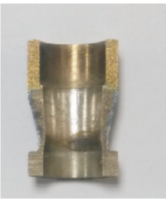
Magnetic Pulse Welding

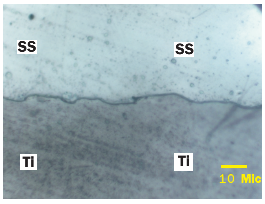
Titanium to SS-304 Dissimilar Metal Joints by Magnetic Pulse Welding

Shobhna Mishra[1]*, JMVVS Aravind[1], Surender K. Sharma[1], G. Kiran Kumar[1], Rashmita Das[1], Basanta K. Das[1], Rishi Verma[1], Renu Rani[1], N. Sathi Babu[1], Archana Sharma[2], Gopa Chakraborty[3], Arun K. Bhaduri[4], Imran Khan[5] and Rajeev Kapoor[6]

[1]Pulsed Power & Electromagnetics Division, Bhabha Atomic Research Centre, Visakhapatnam, Andhra Pradesh-531011, INDIA
[2]Beam Technology Development Group, Bhabha Atomic Research Centre, Visakhapatnam, Andhra Pradesh-531011, INDIA
[3]Metallurgy & Materials Group, Indira Gandhi Centre for Atomic Research, Kalpakkam, INDIA
[4]Homi Bhabha Chair, DAE, Indira Gandhi Centre for Atomic Research, Kalpakkam, INDIA
[5]Reactor Safety Division, Bhabha Atomic Research Centre, Mumbai-400085, INDIA
[6]Mechanical & Metallurgy Division, Bhabha Atomic Research Centre, Mumbai-400085, INDIA



Cut section of Ti-SS welded samples



Ti-SS weld interface micrograph at 1000x

ABSTRACT

The fast reactor fuel reprocessing process flow includes the dissolution stage wherein the chopped fuel sub-assembly is dissolved in nitric acid in titanium-based dissolver units. These units needs to be further joined to the rest of the SS-304 based reprocessing plant along with ensuring the dissimilar metal joint integrity and corrosion resistant. The present work is to study the application of Magnetic Pulse Welding (MPW) for joining of Titanium to SS-304. This technique successfully established joints using a multi-turn and shaper tool coil at a peak magnetic field of 30T (350MPa), 17kHz frequency and impact velocity in the range of 250-350m/s. The welds attained helium leak rate of the order of 10^{-12}mbarl/s and a joining of ~1.2mm is observed with straight to wavy morphology. Microhardness profiling along the joint varied from ~166HV to ~230HV at Ti tube, ~290 to ~330 HV at the interface and ~156 to ~280HV at SS tube.

KEYWORDS: *Magnetic Pulse Welding(MPW), Dissimilar Metal Joining, Titanium, Stainless Steel.*

Introduction

Design of complex hybrid structures made up of dissimilar material combinations to meet the structural and functional requirements has increased the demand of dissimilar metal joining. Similarly, in fast reactor fuel reprocessing plant Titanium (Ti) to Stainless Steel (SS)-304 dissimilar metal joints with high reliability are quite significant. Ti to SS dissimilar metal joints established with fusion welding techniques has been challenging due to the difference in their thermal co-efficient, thermal conductivity and formation of brittle intermetallics. Magnetic pulse welding (MPW) is a solid-state impact welding process that utilizes magnetic pressure for joining of similar and dissimilar metals instead of heat source. This joining process is closely analogous to Explosive Welding (EXW) since both are having similar bonding mechanism i.e formation of jet action and a typical wavy morphology at the joint interface. MPW is a High Velocity Impact Welding (HVIW) technique that establishes lap joints between two colliding materials by utilizing the magnetic pressure generated with an electromagnetic tool coil, schematic as shown Fig.1.

This magnetic pressure is generated when capacitance energy is discharged into the tool coil through a switch and a time-varying magnetic field is established. When a conducting flyer material comes in contact with this magnetic field, eddy current is induced in the flyer that interacts with the magnetic field to produce Lorentz force that corresponds to the magnetic pressure. The flyer deforms under the pressure and accelerates over the stand-off distance available to impact on the target job at the critical velocity to establish a joint between them.

