

Friction Stir Welding of Dissimilar Materials: Influence on Mechanical and Thermal Performance

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ABSTRACT

Friction stir welding (FSW) is a relatively new, state-of the-art solid state joining process. This metal joining technique is derived from the conventional friction welding. In a typical FSW, a rotating cylindrical pin tool is forced to plunge into the plates to be welded (i.e. work piece) and moved along their contact line. During this operation, frictional heat that is generated by contact friction between the tool and work piece softens the material. The plasticized material is stirred by the tool and forced to “flow” to the side and the back of the tool as the tool advances. As the temperature cools down, a solid continuous joint between the two plates is then formed. Because the highest temperature in the FSW process is lower than the melting temperature of the work piece material, FSW yields fine microstructures, absence of cracking, low residual distortion and no loss of alloying elements that are the main advantages of this solid phase process. Nevertheless, as in the traditional fusion welds, a softened heat affected zone and a tensile residual stress parallel to the weld also exist. In this context we have applied this technique to weld Al-Al, Cu-Cu and Al-Cu couples. We studied the effect of experimental parameters like rotational and transverse speed on welding of above metals and consequent microstructure at interface and mechanical properties especially hardness and tensile strength. We obtained intact interface and high mechanical strength for all three couples at the rotational speed ranges from 600-1000 rpm and transverse speed from 40-80 mm/min.

KEYWORDS:Friction stir welding, solid state joining, cylindrical pin tool, plasticized material, melting temperature, hardness and tensile strength

I. INTRODUCTION

Welding is a fabrication process to make high strength joint between two or more parts by heating to their melting temperature, with or without the application of pressure and with or without the use of filler metal. The filler metal has a melting point approximately same as the base metal. The welding process is used to metallurgical join together two metal pieces, to produce essentially a single piece of metal. The process results a ‘Permanent joint’. A good welded joint is as strong as the parent metal. The product is known as ‘Weldment’.

Friction stir welding (FSW) is a solid-state joining process that uses a non-consumable tool to join two facing workpieces without melting the workpiece material. Heat is generated by friction between the rotating tool and the workpiece material, which leads to a softened region near the FSW tool. While the tool is traversed along the joint line, it mechanically intermixes the two pieces of metal, and forges the hot and softened metal by the mechanical pressure, which is applied by the tool, much like joining clay. Friction stir welding (FSW) was invented at The Welding Institute (TWI) of UK in 1991 as a solid-state joining technique, and it was initially applied to aluminum alloys. The basic concept of FSW is remarkably simple. A non-consumable rotating tool with a specially designed pin and shoulder is inserted into the abutting edges of sheets or plates to be joined and traversed along the line of joint . The tool serves two primary functions: (a) heating of work piece, and (b) movement of material to produce the joint. The heating is accomplished by friction between the tool and the work piece and plastic deformation of work piece. The localized heating softens the material around the pin and combination of tool rotation and translation leads to movement of material from the front of the pin to the back of the pin.

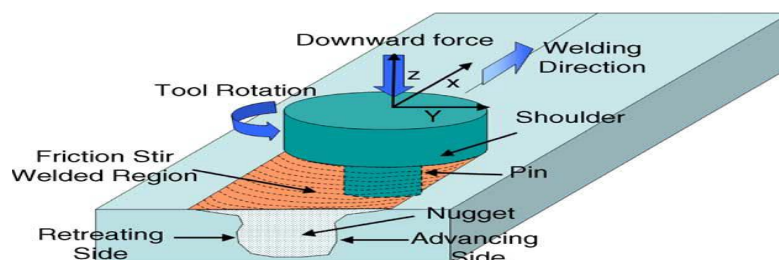


Fig.1 Friction stirr welding[7]

