INVESTIGATION OF THE WELDABILITY OF COPPER TO STEEL TUBES USING THE ELECTROMAGNETIC WELDING PROCESS

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Abstract: Magnetic pulse welding is an innovative joining method which allows joining of dissimilar metal combinations. However, much remains unknown about the process and its parameters. In this paper, the weldability of copper tubes to steel rods and tubes is discussed, with the goal of examining the influence of the wall thickness of the supporting steel tube on the weld and the deformation of the components. Large deformations were observed, causing an undesirable decrease in diameter of the tubes. The quality of the obtained welds was shown to decrease with decreasing inner tube thickness as well, most likely due to the deformation of the workpieces in radial direction. Because of this, it is advisable to use an internal support to prevent deformation of the support tubes. To gain more insight in the precise mechanisms of weld formation and failure, numerical simulations are advised.

Keywords: Magnetic Pulse Welding; Tube Welding; Metallography; Hybrid joint; Copper-steel

1 INTRODUCTION

Magnetic pulse welding is an innovative and promising solid-state impact process which allows joining of dissimilar metal combinations [1]. Combining dissimilar metals gives the advantage of combining the properties of different materials in one product, such as electrical conductivity, strength, weight, corrosion resistance and many more. The process duration is very short, requires only electricity and has no undesired by-products. Welding of tubular components can have many applications, for example in heat exchange or automotive [2]. In this paper, the weldability of copper tubes to steel rods and tubes is discussed, with the goal of examining the influence of the wall thickness of the inner tube on the weld formation and the deformation of the inner component.

2 MAGNETIC PULSE WELDING

2.1 Process description

The magnetic pulse welding process (MPW) is initiated by storing energy from the grid in a capacitor bank and releasing this energy once it has reached a target value. When this value is reached, the capacitor bank is connected with a single-turn or multi-turn coil. A high-power electric pulse is discharged in the coil and generates a magnetic field inside the coil. The workpieces to be joined are placed inside the coil. The set-up is shown in Figure 1. The primary current pulse is a damped sinusoidal current. The magnetic field generated by this current can be concentrated and intensified by a field shaper. Because of the magnetic field, eddy currents are induced in the outer workpiece, named the flyer. This happens according to Lenz's law, the induced current thus opposes the current in the coil. For currents to be induced, the flyer must be made of a sufficiently electrically conducting material. The flyer shields the inner workpiece, named the parent, from the magnetic field. The flyer is accelerated because of the difference in magnetic field on the inside and outside of the flyer. This can also be explained by using Ampère's law, which states that opposing currents will create repelling forces. The accelerated flyer impacts with the parent material at high velocity. Depending on the circumstances, this creates a metal bond between the flyer and the parent material.

Important parameters that can be controlled and influence the resulting weld are the charging voltage, the stand-off distance and the overlap distance. The charging voltage *U* determines the amount of discharge energy *E* provided to the process according to Equation 1, with *C* the total capacity of the capacitor bank. The stand-off distance or air gap *g* is the initial distance between the workpieces and thus equals the distance the flyer will travel before impacting with the parent. The overlap length is the length the flyer tube overlaps with the field shaper.

