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Magnetic Pulse Welding of Two Dissimilar Materials with Various Combinations Adopted in Nuclear Applications

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Abstract

In this paper the joining of two dissimilar metals as Al-SS, Al-Cu and SS-Cu were studied. Commonly, MPW is considered as a non-melting process. Magnetic Pulse machine which is belong to Non-conventional technique instead of conventional technique. Magnetic Pulse Welding (MPW) is a joining process in which lap joint surfaces of cylindrical shape metals, such as pipes and tubes, are welded by impact, using electromagnetic forces. MPW is classified in the group of solid-state bonding processes together with Explosive Welding (EXW). The technique has become an unique and acknowledged welding process because it enables to join similar, as well as dissimilar metals, which is very difficult to weld by traditional methods such as GTAW or EBW due differences in melting points etc. MPW process is very fast, produces no Heat Affected Zone (HAZ) and may be performed without filler metals and protective gases. Nevertheless, it was detected a very thin film (10 to 50 μm) of two welded metals in the form of intermetallic phases, in which melting and solidification processes took place. These inter-metallic phases significantly affect the mechanical properties of the joint. The diffusion of elements in the intermetallic phase was studied for the pattern and the composition of the blended metals and formation of pores etc. The interface typically presents a wavy pattern and mutual diffusion of elements happens in the transition zone. The transition zone is composed of elements intermetallics, micro cracks and micro pores as expected in our study. The effect of the parameters on the morphology, configuration and structure of the interface has been thoroughly studied. The weld interface composition, structure and morphology were studied by optical and Scanning Electron Microscopy (SEM). Energy-Dispersive Spectrometry (EDS) was used in order to evaluate the local distribution of alloying elements at the joint interface and its vicinity and also nano-hardness tests were performed across the bonding zone at regular increments. The results of the joints were analysed for process parameters and based on the result , the process parameters has to be reviewed accordingly to yield best interface weld results.

Keywords: Dissimilar Metals, Interfaces, Inter-Metallic Phases Transfer, Magnetic Pulse Welding, Welding

1. Introduction

The Prototype Fast Breeder Reactor (PFBR) is a 500MWe sodium–cooled fast breeder nuclear reactor presently being constructed by Bharatiya Nabhikiya Vidyut Nigam Limited (BHAVINI) in Kalpakkam, India. The Indira Gandhi Centre for Atomic Research (IGCAR) is responsible for the design of this reactor. The cooling system of the reactor uses liquid sodium and requires additional safety measures to isolate the coolant from environment. The steam generator made of modified 91 steel, is connected to the intermediate heat exchanger, made of AISI 316LN stainless steel with the dissimilar metal weld.

The schematic of the rector system is shown in Figure 1(a) and the steam generator with the dissimilar metal weld in Figure 1(b) currently the dissimilar metal

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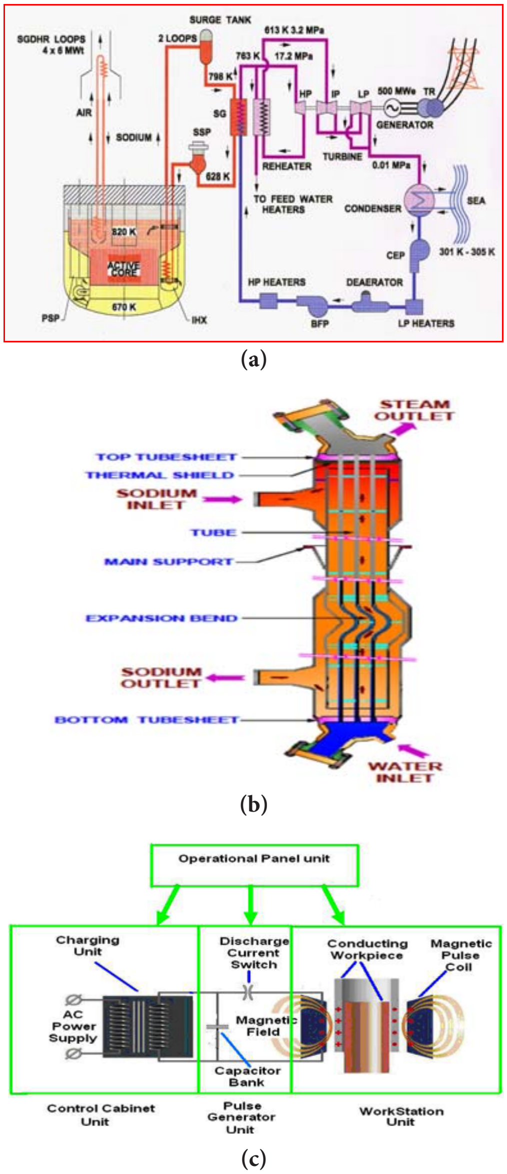


