Impact Welding in a Variety of Geometric Configurations *

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Abstract

Magnetic pulse welding is an electromagnetically assisted high strain rate impact welding technology. The physical principle is similar to explosive welding and it also belongs to solid state impact welding. This high velocity oblique impact welding has been applied to various lap joint configurations. Three different geometric configurations on plate-to-plate welding were studied in this paper. They are direct lap joint, pre-flange lap joint, and lap joint with embedded wires. All of the three welding configurations have been used to provide metallurgical bonds between both similar and dissimilar metal pairs. The welded materials include copper alloy, aluminium alloy, and steels. The plates are centimeter or more thick and often centimeter in extent. The critical welding process parameters were instrumentally investigated by Rogowski Coil and Photon Doppler Velocimetry. Metallographic analysis of the welded interface showed refined grain structure. The mechanical properties of the welded plates were studied by lap shearing, peeling and nano-indentation tests. The test results showed that the impact welded interface has a much greater micro-hardness and fracture toughness than the base metals.

Keywords

Impact welding, Magnetic pulse welding, Welding configuration

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1 Introduction

There is a growing recognition that optimal lightweight structures for automobiles, aircraft and even bicycles are often created from multi-material assemblies. Joining dissimilar high-strength light alloys has therefore been of significant and growing interest. One of the most elegant ways to accomplish dissimilar metal welding is by impact welding. The outstanding advantage of impact welding is that it can minimize the formation of continuous intermetallic phases while chemically bond dissimilar metals [1]. The impact welding does not result in heat affected zone or distortion near to the welded region. Therefore, more attention has been obtained for solid state impact welding on dissimilar materials joint. This paper studied one of the solid state impact welding processes, magnetic pulse welding (MPW). Since 1969, MPW has been successfully applied for tube to tube impulse welding but typically required fairly high electrical energies to be stored in capacitor bank with typical values in the range of 20~100 kJ [2]. With the recent development of MPW, the geometry of the welding workpiece could be cylindrically symmetrical [3] or asymmetrical [4-6]. Studies by Aizawa's group (2005) in Tokyo and Date's group (2007) in Mumbai have developed MPW seam linear welding [4, 5]. These methods tend to use much less energy than those for tube welding. For example, the reported energy to weld aluminium alloy plate about 1 mm in thickness to SPCC steel plate is only about 1.4 kJ [6]. Very rapid rise times (time for actuator to reach maximum primary current) in the capacitor discharge circuit are largely responsible for this efficiency.

The objective of this paper is to investigate the different configurations for MPW. MPW process completes within microsecond and does not involve hazard explosion, and thus it is more industrial acceptable. Three configurations for plate-to-plate welding were introduced with the instrumental measurement of the impact velocity and impact angle. The joint strength was examined by lap shearing, peeling, and nano-indentation tests. The welded interface microstructure was also studied by transmission electron microscopy.

2 Principles of Magnetic Pulse Welding

MPW is closely analogous to explosive welding and it is necessary to have a slight impact angle to form a jet along the mating surface [6]. However, rather than explosives, it uses electromagnetic force to accelerate the flyer plate. Therefore, MPW can be safely and reproducibly used in production environments controlled by an electric power supply. The fine adjustment to parameters is straightforward. With proper design, the energy is fairly efficiently used for accelerating the flyer plate rather than heating or melting the materials.

