Interfacial Morphology and Mechanical Properties of Aluminium to Copper Sheet Joints by Electromagnetic Pulse Welding

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Abstract: This study investigated joining of Al to Cu sheets by electromagnetic pulse welding, which is a solid-state welding process that uses electromagnetic forces to join materials. The interfacial morphology and mechanical properties of the Al/Cu joints were analysed and related to the welding process parameters and weld properties. The centre section of the Al/Cu joints evolved from a non-welded to a welded zone. The welded zone started with a wavy interface, consisting of thick interfacial layers with defects and evolved to a relatively flat interface without an interfacial layer. The interfacial layer thickness is determined by both the discharge energy and the stand-off distance. A higher tensile force, up to 4.9 kN, was achieved at a higher energy and a lower stand-off distance of 2 mm. The tensile force is directly related to the weld width, since a higher tensile force is achieved for a higher weld width. In addition, the presence of interfacial layers can contribute to a small extent to a higher tensile force.

Introduction

Aluminium-copper (Al/Cu) hybrid parts, as a substitution for Cu parts, result in both weight and cost reduction, and are highly relevant in numerous applications related to the electrical, heating and cooling sector [1][2]. However, Al to Cu joined by thermal welding processes presents challenges for achieving a good joint quality, due to their highly dissimilar mechanical and thermal properties which can result in large stress gradients during heating. In contrast, electromagnetic pulse welding is a solid-state welding technology that uses electromagnetic forces to join the materials. In this process, a power supply is used to charge a capacitor bank. When the required amount of energy is stored in the capacitors, it is instantaneously released into a coil, during a very short period of time. The discharge current inducers a strong transient magnetic field in the coil, which generates a magnetic pressure that causes one workpiece to impact with another workpiece. Under the correct circumstances, this leads to an atomic bond between the two metal workpieces. The objective of the present work is to investigate electromagnetic pulse welding of Al to Cu sheets achieved at different welding conditions. The interfacial morphology of the weld interface and the mechanical properties of the Al/Cu sheet joints are analysed and related to the welding parameters and the weld properties.

Experimental procedure for electromagnetic pulse welding of Al to Cu sheets

Electromagnetic pulse sheet welding of Al 1050 H14 (sheet dimensions: 50 mm x 50 mm x 1 mm and 48 mm x 50 mm x 1 mm) to Cu (sheet dimensions: 67 mm x 50 mm x 1 mm) sheets was performed using a Pulsar model 50/25 system with a maximum charging energy of 50 kJ (corresponding with a maximum capacitor charging voltage of 25 kV). The total capacitance of the capacitor bank equals 160 μF. Figure 1 shows the overlap configuration of the Al sheet and Cu sheet in the flat coil. The Al sheet is called the flyer sheet and is located on top of the coil conductor. The Cu sheet is called the parent sheet. The stand-off distance is the distance by which the Al flyer sheet is separated from the Cu parent sheet prior to discharge. The overlap is the overlap distance between the flat coil and the Al flyer sheet. The free length is the part of the Al flyer sheet that is being accelerated.
Figure 1: Overlap welding configuration of the Al flyer sheet and Cu parent sheet

An overview of the selected welding parameters is shown in Table 1. In total, 27 different welding conditions were tested. The discharge energy, stand-off distance and overlap distance were varied, whereas the free length was fixed throughout all experiments.

Table 1: Selected welding parameters for electromagnetic sheet welding of Al to Cu sheets

| Discharge energy [kJ] | Stand-off distance [mm] | Overlap distance between the flat coil and Al flyer sheet [mm] | Free length [mm] |
|-----------------------|------------------------|---------------------------------------------------------------|-----------------|
| 10, 12, 14, 16, 18    | 2, 3, 4                | 8, 10                                                         | 15              |

Weld interface

Figure 2 (left) shows a typical Al/Cu sheet weld and Figure 2 (right) a typical metallographic cross-section obtained at the centre of the weld. The first impact is at the right extremity of the Al flyer sheet, after which the weld formation advances to the left. In general, all metallographic cross-sections show that Al/Cu sheet joints evolve from a non-welded zone to a welded zone. The weld length corresponds to the length of the welded zone.

Figure 2: (left) As-welded Al/Cu sheets (right) Metallographic cross-section of the Al/Cu sheet

Based on measurements and modelling studies performed by other authors, the evolution of the non-welded to the welded zone can be attributed to the evolution of pure normal Lorentz forces to a combination of normal and shear Lorentz forces [3][4][5][6], the increase of the impact angle [7][8] and the change of the impact velocity [3] during the welding process. The direction and the magnitude of the Lorentz force determine the impact angle between the flyer and parent sheet. The combination of the impact angle and the impact velocity is defined in the so-called welding window, which specifies the requirements of the impact velocity and the impact angle for welding to occur [5][7][8]. Under the correct conditions, a jetting effect can then take place that effectively removes the oxides from the surfaces and allows for atomic bonding to occur.

Interfacial morphology of the welded zone

Figure 3 shows a detailed view of the typical evolution of a welded zone (indicated in Figure 2, right). At first, a relatively flat interface with a small interfacial layer containing macrocracks and pores is observed (Figure 3a). Subsequently, the interface waviness amplitude, defined as the difference between the maximum and the minimum of a wave, and the thickness of the interfacial layer increase. The interfacial layer becomes strongly porous, with randomly dispersed porosities in different sizes. In addition, transverse microcracks, restricted to the interfacial layer, are noticed.
(Figure 3b). This is followed by a more homogeneous interfacial layer with a similar thickness but less porosities (Figure 3c). Further along the weld, the thickness of this homogeneous interfacial layer decreases (Figure 3d) and towards the end of the weld, a small wavy interface and thin interfacial layer without any defects is present (Figure 3e). Finally, the interface becomes relatively flat, without any visible interfacial layers (Figure 3f).