Figure 1. **(a)** Schematic of the rector system. **(b)** The steam generator with dissimilar metal weld. **(c)** Magnetic Pulse Welding Power Supply Set Up with capacitor bank.

weld is a tri-metallic transition joint and uses a multi–pass Tungsten Inert Gas (TIG) welding the complex design of the joint was necessary to minimize thermal stresses. ER16-8-2 is an filler material with 16% Cr 8% Ni and 2% Mo, used for high temperature austenitic stainless steels, alloy 800 is an Inconel alloy with very good creep rupture properties above 600 Inconel 182 is an electrode used in dissimilar metal welds of stainless steel joined to carbon steel experience with dissimilar metal weld joints has shown that a considerable number of failures occurred at a very early stage in service than expected, especially in power plants, an extensive failure analysis was carried out at IGCAR on dissimilar metal welds between 2.25Cr-Mo ferritic steel and AISI type 316 stainless steel with and without Inconel-82 buttering using non–destruction X-Ray Diffraction (XRD) technique and to assess the effectiveness of the buttering on the extent of reduction in the residual stress.

To avoid the complex design, it is proposed the two dissimilar materials by Magnetic Pulse Welding. The Magnetic Pulse Welding (MPW) is solid-state joining process employed for both similar and dissimilar conductive metal combinations viz., aluminum, brass, and copper to steel, titanium, stainless, aluminum, magnesium copper etc. MPW system's architecture consists of a dedicated AC power supply, bank of capacitors, a high-speed switching system and a coil (Figure 1(c)). The parts to be joined are inserted into the coil. The capacitor bank is charged and the high-speed switch is activated. A strong magnetic flux is created around the coil as per the principle of electromagnetic flux generated in a winding excited with an AC power supply. When the current is applied and as a result eddy currents are formed in the parts. The eddy currents oppose the magnetic field in the coil as per Lenz Law of Electromagnetics and an opposing force is generated[1]. This force drives the materials together at a tremendous high rate of speed and creates weld (Figure 2).

When a high magnetic field B is suddenly generated and penetrated into metal, then the eddy currents (current density I pass through them and as a result, an electromagnetic force of F = I × B acts mainly on the base metal and it is accelerated away from the coil and collides rapidly with the target metal. The eddy current I and the magnetic pressure p are given as following:

$$\Delta \times \vec{i} = -k\left(\frac{\partial \vec{B}}{\partial t}\right)$$

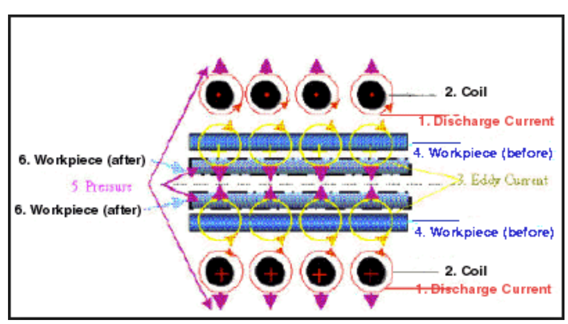


Figure 2. Magnetic Pulse Welding (MPW) principle.