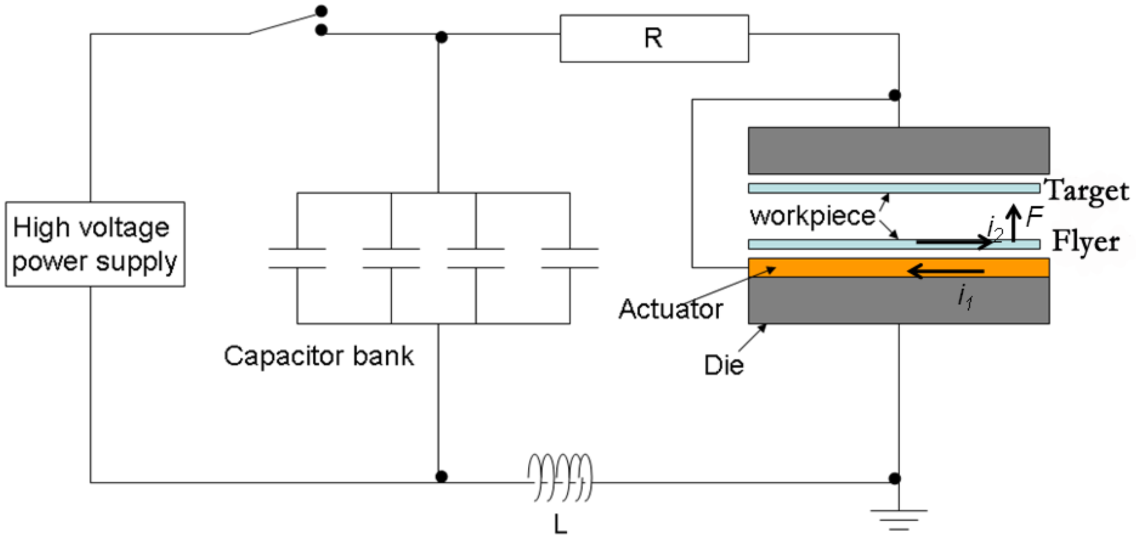


Figure 1 Schematic diagram of MPW system.

As shown in Figure 1, the MPW system includes a capacitor bank, an actuator, and workpieces. The capacitor bank simply consists of an inductance-capacitance circuit and an actuator of some impedance. Both the flyer plate and the target plate were supported by insulated layers with certain standoff distance between them. The electromagnetic actuator was connected to the capacitor bank. When capacitors are discharged, the current with high density flows through the conductive actuator, which is regarded as primary current. If there is a closed current path, the associated electromagnetic field induces a strong secondary current through the nearby metal workpiece (flyer plate). Therefore, the flyer plate carries current and stays in the electromagnetic field. Since the primary current and the secondary current generally travel in opposite directions, their interactions result in a strong repulsive force, which is the Lorentz force. As shown in Figure 2, the flyer plate is repelled from the actuator and accelerates with sufficient velocity for impact welding. MPW uses an electromagnetic field, and thus the flyer plate must be electrically conductive and plastically deformable, or coupled to a conductive driver.

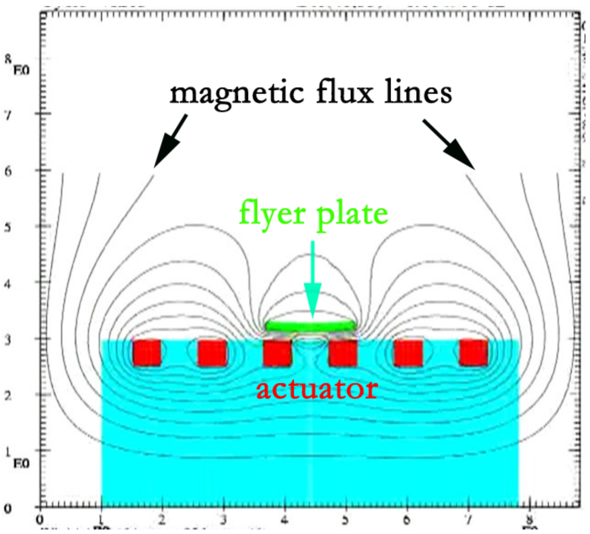
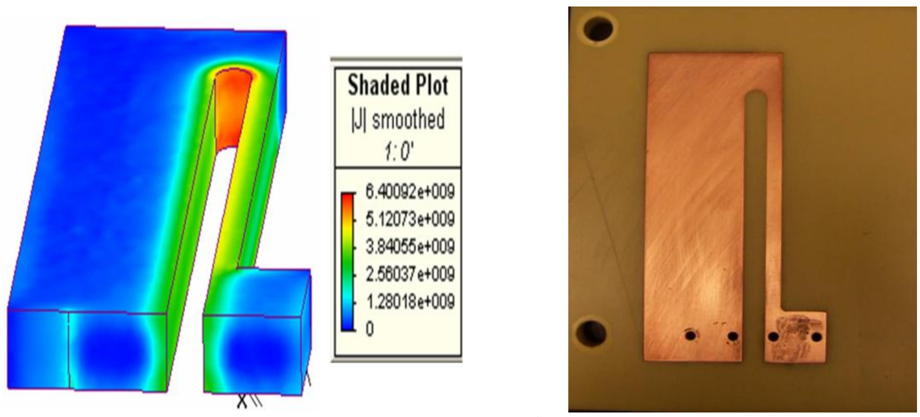


