Joining of dissimilar materials using the magnetic pulse process

Koen Faes, Oleg Zaitov
Belgian Welding Institute, Technologiepark 935, 9052 Zwijnaarde, Gent, Belgium

W. De Waele
Laboratory Soete, Ghent University, Technologiepark 903, 9052 Zwijnaarde, Gent, Belgium

Abstract

In magnetic pulse welding, electromagnetic forces are used to deform, accelerate and weld workpieces. The process is mostly used for tubular specimens. In this study, experiments were performed to investigate the weldability of various material combinations. The weld quality was assessed based on metallographic examinations, scanning electron microscopy and hardness measurements. The weld interface morphology, the intermetallic phases and the most common weld defects are described.

Keywords

Electromagnetic Pulse Welding, Dissimilar Materials

Introduction

Electromagnetic forming and welding has been studied in detail by many researchers for both flat sheets and axisymmetric components (tubes) [1-6]. In electromagnetic forming or welding operations, the energy stored in a capacitor bank is discharged rapidly through a magnetic coil (see Figure 1). Typically a ring-shaped coil (Figure 3) is placed over a tubular workpiece. The magnetic field produced by the coil generates eddy currents in the tube. These currents, in turn, produce their own magnetic field. The forces generated by the two magnetic fields oppose each other. Consequently, a repelling force between the coil and the tube is created. The forces generated can for example be used to collapse the tube with high velocity onto an internal workpiece. A high-pressure collision is then created between the two surfaces of the metals to be joined. Under precisely controlled conditions a solid-state weld can be realized.

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 during a very short time and to drive the mating surfaces together. This allows 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, thereby allowing the atomic forces of attraction to come into play. There are a number of explanations for the precise mechanisms at the collision point, but all agree that the metals momentarily are brought into a visco-plastic state [8].

Experiments described in literature show that a wavy or a flat bond interface is created. If an intermetallic layer is formed, this is caused by mechanical mixing, intensive plastic deformation and/or melting. The temperature increase to create these melting phenomena is believed to occur due to Joule effects and the collision itself. Because the process takes place in a very short lapse of time, heating is not enough to generate a temperature increase in a wide area, so there is no significant heat affected zone, as can be concluded from previous investigations [9].

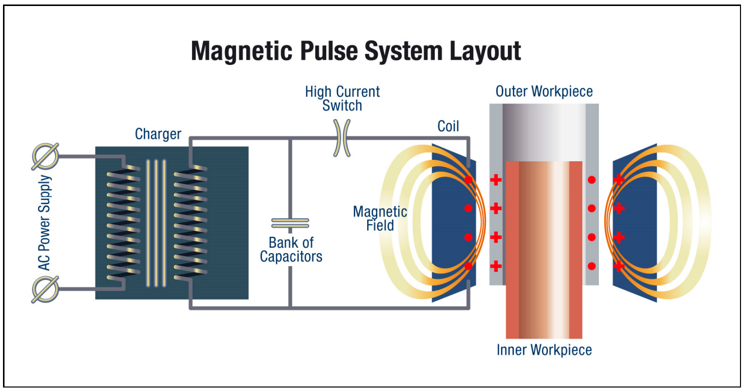

Fig. 1: *Principle of magnetic pulse welding [7]*

Welding experiments

In the frame of the collective research called "Soudimma", welding experiments were performed in order to investigate the weldability of various material combinations, such as:

- aluminum - aluminum,
- aluminum - mild steel,
- aluminum - copper,
- copper - brass,
- copper - mild steel,
- copper - aluminum
- copper - stainless steel.

In the list above, the first mentioned material is the outer tubular material. The experiments were performed with solid internal workpieces. The tubes had an outer diameter of 25 and 45 mm and wall thicknesses of 1, 1,5 and 2 mm. For example, a weld of an aluminum tube with a steel internal workpiece is shown in Figure 2.

Fig. 2: *Aluminum-steel weld (tube diameter: 45 mm, wall thickness: 1,5 mm)*

The experiments were performed using a BMax 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 3).

