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Studies on Press-forming of Aluminum Alloys in the Coexisting State of Liquid and Solid

(3rd Report. Mechanical Properties of
Injection-formed Aluminum Alloys)*

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This investigation has been performed in order to examine if it is possible to fill the die cavity with aluminum alloy through a nozzle and to examine the mechanical characteristics of the injected and formed products.

It is clear that it is possible to fill the die cavity with an alloy and form the products when the die temperature is equal to the temperature under coexisting state of liquid and solid of the alloy. The tensile strength of the products becomes maximum when the die temperature is fixed in the middle of the temperature range under coexisting state of liquid and solid. The filling-up process of a billet is as follows. The billet is injected through a nozzle in the shape of a bar and after reaching the top inside the die it flows and spreads down along the wall and the following billet fills the center part.

1. Introduction

The previous reports have shown that the products pressed¹⁾ and extruded²⁾ within the range between the solidifying temperature and the liquidizing temperature have superior mechanical properties.

In this report, the injection-forming method under the coexisting state of liquid and solid is examined from the viewpoint of manufacturing products of specific forms. That is, the method in which the alloy in the coexisting state of liquid and solid is injected and poured into a die cavity through a small nozzle and then molded to a specific form, is proved feasible with respect to the shape, the microstructure and the mechanical properties. Squeezing an alloy of the coexisting state of liquid and solid through a nozzle is necessitated to break a rough structure, set up a fine structure and to fill up a die cavity uniformly with the material.

As similar injection-forming methods, there are available an injection mold method and a die casting method. The former has been used only for plastic material and not used for metallic material. The latter can not be free from gas holes because a melting material is used, so it is difficult not only to get superior mechanical properties but also thick products.

2. Experimental Apparatus and Experimental Methods

Fig. 1 shows the main system of an injection-forming machine which has been partly improved from the one reported in the previous paper¹⁾. It has not only a die cavity and a container but also a nozzle. A billet is heated inside the container, injected through the nozzle and poured into the die cavity by the plunger. Fig. 2 shows the dimensions of the die cavity, the nozzle and the container. Those parts are

Fig.1 The structure of the injection-forming machine.

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made of SKD4 of HRC58. The size of billets is 10mm in diameter and 60mm in length.

A furnace is attached around the die, the nozzle and the container. Those parts and the billet are heated to a specific temperature. The dies temperature is measured at the point (a) inside the die shown in Fig. 3. Fig. 3 also shows each temperature inside the die and the billet when temperature at the point (a) reaches 600°C. The billet temperature is 587~592°C which is about 10°C lower than that at the point (a).

Table 1 shows the chemical composition of the billets used. Table 2 shows the solidifying temperature and the liquidizing temperature of the billets measured by a thermal analysis method. There appear two solid phases, i.e., α phase and β phase when the temperature of Al-4Cu-20Si alloy is at solidifying point. The billet is put into the container and kept for 30 minutes after the die and the container are heated to the specific temperature. Then it is pushed out of the container in to the die cavity through the nozzle by the plunger. The plunger speed is about 2 cm/s and it takes 3~4 seconds to fill up the die cavity. Fig. 4 shows the relation between

Fig. 2 The shapes of the die cavity, the nozzle and the container.

Fig. 3 Temperature distribution of the die cavity and the container.

the temperature curve of the die and the pressure. Even after the filling-up is finished, pressing is continued until the die temperature falls to 120°C, then the injection-formed product is taken out.

The relation between the plunger stroke and the extruding pressure to push a billet in to the die cavity out of the container is examined. In order to determine a suitable range of the die temperatures at which the product of a fine shape can be formed, injection-forming is performed at three dies temperatures; the temperature within the range between the solidifying temperature and the liquidizing temperature, the one slightly higher than that and the one slightly lower than that.

The tensile strength and the elongation are measured with test pieces shown in Fig. 5 which are cut out from the formed products. Five products are made in all to measure the tensile strength and the elongation, and the average value of the products except two values of maximum and minimum is calculated. The stress-strain diagrams and the plunger stroke-extruding pressure curves are adopted only when their tendencies are moderate. Microstructures are observed at the vertical sections of the products etched with 0.5 % HF solvent. These measurements and observations are performed after 7~8 days since the injection-formed products are obtained.

