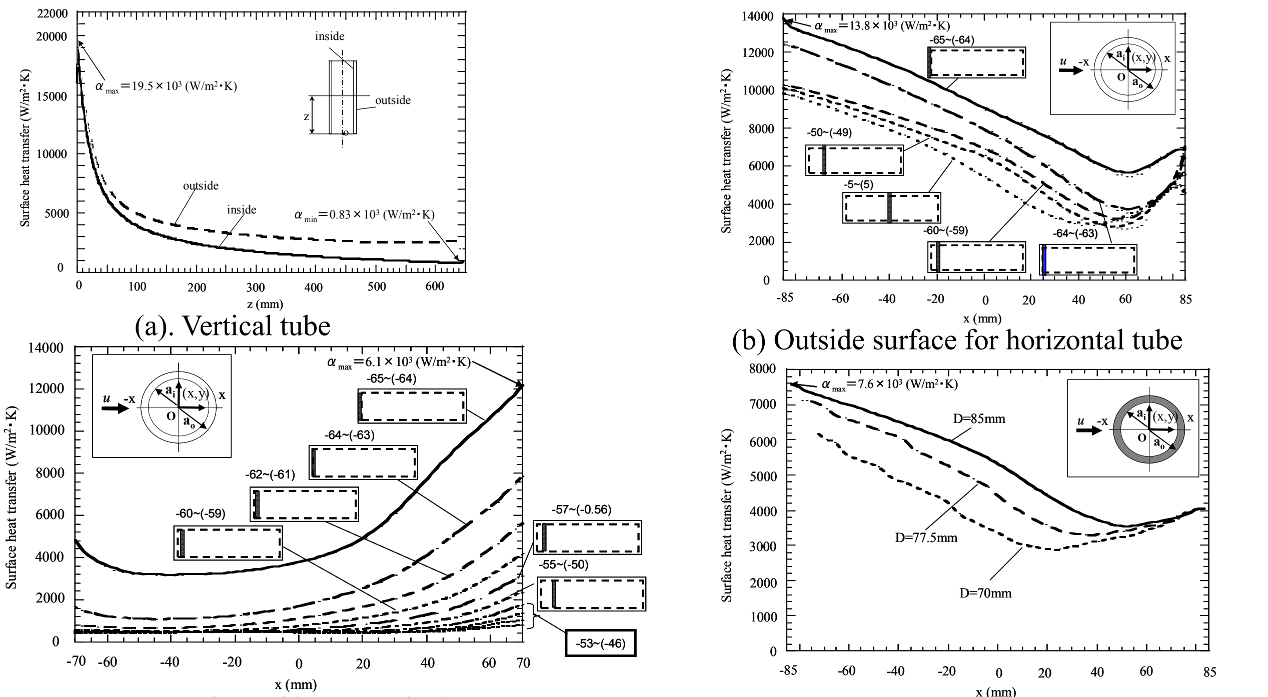
Fig. 2 Finite element mesh of ceramics tube

Surface Heat Transfer Coefficient for Vertical and Horizontal Tubes

To calculate the thermal stress, it is necessary to know the surface heat transfer coefficient α when the tube dips into the molten aluminum. In this paper, three-dimensional (3D) model for horizontal tube and axi-symmetric model for vertical tube are analyzed by using the finite volume method to calculate α when the ceramics tube is dipped into the molten metal. Figure 3 shows the results of α for the 3D and axi-symmetric models at $u = 25\text{mm/s}$. As shown in Fig. 3, the values of the surface heat transfer coefficient α of inner of tube are smaller than outer of tube for 3D and axi-symmetry models.

