Effects of Die Angles on Pressure Distribution of Die Block Surfaces and Extrudability in Hot Extrusion

By Mitsugu Tokizawa and Norio Takatsuji

The effect of die angles has been investigated by means of metallographic observation and visio-plasticity analysis in order to optimize the design of the hot extrusion die. In addition, the distribution of pressure acting on the surface of the die block has been evaluated through the analysis of the output of high-temperature strain gage attached to the external surface of the die block. The flat die of 90° die semi-angle brings about the lowest extrusion pressure of all dies. For the 90° die semi-angle, the flow speed under the same ram load is larger than that for any other semi-angles, and the best extrudability is attained. For the die semi-angle smaller than 90°, the metal flow becomes more parallel with the die surface and is suppressed more easily by the sliding friction with the die surface, the flow speed decreases under the same ram load and the internal sliding friction also results in lower extrudability. The highest pressure acts on the bearing part for every die semi-angle. As the die semi-angle becomes larger, the pressure acting on the bearing tends to decrease. For the 90° die, the pressure becomes about 60% of that for the 45° die. A comprehensive examination of the optimum die semi-angle shows clearly that the 90° die is most suitable for hot extrusion in terms of extrudability and die performance.

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I. Introduction

In extrusion, the die block is subjected to very high pressure because the billet is pressed against the die block in the container. In order to optimize the design of the die for lower extrusion pressure and longer life, the effect of the die angle on extrudability and pressure distribution on the surface of the die block should be investigated. For example, Saga et al. carried out an approximate analysis of the pressure distribution in cold backward extrusion of aluminum. In this case, they analytical solution of the relationship between circumferential strain at the external surface of the extrusion container and the pressure distribution acting on the container wall, where the container was regarded as a hollow cylinder. There have been other reports on the methods of scattered-light photoelasticity and pressure pin. These reports, however, deal with cold backward extrusion with particular emphasis on the die design. Only a few reports discuss the hot workability with respect to extrudability which means the extruding speed at a given extruding load. Difficulties in studying hot extrudability, compared with cold working, come from the complicated nature of the effect of frictional stress between the tool and the material surface and the lack of knowledge about the temperature distribution. In addition, the upper limit temperature of strain gages to measure stresses is about 573 K because of errors in the measurement caused by incorrect sticking of foil strain gages.

With respect to the study on mechanics of extrusion, Kudo et al. analyzed the relationship between die angle and extrusion pressure in cold extrusion by using the slip line method, and obtained an optimum die semi-angle for minimizing the extrusion pressure. Altan et al. discussed the characteristics of hot extrusion of both copper and steel as a function of ram speed, extrusion ratio, die angle, etc. based on the analysis of the flow line, strain rate and strain distribution. No mention, however, is made of the relationship between the extrusion pressure and die angle.

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In this report, therefore, the effect of the die angle on the extrusion pressure and the flow speed of extrusion material has been investigated by means of metallographic observation and visio-plasticity analysis in order to optimize the die semi-angle in hot extrusion of an aluminum alloy and a 22 mass%Al-Zn alloy. Also, the effect of die angle on the distribution of pressure acting on the surface of the die block has been evaluated by using numerical analysis of the output of a high-temperature strain gage attached to the external surface of the die block. And the design for hot extrusion die is optimized in terms of extrudability and die performance.

II. Experimental

1. Experimental materials and extrusion method

Materials used for the experiment contain aluminum 6063 alloy treated for homogenization by 833 K-10.8 ks, 7003 alloy homogenized by 803 K-28.8 ks and Zn-22 mass%Al eutectoid alloy held for 180 ks at 623-653 K and then water quenched. The materials are machined to cylindrical billets of ø60 mm × 80 mm. Tables 1 and 2 show the chemical composition and the extrusion conditions for each material, respectively.

The experimental apparatus for hot extrusion, shown in Fig. 1, is composed of the alloy tool steel for hot working. The apparatus is heated to a temperature about 20 K higher than the working temperature in the electric furnace or the convection type constant temperature oven while the temperature with thermocouples is measured, and the billet is extruded by using a 980 kN(100 tf) or 3920 kN hydraulic press. For this extrusion of the hydraulic press, constant ram speed and constant extrusion pressure are applied. In the former condition, the extrusion pressure and the circumferential strain on the external surface of the die block are measured. In the latter, the mean extrusion speed of the extruded material under working is measured. Lubricants are not used because their effect cannot be retained except at the beginning of working.