$$E = \frac{1}{2} C \cdot U^2 \tag{1}$$

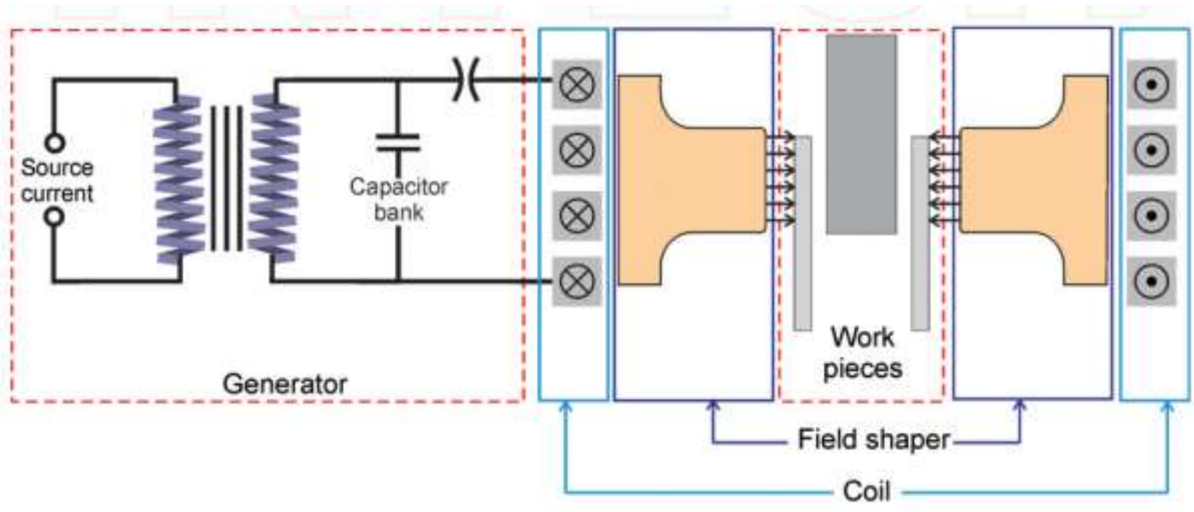

Figure 1. Magnetic pulse welding set-up [1]

2.2 Weld interface

Two possible explanations for the bonding mechanism in MPW have been proposed in literature [2]. One assumes that a solid-state mixing process of the two materials takes place, while the other assumes that bonding is caused by local melting and solidifying on a submicron scale. Several factors influence the ability of a metal pair to bond, such as compatibility due to different crystal structures and orientations, electronic properties and other surface effects [2]. Most successful welds show a wavy pattern between the two welded materials, as illustrated in Figure 2. This is believed to be the result of the interference of compressive shock waves caused by the dynamic collision or the jetting phenomenon [1]. The jetting phenomenon is the creation of a jet of material in front of the collision point, which is expulsed due to its high speed.

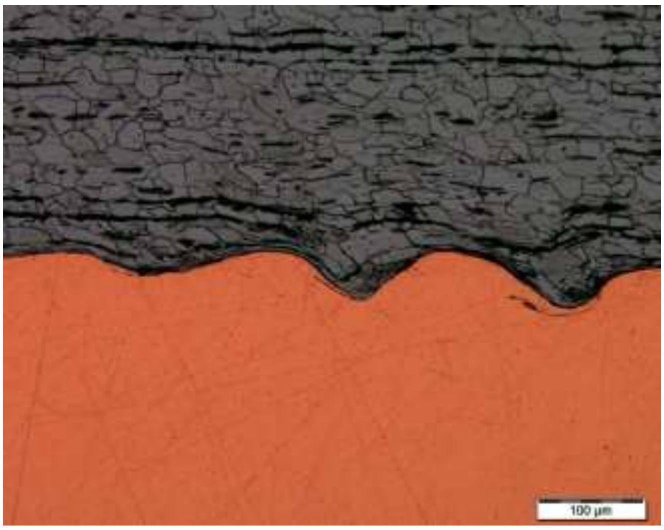

Figure 2. Wave formation in a copper-steel weld interface

The wave formation can become irregular and can give rise to softening or melting of the materials. This could be either caused by the predomination of the jetting phenomenon or according to the Kevin-Helmholtz instability model [1]. Cavities or voids can be formed in the jetting affected zone because of molten fluid, solidification shrinkage or fragmentation. The high cooling rate can also give rise to shrinkage cracks, while cavitation during melting can give rise to porosities. An example of these defects is shown in Figure 3. When different materials are welded at high impact speeds, intermixing of the material can occur, giving rise to an intermetallic phase. The formation of intermetallic phases should be limited, because these can be very brittle. This can be achieved by using low pulse energies [3]. Below a certain thickness, the intermetallic layer rarely contains the aforementioned defects, and when a wavy interface occurs, the intermetallics are observed to often form at the crests of the waves in melt pockets [4].