$$p = \frac{\left(B_o^2 - B_i^2\right)}{2\mu} = \left(\frac{B_o^2}{2\mu}\right)(1 - e^{-2x/\delta})n$$

$$\delta = \sqrt{\frac{2}{\omega k \mu}} \text{ and } k \;\; \omega = \frac{1}{\sqrt{LC}}$$

Where K, μ, τ, B_o and B_i are the electrical conductivity, magnetic permeability, thickness, the magnetic flux density at lower and upper surfaces of Al, respectively. The depth of skin effect (δ) can be obtained by calculation of angular frequency (ω) and it is governed by the complete MPW system's inductivity L and its capacity C. The skin depth becomes important parameter especially for thin metal bonding process. When the thickness of the base metal is the same as the skin depth, then magnetic pressure equals 85% of its maximum value and it reaches 97% when the base metal thickness is twice of the skin depth. The appropriate skin depth and higher magnetic pressure can be adjusted by the frequency of the discharge current[2].

At the moment of collision the colliding surfaces can be cleaned by a large kinetic energy getting before the collision. The velocities attained during this process range from 250 m/s to 500 m/s and the joining process completed within microsecond. Because of the short impact period, the extent of heating might be minimal along the joints[3]. Therefore, comparing to the traditional fusion welding process, no significant heat affected zones is produced in MPW joints and it can be noticed as a main advantage.

The practical limitations of MPW relate to handling very high electrical currents. The major limitation of MPW equipment concerns the electrical connections between capacitors, switch, and coil. Very large metal components cannot be formed due to problems in design of very large coils[4]. It is very expensive equipment, just if able only by important mass production[18].

The experimental results and welding characteristics for several samples such as *Al-Al* and *Al-Fe* are reported in the available literatures already. However, Al-SS, Al-Cu and SS-Cu tubular combination which has greater demand in nuclear industries has been less reported with respect to MPW process. Moreover, the metallurgical characterization and non-destructive tests on MPW specimens in the available literatures are scanty. Hence, in this study, an attempt is being made to weld Al-SS, Al-Cu and SS-Cu tubular components using MPW process. Further, mechanical testing and metallurgical characterizations by destructive and non destructive methods are being carried out[8].

2. Experimental Prior and Procedures

The three specimens are employed in this study. However a typical one specimen consists of Cu (Driver) and Al (Flyer). The MPW equipment that is used in this study has a maximum charging energy of 10 kJ, Current of 12 kA and a Voltage of 10 kV. An outer Cu pipe was machined to be 2 mm thick, 80 mm long, and 40 mm in diameter. An inner SS pipe 9 mm thick, 90 mm long, and 36 mm in diameter was employed. For the pipe joint, the gap between the Cu and SS was 1mm. The specimens are ground using emery paper to remove marks sustained during machining. First, the voltage had to be charged according to the welding conditions. Then welding is carried out by electromagnetic force from discharged current through a working coil which develops a repulsive force between the induced currents flowing parallel and in the opposite direction in the tube[14]. Figure 3 shows few typical samples dimensional diagram, specimens after weld and cut cross section and inner weld view respectively.

It may be observed that there is a reduction in diameter in the area of the weld[8]. After welding, the work pieces are cross sectioned and prepared for examination by standard metallographic procedures such as mechanical polishing down to 1-micrometer grit and light chemical etching. The samples were then examined by optical and scanning electron microscopy.

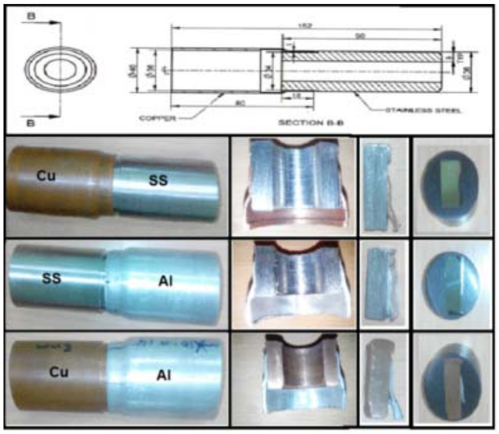


Figure 3. MPW specimen dimensional diagram with cut cross section and inner weld view.

