Effects of Lubrication and Surface Finish in Forming Aluminum Alloys
Focus Upon Aluminum Body Panels

Paul Bosler | Fuchs Lubricants Company & Hyunok Kim | EWI

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Acknowledgement

• Greatly thank great technical supports from Dr. Mehdi Shafiei, Novelis, Kidambi Kannan from AutoForm, and Mr. Pete Krause and Brian Hanz form AMEPA.
Lightweighting

- Lightweighting has become an important strategy for automotive OEMs.
- Light weight vehicles help meet CAFE standards & global vehicle platforms.
- Crashworthiness remains critical. Fuel efficiency without sacrificing safety.
Global Forming Diagram

Courtesy: Danny Schaeffler, Engineering Quality Solutions
New Metals and Mixed Metal Strategies
Aluminum Use over the Years

Simple to Complex Part Stampings

1990 Lincoln Town Car Hood (*hatch style*)

2017 Lincoln MKZ Hood (*flow-through style*)

Complete body and closures on the 2019 Ford F150
Aluminum Use in the Future

Aluminum Structural Components

Aluminum parts unique to e-mobility
Forming Aluminum – Challenges for Lubricants
Aluminum Challenges - Viscosity Restrictions

- Light blanks can be difficult to separate.
- Viscosity of lubes designed for steel can create hydraulic effect.
- Higher viscosities can interfere with adhesives.
Aluminum Challenges – Surface Deposition

• Aluminum can lack the topography on which lubricants can deposit.

• Lubricants for aluminum must promote polarity and good wetting.

• Lubricant boundary mechanism is its most important aspect to forming aluminum.
Aluminum Sheet Metal Surfaces

**Mill Finish**

- "Trapped surface volume"
- 0.3 – 0.5 g/m² (MF)

**EDT**

- 0.9 – 1.3 g/m² (EDT)

Surface asperities effect lubricant levels
Mechanical Resistance

1.5 g/m² soft wax

- Understand advantages and disadvantages to lube above asperities
  - Additional lubricity?
  - Squeegeed to edge of blanks?
  - Build up on tooling?
  - Hydraulic effect?
Aluminum Challenges – Effect on EP Additives

Lubes designed for steel with extreme pressure (EP) additives are not as effective on aluminum.

- Different surface polarity prevents absorption of EP additives.
- Lacks ferrous to form metallic salts.
- The surface difference benefits more from polar additives.

EP additives react with steel with better absorption to better protect during forming.

Aluminum’s shielded surface less reactive with EP additives.
Aluminum Challenges – Adhesive Compatibility

Aluminum (and dissimilar metals) can be difficult to weld.

More reliance upon adhesives for joining

- Adhesives are applied before pretreatment cleaning.
- Lubricant residues must be compatible with adhesives.
Lubricants and Adhesive Compatibility

Several characteristics of lubricants can influence compatibility with adhesives.

**Viscosity**
More viscous lubricants can be difficult to permeate.

**Coating Weight**
Heavier coating weights of lubricant can interfere with bonding.

**Chemistry**
Non-polar characteristics of water-based lubes can be incompatible with more polar adhesives. Common lube additives can have adverse effects on bonding.
Lubricant Requirements for Aluminum

• Good wetting and surface polarity

• Substantial boundary lubrication

• Minimal or buffered alkalinity
  *To prevent corrosion*

• Compatibility with adhesives

• Auto Approvals
  *Growth area is in BIW & Closures.*
Lubricant Strategies for Aluminum Body Panels
Growth in BIW & Closures

- Primarily formed by OEMs
- Potential growth into Tiers
  - EU OEM stamping needs
  - More growth than capacity
  - Segregated scrap requirements
Processes in Body in White

Skin pass – [surface treatment] – oiling

Mill Oil
Prelube
Hot Melt

leveling

[washing]

[washing]

stacking

[lubricating]

stamping

welding – adhesive bonding

pretreatment – e-paint

painting [cavity protection]

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Current Landscape for Lubricants for ABS

• **Existing Mill Oils / Prelube**
  - Must be automotive approved
  - Both designed for compatibility with aluminum and steel – *but focus on steel*
  - Mill oils designed primarily for prevention of corrosion (oxidation)
  - Prelubes for forming but too heavy for aluminum

• **Existing Hot Melt**
  - Must be automotive approved
  - Heavier viscosity and thixotropic
  - Very good formability on aluminum
  - Significant issues in post treatment

• **Blankwash**
  - Must be automotive approved
  - Oil and water based – *trending toward oil*
  - Many derived from approved mill oils
  - Designed to clean and lubricate blanks for stamping
Hot Melt