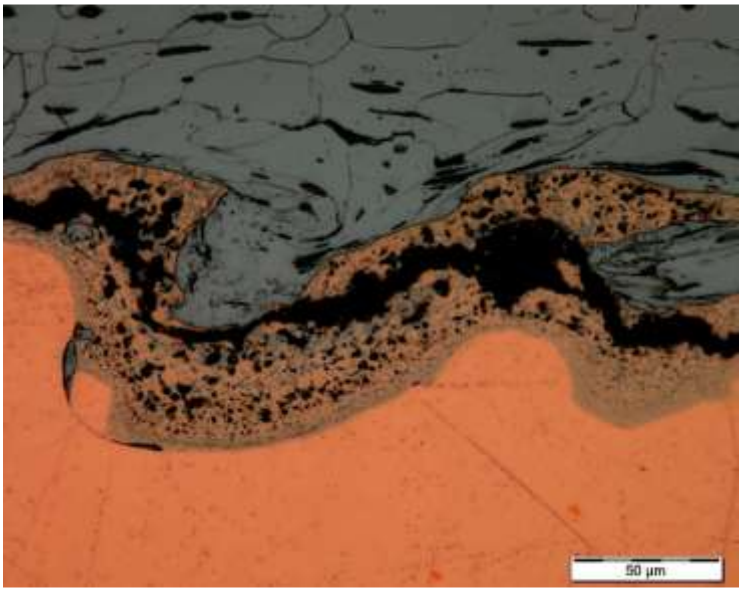

Figure 3. Intermetallic phases, porosities and cracking in a copper-steel weld interface

3 EXPERIMENTAL STUDY

3.1 Materials and specimens

In this investigation, copper tubes were welded to steel rods and tubes. The copper used is Cu-DHP R220 and was welded to cold worked carbon steel. A single turn coil was used with a field shaper and a capacitor bank with a total capacity of 160 µF. The copper tubes have an outer diameter of 22.22 mm and a wall thickness of 0.89 mm. The steel inner workpieces have an outer diameter such that the stand-off distance is varied between 1.0 mm, 1.5 mm and 2.0 mm. Three inner workpieces were used; a full rod, and tubes with a thickness of 3 and 2 mm. The overlap length of flyer and field shaper was chosen equal to 8 mm. Previous experiments with longer overlaps showed worse results, while a lower overlap would result in a shorter weld, which is also unfavourable. The specimen configuration is shown in Figure 4.

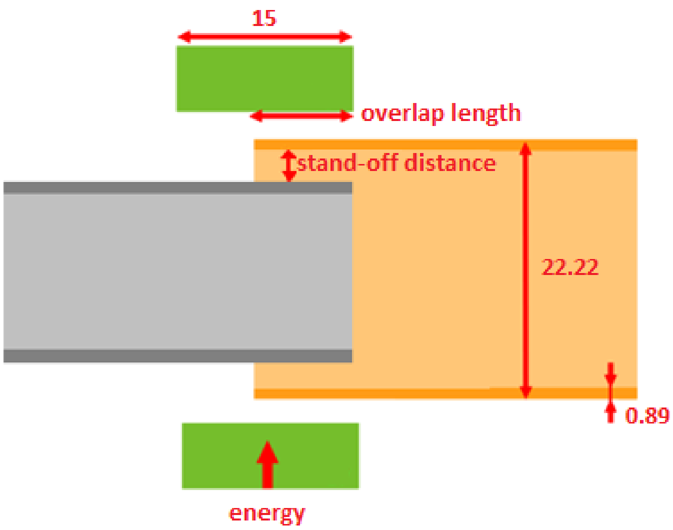

Figure 4. Tube-to-tube specimen configuration [5]

3.2 Evaluation procedure

To obtain a first impression of the weld quality, a non-destructive test is performed where the inside of the tube(s) is subjected to an air pressure of 8 bar. The ends of the workpieces are sealed and the whole is submerged in water. The leak-tightness of the weld can be visually inspected. When air bubbles escape from the assembly, there are either some severe imperfections present, or there was no weld formed at all. In case of leakage, the pressure loss per time unit through the weld is noted, as a measure of the severity of defectiveness. The set-up for the leak test is shown in Figure 5.