As a result of this process a joint is produced in ‘solid state’. Because of various geometrical features of the tool, the material movement around the pin can be quite complex. During FSW process, the material undergoes intense plastic deformation at elevated temperature, resulting in generation of fine and equiaxed recrystallized grains. The fine microstructure in friction stir welds produces good mechanical properties. FSW is considered to be the most significant development in metal joining in a decade and is a “green” technology due to its energy efficiency, environment friendliness, and versatility. As compared to the conventional welding methods, FSW consumes considerably less energy. No cover gas or flux is used, thereby making the process environmentally friendly. The joining does not involve any use of filler metal and therefore any aluminum alloy can be joined without concern for the compatibility of composition, which is an issue in fusion welding. When desirable, dissimilar aluminum alloys and composites can be joined with equal ease. In contrast to the traditional friction welding, which is usually performed on small axis symmetric parts that can be rotated and pushed against each other to form a joint, friction stir welding can be applied to various types of joints like butt joints, lap joints, T butt joints, and fillet joint. In this case, a rotating tool is inserted in a monolithic work piece for localized micro structural modification for specific property enhancement. For example, high-strain rate super plasticity was obtained in commercial 7075Al alloy by FSP. Furthermore, FSP technique has been used to produce surface composite on aluminum substrate, homogenization of powder metallurgy aluminum alloy, micro structural modification of metal matrix composites and property enhancement in cast aluminum alloys. FSW is emerging as a very effective solid-state joining/processing technique. In a relatively short duration after invention, quite a few successful applications of FSW have been demonstrated.

1.1 Objectives

The main objective of this project is to join two dissimilar materials with the help of Friction Stir Welding, find out relation between speed and feed of the tool with the different mechanical properties of the weld joint; i.e. to study Strength, Hardness and microstructure.

Factors considered are given as follows:

Tensile Strength–Materials are tested across the weld zone to determine the tensile strength at different points and compare them to the base materials.

Hardness–Materials are tested across the weld zone to determine the hardness at different points and compare them to the base materials.

Microstructure – Microstructure of the weld joint gives the clear idea about the bonding of two different materials.

II. METHODOLOGY

The two dissimilar materials required for joining with the help of welding process are selected. After selection FSW process carry out and join two dissimilar materials with butt weld joint. The desired model is shown in fig.3

For measurement of Tensile strength, Hardness and microstructure of weld joint instruments can be used. Figure 2 presents a schematic view of FSW. A specially designed cylindrical tool, made from a hard and wear-resistant material relative to the material being welded, with a profiled pin is rotated and plunged into the abutting edges of the plates to be joined. The height of the pin will be just short of the thickness of plates to be welded so that during the plunging, the shoulder of the tool comes in contact with the plate surface before the pin penetrates through the plates. The plates have to be clamped onto a backing bar in a manner that prevents the abutting joint faces from being forced apart. After entry of the profiled pin to almost the thickness of the material and to allow the tool shoulder to just penetrate into the plate, the rotating tool will translate along the joint line. Frictional heat generated between the wear-resistant welding tool and the material of the plates causes the latter to soften without reaching the melting point and allows traversing of the tool along the weld line. The plasticized material is transferred from the leading edge of the tool to the trailing edge of the tool, where it cools and consolidates to produce a high-integrity weld in the solid phase. Thus, the process involves relatively high temperatures and very high strain rates. The plasticized material will get forged by the intimate contact with the tool shoulder and the pin profile during this process. The process includes advantages like high-strength welds, low distortion, no need for filler material, no need of post weld treatments, and immunity towards defects and property deterioration associated with the solidification process in fusion welding. These advantages are attributed to the fact that the FSW process takes place in the solid phase below the melting point of the materials to be joined. Other advantages include a highly repeatable weld process with low defect rates and reduced safety concerns due to the elimination of weld fumes.

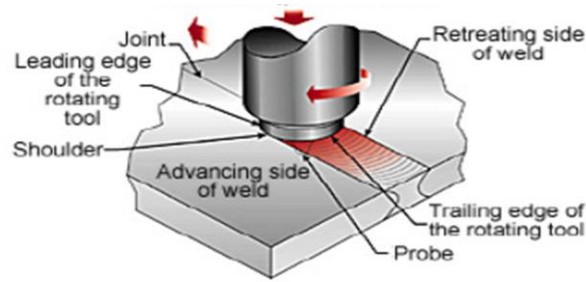


Fig 2. Methodology[2]

To calculate the properties like Tensile Strength, Hardness by using Universal Testing M/C, Brinell hardness test apparatus and microstructure on Field Emission Gun Scanning Electron Microscope are used.