- **Thixotropic wax lubricant**
  - Contains a high percentage of wax
  - Melted and applied to coil stock and re-solidified
  - Provides exceptional boundary lubricity
  - Very effective in aluminum forming
  - Automotive approved

- **Three primary global suppliers**
  - Fuchs (*Anticorit PL 39 SX*)
  - Quaker (*Ferrocote DC2-90*)
  - Zeller Gmellin (*Multidraw E1*)
Comparing Hot Melt vs. Traditional Approved Oils

EWI cup draw test

- At 1000 psi binder, hot melt does not fracture
- Both conventional light and high viscosity traditional oils fracture at 1000 psi
Disadvantages

• **Mill or Outside Processor**
  - Specialized application equipment required
  - Build up in application cabinet
  - Can be difficult to reliably apply light coating weights

• **Press Shop**
  - Coating can melt during transportation and storage
  - Squeegeed to sides of blanks in straightening rollers
  - Blanks sticking together
  - Potential build up in press dies

• **Paint Shop** *(if soil input is heavy)*
  - Requires increased heat to cleaner to remove/substantial increased energy costs
  - Plumbing and filters clog if not separately heated
  - Higher paint rejects
Lubricant Development Goals

- Most automotive approved oils were designed primarily for performance on steel.
- *Project:* Develop a conventional oil specifically for performance on aluminum
- Must provide lubricity similar to hot melt
- Must eliminate blanks sticking together
- Must clean at lower temperatures
- Must reduce paint rejects
- Must be compatible with structural adhesives
Project Summary

Tribology and Production Trials
Test Summaries

• An aluminum supplier has run stamping trials comparing hot melt with Fuchs’ new oil (45A) on aluminum inner door panels.
• EWI Forming Center Consortium (FCC) ran tribology tests and cup draw tests comparing hot-melt and 45A.
• Auto OEM has run cup draw testing, adhesive compatibility, and cleaning.
CASE STUDY-1
EFFECTS OF DIFFERENT ALUMINUM SURFACE FINISHES ON FRICTION AND LUBRICANTION IN COLD FORMING
Objectives

• Determine the effect of the aluminum surface finish on lubrication and friction
• Characterize the friction and lubrication conditions in cold forming of aluminum sheet materials with different surface finish conditions
Approach

• Task 1 - Conduct Twist Compression Test (TCT) and Strip Draw Tests
• Task 2 - Determine Friction Model using TriboForm®
• Task 3 - Conduct Cup Draw Testing
Aluminum Alloys and Lubricants

- The same grade aluminum alloys with three different surface finishes were tested:
  - Mill surface-finish (MF) (0.9 mm)
  - Electro discharge texturing (EDT) surface-finish (1.0 mm)
  - Novelis micro texture (NMT) surface-finish (TCT and strip draw testing only)

Fuchs supplied EWI two different lubricants:
- Lubricant weight (g/m²) to roughness (µm) ratio of 1:1
  - Dry-film lubricant: Anticorit PL 39 SX
  - Wet lubricant: Anticorit PL 45A
- MF range: 0.3 – 0.5 g/m²
- EDT range: 0.7 – 1.4 g/m²

EWI completed tensile testing on both MF and EDT materials with r value.

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<tr>
<th>Temper</th>
<th>UTS (Rm)</th>
<th>YS (Rp0.2)</th>
<th>total elongation</th>
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<tr>
<td>T4 Delivery (e)</td>
<td>≥230 MPa</td>
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<td>≥22%</td>
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<td>T4 Delivery (s)</td>
<td>≥220 MPa</td>
<td>≤160 MPa</td>
<td>≥23%</td>
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<td>T6 2% pre-strain, 20 min @ 185°C (e)</td>
<td>≥290 MPa</td>
<td>≤250 MPa</td>
<td>≥16%</td>
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e = typical for exterior applications; s = typical for structure applications
Twist Compression Test (TCT) and Strip Draw Test

- Fuchs conducted TCT and strip draw testing on the selected lubricant and aluminum finishes based on EWI’s supplied test matrix.

The coefficient of friction, μ, between the tool and the workpiece is determined by the following formula:

\[ μ = \frac{T}{P \times r \times A} \]

Where:
- \( T \) = torque transmitted from the tool to the workpiece
- \( r \) = mean tool radius
- \( P \) = pressure exerted by the tool against the workpiece
- \( A \) = cross-sectional area of the tool

Annular Tool OD = 1 in
Annular Tool ID = 0.75 in

 Twist Compression Test at Fuchs

 Strip Draw Test at Fuchs
TCT Matrix

- Three surface textures of the same 6xxx aluminum were tested.
- Two different lubricants were tested.
  - MF range: 0.4 g/m²
  - EDT range: 1.0 g/m²
- Three different pressures were selected from the preliminary simulation of cup drawing.