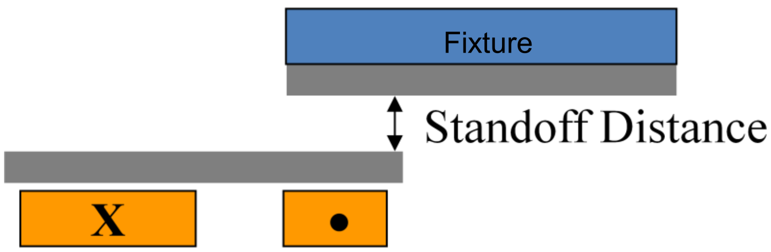
Figure 2 Illustration of magnetic flux lines during impact welding process [7]. The abscissa and the longitudinal axes is the length scale and the unit is millimetre.

3 Configurations for MPW on Plate-to-Plate Joint

3.1 Direct lap Joint



(a) Magnet® simulated current density (unit: A/m^2) *(b) Real actuator for lap joint*

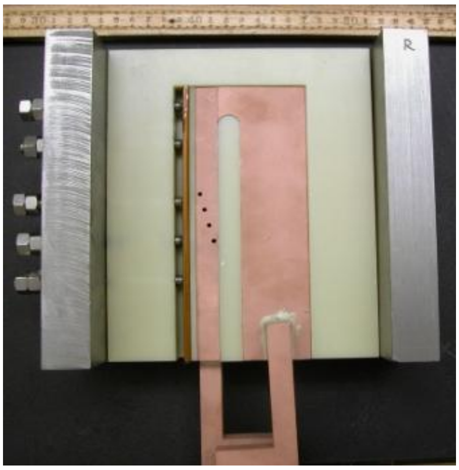


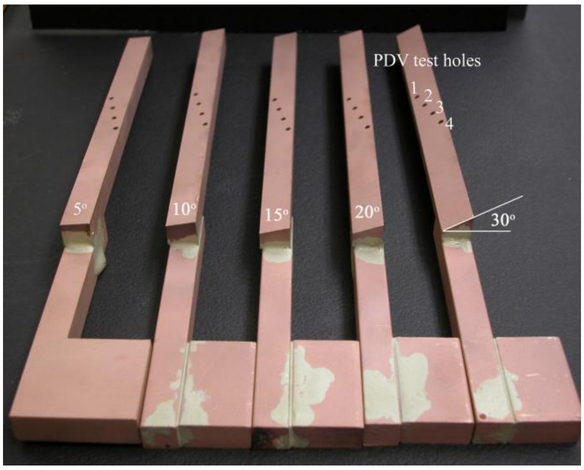
(c) Illustration of welding system (Some of the supporting blank holders are ignored in the figure.)

Figure 3 Schematic of the first generation flat bar actuator.

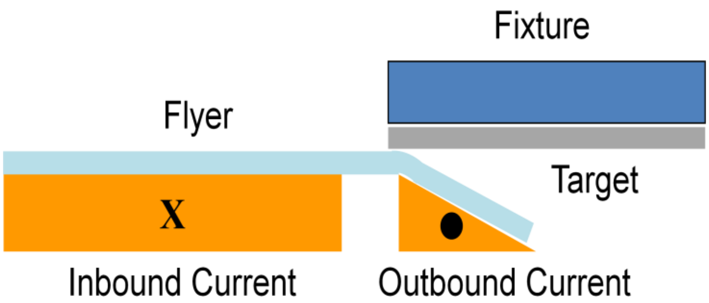
The direct lap joint was carried out on one asymmetrical '∩' shape flat bar actuator. The actuator material is half inch thick copper alloy C2C18150. As shown in Figure 3, the narrow leg and the wide leg have different current densities and the current is condensed on the narrow leg. Hence the being welded region is set right above this narrow leg.