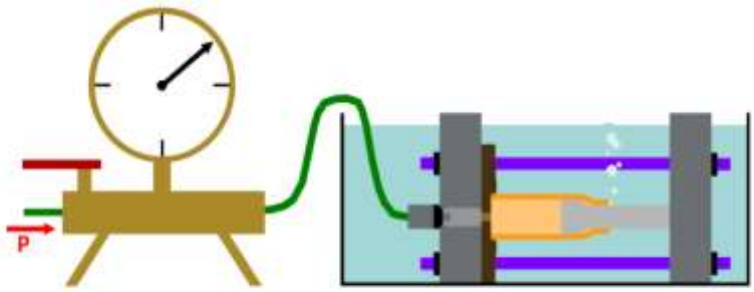

Figure 5. Leak test set-up

To determine the actual cause of leaking welds or to assess the quality of leak-tight welds, a metallographic inspection is required. The samples are cut, embedded in epoxy resin and polished. The weld length and, in case of tube-to-tube connections, the inner diameter decrease are measured. Special attention is paid to the presence of intermetallic phases, porosities and cracks. The continuity of the weld should also be inspected. Important to note is the fact that there is a cut in the field shaper, as shown in Figure 6 (A). This to assure that the current does not flow only at the outside of the field shaper, which would be the case if no cut is present (B), but flows as close to the workpieces as possible (A).

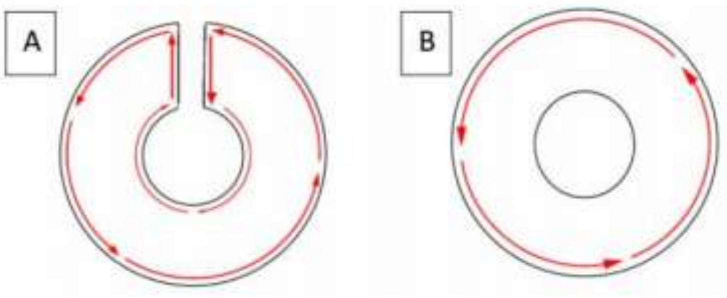

Figure 6. Cut in field shaper gap to force current to the inside [6]

Because of this, the magnetic field is slightly weaker at the location of the field shaper cut. Therefore, the part of the weld at this location receives less energy and thus the weld is usually a bit shorter there. Care is taken to mark this location and cut the samples here, in order to investigate the worst part of the weld.

4 RESULTS AND DISCUSSION

4.1 Leak tests

Performing leak tests on the samples with a steel rod as inner workpiece revealed that all the welds with 1.0 mm stand-off distance had failed. The other welds with stand-off distances of 1.5 mm and 2.0 mm passed the leak test, thus most likely are sound welds. Tube-to-tube welds did however produce several leak-free welds for all levels of stand-off distance, showing the inner workpiece thickness to have an important influence on the process. The 3 mm thickness tubes showed better results than the 2 mm tubes. Leak tests give a first impression of the weld quality, however no explanations can be provided for the results without further investigation of the weld, for example by optical microscopy.

4.2 Metallographic inspection

The metallographic inspection of a weld allows to evaluate the joint quality by characterizing and quantifying such aspects as intermetallic phases, imperfections, weld length and specimen deformation. The focus of this research is to examine the effect of decreasing the inner workpiece thickness. Previous experiments on tube-to-rod connections showed a suitable energy level for successful welds to be around 20 kJ.

