The Effect of Lubricant Viscosity in Cold Forward Plane Strain Extrusion Test

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Abstract

The effect of lubricant with three different viscosities was investigated by plane strain extrusion experiments and visioplasticty analyses. The lubricant is additive free paraffinic mineral oil. VG30 is a low viscosity lubricant with kinematic viscosity of 32 mm²/s at 40ºC. VG95 is a medium viscosity with kinematic viscosity of 92 mm²/s at 40ºC. VG460 is a high viscosity with kinematic viscosity of 462 mm²/s at 40ºC. The experiment used a cold work plane strain extrusion apparatus consist of a pair of taper die and a symmetrical workpiece (billet). The billet material was annealed pure aluminum A1100. The experiments were conducted at room temperature. The experimental results are focusing on the extrusion load, billet surface roughness, billet surface and grid pattern observation. The distribution of velocities and effective strain on the sliding plane of taper die were analyzed quantitatively, by using the visioplasticty method. From the results, low viscosity lubricant would give high extrusion load, however, low viscosity lubricant could produce product surface with low surface roughness.

Keywords: Extrusion, Paraffinic Mineral Oil, Visioplasticty, Velocity

1. Introduction

In general, the function of lubricant is to control the friction and wear in a given system. One of the parameter that plays a fundamental role in lubrication is oil viscosity. Different oils exhibit different viscosities, and show difference behavior in reducing the friction and wear. At first glance, oils with
high viscosity lubricant would give better performance compared to low viscosity lubricant, however, high viscosity lubricant require more energy to be sheared. Consequently the lower losses are higher and more heat will be generated. It would cause the failure in contacting surface [1].

In metal forming, the viscosity of lubricant is important because it is a part of the study in lubricant rheology. The response of lubricant to the high pressure, shear rates and temperature are important, and these parameters are influence by the viscosity of lubricant [2].

In deep drawing process, low viscosity lubricant increased the forming load, and creates stick-slip condition [3]. The viscosity of lubricant also influence the product surface roughness, and low viscosity lubricant has tendency to have more metal-to-metal contact between tool and workpiece surface [4].

In roller bearing, the high viscosity oil could reduce the vibration level [5]. In compressor, the combination of lubricant and refrigerant influenced the surface damage of the components. Low viscosity oils gave rise to a boundary lubrication condition, resulting in severe wear, material transfer and friction [6]. In rolling process, the viscosity of lubricant affected the forming load, however the effect of viscosity was not observnable at lower speed and lower reduction conditions [7].

In present study, the effects of lubricant viscosity in cold work plane strain extrusion process were investigated. The test lubricant is additive free paraffinic mineral oil. Three different viscosities were tested. Experimental works were done in room temperature. The results were focused on extrusion load, product surface condition, sliding velocities and effective strain.

2. Experimental Procedure
2.1. Experimental Apparatus

Figure 1 shows the schematic sketch of plane strain extrusion apparatus used in the experiments. The main components are container wall and taper die, and workpiece (billet). The taper die has 45-degree die half angle. The taper die is made from tool steel SKD11 and necessary heat treatment were done before the experiments. The experimental surface of taper die (surface which contact the billet) were polished with abrasive paper and have surface roughness Ra approximately 0.15 μm. The lubricant with specified amount was applied on this surface before the experiments. The other surfaces of experimental apparatus were applied with same type of test lubricant. Taper die has Vickers hardness of 650 Hv.

Figure 2 shows the schematic sketch of billets used in the experiments. The material of billet is pure aluminum A1100. The billet’s shape was made by the NC wire cut electric discharge machining device. Two similar billets were stacked and used as one unit of billet. One side of the contact surface of the combined billets was the observation plane of plastic flow in plane strain extrusion. The observation plane is not affected with the frictional constraint by the parallel side walls.

