EXPERIMENTAL INVESTIGATION OF THE WELDABILITY OF TUBULAR DISSIMILAR MATERIALS USING THE ELECTROMAGNETIC WELDING PROCESS

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Abstract: This paper describes the magnetic pulse welding process (MPW) for tubes. Material combinations of aluminium to steel and copper to aluminium were experimentally evaluated. The first major goal of this work is to experimentally obtain the optimal input parameters like the discharge energy, the stand-off distance and the tool overlap for MPW of the material combinations. Welding windows with all possible input parameters are created for both material combinations. Furthermore, a comparison is done between three coil systems; a single turn coil with field shaper, a single turn coil with a field shaper and transformer and a multi-turn coil and field shaper. Metallographic investigation of the samples, hardness tests and leak tests were executed to determine the most suitable machine set-up and the optimal input parameters for each set-up. A second major goal is to determine the influence of the target tube wall thickness on the deformation of tube-tube welds when no internal support is used.

Keywords: Electromagnetic pulse welding; dissimilar materials; tube; comparison coils; internal support

1   INTRODUCTION

Global trends force the industry to manufacture lighter, safer, more environmentally friendly, more performant and to use cheaper products. Joining of dissimilar materials is getting more and more interest for these purposes. Magnetic pulse welding (MPW), a welding process that emerged in the beginning of the 70's as a spin off technology of nuclear energy programs [1], can be used to join dissimilar materials in just a few microseconds. In applications that require the combination of high strength steel and the high thermal conductivity of copper or aluminium, MPW seems very promising [1]. MPW also results in a higher productivity and a higher joint quality.

Magnetic pulse welding has some distinct advantages. First of all, MPW consumes less energy, less material and less man-hours compared to traditional welding processes. Secondly, it has a very short process time and requires no surface preparation what makes it very suitable for automation. Most important, it is a welding process that allows joining of dissimilar metals. Metal combinations like aluminium-steel, aluminium-copper, copper-steel, etc. have been investigated at the Belgian Welding Institute [2]-[5]. Another advantage is that there is no heat affected zone in comparison with traditional welding techniques. The base materials are only affected in a very small zone (20-50 μm) where the weld is created. Therefore, heat treatments that were performed prior to the welding process will not be affected. A fifth advantage is the exchangeability of the equipment. Different coils can be changed in a limited amount of time. The whole installation and equipment can also be used for crimping or forming of tubes.

MPW does have some disadvantages as well. The flyer material must have a good electrical conductivity or a conductive driver that pushes the flyer material to the parent workpiece is needed. The driver has to be removed after each weld, what consumes time. Secondly, the inner material must have a sufficient strength to withstand the impact and pressure of the flyer workpiece without deforming. The process is also only suited for thin workpieces and only for tube or sheet connections. Furthermore, the size of the parts is limited. Another disadvantage is that the input parameters to perform a good weld have to be determined experimentally which makes the process costly and therefore only suitable for large production series. Also safety has to be taken into account. Due to the high currents and voltage, there is a danger during day operations and maintenance. The combination of these advantages and disadvantages makes the process (up to now) only suitable for large companies and big industry branches like nuclear, aerospace, automobile industry, ordnance, packaging and electrical industries [1], [2], [6].

MPW is a cold process and can be categorized within the solid-state welding processes. Solid-state welding means that the metallurgical bond is produced without fusion, so there is no liquid to solid transformation compared to common welding processes. During the process, the parts are accelerated to a
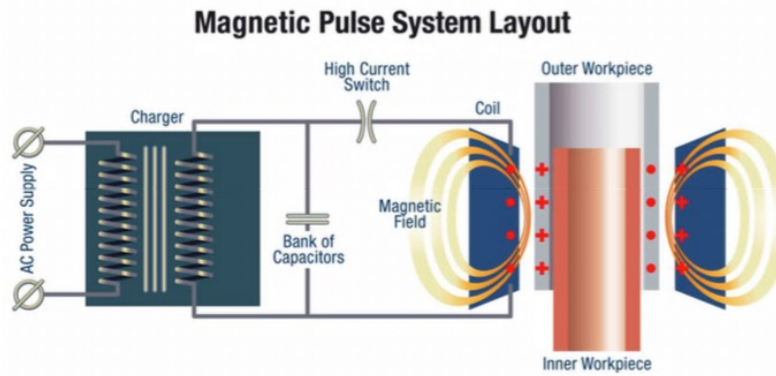
Figure 1. Principle of magnetic pulse welding [7].

