The Journal of CPRI,
Vol. 13, No. 1, March 2017 pp. 125-130

Electromagnetic pulse welding for joining of aluminium tube to uncoated and copper coated steel rod

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Reliable and cost effective joining methods are essential for the development of hybrid structures involving dissimilar materials. Electro Magnetic Welding (EMW) is one such technology which can be used for joining of dissimilar materials. In an EMW the pulsed current with a very high amplitude and frequency produces Lorentz forces and a high magnetic pressure well beyond the material yield strength, causes acceleration and one of the work pieces impacts onto the other part with a collision. Present study deals with the application of EMW for joining of tubular aluminium workpiece to uncoated and copper coated steel rod. The electromagnetic pressure necessary for joining is estimated. Joint is analyzed for the microstructure and hardness.

Keyword: Impact, electromagnetic, lorenz force, steel welding

1.0 INTRODUCTION

Electro Magnetic Welding (EMW) is an impact welding process in which coalescence takes place at the interface of the materials called flyer and target due to high velocity electromagnetic pulse force or Lorenz force. Lorenz forces are generated by the interaction of the repelling magnetic fields due to the induced eddy currents between coil and the adjacent flyer workpiece, inducing high velocity impact of flyer workpiece on to a target workpiece with severe plastic deformation, thus producing a metallurgical bonding at the interface of the two materials. Metallic combinations like aluminium to copper, aluminium to nickel, aluminium to titanium, copper to steel which are not normally compatible can be joined by EMW [1].

Aluminium– steel transition joints find many applications like drive shafts of automobiles, cryogenic coupling for liquefied storage vessels and pipe works, bus bar connections in electrolysis plants. Soft interlayer like copper coating is used as reaction promoters and stress reliever which are commonly developed at the interface of aluminium-steel joints [2]. In the present paper, authors have attempted joining of aluminium tube to both uncoated and copper coated steel rods using electromagnetic welding. Aluminum AA6005 has been selected for the studydue to its excellent combination of high strength, formability and corrosion resistance.

1.1 Mathematical Framework of Electromagnetic Welding

In an electromagnetic welding process, a small displacement of solid structure in an electromagnetic media modifies the magnetic flux. There is a strong coupling with electro-magnetic-mechanical systems. In an electromagnetic field model, magnetic vector potential $\vec{A}$ is chosen as a system variable and is defined by the equation (1) with respect to magnetic flux density $\vec{B}$ in tesla.

$$\nabla \times \vec{A} = \vec{B} \quad ...(1)$$

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Maxwell equations (2), governing the electrical field in a media undergoing time-dependent magnetic diffusion and motion of the solids in terms of magnetic vector potential is

$$\nabla \times \frac{1}{\mu}\left(\nabla \times \vec{A}\right) = J - \sigma\frac{\partial \vec{A}}{\partial t} + \sigma(\upsilon \times \nabla \times A) \qquad ...(2)$$

Where J, $-\sigma\frac{\partial \vec{A}}{\partial t}$, $\sigma(\upsilon \times \nabla \times A)$, μ, σ,υ, t are current density in the induced current density in tube, displacement current, permeability of the material, conductivity of the material, velocity and time respectively. Neglecting displacement current, the electromagnetic models can be expressed by equations (3) to (5) at different regions of tube and coil. [3-4].

At coil region

$$\nabla \times \frac{1}{\mu}\left(\nabla \times \vec{A}\right) = J \qquad ...(3)$$

At free air region around the tube and coil

$$\nabla \times \frac{1}{\mu}\left(\nabla \times \vec{A}\right) = 0 \qquad ...(4)$$

At tube region

$$\nabla \times \frac{1}{\mu}\left(\nabla \times \vec{A}\right) = -\sigma\frac{\partial \vec{A}}{\partial t} \qquad ...(5)$$

For an axi-symmetric case, governing equation for electromagnetic field, in terms of magnetic vector potential ($A_{\emptyset}$) in the Ø-direction is given by the equation (6)

$$\frac{1}{\mu r}\frac{\partial^2 (rA_{\emptyset})}{\partial r^2} + \frac{1}{\mu r}\frac{\partial^2 (rA_{\emptyset})}{\partial z^2} + \sigma\left[-\frac{\partial A_{\emptyset}}{\partial t} + \left(\frac{\partial x}{\partial t} \times B\right)\right] + J_{\emptyset} = 0 \qquad .(6)$$