2. Visio-plasticity analysis

The visio-plasticity analysis is applied to obtain the effective strain rate contour (\(\dot{e}\)) chart in order to quantitatively study the metal flow in the billet. First a composite billet, divided at

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**Table 1 Chemical composition of billet.**

| Alloy     | Mg  | Si  | Fe  | Cu  | Zn  | Al   | Heat treatment          |
|-----------|-----|-----|-----|-----|-----|------|-------------------------|
| 6063      | 0.52| 0.42| 0.22| 0.00| 0.00| bal. | 833 K-10.8 ks A.C.       |
| 7003      | 0.78| 0.04| 0.14| 0.15| 5.76| bal. | 803 K-28.8 ks A.C.       |
| Zn-22 mass%Al | —  | 0.00| 0.00| 0.00| bal.| 22.0 | 623 K-180 ks W.Q.        |

**Table 2 Extrusion conditions.**

| Billet      | Extrusion ratio | Ram speed mm·s⁻¹ | Extrusion temperature |
|-------------|-----------------|------------------|-----------------------|
| 6063        | 36              | 1.5              | 773 K                 |
| 7003        | 36              | 1.5              | 773 K                 |
| Zn-22 mass%Al | 36            | 1.1              | 523 K                 |

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the meridian plane, is preliminarily extruded by a stroke of 50 mm while establishing a stationary extruding status. The discard is divided at the meridian plane, and the grid lines are then machined at 3 mm intervals on one surface. Next, a composite billet, coated thinly with the lubricant on the meridian plane in such a degree that the lubricant does not exude to the side face of the billet, is extruded in a stroke of 2 mm, divided again, and then cleaned. The deformation of the grids is measured using a projector and compared to the original forms before the working. The details of measuring the grid deformation and determining the effective strain rate contour chart have been given in the previous report(8).

3. Measurement of pressure acting on surface of die block

At present, it is very difficult to find a high-temperature strain gage which can meet the requirement for the measurement of hot extrusion temperatures of aluminum alloys, above 673 K. Therefore, in the present work the Zn-22 mass%Al eutectoid alloy is used for the billet material to simulate the aluminum alloy in terms of both the metal flow characteristics of the internal shearing deformation type and the extrudability at about 523 K. The high-temperature strain gage of KYOWA (KFA-2-D21-16) is stuck on the external surface of the die block. The pressure distribution acting on the surface of the die block is measured experimentally from the calibration curves obtained by the strain gage method described above.

Figure 2 shows the die block used for the experiment in the die semi-angle range of 45° to 90°. An orifice diameter of 10 mm (extrusion ratio 36) and a bearing length of 2 mm are maintained constant. In addition, the container and the die block are integrated into one body with a constant distance of 45 mm from the die surface to the splicing surface, in order to have the same effects of the splicing surfaces. The high-temperature strain gages are at-

![Fig. 2 Extrusion die block.](image-url)
Effects of Die Angles on Pressure Distribution of Die Block Surfaces and Extrudability in Hot Extrusion

Attached to the six positions shown in Fig. 2. Strain gage 6 is attached to the external surface of the die block at the bearing position for each die block. Strain gage 4 is stuck at the external surface of the die corner for the 45°, 60° and 75° dies. The 3 lines type active gage method is applied to detecting the circumferential strain on the external surface of the die block during hot extrusion. The strain is amplified by the Strain Meter made by SHINKOH (DSA-605-C) under ram strokes and extruding pressure and recorded with the Multicorder made by GRAPHTEC (MC6800(B)-6) simultaneously. The calibration curves of the circumferential strains and the compression pressure acting on the surface of the die block are drawn as follows. The orifice of the experimental die, shown in Fig. 2, is hermetically sealed with a plug, then the plasticine is charged in the die block in various quantities and compressed with the 294 kN Amsler universal testing machine. The circumferential strains on the external surface of die block during the stepwise extrusion process and the compression pressure are measured. Figure 3 shows an example of the calibration curves for each strain gage with the 90° die.

III. Results of Experiment and Discussions

1. Effect of die angle on extrusion pressure and flow speed of extrusion material

Figure 4 shows the effect of the die angle on the extrusion pressure for hot extrusion of 6063, 7003 and Zn–22 mass%Al eutectoid alloys. In all the pressure curves the flat die with a 90° die semi-angle shows the lowest required extrusion pressure. In cases of smaller die semi-angles, an upward trend in the extrusion pressure is observed. Even for the 105° die, the same upward trend is revealed though the result is not shown in the figure. For the Zn–22 mass%Al alloy, the experiment becomes impracticable because the die surface is removed in the extrusion direction.