The interface morphology established in HVIW is known to be resulting from the jet effect and is classified into four types i.e. flat interface, wavy interface, vortex wave and continuous transition layer along the interface in the bond zone[3]. The worthiness associated with this technique is that there is no heating and melting of bulk material in this process, which eliminates formation of Heat Affected Zones (HAZ) and undesired oxides and nitrides at the joints, thereby avoiding

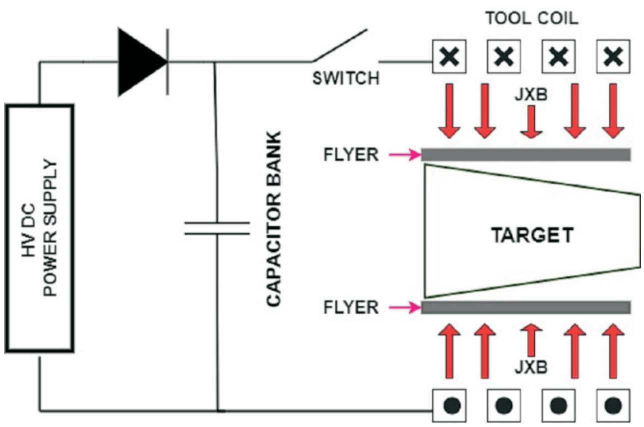


Fig.1: Schematic of MPW system.

**Author for Correspondence: Shobhna Mishra*
E-mail: shobhnam@barc.gov.in

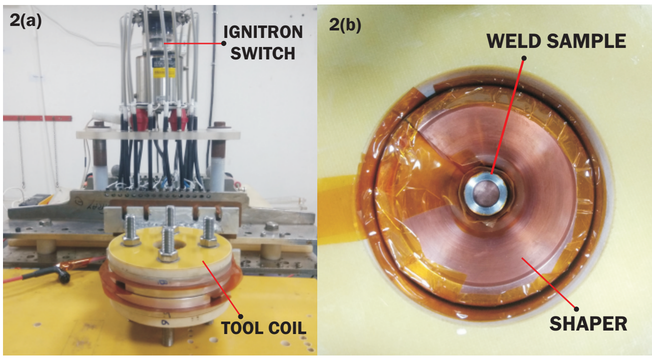


Fig.2: Experimental setup.

joint failures. This dissimilar joining technique is successfully employed to establish Ti tube to SS tube joints and the weld quality is examined with Helium leak rate, optical micrograph and micro hardness studies across the weld interface.

MPW Experimental Setup

A 200kJ/44kV capacitor bank system with total capacitance of 208μF is designed and developed for the MPW experiments. The experimental set up consists of a capacitor bank module comprising of four capacitors, having capacitance of 52μF each, charged through a High Voltage DC power supply with 25kV rated voltage and 800mA output current and the load i.e tool coil which is connected to the capacitor module through a high voltage and high current ignitron switch, as shown in Fig.2(a).

The magnetic field necessary to establish the required magnetic pressure is generated with a 4-disc aluminium alloy electromagnetic coil and is concentrated into the desired volume with a copper shaper, as shown in Fig.2(b).The job assembly comprises of a flyer, target, a copper mandrel to prevent target deformation and a copper driver over the flyer tube to eliminate magnetic field diffusion due to relatively low electrical conductivity of titanium, whose thickness has a direct co-relation with the system frequency. In the present setup, the flyer consists of Ti tube with copper driver and the target consists of SS tube supported with an inside copper mandrel, as shown in Figs.3&4. Table 1 shows material properties of Ti, SS-304 and Cu.

A critical impact angle between the colliding surfaces is necessary to ensure sufficient stand-off distance, i.e the initial gap between the impacting components, for accelerating the flyer to achieve the required impact velocity. In the present work, impact angle is provided on the SS target tube which

Table 1: Material properties.

Material	Property	Value
Ti (Grade-2)	Yield strength, σ_y(MPa)	355
	Density, ρ(kg/m^3)	4520
	Electrical Conductivity, σ(S/m)	2.38 x 10^6
SS-304	Yield strength, σ_y(Mpa)	205
	Density, ρ(kg/m^3)	8000
	Electrical Conductivity, σ(S/m)	1.5 x 10^6
Copper	Yield strength, σ_y(MPa)	60
	Density, ρ(kg/m^3)	8960
	Electrical Conductivity, σ(S/m)	58 x 10^6

provides a gradually increasing stand-off distance for the Ti flyer, as seen in Fig.4 from point 1 to 2, so as to collide with the target at the critical impact velocity.

