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Assessment of Weld Quality and Impact of Process Parameters for Aluminum-Copper through MPW

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Abstract:

The robust state bonding process is Magnetic Pulse Welding (MPW) that uses the dynamic of electromagnetic/mechanical phenomena in order to create a bond with a high-speed effect. In the interface, there will be formation of ripples, solid connections and localized deformation of plastic and this is due to effect of fast-moving plate on base metal. The effect of the key geometric parameters (surface, pitch and free length) and the energy input on weld generated by MPW is understood. In order to determine the underlying relations for the different sheets of copper and aluminium, the experimental design procedure for Taguchi was used. The weld quality has been assessed based on four performance parameters: the welding volume, interfacial layer size, lap shear thickness and flyer sheet thickness reduction. In comparison to the small attention paid by these criteria in other journals, the effect of the overlap and free duration was not insignificant. The present research aims to weld Al to Cu by using MPW and at better understanding the link between different process factors viz. power and velocity of impact for the morphology, angle of impact, strength and microscopy characteristics of the bond region and flyer thickness/geometry. The results obtained from this study of this work provide useful perspectives on the procedure of welding and the Al/Cu combination window of weld ability.

Keywords: Taguchi design; dissimilar sheet welding, interfacial layer; magnetic pulse welding,

1. INTRODUCTION

MPW is an advanced technology for solid-state that is linked to the pressurized solder processes community. The procedure can be used in the overlap configuration to suit tubular and sheet metals. With a high speed and a specific angle, there is the generation of Jet along the surface of materials. This jet removes the need for pre-process cleaning from surfaces pollutants such as oxide films. No pre-solder cleaning is generally necessary. [1]. In many industrial applications, the connection of different materials is becoming increasingly significant. Pioneering structures need components with high-performance that combine high ratio of strength/weight, enhanced resistance to corrosion, high electrical/thermal conductivity, or high temperature resistance that can only be achieved with the combination of different materials with different main properties.

(Cu) and (Al) are two technical materials that are widely employed in electric power, transportation and aerospace [2]. Bimetallic dissimilar junctions made of Al and Cu are lighter and less expensive than Cu/Cu assemblies, making them ideal for electrical applications where the conductor's cross-section area must be big to handle high current. However, in the recent decade, efforts have been made to enable metallurgical welding between these two dissimilar metals due to the difficulty in producing a bolted joint which is electrically stable for long term [3-4].

There are currently many welding processes available to combine different parts of similar and diverse materials to create a product with assembled mechanical properties equivalent to those of the base material. Nevertheless, the fusion welding of different metals is always restricted because of their physical properties or because of its intermetallic affinity. Due to fragile phases in weld some techniques of fusion welding are used like bracing and laser spot welding and this is for Al/Cu joints which does not have appropriate results [5-6].

Ben-Artzy et al. [9] It indicates that the K.E. of the flyer can be transformed into heat through two mechanisms during the MPW process: massive plastic deformation of the metals caused by wave-construction and wave-induced interface and extreme surface deformation while generating the flyer. This can cause the interface to melt the metal locally. The molten layer may be limited in some cases to local interface pockets, while in others there may be a melted material in a continuous layer and consequently an intermetal compound. In a single joint, both mechanisms are also identified. [7–10].

There is a scarcity of data on the effect of process (e.g., energy input) and for joined sheet metals, the impact on weld quality by the geometrical parameters. To explore the underlying associations, Al-Cu joints by MPW are investigated. The weld quality can be determined by a number of factors, including the length of the weld, the thickness of the intermetallic sheet, the lap shear power, and so on.

There are some opposing viewpoints about the inter metallic layer's thickness and other factors related to interfacial layer. On the one side, some writers prefer intermetallic layer of about 5m thickness which have straight interface, and say that localized melting pockets are in correlation with wavy interface. Furthermore, the intermetallic phases that are formed may be brittle. [11]. Some others claim that mechanical interlocking necessitates a wavy interface to produce high weld strength [12]. According to a third viewpoint, strength of bond is reduced abruptly when interface compounds have critical width and it is also observed that they have brittle characteristics [13].

Many experts investigated geometrical and metallurgical aspects of MP welds & Al/Cu EXW [14–16]. Molten and reconsolidated materials and oxide inclusion are the aspects of the formation of wave that have been researched the most and intermetal process, in the pockets and films. The literature also discusses the development of incomplete areas of welding, recrystallization zones, voids, heavy plastic deformation, pores and cracks. Despite the current expertise, further investigations are still not possible due to the lack of consensus in the field of Al/Cu magnetic pulse welding (MPW). This paper seeks to explain how the process parameters affect Al-Cu pairs' joint intensity and interfacing morphology.

