Evaluation of Lubricants for Stamping of Al 5182-O Aluminum Sheet Using Cup Drawing Test

Lubricants are necessary to avoid adhesion, galling, and scratching in aluminum stamping processes. In this study, various lubricants, including dry lubes and wet lubes, were evaluated using cup drawing test (CDT) for stamping of Al 5182-O aluminum sheets. The effects of surface texturing, with electro-discharge texturing (EDT) and mill finish (MF), on the friction behavior were also investigated. Furthermore, the methodology to evaluate the performance of lubricants was established based on (a) maximum applicable blank holder force (BHF) and (b) draw-in length in flange or flange perimeter of formed cups. Finite element (FE) simulations were carried out to determine the coefficient of friction (CoF) at tool–workpiece interface during deep drawing under different lubrication conditions. Flow stress data of Al 5182-O material were obtained using viscous pressure bulge (VPB) and tensile tests. In this study, it was confirmed that, in forming Al 5182-O, dry film lubricants have better lubricity than wet lubricants. A better lubrication condition was found with EDT surface texture. [DOI: 10.1115/1.4030750]

Keywords: aluminum stamping, lubrication, surface texturing, finite element analysis

1 Introduction

Lightweight materials, such as aluminum alloys, are increasingly used in sheet metal forming of automotive parts. In forming aluminum alloys, adhesive wear and galling, due to insufficient lubricant, can greatly affect the quality of stamped parts [1]. The right lubricant can reduce or even avoid failures associated with wrinkling and premature fracture, thus increasing the process window [2]. There are mainly two types of lubricants used for aluminum sheet metal forming: dry-film lubricants and mineral oil based lubricants. Lubricants used in stamping lines are mainly based on mineral oils. They have good deep drawing performance and can be used in forming complex parts, such as inner door panels with most metals [3]. In recent studies, dry film lubricants have been used in forming to avoid scratching and galling of the tools [4,5]. Regarding the evaluation of various lubricants, twist compression test [6], deep drawing test (including CDT [7], and strip drawing test [8]) are found to be most practical testing methods. Using inverse analysis and the measured data from CDT tests, the CoF can be estimated with FE simulation. At the Center of Precision Forming (CPF), it was concluded that, compared with other lubricant testing method, the CDT can emulate the “near-production” conditions well [7]. It should be noted that the present testing method applies primarily for deep drawing operations. However, in conducting FE simulations of stamping operations, for practical reasons, only one average value of CoF is used. Thus, the CoF obtained from the CDT can be used in FE analysis of stamping.

The surface finish of the sheet also affects the lubrication during forming. Aluminum sheet is commercially available in two surface finishes: MF and EDT [3]. By using 2D and 3D measurements, it is reported that EDT can provide a higher closed void area ratio in the sheet surface to ensure a better lubricant distribution and transport than MF. As a result, a lower CoF could be achieved by using EDT [9,10]. From a microscopic scale point of view, the characterization of the asperities and valleys on the die and workpiece surfaces could provide more reasonable explanations for many tribological phenomena in sheet metal forming [11]. For a given tool, sheet material, and surface finish, the friction is also affected by rolling direction of the sheet, sliding direction of the contacts [9] and the contact pressure as well as relative velocity and interface temperature [12]. The well-known Striebeck curve was applied to describe the dependency of friction on contact pressure, sliding velocity, and dynamic viscosity of the lubricant [13]. From the experimental study on the strip drawing of Al sheets, adhesive wear was found to occur as a result of local peak stress and temperature rise [1].

In the present study, a methodology was established to evaluate the performance of different lubricants for stamping of Al 5182-O sheets. Selected lubricants were evaluated by using CDT in a hydraulic press. The effects of two different surface texturing, MF and EDT, were investigated in detail. The specific objectives are to: (a) select the lubricants that perform best in drawing of aluminum sheet 5182-O, (b) compare the friction behavior between MF surface and EDT surface, and (c) determine the CoF at the tool–workpiece interface under various lubrication conditions. The obtained CoF for selected lubricants can be used as input into FE simulations of stamping with complex geometries used in automotive production, such as hoods, decklids, and doors.