Microanalysis by wavelength dispersive spectroscopy was utilized to evaluate the local distribution of alloying elements at the joint and its vicinity.

3. Results and Discussion

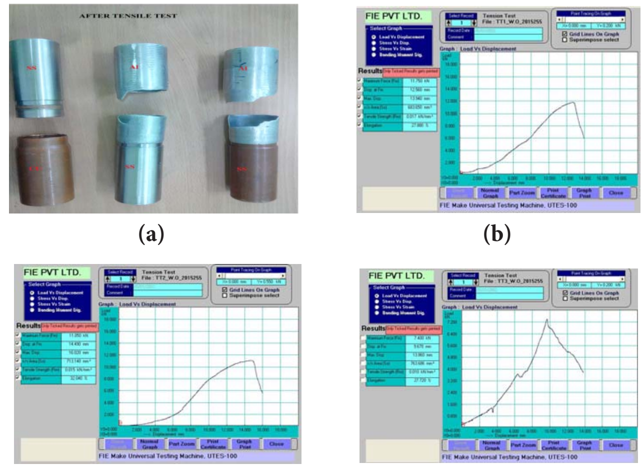
The welded specimens are subjected to destructive and non destructive tests to evaluate its quality and strength. Metallurgical characterizations are performed to analyze the bond integrity and examined for presences of intermetallic phases[5,6].

3.1 Tensile Test

Welded samples are tested on a standard tensile testing machine. In all cases, failure occurred in the region away from the weld area. The tensile results emphasizes that ductile failure of a welded Al-SS, Al-Cu and SS-Cu Rod/Pipe occurs at a distant from the weld. There is no failure on the weld interface[15].

Sl. No.	Specimen Description	Tensile Strength in kN
1	Al - SS	11.750
2	Al - Cu	11.050
3	SS - Cu	07.400*
*During the testing specimen got broken at weld joint		

SS-Cu dissimilar metal configuration having failed in tensility, the improved configuration needs to be analyzed and tested; the base parameters tested with this configuration however has provided viable results, which would supplement further analyzing the same for testing again for tensility. The reports of the same are enumerated in the upcoming paragraphs.



(a) (b) (c) (d)

Figure 4. **(a)** Specimens after Tensile test. **(b)** Al-SS Tensile test graph. **(c)** Al-Cu Tensile test graph. **(d)** SS-Cu Tensile test graph.

3.2 Metallography Test

For all the three welded samples, the optical microscopic examination was done and the results observed were as expected in all the aspects of perfections and integrity. First sample (Al-Cu), that was examined under optical microscope after etching and polishing then the bonding of two materials were verified with magnification ranging from 10X to 100X and observed that there is no imperfections and defects noticed and integrity of both the materials is intact[6,7].

3.3 Radiography Test

Radiography tests are performed for investigating the presence of pore/cluster of pores if any and also to examine the effectiveness of the fused dissimilar joints. X-ray mode with 150KV and 10mA source is used for this study. The exposure time was about 100 seconds and ASME Sec V is the standard being used (No particular standard given in literatures). Figure 5 shows the post radiographic examined samples.

The results of the radiography suggest that the quality is good and free from impurities/pores. Further, it illustrates good fusion in many samples. However, in few more samples, the response appears to indicate lack of fusion. It is important to note the fact that, radiography is not a suitable technique for solid state bonds as the thin line of interlayer's formed at the weldment are not identified generally by x-ray.

3.4 Micro-Structural Analysis

Microstructures of cross sections of the different configurations of dissimilar welds are presented in Figure 6 (a), 6 (b) and 6 (c).

