TORQUE RESISTANCE OF JOINTS MADE BY MAGNETIC PULSE CRIMPING

D. Bogaert[1], W. De Waele[2], K. Faes[3] and O. Zaitov[3]

[1] Ghent University, Belgium
[2] Ghent University, Laboratory Soete, Belgium
[3] Belgian Welding Institute, Belgium

Abstract The possibility to use strong electromagnetic pulses to plastically deform electrically conductive materials has been known for several decades. Despite its energy-efficiency and potential cost-efficiency, wide-spread use of the technology on an industrial level hasn't been reached. As recently shown by Schäfer and Pasquale [1], more research towards industrial applicability is being conducted. This thesis will experimentally investigate the feasibility of realizing torsion resistant tube joints manufactured by magnetic pulse crimping. To get acquainted with the subject, first a literature study was performed. The general principles of the electromagnetic pulse technology were studied. Differences between the widely investigated welding technology and less documented crimping technology were obtained. Through the results of earlier work [2] on crimping of tubes to obtain axial strength, it became clear that the crimping process requires an optimization of geometrical parameters of the workpieces. This optimization is considered the main focal point of this thesis.

Keywords: magnetic pulse; crimping; torsion stiffness; tubes.

1 ELECTROMAGNETIC PULSE CRIMPING

1.1 Introduction

As reported in literature and investigated by the Belgium Welding Institute, electromagnetic pulse (EMP) welded tubes with the required torsional joint strength have already been manufactured. [3] Some negative characteristics inherent to welding (e.g. presence of voids on brittle intermetallic layers at the weld interface) do not emerge in the crimping process. Besides that, crimping requires less energy input and would make the EMP process more durable. Those benefits can result in a larger overall applicability of the crimping process.

1.2 General process overview

To plastically deform or join mechanical workpieces, the EMP process generates strong magnetic forces. Thereto, an EMP system, as shown in Figure 1, consists of a connection to the AC-grid, a transformer to reach the high operating voltage, a bank of capacitors to store the energy needed for the pulse, a high current switch to release the electromagnetic energy and a magnetic coil system to generate the electromagnetic field and force.

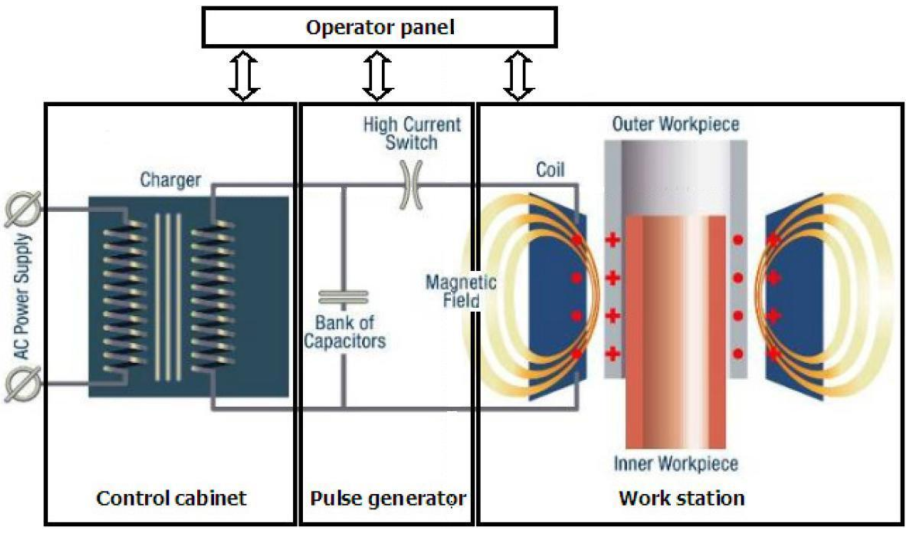


Figure 1. Setup overview [4].

During the course of the 15 to 25 microsecond process, the magnetic field penetrates the workpiece wall. The resulting pressure pulse acts orthogonally on the magnetic field inside the coil, and the Lorentz repulsion force causes the tube to repel away from the coil. Hereby a collision with the inner workpiece is achieved. When the applied magnetic force is greater than the workpiece material's yield strength, permanent plastic deformation occurs.