Where X is the displacement [4]. Magnetic force density is given by equation (7)

$$\vec{f} = \vec{J} \times \vec{B} = \frac{1}{\mu}\left(\nabla \times \vec{B}\right) \times \vec{B} \qquad ...(7)$$

2.0 EXPERIMENTAL DETAILS

The experiment consisted of joining aluminium tube to the uncoated 0.18 carbon steel rod as well as aluminium tube to the copper coated 0.18 carbon steel rod. Commercially available extruded AA6005 aluminum pipe of 3mm thickness, in the as received condition, has been cut to the required size and machined to the required thickness. Copper coating is done on the outer surface of steel rod to a thickness of about 100µm by electroplating method. Geometrical details of the aluminium flyer tube and steel target is given in Figure 1

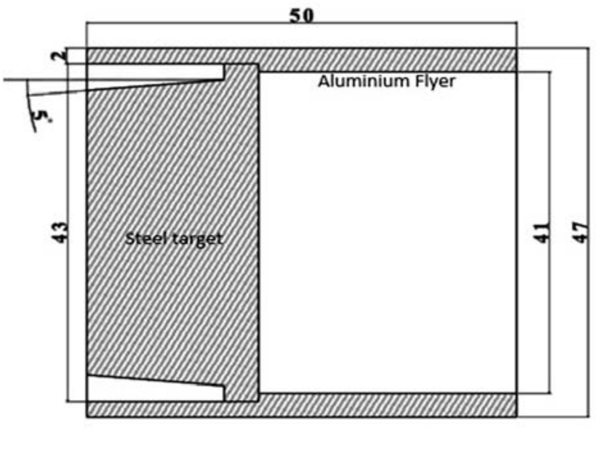


FIG 1: GEOMETRICAL DETAILS OF ALUMINIUM FLYER WORK PIECE AND INNER STEEL ROD.

The experiments are carried out in a 40 kJ/ 20 kV electromagnetic welding machine at Bhabha Atomic Research Centre, Mumbai. The schematic layout of EMW process and electromagnetic coil used in the experiment is shown in Figure 2

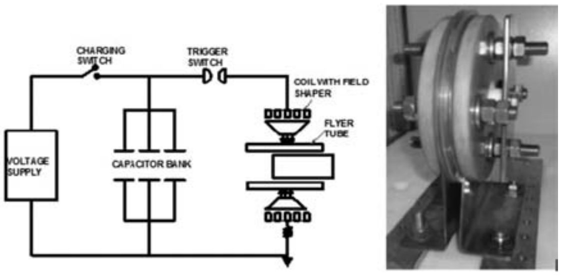


FIG. 2. SCHEMATIC DIAGRAM OF EMW PROCESS AND ELECTROMAGNETIC COIL [1,4].

The coil has three effective numbers of turns with an active length of 20 mm. The setup is charged at a voltage of 17 kV, 10 kHz frequency for both uncoated and copper coated steel rod samples. The samples are cut along the longitudinal direction, mirror polished with a fine sand paper for the micro examination.

Micro examination of the joint interface has been evaluated by using AxioVert, A1, Zeiss optical microscope, with image analyzer Clemex Vision

PE. Micro hardness evaluation has been done across the joint interfaces, by standard ASTM E384-16 test method, using Matsuzawa-MMTX7 hardness tester, with a load of 100g and dwell time 10s.

The joint tightness is tested using a VS Series Agilent helium leak detector, of sensitivity 10^{-12} torr-l/s. Helium is sprayed on one side of the joint after creating a vacuum level of 5.9×10^{-9}torr-l/s. Trace of helium sensed on the other side of the joint by the leak detector has been taken as a measure for tightness of the joint.

3.0. RESULTS AND DISCUSSION

Parameters mainly voltage, current, magnetic pressure governing the EMW are calculated based on the mechanical pressure necessary for inducing acceleration for impact and deformation of the workpiece [5]. Using the parameters of the flyer workpiece geometry and mechanical properties, mechanical pressure needed for the acceleration and deformation of the flyer workpiece has been found to be 286MPa by the equation (8)

$$P_{Mech} = \left[\frac{\rho {V_C}^2}{2S} + \frac{2\sigma_y}{r}\right] \mathrm{T} \qquad \text{...(8)}$$

Where ρ density of the flyer tube,V_C impact velocity, S standoff distance,σ_y yield strength, r radius of the tube,T thickness of the flyer tube.

