Chapter 33

Research Findings: Magnetic Pulse Welding of Aluminium Alloy

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In this present work joining of 66 mm diameter, 1.5 mm thick Aluminium 5052 tube to 40 mm thick Aluminium 5052 tube-sheet is achieved with the application of expansion Magnetic Pulse Welding (MPW). Quality welds are achieved for impact velocity 160-360 m/s against an impact angle of 6 degrees and discharge current of 148 kA, corresponding to magnetic field of 19 T (150 MPa) at a frequency of 13 kHz. The weld characterization was done on the tube-tube sheet weld sample by performing the helium leak test, pull out test, interface micro-hardness profiling and optical micrographs of the weld interface are analysed to affirm periodic wavy pattern of the interface.

33.1. Material

Aluminium alloy of 6000 series is widely reported to be used in several research reactors and cold neutron sources [1]. Application of expansion MPW has been studied and published by S. Mishra and et al [2]. Although under un-irradiated condition, 5000 and 6000 series alloys are different in their microstructure and properties, 5000 series that is solid solution strengthened by magnesium (principal alloying element) slowly transform into 6000 series alloys under neutron irradiation [1]. Al 5052 alloy are known to have good formability and resistance to corrosion in flowing water. This alloy consists nominally 2.5% of magnesium which results in formation of magnesium silicide (Mg_2Si) due to transmutation produced silicon, contributing to the alloy's irradiation induced strength and high resistance to swelling and cavity formation. Hence, this grade of aluminium alloy also finds its application as the major component material in the nuclear research reactors. The other major advantage of this alloy grade is its resistance to cavity formation under neutron irradiation to fast and thermal fluence [3]. This grade of aluminium possesses tensile yield strength of 90 MPa and 195 MPa of ultimate tensile strength [4].

33.2. Expansion MPW of Aluminium 5052 alloy

In this work, a 100 mm long tube of Al-5052, 66 mm diameter and 4 mm thick is welded to a 40 mm thick tube-sheet. Wherein, the tube thickness is reduced from 4 mm to 1.5 mm at the intended weld region. Magnetic field produced with a multi-turn copper reinforced expansion coil generates a magnetic pressure, which causes the Al tube to expand and impact on the outer 40 mm thick Al tube-sheet, eventually getting welded with each other. One important pre-requisite is the position of flyer tube relative to the solenoid coil, which must be concentric, so as to ensure uniformity in magnetic field and magnetic pressure within the annular volume between flyer tube and coil. This is to ensure uniform magnetic pressure over the tube. To ensure this concentricity of coil-tube-tube-sheet, a delrin fixture arrangement is made to hold the assembly intact in position during the weld, as shown in Figure 33.1.

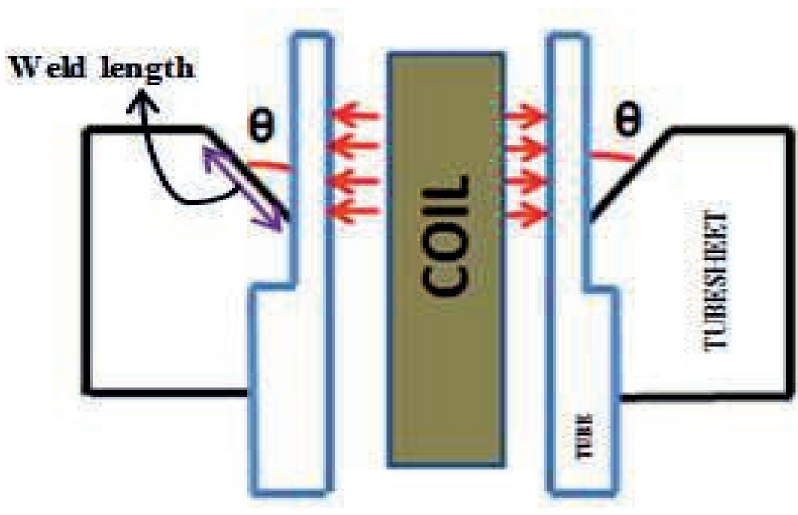

Figure 33.1. Schematic view of coil-job placement with impact angle between tube and tube sheet.

Minimum mechanical pressure necessary for acceleration and impact of the flyer tube on to the target tube-sheet is estimated from Eq. (33.1) [5-7]

$$P= t\ [\rho V_p^2\ /2.s + 2\sigma_y/R] \tag{33.1}$$

Where, t (m) is flyer tube thickness, $\rho\,(kg/m^3)$ is density of tube material, s (m) is the initial stand-off, σ_y (MPa) is the yield strength of tube material, V_p (m/s) is the tube impact velocity, R (m) is the tube initial radius.

