Measurement of Coefficient of Friction under Bulk Plastic Deformation by Using Plane Strain Extrusion Apparatus with Plane Plate Tool and Taper Die

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A series of experiment to measure coefficient of friction under bulk plastic deformation in plane strain extrusion was carried out by using the apparatus in which a taper die and a plane plate tool were arranged in facing each other. The plane plate tool had detection part of the normal and frictional forces acting on the tool surface so that coefficient of friction could be measured. Conditions of frictional constraint on the surface of plane plate tool were changed by applying the lubricant with high viscosity or lubricant with low viscosity. While, lubricant applied to the other contact surfaces with billet such as the surfaces of taper die and sidewall was fixed to one kind. Billet was made of Aluminum (A1050-JIS) and the extrusion apparatus was made of SKD-11-JIS. Then, the values of coefficient of friction were measured and surface conditions of a billet were investigated on the plane plate tool side. Differences of the conditions of material flow and effective strain in whole area of deformation zone of a billet, which were affected with different frictional constraint on the surface of plane plate, were also investigated by carrying out the visioplasticy analysis.

Keywords: coefficient of friction, plastic deformation, plastic flow, visioplasticy method, extrusion

1. Introduction

The conditions of surface of a product and plastic flow of a work-piece sliding on the surface of a tool are affected with frictional constraint in a metal forming process. Reduction of frictional constraint leads to decrease of forming load and elongation of tool life. Therefore, an appropriate lubricant is applied to the surface of a tool in contact with a work-piece to achieve preferable forming condition in many cold and hot metal forming processes.

Frictional constraint is represented by the equation; i.e., frictional force equals to normal force acting to the tool surface multiplied by coefficient of friction. Some sensors have been developed to measure frictional force in a metal forming process such as rolling and extrusion. The pin-type sensor was used in rolling by G. T. van Rooyen et al. [1]. Yoneyama et al. [2] developed the friction sensor in extrusion apparatus, in which the strain due to friction force appeared on the surface of bottom thin plate, was measured by the strain gauges and related to FEM analysis. Kawai et al. [3] and Nakamura et al. [4] developed the testing method to analyze seizure phenomenon under the friction condition.

The authors had developed the plane strain extrusion apparatus with plane plate tool and taper die, and the effects of frictional constraint at the lubricated surface of plane plate tool on the extrusion load and deformation conditions such as plastic flow velocity and effective strain in a deformation zone of a billet in steady state extrusion had been investigated [5, 6]. A defining characteristic of the apparatus is that plastic flow of the surface area of a billet in contact with plane plate tool is not affected by tool geometry with straight and flat surface but affected with frictional constraint on the tool surface, and shearing deformation of surface area of a billet sliding on the surface of plane plate tool is caused only by frictional constraint at the tool surface under bulk plastic deformation.

In the present investigation, a series of plane strain cold extrusion of A1050-JIS aluminum billet were carried out by using the above-mentioned apparatus, and the values of coefficient of friction on the surface of plane plate tool lubricated with high viscosity lubricant or low viscosity lubricant were measured by using the force sensors built in the plane plate tool. The surface conditions of a billet slid on the surface of plane plate
tool that was lubricated with high viscosity lubricant or low viscosity lubricant were compared mutually. Furthermore, the effects of different frictional constraint at the surface of plane plate tool on the plastic flow condition and effective strain distribution in a deformation zone of a billet were analyzed quantitatively in steady state extrusion condition.

2. Experimental apparatus, method of visioplasticity analysis and experimental method

2.1. Apparatus of plane strain extrusion

Figure 1 shows the schematic sketch of the plane strain extrusion apparatus in which a taper die and a plane plate tool are arranged in facing each other. The taper die with die half angle of 45 degrees and container is one body construction. The inner case includes sidewalls by which plastic flow is confined to plane strain condition. The detection part of frictional force acting on the tool surface is built in the plane plate tool. A billet with rectangular cross sectional area was placed in the cavity surrounded by the taper die, container, plane plate tool and sidewall, and extruded by punch stem that was moved by the oil-hydraulic press machine. The load cell to measure extrusion load and displacement sensor to measure press ram stroke are equipped to the oil-hydraulic press machine.