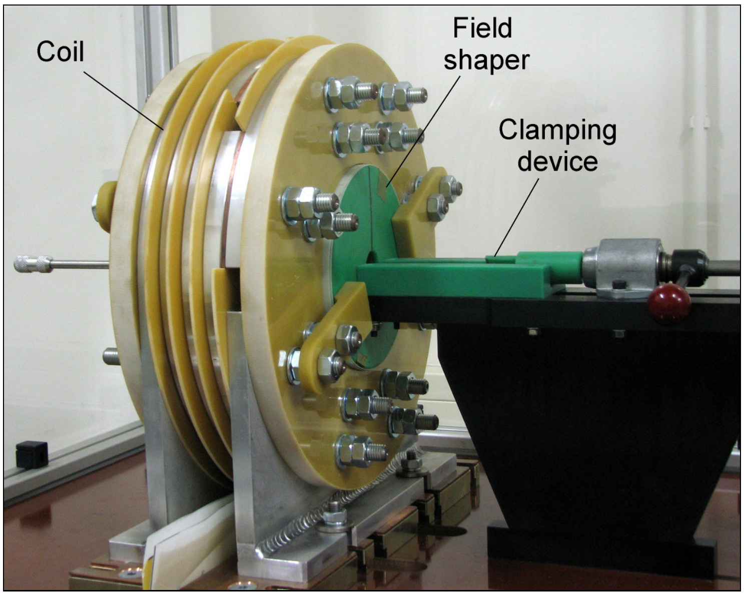

Fig. 3: *Multi-turn coil used in the experiments*

The weld quality was assessed by means of metallographic examinations. Hereto, the welded zone of each workpiece is 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. Also scanning electron microscopy (SEM) and energy dispersive X-ray analysis (EDX) was performed.

Parameter optimization

The process parameters for joining the tubes to the solid workpieces were optimized experimentally. The optimization 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.

During the optimization process, it was observed that the position of the tube end in the field shaper is of high importance, characterizing the overlap of the field shaper with the tube. The field shaper overlap has a significant influence on the impact velocity and 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, a maximum allowable overlap of the field shaper exists.
Also the capacitor charging voltage and the air gap width (stand-off distance between the outer and the internal workpiece) are parameters of importance.

Macroscopic observations

A weld joint can be divided in 3 zones. An example of a copper-brass joint is shown in Figure 4. Actual welding of the materials only occurs in the middle part of the weld zone. As the tube will impact the solid workpiece from left to right in this figure, the zone at the left without weld formation, is called the run-in zone. The right zone is called the run-out zone. The notches created in these areas can be very detrimental in case of dynamic loads or in corrosive environments, as also stated in [10].

No clear correlation is found between the lengths of the run-in and the 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. It is noticed that the angle increases for a higher energy level.

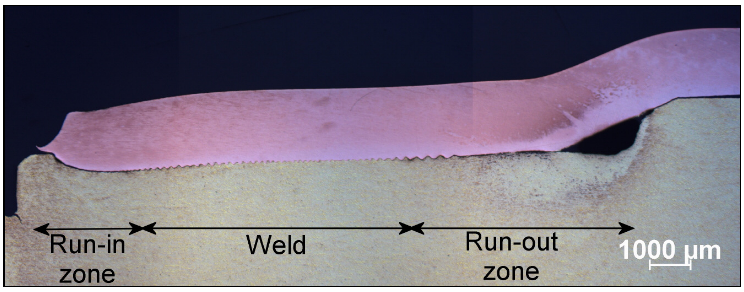

Fig. 4: *Metallographic section of a typical copper-brass weld*

Generally, the internal workpieces are severely deformed by the impact. The most pronounced deformation occurs in the run-in zone. From there on, the deformation of the internal workpiece gradually declines towards the end of the weld (from left to right in Figure 4). This experimental observation proves that the impact of the tube first occurs at the run-in zone. The indentation in this zone is found to be between 0,5 and 1,0 mm. At a lower energy level or with a smaller air gap width, the deformation decreases. The width of this severely deformed zone increases for a longer overlap of the field shaper with the tube. These high deformations show that in case a tube is used as internal workpiece, an internal support should be applied to prevent deformation.

