Joining of Copper to Brass Using Magnetic Pulse Welding *

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Abstract

In magnetic pulse welding, electromagnetic pressure is used to deform, accelerate and weld workpieces. The process is mostly used for tubular specimens.
In this study, experiments were performed in order to investigate the weldability of copper tubes to brass solid workpieces. The tubes had an outer diameter and wall thickness of 25,0 mm and 1,5 mm respectively. A multi-turn coil with 5 windings in combination with a field shaper was used to focus the electromagnetic flux and thus realize the high pressures needed for welding.

The process parameters for joining these materials were optimised for maximum weld length. The parameters taken into account were the position of the field shaper relative to the workpieces, the width of the air gap between the tube and the internal workpiece and the energy level. The weld quality was verified based on metallographic examinations, scanning electron microscopy and hardness measurements.

Keywords

Magnetic Pulse Welding, Copper, Brass

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1 Introduction

In magnetic pulse welding, a very high energy current is discharged through a coil. The high and extremely fast current discharge creates electromagnetic forces between the coil and the outer tubular workpiece, which accelerates the latter towards the inner workpiece. A high-pressure collision is then created between the two surfaces of the metals to be joined [1]. Under precisely controlled conditions a solid-state weld can be realised.

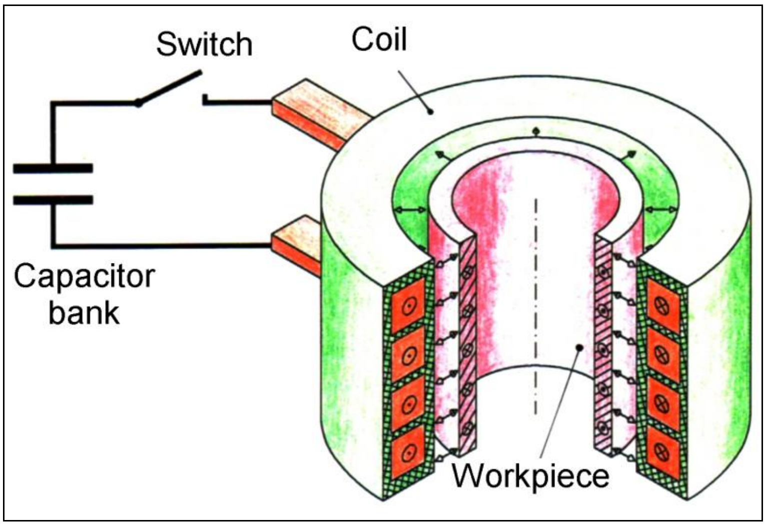

Figure 1: *Principle of magnetic pulse welding*

As in explosive welding, during the process a jet is created between the two surfaces to be joined. This jetting action removes all traces of oxides and surface contaminants, allowing the impact to plastically deform the metals for a very short time and to drive the mating surfaces together. This allows the contact of two virgin surfaces, stripped of their oxide layers. The surfaces are pressed together under very high pressure, bringing the atoms of each metal into close contact with each other, thereby allowing the atomic forces of attraction to come into play. There are a number of explanations for the precise mechanism at the collision point, but all agree that the metals momentarily behave like liquids, even though they remain solid [2].

2 Overview of the welding experiments

In this study, a total of 81 magnetic pulse welding experiments were performed in order to investigate the weldability of copper tubes to brass solid workpieces. The tubes had an outer diameter and wall thickness of 25,0 mm and 1,5 mm respectively. The properties of the materials are summarised in Table 1.

	Copper	Brass
Designation	EN 12449 Cu-DHP R290 (Mat. No.: CW024A)	EN 12164 CuZn39Pb3 (Mat. No.: CW614N)
Chemical composition (wt%)	Cu: 99,9 %	Cu: 57 - 59 % Pb: 2,5 - 3,5 % Zn: rest
Yield stress (MPa)	min. 250	min. 250
Tensile strength (MPa)	min. 290	min. 430

Table 1: *Overview of materials used*

The experiments were performed using a Pulsar model 50/25 system with a maximum charging energy of 50 kJ (corresponding with a maximum capacitor charging voltage of 25 kV) and a discharge circuit frequency of 14 kHz. The total capacitance of the capacitor banks equals 160 µF. The pressure resulting from the magnetic flux induced by a multi-turn coil is concentrated over the processing area using a field shaper with a width of the workzone equal to 15 mm (see Figure 2).

