Determination of suitable driver materials for electromagnetic sheet metal forming

Soeren Gies
Introduction

Effect of driver sheets

State of the art

Experimental setup and procedure

Results

Summary and Outlook
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Introduction

- **Objective:** Electromagnetic forming of stainless steel 1.4301 and 1.4509

- **Challenge:** Low electrical conductivity of stainless steel

- **Solution:** Use of driver sheets
Working principle of driver sheets:

- **Upper tool** (Forming die)
- **Lower tool** (Flat working coil)
- **Driver sheet**
- **Coil winding**

**Workpiece:** 1.4301, \( t_W = 0.8 \text{ mm} \)

**Driver:** Aluminum, \( t_D = 0.8 \text{ mm} \)
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Use of driver sheets causes **two opposing effects** in the energy conversion sequence.

Energy conversion sequence: *Risch, 2009*
Use of driver sheets causes **two opposing effects** in the energy conversion sequence.

**Trade off:** higher magnetic pressure vs. additional forming energy.
Effect of driver sheets

Use of driver sheets is beneficial if the following condition is fulfilled:

\[
\text{Additional kinetic energy} > \text{Additional forming energy for driver}
\]

\[
\text{Optimum} \quad \text{MAX} \left( \frac{\text{Additional kinetic energy } E_{\text{kin}}}{\text{Additional forming energy for driver } E_{\text{form}}} \right)
\]

Self-evident consequences:
- High electrical conductivity $\rightarrow E_{\text{kin}}$ ↑
- Low yield strength $\rightarrow E_{\text{form}}$ ↓

Question: Which driver material and which driver thickness $t_D$ maximize the energy ratio?
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**State of the art**

**Scientific investigations using driver sheets:**

- **Seth et al. (2004)**
  - Workpiece: Low-alloy carbon steel, \( t_W = 0.1 \text{ mm} - 0.38 \text{ mm} \)
  - Driver: Aluminium EN AW-6111 T4, \( t_D = 1 \text{ mm} \)

- **Li et al. (2012)**
  - Workpiece: Ti-6Al-4V, \( t_W = 0.5 \text{ mm} \)
  - Driver: CU-DHP, \( t_D = 0.5 \text{ mm} \)

- **Andersson and Syk (2008)**
  - Workpiece: X5CrNiMo17-12-2, \( t_W = 0.25 \text{ mm} / \text{DP600}, t_W = 0.7 \text{ mm} \)
  - Driver: Copper, \( t_D = 0.6 \text{ mm} \)

- **Srinivasan et al. (2010)**
  - Workpiece: Titanium, \( t_W = 0.076 \text{ mm} \)
  - Driver: Copper, \( t_D = 0.381 \text{ mm} \)

- **Ishibashi et al. (2011)**
  - Workpiece: X5CrNi18-10, \( t_W = 0.15 \text{ mm} \)
  - Driver: EN AW-1050-H24, \( t_D = 0.3 \text{ mm} \)
Scientific investigations using driver sheets:

- Tillmann et al. (2008)
  - Workpiece: DC04, $t_W = 0.8$ mm
  - Driver: Copper (sputtered), $t_D = 0.65$ mm (optimum)
  - Recommendation: $t_D = \sigma_s$

- Bely et al. (1977)
  - Recommendation: $t_D = 0.5 \cdot \sigma_s$

- Desai et al. (2011)
  - Workpiece: Stainless steel
  - Driver: Aluminum, Copper
  - Recommendation: Aluminum $\rightarrow$ $t_D = 0.8 \cdot \sigma_s$ / Copper $\rightarrow$ $t_D = \sigma_s$

- Contradicting recommendations
- No recommendation regarding optimal driver material
- No consideration of mechanical workpiece parameters

$t_W \equiv$ Workpiece thickness
$t_D \equiv$ Driver thickness
$\sigma_s \equiv$ Skin depth
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Free forming of workpiece and driver

Pulse generator used: Maxwell Magneform 7000
- Max. charging energy $E_C = 20$ kJ
- Inner resistance $R_i = 4.2$ mΩ
- Short circuit frequency $f^* = 25$ kHz
- Inner inductance $L_i = 60$ nH
Experimental Setup and Procedure

1. Free forming of workpiece and driver

- Upper tool (Drawing ring)
- Lower tool (Flat coil)
- Coil winding

2. Measuring of workpiece height $h_w$

Pulse generator used: Maxwell Magneform 7000

- Max. charging energy $E_C = 20$ kJ
- Inner resistance $R_i = 4.2$ m$\Omega$
- Short circuit frequency $f^* = 25$ kHz
- Inner inductance $L_i = 60$ nH

$h_w$ = Workpiece forming height

$t_w$ = Workpiece thickness

$t_D$ = Driver thickness
**Experimental Setup and Procedure**

**Scope of investigations:**

- **Workpiece material**
  - **1.4301**, \( t_W = 0.5 / 0.8 / 1.0 \) mm
  - **1.4509**, \( t_W = 0.5 / 0.8 / 1.0 \) mm
  - **DC04**, \( t_W = 0.5 / 0.8 / 1.0 \) mm
  - **EN AW-5083**, \( t_W = 1.0 \) mm