A square grid pattern measuring the material flow in extrusion process was scribed by NC milling machine on the observation plane of billet. The grid lines were V-shaped grooves with 0.5 mm deep, 0.2 mm wide and 1.0 mm interval length. The billets were annealed before the experiments. The experimental surface of billet (surface which contact the taper die) has surface roughness Ra approximately 2.5 μm. The Vickers hardness of the billet is 38 Hv.
2.2. Lubricants

The testing lubricant is additive free paraffinic mineral oil with three different viscosities, marked as VG30, VG95 and VG460 respectively. VG30 is a low viscosity lubricant with kinematic viscosity of 32 mm$^2$/s at 40°C. VG95 is a medium viscosity with kinematic viscosity of 92 mm$^2$/s at 40°C. VG460 is a high viscosity with kinematic viscosity of 462 mm$^2$/s at 40°C. The details of the testing lubricants are shown in Table 1.

One drop of testing lubricant (approximately 25 mg) was applied on the experimental surface of taper die before the experiment. The initial lubricant amount was capable to create full film lubrication regime at the early stage of extrusion process.
<table>
<thead>
<tr>
<th></th>
<th>VG30</th>
<th>VG95</th>
<th>VG460</th>
<th>Test method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density at 15°C (kg/liter)</td>
<td>0.8715</td>
<td>0.8725</td>
<td>0.9035</td>
<td>ASTM D1298-85(90)</td>
</tr>
<tr>
<td>API Gravity</td>
<td>30.77</td>
<td>29.66</td>
<td>25.03</td>
<td>ASTM D1298-85(90)</td>
</tr>
<tr>
<td>Kinematic viscosity at 40°C (cSt)</td>
<td>26.54</td>
<td>90.12</td>
<td>455.1</td>
<td>ASTM D445-94</td>
</tr>
</tbody>
</table>

2.3. Experimental Procedure

The plane strain extrusion apparatus was assemble and placed on the press machine. The forming load and displacement data were recorded by computer. The experiments were carried out at room temperature. Extrusion was stopped at piston stroke of 35 mm, where the extrusion process is in steady state condition. The ram speed, \( V_o \) is constant at 0.85 mm/s. The experiments were carried out at Strength Laboratory, Faculty of Mechanical Engineering, Universiti Teknologi Malaysia. After the experiment, the partially extruded billets were taken out from the plane strain extrusion apparatus and the combined billets were separated for the surface roughness measurement and plasticity analysis.

2.4. Visioplasticity Method

Figure 3 shows the schematic diagram of the x-y orthogonal coordinates system used in the analysis of the deformation zone, using the plastic flow lines that appeared during the steady state extrusion condition. Figure 3 also shows some of the variables used in the analysis and calculation, and the position established in the same coordinates system in the observation plane of billet.

The plastic flow velocity in the deformation zone, the effective strain rate and the effective strain were calculated using equation (1) to (5). Since, the analytical calculation procedure is explained in earlier publication, it is omitted here [8].

\[
\psi_i = X_i \left| V_o \right|
\]

Flow function

Velocity component (Velocity in x-direction: \( u \), velocity in y-direction: \( v \))

\[
u = \frac{\partial \psi}{\partial X}, \quad v = -\frac{\partial \psi}{\partial X}
\]

The strain rate component (s-1)
The effective strain rate (s−1)
\[ \dot{\varepsilon}_x = \frac{\partial u}{\partial x}, \quad \dot{\varepsilon}_y = \frac{\partial v}{\partial y}, \quad \dot{\gamma}_{xy} = \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \] (Model 3)

The effective strain rate (s−1)
\[ \dot{\varepsilon} = \frac{2}{3} \sqrt{\frac{3}{4} \dot{\varepsilon}_x^2 + \dot{\gamma}_{xy}^2} \] (Model 4)

The effective strain (time integration value of the effective strain rate along the flow line)
\[ \varepsilon = \int \dot{\varepsilon} \, dt \] (Model 5)

In the equations, \( V_o \) is the velocity of the press ram in mm/s, and \( X_i \) is the distance in mm from the \( y \)-coordinate axis \((X = 0)\) of the \( i \)-th flow line in the region where deformation does not occur.

3. Results and Discussion

3.1. Extrusion Load

Figure 4 shows the extrusion load – piston stroke curves. The figure shows that the extrusion load in the cold work extrusion process reached the constant level and the extrusion process become steady state condition at the piston stroke more than 25 mm. The extrusion load at steady state condition (at piston stroke 35 mm) for VG30, VG95 and VG460 are 90.9 kN, 77.0 kN and 70.6 kN respectively. The extrusion load is higher as lubricant viscosity becomes lower.