In order to study the impact angle and impact velocity effects for lap joint, the second generation flat bar actuator was designed as shown in Figure 4. They can offer different initial launch angles. Figure 4(a) presents the actuator which is assembled into the die. The narrow leg has a chamfered angle and four through holes with 2.54 mm diameter. The holes are used to assemble the laser beam probes for impact velocity measurement at different locations. The chamfered angle determines the initial launch angle as shown in Figure 4(b). The narrow leg has been chamfered into 5º, 10º, 15º, 20º and 30º angles. Accordingly, the being welded flyer plates were bent to such angles which were regarded as the initial launch angles. The impact angles should be no larger than the initial launch angles.





(a) Second generation of the flat bar actuator (b) Narrow leg with different chamfered angles



(c) Illustration of welding system

Figure 4 Second generation of the flat bar actuator.

3.2 Pre-flange Lap Joint

MPW was also conducted to flange and weld workpieces together by the pre-flange configuration as shown in Figure 5. The pre-flange actuator can be regarded as a bar actuator, however the inbound leg and outbound leg are not in the same plane. The being welded plate was bent and inserted beneath one of the actuator legs with certain pre-flanged angle. Once the primary current goes through the actuator, the Lorentz force from the outbound leg will push the flyer down against the target and weld them together with high impact velocity. Therefore, with such built in impact angle, the flyer plate undergoes flanging and welding at the same time.

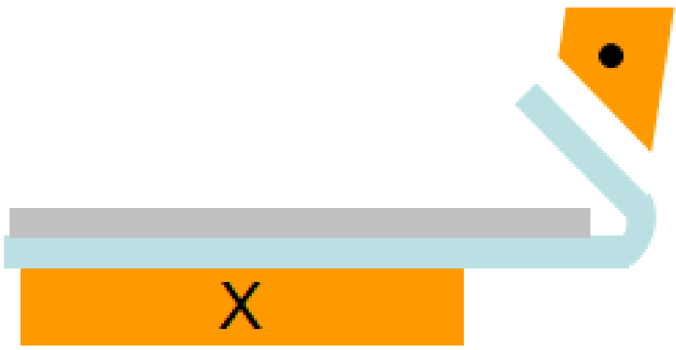
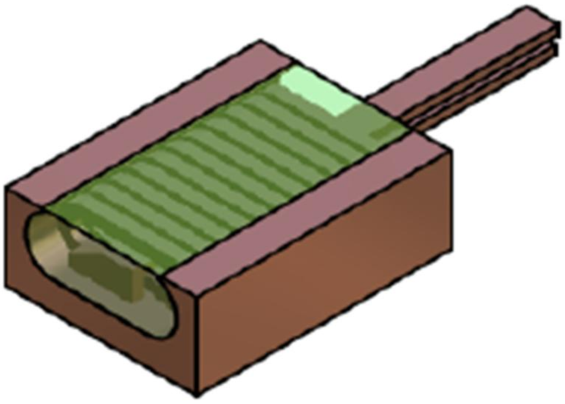


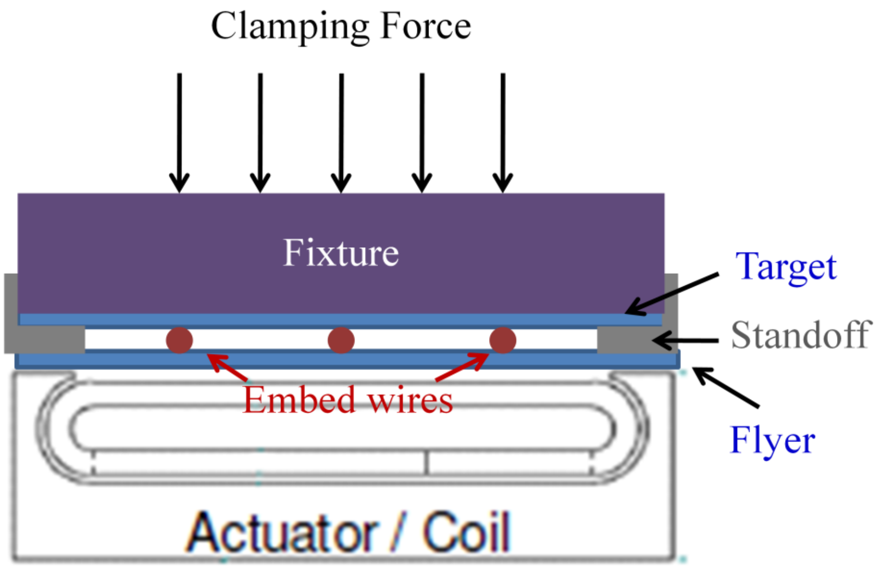
Figure 5 Pre-flange actuator with workpieces. The inbound and outbound currents were labeled onto the actuator. (The supporting blank holders are ignored in this figure.)