The whole apparatus was made of tool steel, SKD11 (JIS) and hardened and tempered. Extrusion ratio is at around 2 in this apparatus. Hardness of dies is 680 HV and surface roughness on the surface of plane plate tool is finished in 0.05 μmRₐ.

2.2. Billet

Figure 2 shows the schematic illustration and dimensions of the billet split into two halves along the observation plane of plastic flow. The billet material was commercially pure aluminum A1050-JIS that could be extruded with relatively low extrusion load at room temperature. The inner sides of the stacked half billets are the observation planes of plastic flow in steady state extrusion condition. A square grid line pattern of 1mm grid spacing was scribed on one side of the inner sides of the stacked half billets with fine grooves by using NC milling machine. Cross section of each groove was V-shape with 0.2 mm width and 0.07 mm depth. We confirmed that the grooves scribed on one side of the inner sides of the stacked half billets were filled with billet itself at initial stage of extrusion process, and plastic flow of a billet in extrusion process was not affected with the above fine grid line pattern. The surface roughness on the test surface of a billet was finished in 0.3 μmRₐ. The billets prepared by the above procedure were annealed by furnace cooling after heating in 2 hours at 350°C so that the rolling texture was annihilated and the recrystallized structure with isotropic mechanical properties could be established. Hardness of the billet was 28 HV.

2.3. Plane plate tool with detection part of frictional force

Figure 3, (A) illustrates the normal force W and frictional force F acting on the surface of plane plate tool at detection part of frictional force in extrusion process. The forces W’ and F’ are the normal force and frictional force acting on the surface of billet respectively, (where, F=F’ and W=W’). Width of the detection part of frictional force is 10 mm, which corresponds to width of plane plate tool, and length of that part is 4.3 mm. The detection part is in the range of 5.7 mm and 10.0 mm measured from the die exit position, and located within the region of deformation zone of a billet in extrusion process. The above mentioned measurement area of the applied forces corresponds to the zone between Y=6.7 mm and 11 mm in X-Y coordinate system in Fig. 5 which is shown later.

Figure 3, (B) shows the forces F₁ with working angle θ₁ and F₂ with working angle θ₂ acting on the tool surface in extrusion process. The forces F₁ and F₂ are related with the normal force W and frictional force F by equations (1) and (2). When working angle θ₁ and θ₂ are fixed to 45°, the normal force W and frictional force F acting on the tool surface are calculated by equations (3)
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and (4), which are derived from equations (1) and (2).

\[ F_A = W \cos \theta_1 - F \sin \theta_1 \]  \hspace{1cm} (1)

\[ F_B = W \cos \theta_2 + F \sin \theta_2 \]  \hspace{1cm} (2)

\[ W = F_A + F_B \]  \hspace{1cm} (3)

\[ F = \frac{F_B - F_A}{\sqrt{2}} \]  \hspace{1cm} (4)

Furthermore, coefficient of friction \( \mu \) in equation \( F = \mu W \) is calculated by Eq. (5).

\[ \mu = \frac{F_B - F_A}{F_A + F_B} \]  \hspace{1cm} (5)

The forces \( F_A \) and \( F_B \) were measured separately by using two types of plane plate tool expressed as T+45D and T-45D; i.e., the extrusion experiments were carried out twice under the same extrusion conditions, and the force \( F_A \) was measured by using the plane plate tool, T+45D, and \( F_B \) by using the plane plate tool, T-45D, respectively.

Figure 3, (B), (a) and (b) represent the photographs of detection part of frictional force. A tiny square column with the same width as that of plane plate tool was formed in plane plate tool at detection part of frictional force by wire cut electric discharge machining, and the strain gauges in 2-gauges strain measurement system were adhered on both side surfaces of the column with sensing direction parallel to the compressive force \( F_A \) or \( F_B \) direction. Epoxy adhesive was filled into the narrow gap between the column and the tool body to prevent inflow of billet material to the gap and also to avoid bending of the column in extrusion process. Calibration test to determine conversion ratio between applied load (compressive force) and measured output strain was carried out in the force range, 300 N to 7 kN.