Thermal Stress for Vertical Tube

The vertical tube model with the length of 1300mm as shown in Fig. 1 (a) is considered when half of the tube is dipping into molten aluminum at the speeds of $u = 2\text{mm/s}$ and $u = 25\text{mm/s}$. It should be noted that $u < 2\text{mm/s}$ is too slow and not convenient and $u > 25\text{mm/s}$ is too fast and not safe. When $u = 2\text{mm/s}$, a constant value $\alpha_m = 1.523\times10^3\,\text{W/m}^2\cdot\text{K}$ [3] is applied for dipping step by step along the inner and outer surfaces ($r_i = 70\text{mm}$, $r_o = 85\text{mm}$) until reaching half tube. The results are shown in Fig. 4. The figure indicates the maximum tensile principle stress σ_1, maximum compressive principle stress σ_3, maximum stresses components σ_r, σ_θ, σ_z and maximum shear



(a). Vertical tube

(b) Outside surface for horizontal tube

(c) Inner surface of horizontal tube

(d) Tube ends of horizontal tube

Fig. 3 Surface heat transfer coefficient for 3D and axi-symmetry model as a function of x and z in the molten metal with the velocity u=25mm/s

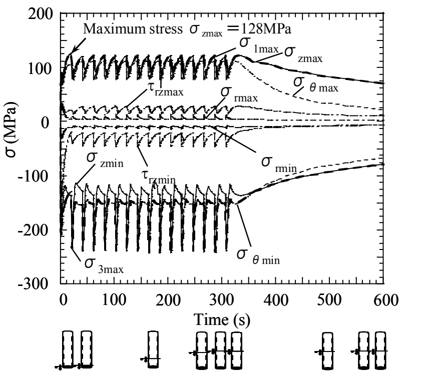


Fig. 4 Maximum stresses vs. time relation for vertical tube ($u = 2$mm/s).

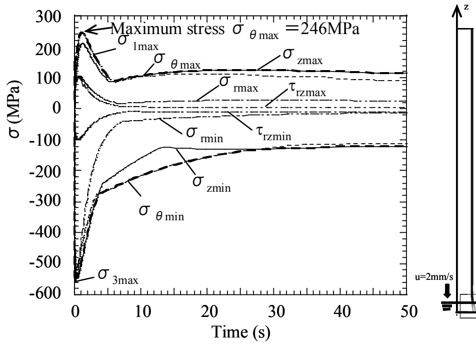


Fig. 5 Maximum stresses vs. time relation for vertical tube ($u = 25$mm/s)

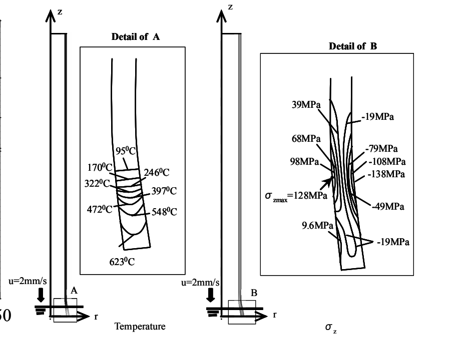


Fig. 6 Temperature and stress distribution for vertical tube ($u = 2$mm/s , $t = 20.5$s).

stress τ_{rz}. From Fig. 4 it is found that $\sigma_{z\max}$ has a peak value of 128MPa at $t = 20.5$s . The maximum thermal stress $\sigma_{z\max} = 128$MPa does not decrease while half of the tube is dipping into the molten metal. Then, the stress decreases gradually after half dipping is finished. Since sixteen types of partially dipping model are utilized, fluctuation of stresses appears as shown in Fig. 4.

Thermal stress is considered when the tube in Fig. 1 (a) dips into molten aluminum fast at $u = 25$mm/s . The surface heat transfer is applied as follows:

1. When $t = 0 - 60$s , the values in Fig. 3 (a) is applied at the inner and outer surfaces for simple tube. Also the maximum value, in Fig. 3 (a) is applied at the lower end surface ($z = 0$mm) for vertical tube.
2. When $t > 60$s , the minimum value, in Fig. 3 (a) is applied for the exposed surface until reaching half tube for vertical tube.