2.1 FSW Process Setup

The self-reacting FSW process eliminates or minimizes some of the disadvantages by providing a bottom shoulder in place of an anvil. These improvements include the reduction of process loads and an increase in welding speed. The weld head uses two shoulders that interface with the top and bottom surfaces of the work pieces being joined. These top and bottom shoulders are independently actuated and biased to follow the profile of a work piece and supply a balanced load to the opposed surfaces of the work piece during the welding operation.



Fig.3. Experimental set up of FSW in BARC

G—types of two dimensional gantry B—Maximum thickness of welding i.e. on Aluminium alloy is 16mm 1107—The size and route of platform (X: 1100mm, Y: 700mm). Preliminary visual inspections and microscopic observations of the joint section showed the presence of internal defects, such as tunnel defect and kissing bonds at rotating speeds lower than 600 rpm, significantly reducing the process window. Tool Used for experimentation— Cylindrical threaded tool steel and Dimensions –Tool diameter 20mm, Tool pin diameter – 6 mm, Tool pin length – 4.5 mm, Tool downward speed – 2mm/min and Dwell – 30 sec.

2.2 Testing and Experiment

Different working conditions are considered for finding out actual behaviour of hardness and tensile strength. One can predict the behaviour of the hardness and tensile strength for the mentioned factors. But when the factors are varied over a certain range, the behaviour may change accordingly. This will help to consider the effect of the defects on system response practically. Criteria used for selection of factors used have been explained in the following subsection.

2.3 Selection of parameters

The most important stage during the experimentation is to select the critical parameters affecting the performance welded joints. In performance of friction stir welding several parameters are involved in its configuration such as rotational speed and feed of the tool, tool depth, tilt angle of the tool. These parameters are contributing in the performance of friction stir welding among which some parameters are critical whose effect on performance of

friction stir welding cannot be predicted directly such as speed and feed. Hence in order to improve performance of friction stir welding the effect of these parameters on the weld joint needs to be evaluated. The parameters are selected in this study are speed and feed. The parameters and their levels are listed in Table.

Level/ Factors	Speed (rpm)	Feed (mm/sec)
1	400	20
2	600	40
3	800	60
4	1000	80
5	1200	100

Table.1 Parameters and their levels

2.4 Experimental Setup

Joining LM6 aluminium and commercial copper alloys by FSW has been a great interest for research now days. The welds were made with a cylindrical pin tool on FSW machines. The experimental setup for this work piece is shown in Fig.4. The quality of weld produced by FSW process is decided by parameters like rotational speed of the welding tool, transverse speed, welding tool material properties, tilt angle of the tool, etc. The work piece materials are LM6 aluminium alloy and commercial copper alloy whose chemical compositions listed in Table 1. A cylindrical pin tool made of H13 steel is used for FSW.

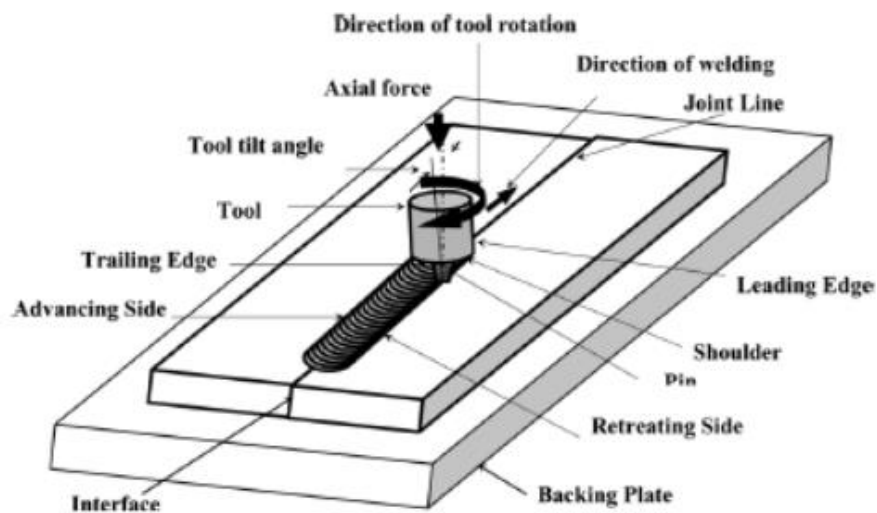


Fig.4 Experimental setup and process parameter of FSW[]