2. WELDING CONDITIONS FOR ELECTRO-MAGNETIC WELDING

Pulse welding is the method of impact welding. When welding, a sheet is accelerated to a speed of a few hundred m/s over a short distance, which is termed as stand-up distance. Then, a collision is produced with a rigid parent platter and a sound solder is formed provided the speed is sufficiently high and have the specific angle between the plates. The shape of a so-called jet is a third state. This impact wave will remove oxides and other contamination from the surfaces of both colliding plates.[17-25]

Different energy sources may be used to accelerate the flyer sheet, including explosives, magnetic fields, and even lasers. The method is known as electromagnetic pulse welding when a pulsed magnetic field is used. There are two key steps to magnetic field acceleration. The first step is to charge a big capacitor bank, which typically contains hundreds of thousands of capacitors approximately 50-100 kJ of energy. The charging voltage (V) can adjust the energy of the capacitor bank (E), as shown in equation 1.

$$E = CV^2 \quad (1)$$

If the condenser bank has been filled, the energy is released by using high-current switches using a dedicated coil. In this circuit a damp sinusoidal current is induced which can be measured on the basis of the RLC equivalent circuit principles. Form of this damp AC current is 10 to 50 kHz and the amplitude is 50 to 800 kA. In order to allow these high currents, it is important for the whole machine to have a low conduction load.

With the perception of the spindle and sheet as two parallel conductors the sheet weld setup can be simplified. If both hold a flow in the opposite direction, Ampere's legislation stipulates that the two drivers will repel one another. Furthermore, in the Lenz' law it is stated that the direction of induced current is opposite to oppose the magnetic field. The combination [26-31]of these laws means that a high transient current pass through the spindle. The transient current is induced in the flyer plate in an opposite direction. The flyer plate is set up with an isolator and on the top of the coil. The acceleration of flyer plate away from the coil is the consequence of the repelling behaviour of these currents. (Shown in Fig. 1)

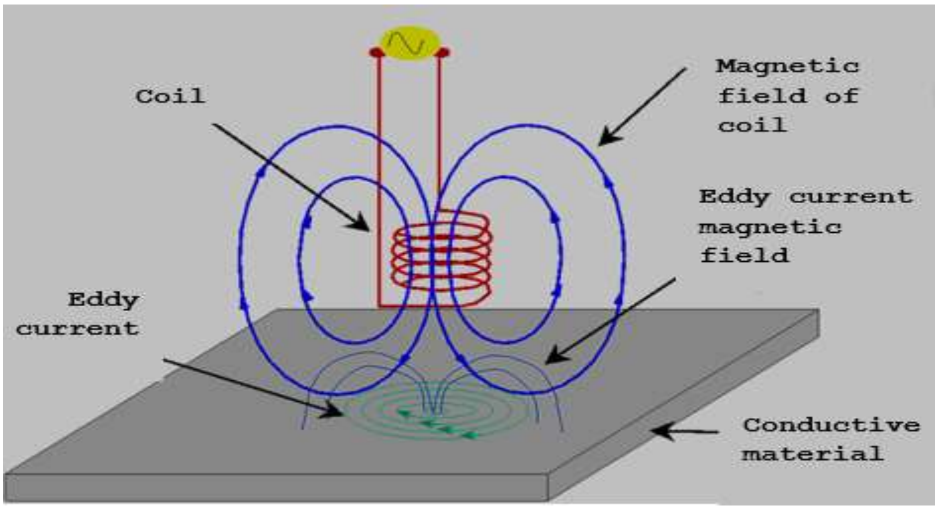


Figure 1. Figure Showing Schematic of the eddy currents [4].

The impact of 4 variables on quality of weld was studied:

- Overlapping distance of sheet to actuator: described as the horizontal distance overlapping the actuator/coil by a flyer sheet. The overlap can range from 0 to 10 mm. For practical purposes, there is no use of overlap which is below 5mm.
- Free length: The horizontal distance between the flyer sheet's extremity and the location of the spacer is called the spacer distance (see Figure 2). The point at which the flyer sheet bends during the process, as well as the impact angle, are both affected by this duration.
- Stand-off distance: The distance between the parent sheet and the flyer is known as the stand-off distance. The flyer sheet's final impact velocity is influenced by this wavelength. The impact angle is also influenced by this parameter.
- Energy: The discharge of current through the coil will vary according to the quantity of energy held in the capacitors
- (Frequency): Despite the fact that this parameter is not directly regulated, if the geometrical parameters are changed, the coupled inductance of the setup changes, influencing the discharge current frequency specified by the analogous RLC circuit.