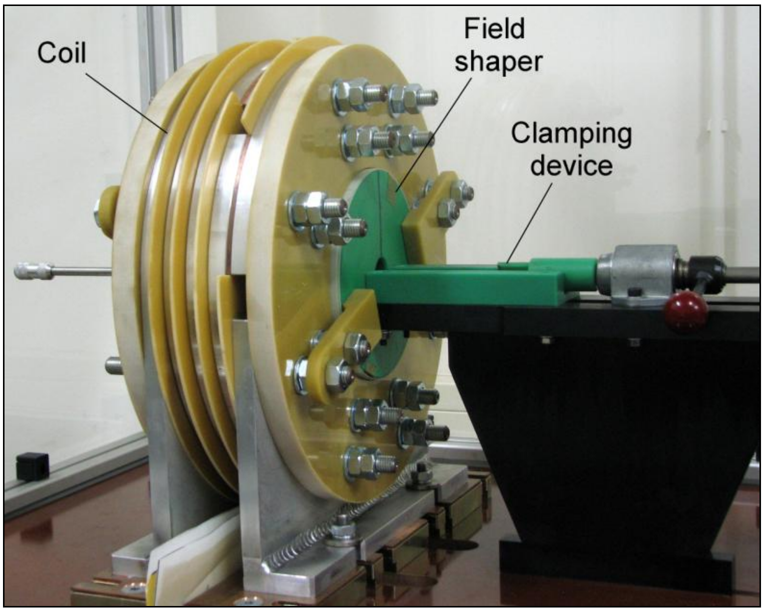

Figure 2: *Multi-turn coil used in the experiments*

The workpieces were positioned inside the field shaper in the overlap configuration. Various settings of the process parameters were used: the width of the air gap between the tube and the internal workpiece (s in Figure 3), by changing the outer diameter of the internal workpiece, the position of the field shaper relative to the workpieces (l_{FS} in Figure 3) and the charging voltage of the capacitors, determining the energy level. The overlap distance of the tube and internal workpiece and the discharge current frequency were kept constant.

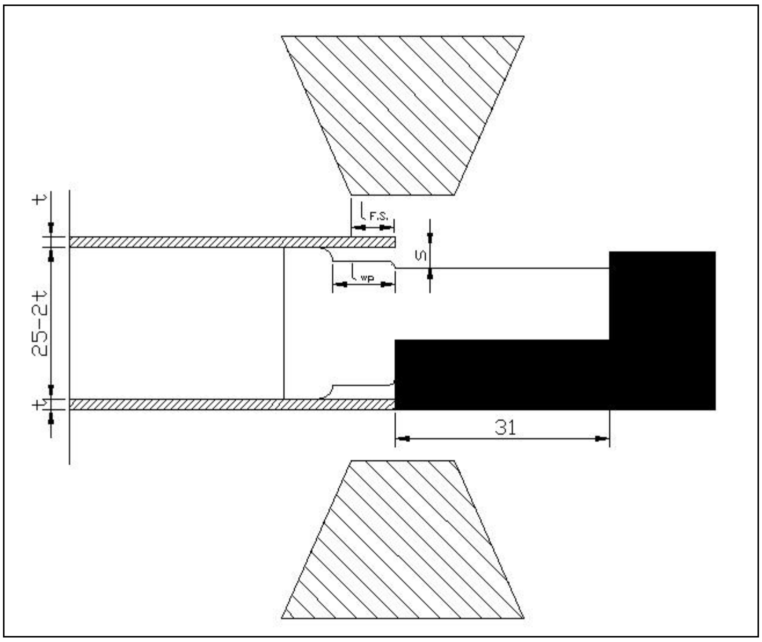

Figure 3: *Experimental test setup*
(l_{FS}: tube end position in the field shaper
s: air gap widt
l_{wp}: overlap length of the workpieces)

3 Parameter optimisation

The process parameters for joining the copper tubes and the brass solid workpieces were optimised experimentally. The parameter ranges used in the various experiments are summarised in Table 2. The optimisation was performed based on the measurement of the length of the welded zone. The weld length was defined as the average value of the weld lengths measured at two sides of a metallographic specimen (see Figure 5). The weld lengths which were encountered were maximum 7 mm.

