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Research Paper

FINITE ELEMENT MODELING AND THERMO-MECHANICAL ANALYSIS OF FRICTION STIR WELDED Al/Cu BIMETALLIC LAP JOINTS

M Satya Narayana Gupta[1]*, B Balunaik[2] and K G K Murti[3]

*Corresponding Author: ***M Satya Narayana Gupta,*** ✉ msngupta.m@gmail.com

Friction stir welding is an emerging solid state welding method which is finding increasingly widespread industrial acceptance for joining similar and dissimilar materials. Aluminium to Copper bimetallic lap joints have got wide acceptance in the electrical and electronic industries. A three dimensional finite element model has been developed to study the thermo-mechanical history of the Al/Cu bimetallic lap joints. In this investigation, moving co-ordinate has been used to model the three dimensional heat transfer process because it reduce the difficulty of modeling the moving tool. Micro-hardness analysis has been carried out on friction stir welded joints.

Keywords: Al/Cu bimetallic lap joints, Friction stir welding, Finite element method, Thermo-mechanical analysis, Micro-hardness

INTRODUCTION

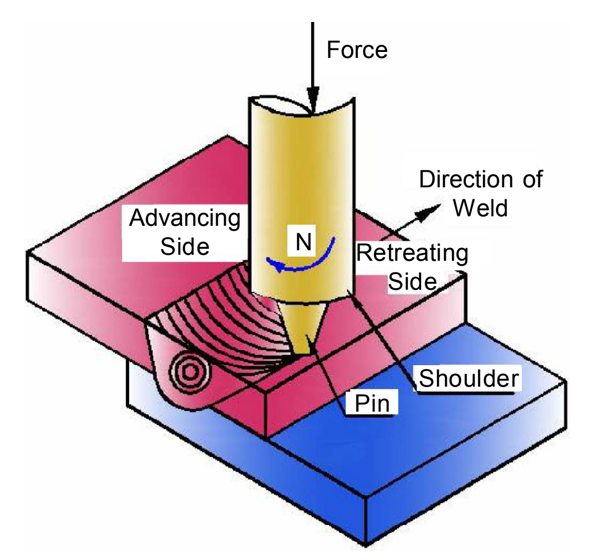
With the rapidly increasing price of copper, electrical equipment manufacturers are going for more and more usage of aluminium in place of copper such as in busbars, heat sinks, panel boards, etc. Various factors affect the choice of conductor material for high current bus system. Generally, aluminium is chosen for one portion of the system and copper for another. Where two conductors meet, a transition must be made. Originally, this transition was made with bolted joints (William, 1980; and William, 1997). Due to the difficulty in making electrically stable long-term bolted joints between these two dissimilar metals, much effort has been focused on transitions made using welded copper to aluminium materials.

Attempting to weld aluminum to copper by conventional means through the application of thermal energy to melt and fuse the two metals can result in an unreliable weld. The oxide layer on aluminium is difficult to remove, the melt

[1] Department of Mechanical Engineering, Aurora's Engineering College, Bhuvangiri, Andhra Pradesh, India 508116.
[2] Department of Mechanical Engineering, GRIET, Bachupally, Hyderabad, Andhra Pradesh, India 500072.
[3] Department of Mechanical Engineering, JNTU, Hyderabad, Andhra Pradesh, India 500072.

temperatures of the two metals are not close, the two metals exhibit high thermal conductivity and alloying of the two metals creates a brittle inter-metallic (Bekir and Ahmet, 1995; and Behcet, 2008) that is mechanically and electrically unreliable. The common technique to accomplish this metallic bond has been to plate aluminum with another metal that facilitates soldering. This practice involves many steps, is environmentally unfriendly and is used for only small joints. An alternative for design engineers is to weld copper to aluminium using friction stir welding. FSW is an innovative solid state joining process in which the material that is being welded does not melt and recast (Mishra and Ma, 2005; and Fratini *et al.*, 2007). The welding process in this case requires that the parts to be joined are kept in position firmly. A non-consumable rotating tool with a specially designed shoulder and pin is plunged completely into the overlap surfaces until the shoulder touches surface of the joint and traverses along the line of seam as shown in Figure 1.

