Evaluation of stamping lubricants in forming advanced high strength steels (AHSS) using deep drawing and ironing tests

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In forming AHSS, the lubricant must reduce the friction between die and sheet as well as the effect of heat generated from deformation and friction, especially in forming at high stroking rates. In this study, the effectiveness of stamping lubricants was evaluated by using the deep drawing and ironing tests. Various stamping lubricants were tested in forming of DP590 GA round cup samples. In these tests, the performance of lubricants was ranked via evaluation criteria that include punch force and the geometry of tested specimens. Deep drawing tests were conducted at two different blank holder forces, BHF (30 and 70 ton) at a constant ram speed (70 mm/s). The ironing tests were conducted to evaluate the performance of lubricants at higher tool–workpiece interface pressure than that is present in deep drawing. Polymer-based thin film lubricants with pressure additives (e.g. Lubricants A and B) were more effective than other lubricants as shown by the force (e.g. maximum punch force and applicable BHF without cup fracture) and geometry indicators (e.g. draw-in length, flange perimeter and sidewall thinning).

The pressure and temperature distributions at the die–sheet interface were predicted by FE simulation of deep drawing and ironing tests. As expected, the value of interface pressure and temperature were maximum at the die corner radius.

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1. Background

Various tribotests developed over the years are used to evaluate the performance of stamping lubricants under laboratory conditions. These include the strip draw test used by Vermeulen and Scheers (2001) and draw bead test used by Dalton and Schey (1992), as shown in Fig. 1. The limiting dome height (LDH) test was also used to evaluate lubricants for stamping (Schey, 1983). In this test, the location of the fracture point depends upon the frictional condition between the punch and sheet. LDH test is limited to generate a relative sliding motion at the tool–sheet interface, because the sheet material is mainly stretched during the test. A strip reduction test was introduced by Andreasen et al. (1997) and it was extensively used to evaluate lubricants in terms of the severity of galling for ironing stainless steels by Olsson et al. (2004). In this test, the thickness of the metal strip was reduced intentionally when it is pulled through a roller element (Fig. 1). Kim et al. (2008) used the twist compression test (TCT) was widely used to estimate the coefficient of friction (COF) for stamping lubricants as a function of time. However, TCT was found to have a limitation to generate plastic deformations during the test.

These tests are helpful in evaluating the performance of a lubricant at different locations in the die where the deformed sheet is under different states of stress and strain (Fig. 1). This may be one of the reasons why we obtain different values for the coefficient of friction, while conducting different tests with the same sheet material and lubricant. In addition, these tests have limitations in emulating process conditions (temperature, contact pressure and speed) that exist in real stamping operations. Evaluating lubricants in real production conditions is difficult and expensive. Therefore, a good laboratory tribotest, that can emulate the conditions found in stamping operations, is very useful and practical.

2. Objectives

The main objectives of this study are to:

• Evaluate the effectiveness of stamping lubricants selected for drawing and ironing dual phase (DP) 590 galvannealed (GA) material with a given die material (D2 Tool steel) under near production conditions.

• Predict the critical pressure and temperature at the die–workpiece interface that may cause the breakdown of lubricant film and result in galling.

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3. Approach

3.1. Deep drawing and ironing tests

The deep drawing test was successfully used for the evaluation of dry film lubricants to draw aluminum body panels by Meiller et al. (2004). Using the rectangular shape deep drawing tool, Wagner et al. (2002) compared the performance of an oil-based lubricant and other dry film lubricants. Their study concluded that one of dry film lubricants offered a larger process window for obtaining larger drawing depth and the deep drawing test well reflected on the production condition. In deep drawing, the most severe friction usually takes place at the flange area as shown in Fig. 2. The lubrication condition in the flange area influences (a) the thinning and possible failure of the sidewall in the drawn cup, and (b) the draw-in length, \( L_d \), in the flange (Fig. 2). As the blank holder pressure, \( P_b \), increases, the frictional stress, \( \tau \), also increases based on Coulomb's law, as shown in Eq. (1). Therefore, lubricants can be evaluated in deep drawing by determining the maximum applicable blank holder force without fracture in the cup wall.

\[
\tau = \mu P_b 
\]  

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

In using the deep drawing test, qualitative and quantitative analyses can be made to determine the effectiveness of lubricants, based on the following criteria proposed by Kim et al. (2007):

- The maximum punch force attained (the lower the force, the better the lubricant).
- The maximum applicable blank holder force, BHF (the higher BHF that is applied without causing fracture in the drawn cup, the better is the lubricant).
- Visual inspection of galling and zinc-powdering (in forming galvanized steels).
- Measurement of draw-in length, \( L_d \), in the flange (the larger the draw-in length, the better the lubrication).
- Measurement of the perimeter in flange area (the smaller the perimeter, the better the lubrication).