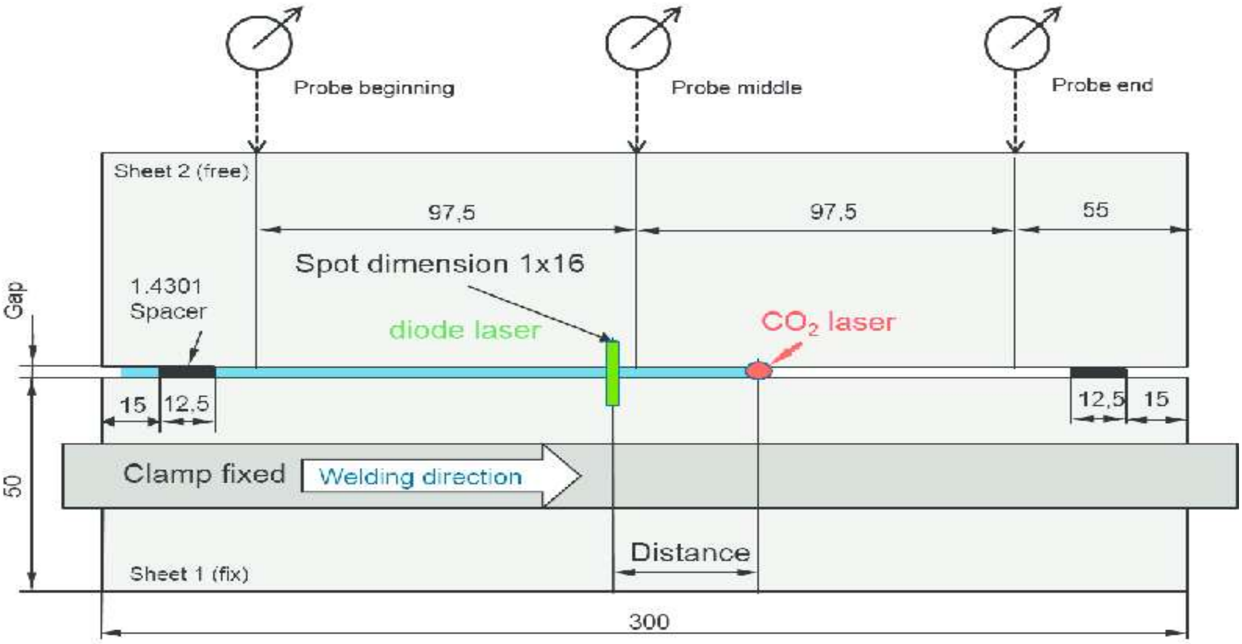


Figure 2. Depiction of Varied geometrical parameters.

Pulsar system of type MPW 50/25 is used as equipment for MPW and it is combined with a coil which is manufactured by Poynting. Table 1 shows its characteristics-

Table 1. Characteristics Of Weld Equipment Poynting SMU fwd. 150-1/10

Poynting SMU fwd. 150-1/10				
Maximum permitted voltage	**Main coil conductor length**	**Maximum permitted current (at reduced lifetime**	**Main coil conductor width**	**Dimensions**
30 kV	260 mm	300 kA (440 kA)	12 mm	350 × 240 mm

Table 2. Characteristics Of Weld Equipment Pulsar MPW 50/25

Pulsar MPW 50/25				
Maximal storage energy	**Maximal pulse current**	**Voltage-energy ration**	**Maximal charging voltage**	**Maximal pulse energy**
60 kJ	600 kA	$V = \sqrt{E}$ 90	30 kV	50 kJ (25.40 kV)

3. METHOD OF INVESTIGATION

The base material of copper is ETP Cu R240 and for Aluminium is Al 1050 H14. In Table 2 their characteristics are shown-

Table 3. Table Showing Mechanical characteristics of Metal

	Density	Yield stress	Ultimate tensile strength	Elastic modulus
Al 1050 H14 [5]	2710 kg/m³	103 MPa	115 MPa	71 GPa
ETP Copper R240 [6]	8940 kg/m³	180 MPa	240-300 MPa	127 GPa

An experimental approach has been repeatedly adopted to achieve reproductible outcomes. The approach was composed of different aspects that were clarified in the following paragraphs. Both surfaces of the metal plate Al and Cu have been manually washed by the removal of oxides and other pollutants first by scoring with steel wool, followed by acetone to remove potential fats. For the study of welded quality, the welded plates were cut in six parts: 3 specimens 45 mm wide, one specimen 5 mm wide, two specimens left and right of the welded field. For the testing of welded quality, the plates were cut into six pieces.

The weld width could be calculated since the last two specimens were manually peeled. Near the middle of the weld, a sample for metallographic analysis was taken. The scale and composition of the interfacial layer, the number of cracks and pores and the length of the weld were all measured during the metallographic analysis. We'll go through some common outcomes

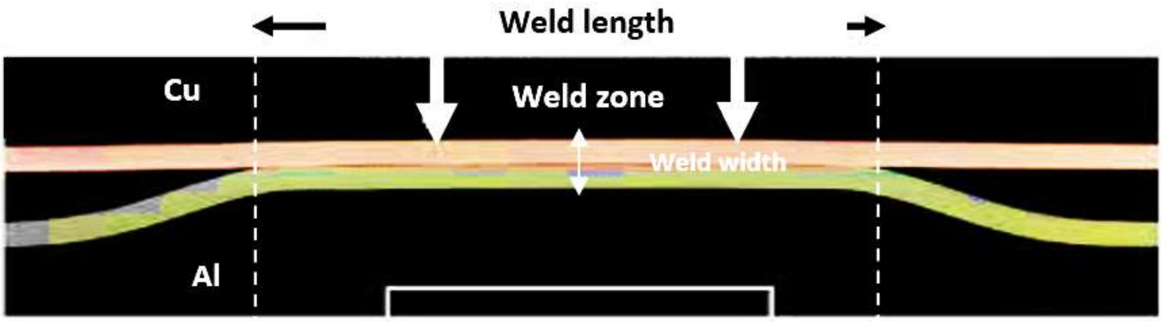


Figure 3. Figure Showing Defined Weld Width & Length

The range of possible parameter settings was calculated after the first series of screening experiments, see Table 3. Based on such values, for a complete factorial design, at least 54 experiments would be necessary. The number of experiments has been reduced substantially by using experimental design techniques. However, this leads to a compromise: a greater number of tests lead to greater statistical certainty regarding the findings. A Taguchi design with the following advantages was used in this study.
Taguchi's designs are orthogonal for main effects, but have two-way interactions, either aliased or confused main effects. Taguchi's main role is the strong design, investigates and identifies factors that influence the response value, variable or dispersive response and at the same time minimizes variability because of uncontrolled factors or noise. [7].

