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Reduction of Thermal Stress for Ceramics Stalk Dipping into Molten Metal

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Low pressure die casting (LPDC) is defined as a net shape casting technology in which the molten metal is injected at high speeds and pressure into a metallic die. LPDC is playing an important role in the foundry industry as a precision of low-cost and high-efficiency forming technique. The ceramics tube called stalk has high temperature resistance and high corrosion resistance. However, care should be taken of the thermal stresses when the stalk is dipped into the molten aluminum because of its low fracture toughness. It is important to develop the new stalk to reduce the risk of fracture due to the thermal stresses when dipped into the molten aluminum. In this paper, therefore, the finite element method is applied to calculate the thermal stresses when the stalk is dipped into the crucible with varying the dipping speeds and directions.

Keywords: *Thermal Stress, Low Pressure Die Casting, Stalk, Molten Aluminum, FEM*

1 Introduction

Low pressure die casting (LPDC) is especially suitable for producing axi-symmetric components such as light automotive wheels, cylinder head, piston and brake drum. Low pressure die casting is defined as a net shape casting technology in which the molten metal is injected at high speed and pressure into a metallic dies. The low pressure die casting process is playing an increasingly important role in the foundry industry as a precision of low-cost and high-efficiency forming technique.

Typically operating sequence for the low pressure die casting is shown in Figure1. The process is that the permanent die and filling systems are placed over the

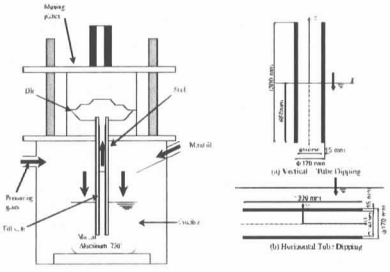


Figure1 Schema of the low pressure die casting machine

furnace containing the molten alloy. The filling of the cavity is obtained by forcing the molten metal by means of a pressurized gas in order to rise into a ceramic tube, which connects the die to the furnace. The ceramic tube called stalk has high temperature resistance and high corrosion resistance.

In this paper, the finite element method will be applied to calculate the thermal stresses when the tube is dipped into the crucible with varying dipping speed and direction.

2 Analysis Method

2. 1 MATERIAL PROPERTIES OF TUBE

In low pressure casting machine in Figure1, the tube is 170mm in diameter and 1300 mm in length. Recently they are usually made of ceramics because of its high temperature resistance and corrosion resistance. Table1 shows the physical properties of molten aluminum at 1023K (750°C). Table 2 shows the properties of ceramics called Sialon used as the tube.

2.2 SURFACE HEAT TRANSFER

To calculate the thermal stress, it is necessary to know the surface heat transfer α when the stalk dips into the molten aluminum. Since three-dimensional thermo-fluid analysis to estimate α is very complicated, two dimensional (2D) solutions will be considered. Zukauskas (1-2) proposed the following equation to estimate Nusselt number when a two-dimensional cylinder in the fluid with the velocity u.

$$Nu_m \equiv \frac{\alpha_m \cdot D}{\lambda} = C_1 \cdot \mathrm{Re}^n \cdot \mathrm{Pr}^{0.37} \cdot \left(\frac{\mathrm{Pr}}{\mathrm{Pr}_w}\right)^{0.25} \tag{1}$$

$$\mathrm{Re} = \frac{u \cdot D}{\upsilon}, \quad \mathrm{Pr} = \frac{C_p \cdot \eta}{\lambda} \tag{2}$$

Here, α_m is the average heat transfer coefficient, λ is thermal conductivity, D is a diameter of the cylinder, C_1 and n are constants determined from Reynolds number (3, 4). Also, Re is Reynolds number, Pr is Prandtl number, and subscript w denotes the property for temperature of cylinder wall. The velocity u can be calculated by the diameter of the stalk divided by the time when the stalk dips into the molten aluminum, which is usually, $u = 2-25mm/s$. The values of isobaric specific heat C_p, viscosity η, kinematics

velocity v are taken from reference (5) and as shown in Table1. Substituting these into Eqs. (1) and (2), Nu_m is given from α_m. Namely,

$$\alpha = 1.523\times10^3\, W/m^2\cdot K \quad \text{(When } u\text{=2mm/s).} \quad (3)$$

$$\alpha = 11.27\times10^3\, W/m^2\cdot K \text{ (When } u\text{=25mm/s).} \quad (4)$$