The decrease of the steel workpiece inner diameter due to deformation is shown in Figure 7. Figure 7, left, shows the influence of the stand-off distance for a constant discharge energy of 20 kJ. Figure 7, right, shows the influence of the discharge energy for a constant stand-off distance of 2 mm. The radius decrease has been determined at the side opposite to the field shaper cut, as the most severe deformation is expected to occur there. The decreases in radius at the field shaper cut were all between 0% and 45% less in value, hence proving the assumed lower deformation compared to the other side. Obviously, the radius decreases more with increasing discharge energy and decreasing tube wall thickness of the inner workpiece, the first giving more energy available for deformation and the second decreasing the resistance against deformation. A larger stand-off distance also shows a larger indentation, as the flyer is given more space to accelerate.

This assuming the flyer has not reached its deceleration point over the distance of 2 mm. To be certain about this, numerical simulations or velocity measurements should be performed. The average radius decrease of the tubes with 3 and 2 mm thickness equals 0.61 mm and 1.42 mm respectively. This deformation is most likely unacceptable, depending on the application, as this causes a decrease of up to 25% in diameter. This equals losing almost half of the inner tube area, which for example for fluid applications is very severe. Therefore, it is advisable to use some kind of internal support when welding tubular components. An example of the radius decrease for inner tubes with 2 mm and 3 mm thickness is shown in Figure 8.

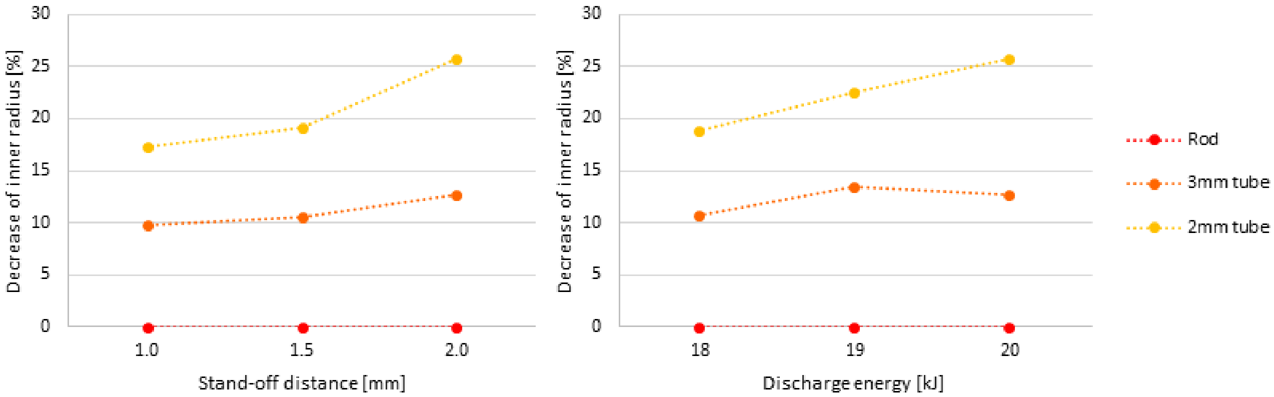

Figure 7. Decrease of inner radius of steel inner workpiece as a function of stand-off distance (left; with 20 kJ discharge energy), discharge energy (right; with 2 mm stand-off distance) and inner workpiece thickness