high velocity by repulsive magnetic forces. The repulsive magnetic forces are a result of the interaction between the opposing magnetic fields of a coil and eddy currents induced in the metallic workpiece. A schematic representation of the process can be seen in Figure 1. The workpiece impacts on the target workpiece with a velocity of more than 300 m/s and a metallic bond forms between the two materials [8]. Being a solid-state welding process based on pressure, MPW allows joining of dissimilar materials [1].

This research work focusses on MPW of tubular parts. First the optimal parameters for welding aluminium tubes to steel bars and copper tubes to aluminium bars are investigated and determined. Next, an experimental comparison is done between using a single turn coil (with and without a transformer) and a multi-turn coil. It is investigated which set-up delivers the best weld characteristics. The last stage of the experimental work investigates tube-tube welds of aluminium to steel tubes. First, the weld formation is investigated when no internal support is used for the inner tube. Next, different internal supports are explored or designed and finally tested.

2   EQUIPMENT, MATERIALS AND METHODOLOGY

2.1.   MPW equipment

The experiments were executed at the Belgian Welding Institute (BWI) on a magnetic pulse welding setup BMax MPW 50/25 with a capacitance bank of 160 μF. Different coils can be connected to the MPW machine. During this research, three different coil systems were used. A copper single turn coil with field shaper, a single turn coil with fieldshaper and transformer and a multi-turn coil with fieldshaper. A field shaper is used to concentrate the magnetic field to a certain region. A transformer can be connected to increase the current through the coil, but decreases the current discharge frequency. In order to measure the discharge current, a Rogowski coil with different integrators, was used.

2.2.   Materials

Two dissimilar material combinations were investigated in this research work, aluminium to steel and copper to aluminium. Experiments of tubes to solid workpieces were executed with aluminium EN AW-6060-T6 and EN AW-3103-H14 as flyer tubes to S355J2 as parent workpieces. Furthermore, for the copper-aluminium combination, Cu-DHP R250 and EN AW-6082-T6 were used. The tube to tube experiments were all executed with EN AW-6060-T6 and S355J2.

2.3.   Methodology

To find the optimal parameters for welding tubular parts, the configurations shown in Figure 2 and 3 were used. The flyer tubes had an outside diameter of 28.0 mm with a wall thickness of 1.3 or 0.9 mm and a length of 50 mm. Depending on the wall thickness of the flyer tube and the desired stand-off distance (gap), the diameter of the internal workpieces was varied between 21 and 24 mm. According to Demonie [2], the free length does not have a big influence on the weldability and the weld length. As such, a free length of 15 mm was used for all experiments. Previous research at the BWI by Demonie et al. [2] and Broekhove [3] demonstrated that for welding tubes with a wall thicknesses of 1 mm, the optimum gap is between 1 and 2 mm and the optimum overlap is between 6 and 12 mm. In order to find the parameters with the best weld characteristics, three input parameters were systematically varied. The input energy was varied between 14 and 21 kJ, the overlap between 8 and 10 mm and the gap was equal to 1, 1.5 and 2 mm.

After each welding experiment, different steps followed to determine the weld characteristics (weld length, intermetallic layer, porosities, irregularities, etc.). First of all, a leak test was performed to determine if the performed weld was leak tight or not. The specimens were compressed with air at approximately 8 bar and put into a water bath. After 5 minutes the pressure inside the sample was measured again to determine the