Weld interface morphology

For some material combinations, a wavy weld interface is observed, more specific for the combinations aluminum-aluminum, copper-brass, copper-steel and copper-stainless steel. In Figure 5, a macrographic section of a copper-steel weld is shown. The other material combinations have a flat or nearly flat weld interface. As an example, the weld interface of a copper-aluminum weld is shown in Figure 7. The wave formation process is however not mandatory for a good bonding, as stated by some authors. Moreover, waves can also be observed in regions where no bonding occurred.

The wavy pattern is also observed in joints realized by explosion welding. This transition zone between the 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 workpieces and the jet formation.

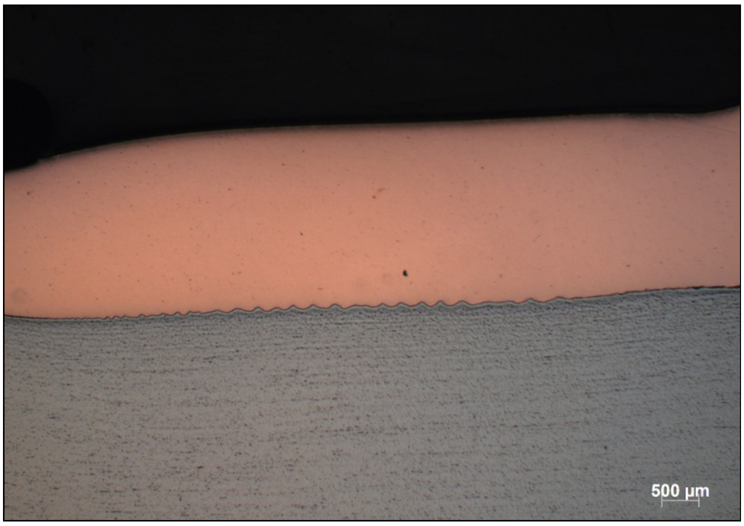

Fig. 5: *Metallographic section of a typical copper-steel weld*

The process of wave formation is dependent on the process parameters and the parts' geometry [11]. Also in [11], the collision energy, the impact angle and the geometry of the joint are found to have the most significant influence on the waves' characteristics. It is proved that the interface wavelength was proportional to the geometry of the internal part. The initial gap between external and internal workpiece influences the impact angle which defines the relationship between the collision point velocity and the weld propagation velocity. Also the charging energy of the capacitor and the initial gap determine the collision velocity of the outer tube.

Fig. 6: *Wavy weld interface of a copper-steel weld (detail of figure 5)*

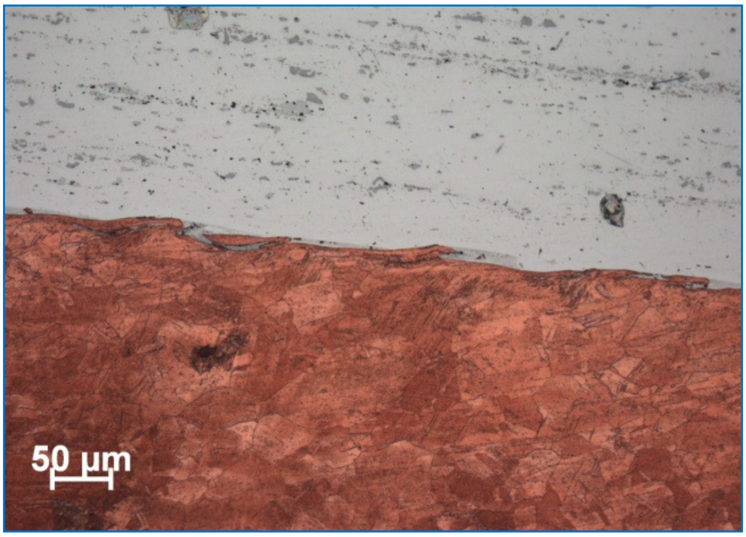

Fig. 7: *Weld interface of a copper-aluminum weld (with a small and flat intermetallic layer)*

Intermetallic layers

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 has also been stated in literature [9].