Parameter	Setting range
Tube end position in the field shaper	Centre of field shaper + 0,5 up to + 5,5 mm
Air gap width	0,8 - 2,5 mm
Capacitor charging voltage **Energy**	12 - 20 kV 11,5 - 32 kJ

Table 2: *Overview of the parameter variations used*

During the welding experiments, it was observed that the tube end position in the field shaper is of high importance, characterising the overlap of the field shaper with the outer tubular workpiece. It was found that for different air gap widths, good weld quality is obtained for different ranges of tube end positions. This means that the field shaper overlap has a serious influence on the impact velocity and/or the impact angle. The zone subjected to magnetic pressure increases with increasing field shaper overlap. This means that the total force will be higher, which will influence the impact velocity. However, also a maximum allowable overlap of the field shaper exists. As the impact velocity will be large enough for larger overlaps, the impact angle must have reached values outside the possible range for welding. This indicates that the field shaper overlap also influences the impact angle.

Further, it was demonstrated that no bonding occurred when using an air gap smaller than 1,0 mm or larger than 2,0 mm. The optimal air gap width was found in the range of 1,0 to 1,5 mm for all welding experiments. An overview of suitable process parameters for an air gap width of 1,0 mm is shown in Figure 4. The optimal position of the tube end equalled 2,5 mm out of the centre of the field shaper and the minimum required energy level was equal to 26 kJ.

The overlap distance of the tube and internal workpiece and the discharge current frequency were kept constant

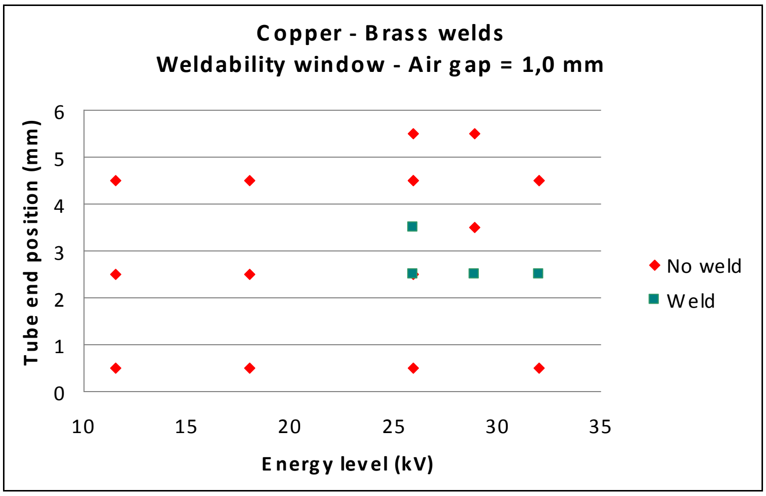

Figure 4: *Suitable parameters for joining copper to brass when using an air gap of 1,0 mm*

4 Metallographic observations

The weld quality has been assessed visually by means of metallographic examination. Hereto, the welded zone of each workpiece was isolated and cross-sectioned. After embedding in epoxy, the specimens were prepared by standard metallographic procedures; mechanical polishing down to 3 µm and chemical etching. The samples were etched by ammonia activated with hydrogen peroxide, during 20 seconds and finally examined by optical microscopy.

4.1 Macroscopic observations

The weld joint can be divided in 3 zones, which are shown in Figure 5. Actual welding of the materials will only occur in the middle part of the working zone. As the tube will impact the solid workpiece from left to right in this figure, the zone on the left without weld is called the run-in zone and the right zone is called the run-out zone. No clear correlation was found between the lengths of the run-in and run-out zones and the settings of the process parameters.

At the end of the run-out zone, the tube makes a certain angle with the internal workpiece. This angle was measured for all experiments. It was noticed that the angle increases for a higher energy level. The overlap distance of the tube and internal workpiece and the discharge current frequency were kept constant for experiments with a higher energy level and for experiments with a longer overlap of the field shaper with the outer tube.

