Fully coupled multiphysics finite element simulation of magnetic pulse welding of flat parts

Uwe Dirksen
Poynting GmbH, Dortmund, Germany
1) Application of Electromagnetic pulse welding MPW

2) Fully coupled multiphysics finite element simulation

3) Finite element analysis in product and process design for MPW
Magnet Pulse Welding MPW of composite sheets with metal inserts (assembling of hybrid parts)

polymer/composite

embedded aluminium

metallic joining partner

Magnet Pulse Welding MPW of sheet metal with inserted composite

composite sheet or prepreg

metal base plate / sheet

aluminium sheet

welded sandwich sheet

Composite part, cone with flanged end

Clamping sheet (aluminium flyer)

Flange plate (aluminium or sandwich)
Electromagnetic Forming (EM) of Sheet Metal – Principle

**Flat forming setup and process principle**

- **workpiece (forming states)**
- **die / drawing ring**
- **flat coil (multi-turn)**
- **coil current \( I \)
- **magnetic field \( B \sim H \)**

### Magnetic Pressure Impulse

- **\( I(t) \rightarrow H(t) \rightarrow p(t) \)**

 acting between tool coil and workpiece at a certain radial position, but at \( r = 0 \) always \( p(t) = 0 \)

\[
p(t) = \frac{1}{2} \cdot \mu_0 \cdot \left( H_{gap}^2(t) - H_{diff}^2(t) \right)
\]
Numerical Modelling of Process

Flat forming setup and process principle

- Workpiece (forming states)
- Die / drawing ring
- Flat coil (multi-turn)
- Magnetic field $B \sim H$
- Coil current $I$

Electric oscillating circuit

- Electro-magnetic field
- Temperature
- Structural mechanics
- Lorentz forces
- Voltage, current
- Electrical conductivity
- Joule heating
- Geometry
- Material behaviour
- Plastic work

Co-funded by the European Union
Selected Finite Element Types

### Physical Domain

<table>
<thead>
<tr>
<th>Physical Domain</th>
<th>ANSYS 2D Element Types</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical circuit</td>
<td>Circu124 / Circu125</td>
</tr>
<tr>
<td>Electromagn. field</td>
<td>Plane233: 2D 8 node electromagnetic solid</td>
</tr>
<tr>
<td>Structural mech.</td>
<td>Plane223: 2D 8 node coupled-field solid</td>
</tr>
<tr>
<td>Temperature</td>
<td>Plane223: 2D 8 node coupled-field solid</td>
</tr>
</tbody>
</table>

### Physical Domain

<table>
<thead>
<tr>
<th>Physical Domain</th>
<th>ANSYS 3D Element Types</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical circuit</td>
<td>Circu124 / Circu125</td>
</tr>
<tr>
<td>Electromagn. field</td>
<td>Solid236: 3D 20 node electromagnetic solid</td>
</tr>
<tr>
<td>Structural mech.</td>
<td>Solid226: 3D 20 node coupled-field solid</td>
</tr>
<tr>
<td>Temperature</td>
<td>Solid226: 3D 20 node coupled-field solid</td>
</tr>
</tbody>
</table>
1 mesh for all physical domains
Fully automated simulation using ANSYS APDL script
Solver: Sparse
Example of Finite Element Analysis

Coil (single turn, width 8mm)  
Frec140x130-1/08

Clamping Sheet  
AW5754, t = 2mm

Composite body  
Thickness of flange: 4.2mm

Base plate  
AW5754 or AW6082
Skin depth \( \delta_s \) in conductors (coil, workpiece) must be considered.

\[
\delta_s = \frac{1}{\sqrt{\pi f \mu \kappa}}
\]

- \( f \): Frequency of current
- \( \mu \): Magnetic permeability
- \( \kappa \): Electrical conductivity

Skin depth \( \delta_s \) in copper at \( f = 10 \text{ kHz} \):
\( \delta_s = 660 \mu\text{m} \)

Air must be meshed.

Meshing and Air-Remeshing
3D Finite Element Simulation
Meshing and Performance

Nodes: 638910
Elements: 422731
1 Time-step: 30 - 45 min

Nodes: 66584
Elements: 44032
1 Time-step: 1 - 1.5 min
2D planar simulation model for sheet parts
No symmetry axis exist!