In some welds, intermetallic layers are observed (see for example Figure 10). Such 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 [9].

The intermetallic phases at the weld interface are present in all welds. In [12], it is stated that the composition and the arrangement of the intermetallic phases depend on the process parameters. For a flat waveless weld interface, as for example in the aluminum-steel welds, the intermetallic phases have the form of a film (Figure 8). Also regions are observed where no intermetallic phases were present or could be detected.

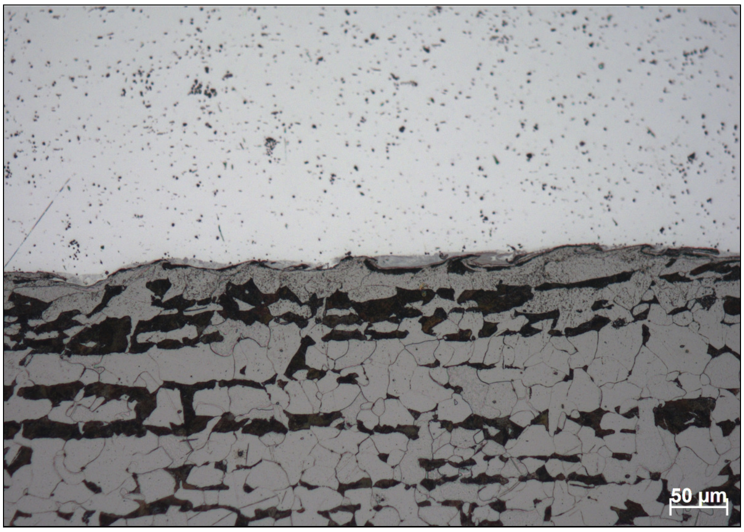

Fig. 8: *Flat weld interface of an aluminum-steel weld*

The thickness of the intermetallic layer increases for a higher applied energy. Using a low pulse energy, a thin intermetallic phase is formed (Figure 9). When using a higher energy level (i.e. a higher charging voltage of the capacitors or a larger stand-off distance between the tube and the internal part), a layer thickness between 25 and 50 µm can be achieved (Figure 10). The intermetallic layer is usually thicker when a wavy weld interface is present.

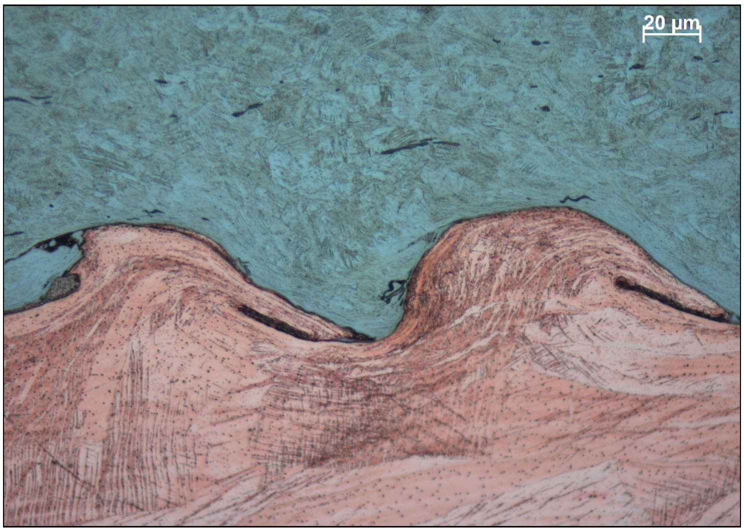

Fig. 9: *Thin intermetallic layer observed in a copper-stainless steel weld, executed with a low energy level*

Fig. 10: *Large intermetallic layer observed in a copper-stainless steel weld, executed with a high energy level*

Weld defects

Cracking

When realizing a weld at a high energy level, the intermetallic layers are large and susceptible for cracking. In Figure 11, an example is shown of severe cracking parallel to the weld interface. The interlayer is in this case not able to withstand the residual stresses in the outer tube.