- **Driver material**
  - **CU-ETP**, \( t_D = 0.3 / 0.5 / 0.7 / 0.8 / 1.0 / 2.0 \) mm
  - **EN AW-1050A**, \( t_D = 0.3 / 0.5 / 0.7 / 0.8 / 1.0 / 2.0 \) mm

- **Charging Energy** \( E_C \)
  - \( E_C = 1.0 / 1.8 / 2.4 \) kJ
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Results

Workpiece:
Material 1.4509
Thickness $t_w = 0.8$ mm

$h_w = \text{Workpiece forming height}$
$t_w = \text{Workpiece thickness}$
$t_D = \text{Driver thickness}$

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**Workpiece:**
Material 1.4509
Thickness $t_w = 0.8$ mm

$h_w = $ Workpiece forming height
$t_w = $ Workpiece thickness
$t_D = $ Driver thickness

Optimum

$t_D \approx 1.05 \sigma_S$

Driver thickness $t_D$
Skin depth $\sigma_S$
Results

**Workpiece:**
- Material: 1.4509
- Thickness $t_w = 0.8$ mm

$h_w = \text{Workpiece forming height}$
$t_w = \text{Workpiece thickness}$
$t_D = \text{Driver thickness}$

![Diagram showing the workpiece with dimensions and labels.]

**Optimum**
$t_D \approx 1.05$

**Forming height** $h_w$ in mm

**Driver Forming Energy** $E_{\text{Form}}$

**Kinetic energy** $E_{\text{Kin}}$

\[
\frac{\partial E_{\text{Form}}}{\partial t_D} > \frac{\partial E_{\text{Kin}}}{\partial t_D}
\]

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**Workpiece:**

Material: 1.4509
Thickness $t_w = 0.8$ mm

$h_w = \text{Workpiece forming height}$

$t_w = \text{Workpiece thickness}$

$t_D = \text{Driver thickness}$

Optimum $t_D \approx 1.05$

$E_{Form} = \text{Driver Forming Energy}$

$E_{Kin} = \text{Kinetic energy}$

$rac{\partial E_{Form}}{\partial t_D} < \frac{\partial E_{Kin}}{\partial t_D}$

$rac{\partial E_{Form}}{\partial t_D} > \frac{\partial E_{Kin}}{\partial t_D}$

Driver thickness $t_D$

Skin depth $\sigma_S$
Results

Workpiece:
Material: 1.4509
Thickness $t_w = 0.8$ mm

$h_w$ = Workpiece forming height
$t_w$ = Workpiece thickness
$t_D$ = Driver thickness

<table>
<thead>
<tr>
<th>Charging Energy $E_C$</th>
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<tr>
<td>1.0 kJ</td>
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<td>2.4 kJ</td>
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<th>CU</th>
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</thead>
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<tr>
<td>Skin depth $\sigma_S$</td>
<td>0</td>
<td>0.5</td>
</tr>
<tr>
<td>AL</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CU</td>
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Forming height $h_w$ in mm

Driver thickness $t_D$
Results

Workpiece:
Material: 1.4301
Thickness $t_w = 0.8$ mm

$h_w = \text{Workpiece forming height}$
$t_w = \text{Workpiece thickness}$
$t_D = \text{Driver thickness}$

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Driver Sheets SotA Setup and Procedure

Summary
Conclusions

- Aluminium should be favoured as driver material
- Optimum driver thickness $t_{D,\text{opt}} \approx 1.1 \cdot \sigma_s - 1.2 \sigma_s$
- Effect of charging energy $E_C$ because of varying strain
- In case of very small strains (e.g. calibration) copper should be favoured
Results

- Comparision of optimum driver thicknesses $t_{D,\text{opt}}$
  
  *(Driver material: AL)*

<table>
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<th>Workpiece material</th>
<th>Workpiece thickness $t_W$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.5 mm</td>
</tr>
<tr>
<td>1.4301</td>
<td>0.95$\cdot\sigma_s$</td>
</tr>
<tr>
<td>1.4509</td>
<td>1.0$\cdot\sigma_s$</td>
</tr>
</tbody>
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Conclusions:

- Increasing workpiece thickness $t_W \rightarrow$ Increasing optimum driver thickness $t_{D,\text{opt}}$
- Rule of thumb: Optimum driver thickness $\approx \sigma_s$ (AL)
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Summary and Outlook

**Summary:**
- Aluminum should be favoured as driver material
- Positive correlation between workpiece thickness $t_W$ and optimum driver thickness $t_{D,\text{opt}}$
- Rule of thumb: Optimum driver thickness $\approx \sigma_s$ (AL)

**Outlook:**
- EMF of stainless steel into a conical die using the optimum driver material and thickness
- Analytical calculation of the optimum driver thickness $t_{D,\text{opt}}$
Questions?