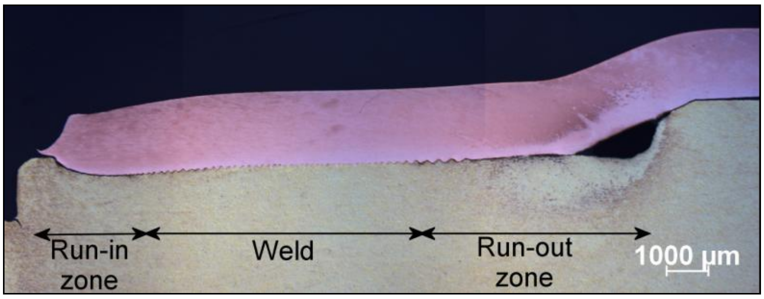

Figure 5: *Metallographic section of a typical weld*

In general, the inner workpieces were severely deformed during the impact. The most pronounced deformation occurs at the run-in zone, where the inner workpiece is compressed in a narrow zone. From there on, the deformation of the inner workpiece declines gradually towards the end of the weld (from left to right in Figure 5). This experimental observation proves that the impact of the tube occurs first at the run-in zone. The indentation in this zone was found to be between 0,5 and 1,0 mm. At a lower energy level and a smaller air gap width, the deformation decreases. The width of this severely deformed zone increases for a longer overlap of the field shaper. These high deformations show that in case a tube is used as internal workpiece, a mandrel should be applied to prevent deformation.

4.2 Weld interface morphology

The weld interface showed a typical wavy pattern (see Figure 6), similar as observed in joints realised by explosion welding. This transition zone between the dissimilar materials is believed to be caused by mechanical mixing, intensive plastic deformation and/or local melting. Temperature increase at the weld interface occurs due to Joule heating, the collision of the two pieces and the jet formation. Because the process takes place in a short lapse of time, heating is not enough to generate a temperature rise in a wider area, so there is no significant heat affected zone, as also has been stated before [3].

The dark zones in Figure 7, located in the brass material, are the result of severe plastic deformation. The size and orientation of the microstructural components in this zone have changed due to the impact. The Pb-particles have grown because of local melting.

The wavelength and amplitude variation along the weld interface was measured. The wave amplitude remains fairly constant along the weld interface and was approximately equal to 15 µm. The wavelength was found to increase towards the end of the weld (right in Figure 5) and varied between 50 and 160 µm.

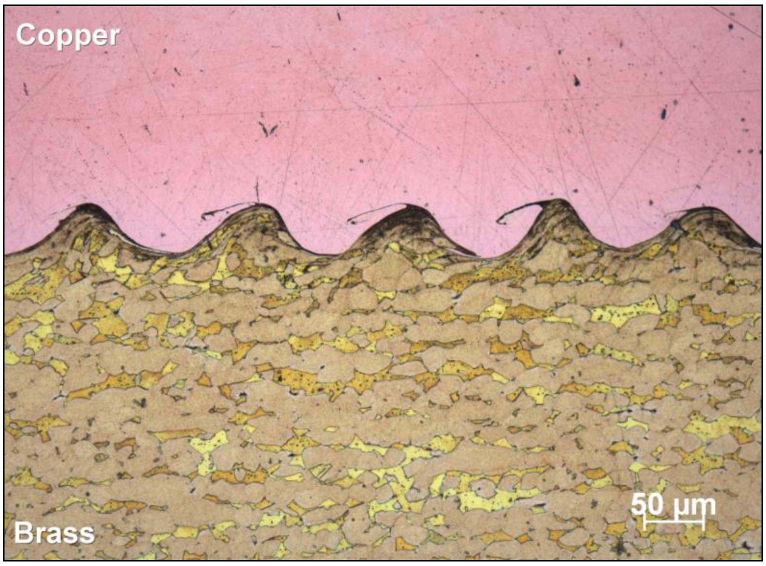

Figure 6: *Interface morphology of a copper – brass weld*

Figure 7: *Detail of Figure 6*

4.3 Microstructural observations

In some welds intermetallic layers were observed (see Figure 8). Such interface layers may support two possible mechanisms of bond formation: bonding as a result of solid-state processes based on accelerated mass transfer due to intensive plastic deformation at very high rates, and bonding as a result of solid-liquid interaction and based on the formation of a thin layer of molten metal between the components [3].