In this study, the deep drawing tests were conducted under process conditions that are present in practical stamping operations. Major emphasis was put on emulating: (a) sheet–die interface pressure levels that are similar to those occurring in production, by adjusting BHF, and (b) punch speeds that are similar to those found in mechanical stamping presses.

In the ironing test, initially a round cup is deep drawn from a circular blank and later ironed. As shown in Fig. 3, the sheet–die
interface is subjected to higher contact pressure. Furthermore, the ironing die can be heated to the range of temperatures that exist in production.

The lubricants used in the ironing test are evaluated based on the following criteria:

- The maximum ironing load attained (the lower the load, the better the lubricant).
- Visual inspection of galling (good lubricant has less galling through the die contact zone).
- Surface topography (roughness and microscopic topology) of the ironed cup after test.

3.2. Experimental setup

3.2.1. Description of the tooling

The deep drawing tooling is located in a 160 metric-ton hydraulic press that has a maximum ram speed of 300 mm/s, Fig. 4. A draw die attached to the upper ram moves down and forms a cup sample over a stationary punch. The preset constant blank holder force is applied by the CNC-controlled hydraulic cushion pins. During the test, the punch force is measured by a load cell located at the bottom of punch and the displacement of the die is recorded by a laser sensor.

In deep drawing test, the draw ratio (blank diameter/punch diameter) was selected to be 2.0. The drawing depth was selected to be about 80 mm to leave some flange area for measuring the draw-in length and the perimeter of the flange. Round blanks (305 mm diameter and 1.24 mm thick) were cut from DP590 GA steel sheet. The ironing tooling was a modified deep drawing tooling with an ironing ring insert above the draw die as shown in Fig. 5.

3.2.2. Test procedure

Detailed test procedures are given in Fig. 6. After deep drawing, the cup geometry drawn to the height of 77 mm was trimmed to a height of 50 mm by machining. Analysis of the punch force–stroke curves and visual inspection of die and the drawn cup surface were conducted after deep drawing and ironing stages.

3.2.3. Lubricant selection

In our study, six commercially available lubricants were provided by different lubricant manufacturers and were tested by deep drawing and ironing tests. To obtain the uniform coating weight of lubricant on sheet samples, the weight of the blank was measured by a digital balance (1/1000 g resolution) before and after the lubricant application by using a pipette and a sponge roller. Details of lubricant properties are given in Table 1.

3.2.4. Characterization of sheet and tool surfaces

The surface roughness of the initial sheet blank and die surface was measured by using a mechanical stylus profiler. The arithmetic average value, \( R_a \), was mainly used for characterizing the surface roughness. Multiple measurements were conducted at different locations in circumferential direction. The span of a single measurement was set to be 4 mm. The \( R_a \) value of sheet surface was found to be 1.04 \( \mu m \) and a drawing die was properly polished to obtain the \( R_a \) value of 0.1 \( \mu m \) before the test. In addition, micrographs of the sheet surfaces (DP590 GA) before the test were obtained by SEM (scanning electron microscope), as shown in Fig. 7.

3.2.5. Test conditions

The conditions used for deep drawing and ironing tests are given in Table 2 and Table 3. In each experiment, three samples were tested at a constant ram speed (70 mm/s). Two levels of BHF were selected for deep drawing test based on the preliminary FE simulations of a round cup drawing for DP590 and experimental trials. In ironing test, blank holder was not used because the flange of drawn sample was trimmed as described in Fig. 6.
Fig. 5. Schematics of ironing tooling.

Table 1
Properties of lubricants tested.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Lub A</th>
<th>Lub B</th>
<th>Lub F</th>
<th>Lub M</th>
<th>Lub N</th>
<th>Lub P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lubricant type</td>
<td>Polymer-based lubricant with EP additive</td>
<td>Polymer-based lubricant with EP additive</td>
<td>Chlorinated water emulsion lubricant</td>
<td>Synthetic water emulsion lubricant</td>
<td>Straight oil lubricant</td>
<td>Straight oil lubricant</td>
</tr>
<tr>
<td>Viscosity (centistroke)</td>
<td>26–562</td>
<td>880–1152</td>
<td>11.5–13.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coating weight (g/m²)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3.3. Deep drawing tests