III. RESULT ANALYSIS

Microstructural development

The microstructures for Al-Cu couple obtained at rotational speed of 800 rpm and transverse feed of 60 mm/min were observed under FEG SEM (Field Emission Gun Scanning Electron Microscope). It can be clearly seen from the micrographs obtained at different magnifications with these parameters that the interface produced is intact with no open porosity or any such defect. This emphasizes intimate mixing of Cu and Al took place by FSW with these parameters. This is further reflected in terms of hardness and tensile strength.

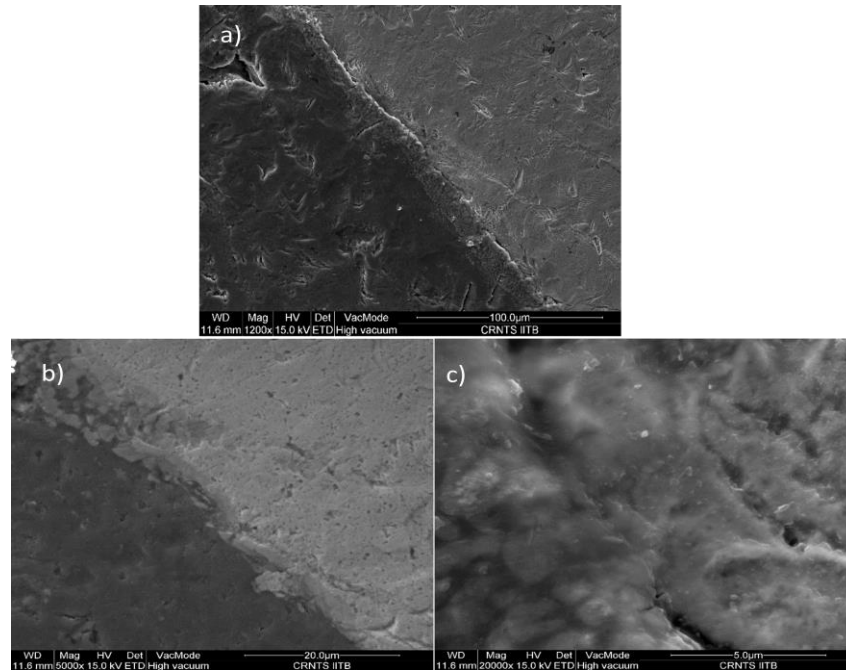


Fig .5 Showing microstructures at the interface obtained by joining Al-Cu couple by FSW at rotational speed of 800 rpm and transverse feed of 60 mm/min at different magnifications a) at 1200X , b) at 5000X and c) 20000X

Tensile Strength and Hardness Test

Aluminium alloy LM6 and commercial copper alloy having each 110 mm in length, 55 mm in width and 6 mm in thickness was used. The copper plate was placed at advancing side and aluminium plate at retreating side. The metal plates were butt welded and stir them together with a rotating straight cylindrical threaded tool. The tool used is cylindrical threaded tool steel and offsetting it to copper side at 2mm. The FSW process is divided into three stages, namely (1) plunge, (2) dwell, and (3) traverse stages. During the plunge stage, the pin tool first moves down vertically and then start rotating during the dwell stage for next 30 sec, followed by moving along the weld line with rotation during the traverse stage. In order to avoid complexity during the initial plunge stage, heat generation was only considered during the dwell and the traverse stages. The welded work pieces were cut into 'I' section specimens with the help of milling machine as shown below.