These layers were analysed using scanning electron microscopy. It was demonstrated that the interlayer becomes copper-enriched: the chemical composition of the layer shown in Figure 8 consisted of 75,6% Cu, 22,1% Zn and 2,3% Pb.

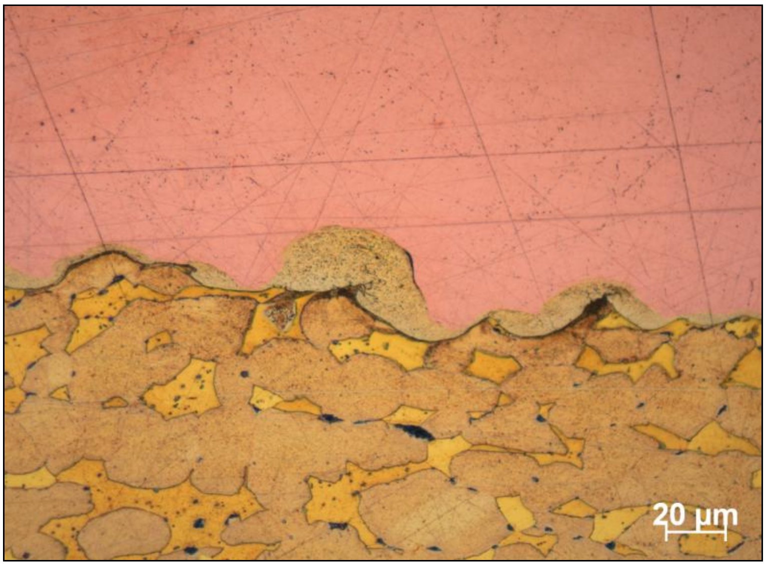

Figure 8: *Intermetallic layer observed in a copper-brass weld*

The intermetallic layers are susceptible for cracking, as shown in Figure 9 and Figure 10. In some welds, the interlayer was not able to withstand the residual stresses in the outer tube.