Figure 4 shows the apparatus for calibration test and the relation between applied load and measured strain, (B).

Figure 3 The forces acting on the surface of plane plate tool, (A), and two types of plane plate tool named as T+45D and T-45D to measure the forces \( F_A \) and \( F_B \), (B)

Fig. 4 Schematic sketch of the apparatus for calibration test of detection part of frictional force, (A), and the relation between applied load and measured strain, (B)
2.4. Visco-plasticity analysis of plastic flow

The conditions of plastic flow and effective strain in the whole deformation zone of a billet, which were affected with frictional constraint on the surface of plane plate tool, were investigated quantitatively by applying the visioplasticity analysis [7]. Fig. 5 illustrates the flow field and deformation zone of a billet and $X-Y$ rectangular coordinate system used in the visioplasticity analysis of plastic flow in steady state plane strain extrusion. The grid lines scribed on the split surface of a billet, which were originally parallel to the direction of extrusion, represent the flow lines and the grid lines, which were originally normal to the direction of extrusion, represent the constant time lines in steady state extrusion. Flow function (mm$^2$/s) of each flow line in plane strain extrusion is calculated by equation (6).

$$
\psi_i = X_i \sqrt{v_0}
$$

Where, $v_0$ (mm/s) is the speed of press ram movement, and $X_i$ (mm) is the distance of the $i$-th flow line measured from the $Y$ coordinate axis ($X = 0$) in the region where deformation does not occur as shown in Fig. 5. Velocity components, $u$ and $v$ (mm/s), and absolute value of combined velocity $|v|$ (mm/s) are calculated by equations (7), (8) and (9).

$$
u = \frac{\partial \psi}{\partial Y}
$$

(7)

$$
\nu = \frac{\partial \psi}{\partial \lambda}
$$

(8)

$$
|v| = \sqrt{u^2 + v^2}
$$

(9)

Strain rate components ($s^{-1}$) are calculated by equations (10).

$$
\dot{\varepsilon}_X = \frac{\partial \dot{u}}{\partial X}, \quad \dot{\varepsilon}_Y = \frac{\partial \dot{v}}{\partial Y}
$$

(10)

Effective strain rate ($s^{-1}$) is calculated by equation (11).

$$
\dot{\varepsilon} = \frac{2}{3} \sqrt{3 \dot{\varepsilon}_X^2 + \frac{3}{4} \dot{\varepsilon}_Y^2}
$$

(11)

Effective strain is calculated by equation (12) that represents time integration of the effective strain rate along the flow line.

$$
\varepsilon = \int \dot{\varepsilon} dt
$$

(12)

2.5. Experimental method

In the present investigation, the lubricants with two clearly different viscosities were selected as the test lubricants so that distinct values of coefficient of friction in two lubrication conditions could be measured by the extrusion apparatus. Then, paraffinic mineral oil with low viscosity, VG32, expressed as P-VG32, or paraffinic mineral oil with high viscosity, VG1000, expressed as P-VG1000, was used as test lubricant applied to the surface of a plane plate tool. Initial mass of oil film on the surface of plane plate tool was set to 15 mg (2.2 mg/cm$^2$) at each extrusion experiment by using the electronic balance. Approximately equal amount of paraffinic mineral oil with medium viscosity, VG460, expressed as P-VG460, was applied to the surfaces of taper die, container and sidewalls, which were in contact with the other surfaces of a billet. The extrusion experiments were carried out at room temperature. Where, we confirmed that the plastic flow conditions in plane strain extrusion with the above lubrication conditions were little affected with difference in room temperature such as 27°C or 18°C.

