Improving the Life of High-Strength Steel Stamping Dies

Report on A/SP Tribology Team Die Wear Study

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Outline

• Objectives
• Experimental Design
• Results
• Analyses
  – Statistical
  – Surface (Microscope)
  – Wear (Interferometry, SEM)
• Conclusions
Objectives

Support the implementation of AHSS initiatives.

• Study die wear issues in a controlled environment
• Investigate strategies for improving die life.
• Develop an understanding of die wear with AHSS to help anticipate and deal with problems.
• Die wear study - 48,000 “parts” with 16 different conditions for a total of 768,000 parts.
## Die Wear Study - Test Variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>Expected* Low Abrasive Wear</th>
<th>Expected* High Abrasive Wear</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sheet Coating</td>
<td>Hot-Dipped Galvanized (GI)</td>
<td>Galvanneal (GA)</td>
</tr>
<tr>
<td>Base Steel</td>
<td>HSLA</td>
<td>DP600</td>
</tr>
<tr>
<td>Bead Radius</td>
<td>7mm</td>
<td>5mm</td>
</tr>
<tr>
<td>Lubricant</td>
<td>Dry Film (DF)</td>
<td>Mill Oil (MO)</td>
</tr>
<tr>
<td>Bead Coating</td>
<td>CrN on D2</td>
<td>Uncoated D2</td>
</tr>
<tr>
<td>Thickness</td>
<td>1.2 mm</td>
<td>1.6 mm</td>
</tr>
</tbody>
</table>

* It was expected that abrasive wear would be higher with higher contact stress, softer die materials, and less viscous lubricants
## Die Wear Study – L16 Test Matrix

<table>
<thead>
<tr>
<th>Test #</th>
<th>Seq #</th>
<th>Sheet Coating</th>
<th>Base Steel</th>
<th>Bead Radius (mm)</th>
<th>Lube</th>
<th>Bead Coating</th>
<th>Thickness (mm)</th>
<th>Actual Thickness (mm)</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>4</td>
<td>GA DP600</td>
<td>5</td>
<td>DF D2</td>
<td></td>
<td></td>
<td>1.2</td>
<td>1.19</td>
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<tr>
<td>2</td>
<td>7</td>
<td>GA DP600</td>
<td>5</td>
<td>DF CrN</td>
<td></td>
<td></td>
<td>1.6</td>
<td>1.60</td>
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<tr>
<td>3</td>
<td>16</td>
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<td>MO D2</td>
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<td></td>
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<td>1.18</td>
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<tr>
<td>4</td>
<td>8</td>
<td>GA DP600</td>
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<td>MO CrN</td>
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<td>1.60</td>
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<tr>
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<td>11</td>
<td>GA HSLA</td>
<td>5</td>
<td>MO D2</td>
<td></td>
<td></td>
<td>1.6</td>
<td>1.66</td>
</tr>
<tr>
<td>6</td>
<td>14</td>
<td>GA HSLA</td>
<td>5</td>
<td>MO CrN</td>
<td></td>
<td></td>
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<td>1.21</td>
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<tr>
<td>7</td>
<td>6</td>
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<td>DF D2</td>
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<td>1.67</td>
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<td>DF CrN</td>
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<td></td>
<td>1.2</td>
<td>1.21</td>
</tr>
<tr>
<td>9</td>
<td>12</td>
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<td>MO D2</td>
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<td>1.57</td>
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<td>MO CrN</td>
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<td></td>
<td>1.2</td>
<td>1.16</td>
</tr>
<tr>
<td>11</td>
<td>9</td>
<td>GI DP600</td>
<td>7</td>
<td>DF D2</td>
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<td>1.6</td>
<td>1.59</td>
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<td>12</td>
<td>15</td>
<td>GI DP600</td>
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<td>DF CrN</td>
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<td></td>
<td>1.2</td>
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<td>2</td>
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<td>5</td>
<td>DF D2</td>
<td></td>
<td></td>
<td>1.2</td>
<td>1.20</td>
</tr>
<tr>
<td>14</td>
<td>10</td>
<td>GI HSLA</td>
<td>5</td>
<td>DF CrN</td>
<td></td>
<td></td>
<td>1.6</td>
<td>1.63</td>
</tr>
<tr>
<td>15</td>
<td>1</td>
<td>GI HSLA</td>
<td>7</td>
<td>MO D2</td>
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<td></td>
<td>1.2</td>
<td>1.21</td>
</tr>
<tr>
<td>16</td>
<td>5</td>
<td>GI HSLA</td>
<td>7</td>
<td>MO CrN</td>
<td></td>
<td></td>
<td>1.6</td>
<td>1.59</td>
</tr>
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</table>
## Die Wear Study - Responses