3.3 Lap Joint with Embedded Wires

The uniform pressure (UP) actuator developed by Daehn, Kamal and Banik [8, 9] has been used for electromagnetically assisted forming process. Recently, it was applied for wire embedded plate-to-plate welding. The impact welding was conducted with embedded wires between the flyer and the target plates. The embedded wires are attached to the target plate prior to welding. These wires were used to make the flyer contact onto the target with certain impact angle. If there is no wire between them, the UP actuator accelerates the flyer plate against the target plate parallel but no joint can be formed after such parallel impact. As shown in Figure 6(a), UP actuator is a solenoid actuator with several turns. The flyer plate is loaded onto the outer channel. And it undergoes approximately uniform pressure from the inner actuator during the impact process. In order to fix the target plate during impact process, a top die is put onto the target plate and the welding system is then clamed down with 5000 psi pressure to avoid the top fixture moment as shown in Figure 6(b). One of the welded samples was shown in Figure 6(c). The welded plate materials were AA6061 and the embedded wire is steel. The thickness of the plate is 0.254 mm and the wire diameter is 0.25 mm.



(a) Illustration of uniform pressure actuator[8]



(b) Welding system with uniform pressure actuator

(c) Welded sample with embedded wires

Figure 6 Uniform pressure actuator applied for plate-to-plate welding with embedded wires.

4 Impact Velocity and Impact Angle Measurement

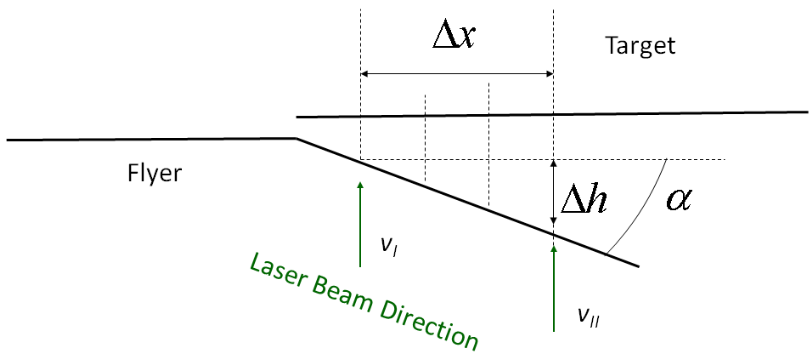


Figure 7 Schematic of impact angle measurement. (In order to measure the moving flyer plate velocity, the laser beam direction needs to be perpendicular to the flyer plate, which is very difficult in real experiment. In this study, two individual laser beams were used to measure the specific point velocity rather than the moving surface velocity. Hence, the beam direction is not perpendicular to the flyer plate.)

During impact welding process, the fiber optic laser beams aim at the flyer surface and capture its entire movement. A subroutine for Matlab program has been developed which is capable to analyses the raw PDV data into the impact velocity versus time profile directly. PDV probes can be used to measure multiple velocities at different specific locations. As shown in Figure 7, two individual laser beams were used to measure the specific point velocities at position *I* and position *II*. During impact welding, the flyer plate collides onto the target plate forming an initial welding line and this welding line moves along the being welded interface. Due to the oblique impact, the flyer plate travels in shorter distance to collide the target plate at the position of the initial welding line, than at the position of the final welding line. Assuming the flyer plate is rigid before collision and deformable after collision, the impact angle can be calculated as Equation (1~2).

