Finite Element Study on Thermal Fatigue Depth of Aluminum Alloy Die Casting Die

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ABSTRACT: A three-dimensional finite element model of the front cover die casting made of aluminum alloy was established by PRO/E and PROCAST software. Thermal balance formation of die casting die and temperature curves of the die cavity surface at different locations were analyzed. The results showed that the nearer the distance from die cavity surface, the greater temperature fluctuation. The thermal fatigue depth of the front cover die casting die was only 0.9mm.

1 INTRODUCTION

The main failure mechanism of aluminum alloy die casting die is the thermal fatigue (Yu, 1998), and thermal fatigue failure accounts for about 70% (Zhou, 2005). Melting temperature of aluminum alloy is 600 ~ 760°C, cavity surface temperature of the die casting die is up to 600°C above (Klobčar, 2008). Thermal fatigue is mainly due to excessive thermal stress which is greater than the thermal fatigue limit in the die casting cycle. Moreover, the thermal stress is caused by temperature fluctuations of die casting die. So it becomes more and more important that understanding the evolution of surface temperature change rules, the formation of the heat balance and thermal fatigue depth of die casting die. Hsieh (1989) and other researchers studied the effects of cooling process, cooling water temperature and cooling pipe diameter, die preheating temperature, pouring temperature and other factors on die temperature field. But there is rare reports about thermal fatigue depth for aluminum alloy die casting die.

In this paper, the 3D geometrical model and FEM of front cover made of aluminum alloy were established using the PRO/E and PROCAST software, respectively. Thermal equilibrium formation rules of aluminum alloy die casting die were obtained by analyzing temperature-time curves of some points with different distances from die surface, and the thermal fatigue depth of the die casting die was determined.
2 NUMERICAL SIMULATION

2.1 The establishment of model

Figure 1 shows the part drawing of front cover made of aluminum alloy A390. Figure 2 shows simplified model of fixed half and moving half of die casting die.

Figure 1. Part drawing of front cover die casting. Figure 2. Simplified model of die casting die.

2.2 Parameter settings

Preheating temperature of die casting die was 200°C, and pouring temperature was 700°C. Heat transfer coefficients of casting part-die, die-die, die-air and die-release agent were 1500, 1000, 5, 500 W/(m²·°C), respectively. Due to die cavity was quickly filled with liquid metal in several milliseconds, at the same time, the simulation was focus on the die, the filling process did not take into account. Cycle time of die casting was 30s, start filling at 0s, open die at 15s, push-off die casting at 20s, injection release agent at 23s, end of spraying at 25s and clamping die at 29s.

Figure 3. (a) Nominal yield strength and (b) modulus of elasticity vs. temperature for the material used in die.
2.3 Physical parameters

A hot work tool steel H13 was used in the die, the nominal yield strength and the modulus of elasticity for this steel at different temperatures are shown in Figure 3.

3 RESULTS AND DISCUSSIONS

Figure 4 shows a schematic representation of the warm-up phase of die casting die with an initial pre-heat temperature of $T_o$ (Shirgaokar, 2008). The average die temperature before the start of the die casting cycle ($T_i$) increases until a steady-state cycle is reached ($T_{min}$). As shown in Figure 4, the starting die temperature ($T_i$) at a selected point for an arbitrary die casting cycle prior to reaching steady-state can be expressed as the summation of the starting temperature ($T_o$, ambient or preheat) and the temperature increase from each of the previous die casting cycles ($\delta T$):

$$T_i = \delta T_{i-1} + \delta T_{i-2} + \delta T_{i-3} + \ldots + T_o = \delta T_o + \Delta T$$

(1)

Temperature change at each point can be simulated by continuous and multi-cycle die casting process, each working cycle consists of die casting, cooling, open die, injection release agent and clamping die. After the die temperature reaches steady state, the $T_{max}$ and $T_{min}$ temperature remain constant, and temperature increment ($\delta T$) during each die casting cycle is equal to zero.

![Figure 4. Die casting die surface heating process diagram.](image)

Figure 5 shows the location of selected points at different distances from die surface. Figure 6 shows temperature-time curves of 8 selected points on die casting die surface. The 8 curves, line 1, 2, 3, 4, 5, 6, 7, 8, represent 8 temperature-time curves of 8 selected points whose distances from die surface were 0, 1, 2, 3, 5, 10, 20, 50 mm, respectively. As shown in Figure 6, die casting die temperature gradually stable and comes into thermal steady-state from the preheat temperature 200°C after about 80 die casting cycles. In the process of the thermal equilibrium formation, temperature increment ($\delta T$) of each die casting cycle is not exactly the same, has maximum values at the start cycle, and become more and more small with the increase of die
casting cycles. When the thermal equilibrium is reached, temperature increment (\(\delta T\)) is zero. Figure 7 shows the temperature amplitudes of 11 points after thermal steady-state. The nearer the distance from the die surface, the greater temperature fluctuation. The biggest temperature fluctuation about 28°C happens on the die surface, i.e., point 1. There is no temperature fluctuation beyond 20 mm distance from die surface. It demonstrates that hot and cold cycle during die casing only affects 20mm distance from die surface which is the thermal fatigue section.

Figure 5. Location of selected points.

Figure 6. Temperature-time curves of 8 selected points.
Malm and Norström proposed a material-related model for a general case of thermal fatigue (Maim & Norström, 1979). It is based on a simplified analysis of the elastic and plastic strains caused by the thermal cycling. Plane stress conditions are assumed and the material is isotropic, elastic-ideal-plastic and exhibits no change in behavior during the repeated thermal cycling. In addition, they assumed that equilibrium conditions in stress and strain are reached at the maximum and minimum temperature, respectively.

Malm and Norström’s model can be formulated as Eq. (1) to estimate a critical die temperature \( T_2 \) under which no plastic deformation will occur during thermal cycling:

\[
T_2 \leq T_1 + \frac{(1 - \nu_2)\sigma_2}{\alpha E_2}
\]  

(1)

\( T_1 \) is the lower equilibrium temperature; \( \alpha \) is the thermal expansion coefficient; \( \nu_2 \), \( E_2 \) and \( \sigma_2 \) is the Poisson’s ratio, modulus of elasticity and yield strength of die material at \( T_2 \), respectively.

Solving Eq. (1) with \( T_1 = 410 \) °C, \( \nu_2 = 0.3 \), \( \alpha = 12\times10^{-6} \), and \( E_2(T) \) and \( \sigma_2(T) \) according to Fig. 3 gives \( T_2 \) about \( \leq 521 \) °C. The maximum compressive stress at \( T_2 \) equals the yield stress at 521°C, which is about 362 MPa, cp. Figure 3.

Below the depth corresponding to \( T_2 \), the deformation is fully elastic (Persson, 2004). In addition \( T_2 \) is well below the tempering temperature of the tool steel H13, which means that only slow degradation of the mechanical properties of the material, if any at all, is expected. Consequently, the maximum crack length equals the depth of \( T_2 \), and it can be estimated from Figure 8 to \( \approx 0.9 \) mm. This clearly demonstrates that thermal fatigue cracking in die casting die is limited to a thin surface layer.
4 CONCLUSIONS

(1) The three-dimensional finite element model of aluminum alloy front cover part was established using PRO/E and PROCAST software.

(2) The temperature curves of different distances of selected points from the die surface were analyzed. The nearer the die surface, the larger temperature fluctuation.

(3) The cyclic temperature range decreases from the die surface and inwards. The depth of the fatigued surface layer (0.9mm = the maximum length of thermal fatigue cracks) equals the thickness of the surface layer within which a temperature of 521℃ is exceeded.

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