There is a prominent difference in the quality of welding particularly for these configurations, and in general there is no bonding or minimal bonding in the corners and start-end zones, however the center of the welds showed a exemplary bonding or bond integrity. This may be regarded as the important feature or even the very unique feature of this type of welding. The inadequacy in bonding at the corners of the weld zone is a typical feature of MPW cylindrical parts and according to literature is not critical for many applications[11,12]. The minimally bonded

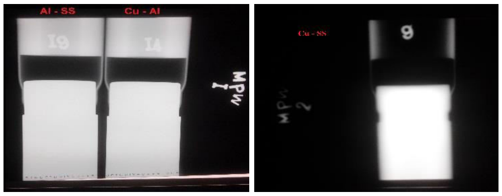
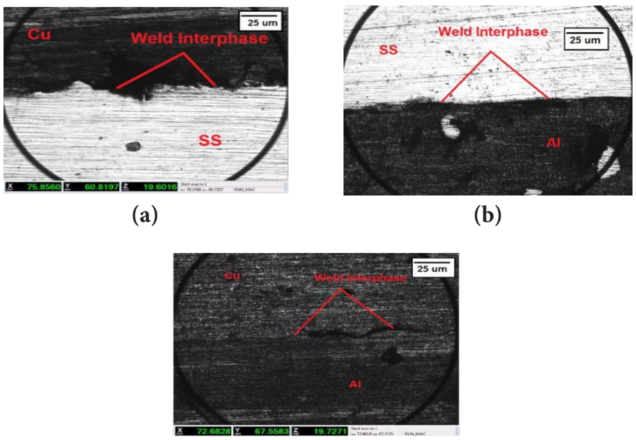


Figure 5. Al/SS, Al/Cu and Cu/SS weldment specimen subjected to radiography.



(a) (b)

(c)

Figure 6. **(a)** Cu-SS specimen viewed under the optic microscope. **(b)** SS-Al specimen viewed under the optic microscope. **(c)** Cu-Al specimen viewed under the optic microscope.

corners of the weld specimen however pose undesirability and less adaptive in corrosive environments and in the case of recurrent cycled loads.

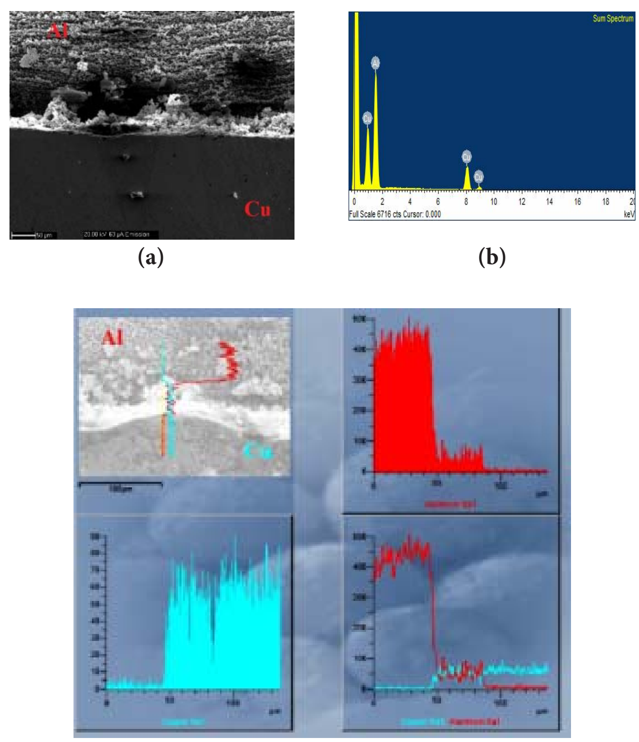
The wave pattern by the side of the interface significantly depends on sample geometry and to a negligible degree on the process parameters. Substantial utility of dissimilar specimen cylinders and relatively low pulse energies inhibited the wave formation. Contrary, applying hollow dissimilar combines' cylinders and high pulse energies pronounced waves are visible, especially in the middle section of the welds (Figure 6(c)). This geometrical influence is in accordance with findings in[11]. It is imperative to note that the wave formation process is not mandatory for a good bonding. It is furthermore worth mentioning that to some extent wave formation could also be observed in regions without bonding. Circumventing the formation of intermetallic phases at the welding interface is impossible. The extent of interface depends on the process parameters and is fairly connected with the structure of the interface.