Figure 3: Evolution of a typical weld interface from (a) the start to (f) the end of the welded zone (from right to left in Figure 2)

Table 2 summarizes the wt% Cu (detected by Energy Dispersive X-Ray Spectroscopy), range of maximum interfacial layer thickness, range of waviness amplitude, and defects present in the different interfacial layers of the welded zone in Figure 3.

| Colour observed by optical microscopy | Position within the welded zone | %wt Cu | Maximum interfacial layer thickness [μm] | Waviness amplitude [μm] | Defects |
|--------------------------------------|--------------------------------|--------|----------------------------------------|-------------------------|---------|
| Light grey                           | Mainly at the weld end, sometimes also in the weld middle | 31-41 | 2-10                                   | < 6                     | No or small porosities |
| Dark grey, in combination with light grey | Weld middle & weld start | 54-62 | 3-26                                   | 6-11                    | Medium-sized porosities, mainly transverse cracks |
| Brown, in combination with light grey and dark grey | Weld start | 72-75 | 14-36                                  | 6-11                    | Large porosities, transverse and longitudinal cracks |

The interface layers, found along the weld interface, can be formed by either solid-state mechanical mixing [9] or localised interfacial heating with subsequent fast cooling [10][11]. Spherical and irregular pores within the interfacial layers, as observed by the Scanning Electron Microscope (SEM) in Figure 4, can originate from metallurgical preparations and/or localized interfacial heating. The change of the interfacial morphology within the welded zone can be attributed to the continuous variation of the impact velocity and impact angle during the welding process, as found in [7][8]. The presence of a higher wt% Cu at the start and the middle of the welded zone possibly indicates that the impact energy at those locations is sufficient to allow more mechanical mixing of Cu with Al and more heating of the materials. In contrast, the presence of less wt% Cu towards the end of the welded zone may indicate that the impact energy decreases, promoting less mixing and less heating of the materials.
Interfacial layer thickness of the welded zone

The maximum interfacial layer thickness and hence its structural and chemical composition are determined by both the stand-off distance and the discharge energy. At an overlap of 10 mm, a discharge energy of 14 kJ and a stand-off distance of 4 mm, the welded zone consists of a weld interface with an interfacial layer thickness of 4 μm (Figure 5a). At the same overlap and discharge energy, but with a decreased stand-off distance of 3 mm, the welded zone consists of a weld interface with a large interfacial layer thickness up to 28 μm, and several porosities and transverse microcracks (Figure 5b). The change of the weld interface for a lower stand-off distance can be attributed to the larger impact velocity for a stand-off of 3 mm. When using a stand-off distance of 4 mm, it is likely that the velocity was already decreasing prior to impact, leading to a lower impact velocity compared to the situation when using a stand-off distance of 3 mm. For this reason, it was assumed that more kinetic energy is available for a stand-off distance of 3 mm that can be transformed into energy for bonding. In that case, also more localised interfacial heating can take place, as observed in [12], resulting in a larger interfacial layer thickness. A similar observation is found for the effect of the discharge energy on the interfacial layer thickness. At the same overlap and stand-off distance, but at a higher discharge energy, the interfacial layer thickness increases and contains more defects.

Weld width

Figure 6 shows the weld width as a function of the discharge energy, for different combinations of the stand-off and overlap distance. A higher weld width is achieved at a higher discharge energy and at a lower stand-off distance of 2 mm.
Tensile force

Figure 7 shows the tensile force as a function of the discharge energy, for different combinations of the stand-off and overlap distance. The same trend as for the weld width is observed: a higher tensile force is achieved at a higher discharge energy and at a lower stand-off distance of 2 mm.

Figure 8 (left) shows that the tensile force is directly proportional to the weld width: a higher tensile force is achieved for a larger weld width, since both are determined by a higher discharge energy and a stand-off distance of 2 mm. In addition, the tensile force is to a small extent related to the maximum interfacial layer thickness (Figure 8 right). For most welding conditions, the welds with a higher tensile force (4-4.8 kN) have a large thickness (10 to 36 μm), whereas the welds with a lower tensile force (3-4 kN) have a small thickness (4 to 14 μm). The exception are welds at a stand-off distance of 2 mm and an overlap of 10 mm, where all welds exhibit a higher tensile force (4-4.6 kN), but exhibit a small thickness (0 to 14 μm). Therefore, although a higher energy generally result in a larger interfacial layer thickness, the increase of the tensile force at a higher discharge energy shows that the presence of interfacial layers do not necessarily weaken the welds.
Conclusions

Al to Cu sheets are joined by the electromagnetic pulse technology at different welding conditions. The following conclusions can be drawn from the present experimental study:

- The centre of the Al/Cu sheet joints evolve from a non-welded zone to a welded zone.
- The welded zone evolves from a thick, wavy interface with pores and cracks to a relatively flat interface without visible interfacial phases and defects. An increase in maximum interfacial layer thickness is achieved at a higher discharge energy and a stand-off distance of 3 mm, whereas a higher weld width is obtained at a higher discharge energy and a stand-off distance of 2 mm.
- A higher tensile force is achieved at a higher discharge energy and a stand-off distance of 2 mm, and is directly related to the weld width and to smaller extent to the maximum interfacial layer thickness. A higher weld width results in a higher tensile force, whereas the presence of an interfacial layer can possibly contribute to a higher tensile force.

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