3.3.1. Load–stroke curves

The load–stroke curves measured in testing various lubricants were compared for a fixed ram speed (70 mm/s), as shown in Fig. 8. The maximum punch force depends on the friction condition at the tool–sheet interface. Lub A and Lub B showed about 5 ton lower punch force than other lubricants as the stroke increased. As the BHF increases from 30 to 70 ton, sheet blanks coated by Lubricants A and B were successfully deep drawn while sheet specimens coated by other lubricants were fractured during deep drawing, Fig. 9. The maximum punch forces, $F_{\text{max}}$, measured for various lubricants at both BHF 30 and 70 ton, are shown in Fig. 10. The maximum punch force increased about 2–4 ton with increasing BHF because the higher contact pressure at the sheet–tool interface in the flange region causes higher friction forces. Most sheet samples coated with various lubricants were fully drawn at BHF 30 ton. However, the sheet samples coated with Lubricants F, M, N and P were fractured at BHF 70 ton. When the $F_{\text{max}}$ exceeded 43 ton, it resulted in the sample fracture, Fig. 10. Lub B showed a superior performance than all other lubricants and Lub A gave the second lower $F_{\text{max}}$, regardless of the BHF’s. Other Lubricants F, M, N and P are almost equal in performance at the BHF of 30 ton.

3.3.2. Comparison of perimeter and flange draw-in length

The perimeter or draw-in length of flange can be used as another friction indicator, instead of sidewall thinning distribution in the drawn cup. The smaller perimeter indicates a better performance of the lubricant. As shown in Fig. 11, Lub A and Lub B gave smaller perimeter within the measurement error bar compared to other lubricants. The perimeter of fractured cup samples were not measured at BHF 70 ton, because the fracture point and shape were not consistent enough to measure the average perimeter value from three samples.

In measuring the draw-in length, due to the non-circular shape of the flange area, four measurements were taken in different radial directions as shown in Fig. 12. Based on the measurement of
draw-in lengths, as shown in Fig. 12, Lub A and Lub B gave slightly better performance than other lubricants.

3.3.3. FEA for deep drawing

In our experiments, it was not practical to measure the temperature and pressure at the tool–workpiece interface. Therefore, the thermal–mechanical coupled FE simulations were conducted by using the commercial code, DEFORM-2D, to predict the interface temperature and pressure generated during the test.

By considering the actual geometry of tool and workpiece, 2D axisymmetric FE model was prepared to simplify the tool–workpiece configuration as shown in Fig. 13. The material properties of DP590 GA were obtained by the viscous pressure bulge (VPB) test. These data, as shown in Fig. 13, were used as the input data in the deep drawing and ironing simulations. Detailed information of VPB test is available in Gutscher et al. (2004).

In thermal–mechanical coupled FE simulations, the sheet material properties, friction coefficient ($\mu$ or $m$) and heat transfer coefficient (HTC) are the critical input parameters to obtain the reliable simulation results. In deep drawing simulation, a constant value of COF ($\mu$) was used. However, for ironing simulations, the constant shear friction factor, $m$, was used ($\tau_f = \frac{m \sigma}{\sqrt{3}}$, with $\tau_f$=frictional shear stress, $\sigma$ = flow stress of the blank material). Thermal properties of tool and workpiece were obtained from the
Fig. 7. Micrographs of DP590 GA specimen by using SEM.

Fig. 8. Load–stroke curves obtained for various lubricants tested at a low BHF.

Fig. 9. Load–stroke curves obtained for various lubricants tested at a high BHF.

Fig. 10. Maximum punch force attained for various lubricants.
material database in DEFORM and the material handbook website (www.efunda.com/materials). The heat transfer coefficient was selected from the previous sensitivity analyses conducted by FEA and TCT results, since the same tool material (D2) and same lubricants were used in both tests (Kim et al., 2008). Details of thermal properties and simulation parameters used in FE simulations are given in Table 4. The sheet was meshed with 3 elements along its thickness and with 1000 elements. The sheet was considered as a plastic object and the other objects (die, punch and blank holder) were considered as rigid.