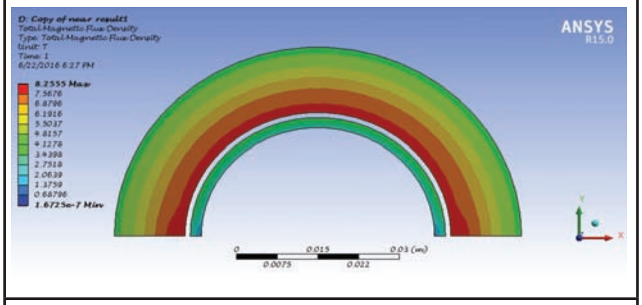


FIG. 3. MAGNETIC FIELD PATTERN BETWEEN OUTER FLYER WORK PIECE AND INNER DIAMETER OF THE ELECTROMAGNETIC COIL.

Finite Element Method (FEM) magneto- static analysis is performed using commercial ANSYS 15.0 software on a two dimensional single turn coil to determine magnetic field pattern and the coupling between the flyer and coil. Magnetic field pattern in the Figure 3, has maximum magnetic field at the inner surface of the coil. FEM analysis of magnetic flux density indicated 50% coupling between the flyer and coil respectively.

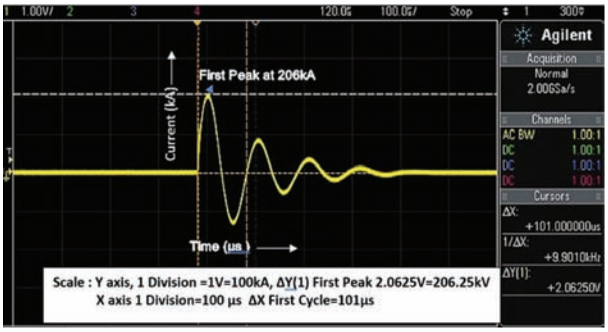
The theoretical discharge current I in the electromagnetic coil necessary to generate magnetic pressure of 286 MPa is found to be 203 kA using the equation (9) for 50% coupling.

$$I = \sqrt{\frac{2P_{Mech}l^2}{\mu N^2}} \qquad \text{...(9)}$$

Where l is the length of the coil and N is number of turns in the coil. The theoretical voltage is calculated by using the equation (10)

$$V = \frac{I}{\sqrt{\frac{C}{L}}} \qquad \text{...(10)}$$

For theoretical current of 203 kA, total capacitance C of the system 224 µF, total inductance L of the system 1.52 µH the theoretical charging voltage is found to be 16.75 kV.



Scale : Y axis, 1 Division =1V=100kA, ΔY(1) First Peak 2.0625V=206.25kV
X axis 1 Division=100 µs ΔX First Cycle=101µs

FIG. 4. EXPERIMENTAL WAVEFORM AT 17 KV

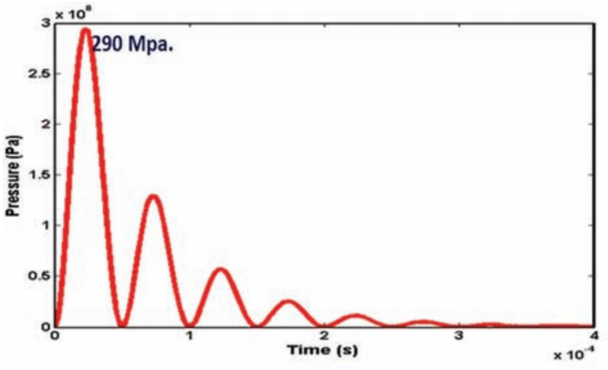


FIG. 5. UNDER DAMPED MAGNETIC PRESSURE.

For the experimental discharging voltage of 17 kV, the first peak current recorded in the Figure 4 is found to be 206 kA at 25 µs. Corresponding experimental magnetic pressure of 290 MPa. as shown in the Figure 5 is in good agreement with theoretically calculated pressure values.