The billet was extruded by using the oil-hydraulic press, and extrusion was ceased abruptly at press ram stroke 42mm in steady state extrusion condition at which extrusion speed was held at a constant value. Extrusion load, press ram stroke and forces acting on the plane plate tool were measured during the whole extrusion process. Surface condition was investigated by measuring the surface roughness and by microscopic observation. The velocity field and effective strain distribution in deformation zone of a billet were calculated at steady state extrusion condition by applying the visioplasticity method. The values of coefficient of friction were determined with the measured values of frictional force and normal force acting on the surface of plane plate tool under the actual testing conditions involving surface conditions of the plane plate tool and billet, applied lubricant, sliding speed and temperature.

3. Experimental results

Figure 6, (A) and (B) show the extrusion loads and compressive forces, $F_A$ and $F_B$, with regard to press ram stroke measured in the extrusion experiments in which lubricant applied on the surface of plane plate tool was P-VG32 or P-VG1000. Lubricant applied on the surfaces of taper die and sidewalls was P-VG460 in all extrusion experiments. We could confirm that the extrusion load and press ram stroke curves measured by using two types of tool expressed as T+45D and T-45D coincide with each other’s at the same extrusion condition. The variations of extrusion load and compressive forces show a similar tendency with regard to press ram stroke in both
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Lubricants, P-VG32 and P-VG1000. Extrusion load shown in Fig. 6 (A) characterized with low viscosity lubricant P-VG32 is higher than that shown in Fig. 6 (B) characterized with high viscosity lubricant P-VG1000. Compressive force $F_A$ measured by using the T-45D tool is higher than compressive force $F_A$ measured by using the T+45D tool in both lubrication conditions as shown in Fig. 6 (A) and (B). Difference between two compressive forces $F_A$ and $F_B$ was a little when high viscosity lubricant P-VG1000 was applied on the surface of plane plate tool as shown in (B).

The values of normal force and frictional force were calculated with referring to the measured values of $F_A$ and $F_B$ and by using the equations (3) and (4). Fig. 7 shows the values of normal force and frictional force with regard to press ram stroke in steady state extrusion in which ram speed of hydraulic press machine becomes in stable condition. Ram speed at steady state extrusion was 5.21 mm/s in extrusion applying lubricant P-VG32 and 5.11 mm/s in extrusion applying lubricant P-VG1000, respectively. Little difference in normal force and notable difference in friction force can be observed between extrusion experiments in which different lubricant P-VG32 or P-VG1000 was applied on the surface of plane plate tool.

Figure 8 shows the coefficient of friction on the surface of plane plate tool with regard to press ram stroke. Referring to the data in press ram stroke 25-40 mm, the values of coefficient of friction could be determined as 0.1 when lubricant P-VG32 was applied on the surface of plane plate tool and as 0.05 when lubricant P-VG1000 was applied on the same surface.
mutual comparisons of surface roughness of partially extruded billet on plane plate tool side. Surface condition of a billet slid on the tool surface with bulk plastic deformation could be related to its plastic strain, surface roughness of a tool and thickness of lubricant layer. Referring to Figs. 9 and 10, we could confirm that the conditions of frictional constraint on the surface of plane plate tool were the same in both extrusion experiments using two types of plane plate tool expressed as T+45D and T-45D. Surface roughness $Ra$ of the billet in contact with plane plate tool was 0.05-0.06 $\mu$m in the area between $Y = 6.7$ mm and 11.0 mm when low viscosity lubricant, P-VG32, was applied. In this case, surface of the billet was smooth and little abrasion of aluminum could be observed on the billet surface. The above results mean that thin lubricant layer was formed on the surface of plane plate tool with application of low viscosity lubricant. On the other hand, surface roughness of the billet was 0.15-0.3 $\mu$m when high viscosity lubricant, P-VG1000 was applied. In this case, surface of the billet became rough but abrasion could not be seen on the test surface. These results mean that thick lubricant layer was formed on the surface of plane plate tool with application of high viscosity lubricant.

