FEM stress analysis of the cooling hole of an HPDC die

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Abstract. Cracking at a cooling hole is a typical die failure mode in a high-pressure die-casting (HPDC) die. We simulated the thermal distortion of a die considering the HPDC machine deflection and revealed a stress concentration at the cooling hole. The stress concentration at the cooling hole changes after injection or after spraying and blowing air. The cooling hole top remains in a compression stress state 5, 10, and 20 mm deep from the die surface, but the stress amplitudes are higher when the depths are shallower. It was suggested that cracking takes place due to the high compressive stress and that the shear stress assists the propagation of the initiated crack. On the other hand, the stress condition at the R portion of the cooling hole is always a tensile state, but the mean stress and stress amplitude values were not found to be in the range that causes fatigue fracture. It was demonstrated that the developed analysis is valuable in designing the cooling hole of an HPDC die.

1. Introduction
The life of a die-casting die is shortened by typical cracking such as heat checking and gross cracking. It was reported [1] that half of the cracking takes place at the cooling holes or at the cavity corners. It is considered that the main reasons for the cracking are thermal stresses and the die material properties. However, since heating is inevitable in die-casting dies, it is not easy to suppress the generation of the thermal stresses. Therefore, it is important to predict the thermal stresses and to minimize them during the die design stage. Die temperature control is also important. In casting, too low of a die temperature causes a shortage of molten metal, and too high of a die temperature causes seizure. The die is heated by the molten metal and is cooled by the cooling spray as well as the cooling water provided. The cooling spray is easy to adjust at the production site after the installation of the completed die. On the other hand, since internal cooling through cooling holes is very efficient, a cooling hole is positioned in the high-temperature region of the die with the top of the hole positioned in the vicinity of the cavity surface. However, if the cooling hole is positioned too close to the die surface, the surface temperature becomes too low, and the low strength between the cooling hole top and the cavity surface is likely to cause cracking. In general, we can use two types of cooling circuits. One is spot cooling, which normally has the cooling hole positioned vertically in relation to the cavity surface, where the localized position of the cavity is preferentially cooled. The other is line cooling, which has the cooling hole parallel to the cavity surface, where a wide area of the cavity surface can be cooled. In this analysis, we investigate the spot cooling case.

As mentioned above, it is important to manage the die temperature and to prevent cracking near the cooling hole. The depth of the cooling hole greatly influences the heat extraction. However, there are few reports on the relationship between the depth of the cooling hole and cracking. Tamura et al. [2, 3] tried to predict the cracking from the cooling hole using computer-aided engineering (CAE). They observed the effect of the cooling hole depth on the thermal stresses, but it remained to be an introduction of the prediction method. In normal die design, the designer intentionally challenges and determines the limit depth based on his experience. However, this is not always successful.

Our recent CAE analyses combined with actual experimental observations revealed issues in high-pressure die casting (HPDC), such as the relationship between the HPDC machine distortion and the
die deflection [4], flashing caused by the thermal die deflection [5], warpage of the products [6], and heat checking at the die surface [7]. These studies observed that the modeling range and the restraint conditions influence the deflection. The modeling analysis including the entire HPDC machine and the injection system also simulated how plunger rod misalignment influences the product quality [8].

In this study, we carry out a similar approach that reproduces the following three elements: the die-locking force, the casting pressure, and the thermal stress. First, the casting and solidification simulation reveals the temperature distribution of the die. A comparison of the measured die surface temperature with the calculation confirms the validity of the simulation. Then, finite element method (FEM) stress analysis evaluates the stresses around the cooling hole.

2. Simulation
The analysis modeling and the simulation were carried out in accordance with the actual casting equipment and casting conditions. The product was a flat-shaped JIS-ADC12 part. The HPDC used an oil-based die release agent. The boundary conditions were similar to those in the previous report [7], some of which are introduced below.

2.1. Die temperature distribution
The steady-state die temperature distribution was obtained using the casting and solidification simulation software ADSTEFAN Ver. 2013. Figure 1 shows the computer-aided design (CAD) model of the die inserts. Figure 2 shows the positions of the cooling holes. Cooling holes 1, 2, 4, and 5 had a diameter of 17 mm, and cooling holes 3 and 6 had a diameter of 13 mm. The distances between the tops of cooling holes 1–6 and the die surface were 14, 12, 13, 12, 10, and 11 mm, respectively. The depths of cooling holes 4 and 5 were 10 mm and 12 mm, respectively, in the actual die. These original designs did not show any cracking of the cooling holes. Therefore, the calculation intentionally added cooling hole 5 with a depth of 5 and 20 mm and cooling hole 4 with a depth of 3 mm and 20 mm to generate high-stress conditions.