To generate this mechanical pressure, magnetic flux density required for welding is found by using Eq. (33.2) [2, 5, 7, 8].

$$P=B^2/2\mu\ (1-e^{-2t/\delta}) \tag{33.2}$$

Where, f is discharge frequency, μ is the permeability of the material, σ is the conductivity of the material, t is flyer tube thickness, δ is the skin depth. The impact pressure and impact velocity are the two critical parameters that decide the occurrence of weld and its quality [7]. To produce this magnetic field the discharge current necessary for an eight-turn solenoid coil is found to be 148 kA at a frequency of 13 kHz. In MPW, voltage is the only parameter which can be varied based upon the job to be done. The current induced in the inner tube, due to the capacitor bank discharge, tends to penetrate the tube thickness up to a depth known as skin depth. This skin depth depends upon the flyer material's electrical conductivity σ(S/m), magnetic permeability μ and system frequency f (Hz). The flyer tube thickness should be at least equal to the skin depth, δ given by Eq. (33.3) [2] so as tolimit the magnetic field diffusion.Hence, the system frequency is so chosen, such as to limit the magnetic field diffusion within the tube thickness.

$$\delta\ = 1/\sqrt{\pi\sigma\mu f} \tag{33.3}$$

Figure 33.2 shows the discharge waveform, where the green waveform is the current discharged into the coil required for welding and the purple waveform is the crowbarred current which is purposely bypassed from the coil so as to increase its life by preventing unnecessary heating caused due to unwanted current. This coil current generated a magnetic field of ~19 T over the 66 mm inner diameter of the flyer tube, which corresponds to a magnetic pressure of ~150 MPa, as calculated from Eq. (33.2) required deforming and accelerating the flyer to hit the target tube-sheet. An impact angle is provided on the tube-sheet inner diameter so as to initiate the jetting action. For a successful weld, the required minimum impact velocity of 175 m/s (also called critical velocity), as calculated from Eq. (33.4) for Al-5052, is achieved for an impact angle, θ of 6 degrees along a 20 mm weld length zone as shown in Figure 33.1.

$$V_p = \sqrt{\frac{\sigma_U}{v_S}} \tag{33.4}$$

$$V_p = 2V_C \sin\frac{\beta}{2} \tag{33.5}$$

Where σ_U is the ultimate tensile strength and V_S is bulk sound velocity of the flyer tube [9] Also, the impact velocity, V_p and collision velocity, V_C is related by Eq. (33.5), where β is the collision angle [10].

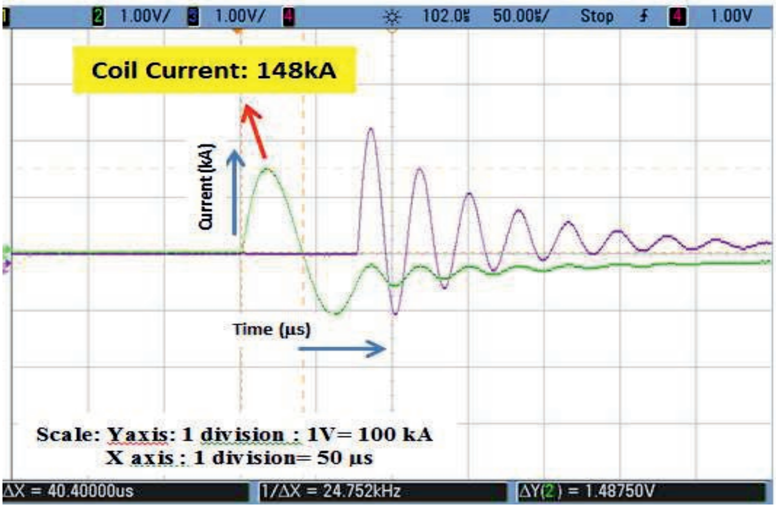

Figure 33.2. Experimental Waveform.