$$\alpha = tg^{-1}\frac{\Delta h}{\Delta x} \tag{1}$$

in which, Δh is the travelling distance difference and Δx is the distance between the two measured positions. The travelling distance difference can be calculated as:

$$\Delta h = \int v_2 dt_2 - \int v_1 dt_1 \tag{2}$$

v_1 and v_2 are the velocities at the positions *I* and *II*, t_1 and t_2 are the total travelling times for the impact process at position *I* and position *II*. The welding map for Cu-Cu joint on the second generation flat bar actuator was measured and shown in Figure 8. For 0.254 mm thick Cu plate-to-plate welding, the welded velocity was larger than 250 m/s and the impact angle was in the range of 2°~7°.

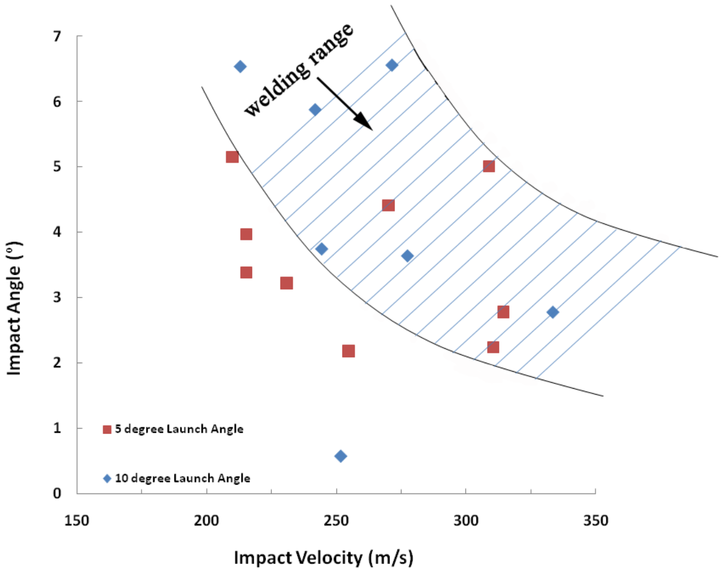
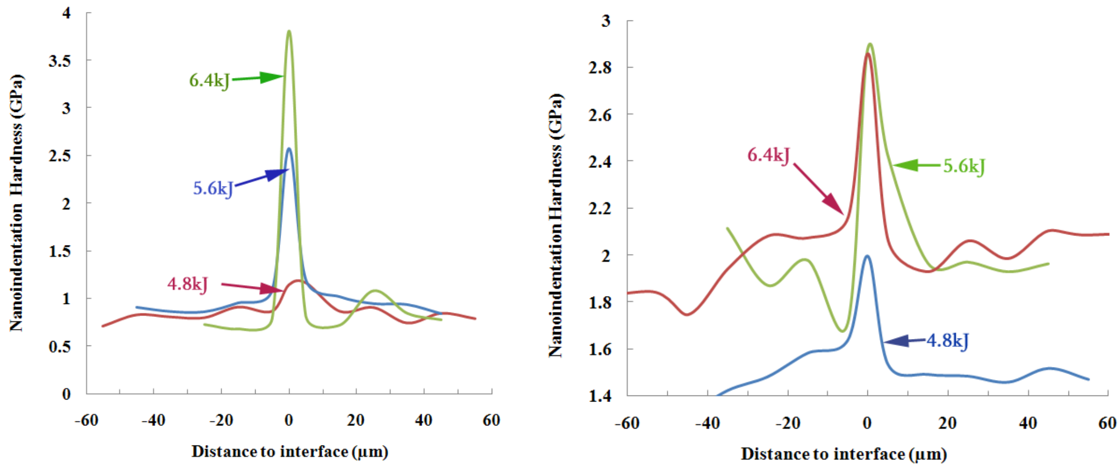


Figure 8 Weldability map for Cu110 joints of 0.254mm thick plates.