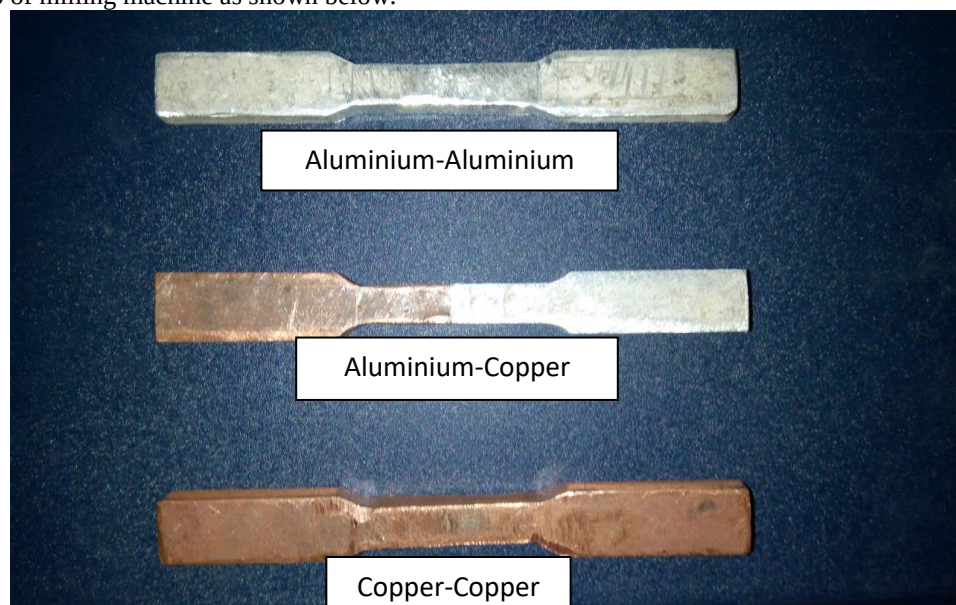


Fig. 6 Specimen for Tensile Strength and Hardness

The specimens were tested on UTM machine for tensile strength and for hardness Brinell hardness apparatus was used. The results are given in the table 2.

Sr. No.	Sample Name	Speed(rpm)	Feed(mm/min)	Tensile Strength(N/mm ²)	Hardness (BHN)
1	Al-Al	600	40	73.9	66
2	Al-Al	800	60	80.42	72
3	Al-Al	1000	80	66.13	60
4	Cu-Cu	600	40	110.52	84
5	Cu-Cu	800	60	145.71	98
6	Cu-Cu	1000	80	122.08	90
7	Al-Cu	600	40	51.62	58
8	Al-Cu	800	60	64.81	79
9	Al-Cu	1000	80	34.83	42
10	Al-Al	400	20	Sample Failed	
11	Cu-Cu	400	20	Sample Failed	
12	Al-Cu	400	20	Sample Failed	
13	Al-Al	1200	100	Sample Failed	
14	Cu-Cu	1200	100	Sample Failed	
15	Al-Cu	1200	100	Sample Failed	

Table.2 Experimental Results

IV. DESIGN PROPERTIES

4.1 Hardness

Fig.6 shows the images of the test conducted at various rotational speeds for Al to Cu. Hardness measured from 0.5 mm from weld centre at the advancing side for all samples. At rotational speed of 600 RPM and feed of 40 mm/min hardness is 58 BHN. At speed of 800 RPM and feed of 60 mm/min high value is measured i.e. 79BHN. At speed of 1000 RPM and feed of 80 mm/min low value of i.e. 42 BHN.

4.2 Tensile Strength

The ultimate tensile strength (UTS) is a measure of maximum load at which the materials begin to deform plastically. Aluminium to copper joints, the UTS at rotational speed of 600 RPM and feed of 40 mm/min was 51.62 (N/mm²) and at speed of 1000 RPM and feed of 80 mm/min it was 34.83(N/mm²). Aluminium to copper combination revealed that at speed of 800 RPM and feed of 60 mm/min high UTS value i.e. 64.81(N/mm²) was measured.

4.3 Microstructure

The microstructures for Al-Cu couple were observed under Field Emission Gun Scanning Electron Microscope (FEG SEM). The respective microscopic images are presented in Fig 5. Fig. shows the microstructure measured at various points. Surface roughness refers to the small, finely spaced deviations from the nominal surface that are determined by the materials characteristics and process that are selected or it is measure of peaks and valley caused by machining process. In machining, the increase in cutting speed at low feed rate and depth of cut produced smooth surface roughness. In FSW also, low surface roughness was produced at high spindle rotation.

