Experimental evaluation of palm oil as lubricant in cold forward extrusion process

S. Syahrullail*, B.M. Zubil, C.S.N. Azwadi, M.J.M. Ridzuan

Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, 81310 UTM Skudai, Johor, Malaysia

ARTICLE INFO

Article history:
Received 17 May 2010
Received in revised form
24 February 2011
Accepted 8 May 2011
Available online 23 May 2011

Keywords:
Aluminum
Palm stearin
Visioplasticity
Mineral oil
Extrusion

ABSTRACT

Today, vegetable oil is much desired for its application as a lubricant in metal forming processes, because it is a renewable resource and has high biodegradability compared to mineral oil. According to the Organization for Economic Cooperation and Development for the European Union 301C (OECD) testing method, the biodegradability levels of vegetable oils are better compared to petroleum-based lubricants. Palm oil is used more often than other vegetable oils. Therefore, palm oil has the potential to fulfill the demand for vegetable-based lubricants. The purpose of this paper is to evaluate the viability of palm oil when used as a lubricant in cold work such as the forward plane strain extrusion process. The performances of palm oil were compared with additive-free paraffinic mineral oil. Experimental work with a plane strain extrusion apparatus with a symmetrical workpiece was carried out at room temperature. The material of the workpiece is annealed pure aluminum A1100. The visioplasticity method was used to calculate the velocities and effective strain in the deformation zone of the workpiece. The results obtained from the experimental work showed that palm oil has satisfactory lubrication performances, as compared to paraffinic mineral oil, and has advantages in reducing the extrusion load.

© 2011 Elsevier Ltd. All rights reserved.

1. Introduction

Ecological factors are gaining importance in our society. Bearing in mind that our environment is being increasingly contaminated with all kinds of pollutants, any reduction is welcome. From an environmental point of view, and compared to a number of other chemical products, lubricants are not particularly problematic. A large proportion of lubricants pollute the environment either during or after use. It has been stated that 5–10 millions tons of petroleum-based oleochemicals enter the biosphere every year. About 40% comes from spills, industrial and municipal waste, urban runoff, refinery processes, and condensation from marine engine exhaust [1]. These oleochemical pollutants are derived from the food industry, petroleum products, and byproducts such as lubricating, hydraulic, and cutting oils.

The terminology used in connection with environmental compatibility can be split into two criteria, i.e., subjective and objective. The non-measurable or subjective criteria are environmentally friendly and environmentally compatible. The objective criteria, among others, include biodegradability, water solubility, ecological toxicity, efficiency improvements, etc. Normally a biodegradability of at least 60%, according to OECD 301, is considered the main objective criterion for bio-lubricants. One of the possible lubricants that can satisfy this need is vegetable oil, which can offer significant environmental advantages with respect to resource renewability, biodegradability, and adequate performance in a variety of applications [2].

Natural fatty acid oils such as castor oil, palm oil, rapeseed oil, soybean oil, sunflower oil, and tallow oil have been used in lubricants for years. They are the so-called triglycerides of more or less unsaturated fatty esters. This type of base is biodegradable and, compared to mineral oils, will show excellent tribological qualities such as low friction coefficients and good wear protection. Their range of use is limited by lower stability against thermal oxidative and hydrolytic stress and partly inferior cold flow properties. These limits can be improved gradually with additives.

In Malaysia, palm oil has the possibility to be used as an industrial lubricating oil. Palm oil is vegetable oil, which is biodegradable, and also has a high production rate, which could fulfill the demand for vegetable-based lubricating oil in the future. One hectare of palm trees can produce almost 10 times as much oil compared to other sources of vegetable oil [3]. Therefore, palm oil has the potential to fulfill the supply volume in the demand for vegetable-based lubricants.

In this research, we examine RBD palm stearin (a type of refined palm oil) used as a lubricant in a cold work forward plane strain extrusion process. The extrusion load from the experimental work...
was recorded. The surface roughness of billets was measured after the experimental work. The velocity and effective strain distribution in the deformation area of the workpiece extruded with RBD palm stearin was investigated using the visioplasticity method [4]. The evaluations were focused on extrusion load, surface roughness, velocity distribution, and effective strain distribution. The velocity and strain distribution in the deformation region is important in metal forming in order to know the quality of the product. It also provides information about the lubricant quality that can prevent tool wear and control the material flow [5].