2 Experimental Procedures

2.1 Sheet Materials. In the present study, the sheet materials were characterized by both standard tensile test and VPB test. The tensile tests were conducted in rolling, diagonal, and transverse
Table 1  Mechanical properties of Al 5182-O from tensile tests (conducted by Honda R&D)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Ultimate tensile stress (MPa)</th>
<th>Yield stress (MPa)</th>
<th>R-value at strain 15 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RD1</td>
<td>291.1</td>
<td>128</td>
<td>0.69</td>
</tr>
<tr>
<td>RD2</td>
<td>291.4</td>
<td>125.8</td>
<td>0.72</td>
</tr>
<tr>
<td>DD1</td>
<td>279.8</td>
<td>120.9</td>
<td>1.08</td>
</tr>
<tr>
<td>DD2</td>
<td>279.8</td>
<td>121.7</td>
<td>1.1</td>
</tr>
<tr>
<td>TD1</td>
<td>285.8</td>
<td>123.7</td>
<td>0.79</td>
</tr>
<tr>
<td>TD2</td>
<td>284.9</td>
<td>124.1</td>
<td>0.88</td>
</tr>
</tbody>
</table>

2.2 Lubricant Samples and Surface Textures. In this study, 14 lubricants were evaluated. All the lubricants are used as received, except lubricant I, which had to be diluted with water in the ratio of 1:3 (lubricant/water). The coating weight applied on the blank was 1 g/m² for all lubricants. The details of lubricant type and application method are summarized in Table 2. The time period, from the application of a wet lubricant until the test is completed, was approximately 5 min.

Application of lubricants on the blank was done by using a pipette and draw down bar #0. Each lubricant was spread all over the blank surface on both sides uniformly. Three drops of the lubricant were applied on each side of blank to achieve a coating weight (1.0 g/m² ± 0.3 g/m²). Since it is difficult to manually apply the dry film lubricant in the laboratory scale, some of the dry film lubricants were required to be precoated by the lubricant companies with the same amount as wet lubricants. The coating weight/amount was verified by measuring a few samples using the laboratory balance before and after lube application. Additionally, the applied lubricant thickness was verified by using a portable tool (Microderm CMS). The coating weight measured by Microderm CMS tool was around 1.24 g/m², which was within the range of the coating requirement, recommended by the lubricant suppliers.

The 5182-O aluminum sheets were available with two different surface texturing, MF and EDT. Three-dimensional view of EDT surface texture measurement, conducted by Honda Engineering, is shown in Fig. 2. In order to have better understanding about the difference in the surface topography, the roughness parameters, Ra and Rz, were compared in Table 3. It can be seen that the EDT texture provide higher deviation values and the pocket structure on the surface can definitely effect the lubricated contacts.

2.3 Principles of CDT–CDT. The cup drawing process is extensively used to evaluate the performance of lubricants. The schematic of CDT is illustrated in Fig. 3. In cup drawing, the most severe friction takes place at the flange and die corners.

Table 2  Lubricants and their details as provided by lube companies

<table>
<thead>
<tr>
<th>Lubricant code</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lubricant type</td>
<td>Petroleum oil</td>
<td>Petroleum oil</td>
<td>Petroleum oil, additive blend</td>
<td>Petroleum oil, additive blend</td>
<td>Emulsified oil (semisynthetic)</td>
<td>Dry film</td>
<td>Mineral oil based</td>
</tr>
<tr>
<td>Application method</td>
<td>Draw down bar #0</td>
<td>Draw down bar #0</td>
<td>Draw down bar #0</td>
<td>Draw down bar #0</td>
<td>Draw down bar #0</td>
<td>Draw down bar #0</td>
<td>Lube company applies</td>
</tr>
<tr>
<td>Lubricant code</td>
<td>H</td>
<td>I</td>
<td>J</td>
<td>K</td>
<td>L</td>
<td>M</td>
<td>N</td>
</tr>
<tr>
<td>Lubricant type</td>
<td>Mineral oil based</td>
<td>Mineral oil based</td>
<td>Water based</td>
<td>Water based</td>
<td>Water based</td>
<td>Dry film</td>
<td>Dry film</td>
</tr>
<tr>
<td>Application method</td>
<td>Draw down bar #0</td>
<td>Draw down bar #0</td>
<td>Draw down bar #0</td>
<td>Draw down bar #0</td>
<td>Draw down bar #0</td>
<td>Lube company applies</td>
<td>Lube company applies</td>
</tr>
</tbody>
</table>

Fig. 2 3D measurements of surface texture (Al 5182-O, 1.5 mm): (a) EDT and (b) MF, provided by Honda Engineering
The lubrication condition in this flange area influences the thickness distribution in the side wall of drawn cup. It also affects the draw-in length, \(L_d\). As the blank holder pressure \(P_b\) increases, the frictional stress \(\tau\) also increases based on Coulomb’s law (Eq. (1))

\[
\tau = \mu \cdot P_b
\]

where \(\tau\) = frictional shear stress, \(\mu\) = coefficient of friction, and \(P_b\) = blank holder pressure.