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Frequency</th>
<th>Units</th>
<th>Measurement Device</th>
<th>Accuracy</th>
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<tbody>
<tr>
<td>Pull Force</td>
<td>20 Hz</td>
<td>N</td>
<td>Load Cell</td>
<td>± 50 N</td>
</tr>
<tr>
<td>T in</td>
<td>20 Hz</td>
<td>°C</td>
<td>K-Type Thermo Couple</td>
<td>± 0.9 °C</td>
</tr>
<tr>
<td>T out</td>
<td>20 Hz</td>
<td>°C</td>
<td>K-Type Thermo Couple</td>
<td>± 0.9 °C</td>
</tr>
<tr>
<td>T die</td>
<td>20 Hz</td>
<td>°C</td>
<td>K-Type Thermo Couple</td>
<td>± 0.9 °C</td>
</tr>
<tr>
<td>Curl</td>
<td>1/Test</td>
<td>mm</td>
<td>Circle Graphs</td>
<td>± 5 mm</td>
</tr>
<tr>
<td>Strain</td>
<td>2/Coil</td>
<td>mm</td>
<td>Ultrasonic Thickness Tester</td>
<td>0.01 mm</td>
</tr>
<tr>
<td>Scoring</td>
<td>2/Coil</td>
<td>---</td>
<td>Digital Optical Microscope</td>
<td>100X</td>
</tr>
<tr>
<td>Wear Volume</td>
<td>1/Test</td>
<td>Cm³</td>
<td>Zygo White Light Interferometry</td>
<td>0.5 µm</td>
</tr>
<tr>
<td>Wear</td>
<td>1/Test</td>
<td>---</td>
<td>Scanning Electron Microscope</td>
<td>± 5 µm</td>
</tr>
</tbody>
</table>
Die Wear Test Apparatus

<table>
<thead>
<tr>
<th>No.</th>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Decoiler/Leveler</td>
<td>42” OD, 12 ID x 4” wide</td>
</tr>
<tr>
<td>2</td>
<td>Coil</td>
<td>2” coil - 0.040” thick, 2200’, 1000 lb</td>
</tr>
<tr>
<td>3</td>
<td>Guide Rollers</td>
<td>Vertical and horizontal guiding</td>
</tr>
<tr>
<td>4</td>
<td>Lubricator</td>
<td>Air brush spray top and bottom</td>
</tr>
<tr>
<td>5</td>
<td>Die Set and Inserts</td>
<td>Guided die set with bead inserts (3/set)</td>
</tr>
<tr>
<td>6</td>
<td>Feeder - 0-6” stroke</td>
<td>6000 lb hydraulic with hydraulic clamps</td>
</tr>
<tr>
<td>7</td>
<td>Cut-off</td>
<td>Synchronized with feeder</td>
</tr>
</tbody>
</table>
DWT Tooling

R=8mm; t=1.6mm
Surface Reference Only
Note: Weight of individual inserts are to be less than 170g

5mm

7mm
Restraining Force Data

Test 3   GA   DP600   7 mm   Mill Oil   D2   1.2 mm

<table>
<thead>
<tr>
<th>Results</th>
<th>Aver.</th>
<th>Min.</th>
<th>Max.</th>
<th>Std.D.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tin (°C)</td>
<td>16.37</td>
<td>-500</td>
<td>130.66</td>
<td>48.4643</td>
</tr>
<tr>
<td>Die In (°C)</td>
<td>45.16</td>
<td>-51.03</td>
<td>155.75</td>
<td>2.0072</td>
</tr>
<tr>
<td>Tout (°C)</td>
<td>42.18</td>
<td>-500</td>
<td>499.76</td>
<td>13.8943</td>
</tr>
<tr>
<td>Pull Force (N)</td>
<td>11452.8</td>
<td>164.2</td>
<td>59825.6</td>
<td>525.45</td>
</tr>
<tr>
<td>Pull Speed (m/s)</td>
<td>0.123</td>
<td>0.101</td>
<td>0.132</td>
<td>0.0026</td>
</tr>
</tbody>
</table>

File to be processed:
Test 5 - 0-48001.dct

Total Number of Strokes: 48001
Transformation - Restraining Force to Stress

Effect of Stress Transformation

Note: Error bars show ± 1 std dev

- True Stress (MPa) \( R^2 = 0.9634 \)
- Restraining Force (N) \( R^2 = 0.8468 \)
Change in Stress (Test Start to Test End)

Δ Stress %

-8.00  -6.00  -4.00  -2.00  0.00  2.00  4.00  6.00  8.00  10.00

D2  D2  D2  D2  CrN  CrN  CrN  CrN  D2  D2  CrN  CrN  D2  D2  CrN  CrN
DF  DF  MO  MO  MO  MO  DF  DF  MO  MO  DF  DF  MO  MO  DF  DF
5  5  7  7  5  5  7  7  5  5  7  7  5  5  7  7
DP600 DP600 DP600 DP600 HSLA HSLA HSLA HSLA DP600 DP600 DP600 DP600 HSLA HSLA HSLA HSLA
GA GA GA GA GA GA GA GA GA GA GA GA GA GA GA
Influence on Stress Level

Sheet Thickness And Bead Radius

Sheet Thickness And Base Steel
Influence on Stress Levels

Design-Expert® Software
Transformed Scale
Sqrt(True Stress avg)

- A1 GA
- A2 GI

X1 = F: Sheet Thickness
X2 = A: Sheet Coating

Actual Factors
B: Base Steel = DP600
C: Radius = Average
D: Lubricant = Average
E: Bead Coating = Average
Change in Strip Temperature vs True Stress

Note: Error bars show ± 1 std dev
Change in Strip Temperature vs True Stress

Design-Expert® Software
Delta Strip Temp.