2 GOAL AND ADVANTAGES OF THE CRIMPING PROCESS FOR TORSION RESISTANT TUBES

As in most mechanical systems, the performance of the manufactured pieces is evaluated based on its mechanical strength. As illustrated in Figure 2, the goal of this thesis is manufacturing tube joints with a torsion resistance higher than the base tube material, using the EMP crimping process.

Figure 2. Illustration of the main process goal [3].

In comparison to conventional quasi-static forming processes, it is clear that EMP forming yields several advantages:

- Very high forming speed, which leads to high strain rates, increased flow stress, increased strain hardening and increased ductility for several steels and metals.
- Automation of the process can eventually lead to a high productivity and economic profitability.
- Higher accuracy due to reduced springback and reduced wrinkling. [5]
- Joining of dissimilar materials is possible, including combinations of dissimilar metals, metals and polymers or composites,...

A more elaborate discussion of the process advantages can be found in a review paper of Psyk et al. [6] and in study by Dehra M.S. [7].

Still some disadvantages are intrinsic to the process as well:

- Only electrically conductive materials can be formed with the process
- The installation requires significant safety measures because of the high currents and voltages resulting in strong magnetic fields.
- High thermal and mechanical loading of the field shaper limits its long-term integrity.

In comparison to electromagnetic pulse welding, clear advantages exist on behalf of system lifetime and energy use.

3 STRENGTH MECHANISMS

In crimp joints, there are 2 main mechanisms adding to the strength of the connection: interference fitting and form fitting.

3.1 Interference fit

The strength of an interference fit depends on 3 factors:

- The residual contact stresses at the interface between both workpieces (σ_{res}). The outer workpiece deforms in a plastic way, the inner workpiece deforms in an almost purely elastic way. The result is a build-up of residual contact stresses between the workpieces when the EMP crimp process has finished.

- The friction coefficient between the outer tube and the inner workpiece (μ).
- The area of the contact zone (A). This area depends mostly on the type of material and on the surface roughness values of the used components.

To disconnect an interference fit, it is now clear that a force F proportional to the three factors is required:

$$F \sim \mu . A . \sigma_{res} \tag{1}$$

3.2 Form fit

The strength of a form fit mainly results from the geometry of the inner workpiece. In a study focused at realizing joints with axial strength, testing of different groove geometries led to the conclusion that rectangular grooves give the highest interlocking forces compared to triangular and circular grooves of the same dimensions [8]. Although circular grooves result in a smaller angle α (see radioscopic pictures in Figure 3), the rectangular grooves still result in a higher pull-out resistance because of the larger amount of shearing, which locks the tube better. These results are easily transferrable to torsional loaded joints as well. The same material (aluminum EN-AW 6060) was used for the tubes and the mandrels.

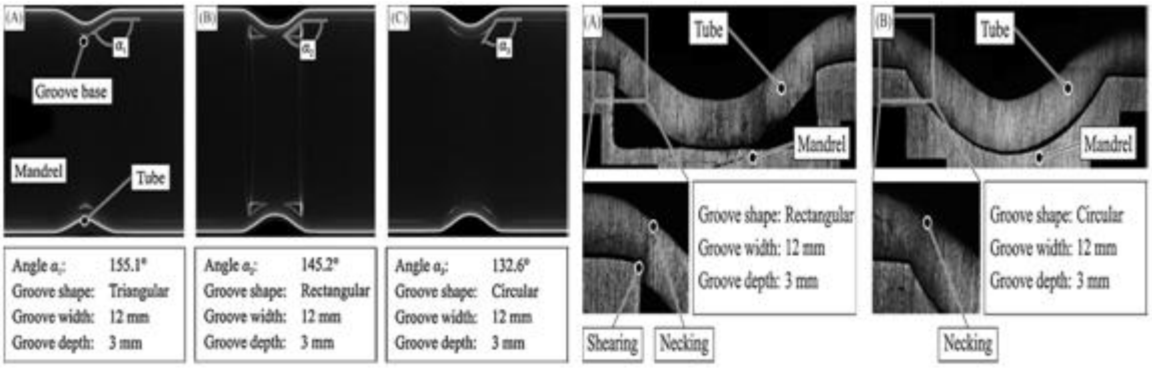


Figure 3. EMP crimping: resulting angle α (left) and comparison of grooves (right) [8].