Figure2 shows numerical solutions for heat transfer coefficient for $u = 25mm/s$. The maximum value $\alpha = 18.13\times10^3\, W/m^2\cdot K$ appears at $x = -85mm$, while the minimum value $\alpha = 3.675\times10^3\, W/m^2\cdot K$ appears at $x = 57.8mm$. The average value is $\alpha_m = 10.9\times10^3\, W/m^2\cdot K$, which is in good agreement with Eq. (4).

2.3 ANALYSIS MODEL

In this analysis, the total number of nodes is 20816 and the number of elements is 19500. Table2 shows mechanical properties of ceramics. Here, Sialon is considered as material of the tube. Temperature of the molten aluminum is assumed as 750°C, and the initial temperature of the tube is assumed as 20°C. Table 3 shows the assumption of heat transfer. Here, 4-node quadrilateral elements will be employed for FEM analysis.

Table 1 the Physical Property of Molten Aluminum at 750°C

Physical Property (dimension)	Al (750°C)
Thermal conductivity (λ (W/m K))	112.2
Roll diameter (D(m))	0.17
Kinematics viscosity (ν (mm²/s))	0.967
Isobaric specific heat (C_P (Kj/kg K))	1.1
Viscosity (η (mPa s))	2.2
Constants in Eq. (1) when $Re = 1\times10^3 - 2\times10^5\,(C_1)$	0.26
Constants in Eq. (1) when $Re = 1\times10^3 - 2\times10^5\,(n)$	0.6

Table 2 Mechanical Property of Ceramics

Physical Property (dimension)	Sialon
Thermal conductivity (W/m K)	17
Specific Heat (J/kg K)	650
Coefficient of Linear Expansion (1/K)	3.0 x10⁻⁶
Young's Modulus (GPa(Kgf/mm²))	294 (29,979)
Specific Weight	3.26
Poisson's Ratio	0.27
Point Bending Strength (MPa (Kgf/mm²))	1050 (10,296)
Fracture Toughness (MN/m$^{3/2}$)	7.5

3 Results and Discussion

3.1 THE THERMAL STRESS FOR THE VERTICAL TUBE DIPPING SLOWLY AT U=2MM/S

The tube model in the low pressure casting machine as shown in Figure1.a is considered when the tube is dipped into the crucible slowly, u=2mm/s. Here total of 19500 elements with 20816 nodes have been used. When $u=2mm/s$, $\alpha_m = 1.523\times10^3\, W/m^2\cdot K$ as shown in Eq. (3) are applied for the whole surface, r=85mm and z=1300mm, since it takes 328s for completely dipping, 16 levels of partially dipping models are considered as shown in the Table 3, and $\alpha_m = 1.523\times10^3\, W/m^2\cdot K$ is applied to the surface touching molten aluminum. Then, the results are shown in Figure3. Figure3 indicates the maximum tensile principle stress σ_1, maximum compressive principle stress σ_3 and maximum stresses components $\sigma_r, \sigma_\theta, \sigma_z$. Since the maximum shear stresses $\tau_{rz}, \tau_{\theta z}, \tau_{r\theta}$ are within 25% of $\sigma_{z\max}$, only the largest shear stress τ_{rz} is

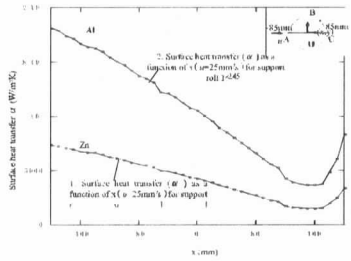


Figure.2 surface heat transfer as function of x(u=25mm/s)

indicated. From Figure3 it is seen that $\sigma_{z\max}$ coincides with σ_1 at t=20.5s, and $\sigma_{z\min}$ coincides with σ_3 at t=165s. As shown in Figure3, therefore only $\sigma_{z\max}$ and $\sigma_{z\min}$ will be discussed because they are almost equivalent to the maximum stresses σ_1 and σ_3, respectively. The stress $\sigma_{z\max}$ has the peak value of 128 MPa at 20.5s.