### Table 4
Simulation parameters and thermal properties.

<table>
<thead>
<tr>
<th>Input data for simulation</th>
<th>Work piece</th>
<th>Die and punch</th>
<th>Blank holder</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material type</td>
<td>DP590</td>
<td>D2 Tool steel</td>
<td>P20 Tool steel</td>
</tr>
<tr>
<td>Object type</td>
<td>Plastic</td>
<td>Rigid</td>
<td>Rigid</td>
</tr>
<tr>
<td>Blank holder force</td>
<td>30 and 70 ton</td>
<td>11 kW/m² K</td>
<td></td>
</tr>
<tr>
<td>Heat transfer coefficient</td>
<td>Selected in a range of COF = 0.01–0.14 and m = 0.05–0.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coefficient of friction (COF) and shear function Factor, m</td>
<td></td>
<td>24.57 W/m K</td>
<td></td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>60.5 W/m K</td>
<td>50.71 W/m K</td>
<td>24.57 W/m K</td>
</tr>
<tr>
<td>Heat capacity</td>
<td>3.41 J/m³ K</td>
<td>3.81 J/m³ K</td>
<td>2.78 J/m³ K</td>
</tr>
<tr>
<td>Emissivity</td>
<td>0.05</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>Initial temperature (°C)</td>
<td></td>
<td></td>
<td>25</td>
</tr>
</tbody>
</table>
The load–stroke curves predicted by FE simulation with two different COF inputs (0.01 and 0.05) are compared with experiments with BHF of 30 ton and with a ram speed of 70 mm/s. Fig. 14.

The small fluctuation in the load–stroke curve observed in the simulation was caused by the oscillation of contact nodes between the punch and a deforming workpiece. By selecting the appropriate coefficient of friction, FE simulation gave a good match with the maximum punch force and the overall trend with experiments.

3.3.4. Predictions of contact pressure at the die–sheet interface

To better interpret the test results, FE simulation was used to predict the contact pressure at the die–sheet interface, since this variable is difficult to measure during the test. Fig. 15 shows the die–sheet interface pressure predicted by FEM simulation at BHF 30 and 70 ton with COF = 0.05. Using the point tracking function in DEFORM, about 70 nodes were selected to calculate the normal pressure values. At BHF 30 ton, the inlet and outlet of the die corner were predicted to generate a very high contact pressure, up to about 400 MPa, while the pressure along the sheet curvature remained between 50 and 150 MPa.

Also, the contact pressure at the straight flange area was predicted to be in the range of 10–45 MPa. At BHF 70 ton, the contact pressures at the inlet and outlet of the die corner were predicted to be 5–10% higher than those predicted by FEM at same points with 30 ton BHF. Therefore, when the sheet comes into the inlet of the die corner, a high contact pressure is expected and this pressure tends to increase as the BHF increases. These severe interface conditions can cause easily lubricant film breakdown and depending on the lubricant, the coefficient of friction at the die–sheet interface may increase significantly during the test.

3.3.5. Temperature distribution at the tool and workpiece

By considering the heat transfer, the thermal–mechanical coupled simulation was conducted to predict the temperature increase and its distribution in the die and deformed sheet. BHF 30 ton and
Fig. 15. FE simulation results at BHF 30 and 70 ton with COF = 0.05: (a) tracking points for calculating pressure distribution at 76 mm stroke and (b) pressure distribution at the deformed sheet and the die corner radius.

Fig. 16. Temperature distribution in the final deformed cup and the drawing die (BHF = 30 ton and COF = 0.05).

Fig. 17. Load–stroke curves measured for ironing tests with lubricants.
COF of 0.05 were selected for the simulation conditions. Fig. 16 presents the temperature distribution of the fully deformed cup at 80 mm stroke. The maximum temperature was predicted to be 86 °C along the die corner radius. This may be caused by the large plastic deformation induced by the high contact pressure and frictional shear stress at a given COF (i.e. $\tau = \mu p$). After metal flows over this die corner, it cools down. Although this maximum temperature, predicted for our given die/sheet geometry, is not high enough to affect the change in lubricant viscosity, this FEM result illustrates that the frictional condition along the deformed workpiece may change because of the large deviation of temperature and pressure. The temperature distribution in the drawing die was also predicted by FEM as shown in Fig. 16. As expected, there is a large deviation in temperatures between the die corner and the flat die surface.

3.4. Ironing test results

3.4.1. Load–stroke curves

The load–stroke curves measured in ironing tests with various lubricants were compared for a fixed ram speed (70 mm/s), as shown in Fig. 17. The maximum punch force depends on the friction condition at the tool–sheet interface. Lub A and Lub B showed about 7–23 kN lower maximum punch force than other lubricants as the stroke increased.