Figure1: Outline of the Single Lap Joint



FSW process offers several advantages over traditional liquid-state welding techniques such as no problems of solidification cracks and porosity right after bonding because of the low input of total heat. These characteristics are valuable especially in the joining of low melting point materials that are difficult to weld using classical fusion welding techniques due to the decrease in strength after welding. Moreover, compared to other solid state joining techniques, the FSW is more flexible in joining components rather large or complex in shape. Friction stir welding creates a high quality weld both mechanically and electrically without intermediate steps.

Thermo-mechanical analysis of Aluminium and its alloys has been the subject of various research works produced over a period of time (Buffa *et al.*, 2006 and 2008; and Hamilton *et al.*, 2009). No research activities have been developed on thermo-mechanical analysis of friction stir welded Al/Cu bimetallic joints so far as known by the authors. The present study focuses on the thermo-mechanical analysis of friction stir welded Al/Cu bimetallic lap joints. Finite Element Analysis (FEA) has been used for thermal analysis to evaluate the temperature distribution and thermal stresses resulting from uneven heating or rapid temperature changes using commercial package ANSYS.

EXPERIMENTAL WORK

The materials used in this study are aluminum and copper rolled plates each with thickness of 3 mm. The rolled plates have been cut into the required size (150 mm × 100 mm) by shear cutting and milling. Lap joint configuration (150 mm × 170 mm) has been prepared to fabricate FSW joints. The chemical composition and mechanical properties of base metals are given in Tables 1a and 1b. The initial lap joint configuration is obtained by securing the plates in position using a mechanical fixture. Figure 2 shows the schematic representation of the relative position of aluminum and copper plates for FSW lap joint. Single pass welding procedure is used to fabricate the joints. A non-consumable rotating tool made of oil quenched and tempered high speed steel (M2) with hardness Rc62 is used. The tool has a shoulder of 15 mm diameter with a taper pin of 5 mm and 3.5 mm diameters and 5.7 mm long as shown in Figure 3. The experiments have been conducted on a

Table 1a: Chemical Compositions of Base Materials (Wt %)

Base Metal	Chemical Compositions (Weight %)								
Pure Aluminium	Al	Si	Mn	Cr	Ti	Cu	Zn	Mg	Fe
	99.64	0.18	0.04	0.001	0.002	0.012	0.001	0.001	0.1
Pure Cupper	Cu	Ag	Sn	Sb	Pb	As	Zn	Bi	Fe
	99.98	0.002	0.001	0.001	0.001	0.002	0.002	0.001	0.002

Table 1b: Mechanical Properties of Base Materials

Base Metal	Mechanical Properties		
	Y.S (MPa)	T.S (MPa)	% Elong
Pure Aluminium	95	119	16.7

Figure 2: Schematic Representation of the Relative Position of Aluminium and Copper

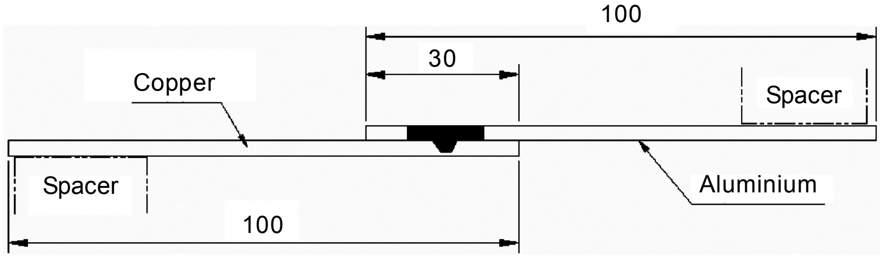


Figure 3: Specially Designed Rotating Tool

friction stir welding machine. The machine has a provision for stepless adjustment of rotational speed, welding speed, tilting angle, plunging feed rate and frictional time.