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<td>10,152 psi (79 Mpa)</td>
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TCT Results

- Dry-film lubricant (DFL) (PL 45A) performed more effectively than a wet lube (PL45A) regardless of the testing pressures and surface texture conditions.
TCT Results - COF

Coefficient of Friction (COF) at 10 seconds of the slide contact
Strip Draw Test Matrix

- Same sheet materials and lubricants were tested.
- The strip draw testing pressures were 10 and 17 MPa which is lower than the TCT test pressure range between 17 and 120 MPa.
- The same sliding speed (10 mm/sec) was used.
- Two orientations, rolling direction/transverse direction (RD/TD), were considered for the sample prep.

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Effects of Surface Texture

- MF and EDT showed similar initial peak load, but EDT showed more stable and lower frictional force.
- NMT showed a slightly lower pulling force in both transition and steady-state response compared to MF and EDT.
Strip Draw Test Results - COF

COEFFICIENT OF FRICTION (COF) FOR RD AT 10 SECONDS OF THE SLIDE CONTACT

- MF PL 39 SX 1.5ksi: 0.146
- EDT PL 39 SX 1.5ksi: 0.130
- NMT PL 39 SX 1.5ksi: 0.121
- MF PL 45A 1.5ksi: 0.169
- EDT PL 45A 1.5ksi: 0.153
- NMT PL 45A 1.5ksi: 0.152
- MF PL 39 SX 2.5ksi: 0.094
- EDT PL 39 SX 2.5ksi: 0.095
- NMT PL 39 SX 2.5ksi: 0.089
- MF PL 45A 2.5ksi: 0.108
- EDT PL 45A 2.5ksi: 0.104
- NMT PL 45A 2.5ksi: 0.085
Major Findings

• DFL (PL 39SX) showed lower COF than wet lubricant (PL 45A).
• Ranking for the lower friction is i) NMT, ii) EDT, iii) MF.
• MF showed higher COF in RD than TD.
• EDT showed similar COF in RD and TD.
• NMT showed slightly higher COF in TD than RD.
Cup Draw Testing

- EWI conducted 6-in. cup draw testing to evaluate two selected lubricants with each material finish.
- Each sample was measured with the OFIS for oil film thickness measurements.
- The lubricants were evaluated based on:
  - Maximum drawing force (lower is better).
  - Maximum blank holder force without fracture (higher is better).
  - Flange perimeter measurements (smaller is better).
Approach – Cup Draw Testing

- Initial Blank Diameter: 12 in.
- Punch Diameter: 6 in.
- Limiting Draw Ratio: 2
- Forming Speed: 12 SPM (shots per minute)

Evaluation criteria:
- Max. punch force
- Max. BHF without fracture
- Flange perimeter

12-in. disc on blank holder

Formed cup (70.3-mm stroke)
Testing Conditions

- Die Stroke: 70.3 mm
- Forming Speed: 12 SPM
- BHF 1: 100 kN
- BHF 2: 120 kN
- BHF 3: 140 kN
- Three repetitions at each BHF for each material/lubricant combination:
  - EDT with DFL
  - EDT with wet
  - MF with DFL
  - MF with wet
Lubricant Film Thickness Measurement

- EWI used AMEPA’s OFIS system to measure the lubricant weight of each sample prior to stamping.

- OFIS system calibrations used:
  - MF with Wet: ALU MF
  - EDT with Wet: ALU EDT
  - MF with DFL: ALU MF F
  - EDT with DFL: ALU EDT F

- Three locations were measured on the top side and bottom side (towards punch) for each sample.
Results – MF with DFL

• All good parts!

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<tr>
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<th>Repetition</th>
<th>Results</th>
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Results – EDT with DFL

• All good parts!

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Results – MF with Wet Lubricant

• Good parts at 100 kN and 120 kN, cracked parts at 140 kN

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MF Wet results
Results – EDT with Wet Lubricant

- Good parts at 100 kN and 120 kN, cracked parts at 140 kN

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<td>3</td>
<td>Crack</td>
</tr>
</tbody>
</table>

EDT Wet results
Load Displacement Data

MF Dry and MF Wet comparable at 120 kN
Maximum Drawing Force

Lower force
Better lubricant

Blank Holder Force (kN)

- MF Dry
- EDT Dry
- MF Wet
- EDT Wet

Maximum Drawing Force (kN)

<table>
<thead>
<tr>
<th>Blank Holder Force (kN)</th>
<th>MF Dry</th>
<th>EDT Dry</th>
<th>MF Wet</th>
<th>EDT Wet</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>228.9</td>
<td>234.3</td>
<td>242.4</td>
<td></td>
</tr>
<tr>
<td>120</td>
<td>251.8</td>
<td>256.8</td>
<td>249.6</td>
<td>262.7</td>
</tr>
<tr>
<td>140</td>
<td>272.0</td>
<td>278.9</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Sheraton Music City Hotel
Flange Perimeter Length

EDT Dry has the smallest perimeter measurement for all three BHFs.