pressure difference and as such a relative measure for the leak tightness. Secondly, the sample was cut in half in the axial direction by a grinding machine through the bonded area, see Figure 4. The sample was visually examined before it was embedded in Caldofix resin. When the resin was fully hardened, the sample was polished. The polished sample was examined by optical microscopy to determine the weld length at locations '1' and '2' (see Figure 5), the appearance of the intermetallic layer, porosities, etc. After the metallographic examination, hardness tests according to EN ISO 9015-2 were executed on a selection of samples to determine the hardness of the intermetallic layer.
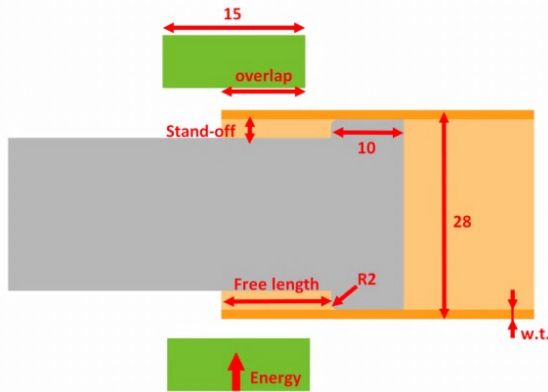

Figure 2. Configurations for joining tubes to solid internal workpieces (with a shoulder).
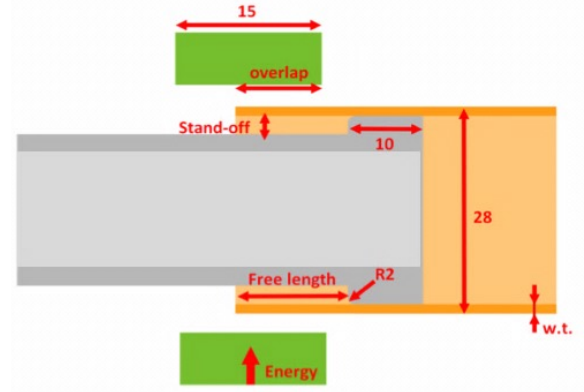

Figure 3. Configurations for joining tubes to tubes (using a shoulder).
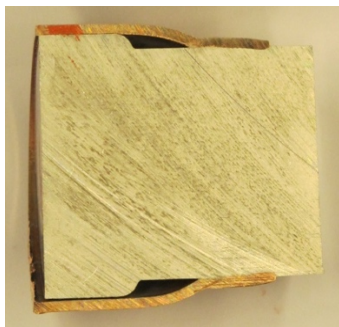

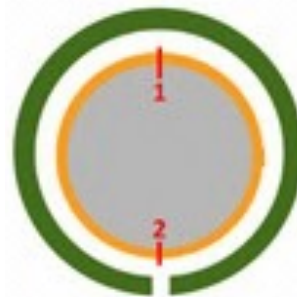
Figure 4. Sample after axial cutting.

Figure 5. Locations for weld length measurements: '1' = 180° away from field shaper cut, '2' = at the field shaper cut [9].