4. Discussion

The values of coefficient of friction on the surface of plane plate tool lubricated with high viscosity lubricant or low viscosity lubricant were determined under bulk plastic deformation by using the plane strain extrusion apparatus with plane plate tool and taper die, as described in the previous section, and the value of coefficient of friction was determined as 0.1 when low viscosity lubricant, P-VG32 was applied and as 0.05 when high viscosity lubricant P-VG1000 was applied on the surface of plane plate tool. Surface roughness of a billet slid on the surface of plane plate tool and the plastic flow condition and effective strain condition in a whole deformation zone, which were affected with the above two different friction conditions on the surface of plane plate tool, were also investigated quantitatively. Those results were explained in the following articles written below.

4.1. Surface condition and coefficient of friction

Surface roughness of a work-piece, which slid on the surface of tool with plastic deformation under lubricated condition, could be related to the oil film thickness and degree of plastic deformation. In the present investigation, the extrusion experiments were carried out by using the same apparatus, and the surfaces of billet slid on the plane plate tool were observed at almost the same degree of plastic deformation. Therefore, we could consider that differences of surface roughness of a billet depend on the oil film thickness. Fig. 9 represents that surface roughness of a billet was as same as that of tool surface when lubricant P-VG32 was applied. Therefore, rate of boundary lubrication condition and contact ratio of billet surface to tool surface were high values when lubricant P-VG32 was applied. While, surface roughness of a billet was rough and adhesion was not observed when lubricant P-VG1000 was applied. This means the existence of thick oil film; i.e., high viscosity lubricant P-VG1000 creates thick oil film between the billet and tool interface in extrusion process and reduces the value of coefficient of friction.

4.2. Plastic flow at steady state extrusion

Figure 11 shows the distorted grid line patterns on the billet surfaces, which were partially extruded and stopped abruptly in steady state extrusion condition.
Extrusion conditions such as lubricant applied on the surfaces of taper die and on both sidewalls, lubricant applied on the surface of plane plate tool, coefficients of friction on the surface of plane plate tool, which were measured in the previous section, and press ram speeds for experiment (A) and (B) are listed in the figure. Outer profile and grid line pattern of partially extruded billet indicate that a little and uniform expansion of billet was occurred in width direction (X direction in Fig. 5) at initial stage of extrusion and fixed at steady state extrusion condition due to initial existence of dimensional clearances between the inner case, taper die, container, plane plate tool and billet. However, we confirmed that thicknesses of the billet and product were not changed from initial values, 10 mm (5 mm × 2), in the whole experimental procedure. Measured widths of the billet and product at steady state extrusion were 15.6 mm and 8.3 mm respectively in extrusion experiment applying lubricant P-VG32 in which maximum extrusion load \( P_m \) measured at initial stage of extrusion was 33 kN and 15.3 mm and 8.0 mm respectively in extrusion experiment applying lubricant P-VG1000 in which \( P_m \) was 29.5 kN. Distorted grid line patterns represent the flow lines and edges of deformation zone (deformation boundaries) in steady state extrusion, which are referred in the visioplasticity analysis of plastic flow.

4.3. Relative flow velocity in deformation zone

Figure 12, (A) shows the distributions of relative flow velocity \( (V/V_0) \) with regard to \( X \) (mm) at some constant position \( Y \) (mm) in the billet as shown in (B) in steady state extrusion in which lubricant P-VG32 or P-VG1000 was applied and coefficient of friction was determined as 0.1 or 0.05 respectively on the surface of plane plate tool. Fig. 12 represents that the distributions of relative flow velocity were affected in some extent with frictional constraint at surface of plane plate tool, and remarkable difference in relative flow velocity due to different frictional constraint can be observed at the surface area of billet on plane plate tool side.

