Magnetic Pulse Forming: Simulation & Experiments

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By: José R. Alves Z.
Outline

1. **Introduction**  
   1. Some applications  
   2. Advantages & disadvantages  
   3. ElectroMagnetic Forming in numbers

2. **Development of a Simulation toolbox**  
   1. Global Strategy  
   2. Setting Up a Simulation  
   3. Examples

3. **Experimental Facilities**  
   1. Machinery Setup  
   2. Examples

4. **Conclusions**
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Magnetic Pulse Welding & Forming

What it is?
Mechanical joining and/or foming of metallic parts by electromagnetic induction

What it has to offer?
- Improved mechanical joints by cold-welded surfaces
- Excellent electric surface conductivity between parts for electric applications
- Weld of dissimilar materials is also possible
- Preservation of surface quality due to lack of contact.

How it works?
1. The coil generates intense magnetic fields near the work piece
2. Induced eddy currents arise on the piece producing repulsive forces
3. This forces accelerate the material to high speeds over 100m/s in a few microseconds.
4. Forming is achieved due to the transformation of the kinetic energy into plastic deformation at high strain rates (over 1000s^-1)
5. The impact at such speeds bonds the surfaces at the atomic level. Thus the high quality of the joint.
Applications

First industrial application used to shrink retaining rings onto neoprene boots. The above picture shows the ball joint before and after assembly.

These anodized Platen for medical instruments were expanded with electromagnetic pressure into a mold.

Aircraft Torque Tubes. These Tubes were anodized prior to forming. The cross section shows the intimate contact of the tube to the steel fitting.

## Advantages & disadvantages

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Contact-free force application</td>
<td>• Limited range of materials</td>
</tr>
<tr>
<td>• Environmentally friendly (no lubricants)</td>
<td>• Low efficiency: ~[2 ; 8]% energy harnessed</td>
</tr>
<tr>
<td>• Joining of dissimilar materials</td>
<td>• High mechanical &amp; thermal fatigue loading on the Coil</td>
</tr>
<tr>
<td>• Significant reduction of elastic springback</td>
<td></td>
</tr>
<tr>
<td>• Production rates from 350-3600 parts/hrs</td>
<td></td>
</tr>
</tbody>
</table>

[V. Psyk et. al., ‘Electromagnetic Forming – A review’, 2011]
EMF in numbers

- **Time**
  Average process time:  
  \[ 50 – 200 \, \mu\text{seconds} \]

- **Speed**
  Average speeds:  
  \[ 100 – 300 \, \text{m/s} \rightarrow 360 – 720 \, \text{km/h} \]

- **Power**
  Order of magnitude:  
  \[ 10\text{MW} \rightarrow 13000\text{HP} \]

- **Consumption (electricity)**
  1 shot \( \approx 0.001 \) euro
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A multiphysical problem

Material properties modification

Heat transfer

\[ \rho C_p \frac{dT}{dt} = \dot{q}_{vol} + \bar{\sigma} : \bar{\varepsilon} + \nabla \cdot (k \nabla T) \]

Joule heating

Electromagnetism

\[ \nabla \cdot (\sigma \nabla \phi) + \nabla \cdot \left( \sigma \frac{\partial \bar{A}}{\partial t} \right) = 0 \]

Deformation (spatial configuration)

Deformation work

Lorentz Body forces

\[ \rho \frac{d\bar{v}}{dt} = \bar{F}_{vol} + \nabla \cdot \bar{\sigma} \]

Material properties modification
Loosy-Coupled Simulation Strategy (Process flow)

1. Start
2. MATELEC (EM Solver)
   - Solve Electric potential - Inductor
3. FORGE (Thermo-mechanical solver)
   - TM Time increment – Work Piece
     - Solve \((T; \vec{u} \text{ or } \vec{v})\)
4. MATELEC
   - EM Time increment block
     - Solve \((\phi; \vec{A})\)
5. Communicate \(\dot{q}; \vec{F}_{\text{lorentz}}\)
6. FORGE
   - Temperature field & Mesh deformation
7. End
   - Yes
     - Exit
   - No
     - EM Remeshing
8. MATELEC
   - EM Time increment block
     - Solve \((\phi; \vec{A})\)
Simulation SetUp - GLPre

A loop is established between both computations

It is possible to analyse

- ElectroMagnetic Aspects only
- Coupled with the thermo-mechanics
Predictive Simulation: The Machine Circuit

\[ V(t) = V_0 + \frac{1}{C} \int_0^t i(\tau) d\tau + Ri(t) + L \frac{di}{dt} \]