3   COMPARISON OF COIL SYSTEMS

3.1   Single turn coil with field shaper

In this test series, the optimal parameters for welding aluminium tubes (EN AW-6060-T6) with two different wall thicknesses (0.9 and 1.3 mm) to solid internal steel S355J2 workpieces (outer diameters: 21, 22, 23 and 24 mm) were determined. The discharge energy was varied between 13 and 23 kJ, the gap was equal to 1, 1.5 and 2 mm and an overlap of 8 and 10 mm was used. The discharge current frequency was approximately equal to 44 kHz. The maximum current was equal to 480 kA. For welds with aluminium tubes with a wall thickness of 0.9 mm, only joints without a welded interface and exhibiting severe leaks with pressure differences ranging from 4.0 to 7.8 bar were achieved. For welds with aluminium tubes with a wall thickness of 1.3 mm, a nearly leak tight joint (pressure difference of 0.8 bar) was obtained at a discharge energy of 21 kJ, a gap of 1.5 mm, an overlap of 8 mm and a free length of 15 mm. This joint also showed a welded interface at both 180° and 0° relative to the field shaper cut. The weld lengths were 2.9 and 2.2 mm, respectively. Experiments performed with the same parameters, but a lower energy of 14 kJ also resulted in a nearly leak tight joint (pressure differences of 0.4 to 0.7 bar). However, since these joints were either not welded or only welded at one side, this suggested that only a weakly crimped connection or a weak metallurgical bond was formed. No increase in hardness across the weld interface was observed. Experiments performed with the same parameters, but with a lower (1 mm) or higher (2 mm) gap, led to joints with severe leaks and no weld formation.
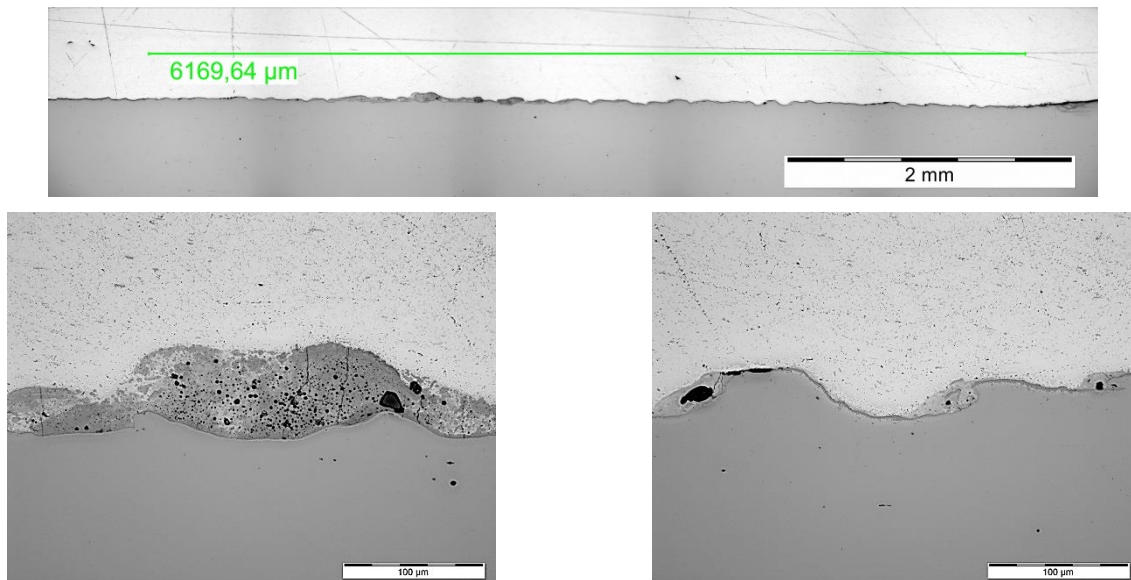
Figure 6. Welded interface of EN AW-6060-T6 aluminium tube to solid internal steel S355J2 at 180° to the field shaper cut (x100) and details of the end and middle of the welded interface (x500), with a single turn coil with fieldshaper and transformer at 17 kJ, gap 2 mm and overlap 8 mm (tube wall thickness: 0.9 mm).

3.2 Single turn coil with field shaper and transformer

In a next test series, experiments were conducted with the same aluminium tubes and solid internal steel S355J2 workpieces. A transformer was used, which is placed between the capacitor bank and the single turn coil with field shaper. The transformer increases the current, but decreases the discharge current frequency, what means that the pulse energy is spread over a longer time. The discharge energy was varied between 15 and 21 kJ. The gap was again choosen equal to 1, 1.5 and 2 mm. The overlap was varied at 8 and 10 mm. The discharge current frequency was approximately equal to 13.7 kHz and a maximum current of more than 490 kA was measured.

For welds with aluminium tubes with a wall thickness of 0.9 mm, the majority of the specimens were completely leak tight. The weld length and interfacial layer thickness ranged from 1 to 6.2 mm and 10 to 60 µm, respectively, see Figure 6. Welds achieved with an overlap of 8 mm exhibited a better leak tightness (completely leak free) and a higher weld length, but a larger interfacial layer thickness (from 10 to 60 µm), compared to welds obtained with an overlap of 10 mm (0 to 3.8 mm and 10 to 20 µm, respectively). At a lower discharge energy, the highest weld quality is obtained for a gap of 2 mm, whereas higher discharge energies displace the welding window to a lower gap of 1.5 mm. This can be explained by the different impact velocity that is required when increasing the discharge energy. The specimen with the longest weld length of 6.2 mm at both sides of the specimen was obtained for a gap of 2 mm, a discharge energy of 17 kJ and an overlap of 8 mm. This specimen exhibited a welded interface with an intermetallic layer thickness up to 60 µm.