The following evaluation criteria are used to determine the “better” performance of the selected lubricants: (a) higher applicable BHF for the successfully drawn part and (b) shorter perimeter in flange area (the perimeter is used in evaluation of the test results because the formed flange is not exactly round and the measurement of the perimeter avoids measuring and averaging several draw-in lengths \((L_d)\)).

2.4 Description of the Tooling and Test Procedure. The CDTs were carried out in a 160 ton hydraulic press, which has a maximum ram speed of 300 mm/s (12 in./s). The schematic of the tooling is shown in Fig. 4. A draw die attached to the upper ram moves down and forms a cup sample with a stationary punch. The preset constant BHF is provided by the CNC hydraulic cushion pins. During the CDT, the punch force is measured by a load cell and the die displacement is recorded by an infrared laser sensor. The flange perimeter is measured using a flexible tape.

The cup draw test is selected because it is relatively simple to conduct and it communicates to the practical stamping engineer how lubrication affects the metal flow and possible cup fracture. In this study, the draw ratio, the ratio of initial blank diameter to cup diameter, was selected to be 2.0. In order to leave enough flange area for measuring, the draw depth 80 mm was selected. Round blanks with 304.8 mm diameter were cut from Al 5182-O sheet.
3 FE Simulation of the CDT

In order to obtain a workable range of BHF for the tests, the FE analysis, using the commercial code PAM-STAMP, was carried out to simulate the CDT process. The FE model was built in commercial software PAM-STAMP. The sheet was modeled with four node quadrilateral shell elements, and the tools were assumed to be rigid. The flow stress curve of Al 5182-O was considered to be independent of strain-rate in the deformation rate used in CDT. The flow stress curve obtained from VPB test was used in the FE model. The yield criterion Yld 2000-2d, having a better description of the anisotropic behavior of Al alloys, was used in the FE model. The required eight yield parameters were characterized in Numisheet 2005 Benchmark for Al 5182-O [15]. All the simulations were conducted under constant BHF and punch speed.

Table 4 FE simulation parameters for obtaining BHF range for CDT

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sheet material</td>
<td>Al 5182-O, 1.5 mm</td>
</tr>
<tr>
<td>Anisotropic values (average)</td>
<td>$R_0 = 0.71, R_{45} = 1.09, R_{90} = 0.84$</td>
</tr>
<tr>
<td>Flow stress curve</td>
<td>VPB test data, as shown in Fig. 1</td>
</tr>
<tr>
<td>Yield criterion</td>
<td>Yld 2000-2d</td>
</tr>
<tr>
<td>Blank diameter</td>
<td>304.8 mm</td>
</tr>
<tr>
<td>BHF</td>
<td>16–24 ton</td>
</tr>
<tr>
<td>CoF</td>
<td>0.1, 0.11, 0.12</td>
</tr>
<tr>
<td>Punch stroke</td>
<td>80 mm</td>
</tr>
<tr>
<td>Forming speed</td>
<td>40 mm/s</td>
</tr>
</tbody>
</table>

Table 5 Predicted results under various BHF and CoF

<table>
<thead>
<tr>
<th>CoF</th>
<th>BHF 16</th>
<th>BHF 18</th>
<th>BHF 20</th>
<th>BHF 22</th>
<th>BHF 24</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>Formed</td>
<td>Formed</td>
<td>Formed</td>
<td>Fracture</td>
<td>Fracture</td>
</tr>
<tr>
<td>0.11</td>
<td>Formed</td>
<td>Formed</td>
<td>Fracture</td>
<td>Fracture</td>
<td>Fracture</td>
</tr>
<tr>
<td>0.12</td>
<td>Formed</td>
<td>Fracture</td>
<td>Fracture</td>
<td>Fracture</td>
<td>—</td>
</tr>
</tbody>
</table>

Fig. 5 Test procedure for the evaluation of lubricants

Fig. 6 Flange perimeter recorded for 13 lubricant tests at 16 ton BHF (B, D, H, and N failed at 16 ton BHF). Note: The y-axis on the graph does not start from 0. The error bands show the deviation between samples.

Fig. 7 Flange perimeter recorded for five lubricant tests at 17 ton BHF (A, C, E, I, and J failed at 17 ton BHF). Note: The y-axis on the graph does not start from 0. The error bands show the deviation between samples.

Test Procedure

Lubricants that cracked at 16 tons were not considered for BHF=17 tons test.

All lubricants cracked at 18 tons. 17 tons graph is used as final judgment.
maximum thinning value is below 20%. Otherwise, the cup gets fracture. As shown in Table 5, the drawability of 5182-O using the present die set was predicted under different BHF and CoF. It was determined that 16–18 ton is a reasonable range for evaluation of the performance of various lubricants in this study.