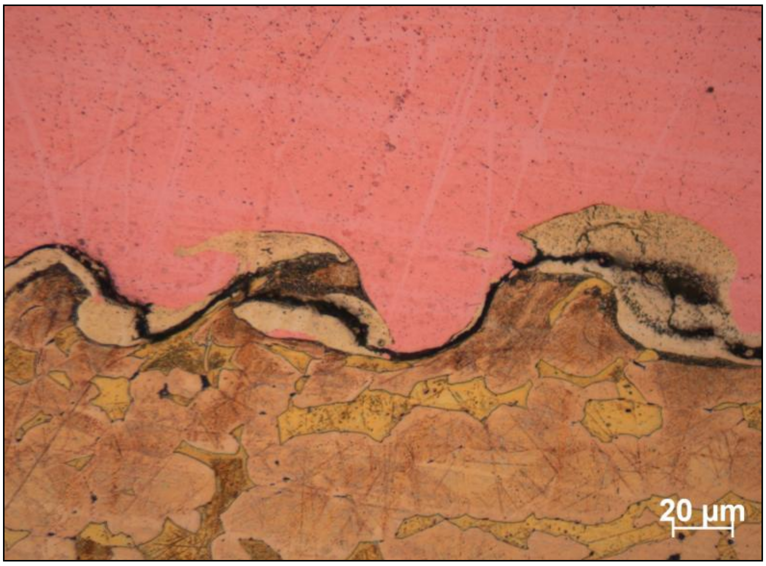

Figure 9: *Cracks in the intermetallic layer*

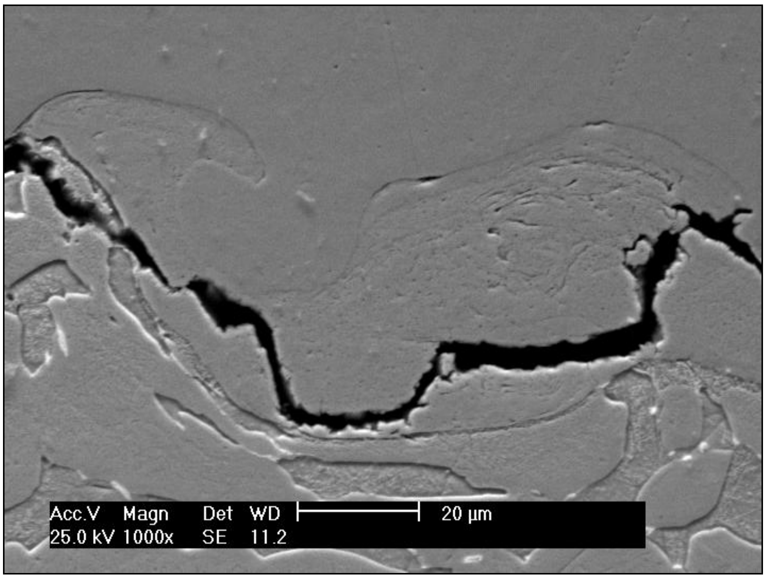

Figure 10: *Scanning electron microscopic analysis of a crack in the intermetallic layer*

4.4 Melting phenomena

In some welds, cracks in the intermetallic layers were observed which are the result of local melting and rapid solidification. A typical example is shown in Figure 11. This indicates that the temperature rise must have been higher than the melting temperature of copper and brass (1083 and 930°C respectively). The observed melt zones reached thicknesses up to 50 µm.

Zones which were molten were found in several samples, but not all of them were located in the welded area itself. Often, evidence of melting was found in the run-in or run-out zone (see Figure 13 and Figure 14). The molten zones were also analysed using scanning electron microscopy (see Figure 12 and Figure 14).