3.4.2. Sidewall thinning distributions

Fig. 18 compares the average values of thinning measured along the sidewall of ironed cup. In ironing test, the sidewall thinning changes depending on the interface friction between ironing die and workpiece, because the friction increases the tensile stress of sidewall during ironing. Therefore, the smaller thinning indicates a good lubrication. To eliminate the variation of ironing ratio due to the different sidewall thinning of drawn cups with various lubricants, only the cup specimens drawn with Lub A and Lub B (with additional drawn cups with these lubricants) were used for ironing tests. From the sidewall thinning measurements of selected cup samples drawn with Lubricants A and B, the deviation of sidewall thinning between the cup samples tested with Lub A and those tested with Lub B was found to be within 0.3 as shown in Fig. 18. In addition, the sidewall thinning of drawn cup was found to change in a range of 2.0–6.0%. Therefore, the actual thinning obtain from the ironing test should be in a range of 1.2–3.1% depending on the lubricant. The final thinning was calculated by measuring the sidewall thickness of ironed cup and initial blank thickness. Three samples tested for each lubricant were measured and each sample was measured on four locations around the circumference.

As shown in Fig. 18, Lub A and Lub B showed smaller thinning distribution than other lubricants. This result also corresponds to the rankings obtained in the deep drawing tests.

3.4.3. FEA of ironing

After completing deep drawing simulation, the cup geometry drawn to the height of 77 mm was trimmed to a height of 50 mm by deleting the elements beyond the cup height of 50 mm and interpolating the strains back into the trimmed geometry. Thus, the history of strain and stress obtained during deep drawing stage was used as input for the ironing simulation. Fig. 19 shows the FE model for the ironing process.

![Fig. 19. FE model of the round cup ironing process.](image-url)
The load–stroke curves for ironing test were predicted by FE simulation with different friction coefficients. In ironing simulation, due to the high contact pressure at the die–workpiece interface, the shear friction factor, \( m \), was used for friction coefficient. Fig. 20 compares the load–stroke curves between selected FE predictions and experiments.

The experimental results were within the FE predictions of \( m = 0.05 \) and 0.12, as shown in Fig. 20. However, the stroke corresponding to the maxim punch force was predicted differently by FEM compared to experiments. This may be caused by the fact that the rigid plastic model used in DEFORM does not consider the elastic deflection of cup specimen. Also, in our ironing simulation, the deep drawn geometry was trimmed and the history of strain was extrapolated to the new trimmed geometry. Therefore, there is some discrepancy between FE model of ironing and the experimental model.

The pressure distribution was calculated for the ironing simulation with friction factor, \( m = 0.1 \), that gave a good prediction of punch force compared to experiments as shown in Fig. 21. The maximum pressure was predicted as 1 GPa at the interface. In ironing simulation, the interface temperature was predicted as shown in Fig. 22. Friction factor, \( m = 0.1 \), was used in this simulation at about 28 mm stroke.

Fig. 20. Comparison of load–stroke curves predicted by FEM with experiments.

Fig. 21. FE prediction of pressure distribution between sheet and ironing die at 27 mm stroke.

Fig. 22. Temperature distribution at the workpiece and ironing die in FE simulation with \( m = 0.1 \).
4. Summary and conclusions

4.1. Summary

• Various stamping lubricants were evaluated to form DP590 GA material by using the deep drawing and ironing tests.
• To predict the pressure and temperature distributions at the die–workpiece interface, FE simulations of these tests were conducted.
• The performance of lubricants in deep drawing tests was evaluated by using (i) the maximum punch force, (ii) the maximum applicable BHF, (iii) visual inspection of zinc-powdering and galling and (iv) draw-in length and perimeter in the flange of drawn cups.
• In the ironing test, the maximum ironing force and the sidewall thinning of ironed cup were compared to evaluate the performance of lubricants.

4.2. Conclusions

The major conclusions drawn from this study are:

• Deep drawing and ironing tests were able to distinguish the performance of different stamping lubricants with AHSS under near production conditions.
• There was no severe galling or powdering in both tests.
• Based on performance evaluation criteria used in deep drawing and ironing tests, Lubricants A and B were most effective.
• Lubricants M, F, N and P gave good drawn parts at 30 ton BHF of deep drawing test, however, they all showed fractures at 70 ton BHF.
• Most lubricants were relatively effective for use in moderate deep drawing operations.
• FE simulation results imply that the variation of pressure at the tool–workpiece interface can influence the local frictional condition. However, the temperature increase was not predicted to be so severe to change the lubricant behavior during the test.
• FE prediction indicates that the contact pressure at the tool–sheet interface becomes more severe as the BHF increases. Therefore, in laboratory tribotests, it is necessary to evaluate the performance of lubricant at the relevant condition that exists in production.

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