3.1 Evaluation of the Welded Samples

The interface microstructure of aluminium AA6005 with uncoated steel (Figure 6) showed a complete bonding with characteristic waviness of electromagnetic welding. Interface microstructure of the aluminium AA6005 with copper coated steel in the Figure 7 showed a good bonding though the characteristic waviness is absent in the microstructure. Micro hardness measured across the joint interface indicated significant increase in the hardness for a large band width at the joint interface as shown in the Figure 8(a) for uncoated sample. The hardness value increased only at the coated interface for the coated steel sample, compared to the aluminium base metal in the Figure 8(b). Thus, indicating that the mechanical strength of the bonding may be poor for coated structures. Helium leak rate for both the samples were in the range of 1 to 3x10^{-8} torr-l/s. Leak tightness at the interface signifies that EMW process offers a strong promise for end closure joint.

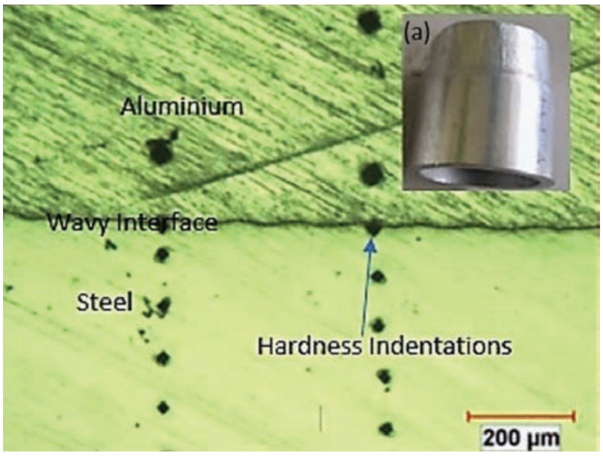


FIG. 6. MICROSTRUCTURE OF JOINT INTERFACE OF ALUMINIUM WITH UNCOATED STEEL (A) WELDED SAMPLE.

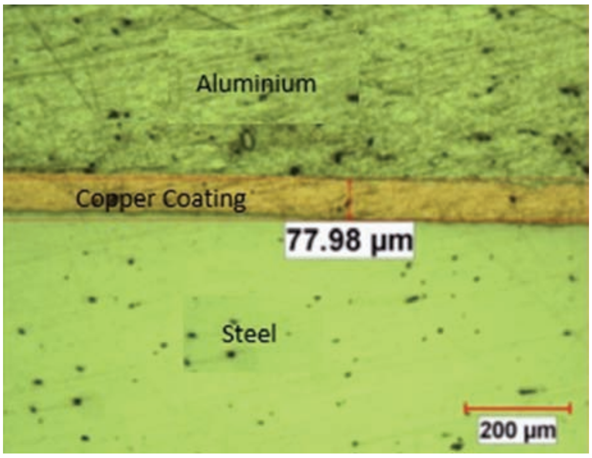


FIG. 7. MICROSTRUCTURE OF WELDED SAMPLES OF ALUMINIUM WITH COATED STEEL.

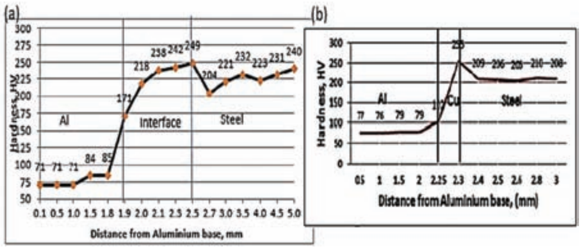


FIG. 8. MICRO HARDNESS PROFILE(A) HARDNESS PROFILE ACROSS ALUMINIUM AND UNCOATED STEEL INTERFACE (B) HARDNESS PROFILE ACROSS ALUMINIUM AND COATED STEEL INTERFACE.

4.0 CONCLUSIONS

- Aluminium/Steel dissimilar metal welding by EMW has been experimentally carried out and theoretically validated combined with FEM for optimum parameters like magnetic pressure and current.
- EMW process has been successful in joining aluminium to uncoated steel which has characteristic wave pattern at the interface. An increased hardness observedat the joint interface and leakproof tested by helium leak facility indicates a satisfactory joint.
- Aluminium to coated steel though resulted in leakproof joint interface, the mechanical strength of the joint needs to be verified.

ACKNOWLEDGMENT

The authors gratefully acknowledge the authorities of APPD, BARC for giving permission and support extended by Dr. Archana Sharma, EMM team of PPSS, APPD, Bhabha Atomic Research Centre while conducting the experiments.

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