Abstract

Casting experiment and a coupled FEM analysis of flow, solidification and thermal distortion in irregular near net shaped billet by semi-continuous casting were carried out to clarify the peculiar problems such as the surface crack and the phenomenon of mold grasped by shaped ingot. By comparing calculated results and experimental ones the cause of surface crack and mold grasped phenomenon were clarified. The surface crack was originated from the force acted from the mold contacting with billet, which was caused by the distortion of solidification contract. The mold grasped phenomenon occurred from the non-uniform deformation which was caused by the non-uniform solidification in the billet cross section.

1. Introduction

Aluminum casting and forging products are used for aircraft, vehicles, industrial machinery, precision machine, etc. Lighter automobiles are increasingly demanded in order to improve fuel efficiency and drivability. Many of suspension components require superior and reliable properties such as high strength and toughness. Aluminum forging, with its high strength and ductility, is a promising alternative for such suspension parts since it can result in weight reduction of up to 40% (compared with conventional steel parts). The high deformability of aluminum forged parts is also highly suitable for maximum safety. But the higher cost of aluminum forgings has, up until now, been a barrier to fully capture the growing market for these applications. Generally, in case of the aluminum suspension forged using the extrusion round bar, it leads to make the manufacturing cost rise because the homogenization, pre-heating and an extrusion processes are necessary. Recently a new DC casting process of near net shaped ingot (beam blank ingot), which aimed to reduce the manufacturing cost of suspension, was proposed [1, 2]. Since the shape of the near net shaped billet is complicated than usual round billet, many troubles in the casting are originated from the ingot shape. For example, the peculiar problems such as the surface crack and the mold grasped by solidifying billet, which led to the interruption of casting, resulted from the complicate shape and casting conditions. The mechanism of these peculiar phenomena had not yet been clarified. In this study, a coupled flow, solidification and thermal deformation FEM analysis and casting experiments of near net shaped semi-continuously cast billet were carried out in order to clarify the peculiar problems. By comparing the calculated results with the experimental ones, the cause of the surface crack and the mold grasped by the solidifying billet during was clarified.

2. Casting experiment

The material used in this study was the high-strength Al-Mg-Si alloy improved from AA6061 and the chemical composition of the alloy was shown; 1.00% Si, 0.18% Fe, 0.40% Cu, 0.83% Mg, 0.37% Mn, 0.27% Cr, 0.02% Ti and remaining of Aluminum. The alloy was cast by a lab-scale DC casting machine using the hot-top method. The schematic shape of mold used in this experiment is shown in Figure 1 and the casting conditions were shown as follows; Casting temperature of 720 °C, Casting speed of 85-110 mm/min, Water supply of 150-200 l/min.

3. Analytical method

3.1 Flow and solidification analysis

In this analysis, the followings were carried out; a coupled flow, solidification and thermal deformation FEM analysis. The geometry used in the study of flow and solidification analysis is as shown in Fig. 1. The calculation domain includes billet, mold and bottom block, where the casting length is 500 mm. The flow and solidification analysis was calculated using a commercial solidification software package of CAPFLOW. Enthalpy method was used to analyze the latent heat evolution of solidification. The temperature dependency of density, specific heat and thermal conductivity were measured. The physical properties and thermal boundary conditions used in the calculation were cited in [3].

3.2 Thermal stress analysis

In this study, thermal stress during casting was calculated by a commercial structure analysis package, ANSYS. The thermal histories obtained from the CAPFLOW were used as input data to an elasto-plasticity model which simulated the thermal stress and distortion of the billet. The calculation domain included the billet, mold and bottom block, where mold and bottom block were assumed to be as a rigid body and their thermal distortion was not considered. In order to simulate the thermal
distortion of the billet the element type was employed for a large deformation element called as SOLID 45. The effect of friction forces which happened between the billet and the bottom block and also between the billet and the mold, was considered by using the contact element called as SURFACE CONTACT 169 and 171, and the friction coefficient was set to 0.1. A multi-linear isotropic work-hardening law was determined to fit the experimental data. Von Mises criterion law determined the yield criterions. Young’s modulus, linear expansion coefficient and the work-hardening were considered as a function of the temperature and these values were obtained by experiment as shown later. In the solid-liquid coexistence region, an average linear expansion coefficient was estimated from a volumetric shrinkage percentage of 6%.

4 Thermal properties
Specific heat of this alloy, thermal diffusivity and linear expansion coefficient were measured from room temperature to 600 or 700 °C. Solidus temperature (580 °C), liquidus temperature (654 °C) and the equilibrium solidification temperature range (74 °C) of the alloy were obtained by specific heat curve [4]. Density and conductivity at each temperature was calculated from these data. The relation between fraction solid and temperature was calculated by the Gulliver-Scheil model using the thermodynamic software, Thermo-Calc.