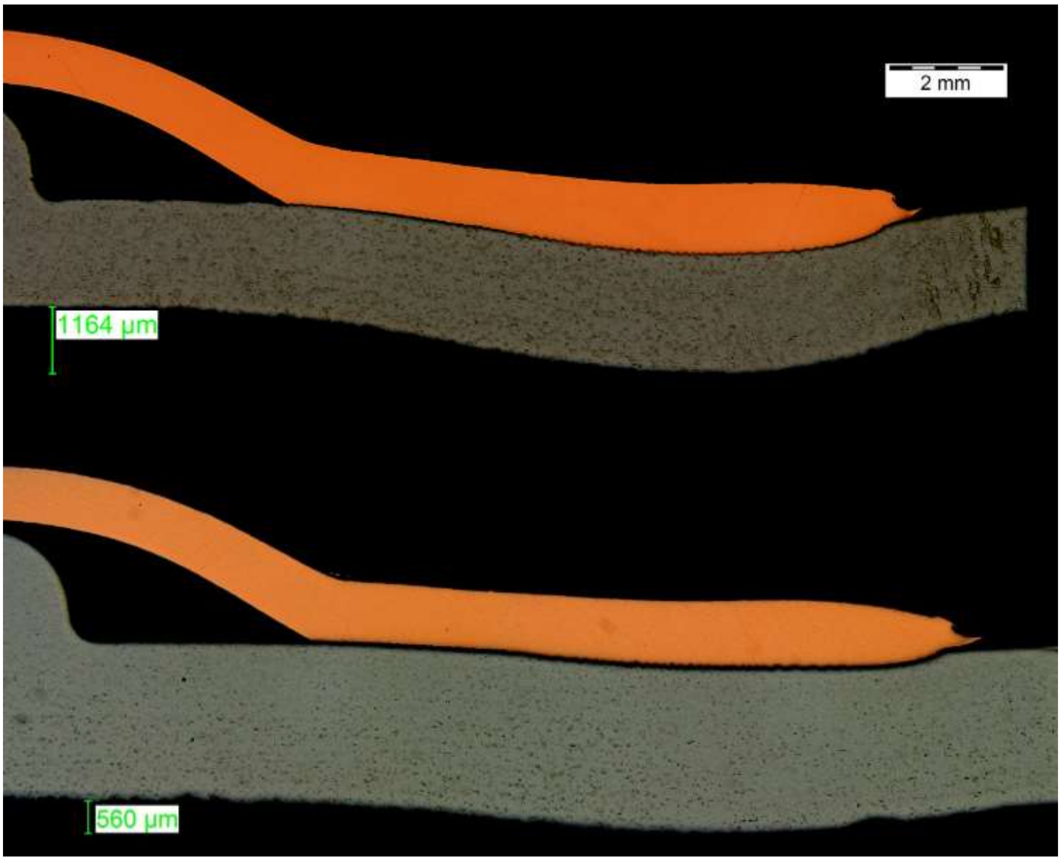

Figure 8. Radius decrease for 2 mm steel tube (top) and 3 mm steel tube (bottom) at 18 kJ discharge energy and 2 mm stand-off distance

The weld length evolution is shown in Figure 9. The experiments with varying stand-off distance were performed with 20 kJ discharge energy. The experiments with a varying discharge energy were performed with a stand-off distance of 2 mm. The length is the average of the lengths measured at the field shaper cut and 180° away from this location. From the measurements, it can be concluded that the weld length decreases with decreasing inner workpiece thickness.