Figure 5 indicates the effect of die angle on the flow speed of extrusion material when each sample is extruded under a constant pressure. When the alloy is extruded at an extruding pressure of 245 MPa (extrusion force 686 kN),
the 90° die brings about the largest flow speed of extrusion material of all alloys. With the reduction in the die semi-angle, the flow speed of the extrusion material tends to decrease.

It may be concluded, therefore, that the 90° die shows the best extrudability with low extrusion pressure and large flow of extrusion material compared with other dies. Consequently, the reasons for this result are examined referring to the metal flow on the meridian plane of the discard after completion of extruding.

Figure 6 shows the effective strain rate contour obtained from the grid line analysis in the hot extrusion of 6063 alloy. An inner zone, encircled by the boundary line of an effective strain rate $\varepsilon = 0$, represents the plastic deformation zone approximately. For the 90° die, this zone extends to a considerable extent exhibiting a metal flow spreading around the die orifice covering the die surface and the vertical axis. For the 45° die, on the other hand, the metal flow becomes narrower along the die surface with a longer length of sliding friction $D_l$ on the die surface than that for the 90° die. The high strain rate zone of $\varepsilon = 2.0$ or more is concentrated in the die orifice for both 45° and 90° dies. However, for the 45° die, the metal flow from the center axis is more dominant while the metal flow near the die surface is suppressed. For the 90° die, there is a significant flow along the die surface with uniform metal flows in all directions from the center axis to the die surface.

Figure 7 shows the macro-structure of the meridian plane in discard of each alloy. For 6063 and 7003 alloys, etching with aqua regia is applied, while the etching liquid of 20% nitric acid dripped with 1~2% ammonia water is used for the Zn-22 mass%Al eutectoid alloy. For either alloy, the metal flow can be divided
Effects of Die Angles on Pressure Distribution of Die Block Surfaces and Extrudability in Hot Extrusion

6063 alloy

45° die  
90° die

(a) Schematic representation of shearing deformation region.

(b) Effect of die semi-angle on $S_L$ and $D_L$ shown in (a)

7003 alloy  Zn–22mass%Al

Fig. 7 Effect of die semi-angle on plastic flow observed from macrostructure.

Fig. 8 Effect of die semi-angle on plastic flow of material during hot extrusion.

8(b) compares metal flows as a function of die angle, with the parameters of the length of internal shearing deformation $S_L$ and sliding friction length $D_L$ on the die surface as shown in Fig. 8(a). $S_L$ and $D_L$ tend to decrease where the die semi-angle becomes larger for each alloy. Therefore, the better extrudability for the 90° die might come from reduced frictional resis-
2. Effect of die angle on pressure distribution acting on die block

Figures 9 and 10 show the relationship between circumferential strain and ram displacement with the 90° and 45° dies, obtained from the model experiment for the Zn-22 mass%Al eutectoid alloy extruded at 523 K. Referring to strain curves 1 – 4 with the 90° die shown in Fig. 9, the circumferential strain increases abruptly at the beginning of extrusion and reaches a peak at the ram stroke \( S_t \) of about 8 mm. Then, the strains remain almost unchanged up to about \( S_t = 40 \) mm, but decrease abruptly when the dummy block passes the position of each strain gage attached. In strain curves 5 and 6 for the gages attached to the external surface of the die block in the dead metal zone and the bearing position, the circumferential strains show a sudden increase similar to those in 1 – 4 from the beginning to \( S_t = 8 \) mm and then tend to increase gradually. Therefore, a large strain is created near the bearing part of the die orifice at the end of extrusion period. On the contrary, the strain in the dummy block side becomes smaller. For the 45° die shown in Fig. 9, the trends of the strain curves are similar to those with the 90° die. The circumferential strains on the die surface and the bearing position, as shown in strain curves 4 – 6, increase gradually as extrusion proceeds. For the 90° die, the strain reaches a peak after the material is filled in the die block. For the 45° die, on the other hand, the material becomes full after the strain reaches a peak. These phenomena are explained as follows. The metal flow for the 90° die, such as internal shearing, is formed after the die block is filled with the material and extrusion material comes out of the die orifice. For the 45° die, on the contrary, the metal flow is created when the material is filled in the die block while the material is flowing into the nose.