2. Experimental conditions

2.1. Experimental apparatus

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

Fig. 1(b) shows a schematic sketch of the billets used in the experiments. The billet material is pure aluminum (A1100). The billets’ shape was formed by an 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 was not affected by the frictional constraint of the parallel side walls. A square grid pattern measuring the material flow in the extrusion process was scribed by the NC milling machine on the observation plane of the billet. The grid lines were V-shaped grooves with 0.5 mm depth, 0.2 mm width, and 1.0 mm interval length. The billets were annealed before the experiments. The experimental surface of the billet (surface, which contacts the taper die) had a surface roughness Ra of approximately 2.5 μm and a Vickers hardness of 38 Hv. Table 1 shows the properties of SKD11 and pure aluminum A1100.

2.2. Lubricants

The testing lubricant is RBD palm stearin. RBD is an abbreviation for Refined, Bleached, and Deodorized. Palm stearin is the solid fraction obtained by fractionation of palm oil after crystallization at controlled temperature. It is, thus, a co-product of palm olein. The average ratio of stearin to olein is about 25:75. The physical characteristics of palm stearin differ significantly from those of palm oil, and it is available in a wider range of melting points and iodine values [6]. In these experiments, a standard grade of palm stearin, which incorporated Malaysian Standard MS 815:1991, was used. The properties of RBD palm stearin are shown in Table 2. RBD palm stearin has a high melting point. As a result, in this experiment, RBD palm stearin remained in a semi-solid condition.

The results obtained from the experiments that used RBD palm stearin were compared with additive-free paraffinic mineral oils, VG95 (written as Paraffin VG95) and VG460 (written as Paraffin VG460). The properties of paraffinic mineral oil VG95 and paraffinic mineral oil are shown in Table 2. The changes of the viscosity for all test lubricants against temperature were measured and plotted as shown in Fig. 2. From the figure, paraffin VG460 has higher viscosity compared to paraffin VG95. At 40 °C, paraffin VG95 and paraffin VG460 have kinematic viscosity of 95 and 461 cSt, respectively. RBD palm stearin has a similar viscosity–temperature curve than paraffin VG95. It has kinematic viscosity of 46 cSt at 40 °C.

Testing lubricant was applied on the experimental surface of the taper die before the experiment. The initial mass amount of lubricant applied was 5 mg (0.4 mg/cm²).

2.3. Experimental procedure

The plane strain extrusion apparatus was assembled into the confinement fixture (outer cover in Fig. 1) and placed on the hydraulic press machine, as shown in Fig. 3. The load cell and

---

### Table 1

<table>
<thead>
<tr>
<th>Element</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>Cr</th>
<th>Mo</th>
<th>V</th>
<th>S</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specified</td>
<td>1.55</td>
<td>0.30</td>
<td>0.35</td>
<td>11.75</td>
<td>0.75</td>
<td>0.95</td>
<td>0.005</td>
<td>0.020</td>
</tr>
</tbody>
</table>

### Table 2

<table>
<thead>
<tr>
<th>Properties</th>
<th>RBD palm stearin</th>
<th>Paraffin VG95</th>
<th>Paraffin VG460</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apparent density at 50 °C, g/ml</td>
<td>0.8069–0.8977</td>
<td>0.8725</td>
<td>0.9035</td>
</tr>
<tr>
<td>Refractive index nD at 50 °C</td>
<td>1.4589–1.4592</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Saponification value, mg KOH/g oil</td>
<td>194–202</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Iodine values</td>
<td>56.0–59.1</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Slip melting point, °C</td>
<td>19.2–23.6</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Viscosity index</td>
<td>159</td>
<td>102</td>
<td>97</td>
</tr>
<tr>
<td>Viscosity at 40 °C, cSt</td>
<td>46</td>
<td>95</td>
<td>461</td>
</tr>
<tr>
<td>Viscosity at 100 °C, cSt</td>
<td>12</td>
<td>10</td>
<td>31</td>
</tr>
<tr>
<td>API gravity</td>
<td>0.13</td>
<td>29.66</td>
<td>25.03</td>
</tr>
</tbody>
</table>
displacement sensor were used to record the extrusion load and the ram displacement; the data was saved in a computer. The hydraulic press machine's ram, with diameter of 65 mm, would strike the experimental apparatus's punch (cross-section area of 30 mm × 10 mm) to extrude the billets. The experiments were carried out at room temperature. Extrusion was stopped at a piston stroke of 35 mm, where the extrusion process achieved a steady state condition. The ram speed was constant at 0.85 mm/s. The forming load and displacement data were recorded by the computer. After the experiment, the partially extruded billets were removed from the plane strain extrusion apparatus and the combined billets were separated. The absence of any protrusion on the side-wall surface was examined.

