OPTIMIZATION OF TUBULAR JOINTS BY PULSED ELECTROMAGNETIC FORMING

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Abstract
This article studies the effect of mandrel surface roughness, gap between mandrel and tube and conicity of mandrel on the strength of the joint obtained by electromagnetic forming process.
Mandrel has made by an AISI 1045 steel and tube an aluminium AA6082-T0.

Introduction
In the last century aluminium alloys became relevant for light weight construction; this was due to improvements in its production process, invention of new alloys with strength comparable to steel alloys. It is however still lagging behind steel, due not only to price, but also to the smaller offering in aluminium joining methods.
The electromagnetic pulse joining process is a variant of electromagnetic forming that can add value to the production process by:
- Alleviating the need of addition material;
- Maintaining thermal tempers, because it is a cold joining process;
- Avoiding mechanical contact with the tool, thus preserving surface finish;
- Being made more portable than presses;

It has disadvantages:
- At least one of the joining partners must be a good conductor;
- Although not recent, it is still little known and has few commercial manufacturers;
- Usually it has high-voltages in the tool (work-coil) that makes it more difficult to design tools for, because electrical considerations are added to the usual mechanical and thermal ones.

Pulsed Electromagnetic Forming
Pulsed Electromagnetic Forming process is a High Speed Metal Forming that deforms sheets of metal in less than 1 ms time.
Simpler to use and less demanding than competing high speed metal forming processes that use explosives and shock waves, it is specially well suited for work with highly conductive metals like aluminium alloys or copper alloys, with pieces from 2 meters down to 1 cm or less.

This process works by discharging a capacitor bank into a work-coil, thereby producing a very strong transient magnetic field that induces another intense secondary transient current in a metal piece
in its vicinity. The work-coil discharge current interacts with the induced current of opposite direction, in accordance with Lenz law, thus repelling each other.

Simple elliptical work-coils are used when forming sheet metal. Simple solenoids are used to compress tubular metal shapes by placing the work-coil solenoid around the closed tubular shape. If expansion is the goal, the solenoid work-coil is placed inside the closed metal shape, and thus expanded upon the current impulse. Pulsed electromagnetic forming also finds applications in joining and cutting by the use of the transient magnetic field pressure generated between work-coil and work-piece.

**Force-fit**

The *force-fit join* of tubes is obtained by first plastically compressing a metal around another in a way that the inside joining partner tube elastically deforms. When the compression stops and compression pressure is alleviated both tube and inside joining partner recuperate elastically. If the inside joining partner piece has a larger elastic modulus an interference force will remain.

This normal interference force acts as static friction normal force preventing the inside and outside partners to separate unless sufficient force is provided.

The processed studied in this work is *pulsed electromagnetic interference joining*. It is the magnetic force between work-coil and outer partner that compresses it around the inside joining partner. The use of a magnetic field to exert pressure is a non-contact method of compressing that has the advantages that no lubricants are needed nor is the other surface scuffed and surface finish damaged.

**Experimental development**

The test specimens are composed of two parts: an AISI 1045 steel male piece of 13 mm or less, and a female AA6082 aluminium alloy tube with outside diameter of 15 mm and inside diameter of 13 mm.

![Figure 1 - General test specimens geometries: a) Steel mandrel; b) Aluminium tube](image)

The mandrel is machined from a steel rod to have the geometry depicted in the Figure 1a) where the diameter in the joining is 13 mm minus two times the desired specimen joining gap to be studied. The surface of the joining area is processed with sand paper in order to obtain the desired roughness.
The tube is machined from an aluminium rod to have the geometry depicted in the Figure 1b). And it is annealed by heating it to 420 degrees centigrade for two hours and half and letting it cool in still ambient temperature air.

The mandrel and tube joining surfaces are cleaned with ethanol to remove grease and particles and blow with compressed air to remove any remaining dust and dry of the ethanol solvent. With the Poynting SMU 1500 electromagnetic forming machine and the respective SMU-K40-12/30 work-coil along with one copper fieldshaper that concentrates the pressure on a 16 mm axial length of the tube, as shown in Figure 2. The tube is compressed around the mandrel inserted in it to produce the force-fit test specimen.