Analytical Details

In MPW, the required magnetic pressure is developed when the corresponding magnetic field is established in the annular space between the tool coil and the tubular conductive flyer. However, the magnetic field required to establish the joint varies based upon the flyer and target material, the standoff distance between them and can be produced by varying the capacitor charging voltage. The current induced in the copper driver tube, due to interaction with the time-varying magnetic field around, tends to penetrate along the tube thickness up to a depth known as skin depth. This skin depth depends upon the driver material's electrical conductivity σ (S/m), magnetic permeability μ and system frequency f(Hz). The driver tube thickness should be at least equal to the skin depth, δ given by(1) [4] so as to limit the magnetic field diffusion. Hence, the system frequency is chosen accordingly.

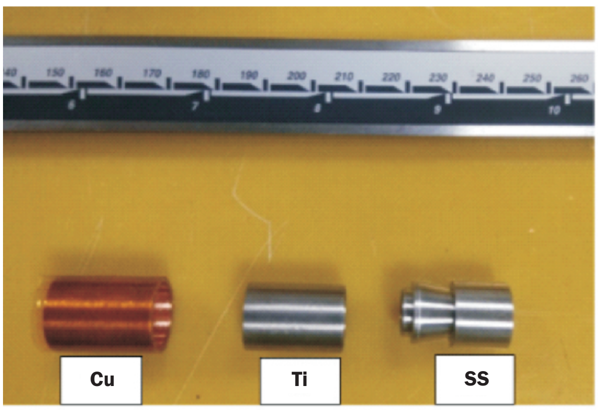


Fig.3: Copper driver & Ti-SS samples.

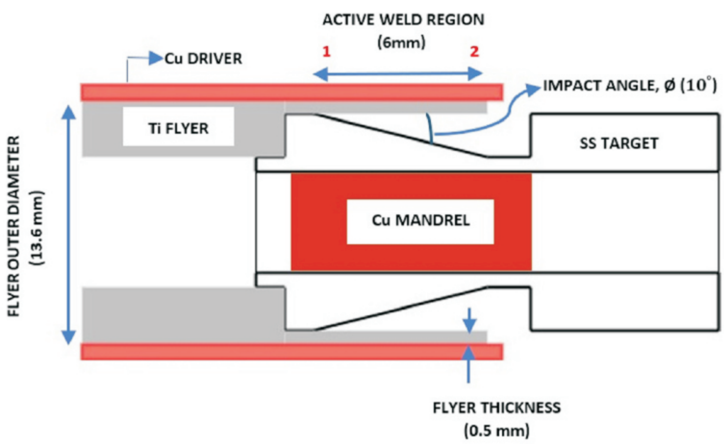


Fig.4: Copper driver & Ti-SS samples.

$$\delta = 1/\sqrt{\pi\sigma\mu f} \qquad (1)$$

The interaction of the time-varying magnetic field with the induced eddy current in the flyer develops a Lorentz force. The total magnetic pressure, *P* (MPa) is obtained by integrating this Lorentz force over the tube and is also the summation of pressure required to deform, P_{def} and accelerate, P_{acc} the flyer tube and is as given in (2) [4, 5]

$$P = P_{def} + P_{acc}$$

$$P = t\,[2\sigma_y/R + \rho U_T^2/2s] \qquad (2)$$

Where, t(m) is flyer tube thickness, ρ(kg/m^3) is density of flyer tube material, s(m) is the initial stand-off, σ_y(MPa) is the yield strength of flyer tube material, U_T(m/s) is the flyer tube impact velocity, R(m) is the flyer tube initial radius. Based upon the flyer and target material the corresponding magnetic field, B(T) can be obtained from equation (3) [4,5].

$$P = B^2/2\mu(1 - e^{-2t/\delta}) \qquad (3)$$

Where, μ is the permeability of the material, δ is the skin depth, t is flyer tube thickness, P is the magnetic pressure. The impact angle, impact pressure and impact velocity are the three critical parameters that decide the occurrence of weld and its quality. In order to obtain a successful weld through MPW a minimum threshold pressure value is to be exceeded. This pressure, P_{thres} is given by the relation (4)[6]

$$P_{thres} = 5\times\text{Hugoniot Elastic Limit } (HEL) \qquad (4)$$

Where, HEL is given by the relation (5)

$$HEL = \frac{1}{2}\left(\frac{K}{G} + \frac{4}{3}\right)\sigma_y \qquad (5)$$

Where, K is the bulk modulus (GPa) and G is the shear modulus (GPa).