33.3. Characterization Results and Discussions

The welded samples are first subjected to non-destructive tests followed by destructive tests to check for its quality. At first the samples are visually inspected for appearance and geometrical differences, confirmed no distortion or damage caused during the welding process. Then the samples are checked for leak tightness in ASM 340 helium leak detector by Pfeiffer Vacuum, having a sensitivity of 5x10^{-1} mbar-l/s. During the helium leak test, the welded samples qualified to the nuclear weld quality criteria, by achieving a helium leak rate of 2.0 x 10^{-10} mbar l/s. Mechanical strength of the weld joint is evaluated by subjecting pull out tension load on the welded samples in a Universal Testing Machine (UTM) of 120 kN capacity. It is observed that the welded samples could sustain a tension load of 19.62 kN (~2 tonnes) without failure and are having a maximum of 35.90 kN (~3.66 tonnes) pull out strength. For microstructural analysis an inverted metallurgical microscope is used, for which the welded samples are cut into sections containing the region of interest using a diamond precision cutting machine. The cut sections are then coarse polished with SiC papers having grit sizes 200 to 1200 and then fine polishing is done on a synthetic cloth with diamond paste up to 1µm finishing level. For proper identification of the microstructure, the polished samples are etched with Keller's reagent before examining them under the microscope. Figure 33.3a shows the longitudinal cut section of the welded sample which is examined under an optical microscope where, Figure 33.3b & 33.3c shows the typical microstructure of magnetic pulse welded interface of Al 5052 tube-tube-sheet. It shows a part of the interface indicating a wavy morphology of the tube-tube-sheet joint that confirms flow of material owing to the severe plastic deformation along the interface, ensuring a strong mechanical interlocking between them.

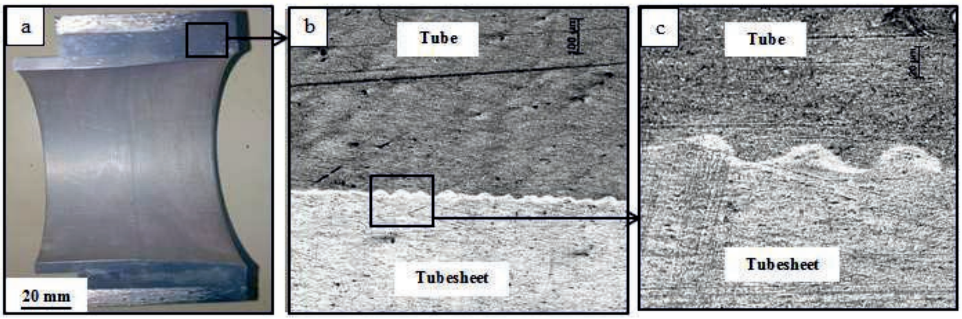

Figure 33.3(a). Longitudinal section cut of welded sample (b). Optical micrograph of Al 5052 weld interface at 100x magnification (c). Optical micrograph of Al 5052 weld interface at 500x magnification.

The reason behind this wave formation is explained by the shock wave theory which claims that shock waves propagate through the metals and creates periodic interference perturbation at the interface. These interferences initiate the Kelvin-Helmholtz instability that creates the interfacial waves [11]. It is noted that the wavelength and amplitude of the interface wave gradually changed along the welding direction having a maximum wavelength of 60 µm and amplitude of 15 µm. This change in wavelength and amplitude is attributed to the collision angle between the flyer plate and the parent plate that which gradually changes during the welding process, as confirmed in previous work [12]. Similar interfacial patterns, which depend upon the impact velocity, are observed in the present work. Figure 33.4 a, b shows the simulated velocity profile (updating acceleration in loop at each step) gained by different sections of the Al 5052 tube along the welding direction over a total weld length zone of 20 mm. For a fixed impact angle i.e 6 degrees when the velocity is low, i.e. below 160 m/s, no weld is seen between (O-A), between 160 m/s to 280 m/s, a straight weld interface is seen (A-B), whereas when velocity is in between 280 m/s to 360 m/s, a wavy weld interface is seen (B-C), as shown in Figure 3c. The difference in impact velocity along the welding length is a contribution of the changing stand-off distance arising due to the tapered geometry of the target tube-sheet. The interface morphology transition represents the onset of kinematics instability, wherein alternative upward and downward jetting occurs due to interfacial shearing.Jet indentation, jet splitting and re-entering into the target are reported to form this periodic metal hump as also observed in the present work [5]. The presence of impact angle facilitates an oblique collision between the flyer-target which produces the tangential collision velocity causing upward and the downward trend that arises with the progressive impact on the target by the impact of velocity driven flyer [13]. Depending on the collision conditions, three prominent morphologies, namely, straight, wavy, and vortical interfacial pattern are seen. It is reported that under the constant collision angle conditions, the interface morphology changed from straight to wavy to vortical with increasing collision velocity [14]. The weld joint, in the present work, is seen to be comprising of ~6 mm of straight weld interface and ~9 mm of wavy weld interface resulting into ~15 mm of bonded weld length, achieved out of the 20 mm weld length zone.

