Evaluation of tool materials, coatings and lubricants in forming galvanized advanced high strength steels (AHSS)

H. Kim\textsuperscript{a}, S. Han\textsuperscript{b}, Q. Yan\textsuperscript{c}, T. Altan (1)\textsuperscript{a,*}

\textsuperscript{a} Engineering Research Center for Net Shape Manufacturing (ERC/NSM), The Ohio State University, Columbus, OH, USA
\textsuperscript{b} School of Mechanical Engineering, Kumoh National Institute of Technology, Gumi, Republic of Korea
\textsuperscript{c} Roll Forging Research Institute, Jilin University, Changchun, China

\begin{abstract}
The major objective of this study is to establish guidelines to select the optimum combination of die materials, coatings and lubricants in stamping galvanized AHSS (DP600, TRIP780 and DP980) for automotive structural parts. For this purpose, Finite Element Analysis (FEA) and various tribotests, e.g. Twist Compression Test (TCT), Deep Drawing Test (DDT) and Strip Drawing Test (SDT), were used. The results of this study helped to determine the critical interface pressure and temperature that initiate lubricant failure and galling in forming galvanized AHSS for a given die material and coating.
\end{abstract}

\section{Introduction}
Forming of galvanized AHSS involves higher contact pressure and temperature at the tool-workpiece interface compared to forming mild steel. These unfavourable interface conditions may easily cause the failure of commonly used lubricants, leading to powdering and galling. As a result, the coefficient of friction at the tool-workpiece interface increases and the tool life is significantly reduced.

\section{Objectives}
The overall objective of this study is to develop reliable guidelines to select optimum combination of tribological parameters (i.e. die material, coating and lubricant) in stamping AHSS for automotive structural parts. The specific objectives are to:

- Develop a methodology to investigate the effect of process parameters (interface pressure, temperature and relative sliding speed) on galling during forming galvanized AHSS.
- Determine critical pressures and temperatures for the initiation of galling at the tool-workpiece interface for selected lubricants and sheet/tool characteristics (material properties, surface finish and coating).

\section{Approach}
FE simulations were conducted to determine the critical pressures and temperatures that may cause the lubricant failure and galling in forming AHSS parts. Based on these simulation results, the experimental conditions in tribotests were selected to emulate the actual conditions that may exist in production.

\subsection{FEA of forming AHSS example parts}

\subsubsection{Simulation of forming a B-pillar}
FEM simulation of forming an ULSAB B-pillar was conducted by using a commercial software, PAM-STAMP 2G. The FE model with geometries of tool and initial sheet blank are given in Fig. 1.

The flow stress of sheet material (TRIP600) was obtained by the Tensile Test and expressed with the Krupkowsky model, as shown in Table 1. The blank holder force (BHF) was determined by the FEM-based sensitivity analyses to avoid wrinkling and excessive thinning of the part. Input data used in FE simulation are given in Table 1.

From the FE analyses, the maximum thinning distribution of the final part was predicted to be 27% as shown in Fig. 2. Based on the Forming Limit Diagram (FLD) prediction of TRIP 600 by FEM, as shown in Fig. 2, this part is expected to be successfully formed.

Galling may take place on die surfaces where the contact pressures are large. Therefore, it is important to emulate these critical pressure conditions in tribotests to study lubricant performance and galling behaviour in forming AHSS.

\subsection{Deep drawing simulation}
The coupled thermo-mechanical FE simulations of a round cup drawing were conducted by using the commercial FEM code, DEFORM-2D. The primary purpose of these simulations is to (i) predict the critical temperature and pressure generated at the
tool-workpiece interface and (ii) consider these critical conditions at tribotests in our study.

From preliminary Deep Drawing Tests, the sheet blank geometry was selected to have 1.24 mm thickness and 305 mm diameter that gave 2.0 limiting draw ratio (LDR). Blank holder force (BHF) was selected as 30 tons from previous experimental tryouts and the coefficient of friction was determined to be 0.05 between the tool and workpiece by comparing FE prediction of load-stroke curve with experiments. The sheet material properties were determined by the Viscous Pressure Bulge (VPB) test at ERC/NSM [1].