A significant hardness increase up to 561 HV and 312 HV in the interfacial layer was detected, compared to the base material. Also a thin strain hardened layer of steel and aluminium was present next to the intermetallic layer, which exhibited a slight increase in hardness near the welded interface. Both the thin strain-hardened layer and the intermetallic layer can influence the interfacial bonding strength.

For welds with aluminium tubes with a wall thickness of 1.3 mm, the majority of the specimens were completely leak tight. Moreover, the range of weld lengths measured is similar to welds with a tube thickness of 0.9 mm (from 2.2 to 6.3 mm), but the range of interfacial layer thickness was much lower (from 10 to 35 µm). The specimen with the longest weld length of 6.3 mm at 180° and 5.8 mm at 0° to the field shaper cut, was obtained for a gap of 1.5 mm, a discharge energy of 21 kJ and an overlap of 8 mm. The discharge energy of 21 kJ required to obtain the longest weld length was significantly higher than for the welds with tubes with a wall thickness of 0.9 mm (17 kJ). This can be attributed to the lower mass that needs to be accelerated. Hence, a lower discharge energy is required to obtain a given impact velocity.
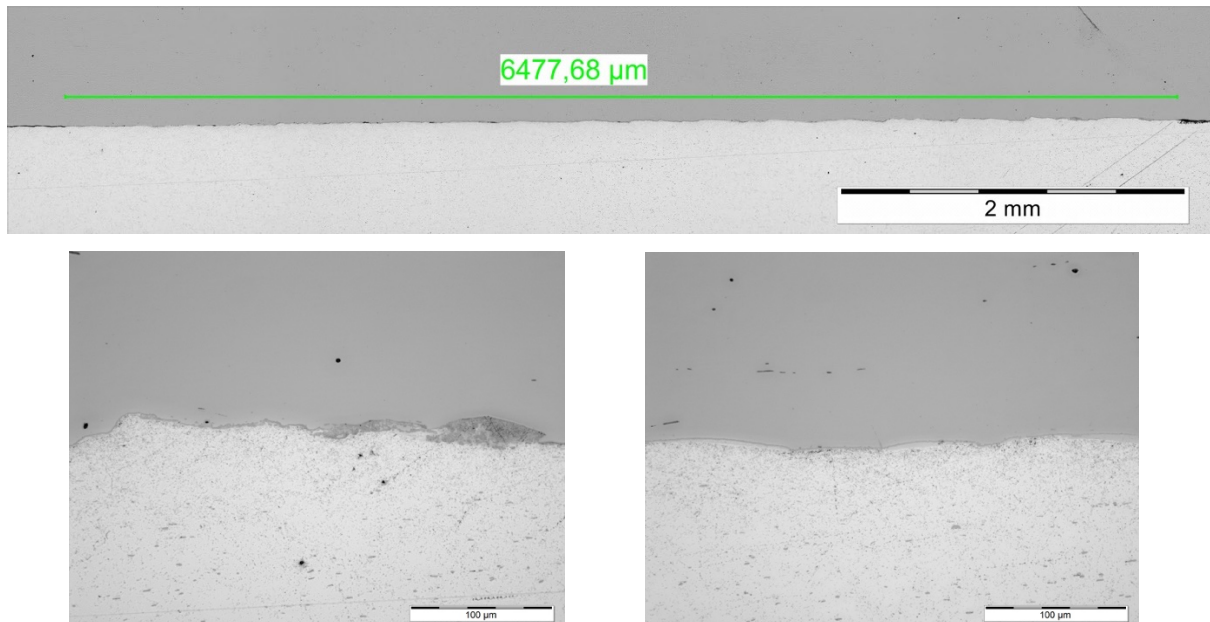
Figure 7. Welded interface of EN AW-6060-T6 aluminium tube to solid internal steel S355J2 at 180° to the field shaper cut (x100) and details of the end and middle of the welded interface (x500), with a multi-turn coil with fieldshaper at 21 kJ, gap 1.5 mm and overlap 8 mm (tube wall thickness: 1.3 mm).