Table 1. The chemical component of the billets used

Name	Cu	Si	Fe
Al-4Cu	3.93	<0.01	0.17
Al-4Cu-20Si	4.08	19.77	0.17

Table 2. The melting point of the billets used

Name	Liquidizing Temperature °C	Solidifying Temperature °C
Al-4Cu	648	580
Al-4Cu-20Si	570	529

Fig. 4 The relation between the die temperature and the pressure.

3. Results and Considerations

Appearances of the products formed at intervals of 10°C of the die temperature are generally divided into three types as Fig. 6(a), (b) and (c) show. (a) is produced at low die temperature. This product proves to be unsatisfactory as the die cavity can not be filled up with material. The die temperatures are 560°C and 570°C in case of Al-4Cu alloy and 500°C and 510°C in case of Al-4Cu-20Si alloy. The extruding pressure is not large enough to fill up the die cavity in these low ranges of temperatures.

(c) is produced at rather high die temperatures. This product proves to be unsatisfactory as the surface of the product becomes rough. These temperatures are 630°C and 640°C in case of Al-4Cu-20Si alloy. In these high ranges of temperatures, the billet absorbs gas so much that gas holes appear on the surface during cooling although the die cavity is easily filled up with material.

The last one (b) is produced at the middle temperatures between the above two. This product proves to be satisfactory as not only the die cavity can be filled up with material but also the surface of the product becomes smooth. These temperatures are 580°C and 620°C in case of Al-4Cu-20Si alloy, which almost fall in the range between solidifying temperature and liquidizing temperature of each alloy. Thus it is concluded that only the injection-forming in the coexisting state of liquid and solid can produce fine products. Fig. 6 shows the case of Al-4Cu-20Si alloy, (a) being at 500°C , (b) at 540°C and (c) at 570°C .

Vertical sections of these satisfactory and unsatisfactory Al-4Cu-20Si alloy

Fig.5 The shape of the specimen for the tensile test.

Fig.6 Appearances of the injection-formed products.

products are observed, as shown in Fig. 7. (a) is a photo of the product formed at high die temperature, whose surface is rough with gas holes found inside. (b) is a photo of the product formed at the die temperature between the solidifying temperature and the liquidizing temperature, whose surface is smooth with no pin hole and no blow hole inside. A product formed at low temperature has a rough surface because the die cavity can not be filled up, although no gas hole appears on the vertical section of the extruded bar. Observational results on Al-4Cu alloy are found to be the same as those of Al-4Cu-20Si alloy.

By observing the metallic structure of Al-4Cu alloy products, an interesting structure can be seen in the products formed at 610°C and 620°C which are relatively high temperatures in the range where desirable products can be obtained. This structure seems to explain the process in which the die cavity is gradually filled with a billet. Fig. 8 shows the macrostructure of the product formed at 620°C . Fig. 9 shows a photo of high magnification of the same product. Fig. 9(a) corresponding to the gray part contacting the inside wall of die cavity in Fig. 8 shows a billet injected at the beginning of filling-up process. This part is composed of dendrite phase wrapped by eutectic of α phase and CuAl_2 phase. Fig. 9(b) corresponding to the middle part which looks like a tree in Fig. 8 shows a billet injected later. This part consists of α phase. The reason why the structures of the center part and circumference are different is supposed to lie in the difference of cooling speed. The circumference of dendrite structure has been cooled relatively fast, but the center part of α phase has been cooled slowly.

This microstructure and Fig. 6(a) suggest the following filling-up process. A billet is injected through a nozzle in the shape of a bar. After the top of the bar reaches the top of the die cavity, the material moves along the inside wall without rolling in a succeeding material until all the die cavity is filled up. At this time, the part along the inside wall cooled com-

a) die temperature : 580°C .

b) die temperature ; 550°C .

Fig.7 Vertical section of the formed products of Al-4Cu-20Si alloy.

paratively rapidly becomes a dendrite structure. The center part cooled rather slowly becomes α phase. The boundary of the two phases becomes a firmly united metallic structure as shown in Fig. 9(c).

