Simulation of electromagnetically formed joints

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AGENDA

- Introduction: joining by electromagnetic forming
- Simulation strategy and modeling
- Numerical joint analysis
- Experimental verification
- Summary: numerical joint design
Joining by EMF – Joining mechanisms

**Interference-fit**
- Elastic-plastic bracing
- Initial geometry
  - Tool coil
  - Tube
  - Aluminum fitting
- Final geometry
  - Joining partner
  - Coil fiber rod

**Form-fit**
- Formation of undercuts
- Initial geometry
  - Mandrel: C45 with axial grooves
- Final geometry
  - Mandrel: C45 with axial grooves
  - Rohr: C35 Ø42,4x3,2 mm

**Metallic bonding**
- Cold welding
- Initial geometry
- Final geometry
- Joining partner
- Tube
- Magnetic pulse welding of sheets aluminum and steel

Source: IUL

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Joining by EMF – Joining mechanisms

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**Form-fit**
- Formation of undercuts
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- Final geometry
- Mandrel: C45 with axial grooves
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**Metallic bonding**
- Applicable for metal-metal joints only.
- Requires extremely high energy.
- Abrupt failure of the joint.

Source: IUL

Rohr: C35 Ø42,4x3,2 mm
Joining by electromagnetic compression – Exemplary material combinations
Joining by EMF – Joining mechanisms

Interference-fit

Joint strength is very sensitive to part cleanliness.
High joint strength might require long joining area.

Form-fit

Formation of undercuts

Initial geometry

Final geometry

Metallic bonding

Applicable for metal-metal joints only.
Requires extremely high energy.
Abrupt failure of the joint.

Rohr: C35 Ø42.4x3.2 mm
Mandrel: C45 with axial grooves
Historical development of joining by electromagnetic forming

Numerous studies focusing on the analyses of joining by EMF have been carried out.

1960
First patent on EMF


Basic research on tube joining interference-fit and form-fit
Basic research on tube welding
Basic research on sheet metal joining
Reports of industrial joining applications

General correlations have been identified…
…but…

…still no explicite and verified tools for designing specific electromagnetic joining applications exist.
Numerical modeling

Input variables
Workpiece, tools
- Geometry
  - Mechanical characteristics (flow curve, Density, …)
  - Electromagnetic characteristics (conductivity, permeability, …)
Pulsed power generator
- Electrical characteristics (C, L, R, loading voltage)

Electromagnetic model
- Determination of the acting loads: force- or pressure distribution at the moments \( t_0 + n \Delta t \)
- LS-Dyna980 beta version (L'Eplattenier et al. 2008)

Mechanical model
- Determination of the displacement during a short period of time \( \Delta t \)

Output variables
Workpiece, tools
- Geometry
  - Mechanical characteristics (displacement, force, pressure, strain, strain rate, …)
- Electromagnetic characteristics (magnetic fields, current density distribution, …)
Exemplary joining task and regarded cross section geometries

<table>
<thead>
<tr>
<th><strong>Tubular joining partner</strong></th>
<th><strong>Shaft</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Material:</strong> C35</td>
<td><strong>Material:</strong> C45</td>
</tr>
<tr>
<td><strong>Outer diameter:</strong> 42.4 mm</td>
<td><strong>Regarded cross section geometries:</strong></td>
</tr>
<tr>
<td><strong>Wall thickness:</strong> 3.2 mm</td>
<td>$\varnothing 36$</td>
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**Pulsed power generator**
- **Capacitance:** 330 $\mu$F
- **Inner inductance:** 0.15 $\mu$H
- **Inner resistance:** 5 m$\Omega$

**Tool coil**
- **Diameter:** 102.4 mm
- **Length (winding):** 120 mm
- **Number of turns:** 6

**Fieldshaper**
- **Length of concentration zone:** 35 mm
- **Diameter of concentration zone:** 44.9 mm
Modeling of the exemplary joining task – Geometrical setup

**Tubular joining partner**
- Material: C35
- Outer diameter: 42.4 mm
- Wall thickness: 3.2 mm

**Pulsed power generator**
- Capacitance: 330 µF
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**Tool coil**
- Diameter: 102.4 mm
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**Fieldshaper**
- Length of concentration zone: 35 mm
- Diameter of concentration zone: 44.9 mm

Number of nodes: 49,000
Number of elements: 171,000 (FEM)
35,000 (BEM)
Material modeling

According to Meyer et al. 2009

\[ \mu = \text{const} = 1 \]

Typical for non-ferromagnetic materials as aluminum, copper, etc.