Figure 4: Extrusion load – piston stroke curves.

3.2. Surface Roughness

Figure 5 shows the arithmetic mean surface roughness Ra distribution measured perpendicular to the direction of extrusion on the experimental surface of billet after sliding against the taper die (tool) surface.
The value of surface roughness Ra could be used to predict the lubricant film thickness on the tool dies in extrusion process; where the high value of Ra means thick lubricant film thickness was occur [9].

From figure, at undeform area (12 mm onwards), low viscosity lubricant VG30 has thinner lubricant film thickness compared to high viscosity lubricant VG460. However, the lubrication condition for all lubricant at undeform area was predicted as full film lubrication condition due to the high ratio of the workpiece and tool surface roughness value [9].

At taper die area (2 mm to 8 mm), billet material was deformed and squeeze the lubricant. According to the low surface roughness values, which almost similar with the taper die surface roughness value, the lubrication condition was predicted as boundary and mixed lubrication condition. Low viscosity lubricant VG30 has more metal-to-metal contact compared to lubricant VG95 and VG460. As a result, the product area surface roughness (-2 mm backward) is lower for billet extruded with low viscosity lubricant VG30. When more metal-to-metal contact occurs, the process need more energy to shear the material and make the extrusion load becomes higher.

Figure 6 shows the CCD pictures of surface condition of billet at product area (sliding plane -4 mm). There are no severe wear were observed.

**Figure 5**: Surface roughness Ra distribution of billet on along the sliding plane of taper die.
3.3. Grid Lines Observation

Figure 7 shows the coordinates used to measure the inclination of grid lines near the taper die. The taper die surface was chosen because the deformation zone of billet was lay at this area. Based on the inclination degree of grid lines, the friction condition between the taper die and billet surface could be justified. The friction condition increases as the inclination degree decreases.

Figure 8 shows the grid slope inclination distribution on the taper die sliding plane. The inlet is at 10 mm and the exit is at 0 mm. For high viscosity lubricant VG460, the difference of inclination
degree at inlet and exit area was not obvious. This shows that VG460 which has high viscosity could remain the lubricant thickness very well and has less frictional constraint. This also reflected in extrusion load where VG460 has the lowest load compared to other experimental condition. For low viscosity lubricant VG30, the difference of inclination degree at inlet and exit area was great. It proved that the metal-to-metal contact for billet which is extruded with lubricant VG30 is more compared to the other experimental condition.

**Figure 7:** Coordinates used to measure the grid inclination at taper die.

**Figure 8:** Grid slope inclination distribution.
3.4. Velocities Distribution and Effective Strain

Figure 9 and Figure 10 show the distribution of the v-component and u-component velocities of billet on along the sliding plane of taper die respectively. Figure 11 shows the relative velocities $v_R$ distribution of billet on along the sliding plane of taper die. The relative velocity $v_R$ is the ratio of the resultant velocity to the ram speed, $V_o$. From the velocities distribution, low viscosity lubricant VG30 has the lowest velocity, followed by lubricant VG95 and VG460.

Figure 12 shows the effective strain distribution of billet on along the sliding plane of taper die. Billet extruded with low viscosity lubricant VG30 showed the highest effective strain distribution compared to the other experimental condition. As stated previously, low viscosity lubricant VG30 has more metal-to-metal contact, and sheared the billet more.

**Figure 9:** v-component velocities.

**Figure 10:** u-component velocities.
**Figure 11**: Relative velocities.

\[ V_R = \sqrt{u^2 + v^2} \]

**Figure 12**: Effectives strain distribution of billet on along the sliding plane of taper die.
4. Concluding Remarks

The effects of lubricant viscosity in plane strain extrusion process were clarified using a cold work plane strain extrusion apparatus. The experimental results and analytical results can be summarized as follows.

1. The extrusion load is higher as lubricant viscosity becomes lower.
2. The product surface roughness is higher as lubricant viscosity becomes lower due to the increment of metal-to-metal contact.
3. Lubricant film thickness between taper die and billet become smaller when the viscosity is changed to smaller values, and vice versa.
4. Material (billet) which is extruded with low viscosity lubricant tends to have low sliding velocity and high effective strain, and vice versa.

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