3.3 Multi-turn coil with fieldshaper

For these experiments, a multi-turn coil was used instead of a single turn coil. The discharge energy was varied between 17 and 23 kJ with gaps of 1, 1.5 and 2 mm and overlaps of 8 and 10 mm. The discharge current frequency was approximately equal to 14 kHz and maximum currents around 200 kA were measured. For welds with aluminium tubes with a wall thickness of 0.9 mm, the majority of the specimens were completely leak tight. The weld length ranged from 0.9 to 6.34 mm for an overlap of 8 mm and from 0.81 to 3.33 mm for an overlap of 10 mm. At lower discharge energies, the highest weld quality is obtained for a gap of 2 mm, whereas higher discharge energies displace the welding window to lower gaps. This can be explained by the different impact velocity that is required when increasing the discharge energy. The specimen with the highest weld lengths of 6.34 mm and 6.22 mm were obtained at a gap of 2 mm, a discharge energy of 17 kJ and an overlap of 8 mm. Similarly to previous experiments, an overlap of 8 mm result in better weld interface properties than an overlap of 10 mm. For welds with aluminium tubes with a wall thickness of 1.3 mm, the majority of the specimens were completely leak tight. Moreover, the range of measured weld lengths is similar compared to welds with a tube thickness of 0.9 mm. The specimen with the longest weld length of 6.81 mm at 180° and 8.64 mm at 0° to the field shaper cut, contained a lot of local melting, pores and cracks. Higher quality weld interfaces and similar weld lengths were obtained by using a gap of 1.5 mm, a discharge energy of 21 kJ and an overlap of 8 mm, see Figure 7. The discharge energy of 21 kJ required to obtain the longest weld length was significantly higher than for the welds with tubes with a wall thickness of 0.9 mm (17 kJ). This can be attributed to the lower mass that needs to be accelerated. Hence, a lower discharge energy is required to obtain a given impact velocity.

3.4 Comparison coil set-ups

Using a single turn coil with field shaper and without a transformer results in poor welding characteristics. Adding a transformer to the single turn coil machine set-up increased the weld characteristics of the samples enormously. Longer weld lengths were obtained and wider ranges for the input parameters are possible to be used. The best weld results were obtained with the multi-turn coil machine set-up. The same optimal input parameters as for the single turn coil with transformer were experimentally determined, but the weld interface layer exhibited less local melting, cracks and pores. It can be concluded that a single turn coil with transformer can imitate the results obtained by using a multi-turn coil.

Table 1. Comparison different coil systems.

Coil System	Leak tightness	Highest weld length [mm]	Hardness	Weld interface
Single turn coil with fieldshaper	No	2.9	No increase	Many cracks and pores
Single turn coil with fieldshaper and transformer	Yes	6.3	High increase	High interfacial layer thickness
Multi-turn coil with fieldshaper	Yes	6.8	High increase	Small interfacial layer thickness

4   JOINING OF ALUMINIUM TUBES TO HOLLOW STEEL TUBES

A test series was conducted with aluminium flyer tubes (EN AW-6060-T6) with a wall thickness of 0.9 mm, joined to steel target tubes S355J2 with 3 different wall thicknesses of 1, 2 and 3 mm. The steel target tubes were unsupported. The purpose of this test series was to investigate how much the outer and inner tubes deform without using an internal support and the impact of the wall thickness of the inner tubes on the deformation. As machine set-up, a single turn coil with a field shaper and a transformer was used. The discharge energy was varied between 17 and 21 kJ. A gap equal to 1, 1.5 and 2 mm was used. The overlap was chosen equal to 8 mm. The discharge current frequency was approximately equal to 13.7 kHz. The maximum current was around 650 kA. For target tubes with a wall thickness of 1 mm, half of the performed tests were not leak tight and all the samples showed severe deformations between 5.2 and 7.8 mm for the internal diameter. For target tubes with a wall thickness of 2 mm, all welds were leak tight and longer weld lengths (up to 5.3 mm) were achieved. The deformations varied between 1 and 2.1 mm for the internal diameter. For target tubes with a wall thickness of 3 mm, all welds were leak tight and long weld lengths (up to 6.6 mm) were achieved. The deformations varied between 0.4 and 0.9 mm for the internal diameter. Figure 8 shows the samples after cutting for the three tube wall thicknesses. In general, for welds with all 3 steel tube wall thicknesses, the longest weld lengths were found for a gap of 2 mm in combination with any discharge energy. The smallest deformation of the inner diameter of the steel target tube for every target tube wall thickness was found for a gap of 2 mm, combined with the lowest discharge energy of 17 kJ, see Figure 9.