Based on the simulation results, the maximum contact pressure and temperature at the die corner radius were predicted to be around 400 MPa and 85.5 °C, respectively at the final stroke of 80 mm as shown in Fig. 4.

### 3.2. The Twist Compression Test (TCT)

TCT is extensively used to evaluate the performance of lubricants, zinc-coatings and tool materials to reduce galling in AHSS forming. In the TCT, a rotating annular tool is pressed against a fixed sheet metal specimen while the pressure and torque are measured (Fig. 5).

The coefficient of friction (COF) between the tool and the specimen is calculated by using Eq. (1)

\[
\mu = \frac{T}{P A}
\]

where \( \mu \) is the COF, \( T \) is the torque transmitted from the tool to the sheet metal specimen, \( r \) is the mean radius of the tool (11 mm), \( P \) is the contact pressure exerted by the tool on the sheet metal specimen, and \( A \) is the cross sectional area of the tool (220 mm²).

#### 3.2.1. Evaluation of zinc-coated sheets using TCT

In each experiment, the test was continued until the COF reached 0.3. Thus, COF = 0.3 was used as an indicator for the start of metal-to-metal contact, based on experience obtained in laboratory tests. Typical COF versus time curves are shown in Fig. 6. Similar data were obtained for different specimen materials, zinc-coatings (e.g. Galvanized, GI and Galvannealed, GA) and contact pressures, as shown in Table 2.

The three different contact pressures were selected as 50, 100 and 170 MPa by considering the TCT machine capacity (i.e. 200 MPa) and the preliminary FE simulations of forming a B-pillar and cup drawing operation for DP 600 steel. Five different zinc-coated sheet specimens were selected for the test and the average surface roughness (\( R_a \)) of the initial sheet surface were measured as shown in Table 2.

After each test, the specimens and the tools were visually inspected for powdering (before cleaning with Acetone) and for galling (after cleaning with Acetone). Thus, the severity of galling and powdering was determined qualitatively (0-no galling/powdering to 3-most severe galling/powdering) as shown in Fig. 7.

The qualitative severity of galling for various zinc-coated specimens and lubricants tested at 170 MPa interface pressure is compared in Table 3. Similar data were obtained for 50 and 100 MPa interface pressures.

No galling was observed in TCT at 50 MPa. However, galling and powdering became severe as the contact pressure was increased to 170 MPa. DP600 GI with Lub B showed the best effectiveness in reducing galling compared with other sheet materials.

In the tests at 170 MPa, DP600 GI and DP500 GI showed different performances in reducing galling when they were tested with Lub B. Based on the scanning electron microscopy and energy dispersive spectroscopy (SEM/EDS) analyses, DP600 GI coating showed a more uniform structure while DP500 GI coating showed high porosity. DP500 GI coating gave relatively higher percentages of alloying elements (Al, Fe and O) compared to DP600 GI. Considering that aluminized steels tend to cause more adhesion and galling than other steels, the aluminum content in the galvanized coating may influence the severity of galling.

#### Table 1

<table>
<thead>
<tr>
<th>Input data used for B-pillar simulation</th>
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<tbody>
<tr>
<td><strong>Input data</strong></td>
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<tr>
<td>Sheet material</td>
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<tr>
<td>Sheet material properties</td>
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<tr>
<td>BHF</td>
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<td>Coefficient of friction</td>
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*Fig. 1.* B-pillar simulation model.

*Fig. 2.* Thinning distribution and FLD analysis of B-pillar simulation.

*Fig. 3.* Contact pressure distribution in the B-pillar part.
3.2.2. TCT evaluation of tool materials with pre-screened stamping lubricants

Various lubricants and tool materials were evaluated using TCT with D2 tool steel at 170 MPa for both GI and GA sheet materials as shown in Table 4.