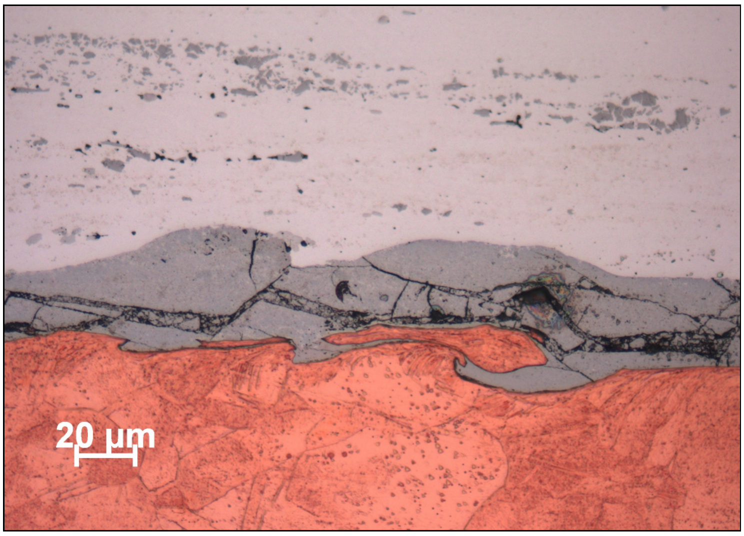

Fig. 11: *Cracks in the intermetallic layer of a copper-aluminum weld, executed at a too high energy level*

In some welds, also cracks perpendicular to the weld interface are observed, weakening the weld interface (see Figure 12 for an example of an aluminum-steel weld). These intermetallic shrinkage cracks are also observed in explosion welding [13]. The mentioned causes are a too high kinetic energy of the flyer plate or a thermal contraction due to the difference in thermal conductivity. Aluminum is a good thermal and electrical conductor, with a thermal conductivity of 250 W/(m•K), while steel has a thermal conductivity of about 43 W/(m•K). This implies that aluminum heats up faster than steel during welding.
There is also a difference of the thermal expansion factor between steel and aluminum. Steel has a linear expansion coefficient α of 12 (10^{-6}/°C). For aluminum this factor is the double; 23 (10^{-6}/°C). This means that the aluminum outer tube will expand twice as much as the steel internal workpiece for a given temperature increase. Due to the

difference in thermal conductivity, steel will not heat up as much and combined with the difference in thermal expansion, the differential expansion between steel and aluminum will be pronounced. After welding, the aluminum tube is fixed in its elongated state. When temperature decreases again, axial tensile stresses will emerge in the aluminum flyer tube. In presence of a brittle intermetallic layer [14], these tensile stresses result in cracks perpendicular to the major stress component.