The Taguchi L-18 design type was used and out of 54 possible combinations, it consists of 18. When performing these Tests, caution must be taken to randomly carry them out. This decreases the probability of error consecutively and eliminates the potential effect of non-experimentally-controlled parameters (i.e., temperature, humidity...) (nuisance variables). Just once were the 18 experiments conducted. Several studies have been conducted twice with unpredictable results to validate their results. Notice that MPW is a highly reproducible method and no second run has been done because of this.

Table 3. Table Showing Values for Input Parameters

Input Parameter	Stand-off	Overlap	Energy	Free length
Values	2 – 4 – 6 mm	8– 10 mm	6.6 – 7.5 – 8.5 kJ	15 – 20 – 25 mm

4. CHARACTERIZATION OF WELD

The consistency of the welding was evaluated through compression testing and microstructure interface tests. At room temperature and 2 mm/min with a servo-electric universal testing machine Instron model 4507, quasi-static compression experiments were performed. For the characterisation of the soldering interface, scanning electron microscopy (SEM) was used. The analyses were performed on the high-resolution SEM FEI QUANTA 400F with field emission gun at an acceleration voltage of 15kV in secondary and back dispersed electron modes. Energy dispersion X-ray spectroscopy evaluated the chemical composition of the interface (EDS). Through X-ray Diffraction, we can study about the phases present at the intermetallic layer. At the European Synchrotron Radiation Facility (ESRF) in Grenoble, (ROBL) Rossendorf beam line's Material research station, this can be done by using synchrotron radiation. Welded samples were cut into slices of around 1 mm in thickness. For this analysis, 6 zones were subjected with dimensions 100 µm × 100 µm. 6^{th} Zone corresponds to Al, 1^{st} zone with Cu and all remaining with weld interface. The incident X-ray beam was monochromatized to 11.5 keV (= 0.1078 nm) at a wavelength of 0.1078 nm.

4.1 Characteristics of Al/Cu Welds

SEM research analysed the interfaces of 3 samples, welded using various energy values. Figure 4 shows the weld interface overview and Fig 5 shows the same area in depth. When increasing discharge energy, the al/cu interfaces reveal different morphology. With increasing pulse energy, the formation of intermetallic phases leads to a less wavy and irregular interface between aluminium and copper. For a greater degree of discharging energy, the thickness of the almost constant intermetallic layer will exceed 80 µm—Fig. 4a. For the higher electromagnetic pulses, we can say that to melt the materials, there is sufficient energy at the interface zone and this will create a continuous intermetallic layer by molten material solidification. Some authors [16–21] claim that the majority of the flyer's cinematic energy is spent on Joule heat during the collision. The temporal and spatial temperature distribution during the impact sold decides whether there is a melting effect, and therefore whether there are intermetallic compounds.

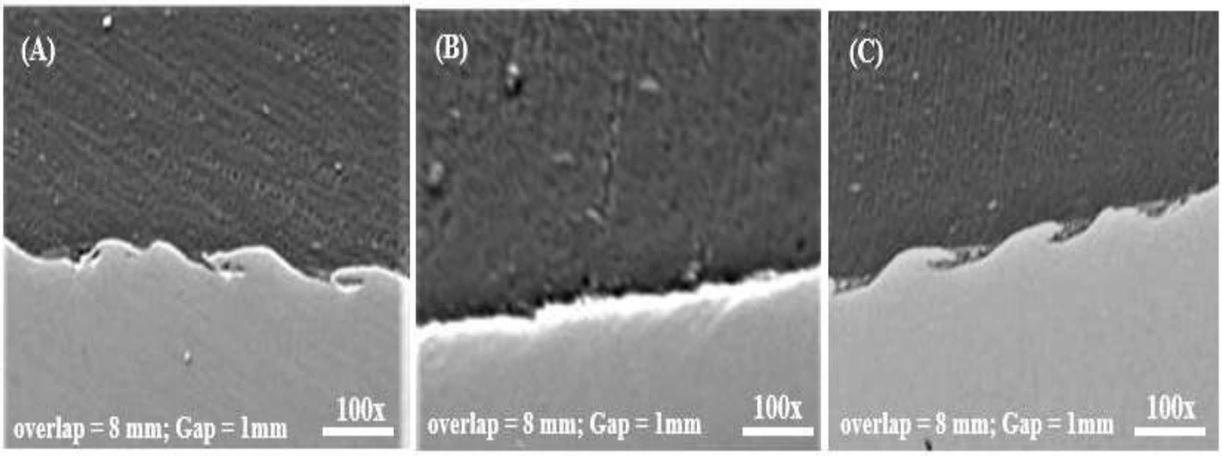


Fig. 4 Depiction of SEM micrographs for different values of discharge energy (A) 15 kJ (B) 10.30 kJ, (C) 12.50 kJ