### 2.4. Visioplasticity method

In the plane strain extrusion experiments, the process terminated at the steady state extrusion condition where the extrusion load and the extrusion speed were maintained at constant levels. The experimental apparatus was disassembled and the billets were removed from the container. The grid lines scribed on the observation plane of billet showed the plastic flow lines that appeared during the steady state extrusion process after the experiment. Pictures of the observation plane of billet were taken and digitized. Fig. 4 shows the schematic diagram of the x–y orthogonal coordinate system used in the analysis of the deformation zone, using the plastic flow lines that appeared during the steady state extrusion condition. Fig. 4 also shows some of the variables used in the analysis and calculation, and the position established in the same coordinate system in the observation plane of the billet.

The plastic flow velocity in the deformation zone, the effective strain rate, and the effective strain were calculated using Eqs. (1)–(5). Since the detail of the analytical calculation procedure is explained in our earlier publication, it is omitted here [7].

**Flow function:**

\[ \psi_i = X_i |V_o| \]  

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

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

**The strain rate component \((s^{-1})\):**

\[ \dot{e}_X = \frac{\partial u}{\partial X}, \quad \dot{e}_Y = \frac{\partial v}{\partial Y}, \quad \dot{e}_{XY} = \frac{\partial u}{\partial Y} + \frac{\partial v}{\partial X} \]  

**The effective strain rate \((s^{-1})\):**

\[ \dot{\varepsilon} = \sqrt{\frac{2}{3} \dot{e}_X^2 + \frac{2}{3} \dot{e}_Y^2} \]  

**The effective strain (time integration value of the effective strain rate along the flow line):**

\[ \varepsilon = \int \dot{\varepsilon} \, dt \]  

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

The extrusion load–piston stroke curves are shown in Fig. 5. The figure shows that the extrusion load in the process reached the steady state condition at a piston stroke of 15 mm. From the figure, the extrusion load for the billet extruded with RBD palm stearin as a lubricant is the lowest compared to those using additive-free paraffinic mineral oils VG95 and VG460. The extrusion loads for paraffin VG95, paraffin VG460, and RBD palm stearin at steady state condition are 77.1, 70.6, and 65.2 kN, respectively.

Before the experiments, tools were lubricated with certain amount (5 mg) of lubricant. At this stage, thick film lubrication condition was expected. Along the process, especially in taper die area where the deformation of billet occurred, the lubricant was squeezed (thinning off) due to the wedge effects. For extrusion process with paraffin VG95, which has low viscosity, the lubricant trapped [8] between the billet and tool surface has low cohesive force so that the thick filmed lubrication was easily destroyed. This makes the metal-to-metal contact area to increase and the frictional constraint to become higher [9]. The boundary lubrication condition was expected at this condition. In contrast, for extrusion using paraffin VG460, which has high viscosity, the cohesive force is high so that the thick filmed lubrication could reside along the extrusion process. The mixed lubrication condition with thick lubricant layer was expected at this condition [10]. This creates low frictional constraint; as a result, the extrusion load for the billet extruded with paraffin VG460 is lower compared to those extruded with paraffin VG95 [11].

Kataoka [12] explained that this phenomenon was using the idea of micro-pool or oil pocket mechanism. For extrusion process with paraffin VG95 (low viscosity lubricant), the trapped lubricant inside the valley of the surface asperities was not enough to supply the lubricant along the extrusion process. However, for extrusion with paraffin VG460 (high viscosity), it facilitates to supply the lubricant along the extrusion process and contributed to the reduction of the extrusion load. From the Striebeck curve [13] the increment of lubricant layer could produce a low frictional constraint, and for this reason the extrusion load for paraffin VG460 is lower compared to paraffin VG95.

However, for the RBD palm stearin, even though it has low viscosity, as similar with paraffin VG95, the adsorption of fatty acids from the palm oil played the role of maintaining the lubricant layer [14] and yielded a low extrusion load compared to paraffinic mineral oil. The boundary lubrication condition is expected in this condition. The low friction coefficient of palm oil (RBD palm stearin) also influenced the reduction of the extrusion load [15].

3.2. Surface roughness

The average values of the arithmetic mean surface roughness Ra of the experimental surface of the billet at the product area (the area in which the deformation was finished) were measured and shown in Fig. 6. The experimental surface of the billet is the surface that contacts the taper die and the container. The measure direction is perpendicular to the extrusion direction.