4 WORKPIECE DESIGN

As mentioned, due to the manifesting strength mechanisms, the geometry of the workpieces is of great importance to the success of the EMP crimping process.

4.1 Groove design

It is planned that most experiments that will be conducted, will have workpieces based on groove geometries reported in studies aiming at designs for optimal axial strength [2].

As shown by Park et al. [9], the transferrable torque of a joint is proportional to the circumferential forces. Because of the axial symmetry in the torque design, we can easily conclude upon:

- The torque transferrable is proportional to the length of the torque joint.
- The deeper the grooves, the more torque transferrable
- The torque transferrable is proportional to the number of grooves in circumferential direction.

This last presumption is justified as long as the different grooves do not affect each other's strength. At a too large number of grooves, the width of the grooves (in circumferential direction) is insufficient in comparison with the groove depth. The design parameters of a rectangular groove, as shown in Figure 4, are explained next.

4.1.1 Groove radius

Because of 2 opposite effects, an optimal value for the groove radii exists. When the groove radius becomes too small, too much necking and according thinning of the tube will occur, and the joint loses its strength. A too large groove radius will allow the tube to move out the groove when a force is applied. Earlier research on this behalf indicates a smaller dependence of necking in torsion loaded joints than noticed in the axial ones. It can therefore be expected that a lower optimal radius will be reached than in the axial cases discussed in [2].

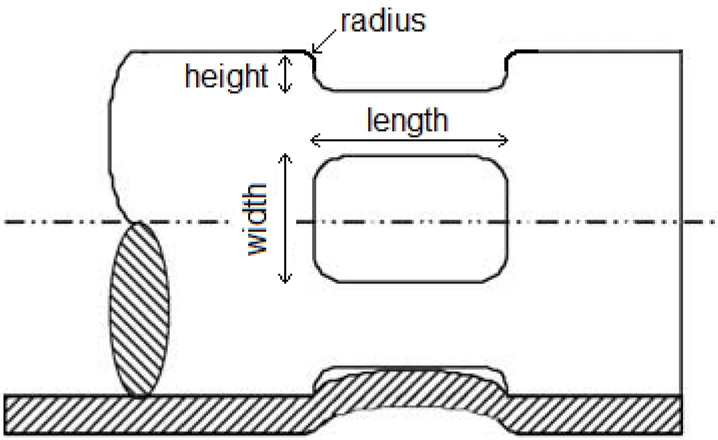


Figure 4. Main geometric design parameters of the used rectangular grooves [9].

4.1.2 Groove depth

Just like for groove radius an optimal value exists. With a deeper groove, the tube is not that easily separated from the inner workpiece when subjected to load. However, a too deep groove leads to severe necking of the tube, which is detrimental towards joint strength.

4.1.3 Groove length

The larger the groove length, the larger the contact area between tube and inner workpiece, and the more friction force is reached. So the higher the length, the stronger the connection. Still, at a certain length a maximum strength occurs. This is because further length increase leads to wrinkling of the tube, which causes a drop in joint strength.

4.1.4 Groove width

Similar as for groove length, an increased strength with increasing width is observed. Furthermore, groove width is limited because spacing is required between subsequent grooves.

The above considerations on groove design lead to an optimal value of grooves. In this thesis, using aluminum tubes of 50 mm diameter and groove depths between 1,8 and 3,3 mm, an optimal value for number of grooves will lie somewhere between 4 and 8. As will be discussed further, in the first experiments a design with 5 grooves is proposed.

4.2 Knurl design

Next to the concept of a groove design, which is mostly based on theory of form fitting and has grooves deeper than the tube wall thickness, a concept based mostly on interference fitting can be proposed. The idea is to create an inner workpiece surface with the ability to transfer as much grip as possible to the outer tube. Eguia et al. [10] proposed the use of a knurl pattern. As seen on Figure 5, a very symmetric and periodic pattern is brought onto the inner workpiece surface. The height of the pattern is smaller than the thickness of the tube wall.

The beneficial effects of these patterns are qualitatively clear. This is, a higher circumferential force can be exerted because of the area of the knurl pattern rectangular to the normal surface. As stated by Eguia et al. [10], a finer knurl pattern gives better results with respect to torsional strength. Still, experiments are needed to determine an improved quantitative understanding of the effectiveness of the knurl pattern in comparison with the groove designs.