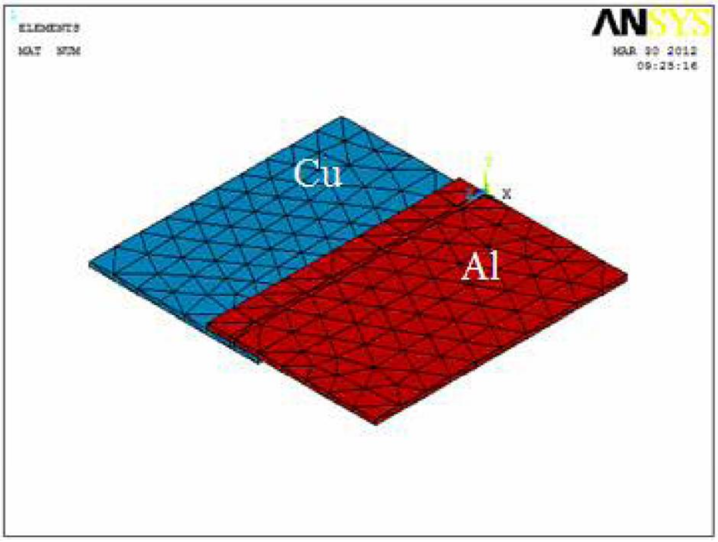
Friction stir welding has been performed at a rotational speed of 1500 rpm, weld speed of 30 mm/min, tool tilting angle of 30 and plunging depth of 5.9 mm. At these values of welding parameters, an adequate welding quality was obtained. Micro-hardness and micro-structural analysis has been carried out on friction stir welded joints fabricated at optimum conditions.

NUMERICAL ANALYSIS

The commercial finite element software ANSYS 12 has been used to model the friction stir welding processes in current research. The SOLID70 element has been used in this analysis because it has a three-dimensional thermal conduction capability and can be used for a steady state or transient thermal analysis and movable heat flux. This element can be replaced by equivalent structural element for the structural analysis. Calculated heat flux has been applied as a surface loads at the element faces. A three dimensional thermal-surface-effect element has been used because heat flux and convection cannot be applied on SOLID70 at the same time. SHELL57 has been used to overlaying onto faces of the base elements made by SOLID70.

Three dimensional SOLID70 elements have been used to mesh the sheets. The mesh was comprised of a total number of 700 elements and 380 nodes. The model has been executed for weld conditions with heat fluxes. The geometry and the boundary conditions of the developed model of friction stir welding are shown in Figure 4.

Figure 4: Finite Element Mesh of Friction Stir Welded Al/Cu Lap Joint



The temperatures obtained in thermal analysis have been applied as element body loads at the nodes in structural analysis. An identical mesh pattern generated for thermal analysis is used in the structural analysis.

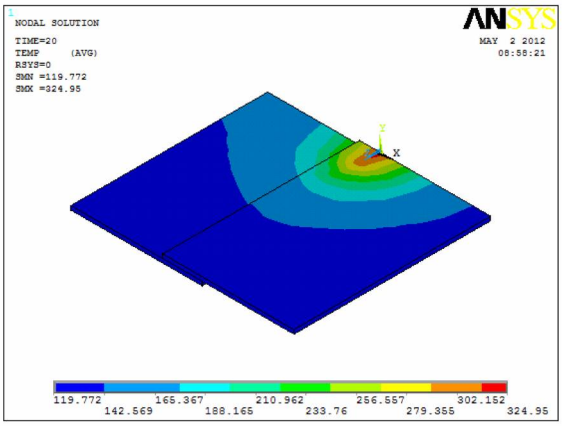
Joining of the plates is achieved through the combined action of friction heating generated at the plate and tool shoulder interface and forging effect created by movement of the pin between two tightly clamped plates.

RESULTS AND DISCUSSIONS

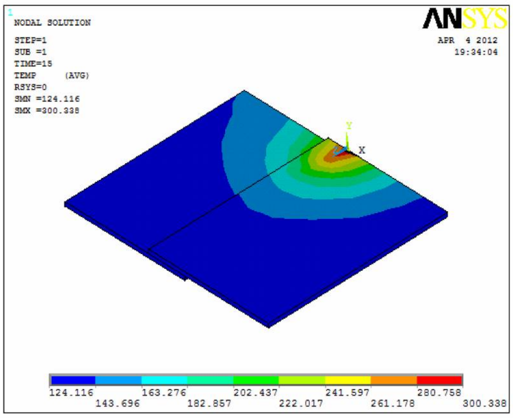
Temperature Distribution

The thermal model developed using ANSYS has been used to find the maximum welding temperatures and temperature profiles of Al and Cu plates. Figure 5 shows the temperature distribution in work pieces at various elapsed times during the simulation. The maximum temperatures has been observed at underneath of the tool shoulder and has the value between 300 °C to 400 °C. This range is lower than the melting temperature of the base metals. From the analysis results, the temperature values are increased with respect to increase in time duration along the weld axis. The maximum temperature increased from 300 °C to 350 °C as time increases from 15 sec to 30 sec.