Figure 5 shows the maximum value of stresses σ_1, σ_r, σ_θ, σ_z and τ_{rz}. As shown in Fig. 5, the maximum tensile stress $\sigma_1 = \sigma_\theta$ increases in a short time. After taking a peak value $\sigma_{\theta\max} = 246$MPa at $t = 1.1$s , it is decreasing. The maximum value 246MPa is larger than that of 128MPa for dipping slowly.

The temperature and stress distributions of vertical tubes are indicated in Figs. 6 and 7. Figure 6 shows temperature and stress distributions of σ_z at $t = 20.5$s , where the maximum stress $\sigma_{z\max} = 128$MPa appears for the tube dipping slowly. Figure 7 shows temperature and stress distributions σ_θ at $t = 1.1$s where the maximum stress $\sigma_{\theta\max} = 246$MPa appears for the tube dipping fast. For dipping slowly at $u = 2$mm/s , the maximum stress σ_z appears at the inner surface of the tube $r = 70$mm just above the dipping level of molten aluminum (see Fig. 6). This is due to the bending moment caused by the thermal expansion of the dipped portion of the tube. On the other hand, for dipping fast at $u = 25$mm/s , the maximum stress $\sigma_{\theta\max}$ appears at the inside of the thickness as shown in Fig. 7. This is due to the large temperature difference appearing in the thickness direction. It may be concluded that vertical tubes should be dipped slowly in order to

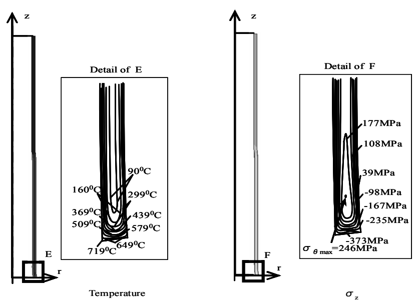


Fig. 7 Temperature and stress distribution for vertical tube $u = 25$mm/s , $t = 1.064$s

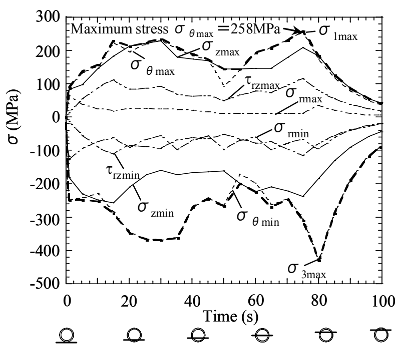


Fig. 8 Maximum stresses vs. time relation for horizontal tube ($u = 2$mm/s).

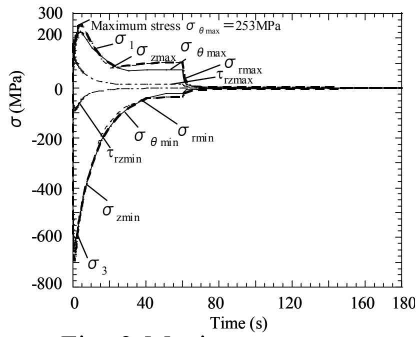


Fig. 9 Maximum stresses vs. time relation for horizontal tube ($u = 25$mm/s)