Figure 13 shows a comparison of the variations of relative velocity of plastic flow at surface areas of billet on taper die side and on plane plate tool side in steady state extrusion. When coefficient of friction on the surface of plane plate tool was changed from 0.1 to 0.05, relative velocity of plastic flow at surface area of billet increases on plane plate tool side and decreases on taper die side. Referring to Fig. 13, mean sliding velocities of billet at the section of frictional force measurement on the surface of plane plate tool were \( V/V_0 = 1.47 \) (\( V = 7.6 \) mm/s) in lubrication condition, P-VG32 and \( V/V_0 = 1.56 \) (\( V = 7.9 \) mm/s) in lubrication condition, P-VG1000 respectively.
4.4. Effective strain in deformation zone

Figure 14 shows a comparison of the contours of constant effective strain and the deformation zones in steady state extrusion. Fig. 15, (A) shows the distributions of effective strain with regard to $X$ (mm) at some positions $Y$ (mm) in the billet as shown in (B) in steady state extrusion in which lubricant P-VG32 or P-VG1000 was applied and coefficient of friction was determined as 0.1 or 0.05 respectively on the surface of plane plate tool. Figs. 14 and 15 represent that deformation zone and effective strain distribution were changed in some extent with frictional constraint on the surface of plane plate tool and remarkable difference could be observed at both surface areas of billet in contact with plane plate tool and taper die.

Figure 16 shows the variations of effective strain of billet at surface areas on taper die side and on plane plate tool side in steady state extrusion. Fig. 16 represents that the values of effective strain of extruded product at surface areas on taper die side and on plane plate tool side are shifted to larger strain level when frictional constraint on the surface of plane plate tool is reduced. Referring to Fig. 16, mean values of effective strain of billet at the section of frictional force measurement on the surface of plane plate tool were 0.37 in lubrication condition, P-VG32 and 0.45 in lubrication condition, P-VG1000 respectively.

5. Conclusions

In the present investigation, the values of coefficient of friction on the surface of plane plate tool were measured in plane strain extrusion of aluminum billet by using the apparatus in which a taper die and a plane plate tool were arranged in facing each other. Lubrication condition on the surface of plane plate tool was changed by applying paraffinic mineral oil with low viscosity, VG32 or that with high viscosity, VG1000. Lubrication conditions of the surfaces of taper die and sidewalls were fixed to application of paraffinic mineral oil with viscosity, VG460. The plastic flow condition and effective strain condition in whole deformation zone of a billet affected with lubrication condition on the plane plate tool were investigated quantitatively by carrying out viso-plasticity analysis. Concluding remarks are summarized below.
Coefficient of friction on the surface of plane plate tool made of SKD 11-JIS could be measured successfully under bulk plastic deformation of aluminum billet. The values of coefficient of friction were 0.05 in application of lubricant with high viscosity, VG1000 and 0.10 in application of lubricant with low viscosity, VG32.

Surface roughness $Ra$ of a billet slid on the surface of plane plate tool was 0.05-0.06 $\mu m$Ra when low viscosity lubricant, paraffinic mineral oil VG32, was applied, and the surface of billet was smooth and little abrasion of aluminum could be observed on the billet surface. The above results represents that thin lubricant layer was formed on the surface of plane plate tool with application of low viscosity lubricant. On the other hand, surface roughness of a billet was 0.15-0.3 $\mu m$Ra when high viscosity lubricant, paraffinic mineral oil VG1000 was applied. In this case, surface of the billet became rough but abrasion could not be seen on the test surface.

Plastic flow and effective strain condition in a billet at whole deformation zone affected with frictional constraint on the surface of plane plate tool were investigated quantitatively by carrying out the visioplastcity analysis. Distributions of relative flow velocity and effective strain in a deformation zone were affected with frictional constraint at the surface of plane plate tool in some extent, and remarkable differences in relative flow velocity and effective strain between different frictional conditions on the surface of plane plate tool could be observed on both surface areas in contact with plane plate tool and taper die. Direct measurement of coefficient of friction and visioplastcity analysis in the present investigation gives us the valuable information that coefficient of friction on the surface of plane plate tool, $\mu = 0.1$ was measured at mean sliding velocity 7.6 mm/s and mean effective strain 0.37 in lubrication condition applying paraffinic mineral oil VG32 and $\mu = 0.05$ was measured at mean sliding velocity 7.9 mm/s and mean effective strain 0.45 in lubrication condition applying paraffinic mineral oil VG1000.

References