(a)   (b)   (c)
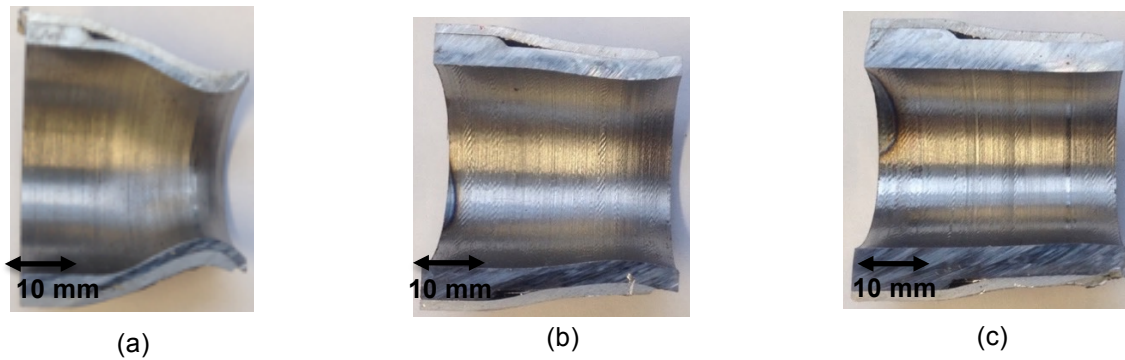
Figure 8. Tube-tube welds without internal support for target tube wall thicknesses 1 (a), 2 (b) and 3 (c) mm
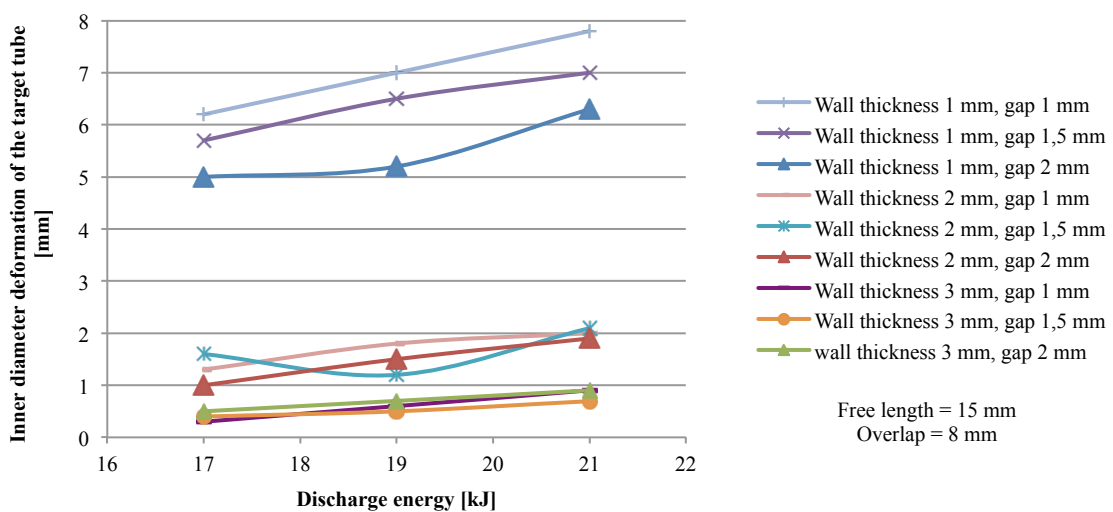