Figure 5: Temperature Profiles of the FSW Al/Cu Bimetallic Lap Joints at Four Subsequent Times



Time = 15 sec



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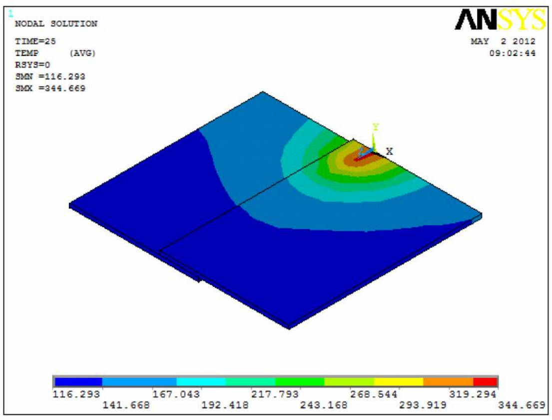

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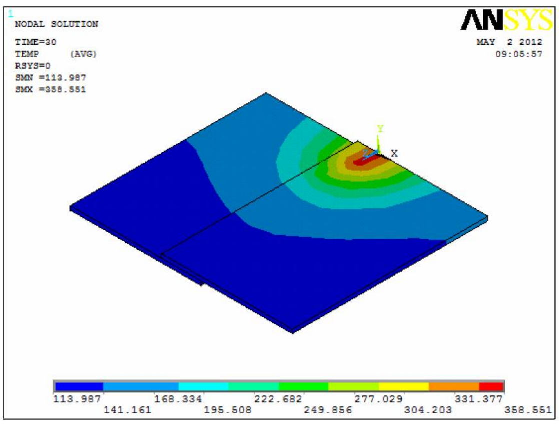
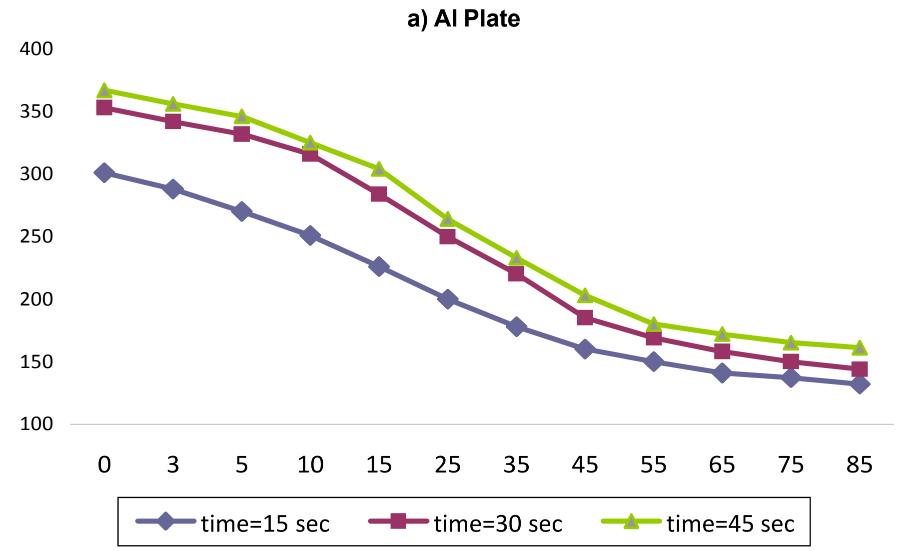
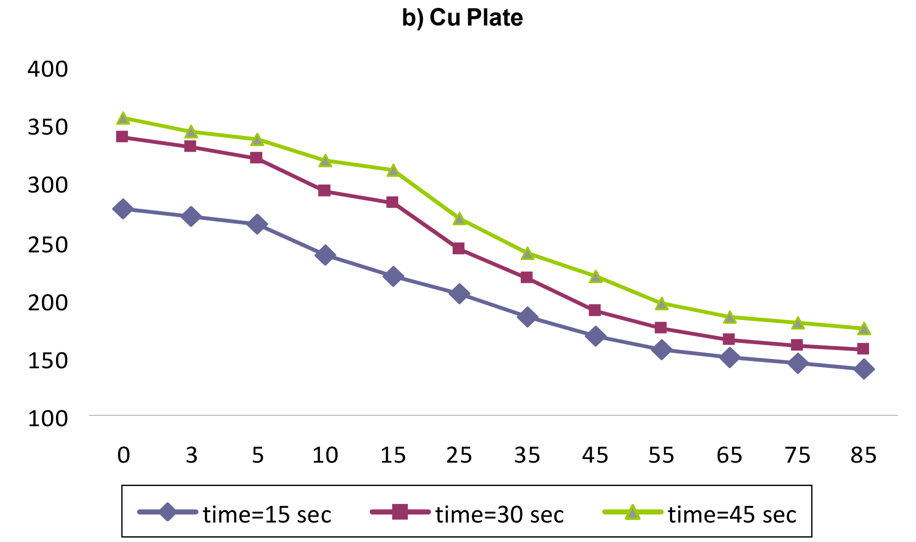