If the interface shows a wavy appearance, the intermetallics mainly concentrate in so called "melt pockets", which are mostly located at the crests of the waves (Figure 6(a)). If EMP produces a wave less interface, the intermetallic phases form a film of varying thickness (Figure 6(b)). It is pointed out that the phase film appears to be interrupted by regions without any intermetallics. For a thickness below 5 microns the intermetallics contain rarely any cracks, voids or pores.

3.5 Scanning Electron Microscopy (SEM) With Energy Dispersive Spectroscopy (EDS)

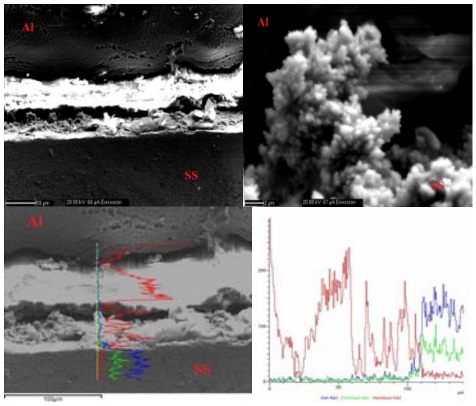
The SEM investigations present more information on bonding and phase formations. The SEM of the Al-Cu welded specimen is shown in Figure 7(a). It may be noted that the dearth of any diffusion layers leads to the postulation that local melting is mainly involved in the phase formation and bonding process along the interface.

As for low pulse energies the intermetallic phases consist primarily of aluminum, it is deduced that solely aluminum but not copper was molten during low energy MPW. Al-rich phases are formed under strong non equilibrium conditions. From the sharp and stepwise transition in chemical composition between the two parent metals

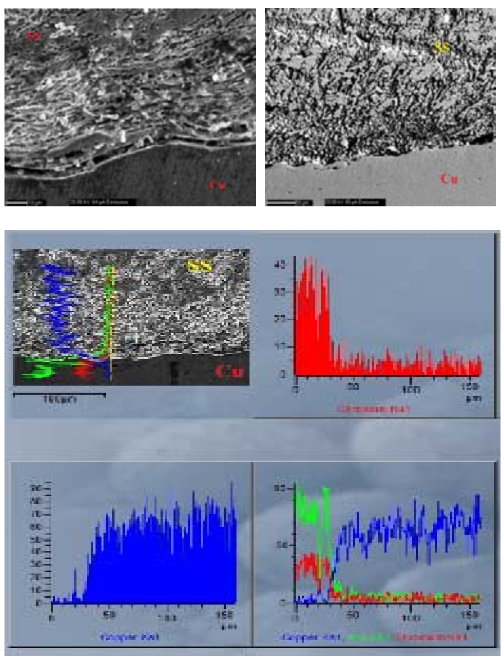


(a) (b)

(c)



(d)



(e)

Figure 7. **(a)** SEM of the Al-Cu welded specimen. **(b)** Sum spectra view of proportionate quantity of metals in the welded portion. **(c)** Graphical analysis of dissimilar metals in intermetallic phase region. **(d)** Wavy pattern and line scanning of Al vs SS. **(e)** SEM and EDS analysis of SS vs Cu.

and the formed intermetallic phases it is in accordance with Carpenter and Wittman[13] who deduced that solid state diffusion is not involved as active bonding mechanism in the process of MPW aluminum to copper.

The Sum spectra of the welded specimen clearly illustrates the % composition of Copper and Aluminium in the weld joints shown in Figure 7(b). The proportionate quantity of Aluminium is remarkably more in the left hand side of the intermetallic region and copper dominates to the right of the curve, the AL-Cu in equal proportion is prevalent at the intermetallic region shown in Figure 7(c). The mixing of the dissimilar metals at the welded joint for the 30um to 40um width of the specimen shows the perfection of the mixing of dissimilar metals.

Al vs SS shows a moderate to low mixing of metals at the weld joint as shown in Figure 7(d). The wavy pattern of bonded area as the unique quality of MPW is clearly depicted in Figure 7(d) and similar studies has been already taken[12,13,16,17].