Products formed at 580°C, 590°C and 600°C which are relatively low temperatures within the range where good products are gained do not have such a dendrite structure as found in Fig. 8. All the parts of them are α phase, so discrimination between the parts injected earlier and later is not easy. But a more precise observation to discriminate the two kinds of phases gives Fig. 10. Fig. 10(a) shows a part injected later which is made of α phase relatively uniform in its crystal size. It suggests that the material exists in the same state as the state just after injecting. Fig. 10

Fig. 8 Macrostructure of the product of Al-4Cu alloy formed at the die temperature of 620°C.

Fig. 9 The photos of high magnification of Fig. 8.

Fig. 10 Microstructure of the product of Al-4Cu alloy formed at the die temperature of 600°C.

(b) is a part injected at the beginning which is made of α phase irregular in its crystal size. It suggests that the material fills the die cavity while being stirred. The products of Al-4Cu-20Si alloy have structures with silicon extensively distributed. Therefore the filling-up process can not be traced by microstructure in this case.

Fig. 11 shows the relation between the plunger stroke and the extruding pressure. The extruding pressure increases with plunger movement and gradually decreases after reaching maximum in any kind of alloy. It increases again in case of low die temperature.

The extruding pressure curve shows that there are irregular points on plunger strokes of 1.7, 5.7, 11.5 and 50.0 mm. In order to find the positions of plunger stroke which bring about irregular pressures, four plunger strokes are calculated. They are the stroke when the billet reaches the edge of the nozzle, the one when the billet fills up the nozzle, the one when the billet reaches the top inside the die cavity on the assumption that the billet injected reaches straight the top of the die cavity and the one when the billet fills up the die cavity. The calculated values are 1.6, 5.5, 11.3 and 49.7mm, which are almost equal to the measured plunger

strokes.

The extruding pressure fluctuates when the plunger comes to the above four positions. These irregular points are not found on Al-4Cu alloy and Al-4Cu-20Si alloy formed at relatively high die temperatures.

Examination of the extruding pressure curves on the assumption that the extruding pressure is the sum of four factors; a friction between the billet and the container, a deformation resistance of the billet at the nozzle, a friction between the billet and the dies, and a pressing force to fill the die cavity with material, suggests that the maximum extruding pres-

sure occurs when the billet fills up the nozzle as well as the die cavity. If this idea is applied to the extruding pressure curves, it is found that the maximum extruding pressure in case of Al-4Cu-20Si alloy formed at 580°C and 600°C occurs when the billet fills up the die cavity. But the maximum extruding pressure scarcely occurs at the authors' hypothetical points. This may be caused by the complex frictions among the billet, the nozzle and the die, and also by the fact that the extruding pressure begins to increase before the die cavity is filled with material.

Fig. 12 shows the stress-strain dia-

Fig.11 The relation between the plunger stroke and the extruding pressure.

Fig.12 The stress-strain diagrams of the formed products.

Fig.13 The relation between the tensile strength and elongation of the formed products and the die temperature.

grams of the formed products. Though the tensile strength of Al-4Cu products is not so high as compared with that of the cast product, the elongation is remarkably large. This is caused by the fact that the products have a structure of a phase with fine intermetallic compound CuAl_2 distributed. On the other hand the elongation of Al-4Cu-20Si products is not so large, but its tensile strength is remarkably large. This is caused by the fact that proeutectic silicon becomes minute.

Fig. 13 is obtained by rewriting Fig. 12 in order to examine the influence of the die temperature on the tensile strength and the elongation. The tensile strength of both alloys increases with an increase of the die temperature and begins to decrease after reaching maximum. The die temperature when the tensile strength becomes maximum is 590°C in case of Al-4Cu-20Si alloy. The phenomenon that the tensile strength becomes maximum at the middle temperature between the solidifying temperature and the liquidizing temperature is also seen in the extruded products²⁾.

4. Conclusions

The results obtained are as follows.

- 1) It is clear that it is possible to fill the die cavity with alloy and form the products when the die temperature is equal to the temperature under the coexisting state of liquid and solid of alloy.
- 2) The tensile strength of the products becomes maximum when the die temperature is fixed in the middle of the temperature range under the coexisting state of liquid and solid.
- 3) The filling-up process of the billet is as follows. The billet is injected through a nozzle in the shape of a bar and after reaching the top inside the die cavity, it flows and spreads down along the wall and the following billet fills the center part.

References

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