Magnetic field intensity

- Linear magnetic behavior
- Nonlinear magnetization

\[ \text{Magnetic field strength in kA/m} \]

\[ \text{Magn. flux density in T} \]

\[ \text{Magn. permeability} \]

Strain rate dependency

\[ \text{Effective strain rate in s}^{-1} \]

\[ \text{Scaling factor for static yield stress} \]

\[ \text{Yield stress in MPa} \]

\[ \text{Strain rate in s}^{-1} \]

\[ \text{Plastic strain in} \]

http://users.physik.fu-berlin.de/~herold/HYS.pdf
Material modeling

Magnetic field intensity

- Linear magnetic behavior
- Nonlinear magnetization

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Typical for non-ferromagnetic materials as aluminum, copper, etc.

\[ H \text{ in MA/m} \]

http://users.physik.fu-berlin.de/~herold/HYS.pdf

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According to Meyer et al. 2009

\[ \text{Scaling factor for static yield stress} \]

\[ \text{Mag. flux density in T} \]

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\[ \text{Yield stress in MPa} \]

\[ \text{Magn. permeability in } \mu \]

\[ \text{Strain rate in } \text{s}^{-1} \]

\[ \text{Plastic strain in } \]
Material modeling

Magnetic field intensity

No significant influence of nonlinear magnetization detected

→ Influence disregarded in the numerical analysis of the joining process
Results of the numerical analyses – Joining by EMF

- Calculated course of current and inductance for shaft geometry I
  - Charging voltage: 16 kV

- Calculated course of current and inductance for shaft geometry II
  - Charging voltage: 16 kV
Results of the numerical analyses – Joining by EMF

\[ L(t) = L_0 + \Delta L(t) = L_0 + f(\Delta A) \]

\[ = L_0 + f\left(\int \int r(\varphi, t) \frac{dr}{dt}(\varphi, t) \, d\varphi \, dt\right) \]

- Calculated course of current and inductance for shaft geometry I
  Charging voltage: 16 kV

- Calculated course of current and inductance for shaft geometry II
  Charging voltage: 16 kV

Charging voltage: 16 kV
Results of the numerical analyses – Testing of the joint

**Shaft geometry I**
- Max. displacement: 2.7 mm
- Rise of gap volume: 97%
- Max. local strain: 0.45
- Strain energy: 1.0 kJ
- Maximum torque: 2300 Nm

**Shaft geometry II**
- Max. displacement: 5.3 mm
- Rise of gap volume: 136%
- Max. local strain: 0.44
- Strain energy: 0.9 kJ
- Maximum torque: 1500 Nm
Experimental verification – Joining by EMF

**Shaft geometry I**

**Shaft geometry II**

![Graph showing coil current and time](chart)

- **Coil current in kA**
- **Time t in µs**
- **Calculated current**
- **Measured current** (mean value from 10 experiments)

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Experimental verification – Testing of the joint

Clamping device (fixed)

Clamping device (rotating; connected to gear drive)

Tube

Shaft

Tactile angle measurement

Torque measurement device at Chemnitz University of Technology, Institute of Engineering Design and Drive Technology
Experimental verification – Joint strength

Torque at failure: approx. 720 Nm
(Start of plastic joint deformation)

Max. torque:
approx. 1450 Nm

Shaft geometry I

Max. torque:
approx. 2410 Nm

Shaft geometry II

Torque at failure: approx. 1415 Nm

Torque at failure: approx. 1450 Nm

Measured torque

Measured torque
Experimental verification – Joint strength

<table>
<thead>
<tr>
<th>Torque at failure in Nm</th>
<th>Simulation</th>
<th>Experiment</th>
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<tr>
<td>Torque at failure in Nm</td>
<td>1350</td>
<td>1450</td>
<td>720</td>
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<tr>
<td>Maximum torque in Nm</td>
<td>2350</td>
<td>2410</td>
<td>1500</td>
<td>1415</td>
</tr>
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</table>

Shaft geometry I

Shaft geometry II

Torque at failure

Maximum torque

Turning angle

Torque

Maximum torque
Summary

- A form-fit joint was designed on the basis of numerical investigations.
  - Simulation of the electromagnetic joining process and
  - Subsequent simulation of the torque loading
- Nonlinear magnetization of ferromagnetic materials has only minor influence in EMF-technologies.
- Strain rate dependency was considered via a scaling the static yield stress.
- The overall strain energy stored in the workpiece after joining is decisive with regard to the transferable torque.
- Knowing the max. displacement and strain is not sufficient for joint design.
- Experimental verification showed good qualitative and quantitative agreement with the simulation considering the achievable torque. (Failure type could not be predicted via this modeling.)