The bonding of the SS vs Al at the welded joint for the 10um to 20um width of the specimen shows the little or moderate bonding in compared to Cu Vs SS.

The bonding of SS-Cu found to be imperfect, due to the applied energy being inadequate for this configuration, however bonding in the range 5um-10um is observed and to make the bonding even more efficient and in line with others, the improvement and further study is required. The bonding was prevalent throughout the specimen however concentrated in the narrow region, which is inadequate for the tensility point of view. The bonded zone is analyzed with SEM methodology and the same can be viewed in Figure 7(e).

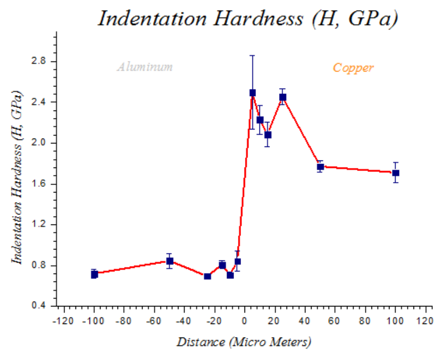
The later studies of MPW would be in this area to further the equally distributed bonding of this SS-CU specimens at the lower KeV as applied for the other samples.

Owing to short bonding time and the finite rates of solid-state phase transformations, there is prospectus that a thin layer on the low-melting point material fused and alloyed with the more refractory metal. Rapid melting and solidification explain the formation of intermetallic phases.

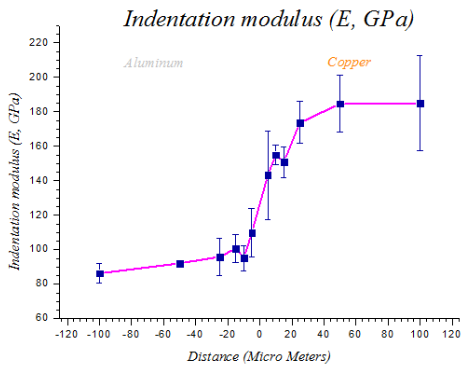
3.6 Nano Indentation

For MPW joint at the discharge voltage of 10kV, the nano indentation test was carried out to measure the micro hardness across the transition zone by using Nano Indeniter XP equipment. Five points near the interfaces on both basic metals and one point on the transition zone were chosen for the test.

The magnitude and the distribution of the micro hardness are given in Figure 8 (a) and (b). It is illustrated that the hardness value in the transition zone is the highest and the values decrease with increasing the distance away from the zone or the interface. It can be attributable to the sharp plastic deformation along the interfaces that causes the gradient of work hardening near the interface.



(a)



(b)

Figure 8. **(a)** Indentation hardness of Al/Cu. **(b)** Indentation modulus of Al/Cu.

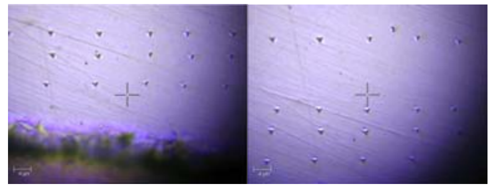
Both the plastic deformation and the hardness reduce with increasing the distance from the interfaces. In addition, the intermediate compounds might be produced in the transition zone that is fragile and has higher hardness than the basic metals[16], which will be analyzed deeply.

Similarly in combination of SS/Cu also the intermediate compounds produced in the transition zone that is fragile and has higher hardness than the basic metals which is shown Figure 9 (a), (b) and (c).

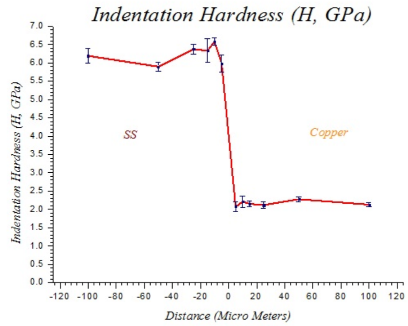
Similarly in combination of Al/SS also the intermediate compounds produced in the transition zone that is fragile and has higher hardness than the basic metals which is shown Figure 10 (a), (b) and (c).