From the figure, comparison among the paraffinic mineral oil shows that the surface roughnesses Ra of the billets extruded with paraffin VG95 and paraffin VG460 have almost similar value. Paraffin VG95 has low viscosity and the boundary lubrication condition was occurring along the extrusion process. The metal-to-metal ratio is high in fact it contributed to the production of the rough surface of the billet extruded with paraffin VG95. However, the surface roughness of the billet extruded with paraffin VG460 is slightly lower compared to those extruded with paraffin VG95. As explained previously, the high viscosity of paraffin VG460 was used to supply the lubricant very well along the extrusion process. This phenomenon produced a thick layer of lubricant between the billet and the tool surface. The asperities on the surface of billet are not further to be flattened by the tool surface [16]. As a result, it produced high surface roughness value [17].

The surface roughness Ra for the product area of the billet, which extruded with RBD palm stearin, is smaller compared to those extruded with paraffinic mineral oils VG95 and VG460. The fatty acids of palm stearin were stuck very well on the tool surface and created a thin layer of lubricant. This would create boundary lubrication condition that allows the billet to deform as similar as the tool surface quality. The tool surface roughness Ra before the experiments is 0.15 μm.

![Fig. 5. Extrusion load vs piston stroke curves.](image1)

![Fig. 6. Surface roughness Ra of the experimental surface of billet at product area.](image2)
Fig. 7 shows the CCD pictures of the experimental billet surface and the roughness curve at the product area (at $Y = -6$ mm) for all experimental conditions. From the observation, no severe wear or galling were found on the experimental surfaces of billets for all experimental conditions. The surface roughness $R_a$ of tools remained the same as the value before the experiments.

### 3.3. Velocity distribution and effective strain distribution

The distribution of $v$-component relative velocity ($v_R$) and $u$-component relative velocity ($u_R$) along the experimental surfaces of the billet is shown in Figs. 8 and 9, respectively. The definition of $v_R$ and $u_R$ is given in Eqs. (6) and (7), respectively.
The direction of \(v\)- and \(u\)-component velocities is shown in Fig. 4. All the experimental conditions show similar patterns of \(v\)-component relative velocity \((v_R)\) and \(u\)-component relative velocity \((u_R)\). The billet extruded with paraffinic mineral oil VG460 shows the highest \(v\)-component and \(u\)-component velocity in the taper die sliding plane (at sliding plane ranges of 2 mm and 8 mm). As explained earlier, the high viscosity of paraffin VG460 created thick lubricant layer compared to paraffin VG95 and RBD palm stearin. It causes the reduction of metal-to-metal contact and as a result, the sliding velocities increased.

The mutual comparison of the \(v\)-component and \(u\)-component velocities in the deformation area is shown in Figs. 10 and 11, respectively. The significant difference between RBD palm stearin and paraffinic mineral oils VG95 and VG460 can be seen clearly.

\[
v_R = \frac{v\text{-component velocity}}{\text{Ram speed}} \tag{6}
\]

\[
u_R = \frac{u\text{-component velocity}}{\text{Ram speed}} \tag{7}
\]

Fig. 12 shows the mutual comparison of effective strain in the deformation area. The value of effective strains for all experimental conditions is increased at the taper die area compared to the inlet area. Billet extruded with RBD palm stearin shows increments in the effective strain area compared to those extruded with paraffin VG95 and paraffin VG460.

4. Conclusion

The velocity and the effective strain distribution in the deformation area of a workpiece extruded with RBD palm stearin were investigated by cold work forward plane strain extrusion experiments.
and visioplasticity analysis. The experimental and analytical results of RBD palm stearin were compared to additive-free paraffinic mineral oils VG95 and VG460. It was found that

1. RBD palm stearin can reduce the extrusion load compared to additive-free paraffinic mineral oil.
2. RBD palm stearin can produce a surface product with a low surface roughness value.
3. The reduction of frictional constraint (reduction of load) affected the velocity and the effective strain distribution in the deformation area of the workpiece.

Acknowledgment

The authors wish to thank the Faculty of Mechanical Engineering at the Universiti Teknologi Malaysia for their support and cooperation during this study. The authors also wish to thank the Research University Grant of Universiti Teknologi Malaysia, Ministry of Higher Education and Ministry of Science, Technology and Innovation of Malaysia for the financial support.

References