3.2 THE THERMAL STRESS FOR THE VERTICAL TUBE DIPPING FAST AT U=25MM/S

The thermal stress is considered when the tube is dipped into the crucible fast, $u = 25mm/s$. Then, the surface heat transfer is assumed in the following way:

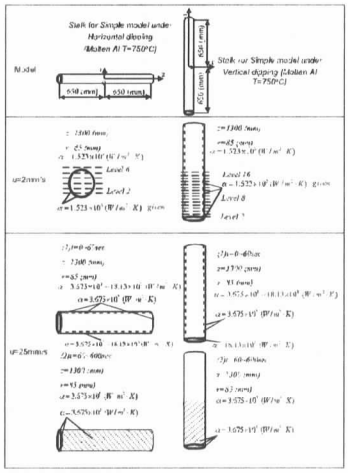
1. When t=0-60s, $\alpha_m = 18.13\times10^3\, W/m^2\cdot K$ as shown in Figure2 is applied to the tube surface, r=85mm, and also $\alpha_m = 3.675\times10^3\, W/m^2\cdot K$, which is the minimum value in Figure2, is assumed at the tube.
2. When $t>60s$, $\alpha = 3.675\times10^3 W/m^2\cdot K$ is assumed for all the surface. Then, the results are shown in Figure4.

As shown in Figure4 the maximum stresses increase in a short time, and has a peak value of 219 MPa at t=1.31s. Namely, the larger stress appears shortly compared to the case of $u = 2mm/s$. It may be concluded that vertical dipping should be slow in order to reduce the thermal stresses.

3.3 THE THERMAL STRESS FOR THE HORIZONTAL TUBE DIPPING SLOWLY U=2MM/S

The horizontal tube dipping into molten aluminum as shown in Figure1.b is considered when the tube is dipped into the crucible slowly at $u = 2mm/s$. Here, total of 45000 elements with 55986 nodes have been used. When $u = 2mm/s$, $\alpha_m = 1.523\times10^3 W/m^2\cdot K$ as shown in Eq. (3) are applied for the whole surface, r=85mm and z=1300mm, since it takes 210s for completely dipping, 6 levels of partially dipping models are considered as shown in the Table 3, and $\alpha_m = 1.523\times10^3 W/m^2\cdot K$ is applied to the surface touching molten aluminum. Figure5 shows the

Table 3 Assumption of heat transfer $\alpha(W/m^2\cdot K)$



results of thermal stress. From Figure5 it is seen that σ_{1max} =258 MPa at t=75s, and σ_{3max} =-310 MPa at t=75s.

3.4 THE THERMAL STRESS FOR THE STALK UNDER HORIZONTAL DIPPING FAST AT U=25MM/S

When the tube is dipped into the crucible fast, $u = 25mm/s$, the results is similar to the case under vertical dipping. Here, the surface heat transfer is assumed in the following way:

1. When t=0-60s, $\alpha_m = 18.13\times10^3 W/m^2\cdot K$ as shown in Figure2 is applied at the tube surface, r=85mm, and also $\alpha_m = 3.675\times10^3 W/m^2\cdot K$, which is the minimum value in Figure2, is assumed at the tube.

2. When $t>60s$, $\alpha = 3.675\times10^3 W/m^2\cdot K$ is assumed for the whole surface. Then, the results are shown in Figure6.

As shown in Figure6 the maximum stresses increase in a short time, and has a peak value of $\sigma_{\theta max}$ =222MPa at t=1.5s. Namely, the larger stress appears compared to the case of $u = 2mm/s$. Therefore a tube should dip fast $u = 25mm/s$ rather than slowly $u = 2mm/s$ to reduce the thermal stress.