4. Reliability Analysis

The Magnetic Pulse Welding (MPW) is one of the reliable methods that can be used for the dissimilar metal joints. The Magnetic Pulse Welding (MPW) provides an excellent tool for achieving of conductive metals such as aluminum, brass, or copper to steel, titanium, stainless, aluminum, magnesium copper and most other metals joints[19]. The



(a)



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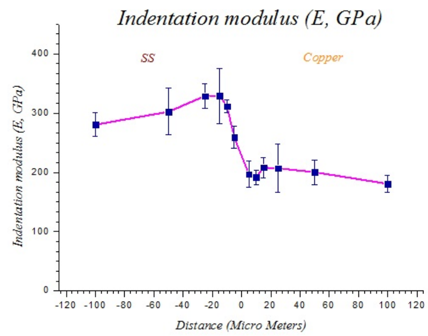
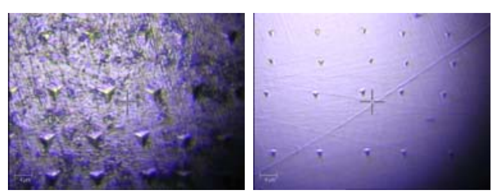
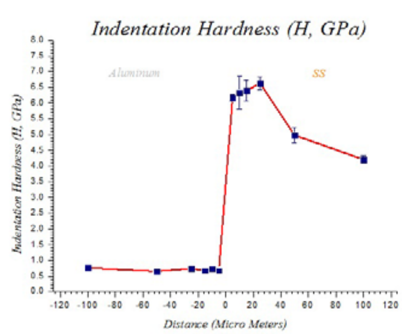


(c)

Figure 9. **(a)** Indentation in SS Side start from interface. **(b)** Indentation Hardness of SS/Cu. **(c)** Indentation Modulus of SS/Cu.



(a)



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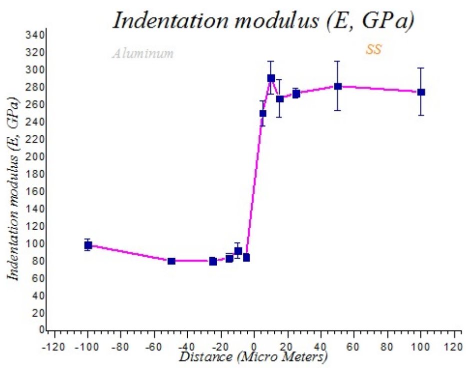

(c)

Figure 10. **(a)** Indentation in Al/SS side start from interface. **(b)** Indentation hardness of Al/SS. **(c)** Indentation modulus of Al/SS.

structure of an interphase region was investigated using a microscope and scanning microscope, Chemical composition was determined by a spectroscope. The Magnetic Pulse Welding (MPW) is reliable and well suited to high-volume production (MTBF typically 1–5 million welds)[20].

5. Conclusion

Magnetic Pulse Welding of three dissimilar configurations of metals is performed and a detailed comparative study between the specimens is done. Specific Observations include the dissimilar metals generates enough heat at the interface to enhance plenty of mass transfer for the precipitation of intermetallic phases. However, the relative amounts of these phases remained small compared to fusion welding processes because the observed transition region is narrow and discontinuous. The type and chemical composition of the created intermetallics depend on the pulse parameters chosen. This behavior is endorsed to different temperature-time system of the process leading to varying amounts of melting of the two base materials. To impound detrimental effects on the mechanical properties of the joints the thickness of the formed intermetallics should not exceed few microns.

Hardness of the welded specimen at the joint region is observed to be the maximum in compared to the either side of transition zones having dissimilar metals. The Magnetic Pulse Welding (MPW) is reliable and well suited to high-volume production. The bonding of dissimilar metals at the interphase region is appreciably high. Above a critical thickness the intermetallics are prone to cracking and spallation. The Cu-SS requires further study in the betterment of bonding.

6. Acknowledgements

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