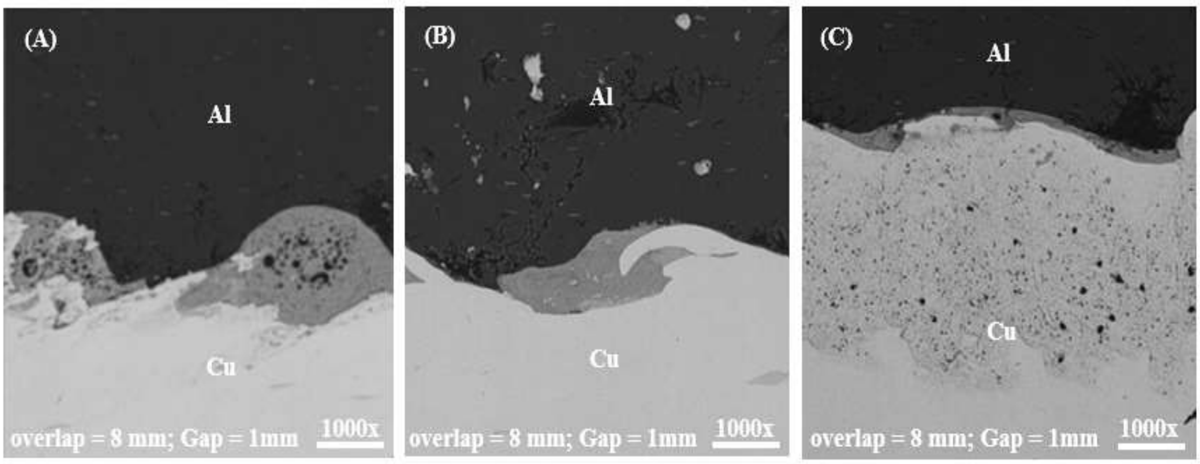


Fig. 5 Depiction of SEM micrographs for different values of discharge energy (A) 15 kJ (B) 10.30 kJ, (C) 12.50 kJ

In [8] Ben-Artzy et al investigated that the temperature at the interface can reach up to 400° due to the crash and shock waves which slide and pull the two metals to be swept. Moreover, the jetting action that removes the surface oxide from the surfaces to be welded will, due to extreme shear deformation, the interfacial temperature is improved near the metal's melting temperature. In addition, the jet does not escape, trapping the hot ejecta within the interface, if the angle of the impact for input energy is too small. The combination of these phenomena will produce a sufficient increase in temperature so that layer at the interface region of both materials is melted.

In Figure 6 obtained XRD data is shown. At Al/Cu interface, two inter- metallic phases co-exist are Al2Cu (Θ) and Al2Cu3 (ε). In several work it is shown that at Al/Cu interfaces, such phases can be the cause of increase in hardness [20, 21].

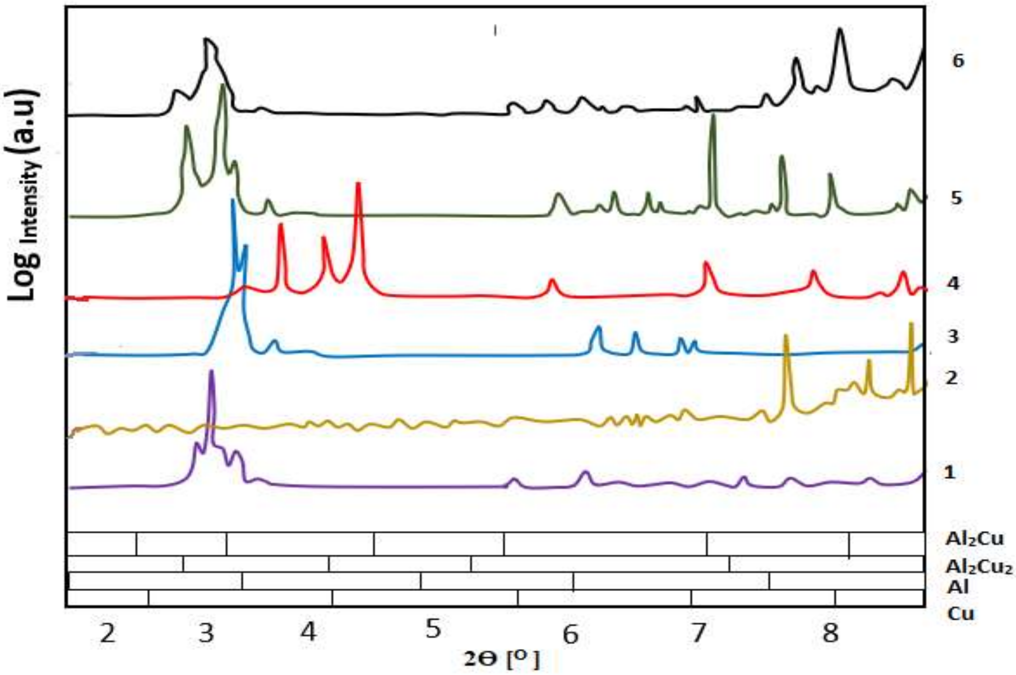
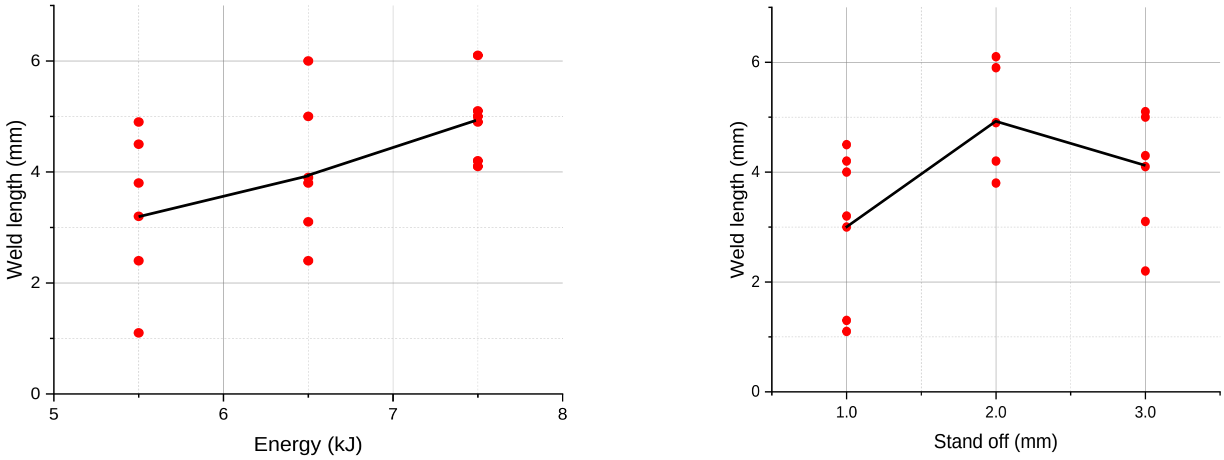