5 Tensile testing during solidification
In this study, tensile test from room temperature to solid-liquid coexistence region was carried out by using the high temperature tensile test equipment with induction heating. At first, the specimen was heated up to temperature above its liquidus temperature, and then kept for a certain period of time. Next, it was cooled down to the test temperature at cooling rate 1 °C/s. By this means, a solidification structure was obtained. Finally, tensile load was applied at strain rate 10^{-2} s^{-1} and the load-displacement was recorded. Apparent Young’s modulus with high temperature was evaluated from each true stress vs strain curve.

Figure 2 shows the relationship between tensile strength and temperature. The tensile strength decreases with the temperature increase. When the temperature reached 625 °C, the value of tensile strength became zero, so the temperature 625 °C is ZST (Zero Strength Temperature) of this alloy at which corresponding solid fraction is 0.74.

Figure 2. Tensile strength versus temperature

6. Results and discussion
6.1 Casting experimental results
Typical fracture occurrence position of the billet is shown in RHS of Figure 3. The cracks are well generated at D, E and F position of the billet as shown in Fig. 3, and the cracks are generated on the surface and then propagate inside the billet. These cracks are different from the round billet cracks which occur in the center of the billet [5-6] and here we call the crack of the near net shaped billet as surface cracks. Fig. 3 also indicates the fractured SEM images. The fractured surfaces of the shaped billet have a rupture structure where intergranular fractures with remaining liquid around interdendritic regions were observed, namely internal crack occurs in the solid/liquid coexisting ( mushy) state above the solidus.

Figure 3. Crack occurrence position and SEM image of the fracture surfaces at position D

6.2 Distortion profile
The comparison of cast and calculated profiles of the billet with designed mold shape is shown in Figure 4. The distortion profile of cast billet agrees well with the calculated ones. Both legs were shifted inside by the solidification contraction. A neck falling phenomenon due to solidification shrinkage is observed. A comparison between calculated and cast butt-curls was made. The calculated value of but-curl (14 mm) agreed well with the cast result (13 mm). Therefore it is considered that this thermomechanical modeling in this study is appropriate from the comparison between cast and calculated distortion of the shaped billet.

Figure 4. Comparison of cast and calculated profile of the billet with designed mold shape

6.3 Mechanism of surface crack
Figure 5 shows the distribution of plastic strain along X and Y directions obtained from thermal distortion calculation at start-up state. It is easily understood for
crack to generate at the D position since the tensile strain of the X direction concentrates in the D position as shown in Fig. 5(a). It is the reason why both legs were shifted inside and contacted with the mold by the solidification shrinkage. Consequently the reaction forces by the mold are generated and the D position receives the tensile stress. It is also likely to generate the cracks at E and F positions because the tensile strain of Y direction concentrate in the E and F positions. A neck falling phenomenon occurred and then the billet contacted to the mold due to solidification shrinkage as shown in Fig. 5, so the reaction force by the mold is generated. As a result, the cracks become easy to be generated since E and F divisions receive the tensile stress. Crack initiation position predicted by the thermal stress analysis reproduced well the real casting result.

6.4 Cause of the mold grasped
The mold grasped by the billet is a peculiar phenomenon that always occurs in the near net shaped billet casting. When the phenomenon occurred, the billet did not move down with bottom block because the mold was clipped by the billet. Figure 6 indicates the distribution of temperature in the cross section of the billet, (a), and the contact situation between the billet and mold, (b) and (c). The solidification is uneven at each location of the billet as shown in Fig. 6(a). Solidification had finished in the areas such as two legs and the neck areas, but the solidification had not yet finished in the center area. The contraction during solidification forced the two legs to shift toward the mold due to the uneven solidification. The mold, hence, is grasped by the billet and so the contact pressure between the billet and mold is generated as shown in Fig. 6(b), (c). It is considered that the phenomenon of the mold grasped by the billet occurs when the contact pressure becomes bigger and exceeds the drawing force applied in the bottom block.

7. Conclusions
A coupled flow and solidification and thermal deformation FEM analysis and casting experiment of near net shaped semi-continuously cast billet were carried out. The causes of the peculiar problems such as the surface crack and the mold grasped by shaped ingot were clarified. The main results are given as follows:
1) The cracks of irregular shaped billet are different from the ones of round billet. They are generated on the surface and then propagate inside the billet. The fractured surfaces of the shaped billet have a rupture structure where intergranular fractures with remaining liquid around interdendritic regions are observed, namely internal crack occurs in the solid/liquid coexisting (mushy) state above the solidus.
2) The surface crack of the near net shape billet is originated from the reaction force which arises by contacting the mold by the distortion of the solidifying billet.
3) The phenomenon of the mold grasped by the billet occurs when the contact pressure becomes bigger and exceeds the drawing force applied in the bottom block.

8. Reference

Figure 5. Distribution of plastic strain along X and Y directions at start-up state

Figure 6. Distribution of temperature in the billet and contact situation between billet and mold