Figure 3 shows the assembled model. The FEM mesh had 1 mm element edge lengths and a total of 30,827,082 elements. The injected temperature of the molten metal was 580°C. The material properties [4] were the same as in the previous report [6]. The temperature dependence of the specific heat is listed in Appendix 2. The die insert material was JIS-SKD61, and the die holder was FCD500. Some of the material properties are listed in the table of Appendix 1. A comparison of the actual die surface temperature after the spray and blown air with the simulated temperature determined the heat transfer coefficient between the product and the die to be 41.9 kW/(m² °C).

In the actual operation, the oil-based die release agent and the blown air cooled the die surface. The oil-based die release agent together with the water cooling kept the die surface temperature relatively high, enabling a short cycle time. It was assumed that the heat of the die was homogeneously removed from the surface into an external air environment of 100°C. A heat transfer coefficient of 0.47 kW/(m² °C) was used during the spraying and air blowing.

The circulating water cooled the die. The temperature of the cooling water was set to 25°C. The heat transfer coefficient between the die and the cooling water was adjusted for the surface temperature of the cooling hole top to be around 60°C.

Two temperature distributions of the die were prepared to calculate the thermal stresses. One was the temperature distribution “after injection,” which is the highest temperature case where the injection pressure transfers the molten metal heat to the die. The other is the state where the product is released from the die, and then the die release agent is sprayed. Hereinafter, it is referred to “after spraying and blowing air.” This die temperature also includes the stages of heat removal during die opening and the releasing of the casting.

One shot of the actual casting process includes 5 stages. Repeating 20 shots calculates the steady-state temperature distribution of the die. The curing time is usually the time until the solidification of the biscuit, but the curing time here was set to 1 s in order to consider the heat transfer time after injection.
2.2. Temperature mapping and deflection analysis

The FEM stress analysis was executed with ANSYS Workbench Ver. 14.0. The temperature distribution obtained was overlaid onto the FEM mesh of the die inserts. Then, the stress was calculated.

The other materials such as structural steel and S55C were represented according to the actual materials used in the machine. Typical material properties are listed in Appendix Table A1. The boundary conditions were set by reproducing the contact conditions among the parts and the constraint conditions, such as the fixation of the parts and the component temperatures [4].

In these calculations, we used two types of constraints for the die. One corresponds to the state after injection, and the other refers to the state after spraying and blowing air. The model after injection includes the die inserts as well as the entire HPDC machine. The total model includes 140,242 tetrahedral second-order elements. The die-locking force and the casting pressure were applied. The die-locking force was applied from the toggle of the movable platen with a load of 2450 kN [4]. A casting pressure of 60 MPa was vertically and homogeneously applied to the cavity surface.

The case after spraying and blowing air did not include the die-locking force or the casting pressure because of the die opening. The model after spraying and blowing air reproduced the die insert, the die holder, and the back plate. The reverse side of the back plate was fixed. The calculation was only performed at the movable die side. The modified Goodman diagram evaluated the fatigue life of the cooling holes.

3. Results

3.1. Matching the simulated temperature with the actual measurement

Figure 4 shows the simulated temperature distribution after injection. Figure 5 shows the case after spraying and blowing air. Note that the color contours are different. The analysis revealed that the surface temperature accurately simulates the actual thermograph.
3.2. Stress around the top of the cooling hole

Figure 6 shows the temperature distributions at cross section A-A’ in Figure 4 (a) after injection and (b) after spraying and blowing air. This cross section is selected as to include cooling hole 5. Figure 7 shows the temperature change along the solid line in Figure 6. The diagram shows the die temperature (up to a 10 mm depth) and shows the surface temperature of the cooling hole (beyond 10 mm). The heat transfer coefficient between the die and the cooling water was adjusted to make the surface temperature of the cooling hole top around 60°C. The variation in the surface temperature of the cooling hole beyond 10 mm comes from the constant heat transfer coefficient.

Figure 6. Die temperature distribution at cross section (A-A’) (a) after injection and (b) after spraying and blowing air.

Figure 7. Die temperature vs. depth of the cooling hole top.

Figure 8 shows the stress distribution corresponding to Figure 6. The cooling holes have multi-axial stresses. High stress values were observed around the cooling hole tops. The observation of the maximum principal stress revealed that the stress takes place along the cooling hole surface. Also, the minimum principal stress at the cooling hole top was vertical to the cooling hole surface. It was found to not cause cracking.