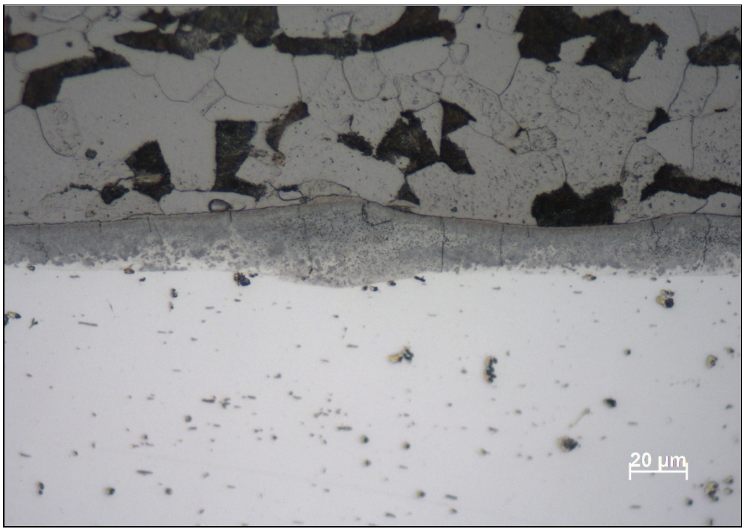

Fig. 12: *Vertical cracks in the intermetallic layer of an aluminum-steel weld*

Melting phenomena

In some welds, cracks and porosities are observed in the intermetallic layers as the result of local melting and rapid solidification. A typical example in a copper-brass weld is shown in Figure 13 and Figure 14. 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 reach thicknesses up to 50 µm. Figure 15 shows an example of a copper-aluminum weld.
Zones which were molten are found in several samples, but not all of them are located in the welded area itself. Often, evidence of melting is also found in the run-in or run-out zone (see Figure 16).

Most probably, the observed cracks at the weld interface are caused by residual stresses in the outer tube and by shrinkage of the material during solidification. It is concluded that there is a considerable risk for melting during the magnetic pulse welding process. A literature survey of both magnetic pulse and explosion welding confirms that continuous molten layers or melt pockets can occur [15]. Also the presence of pores due to the turbulent jet and the rapid solidification has been mentioned before [15]. Melting is generally considered as a disadvantage due to the intermetallic compounds it can generate. These compounds can create a hard and brittle interlayer which is generally susceptible to cracking. In [15], the jet is considered to be the main source for heating of the materials, apart from the heating due to the collision itself. 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.

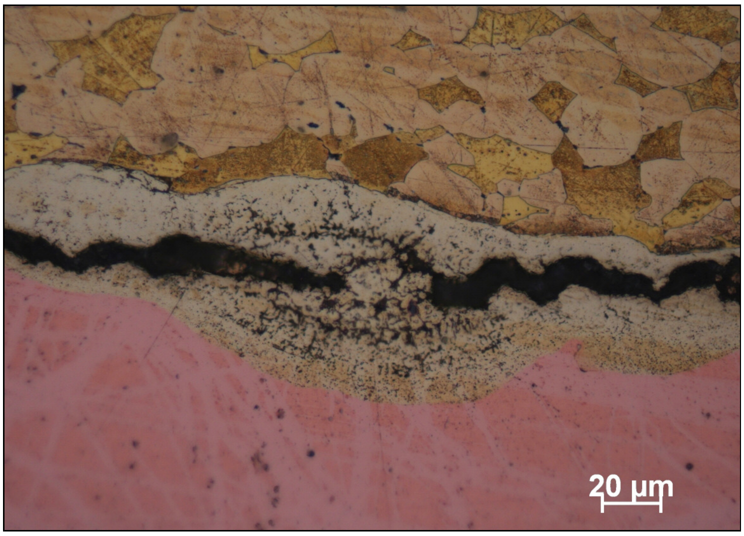

Fig. 13: *Molten zones with cracks along the weld interface of a copper-brass weld*

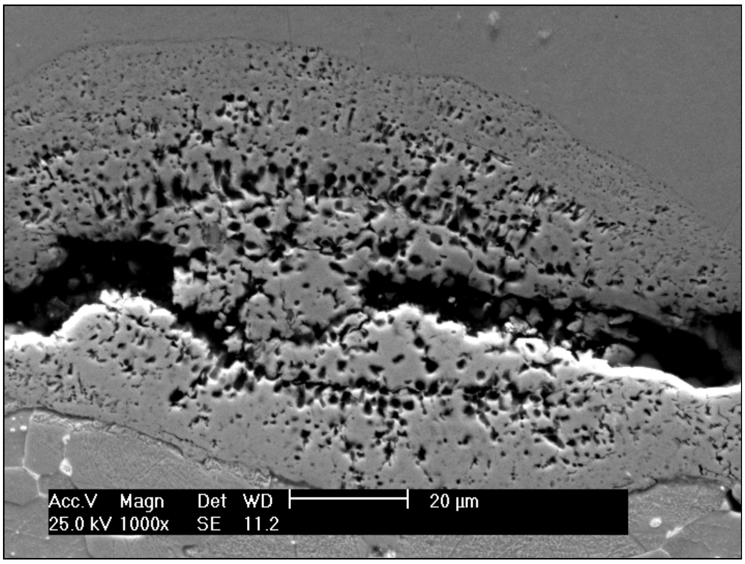

Fig. 14: *Scanning electron microscopic analysis of a molten zone in a copper-brass weld (detail of Figure 13)*