Fig. 6. Al-Cu weld surface XRD patterns

5. RESULTS AND DISCUSSION

Four key weld quality metrics are being discussed: welding volume, shear strength of the lap, interface layer size and aluminium sheet thickness reduction. The effect on weld length is marginal of the overlap and the free length. The energy and stand-off are the two key factors affecting the weld length. Every point in Figure 7 is a unique input parameter combination the connection is build up between the fixed input value and average, which is shown y blue line. Basically, more energy means longer welding times and less reliant on other variables at input. A high energy level also means less dependency on other input parameters. Due to substantial interfacial debonding, there will be shorter lengths of welds even when the input energy is higher. Regarding stand-off reach, the largest (average) soldering length is 2 mm. Please note that this is probably not the best deal. It's possible to understand visually the relationship between the standing and the length of the weld: the plate is pulled off from the coil. After the imposition of first limit the decrease in current is less and the value of magnetic strength is also less when it is away from the coil. The combination of both effects means that there is an optimal stand-off gap. The flyer sheet is already decelerating when the effect is reaching a stopover distance greater than the best value.



(a) (b)

Figure 7(a). Depiction of variation of Energy with Weld-length
Figure 7(b). Depiction of variation of Stand-off with Weld-length

The lap shear strength is a second measure of weld consistency. The shear strength of the lap was found to depend on the thickness of the aluminium sheet next to the welded region. Figure 8 depicts a linear relationship between weld intensity and the minimum thickness of aluminium sheet. The left edge of the right spacer was where the thickness of the aluminium flyer sheet was reduced (see Figure 2). Even when the weld duration was relatively short, no effect of the other parameters could be identified (around 1 mm).

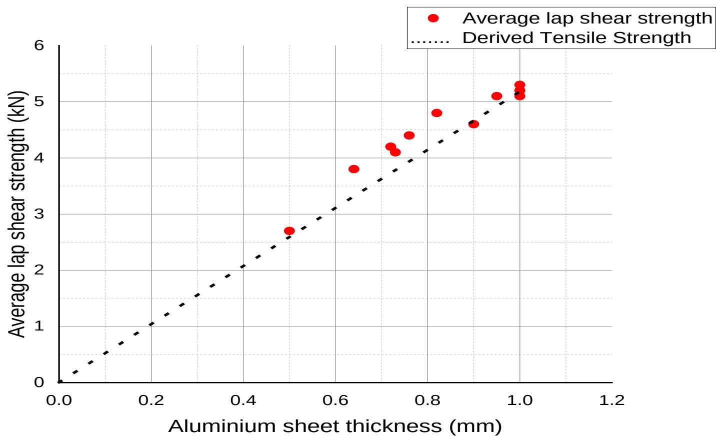
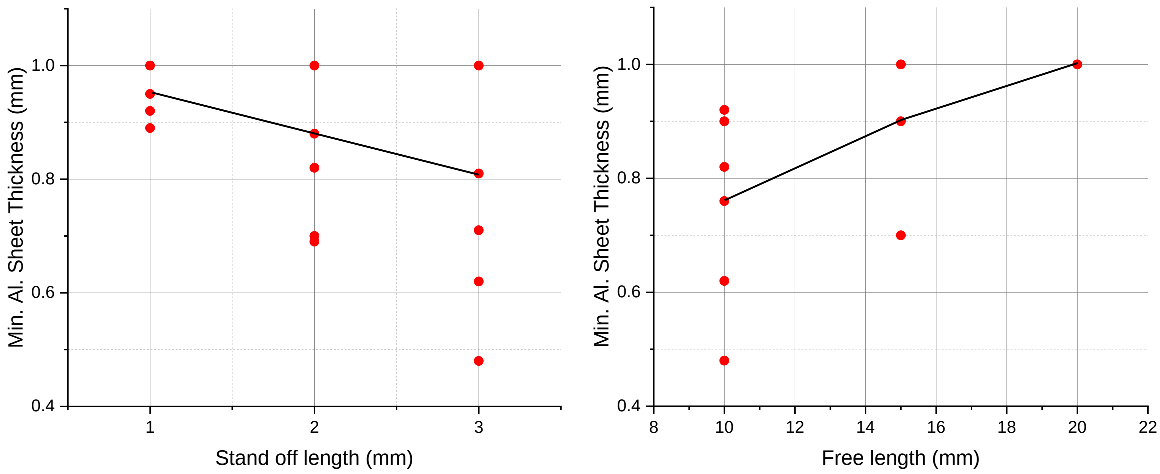