The critical impact pressure, P_c required for jet formation that is related to impact velocity is as given in (6) [6]

$$P_c = \frac{1}{2} Zeq\, U_T \cos \Phi \qquad (6)$$

Where, U_T is the critical impact velocity, Φ is the critical impact angle for jet formation and *Zeq* is the equivalent acoustic impedance of the colliding tubes and is given by (7)[6]

$$Zeq = \frac{2}{\frac{1}{Z_1} + \frac{1}{Z_2}} \qquad (7)$$

Where, $Z_1 = \rho_1 S_1$ is the acoustic impedance of flyer tube, $Z_2 = \rho_2 S_2$ is the acoustic impedance of base tube, S_1 and S_2 are the speeds of sound in the flyer and target tube materials(m/s) respectively, and ρ_1, ρ_2 (Kg/m^3) are the material densities of the two tubes. The minimum velocity of impact U_T, also termed as critical impact velocity required for occurrence of weld in case of dissimilar metal combination can be determined by equating equation (4) and (6) and total magnetic pressure can be determined using equation (2) [6]. Also, the impact velocity, U_T and collision velocity, V_c (m/s)is related by (8), where β is the collision angle [7].

$$U_T = 2V_c \sin\frac{\beta}{2} \qquad (8)$$

Experimental Results

A dissimilar metal joint between 13.6mm diameter, 0.5mm thick Ti to SS tube with impact angle 10° is successfully established using a 4-disc Al alloy coil with copper shaper at a peak magnetic field of 30T (350MPa) corresponding to peak current of 295kA, 17kHz frequency as shown in Fig.5.

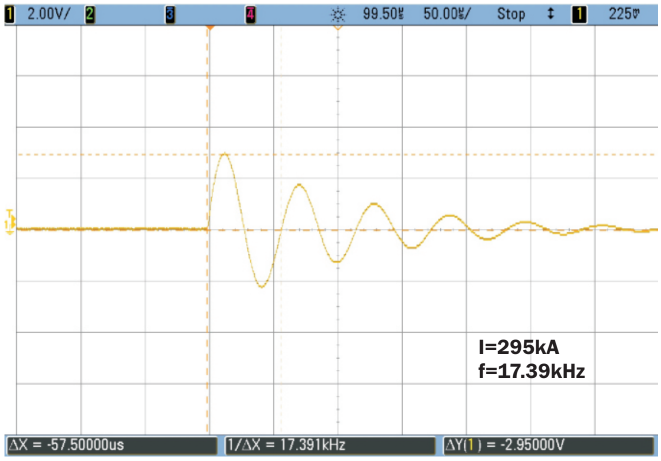


Fig.5: Discharge current waveform.

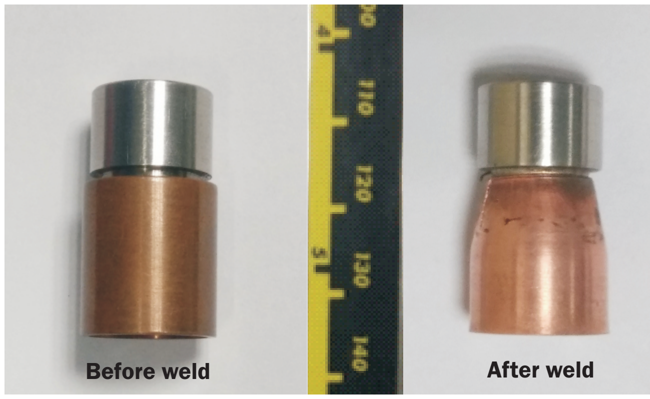


Fig.6: Copper driver & Ti-SS samples.