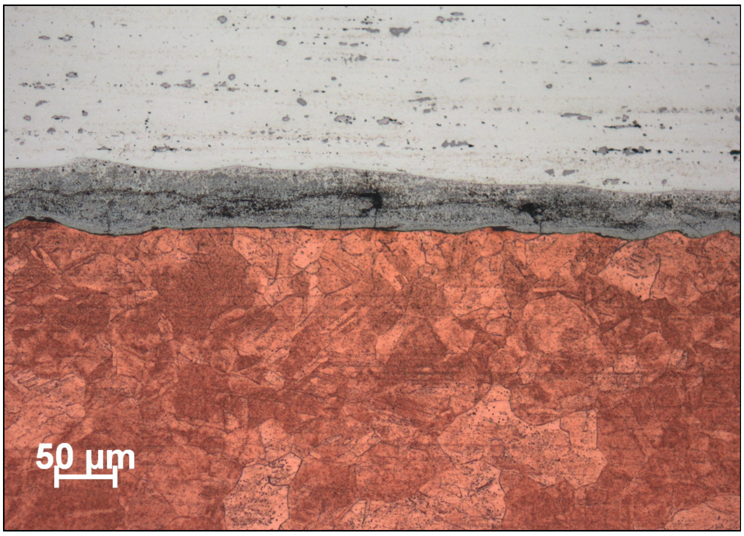

Figure 15: *Copper-aluminum weld interface with local melting*

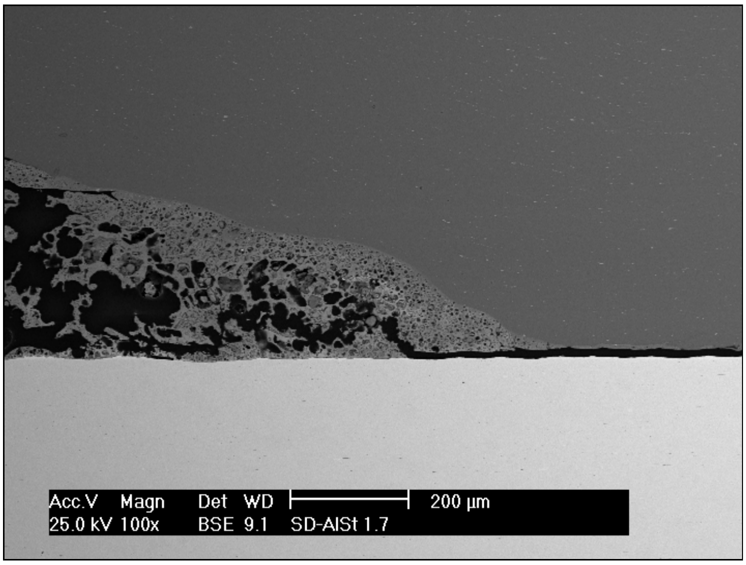

Figure 16: *Molten material in the run-out zone of an aluminum-steel weld*

Hardness measurements

In order to investigate the brittleness of the intermetallic layer in a typical aluminum-steel weld, the hardness at the weld interface zone was measured at 3 different locations: in the aluminum and the steel base material (hardness of resp. 95 and 200 HV0.1), and at the weld interface. Two kinds of weld interfaces were investigated: interfaces with a small (< 5 µm) or non-visible intermetallic layer and interfaces with a large (25-50 µm) intermetallic layer. In case of the latter, the hardness can increase up to 420 HV0.1. The hardness measured at the weld interface without or with a non-visible intermetallic layer was equal to 130 HV0.1. The best weld quality is thus achieved when a thin intermetallic layer is formed at the weld interface.