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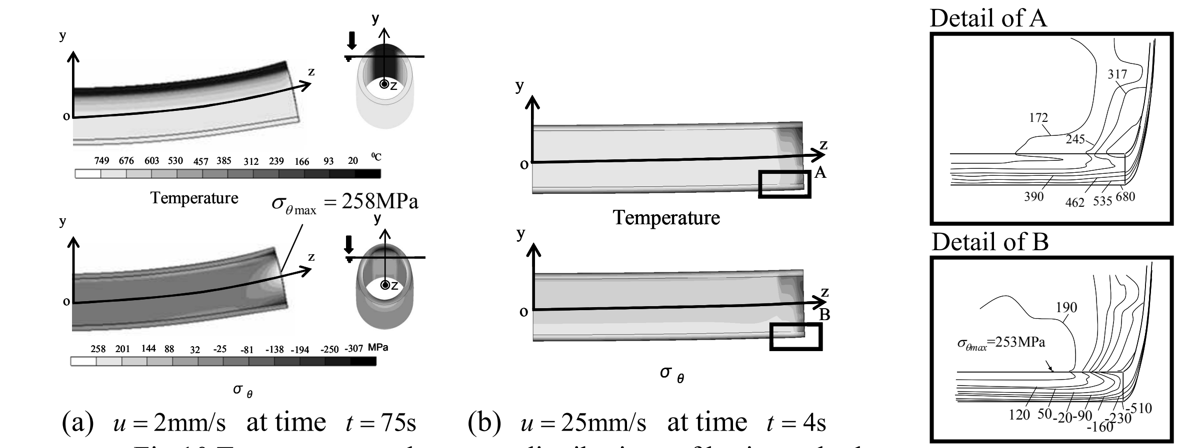

(a) $u = 2$mm/s at time $t = 75$s (b) $u = 25$mm/s at time $t = 4$s

Fig.10 Temperature and stress σ_θ distributions of horizontal tube

reduce the thermal stresses.

Thermal Stress for Horizontal Tube

Thermal stress is considered when the horizontal tube in Fig. 1 (b) dips into molten aluminum at the speeds of $u = 2$mm/s and $u = 25$mm/s. Three-dimensional model will be used for horizontal tube with a total of 15000 elements and 18786 nodes as shown in Fig. 2 (b). When $u = 2$mm/s, a constant value $\alpha_m = 1.523 \times 10^3$ W/m$^2 \cdot$K [3] is applied for dipping step by step along the inner and outer surfaces ($r_i = 70$mm, $r_o = 85$mm). Figure 8 shows maximum values of stresses σ_1, σ_r, σ_θ, σ_z and τ_{rz}. In Fig. 8, the maximum tensile stress $\sigma_{\theta\max} = 258$MPa appears at $t = 75$s.

Thermal stress is considered when the horizontal tube in Fig. 1 (b) dips into the molten aluminum fast at $u = 25$mm/s. Here, the surface heat transfer is applied in the following way:

1. When $t = 0 - 60$s, the values in Figs. 3 (b) - 3 (d) are applied along the inner ($r_i = 70$mm), outer ($r_o = 85$mm) surfaces and tube ends $z = \pm 650$mm.
2. When $t > 60$s, the minimum value in Figs. 3 (b) - 3 (d) is applied for all exposed surfaces.

Figure 9 shows maximum values of stresses σ_1, σ_r, σ_θ, σ_z and τ_{rz}. As shown in Fig. 9 the maximum stress increases in a short time, and has a peak value $\sigma_{\theta\max} = 253$MPa at $t = 4$s. Figure 10 (a) shows the temperature and stress distributions σ_θ for horizontal tube at both ends where $\sigma_{\theta\max} = 258$MPa appears at $t = 75$s for the tube dipping slowly. Figure 10 (b) shows temperature and stress distributions σ_θ at the inner surface of thickness, where $\sigma_{\theta\max} = 253$MPa appears at $t = 4$s for the tube dipping fast. For dipping slowly, as shown in Fig. 10 (a) the maximum stress $\sigma_{\theta\max}$ appears at the inner surface of the tube ends $z = \pm 650$mm. In this case the circular cross section becomes elliptical because of temperature difference between the dipped and upper parts. In other words, the maximum stress $\sigma_{\theta\max}$ appears due to asymmetric deformation. For dipping fast, the maximum stress appears at the inner surface of thickness as shown in Fig. 10 (b). This is due to large temperature difference appearing in the thickness direction. The larger stress appears much more shortly than the case of $u = 2$mm/s. Therefore horizontal tubes should dip fast at $u = 25$mm/s rather than slowly at $u = 2$mm/s to reduce the thermal stress.

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