Time = 30 sec

The temperature profiles from the weld center line to the edges of the Al and Cu plates on the top surface of friction stir weld configuration is shown in the Figure 6. The weld zone temperatures are in the range of 300 to 400 °C. This indicates the plasticity and effectiveness of the stirring. The temperatures are increased as time duration increases. The temperature gradient is more near the weld centerline compare to the edges of the plates.

Figure 6: Temperature Profiles

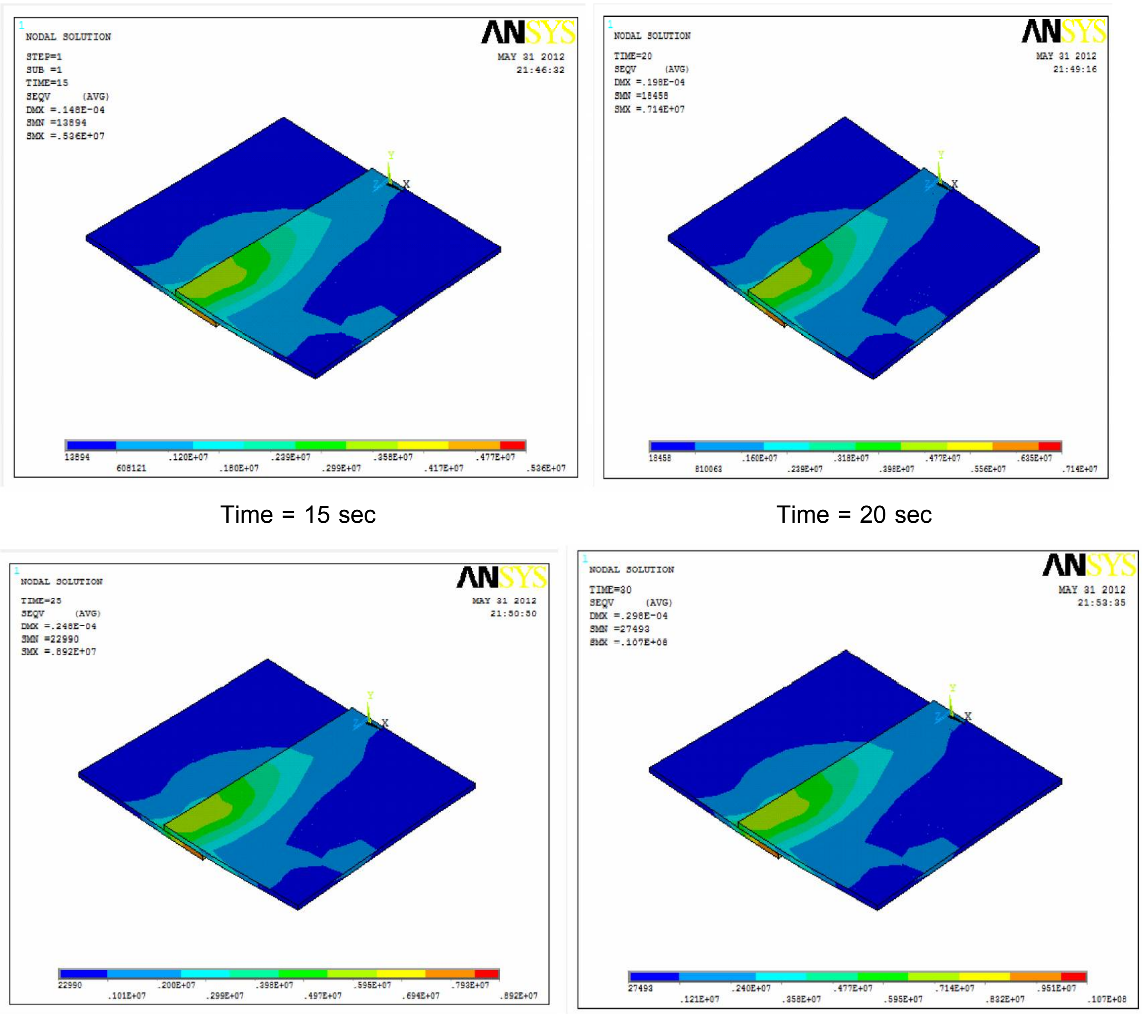




Thermal Stresses

The temperature values obtained from the thermal model has been used as input for the mechanical simulation for predicting thermal stresses. Figure 7 shows the stress distribution in work pieces at various elapsed times during the simulation. From the analysis results, the stress values are increased with respect to increase in time duration along the weld axis. The maximum stress increased

Figure 7: Stress Distribution in the FSW Al/Cu Bimetallic Lap Joints at Four Subsequent Times



Time = 15 sec Time = 20 sec

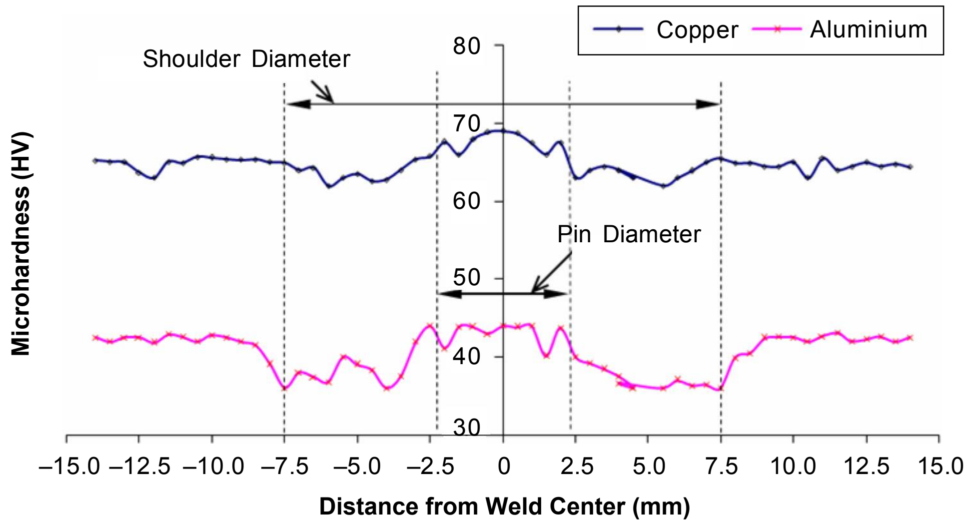
Time = 15 sec Time = 20 sec

from 5.36 MPa to 10 MPa as time increases from 15 sec to 30 sec. These stress values are far less than the yield strength of the base metals.

Micro-Hardness

The results from the hardness measurements are shown in Figure 8. The vertical line represents the position of the tool pin during welding. The hardness varied between 36 and 44 HV and between 62 to 69 HV for Aluminium and copper plates respectively. The minimum hardness in Aluminium and copper was found in the Hheat Affected Zone (HAZ) of both the advancing and retreating side. The hardness of the nugget was higher than that of HAZ and the base metal. This may be attributed to the formation of brittle and hard intermetallic compound (Won-Bae *et al.*, 2005) and very fine recrystallized grains in the nugget zone and grain growth in HAZ (Abdollah-Zadeh *et al.*, 2008).

Figure 8: Micro-Hardness Distribution



CONCLUSION

The thermo-mechanical model of the friction stir welded Al/Cu bimetallic joints has been developed to know the temperature and stress distribution in base metals. The maximum temperature is in the range of the 300 °C to 400 °C and it is below the melting point of the base metal. The maximum stress is 10 MPa and it is far less than the yield strength of the base metals. The minimum hardness in Al and Cu was found in the Heat Affected Zone (HAZ) of both the advancing and retreating side.

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