![Figure 2 - Position of test specimen in cooper fieldshaper](image)

The force-fit specimen is then traction tested on a LCH speedy tester, instrumented in order to record force and displacement during the tensile test. The experiment plan explores the roughness parameter, the conicity parameter, the gap parameter. The roughness is explored through the fabrication of a set of mandrels with same geometry, but with joining surface roughness in one of three ranges. The conicity parameter is explored through the fabrication of a set of mandrels with a few different conicity angles, between positive geometries (Figure 3 – a)) and negative geometries (Figure 3 – b)) but the similar roughness between them.

![Figure 3 - a) Positive mandrel's conicity; b) Negative mandrel’s conicity](image)

The gap parameter is explored through the fabrication of a set of mandrels that have different diameters and thus will make specimens with different joining gaps, but have otherwise the same geometry and very similar surface roughness between them. The test plans are shown in Table-1.

<p>| Table 1 - Test plans |</p>
<table>
<thead>
<tr>
<th>TEST PLANS</th>
<th>TEST</th>
<th>Mandrel Ra [µm]</th>
<th>Mandrel Conicity [°]</th>
<th>Tube-mandrel Radial gap [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>FIRST TESTS (1000 J)</td>
<td>Roughness</td>
<td>[0,1 ; 3,65]</td>
<td>Null</td>
<td>Null</td>
</tr>
<tr>
<td></td>
<td>Conicity</td>
<td>1,3</td>
<td>[-0,8 ; +0,8]</td>
<td>Null</td>
</tr>
<tr>
<td></td>
<td>Radial gap</td>
<td>0,8</td>
<td>Null</td>
<td>[0,1 ; 1,2]</td>
</tr>
<tr>
<td>SECOND TESTS (1300 J)</td>
<td>High roughness</td>
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<td>Null</td>
<td>[0,5 ; 1,2]</td>
</tr>
<tr>
<td></td>
<td>Low roughness</td>
<td>0,5</td>
<td>Null</td>
<td>[0,5 ; 1,2]</td>
</tr>
</tbody>
</table>

**Roughness results**

**Efect of mandrel roughness @1KJ (EMF)**

![Graph showing the relationship between mandrel roughness and extraction force](image)

Figure 4 - Force of extraction of joint vs roughness of mandrel

The pull-out force of the specimens with variable roughness shows an upward trend in strength with the increase in roughness as shown in Figure 4.

**Conicity results**

![Graph showing the relationship between conicity and extraction force](image)
The small range of conicities tested (Figure 5) is consistent with the dimensional errors in turned parts in a not very demanding machining center. The plot of the Figure above shows that the joint strength has negligible dependency with conicity values in the -0.8 to +0.8 degrees.

**Radial Gap results**

Strength of joint vs radial gap for different roughness and energy level

![Graph showing the relationship between strength of joint and radial gap for different roughness and energy levels.](image)

The distribution of the 1 kJ joined specimens clearly shows that an optimal gap exists around the 0.8 mm value.
Consider the high speed of the electromagnetic joining process, the tube wall need some free radial length in order to accelerate, however too much length will cause the tube wall area that is not subjected to the compression pressure to stretch and consequently slow down the previously accelerated wall. It is reasonable to say that there is a gap distance that allows the accelerated wall to hit the mandrel surface of maximum speed and become imprinted with the mandrel roughness pattern and as a result increase the strength need to extract the mandrel from the compressed tube.

**Impact welding**

To certain on the suspected existence of impact welding points, an optimum gap specimen was joined and then cut longitudinally using wire electric discharge machining (WEDM) in order to see if the tube halves would stick to the mandrel surface or instead jump due to the release of axial tensions. It jumped (Figure 7) leaving a clean mandrel surface; therefore there were no impact welding points.

![Figure 7 - Wire EDM cut in axial direction of joint](image)

![Figure 8 - Wire EDM cut in cross section of joint at 1000 J](image)

**Conclusion**

Electromagnetic tube joining is a novel joining process, but being actually mechanical interference phenomena the surface is indeed one of the important parameters to control. A question may arise concerning how much roughness a join can have and still be considered a force-fit joint,
instead of a form-fit joint. Only a set of experiments were the internal micro topography of the tube is mapped before and after the joining and also after the tensile test can shed more light on the subject.

The results show that the gap is a parameter important to consider while designing an impulse electromagnetic joint, and a way to take advantage of the processes' high speed nature.

This work shows that within a certain range of values the conicity of the mandrel needs not be a big concern in practical applications.

In this work there was no impact welding. This may be due to the somewhat dissimilar nature of the materials joined, or to too low impact velocities.

Bibliography


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