In order to estimate the compressive stress at the cooling hole top, Figure 9 shows the minimum principal stress values at the cooling hole surface. It also includes the cases with depths of 5 mm and 20 mm. The stress change at the decreased depth is relatively small after injection. However, the compressive stresses drastically increase with a decrease in the cooling hole depth after spraying and blowing air. The 5 mm deep case has a high compressive stress of 500 MPa.
Figure 8. Mises stress distributions at the cross section (A-A’) (a) after injection and (b) after spraying and blowing air.

Figure 9. Effect of the depth of cooling hole 5 on the principal stress at the hole top.

Figure 10 shows the maximum principal stress distribution near the broken line in Figure 8(a) after injection. A high tensile stress of 550 MPa was concentrated at corner R (indicated by the arrow). A high tensile stress also existed along the depth direction on the cooling hole surface.

Figure 11 indicates the maximum principal stress values after injection and after spraying and blowing air. It also includes the cases with depths of 5 mm and 20 mm. Tensile stresses were observed after injection and after spraying and blowing air. It was found that the shallower the hole depth, the lower the stress. However, the stress amplitude is too small to cause fatigue failure.

The stress amplitude and the mean stress at cooling hole 5 were obtained. Figure 12 shows the fatigue limit diagram. The upper and lower limit stresses are necessary for calculating the stress amplitude and the mean stress. The stress along the hole surface will initiate and open a crack. The minimum principal stress at the cooling hole top was along the hole surface. The lower limit stress was chosen for the case after injection, and the upper limit stress was chosen after spraying and blowing air. The yield limit line and the modified Goodman line are illustrated. For the yield limit line, a 0.2% proof stress of 1300 MPa at room temperature was chosen. The modified Goodman line was given using a fatigue stress of 675 MPa at 10⁶ cycles obtained by rotational bending testing at room temperature and an ultimate tensile strength of 1750 MPa at room temperature. These material data of the die steel SKD61 (HRC 50) were quoted from the steel manufacturers [9, 10]. In the fatigue limit diagram, fatigue failure was not predicted at all cooling hole depths.

Figure 13 illustrates the fatigue limit diagram for cooling hole 4. It is observable that the 3 mm depth case has an increased tensile stress, and it is positioned near the fatigue limit line.
4. Discussion
The depth of the cooling hole influences the stress. A shallow cooling hole generates a compressive stress due to the heat input from the die cavity. Particularly, at a depth of 5 mm for cooling hole 5, a high compressive stress appears at the area between the cooling hole top and the cavity surface. The observed value of 500 MPa shown in Figure 9 is below the yield stress. However, if the hole surface has a low roughness value, the stress concentration causes cracking even under compressive stress. In this case, we can predict the probability that the compressive stress triggers mode-II fatigue fracture and that the shear stress helps propagate the initiated crack. The shear stress at the cooling hole top is as small as 40 MPa but can assist the growth of the initiated crack.

Corrosion is liable to take place at the cooling hole, so we also have to consider the corrosion as a factor that can cause fracture. Also, the surface roughness of the cooling hole is not normally controlled. Poor surface roughness will cause stress concentrations, which can decrease the strength.

A tensile stress of 500 MPa was observed at the cooling hole corner R. It was suggested that the stress causes fatigue failure. However, the stress amplitude is small because of the small stress difference between the states after injection and after spraying and blowing air. Hence, it is concluded that fatigue fracture will not take place.

At cooling hole 4 (Figure 13), a depth of 3 mm was simulated as an extreme case. There is a potential that the portion (open square) causes fatigue fracture due to the stress value being near the fatigue limit.

5. Conclusion
We investigated the probability of cracking at the cooling hole of the die for a flat-shaped HPDC part. The FEM analysis observed the effect of thermal stresses on the stress concentration at the top and at the corner R of the cooling holes. The stress state changes after injection and after spraying and blowing air. At the top of the cooling hole, these stresses had a compressive character. The stress amplitude takes a higher value the shallower the depth. It was suggested that a high compressive stress initiates a crack, and the shear stress assists propagation. On the other hand, the stress at the corner R had a tensile demonstrated that the developed analysis is valuable in designing the cooling hole of an HPDC die.

Appendices

Table A1. Material properties for die and machine.
|                                | Structural steel | SKD61 | FCD500 | S55C |
|--------------------------------|------------------|-------|--------|------|
| Density [kg/m³]                | 7850             | 7800  | 7100   | 7800 |
| Coefficient of thermal expansion [1/K] | 1.20E-05        | 1.50E-05 | 1.00E-05 | 1.20E-05 |
| Young's modulus [N/m³]         | 2.00E+11         | 2.06E+11 | 1.73E+11 | 2.05E+11 |
| Poisson's ratio                | 0.3              | 0.3   | 0.3    | 0.3  |

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