Figure 8. Figure Showing Variation of Minimal Aluminium Sheet Thickness with Avg. Lap Shear Strength

In the figure the dotted line indicates Lap shear Strength which is based on thickness of Al sheet and Al 1050 H14 alloy's ultimate tensile strength. In contrast to the effect of the stand-off distance and free longitude, the impact of energy and the overlap on the minimum Al sheet thickness is negligible. A higher stand-up can reduce aluminium foil thickness considerably, while a low freestanding length often leads to a lower aluminium thickness (Figure 9). Between the two parameters, as illustrated geometrically, a strong interaction was suspected. For a limited value free of charge, i.e., 10 mm, especially when the overlap distance b/w the actuator and flywheel is big, a large deformation takes place at the spacer edge of flyer sheet. 3mm of stand-off distance and overlap b/w actuator of 10mm and flyer sheet is the worst combination.

At the spacer edge this case leads to the strong shear effect on the Al sheet and this interaction is presented in Fig. 10. Practically, the combined parameter (CP) has no meaning. We can say that there will be large reduction observed in thickness of Al sheet by combining the Small (FL) and high (SO), where FL denotes free length and SO denotes stand-off.

$$(4 - SO) \times 5 + FL = CP \quad (2)$$



(a) (b)

Figure 9(a): Figure Showing Variation of Stand-off with Min. Al thickness

Figure 9(b): Figure Showing Variation of Free-length with Min. Al thickness

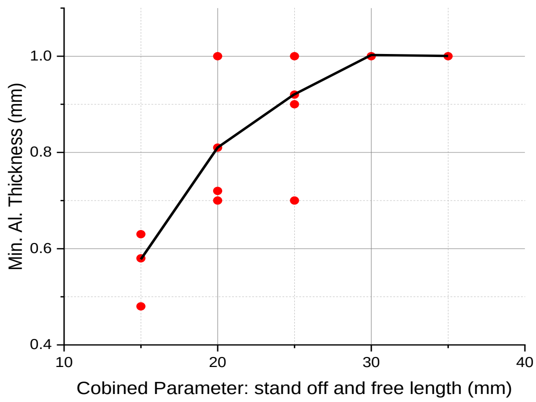


Figure 10: Depiction of Variation of combined free length & stand-off with Min. Al thickness

The thickness of the interface layer is the last measure of the weld efficiency. The thickness of the interface layer for one of three "waves" was measured by this number (figure 11). The average measurement was measured and reproduced with respect to the total weld length and this is done where the intermetallic layer was visible, by a percentage of length.

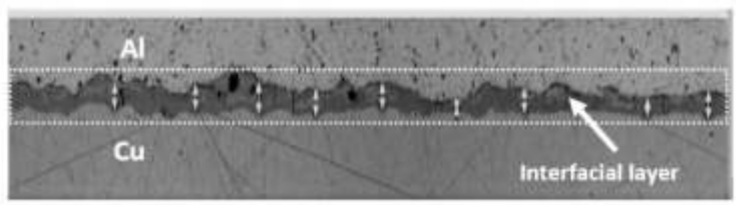


Figure 11: Figure Showing Measurement Methodology for Calculating the Height of the Interfacial Layer

The thickness of the intermetallic layer is affected by various input parameters, but the connections are less pronounced than initially seen. Input power is the first and most prominent force (Figure 12). The thickness of the intermetallic layer also increases as this last-mentioned increase. There is 45 % increase in energy in the average thickness of the interfacial layer. The impact of the stand-off is lower and the limit is reached for a stand-off equal to 2 mm. This metric would be meaningless if the two outliers for a stand-off distance of 2 mm were not present (see Figure 12, top right). More research is needed to confirm the previously indicated relationship.

However, with a free length of 10 mm, the dispersion induced by changes in other input parameters is greatly reduced due to the average thickness of an intermetallic sheet. The average interfacial layer thickness is significantly increased with a specific combination of stand-off and overlap of 2 and 8 mm respectively. The most pronounced influence on the graph is the correlation between energy and the interface thickness. (See Figure 12, top right). Each energy level's maximum thickness is determined by a combination of the previously mentioned input parameters.