Figure 9. Inner diameter deformations for all the different energy levels, gaps and target tube wall thicknesses
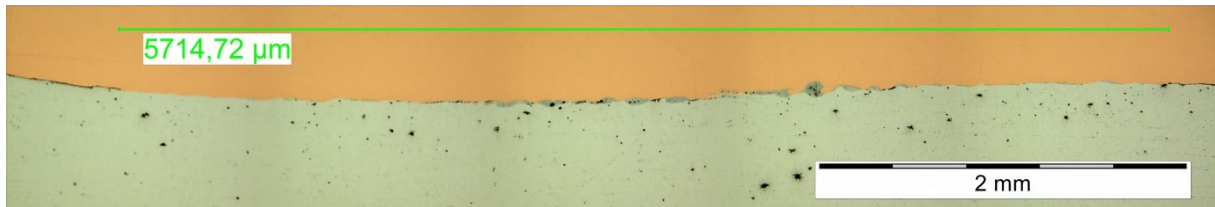
Figure 10. Copper-aluminium weld with flat interface at the start and end of the weld and wavy interface at the middle of the weld.

5   JOINING OF COPPER TUBES TO SOLID ALUMINIUM BARS

In this test series the optimal parameters for welding copper DHP 250 tubes with two different wall thicknesses (0.9 and 1.3 mm) to solid internal aluminium EN AW-6082-T6 workpieces (diameters 21, 22, 23 and 24 mm) were determined. The discharge energy was varied between 8 and 21 kJ with gaps of 1, 1.5 and 2 mm and overlaps of 8 and 10 mm. The discharge current frequency varied around 13.70 kHz and maximum currents of more than 480 kA were measured. For the welds with a wall thickness of 1.3 mm, a tool overlap of 8 mm generally doesn't result in sound welds (i.e. welded at the complete circumference and leak tight). Better results and a larger parameter window were obtained with a tool overlap of 10 mm. In this case, only a gap of 2 mm resulted in sound welds. The optimal energy setting for a gap of 2 mm was 20 kJ. The metallographic examination revealed that at the weld start and the weld end, the interface is relatively flat, without any visible interfacial layers. At the weld middle, a wavy interface is observed, see Figure 10. The interfacial layer is either very small or not visible. For the welds with a wall thickness of 0.9 mm, sound welds can be obtained when using higher energy levels (min. 21 kJ) or a larger gap between tube and internal workpiece (2 mm). The welded interface had the same morphology as described above for the welds with a wall thickness of 1.3 mm.

6   CONCLUSIONS

It has been proven that for welding aluminium tubes to solid internal steel bars using magnetic pulse welding, the optimal settings for the input parameters like discharge energy, tool overlap and gaps can be determined experimentally, see Table 2. Different coil systems were used; a single turn coil with field shaper and with or without transformer and a multi-turn coil with field shaper. The multi-turn coil provides better results for the weld characteristics like the weld length, the size of the interfacial layer and the presence of cracks and pores.

Table 2. Overview optimal input parameters for welding Al tubes to solid steel bars for the different coil systems.

flyer tube wall thickness [mm]	Energy [kJ]	Voltage [kV]	Gap [mm]	Overlap [mm]	Free length [mm]
Single turn coil with fieldshaper					
0.9	/	/	/	/	/
1.3	21	16.2	1.5	8	15
Single turn coil with fieldshaper and transformer					
0.9	17	14.58	2	8	15
1.3	21	16.2	1.5	8	15
Multi-turn coil with fieldshaper					
0.9	17	14.58	2	8	15
1.3	21	16.2	1.5	8	15

For tube-tube welding, the influence of the target tube wall thickness on the deformation of the inner tube was investigated. Internal supports should be employed when target tubes with wall thicknesses of less than 2 mm are used. Future work on tube-tube welding should consider using internal supports that can easily and quick be applied to avoid excessive deformation of the tubes.

The optimal input parameters for welding copper tubes to solid internal aluminium bars with magnetic pulse welding have been determined, see Table 3. The weld interface shows a flat appearance at the beginning and end of the weld. In the middle a wavy interface can be observed with bigger interfacial layers.

Table 3. Overview optimal input parameters for welding Cu tubes to solid Al bars with a single turn coil with fieldshaper and transformer.

flyer tube wall thickness [mm]	Energy [kJ]	Voltage [kV]	Gap [mm]	Overlap [mm]	Free length [mm]
0.9	19	15.41	2	10	15
1.3	20	15.81	2	10	15

7   ACKNOWLEDGEMENTS

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