By observing microscopic images in fig. 5 it is cleared that following mechanisms are dominant in joining dissimilar plates like aluminium and copper.

I] proper mechanical interlocking

II] Force of adhesion

No voids found also no loosen surfaces (third party material).

Above mechanisms are not found in other i/p parameters.

V. CONCLUSION

The present experimental work was an attempt to enhance the influence of FSW parameters on the quality of joint produced and the following conclusions can be derived:

- 1.FSW was effectively employed to join two dissimilar materials like LM6 aluminium alloy and commercial copper alloy sheets of 6 mm thickness and it was revealed that position of materials significantly affects the weld quality.
- 2.Sound defect-free joints were obtained under the larger pin offset of no less than 2mm to the Al matrix, and a good metallurgical bonding between the Cu bulk/pieces and Al matrix was achieved. However, defects formed easily at smaller pin offset due to the hard mixing between the large Cu pieces and Al matrix.
- 3.The Al–Cu butted interface was thin, uniform and continuous at lower rotation rate of 600 rpm and feed rate of 40 mm/min; however, the thick stacking layered structures developed on the interface at rotation rate of 800rpm and feed rate of 60 mm/min and it again get thin at rotation rate of 1000 rpm and feed rate of 80 mm/min.
- 4.Poor tensile properties were obtained at the very large pin offsets and/or low rotation rates due to the insufficient reaction between the Cu bulk/pieces and Al matrix. Sufficient reaction were achieved in the FSW Al–Cu joints produced at rotation rates of 800 rpm and feed rate of 60 mm/min and proper pin offsets of 2mm, resulting in the good tensile strength of 64.81 N/mm² and hardness of 79 BHN were achieved.

VI. FUTURE SCOPE

Despite considerable interests in the FSW technology in past decade, the basic physical understanding of the process is lacking. Some important aspects, including material flow, tool geometry design, wear of welding tool, micro structural stability, welding of dissimilar alloys and metals, require understanding.

VII. REFERENCE

- 1] Aziz, S.B., Dewan, M.W., Huggett, D.J. Impact of Friction Stir Welding (FSW) Process Parameters on Thermal Modelling and Heat Generation of Aluminium Alloy Joints(2016) .
- 2] J.M. Timothy, “Friction Stir Welding of Commercially available Superplastic Aluminium”, 2008, Department of Engineering and Design, Brunel University.
- 3] B.S. Yilba, A.Z. Sahin, N. Kahraman , A.Z. Al-Garni, “Friction stir welding of St-Al and Al-Cu materials” J. Mater Process, Technol,1995.
- 4] D. G. Whitehead, K. O'Hara and M. T. Frost, "Improved Data Collection for an X-Ray Diffractometer," in *IEEE Transactions on Instrumentation and Measurement*.
- 5]H.B. Cary, Modern Welding Technology, Prentice-Hall, New Jersey, 2002.
- 6] <https://www.engineeringtoolbox.com>
- 7] J.E. Spowart, Z.Y. Ma, R.S. Mishra, in: K.V. Jata, M.W. Mahoney, R.S. Mishra, S.L. Semiatin, T. Lienert (Eds.),Friction Stir Welding and Processing.
- 8] J.M. Timothy, “Friction Stir Welding of Commercially available Superplastic Aluminium”, 2008, Department of Engineering and Design, Brunel University.
- 9] M. J. Chung and Seong-Guk Oh, "Development of micro universal testing machine system for material property measurement of micro structure," *2008 International Conference on Control, Automation and Systems*, Seoul, 2008, pp. 970-973.
- 10] P. Xue, D.R. Ni, D. Wang, B.L. Xiao, Z.Y. Ma, “Effect of friction stir welding parameters on the microstructure and mechanical properties of the dissimilar Al–Cu joints”, [Materials Science and Engineering: A](#) Volume 528, Issues 13–14, 25 May 2011
- 11] R. Rai, A. De, H. K. D. H. Bhadeshia and T. DebRoy, “Review: friction stir welding tools”, *Science and Technology of Welding and Joining*, 2011.