Figure 5. Examples of knurl patterns [10].

5 EXPERIMENTS

5.1 Preliminary designs

A qualitative investigation into a multitude of groove designs has been performed. Hereby, 4 inner workpiece (S235) designs were proposed, as illustrated on Figure 6. The applied charging voltage was the only variable process parameter. As will be discussed in the results section, the tube deformation was visually evaluated, leading to a basic understanding of the process behaviour.

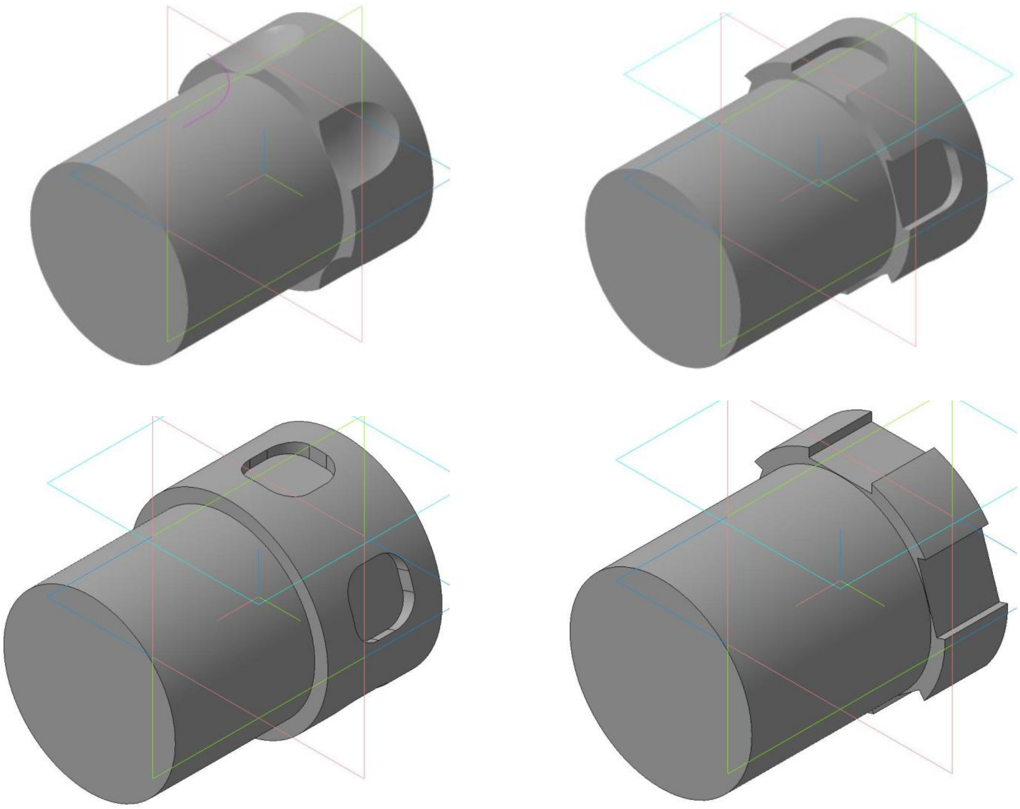


Figure 6. The 4 designs used in the preliminary experiments

5.2 Planned test series

A thorough quantitative investigation of groove designs requires a vast amount of testing. To reduce the overall number of test specimens, the least complex design (bottom right in Figure 6) was chosen for the next test series. The remaining process variables are listed in Table 1. The number of grooves can be considered as another parameter, but is fixed to 5 grooves in this test series.

Table 1. Process variables of the main groove design

N°	Name of the variable	Symbol
1	Groove length	*l*
2	Groove width	*b*
3	Groove depth	*h*
4	Groove radius	*r*
5	Voltage	*V*

From the Box-Wilson method (Design of Experiments) it follows that for 5 variables, $2^5 = 32$ experiments are required to obtain significant knowledge about the crimp joint and to set up guidelines for optimization of the variables. It has been decided to further reduce the number of test specimens to $2^4 = 16$. Thereto a constant groove length is applied throughout the test series. This choice is motivated because of the proportional behaviour of the groove length towards joint torque strength over a large range of length values (illustrated for a spline connection on Figure 7), as was also mentioned by Park et al. [9]. Table 2 gives an overview of the 5 parameters and their planned variations during the experiment. The test matrix leading to the 16 workpieces is given in Table 3. As in Table 2, the plus and minus sign denote respectively the upper and lower settings.