3.3. Deep Drawing and Ironing Tests to evaluate the performance of lubricants under near production conditions

The Deep Drawing and Ironing Tests were used to evaluate the performance of various stamping lubricants in forming of DP590 GA round cup samples. Six wet lubricants tested by previous TCT were evaluated using Deep Drawing and Ironing Tests under near production conditions. In these tests, the performance of lubricants was ranked by comparing the drawing force and the cup geometry (i.e. flange draw-in length and the flange perimeter).

3.3.1. Deep Drawing Test

The Deep Drawing Test was successfully used for evaluation of lubricants by various European automotive manufactures [2,3]. In deep drawing, the most severe friction usually takes place at the flange area as shown in Fig. 8. The lubrication condition in the flange area influences (a) the thinning and, possibly, failure of the side wall in the drawn cup, and (b) the draw-in length, \( L_d \), in the flange, Fig. 8 [4]. As the blank holder pressure increases, the frictional stress at the flange area also increases based on Coulomb’s law [5]. Therefore, lubricants can be evaluated in deep drawing by determining the maximum applicable blank holder force without failure in the cup wall.

Deep Drawing Tests were conducted for DP590 GA (initial thickness = 1.24 mm and blank diameter = 305 mm) at two different BHF, 30 and 70 tons, at a constant ram speed, 70 mm/s. D2

Table 2

<table>
<thead>
<tr>
<th>Conditions used in TCT</th>
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<tr>
<td>Conditions Descriptions</td>
</tr>
<tr>
<td>Tool material D2 tool steel uncoated</td>
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<tr>
<td>Sheet material DP 600 Bare (thickness = 0.6 mm/Ra = 0.58 ( \mu )m)</td>
</tr>
<tr>
<td>DP 500 GI (thickness = 0.8 mm/Ra = 0.72 ( \mu )m)</td>
</tr>
<tr>
<td>DP 600 GI (thickness = 1.0 mm/Ra = 0.34 ( \mu )m)</td>
</tr>
<tr>
<td>DDS GA (thickness = 0.8 mm/Ra = 0.64 ( \mu )m)</td>
</tr>
<tr>
<td>AKDQ GA (thickness = 0.7 mm/Ra = 1.28 ( \mu )m)</td>
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<tr>
<td>Pressures 50, 100, 170 MPa</td>
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<tr>
<td>Testing speed 8.9 RPM (average surface speed = 10.35 mm/s)</td>
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<td>Lubricants Two polymer based lubricants with pressure additives</td>
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<tr>
<td>Environment temperature 22 °C (room temperature)</td>
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</table>

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tool steel was used as die material. The load-stroke curve was measured in testing various lubricants at BHF 30 and 70 tons. The maximum punch force, $F_{\text{max}}$, attained from the load-stroke curve was compared for various lubricants tested at BHF 30 and 70 tons in Fig. 9. At BHF 30 tons, while all the lubricants gave fully drawn cups, Lub A and Lub B showed about 5 tons lower punch force than other lubes as the stroke increased. As the BHF increases from 30 to 70 tons, sheet blanks coated by Lubes A and B were successfully deep drawn while sheet specimens coated by other lubes were fractured during deep drawing, as shown in Fig. 9. This fracture is caused by the failure of lubricant film under high contact pressure.

### 3.3.2. Ironing Test

The Ironing Test was also conducted to further evaluate the performance of the same lubricants tested by Deep Drawing Test. The Ironing Test provides higher pressures (up to 650 MPa) and temperatures at the tool-workpiece interface than the Deep Drawing Test [6], Fig. 10.

The Ironing Tests were conducted at a constant ram speed of 70 mm/s with A2 tool steel as die material. In this test, the maximum punch force and the sidewall thinning change depending on the interface friction between ironing die and workpiece, because the friction increases the tensile stress of side wall during ironing. Therefore, thinning is reduced with good lubrication. The thinning ratio was calculated by measuring the sidewall thickness of ironed cup before and after the test. Three samples tested for each lubricant were measured and each sample was measured in four locations in circumferential direction. Average values of thinning ratio were plotted along the side wall of ironed cup as shown in Fig. 11. Lub A and Lub B showed smaller thinning distribution than other lubricants. This result also corresponds to the Deep Drawing Test results in terms of ranking the lubricants. There was no severe galling observed in the Ironing Test.