3.5 COMPARISON BETWEEN THE RESULTS OF STALK UNDER VERTICAL AND HORIZONTAL DIPPING

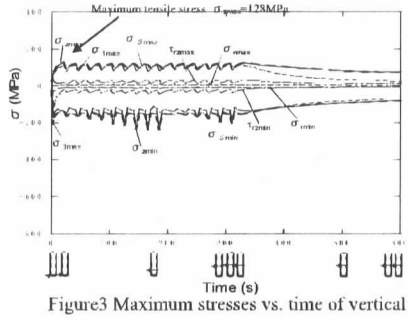


Figure3 Maximum stresses vs. time of vertical tube (u=2mm/s)

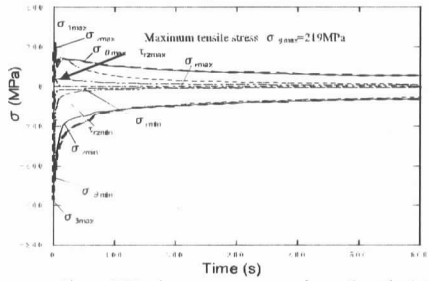


Figure4 Maximum stresses vs. time of vertical tube (u=25mm/s)

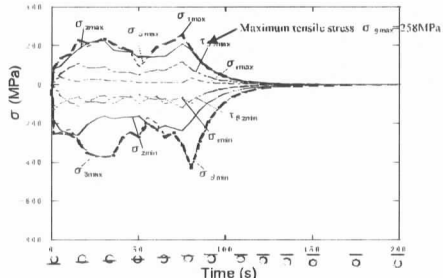


Figure5 Maximum stresses vs. time of horizontal tube (u=2mm/s)

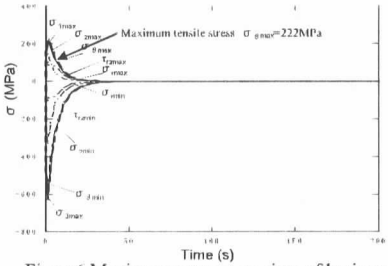
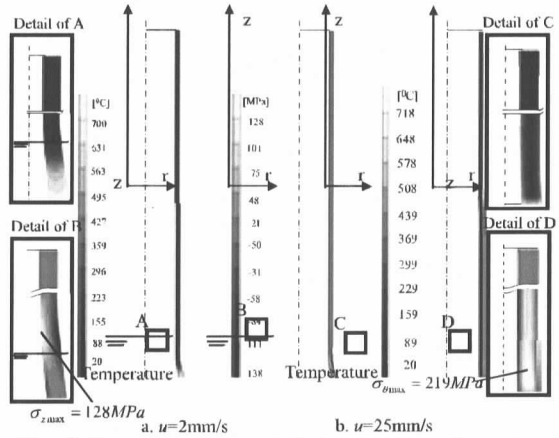


Figure6 Maximum stresses vs. time of horizontal tube (u=25mm/s)

Sialon has been used as the tube because it has high temperature and corrosion resistances. The results of vertical and horizontal tube are indicated in Figures 3-6. The thermal stress of vertical tube for $u = 2mm/s$ has a peak value of σ_{zmax} =128MPa at t=20.5s, which is lower than the value of horizontal tube by about 50%. Namely, the thermal stress for the vertical tube is smaller than the one of horizontal tube.

Figure7.a shows temperature and maximum stress at t=20.5s where maximum σ_{zmax} =128MPa appears when the tube dips slowly. Figure7.b shows temperature and maximum stress at t=1.3s where maximum $\sigma_{\theta max}$ =219MPa appears when the tube dips