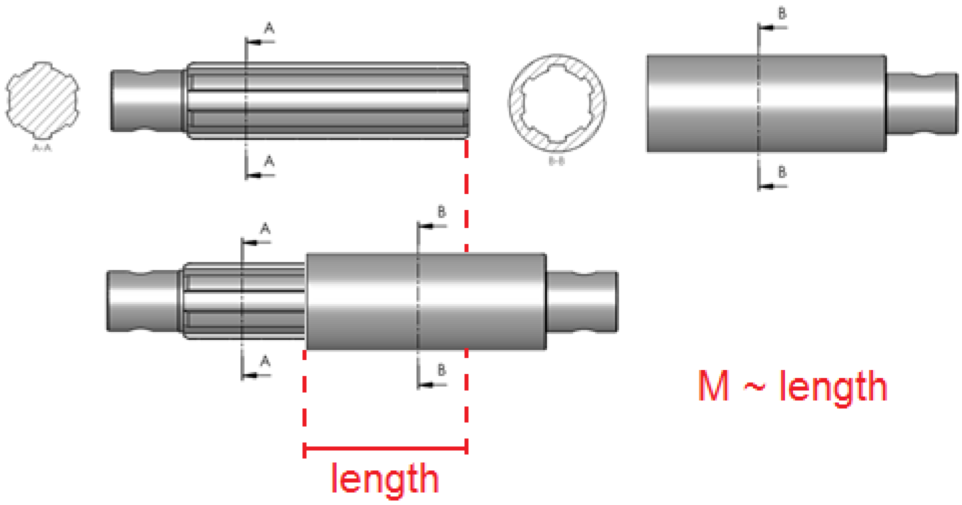


Figure 7. Spline coupling to illustrate the influence of groove length.

Table 2. The process variables of the main groove design and their respective variations.

N°	Name of the factor	DoE Symbol	The main level of the factor	variability interval	Upper value (+)	Lower value (-)
1	Groove length (fixed)	*x0*	12	-	-	-
2	Groove width (mm)	*x1*	10	2	12	8
3	Groove depth (mm)	*x2*	2	0.5	2.5	1.5
4	Groove radius (mm)	*x3*	1	0.5	1.5	0.5
5	Voltage (kV)	*x4*	7	0.5	6.5	7.5

Following to the crimping process, the pieces will be visually inspected and tested in a torsion bench. The acquired results will be compared to the torsional strength of the base material. It is expected, based on earlier work on axial joints [2], that the design with the largest groove width and height, and smallest edge radius, will yield the best results.

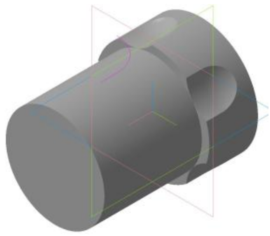
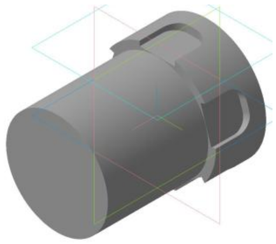
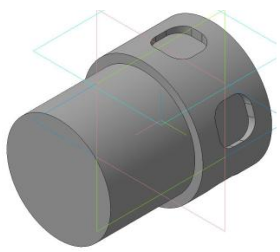
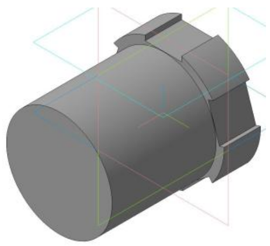
Table 3. Test matrix of the first test series

Number of experiment	x0	x1	x2	x3	x4
1	+	+	+	+	+
2	+	-	+	+	+
3	+	+	-	+	+
4	+	-	-	+	+
5	+	+	+	-	+
6	+	-	+	-	+
7	+	+	-	-	+
8	+	-	-	-	+
9	+	+	+	+	-
10	+	-	+	+	-
11	+	+	-	+	-
12	+	-	-	+	-
13	+	+	+	-	-
14	+	-	+	-	-
15	+	+	-	-	-
16	+	-	-	-	-

6 EXPERIMENTAL RESULTS

The preliminary experiments performed by the BWI had a purely qualitative nature and provided an insight in the overall understanding of the EMP crimping process. Table 4 presents the visual observation together with some conclusions.