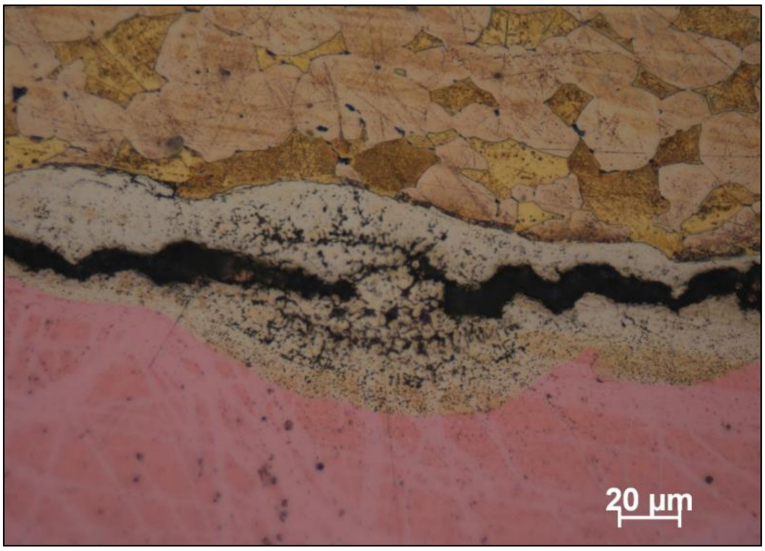

Figure 11: *Molten zones with cracks along the weld interface*

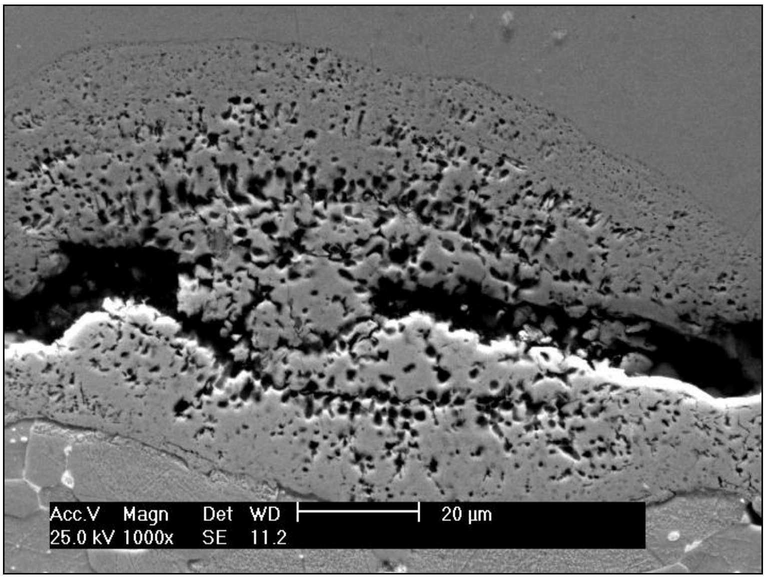

Figure 12: *Scanning electron microscopic analysis of a molten zone*

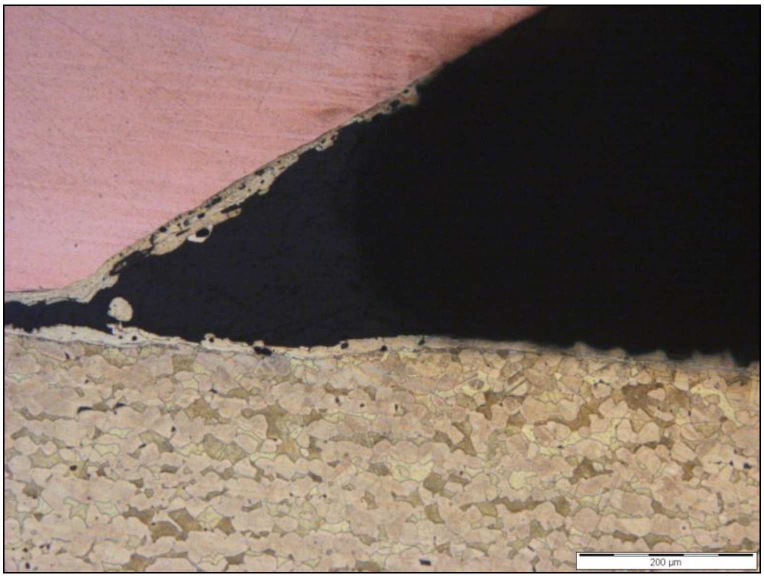

Figure 13: *Molten material in the run-out zone*

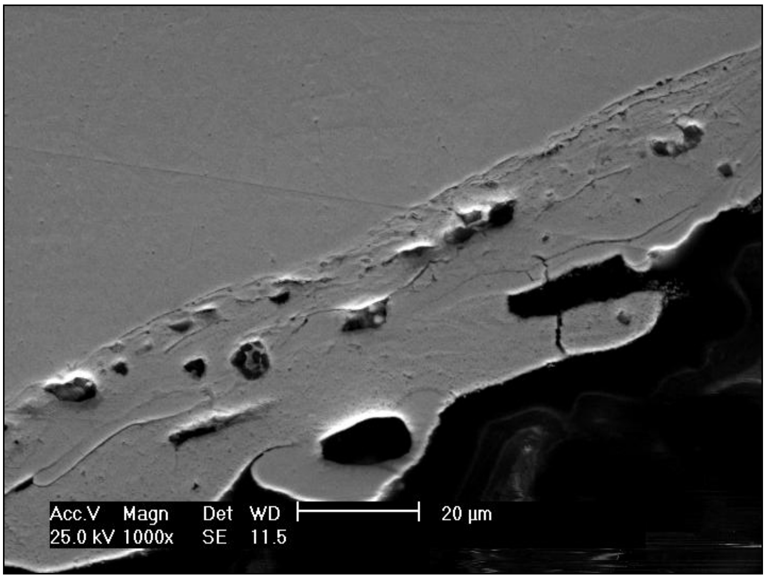

Figure 14: *Scanning electron microscopic analysis of the molten material in the run-out zone (detail of Figure 13)*

Most probably the observed cracks are caused by residual stresses in the outer tube and by shrinkage of the material during solidification. It was concluded that there is a considerable risk for melting during the magnetic pulse welding process. The sharp transition zone which is observed is typical for melting and rapid solidification [4]. A literature survey of both magnetic pulse and explosive welding confirmed that continuous molten layers or melt pockets can occur. Also the presence of pores due to the turbulent jet and the rapid solidification have been mentioned before [4]. Melting has generally been considered as a disadvantage due to the intermetallic compounds it can generate. These compounds can form a hard and brittle interlayer that is generally susceptible to cracking. In a recent paper, the jet has been found to be the main source for heating of the materials, apart from the heating due to the collision itself [4]. The temperature of the interface will increase due to the jet, which is dependent on the impact angle, the impact energy and the impact velocity. Therefore melting can be avoided by either decreasing the energy level or by decreasing the impact angle.