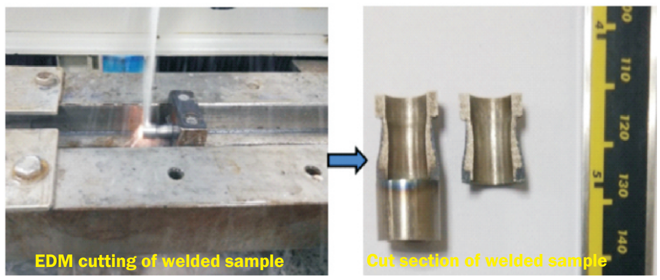


Fig.7: EDM wire cut of welded sample.

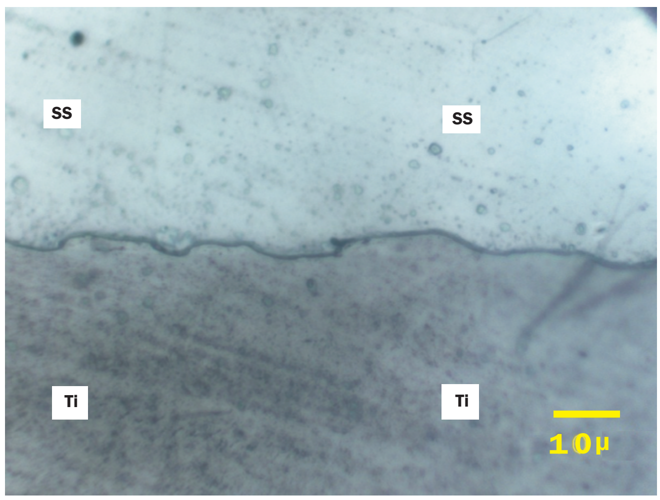


Fig.8: Ti-SS weld interface micrograph at 1000x for impact angle 10^0.

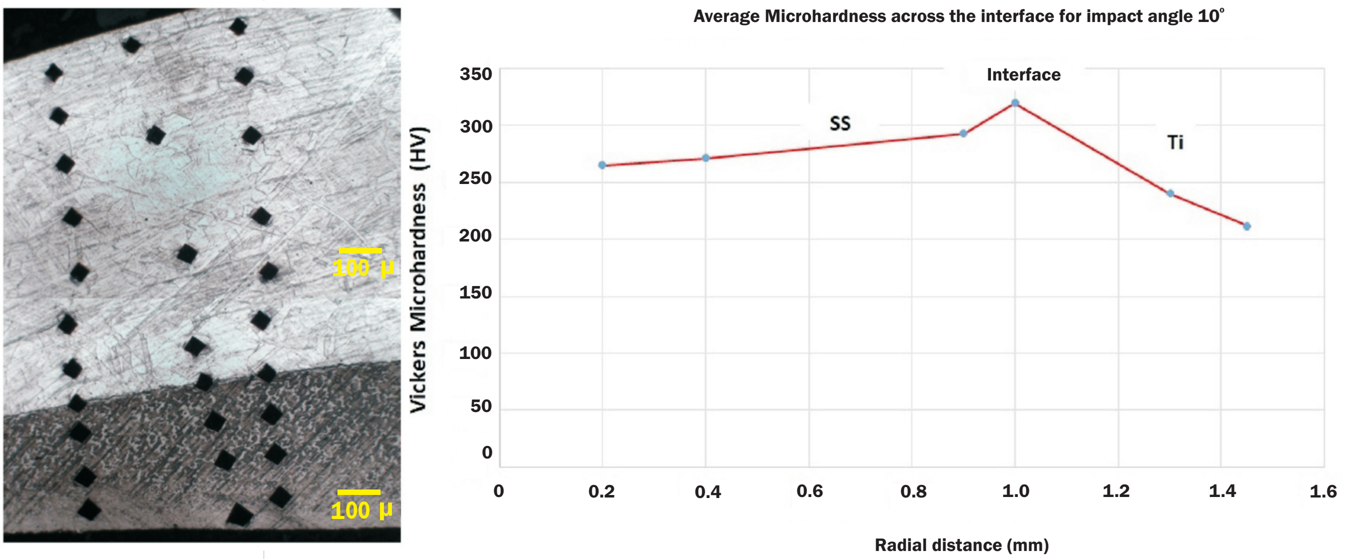


Fig.9: Microhardness indentation and its graphical representation for weld sample with impact angle 10°.