Initial voltage $U_{\text{circuit}}$ of capacitor $C$
Constraint equation:

$$U_{\text{turn}1} - U_{\text{turn}2} = U_{\text{circuit}}$$

$$U_{\text{circuit}} = \sqrt{\frac{2E}{C}}$$

$E$ : Energy

- Ground
- Resistor $R$
- Inductor $L$
- Capacitor $C$
  (initialised with $U_{\text{circuit}}$)
Electromagnetic simulation

Elements representing air

Mechanical-thermal simulation

ca. 50 µm

Elements: Conta172 / Target169
Algorithm: Penalty function > 50 µm
Contact gap:
Evaluation of Product and Process Design

Current Density

Process time $t = 3.0 \mu s$

Coil + flyer

Top view
Rectangular single-turn test coil Frec140x130-1/10

Plastic deformation of copper conductor, caused by local pressure overload along all edges (clearest in the corners)

Deformation indicates the current distribution facing the flyer sheet

Current 400 kA
10 discharges
Evaluation of Product and Process Design
Flyer Sheet Displacement

Process time
\( t = 12.5 \ \mu s \)
- state of the art is determined by basic knowledge of explosive welding (cladding)

- explosive cladding allows to assume stationary conditions, while MPW is used for small workpiece areas resulting in transient geometrical conditions

- nevertheless, dependencies of collision point velocity and collision angle seem to be relevant for process design

- **FE Process Simulation needed to determine, analyse and predict weldability**
Determination of Collision Angle:

- Workpiece contour \( t = 18.50 \mu s \)
- Die contour \( t = 18.50 \mu s \)

\[ y \text{ in mm} \]

\[ x \text{ in mm} \]

\[ \alpha \]

\[ d \]

Determination of Collision Point Velocity:

1. Determination of collision points at each load step
2. Computation of velocity of collision point between load steps
Welding Parameter Impact Velocity

Workpiece contour (t= 18.50 µs)
Die contour (t= 18.50 µs)

Node velocity of N(x,y)
- N(170,2)
- N(168,2)
- N(166,2)
- N(165,2)
- N(164,2)
- N(163,2)
- N(162,2)
- N(161,2)
- N(160,2)

Collision point velocity
- welded collision points

Flyer Velocity $v_y$ in m/s

Process Time in µs

Collision point velocity $v_c$ in m/s

Final Seminar, 24th February 2016
Belgium Welding Institute, Ghent

Co-funded by the European Union
lower limit curve (Wittman):
\[ \alpha = k_1 \sqrt{\frac{HV}{\rho}} \]

HV: Vickers Hardness in N/m²
\( \rho \): material density

surface description
k1: 0,6 high quality cleaned
1,2 imperfectly cleaned
Axisymmetric FEA
Load energy 18 kJ
Overlap o= 0 mm

Total mechanical strain v. Mises

Velocity dy/dt in m/s

0.08 0.23 0.38 0.53 >0.69
-60 60 180 300 420 >540

High strains

Low contact angle

One potential welding zone
t= 18.4 µs

Axisymmetric FEA
Load energy 18 kJ
Overlap o= 3 mm
Chamfer 45°, 1 mm

Total mechanical strain v. Mises

Velocity dy/dt in m/s

0 0.12 0.34 0.57 0.80 >1.05
-60 7 140 273 406 >540

High strains

Low contact angle

One potential welding zone
t= 18.4 µs

Two potential welding zones
t= 21.5 µs

Optimization of Product Design and Process Parameters
Welding / bonding of joined materials is not simulated in the structural mechanics sub-simulation!

No final bonding of components in welded zone.
Feature „Critical bonding temperature“ of contact element Contact172/Contact174 (ANSYS) is used to implement „Virtual Welding“.

Load curve is used to specify the bonded contact elements.

![Graph](image)

- Partner contour with activated virtual welding (t= 70.0 μs)
- Workpiece contour with activated virtual welding (t= 70.0 μs, FUD020)
- Range of activated virtual welding (81.0mm - 87.5mm)
Feature „Critical bonding temperature“ of contact element Contact172/Contact174 (ANSYS) is used to implement „Virtual Welding“.

Load curve is used to specify the bonded contact elements.

Load curve is used to specify the bonded contact elements.

Partner contour with activated virtual welding (t= 70.0 µs)
Workpiece contour without virtual welding (t= 70.0 µs, FUD023)
Workpiece contour with activated virtual welding (t= 70.0 µs, FUD020)
Range of activated virtual welding (81.0mm - 87.5mm)