A: Sheet Coating
B: Base Steel
C: Radius
D: Lubricant
E: Bead Coating
F: Sheet Thickness

Positive Effects

Pareto Chart

<table>
<thead>
<tr>
<th>Effect</th>
<th>t-Value</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>BCF</td>
<td>5.71</td>
<td>1</td>
</tr>
<tr>
<td>B</td>
<td>4.28</td>
<td>2</td>
</tr>
<tr>
<td>C</td>
<td>2.85</td>
<td>3</td>
</tr>
<tr>
<td>CF</td>
<td>2.43</td>
<td>4</td>
</tr>
<tr>
<td>F</td>
<td>1.43</td>
<td>5</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

Bonferroni Limit 3.82734

t-Value Limit 2.22814

Rank
Die Temperature vs True Stress

Note: Error bars show ± 1 std dev

True Stress (MPa)

Temperature (°C)

- DP600 - CrN
- DP600 - D2
- HSLA - CrN
- HSLA - D2
Die Temperature vs True Stress

Note: Error bars show ± 1 std dev
Change in Thinning Strain

Test #

Strain Change (+ thinner)

-4.00 -3.00 -2.00 -1.00 0.00 1.00 2.00 3.00 4.00 5.00

9 13 11 12 6 1 3 5 7 4 16 8 15 10 14 2
Stress Versus Strip Curl

Note: Error bars show ± 1 std dev
Design-Expert® Software

A: Sheet Coating
B: Base Steel
C: Radius
D: Lubricant
E: Bead Coating
F: Sheet Thickness

Positive Effects
Negative Effects

Pareto Chart

Bonferroni Limit: 3.64889

Bonferroni Limit: 2.17881
Area of yellow segment = 
\[ R^2 \cos^{-1}\left(\frac{R-h}{R}\right) - (R-h) \left(2Rh-h^2\right)^{1/2} \]

Where:
- \( R \) is the radius of the bead
- \( h \) is the height (depth) of the wear scar
Design-Expert® Software Wear
A: Sheet Coating
B: Base Steel
C: Radius
D: Lubricant
E: Bead Coating
F: Sheet Thickness

- Positive Effects
- Negative Effects
Observations

- Highest wear with lower strength (HSLA), thinner sheet (1.2), and liquid lubricant (MO)
- Less abrasive wear with CrN than with D2
- CrN showed spalling (Fatigue wear)
- GA less pickup than GI (only test 5 had PU) also noted in Phase 3
- Die and strip temperature higher with GA than GI
- Die and strip temperature higher with DP600 than HSLA.
Wear Analysis – SEM – Uncoated Beads
Wear Analysis – SEM – CrN coated Beads
Run–In of CrN Dies

Normalized Pull Force vs Stroke Range

- AD5PC6
- GD5MC2
- AH5MC2
- GH5PC6
- AD7MC6
- GD7PC2
- AH7PC2
- GH7MC6
Implications

Restraining Force
Effect of Zinc Coating
Curl

Die buyoff
Run-in of dies
Temperature - melt dry films

Temperature – CrN reduces Die temp
Failure mode: uncoated – abrasion
coated - spalling
Conclusions

Restraining force or stress is most influenced by sheet thickness and bead radius. Somewhat surprisingly, sheet coating, was also found to be a significant factor.

- Thinning strains confirm the stress factors.
- A significant interaction was found between base steel and thickness: the strain difference between the HSLA and DP600 increases as sheet thickness increases.
- Wear volume measurements shows both abrasive and adhesive wear. The type of wear was generally related to the type of bead coating.
- In general adhesion was heaviest with the galvanized sheet while abrasion was heaviest with the galvanneal sheet.
- The effect of wear on restraining force and thinning strain was not directly related to one type of wear but more on the nature of the worn surface with pickup generally increasing restraining force.
Conclusions

Unexpectedly, abrasive wear did not in many cases lead to reduced restraining force rather restraining force increased with increased abrasive wear.

- These results appear to be sensitive to bead material with the uncoated D2 showing the strongest tendency for increased restraining force with increased abrasive wear.
- The effectiveness of the wax-based DFL was less than expected possibly due to melting.
- Run-in during the initial 4000 strokes was plotted and shows a significant variation in restraining force during the run in phase.
- The restraining force with the CrN coated beads achieved stability much sooner than with the uncoated D2 beads.
Future Work

- Conduct one factor at a time testing
  - Cast Steel Die Material (S0050A)
  - DP 980
  - DP 780
  - TRIP 780
  - Galvanized/Galvanneal