5 Joint Mechanical Property

The direct lap joint samples were studied by lap shearing, peeling and nano-indentation tests. For both AA6061 and Cu110, the fracture of the lap shearing test was out of the welded region and broke at base metals. AA6061 joints did not show elongation before fractured whereas Cu110 joint had obvious elongation. For dissimilar materials joint, the peeling test results exhibited base metals fracture before the joints were fully pulled apart. Lap shearing and peeling tests qualitatively suggested the impact joint was stronger than the base metals. Nano-indention test quantitatively presents the joint strength as shown in Figure 9. The joint hardness values increased significantly. The strengthened region across the welded interface was quite narrow for AA6061 joint, about 20 μm wide totally. And the impact hardened region was symmetrical with regard to the welded interface, whereas for Cu110 joint, the strengthened region did not show symmetrical pattern, and it was about 30~40 μm wide. The asymmetrical hardening patter may come from different hardening mechanisms or the variation between each indentation. More study is needed to understand this behaviour.



(a) AA6061 joints (b) Cu110 joints

Figure 9 Nano-indentation test results from MPW joints.

6 Joint Microstructure Characterization

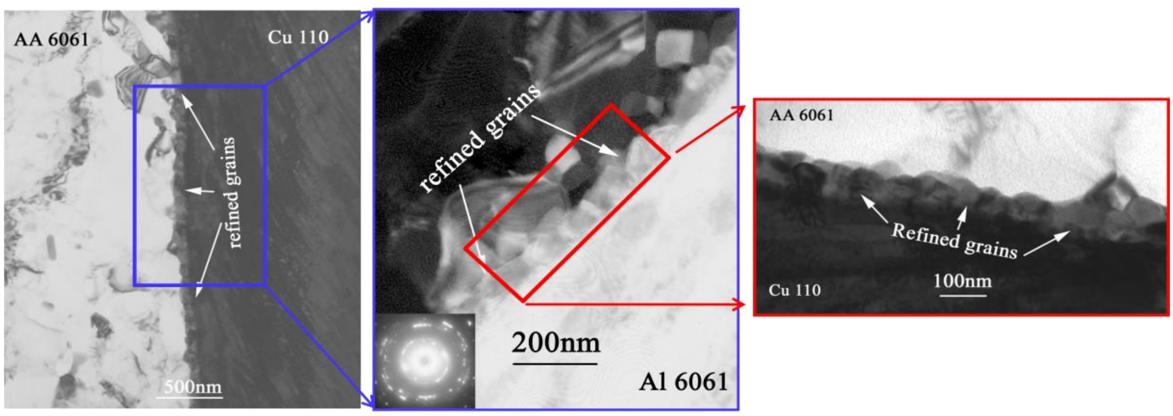


Figure 10 TEM images from Cu-Al joint showing grain refinement after high strain rate deformation. (All images are TEM BF image.)

The high strain rate deformation induced from MPW led to interface grain refinement and final equiaxed nano-crystalline structures despite the different strain paths [10]. The welded interface exhibited ultrafine grain structure, which was of several decade nanometers in diameter as shown in Figure 10. The TEM image was from 5.6 kJ welded Cu-Al interface, which clearly showed that the grain size decrease to nanometer in the impact interface with diffraction pattern changing from spot to ring patter. The interfacial grains transformed into essentially equiaxed nano-crystalline structures by adiabatic heating. As a result, the interfacial grain refinement was attributed to the interface strength increasing, which is in confirmation with the Hall-Petch relation. TEM observation showed the grain size changed from nanometer scale to micrometer scale in a continuous manner from interface to base metal. Such grain size gradient was caused by strain and strain rate gradients from high speed impact welding process. And the ultrafine grains were surrounded by high angle boundaries with the angles larger than 15˚. It was also noticed that the submicron grains near to the impact welded interface were elongated along the impact direction. These high angle boundaries impeded the dislocation motion and strengthened the joint interface.

7 Conclusion

This paper studied the variety of the actuator configurations for magnetic pulse welding on plate-to-plate welding. Three types of configurations: direct lap joint, pre-flange lap joint, and embedded wire lap joint were applied onto plate-to-plate welding. The impact welding was applied onto both similar and dissimilar materials. The impact velocity and impact angle were measured by Photon Doppler Velocimetry. One welding map for Cu-Cu plate was developed. The joint strength was examined and the results indicated interface had greater strength than the base metal which could be explained by the interfacial grain refinement.

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