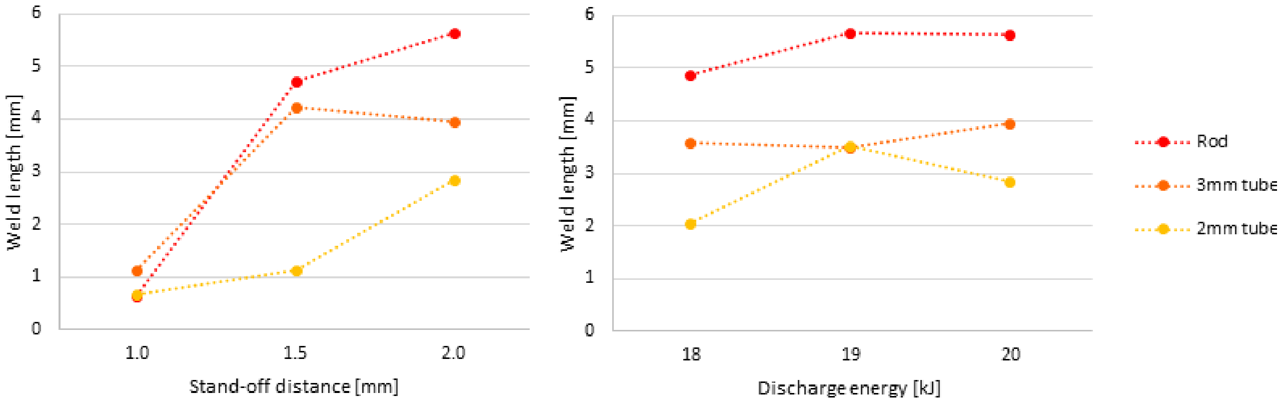

Figure 9. Weld length in function of stand-off distance (left; with 20 kJ discharge energy), discharge energy (right; with 2 mm stand-off distance) and inner workpiece thickness

Microscopical investigations showed that the welds with a 2 mm stand-off distance were either long and continuous, or failed catastrophically due to cracks at the weld interface. The defective welds look as if they cracked after the weld formation. Severe shearing of grains, waviness and some intermetallic phases were present in the broken welds, similar to successful welds, indicating enough energy is present to form a good weld. However, cracking of the weld was most likely not caused by the intermetallic phases, as most of the cracked interface does not show signs of intermetallic phase. The welding speed, also known as the collision point velocity, is much higher than the deformation rate of the inner workpiece in radial direction. Therefore, it is believed that the weld is formed before the deformation of the inner tube in radial direction is initiated [7]. In other words, the inner tube only starts decreasing in diameter after the weld has been formed. Based on this, a possible hypothesis is that the formed weld was not strong enough to withstand the forces caused by the deformation of the inner tube and thus failed at the weld interface. An example of such a failure is shown in Figure 10, compared with a similar unbroken deformation pattern in a tube-to-rod weld, thus without a large radial deformation.

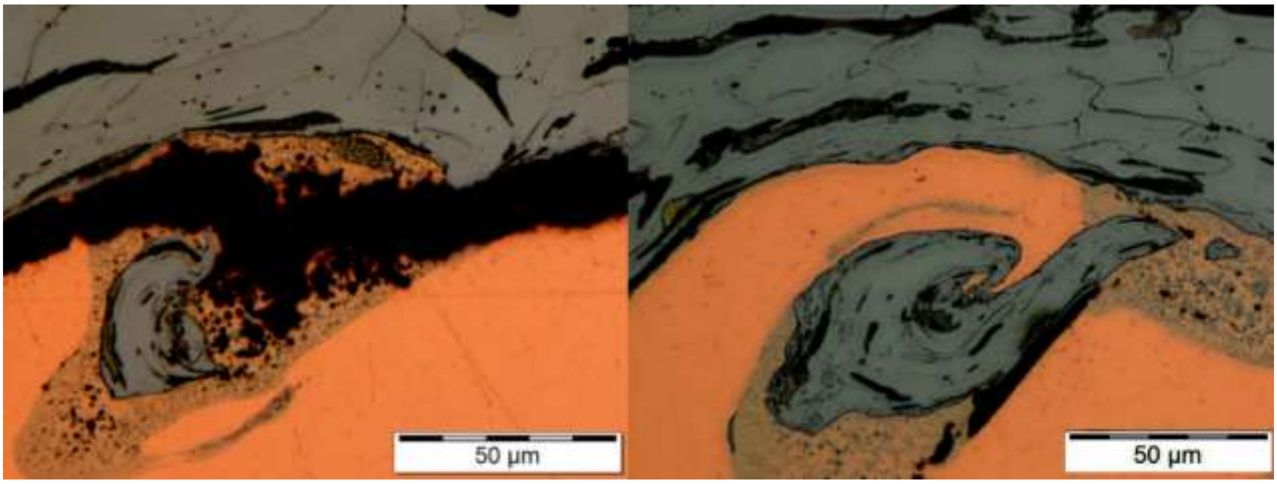

Figure 10. Microstructure of failed weld tube-to-tube (left) and successful weld tube-to-rod (right)