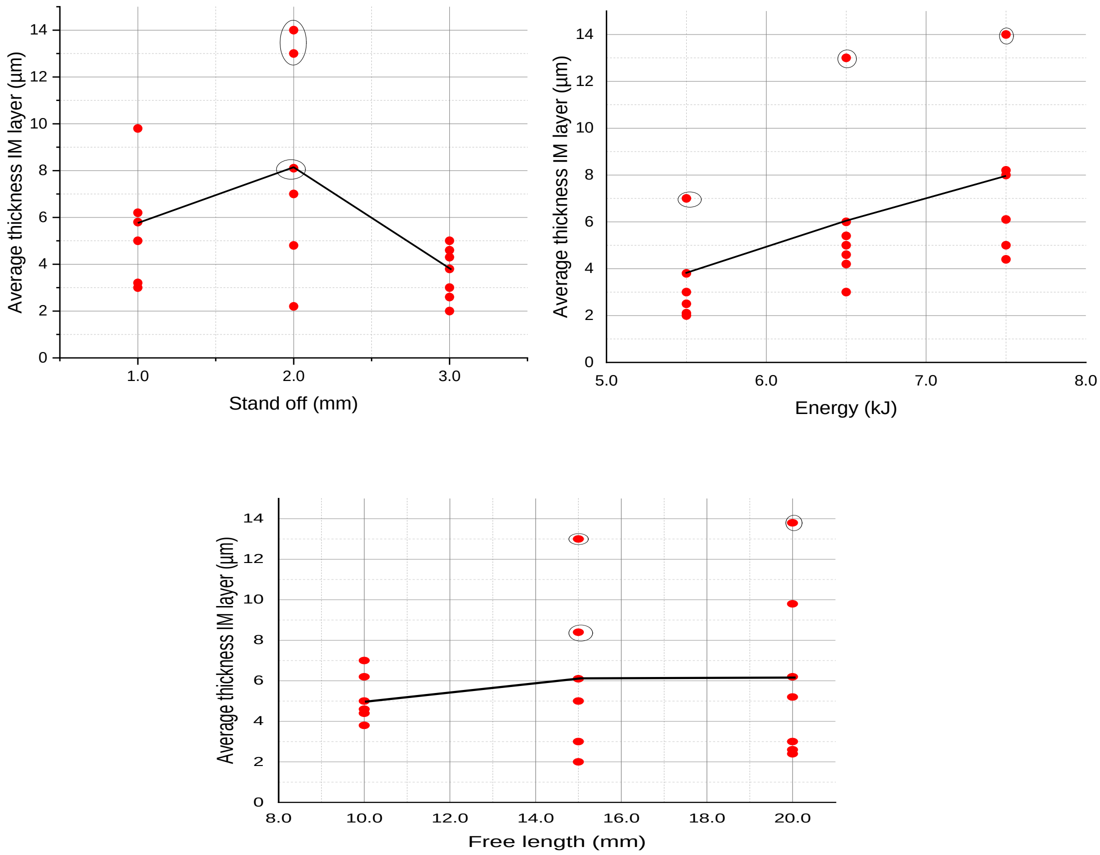


Figure 12: Relationship between the interfacial coating's average height and energy, stand-off and available length respectively.

6. CONCLUSION

The Al/Cu weld specimens have been investigated for the different pair. Through MPW, we can achieve effective welds by combining different process variables. Compression tests examined the power of the Al/Cu weld specimens. The results of the test allow us to distinguish samples that are weld from those that are not welded, so that the welding window can be defined. This area includes the parameter combination of active welds, the area of the restricting surfaces.

- XRD, EDS and SEM have been investigated for samples whose energy is increasing in the composition and morphology of the AL/Cu interface. Evidence of melting was found in the interface region, in particular in samples processed with higher release energy values.
- Multiple sources of heating may contribute to develop the relation between melting and increase in energy. Higher pulse energy values are linked to higher induced currents, which will produce more Joule heating. More power means high speed of flyers; there is discharge of air in the distance between sold parts; there is the square relation between speed and aerodynamic drag (fluid friction), and also contributes to heat generation. Energy discharge by plastic work & Jet formation would also lead to the rise in temperature as cinematic energy increases with the squares of speed.
- Pulse energy should be reduced to a minimum to eliminate intermetallic phases, porosity and melting pockets. The other parameters of the method, such as gap and overlap size, must be optimized so that low release energy values can be used. Here, it should be noted that more static mechanical tests on welded joints should in the future be performed in order to verify weld efficiency.
- At different process conditions, Electromagnetic Pulse Welding technology is used to join sheets of Al to Cu. With the current experimental study, we can draw following conclusions-
- Mostly welds are much stronger than base material.
- In adjacent to the welded zone, lap shear strength is dependent to thickness of Al sheet. There is negligible overlap on minimal thickness of Al sheet and the influence of energy; this is in direct opposition to the free length and effects of the stand-off distance.
- At the weld interface, the inter-metallic layer's thickness is in influence with input energy. The stand –off distance effect is less noticeable; and around 2 mm is the maximum value achieved for stand-off.
- There is minimum influence on the weld length by the free length and overlap. Stand-off and energy are the two main factors which influence weld length.

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