Conclusions

In this study, magnetic pulse welding experiments were performed in order to investigate the weldability of various material combinations. The welding experiments were performed with tubes with a diameter of 25 and 45 mm, welded onto solid internal 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 weld quality was assessed by means of metallographic examination. Two types of weld interfaces were observed: flat and wavy interfaces. A wavy weld interface is similar to an explosion weld joint, showing severe plastic deformation and microstructural redistribution.

At the weld interface, intermetallic layers are formed. In the flat weld interfaces, these layers are present as thin films. Also regions are detected where no intermetallic phases are present or can be detected. Generally, larger intermetallic layers are observed in welds with a wavy pattern. The formation of the intermetallic layers can not be avoided.

It is observed that a considerable risk exists for melting during the process, which can impair the weld quality.
Cracks parallel and perpendicular to the weld interface are observed, especially in the welds with a large intermetallic layer. The presence of cracks is attributed to the difference in thermal conductivity and thermal expansion. For optimum weld quality, the intermetallic layer thickness should be kept minimal by parameter optimization. Recommended is to use the lowest possible weld energy, defined by the capacitor charging voltage and the geometrical parameters.

Acknowledgments

This work is based on the results of the collective research project "SOUDIMMA" (Belgium). The authors would like to thank the Walloon region (DG06) for its financial support.

References

[1]: Kamal, M.; Daehn, G.S. Uniform Pressure Electromagnetic Actuator for Forming Flat Sheets. Journal of Manufacturing Science and Engineering, April 2007, Vol. 129, Issue 2, p. 369-380.
[2]: Shribman, V. Magnetic pulse technology for improved tube joining and forming, Tube & Pipe, Nov.-Dec. 2006, p. 91-95.
[3]: Spitz, B.T.; Shribman, V. Magnetic pulse welding for tubular applications: Discovering new technology for welding conductive materials, The Tube & Pipe Journal, July 2001.
[4]: Aizawa, T.; Kashani, M.; Okagawa, K. Application of Magnetic Pulse Welding for Aluminum Alloys and SPCC Steel Sheet Joints. Welding Journal, May 2007, p 119s-124s.
[5]: Schäfer, R.; Pasquale, P. Split coils and multiple joining coils (MJo). State of the art and upcoming development, International Conference and User Meeting. 22 April 2010, Alzenau, Germany.
[6]: Kallee, S.; Schäfer, R.; Pasquale, P. The industrial use of EMPT. State of the art and future applications, International Conference and User Meeting. 22 April 2010, Alzenau, Germany.
[7]: Figures: Pulsar Ltd.
[8]: Schribman, V. Magnetic Pulse Welding. Proceedings of the BIL/NIL Welding Symposium, Belgian Welding Institute, Brussels, 18/10/2007.
[9]: Schribman, V.; Stern, A.; Livshitz, Y.; Gafri, O. Magnetic pulse welding produces high-strength aluminium welds. Welding Journal 81, April 2002, p. 33–37.
[10]: Marya, M.; Marya, S.; Priem, D. On the Characteristics of Electromagnetic Welds between Aluminum and Other Metals and Alloys. Welding in the World, 49 (2005), p. 74–84.
[11]: Ben-Artzy, A., Stern, N. Frage, V. Shribman, O. Sadot. Wave formation mechanism in magnetic pulse welding. International Journal of Impact Engineering 37 (2010), p. 397–404.
[12]: Göbel, G.; Kaspar, J.; Herrmannsdörfer, T.; Brenner, B.; Beyer, E. Insights into intermetallic phases on pulse welded dissimilar metal joints Proceedings of the 4th international conference, ICHSF 2010. March 9th - 10th, 2010, Columbus, Ohio, USA.
[13]: Vaidyanathan, P. V.; Ramanathan, A. R. Design for Quality Explosive Welding. Journal of Materials Processing Technology, 1992. 32(1-2): p. 439-448.
[14]: Szecket, A., et al. A Wavy Versus Straight Interface in the Explosive Welding of Aluminum to Steel. Journal of Vacuum Science & Technology a-Vacuum Surfaces and Films, 1985. 3(6): p. 2588-2594.
[15]: 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.