The copper driver from the welded sample, seen in Fig.6 is removed by dissolving in nitric acid. The sample is then checked for Helium leak rate to locate leaks if any using a Mass Spectrometer Leak Detector (MSLD) and a leak rate of the order of 10^{-12} mbarl/s is observed. For metallographic analysis the welded samples are cut along longitudinal section with Electric Discharge Machining (EDM) wire cut, as shown in Fig.7.

The sectionally cut samples are then moulded, polished and etched for studying the micrographs of the weld interface with an optical microscope at magnifications from 50x to 1000x, shown in Fig.8. It is observed that a joining of ~1.2 mm is established out of 6 mm active weld region available for impact, as shown in Fig.4, which corresponds to the numerically simulated impact velocity range of 250-350m/s. The joint established comprises of straight to wavy interface morphology as seen in Fig.8 comprising of few waves with maximum wavelength of ~20μm and amplitude of ~3μm. The reason behind the formation of waves along the interface is explained by the shock wave propagating through metals that generates periodic interferences along the interface giving rise to the Kelvin-Helmholtz instability creating interfacial waves .

Microhardness measurements are done over an array of points along and across the weld interface as shown in Fig.9. It is observed that the Vickers hardness varied from ~166HV to ~230HV at Ti tube, ~290 to ~330HV at the interface and ~156 to ~280HV at SS tube. The hardness values are observed to be relatively increasing towards the interface than Ti or SS side, being maximum at the interface. This represents the high strain rate plastic deformation introduced into the flyer and target tube during the welding process along the joint.

Conclusion

The application of MPW on 13.6mm diameter, 0.5mm thick Ti alloy tube to SS-304 tube has been successfully demonstrated with a tool coil comprising of 4-disc multi-turn coil and shaper assembly. From this study the following conclusions are drawn:

- The helium leak rate obtained in the order of 10^{-12}mbarl/s ensured that the joint established is leak proof.
- The straight to wavy pattern of interface observed is considered as an indication of a successful weld. Variation in interface morphology from straight to wavy observed along the ~1.2mm joint length is correlated to the numerically simulated impact velocity i.e 250-350m/s.
- Variation of micro hardness across the weld interface, in the range of ~290 to ~330HV at the interface, indicates severe plastic deformation accompanying grain refinement on both sides of the joint.

Acknowledgments

The authors would like to express their deep gratitude to the support and encouragement given by A. K. Mohanty, Director BARC and B. Venkataraman, Director, Indira Gandhi Centre for Atomic Research (IGCAR).

References

[1] R. Natarajan and Baldev Raj, Fast Reactor Fuel Reprocessing Technology: Successes and Challenges, Energy Procedia, 2011, **7**, 414–420.

[2] Zhenzhen Yu, Sarah M Gilbert and Stephen Liu, Review of Ti to Steel Dissimilar Joining, Research & Development in Material Science, 2018, **5**(5), 507-509.

[3] J. S. Li , R.N. Raoelison , T. Sapanathan , Y. L. Hou , M. Rachik. Interface evolution during magnetic pulse welding under extremely high strain rate collision: mechanisms, thermomechanical kinetics and consequences, Acta Materialia, 2020, **195**, 404-415.

[4] S. Mishra, S. K. Sharma, S Kumar, K. Sagar and A. Shyam, 40 kJ Magnetic Pulse Welding System for Expansion Welding of Aluminum 6061 tube, Journal of Material Processing Technology, 2017, **240**, 168–175.

[5] Shanthala K, Sreenivasa T N, Choudhary Hitesh, Dond Shantharam, Sharma Archana. Analystical, numerical and experimental study on joining of aluminium tube to dissimilar steel rods by electromagnetic pulse force, 2018, **32**(4), 1725-1732.

[6] S. D. Kore, P. Dhanesh, S. V. Kulkarni, P. P. Date, Numerical Modeling of Electromagnetic Welding, 2010, **32**(1), 1-19.

[7] Makato Miyazaki, Kuniaki Sasaki and Masaki Okada, Influence of gap length on collision angle and collision point velocity of magnetic pressure seam welding, Mater. Sci. Forum, 2014, **767**, 166-170.