- **Machine Inductance**
- **Machine Resistance**
- **Machine Capacitance**
- **Chosen Potential** \( \propto \) to desired Energy level

Note: Only process parameter to decide or chose!!
Simulation SetUp - GLPre

Mathematical equation:

\[ V(t) = V_0 + \frac{1}{C} \int_0^t i(\tau) d\tau + R(t) + L \frac{di}{dt} \]
Example Case: **Ring Expansion** [Fenton 1996]

### Mechanical Properties

<table>
<thead>
<tr>
<th>General</th>
<th>Plasticity (Johnson-Cook Model)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Density</strong> $\rho$ [kg/m(^3)]</td>
<td>8924</td>
</tr>
<tr>
<td><strong>Elastic</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Young</strong> $E$ [MPa]</td>
<td>120e3</td>
</tr>
<tr>
<td><strong>Poisson</strong> $\nu$ [-]</td>
<td>0.3</td>
</tr>
<tr>
<td><strong>Thermal</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Conductivity</strong> $k$ [W/m*K]</td>
<td>401</td>
</tr>
<tr>
<td><strong>Specific Heat</strong> $C_p$ [J/kg*K]</td>
<td>356</td>
</tr>
<tr>
<td><strong>Expansion</strong> $\alpha$ [1/K]</td>
<td>16.6e-6</td>
</tr>
</tbody>
</table>
Example Case: **Ring Expansion** [Fenton 1996]
EM Welding
Description

- 5° circular cut (symmetry is assumed at the cut planes)
- Work piece is a deformable solid (Aluminum)
- Receptor is assumed as a rigid solid
- No friction at the contact surface
- No heat conduction between the solids
EM Welding
Description

**Electromagnetic model**
- Inductor
- Air

**Thermo-mechanical model**
- Receptor

*Lorentz Forces
Heat Source

*Temperature
Displacement / deformation

*Work Piece
EM Welding Results

Magnetic Field (x10^-8) [A/m]

Von Mises Stress [MPa]
EM Welding Results
Supersonic velocities are commonly achieved in just a few micro seconds. The impact velocity will determine the quality of the surface bonding.

The residual stresses after impact will also contribute to holding both parts together and reduce the elastic springback.
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Machine Setup

Specifications

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. Energy</td>
<td>20kJ</td>
</tr>
<tr>
<td>Normal Energy</td>
<td>14.5kJ</td>
</tr>
<tr>
<td>Max. Potential</td>
<td>9kV</td>
</tr>
<tr>
<td>Normal Potential</td>
<td>7.2kV</td>
</tr>
<tr>
<td>Power by shot</td>
<td>~9kW</td>
</tr>
</tbody>
</table>

Direct Forming setting

- Flat Metal Sheet Configuration
- Holder modified to enable Photon Doppler Velocimetry
- Weak clamping of the metal sheet
**Results**

- **1.5kV**
- **2.5kV**
- **2.65kV**
- **3kV**

- **Flange wrinkles**
- **Localized Necking**
- **Fracture due to material thinning near clamping**
### Machine Setup
Indirect Forming setting

![Machine Setup Diagram](image)

- **Receptor**
- **Matrix**
- **Hammer**
- **Coil**
- **Work piece**

### Table: Indirect Forming Results

<table>
<thead>
<tr>
<th>Double purpose matrix: Forming &amp; cutting</th>
<th>Test sample: sheet Aluminum 1050 H18</th>
<th>Formed part @3.0kVolts</th>
<th>Formed part @4.0kVolts</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Double purpose matrix" /></td>
<td><img src="image" alt="Test sample" /></td>
<td><img src="image" alt="Formed part @3.0kVolts" /></td>
<td><img src="image" alt="Formed part @4.0kVolts" /></td>
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- Cut process not completed at lower energies
Mechanical Analysis

Before

After

Equivalent deformation along the central axe

3D visualization of deformation with VIC 3D

Fracture zone
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Simulation:
- Software with a interface dedicated to Magnetic Forming.
- Capacity of dealing with large deformation problems.
- Implicit formulation for high accuracy.
- Parallel computation available. Under development.
- Axisymmetric cases with multturn coils are not handle yet.
- Piloting by electric current is not available yet (needed if the electric current history is the known input).

Experimental:
- Photon Doppler Velocimetry is under installation in the machine.
- For tube compression applications the coil needs to be modified.

Thank you for your attention
Questions?