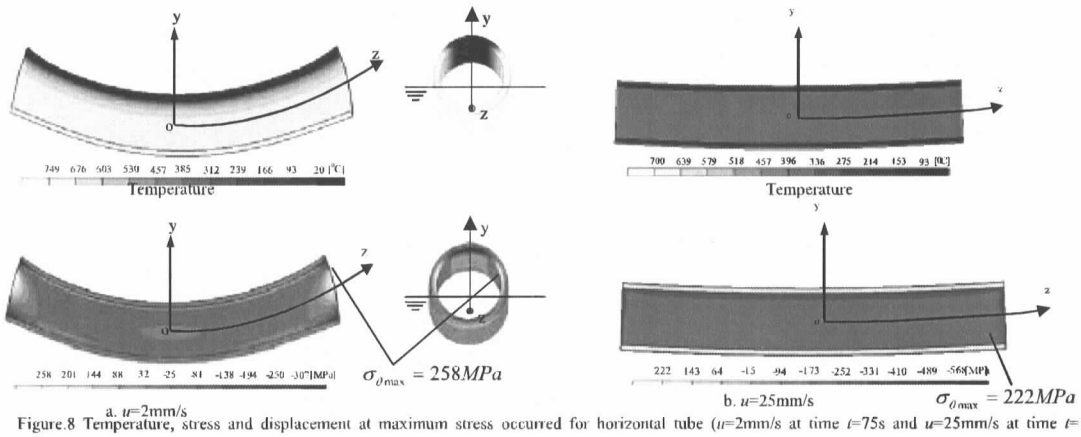
a. u=2mm/s b. u=25mm/s

Figure7 Temperature, stress and displacement at maximum stress occurred for vertical tube (u=2mm/s at time t=20.5s and u=25mm/s at time t=1.31s, displacement $u_z \times 50$)

fast. For the slowly dipping ($u = 2mm/s$), the maximum stress σ_z appears at the inside surface of the tube r=70mm just above the surface of molten aluminum. This is due to the bending moment caused by the thermal expansion of the dipping portion of the tube. On the other hand, for the fast dipping ($u = 25mm/s$), $\sigma_{z\max}$ appears at the inside of the thickness. This is due to the large temperature difference appearing in the thickness direction.

Figure8.a shows temperature and maximum stress distributions where $\sigma_{z\max}$ =258MPa appears when the stalk dips slowly at 75s. Figure8.b shows temperature and maximum stress distributions where $\sigma_{\theta\max}$ =222MPa appears when the stalk dips fast at t=1.5s. For slowly dipping, as shown in Figure8.a, $\sigma_{\theta\max}$ appears at the end of the tube $z = \pm 650mm$ differently from other cases. In this case, $\sigma_{\theta\max}$ appears due to asymmetric deformation. For fast dipping as shown in Figure8.b, the temperature and stress distribution is similar to Figure7.b. This is because when dipping fast, the deformation is almost axi-symmetric.

For vertical tube, fast dipping has a higher maximum stress than slowly dipping. On the other hand for horizontal dipping, fast dipping has a lower maximum stress than slower dipping. This is because for horizontal tube large asymmetric deformation causes large $\sigma_{\theta\max}$ at the end of the tube.



a. u=2mm/s b. u=25mm/s

Figure.8 Temperature, stress and displacement at maximum stress occurred for horizontal tube (u=2mm/s at time t=75s and u=25mm/s at time t=1.5s, displacement $u_y \times 50$)

4 Conclusions

(1) For vertical tube, dipping slowly at u=2mm/s can reduce the thermal stresses compared with the case of dipping fast at u=25mm/s. In other words, when the stalk is set, dipping fast is not suitable for reducing thermal stress.

(2) However, horizontal tube should be dipped fast in order to reduce the thermal stress.

(3) When horizontal tube is dipping slowly, large asymmetric deformations cause large $\sigma_{\theta\max}$ at the end of the tube. If horizontal tube is dipping fast, such large $\sigma_{\theta\max}$ does not appear because the deformation is almost axi-symmetric.

References

(1) Zukauskas A. Heat Transfer form tubes in cross flow. In: Hartnett JP, Irvine Jr TF, editors, Advances in Heat Transfer, vol.8. New York: Academic Press; 1972. p. 131.

(2) Editorial committee of JSME. Data of heat transfer. Tokyo: JSME; 1986. p.61 [in Japanese].

(3) Adachi T, Tamura Y, Yoshioka T. Techniques of Automatic Operation in Continuous Galvanizing Line, Kawasaki Steel Technical Report, vol.34; 1996. p. 18-25.

(4) Nishimura K, Katayama K, Kimura T, Yamaguchi T, Ito M, Newly Develop Techniques for Improving the Quality of Continuous Hot dip Plating Strips, Hitachi Technical Report, vol. 65(2); 1983.p. 121-126 [in Japanese].

(5) Editorial committee of JSME. Data of heat transfer. Tokyo: JSME; 1986. p.323 [in Japanese].