Table 4. Results of the preliminary experiments

Type	N°	Voltage (kV)	Notes (visual control)	Conclusions
	1.1	8	Thinning seems significant (small cracks are uniformly propagated through the perimeter of the grooves)	
	1.2	7	This voltage seems the best for the geometry (the gap between the mandrel and the tube seems small plus shearing of the tube seems not critical)	A voltage of 6.5 kV could be optimal.
	1.3	6	Thinning is at a minimum level. But the gap is a little bit bigger then in 1.2.	
	2.1	6.5	Thinning is minimum (the best variant from the series)	The critical thinning is defined by thinning on the crosscut edge (as height is maximum). The first variant could be used or maybe it's better to decrease the voltage to 6 kV
	2.2	7	Cracks start forming in the crosscut edge. (The design is not optimal as the height is larger at this edge)	
	2.3	7.5	Thinning is maximal on each edge	
	3.1	11	Thinning is critical (Crosscut of the edge has bigger height, and correspondingly bigger shearing)	The critical thinning is defined by thinning on the crosscut edge. The voltages are too big. And maybe the sizes must be changed.
	3.2	10	Almost the same thinning as for 3.1	
	3.3	9	Thinning is a little bit less than in the previous cases	
	4.1	7	Minimum thinning	Design with the least amount of variables to consider. This design should be used in further testing.
	4.2	7.5	Average thinning	
	4.3	8	Maximum thinning, but not as big as in design 3	

As an example, photos of the main design that will be used in the following test series, pieces 4.1-4.3, are given in Figure 8.

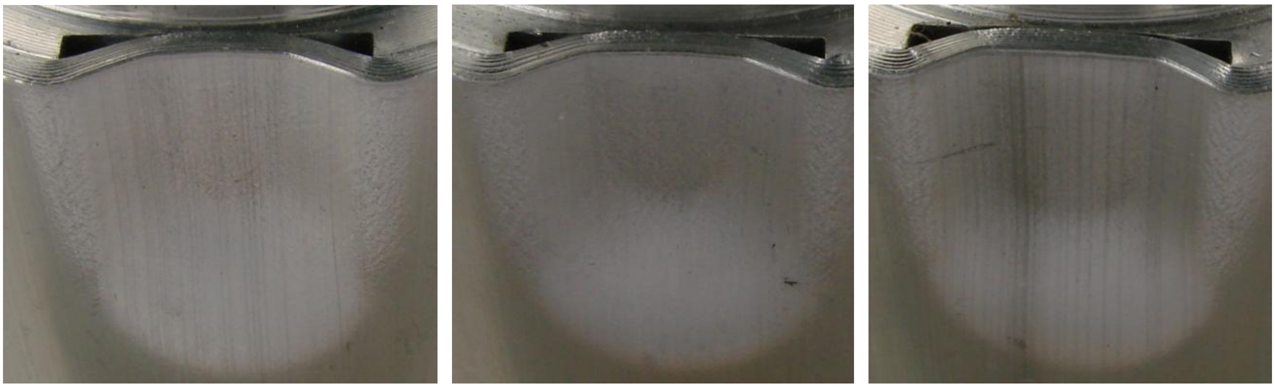


Figure 8. Photos of design 4 at different voltages. (from left to right: 4.1, 4.2 and 4.3)

7 CONCLUSIONS AND FUTURE WORK

Through the results of the preliminary experiments, a big step towards better understanding of the magnetic pulse crimping process for torque joints has been taken. Making use of two distinct design concepts, a groove and a knurl design, possibilities towards both discussed strength mechanisms, interference and form fitting, remain open.

The results of the first test series will give a clear insight in the feasibility of crimp joints for torsion applications.

Following test series based on a groove design, will involve a different number of grooves in the circumferential direction. Also, a more extensive variation of groove parameters is possible, depending on the obtained results from the torsion bench testing.

With respect to the knurl design, it was decided to use 3 different knurl sizes. The performance of these joints will be tested in the torsion bench just like the tubes with groove design. This way, a comparison between the 2 design concepts can be made.

8 ACKNOWLEDGEMENTS

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