5 Hardness measurements

In order to investigate the hardness of the interlayers, Vickers hardness measurements were performed using a Struers Duramin A300D automatic hardness tester with a test load of 1,961 N (corresponding to HV0,2) and an indentation time of 12 sec. A hardness traverse across the weld was performed. The hardness as a function of the location is shown in Figure 15.

The hardness of the copper and brass base materials were measured well outside the weld zone, and were found equal to respectively 104 and 146 HV0,2. The interface layer shows an increase in hardness relative to the base materials. This can be attributed to the severe plastic deformation or to a new fine-grained microstructure produced by melting and rapid solidification of the weld interface.

As the width of the welded interface is in the order of 10 to 30 µm, precisely measuring the hardness of this area with a HV0,2 test is very difficult. The average hardness based on 5 measurements was equal to 183 HV0,2.

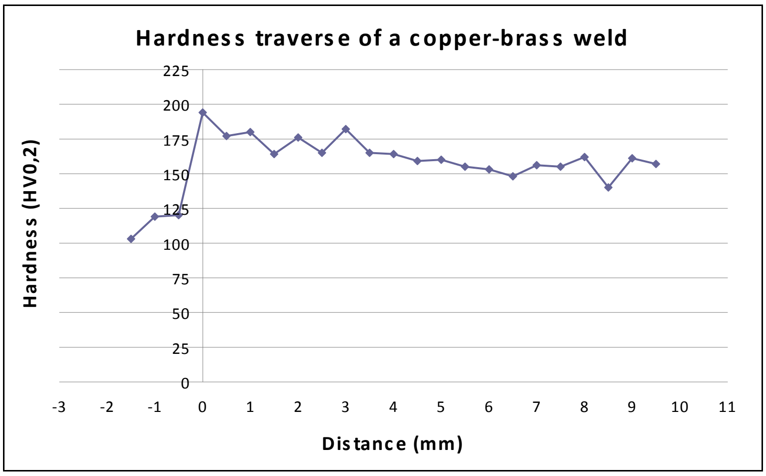

Figure 15: *Hardness traverse*

6 Conclusions

In this study, magnetic pulse welding experiments were performed in order to investigate the weldability of copper tubes to brass solid workpieces. In the experiments, the pressure resulting from the magnetic flux induced by the multi-turn coil is concentrated over the processing area using a field shaper with a width of the workzone equal to 15 mm. The tubes used in the experiments had an outer diameter and wall thickness of 25,0 and 1,5 mm respectively.

The following process parameters have been varied: the width of the air gap between the tube and the internal workpiece, the position of the field shaper relative to the workpieces and the charging voltage of the capacitors. The overlap distance of the tube and internal workpiece and the discharge current frequency were kept constant.

The weld quality was visually assessed by means of metallographic examination. It was observed that a considerable risk exists for melting during the process, which can impair the weld quality.In some welds intermetallic layers were formed, as a result of local melting and rapid solidification. The presence of cracks parallel to the weld interface was attributed to residual stresses in the outer tube and solidification shrinkage. The hardness increase of the interlayer was however moderate. After parameter optimisation, defect-free welds could be realised. The length of the welded zone was maximum 7 mm. A weld interface with a wavy pattern was created, similar to an explosion weld joint, showing severe plastic deformation and microstructural redistribution.

References

[1] *Schribman, V.* Magnetic pulse technology for improved tube joining and forming. Tube & Pipe Technology, nov./dec. 2006, p. 91-95.

[2] *Schribman, V.* Magnetic Pulse Welding. Proceedings of the BIL/NIL Welding Symposium, Belgian Welding Institute, Brussels, 18/10/2007.

[3] *Shribman, V. Stern, A., Livshitz, Y. and Gafri, O.* Magnetic pulse welding produces high-strength aluminium welds. Welding Journal 81, April 2002, p. 33–37.

[4] *Ben-Artzy, A., Stern, A., Frage, N. and Shribman, V.* Interface phenomena in aluminum-magnesium magnetic pulse welding. Science and technology of welding and joining, 13(4): p. 402-408, 2008.