4 Lubrication Tests, Analysis, and Results

4.1 Test Results. Based on the FE simulation results listed in Table 5, the CDTs were conducted under BHF 16 ton, 17 ton, and 18 ton, respectively; 17 ton was found to be the maximum useful BHF for the experiments, since all the cups drawn with all lubricants cracked when BHF was 18 ton. The consistency of lubrication condition is determined by using three samples for each test. The test procedure for the evaluation of all lubricants is shown in Fig. 5.

In the tests, the measurements of $L_d$ could be easily affected by the concentricity deviation of the sample position on the die. Thus, the performance of the lubricants was evaluated by measuring the flange perimeter of the drawn cup using a tape. At 16 ton BHF, all lubricants listed in Table 2 were tested. Lubricants that cracked at 16 ton (B, D, H, and N) were not considered for next round of evaluation, using 17 ton BHF. As shown in Fig. 6, lubricant F shows the minimum flange perimeter among all the tested lubricants, indicating a better performance at 16 ton BHF. At 17 ton BHF, cups could only form with five lubricants, including three wet lubricants G, K, L and two dry film lubricants F, M.

The results under 17 ton BHF are shown in Fig. 7. It can be concluded that, among all the wet lubricants, G, K, and L could be determined as “better performing wet lubricants.” The dry film lubricant F performed “best” at both 16 and 17 ton BHFs.

4.2 Effect of Surface Texturing. The friction behavior of Al 5182-O with EDT surface and MF surface are compared, as shown in Fig. 8.
Fig. 10  Comparison of flange perimeters obtained from simulation and experiment to predict the CoF at 17 ton BHF for Al 5182O/MF

Fig. 11  Thickness comparison between experiment and simulation of drawn cup with lubricant F: (a) rolling direction and (b) transverse direction
shown in Fig. 8. Lubricants K, J, and L were first tested at 16 ton BHF. However, when BHF is increased from 16 ton to 17 ton, the cups fractured when using lubricant J. As shown in Fig. 8, the cups formed with EDT surface show smaller flange perimeters. It can be concluded that, comparing to MF, EDT provides a better lubrication condition in the current experimental procedure.

4.3 Prediction of CoF at Tool–Workpiece Interface. To determine the CoF, the perimeter of the flange obtained at the end of stroke in the simulation is compared to the results obtained in the experiment using PAM-STAMP. The parameters used as input to FE simulation are the same as parameters listed in Table 4, except that (1) BHF s used in the simulation are 16 ton and 17 ton and (2) the CoFs are 0.06, 0.08, 0.1, and 0.12. The predicted flange perimeters under different BHF s and CoFs are shown in Table 6.

As shown in Figs. 9 and 10, the flange perimeters obtained from FE simulations and experiments are compared to determine the CoFs for different lubricants under 16 ton BHF and 17 ton BHF with MF blanks. It can be concluded that (i) the CoFs for lubricants G and K are in the range of 0.08–0.1, (ii) the CoF for lubricant F is around 0.08, and (iii) the CoF for the lubricant I is around 0.12.

4.4 Comparison of Cup Thickness Variation Obtained From Simulations and Experiments. In order to verify the simulation results (CoF), the thickness distributions in the drawn cup obtained from experiments and simulations are compared. The test results for lubricants F and I are selected to verify the results of simulations. As mentioned in Sec. 4.3, the CoF of F is around 0.08 and the CoF of I is around 0.12. The cup samples drawn with lubricants F and I were cut in rolling and transverse directions. The thickness measurements along the rolling direction and transverse direction were completed using Starrett micrometer and are shown in Figs. 11 and 12. It is seen that FE simulations provided a good match with experimental results and the maximum error is around 5%.

5 Summary and Conclusions

In this study, the methodology for evaluating the performance of various commercial lubricants for forming aluminum alloy sheets was established by using CDT and FE analysis. Two surface textures were investigated and compared with different lubricants. The principal conclusions from this study are summarized as follows:

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(1) CDTs were utilized to evaluate various wet and dry lubricants under different BHFs for Al 5182-O sheets with EDT and MF surfaces. The effect of deformation on surface finish, as discussed in Ref. [16], was considered. The criteria used in this study were able distinguish the performance of selected lubricants.

(2) One of the dry film lubricants was found to perform better than wet lubricants with the same amount of coating weight (1 g/m²). In addition, EDT surfaces, with higher roughness, could provide a better lubrication condition than MF surfaces for aluminum stamping.

(3) The FE model used in PAM-STAMP yields reasonable estimate of CoFs and accurate thickness predictions when deep drawing conditions prevail. The lowest CoF 0.08 was determined for one dry film lubricant under the current experimental condition.

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References