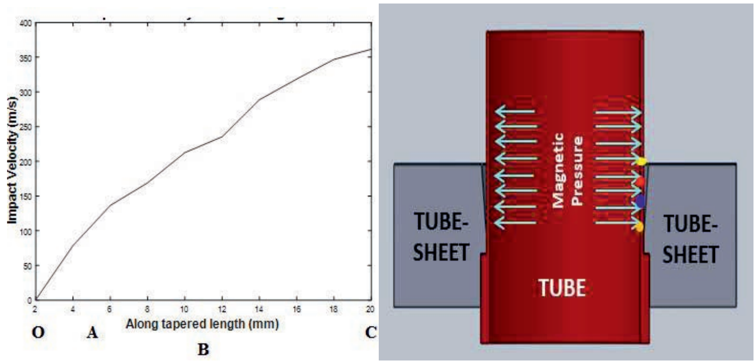

Figure 33.4(a). Schematic showing cut section of Al tube to tube-sheet under magnetic pressure (b). Different sections of tube getting driven with different velocity, O, A, B, C.

Micro hardness at the weld interface is measured by the dead weight method, applying a load of 200 grams for a dwell time of 10 s. The hardness profile across the interface indicates hardness value of ~60 HV at the tube, ~79.9 HV at interface and ~59.5 HV at tube sheet, as shown in Figure 33.5. This increase in interface hardness, relative to parental base metal, is attributed to formation of refined grains due to the severe plastic deformation. This increased hardness at the interface supports the theory that mass transfer between the flyer tube and target tube sheet has taken place due to high strain rate plastic deformation resulting in bond formation [24]. However, this increase in hardness is considered negligible and is harmless as compared to hardness values witnessed in other conventional techniques.

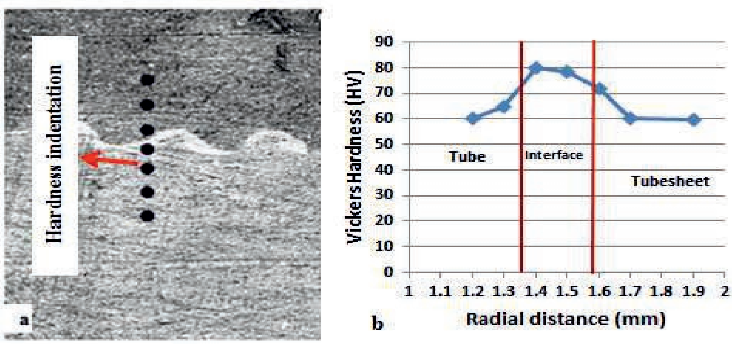

Figure 33.5(a). Hardness indentations on interface and (b). Hardness profile across weld interface.

33.4. Conclusion

The application of expansion MPW on 66 mm diameter, 1.5 mm thick Al 5052 alloy tube to 40 mm thick Al 5052 alloy tube-sheet has been successfully demonstrated with a multi-turn copper electromagnetic coil. Interface joining morphology and the process phenomena observed confirms to the characteristics of joining patterns typical of HVIW technique.

References

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Questionnaire

Q1) What makes Al 5052 alloy, a suitable material to be used in nuclear research reactors?

Q2) What do you understand by the term skin depth?

Q3) What are the interfacial patterns observed in MPW? It is mainly governed by which critical welding parameter?

Q4) Why is maintaining concentricity between the electromagnetic coil and jobs to be welded important?

Q5) The existence of interfacial wavy morphology is attributed to initiation of which instability?

Q6) Increase in hardness at the weld interface is attributed to which microstructural phenomena?

Q7) Determine for a 40 mm outer diameter, 0.5mm thick copper tube, the magnetic field developed corresponding to a magnetic pressure of 200 MPa needed to deform and accelerate it to a velocity of 400m/s. (Take frequency as 20 kHz, Electrical conductivity as 58 S/m).

Q8) How does skin depth vary with frequency? Support your answer with graphical representation forvariation of skin depth with frequency (10 kHz,35 kHz,65 kHz, 100 kHz), for materials like Copper, Aluminium, and Stainless Steel.