Tube-to-tube welds with a shorter stand-off distance, 1.5 and 1 mm, showed a different pattern, where short discontinuous welds were observed. At the side opposite to the field shaper cut, often two short welds are present, separated by a non-welded region, an example of this with an inner tube wall thickness of 2 mm is shown in Figure 11. This non-welded region shows signs of large, almost continuous intermetallic pockets, which have cracked and teared open. Welds made under the same conditions in the tube-to-rod configuration often showed an increase of intermetallic pockets near the middle of the weld. Most likely, it is this region that failed in tube-to-tube configuration due to the deformation of the internal tube after welding, as it is very brittle and the porosities are prone to crack initiation. Opposite to the field shaper cut, the beginning and ending of the weld still remain joined, despite the cracks in the middle. At the side of the field shaper cut, less energy is provided and the beginning of the weld fails as well. This is seen on Figure 11 at the bottom, on the left there is still a small joined region, while on the right side there is not. The region with an increased amount of intermetallic compounds can be explained by the local temperature increase during welding [2]. This is possibly linked with a higher impact velocity, however, simulations or experimental measurements of impact velocity along the weld interface should be performed to gain more insight.

Apart from the obvious drawback of diameter decrease when welding tube-to-tube, a loss in weld quality is thus observed. Again, the conclusion can be drawn that some kind of internal, removable support is advisable.

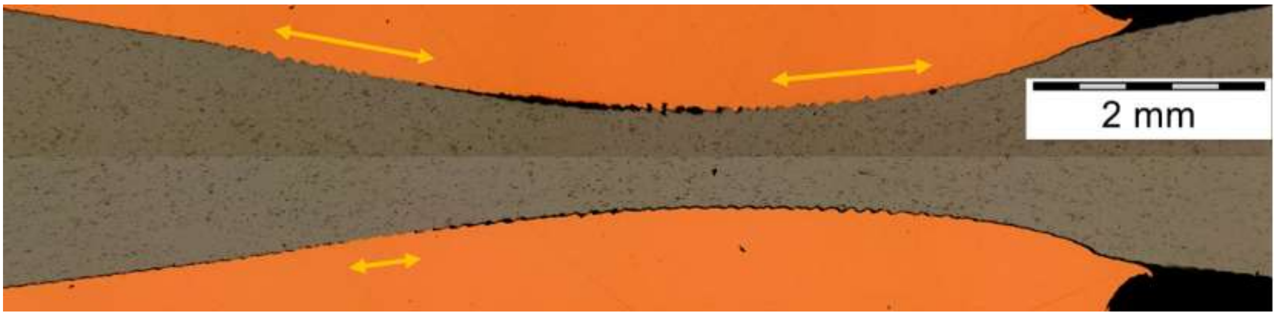

Figure 11. Top: Weld interface with 2 welded regions, opposite of the field shaper cut - Bottom: Weld interface with one welded region and a broken region at the field shaper cut (2 mm inner wall thickness)

5 CONCLUSIONS

The weldability of copper tubes to steel rods and tubes was investigated, with the goal of examining the influence of the wall thickness of the inner tube on the weld formation and the deformation of the components. Large deformations were observed, causing an undesirable decrease in diameter of the internal tubes. The decrease of the inner diameter increased for a higher discharge energy and stand-off distance, and for a lower inner tube thickness. The quality of the obtained welds was shown to decrease, either by breaking of formed welds or by cracking of the intermetallic layer. The failure is most likely caused by the radial deformation after the weld was created. Because of these observations, it is advisable to use an internal support to prevent deformation of the internal tubes. To gain more insight in the precise mechanisms of weld formation and failure, numerical simulations should be performed.

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