### 3.4. Strip Drawing and Ironing Tests

The Strip Drawing Test (SDT) was developed to test the higher grades of AHSS (DP 780, TRIP780 and DP980), because the limited formability of these steels makes the Deep Drawing Test difficult to conduct. Similar concept was used in the Strip Reduction Test to investigate galling [7] and the micro-scale Strip Draw Test to develop a size-dependent friction model [8].

In SDT, two die inserts are used and the final deformed shape has a U-shape. Fig. 12 shows the half model of a drawn strip, with 80 mm depth.

With preliminary FE simulations of this test, four different die radii of 5, 8, 10 and 12 mm were determined to change the contact pressure in the range of 110–260 MPa without any necking of strip that was 356 mm long and 25.4 mm wide. The die insert was made to have four different radii as shown in Fig. 12. In addition, the insert was designed to freely adjust to specific die-punch clearances that can determine the ironing ratio of strip up to 50%. FE simulation predicted the contact pressure at the ironing zone to be about 520 MPa for 20% ironing ratio.

Preliminary tests were conducted to evaluate various die coatings against galling by using the SDT. Since galling is difficult to observe by testing a few samples, 40 strip specimens were continuously tested for each die coating without cleaning the die surface at four different lubrication and contact pressure conditions. The BHF was selected to be 5 and 1 tons for strip drawing and ironing, respectively, to avoid excessive thinning or fracture, through experiments and FE simulations. Detailed test matrix is given in Table 5.
Galling on the die surface was examined qualitatively after testing 40 specimens. The severity of galling was ranked for various die coatings, Fig. 13. The first comparison of galling for various die coatings was made after drawing of 20 specimens and the second comparison was made after ironing of 20 specimens.

As shown in Fig. 13, TiCN coating showed the best effectiveness in reducing galling under all test conditions.

4. Summary and conclusions

In this study, FE simulations of forming AHSS example parts were conducted to determine the preferred test conditions. Thus, by emulating these critical interface conditions, various tribological parameters (i.e. lubricants, zinc-coatings and die materials/coatings) were evaluated to find optimum combinations of tribological parameters for improving lubrication and reducing galling in forming AHSS.

The following conclusions can be drawn from our study:

4.1. From TCT

- For the GA coated sheet with uncoated tools (D2, Cast iron, Vancron 40 and K340-PIN) at 170 MPa, straight oil lubricants (Lub N and Lub P) and dry film lubricants (Lub C, Lub D and Lub E) showed better effectiveness to reduce galling and interface contamination.
- For the GI coated sheet with uncoated tools (D2, Cast iron, Vancron 40 and K340-PIN) at 170 MPa, a polymer film lubricant (Lub B) and a DFL (Lub C) were more effective in reducing galling and interface contamination.
- PVD coated tools (Caldie-PIN/PVD and K340-PVD) showed high COF regardless of sheet coatings and lubricants at 170 MPa contact pressure.
- At lower pressure, 50 MPa, the COF of these coated tools significantly improved in terms of the sliding distance up to COF = 0.3.
- GA coated sheets slightly decreased galling and interface contamination compared to GI coated sheets.
- From EDS analyses, it was found that galling was mainly caused by zinc-coating layers (GI and GA), not by the steel substrate.
- Through hardened tools (Vancron 40, D2 and K340-PIN) showed slightly better performance for reducing galling compared to a cast iron tool.
- Case hardened tool (K340-PIN) did not show distinguishable reduction of galling compared to through hardened tools (Vancron 40 and D2).

4.2. From Deep Drawing and Ironing Tests

- Lubes A and B gave successfully deep drawn cups while sheet specimens coated by other lubes were fractured during deep drawing with a BHF of 70 tons.
- Lub A and Lub B reduced the sidewall thinning compared to other lubricants in Ironing Tests.

4.3. From SDT

- TiCN coating showed the best effectiveness in reducing galling in comparison with other die coatings and uncoated die condition.

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