From the above strain curves and the calibration curves of Fig. 3, the pressure distribution in each die can be obtained. Typically, the curves of the 90° and 45° dies are shown in Figs. 11 and 12, respectively. For the 90° die of Fig. 11, the pressures in the die \( P_1 \sim P_6 \), with the die filled at ram stroke \( S_t = 5 \) mm, are about
Fig. 10 Circumferential strain distribution in extrusion of Zn–22 mass% Al alloy with 45° die block.

Fig. 11 Pressure distribution acting on surface of die block in extrusion of Zn–22 mass% Al alloy with 90° die block.
100 MPa, and are substantially uniform in the die block. The pressure acting on the surface of the die block, in the intermediate period of extrusion namely $S_r = 43$–60 mm, becomes higher than initial $S_r = 5$ mm, namely at about 300 MPa uniformly in $P_1$–$P_4$. However, the pressure tends to increase in the range of $P_4$, the forming position of dead metal, to the bearing position $P_6$. In particular, $P_6$ reaches the highest pressure acting on the surface of the die block, about 500 MPa. However, the distribution of pressure acting on the surface of the die block does not substantially change with different extrusion strokes, exhibiting approximately the same values. Consequently, it is understood that the extrusion conditions remain in a stationary state. At the end of the extrusion period, $S_r = 70$–75 mm, the pressure acting on the surface of the die block decreases in the range of $P_1$–$P_4$ as the dummy block passes. However, the pressure acting on the surface of the die block remains almost unchanged in the range of $P_3$–$P_6$, near the die orifice, same as the values during the intermediate period of extrusion. The highest pressure acting on the surface of die block is recorded at $P_6$, the bearing position. On the other hand, the general tendency of the pressure distribution acting on the 45° die is substantially the same as that for the 90° die, as shown in Fig. 12. However, it is a difference between 90° and 45° dies that the shape of pressure distribution acting on the 45° die at the die-full position ($S_r = 19$ mm) becomes similar to that in the intermediate period of extrusion ($S_r = 43$–60 mm). These phenomena could be explained as follows. For the 45° die, when the die block is filled with the material, the material flows into the nose forming a deformation zone shown in Fig. 7. Thus, the metal flow already becomes such a stationary state as in the intermediate extrusion period.

Fig. 12 Pressure distribution acting on the die block surface in extrusion of Zn–22 mass% Al alloy with 45° die block.
As can be understood from the above, a very high pressure applies to the vicinity of the die orifice in the stationary extrusion condition. In the examination of die strength the most important factor is the pressure acting on the bearing surface. From this point of view, the pressure $P_6$ acting on the bearing surface is shown in Fig. 13 as a function of die angle in the range of $S_t = 43$–75 mm. For the $45^\circ$ die, a pressure of about 800 MPa occurs. With the increase in die semi-angle, the pressure acting on the bearing surface tends to decrease. The $90^\circ$ die receives a pressure of about 500 MPa. Consequently, the pressure acting on the surface of the $90^\circ$ die is about 60% of that of the $45^\circ$ die.

### IV. Conclusions

The effect of die angle has been investigated by means of metallographic observation and viso-plasticity analysis in order to optimize the design for the hot extrusion die. In addition, the distribution of the pressure acting on the surface of the die block has been evaluated by means of numerical analysis of the output of the high-temperature strain gage attached to the external surface of the die block. As a result, the following conclusions have been obtained.

1. The flat die with a $90^\circ$ die semi-angle brings about the lowest extrusion pressure among all dies. For the $90^\circ$ die semi-angle, the flow speed under the same ram load is larger than that for any other semi-angle, and the best extrudability is attained.

2. The macrostructure and the effective strain rate contour are examined in view of metallographic changes. For a die semi-angle smaller than $90^\circ$, the metal flow becomes more parallel with the die surface, and is suppressed more easily by the sliding friction with the die surface. Accordingly, the flow speed decreases under the same ram load, and the internal sliding friction also results in the lowering of extrudability.

3. The highest pressure acts on the bearing part for every semi-angle. As the die semi-angle becomes larger, the pressure acting on the bearing tends to decrease. For the $90^\circ$ die, the pressure becomes about 60% of that for the $45^\circ$ die.

4. By the comprehensive examination of the optimum die semi-angle, the $90^\circ$ (flat) die is concluded to be the most suitable for hot extrusion in terms of extrudability and die performance.

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