Smaller perimeter
Better lubricant

EDT Dry has the smallest perimeter measurement for all three BHFs.
Summary of Major Findings (1/2)

• DFL gave consistent results for both MF and EDT for all three BHFs (100 kN, 120 kN, 140 kN).

• Wet lubricant failed at 140 kN for both MF and EDT.

• MF with both DFL and wet lubricant had similar load-displacement results at 100 kN and 120 kN, while EDT with DFL and wet showed higher load data.

• However, EDT DFL had smaller perimeter measurements for all cases.
Summary of Major Findings (2/2)

- Simulations with friction above 0.1 caused a split part.
- Dry film lubricant (hot-melt) correlates well with a friction around 0.03 for EDT.
- Wet lubrication correlates well with a friction around 0.07 for MF.
- The tested wet lubricant showed good performance to form the aluminum 6xxx sheet without post-process related issues.

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Material</th>
<th>Friction Model</th>
<th>Perimeter (mm)</th>
<th>Max Load (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>MF</td>
<td>0.07 Coulomb</td>
<td>778.4</td>
<td>218</td>
</tr>
<tr>
<td>2</td>
<td>MF</td>
<td>0.12 Coulomb</td>
<td>892.2</td>
<td>230</td>
</tr>
<tr>
<td>3</td>
<td>EDT</td>
<td>0.03 Coulomb</td>
<td>769.1</td>
<td>226</td>
</tr>
<tr>
<td>4</td>
<td>EDT</td>
<td>0.09 Coulomb</td>
<td>783.9</td>
<td>244</td>
</tr>
</tbody>
</table>

Physical Measurements

<table>
<thead>
<tr>
<th></th>
<th>MF</th>
<th>EDT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dry</td>
<td>Wet</td>
</tr>
<tr>
<td>Perimeter (mm)</td>
<td>767.8</td>
<td>771.5</td>
</tr>
<tr>
<td>Max Load (kN)</td>
<td>252</td>
<td>250</td>
</tr>
</tbody>
</table>

AutoForm predicted FLD for case 2

Split Predicted
CASE STUDY-2
EFFECTS OF FORMING TEMPERATURE ON FRICTION IN WARM FORMING OF ALUMINUM
Lab-scale Cup Draw Test

As blank holder pressure ($P_b$) increases, frictional stress ($\tau$) increases based on Coulomb’s law.

- **Evaluation criteria:**
  - Maximum punch force
  - Maximum BHF without fracture
  - Maximum punch stroke at fracture
Cup Draw Testing

Only binder and die were heated to evaluate the lubricants at warm forming conditions.
• Both Forge Ease Al 278 and 280 lubricants showed excellent performances in fully drawing of 7075-T6 materials at high temperatures, 100/150/220°C.
EWI Production Scale WF Testing

• A test part designed by Tower Int’l was run at Diversified Tooling’s American Tooling Center (ATC).

Tower Side Rail Test Part: AA 7075, 1.5 mm
Various Temperatures Applying Lube Wet

150°C

200°C

250°C
Details - Production Run of Tower Side Rail

<table>
<thead>
<tr>
<th>Trial No.</th>
<th>Blank</th>
<th>Blank Temp. at Die (°C)</th>
<th>Final Part Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-3</td>
<td>Dry coated</td>
<td>150</td>
<td>Multiple cracks</td>
</tr>
<tr>
<td>4-6</td>
<td>Dry coated</td>
<td>175</td>
<td>Larger crack at R/t=1 area</td>
</tr>
<tr>
<td>7-9</td>
<td>Dry coated</td>
<td>200</td>
<td>Small crack at R/t=1 area</td>
</tr>
<tr>
<td>11-12</td>
<td>Dry coated</td>
<td>225</td>
<td>Tiny necking at R/t=1 area</td>
</tr>
</tbody>
</table>
Summary of Major Findings

• Production tests similar with results experienced in EWI lab-scale cup draw testing

• Lubricant performs best when dried on blanks prior to forming
  a.) Better part forming at all temperatures
  b.) No splits or necking >= 225°C
  c.) Lower forming temperature provides numerous benefits
     i.) Better part strength
     ii.) Better lubricant film characteristics
     iii.) Lower energy costs
  d.) Dry lubricant film can change emissivity of blank temperature in oven
     i.) Typically, blanks heat faster
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