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Design, Fabrication and Testing of Friction Stir Welded Joints

Ali Akbar Nadim [1], Hakeemuddin Ahmed[2]

Research Assistant, Department of Mechanical Engineering, Muffakham Jah College of Engineering & Technology,Hyderabad, Telangana, India[1]

Associate Professor, Department of Mechanical Engineering,Muffakham Jah College of Engineering & Technology,Hyderabad, Telangana, India[2]

ABSTRACT:Friction-stir welding (FSW) is a solid-state joining process that uses a third body tool to join two faying surfaces. Frictional heat between the welding tool and the work pieces causes the latter to soften without reaching the melting point, allowing the tool to traverse along the weld line. It then mechanically intermixes the two pieces of metal at the place of joint; the softened metal can be joined using mechanical pressure (which is applied by the tool), much like joining clay or dough. In this project, CNC Milling Machine is used to weld the parts together. The parts being welded are made up of dissimilar materials like Aluminum and Copper. The rotational speed is varied from 900 rpm to 1500 rpm while the welding speed is kept constant at 25 mm/min. The other parameter involved is the axial load, which reaches 200 bars. The dimensions of the parts are (100mmx50mmx3mm) which are welded to form a butt joint.

The effect of different tool pin profiles on the quality of the welded joint is also studied for welding. Different tool pin profiles considered are threaded, taper, circular/round and square. The tools are designed using Pro/E and are manufactured on a Lathe machine. After the parts are welded, various practical tests are performed on the welded parts that include the tensile strength, microstructure study and the Vickers's hardness test. The experimental results proved that the highest tensile strength of the welded joint i.e., 81.073 N/mm^2 was achieved with the threaded tool profile at speed 900 rpm with feed 25 mm/min and the highest hardness value of 267HV was achieved with the round tool profile at 1500 rpm and feed of 25 mm/min.

KEYWORDS:Friction-stir welding (FSW), CNC Milling Machine, dissimilar materials, tensile strength,microstructuretest, Vickers's hardness test.

I. INTRODUCTION

Wayne Thomas [1] at TWI (The Welding Institute) invented friction Stir Welding (FSW), and the first patent applications were filed in the UK in December 1991. Friction Stir Welding is a solid-state process, which means that the objects are joined without reaching the melting point. It uses a third body tool i.e., a tool profile to join the two faying surfaces. It mechanically intermixes the two pieces of metal at the place of the join, then softens them so the metal can be fused using mechanical pressure, much like joining clay. The parameters such as the tool profile, the traverse speed, the rotational speed of the tool among others play a crucial role when it comes to achieving a good quality weld. Initially, it was primarily used on aluminium, and most often on extruded and on structures which need superior weld strength without a post weld heat treatment. Later, the process of FSW was extended to different materials such as copper and its alloys, steels and much recently with titanium. Fig. 1 represents the friction stir welding principle in which two dissimilar metal pieces; Aluminium and Copper are butted together with the help of the tool, which has different profiles.

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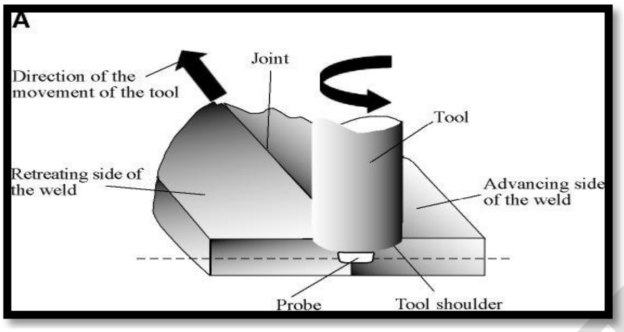

Fig. 1: Schematic diagram of the FSW process: (A) Two discrete metal work pieces butted together, along with the tool (with a probe).

II. MATERIALS AND METHODS

A. MATERIALS: The materials that have been used in this work are Aluminium 6061 alloy and Commercial Copper. The mentioned two materials are dissimilar materials. When compared to Copper, Aluminium is a softer metal; the tensile strength and hardness values of Copper are relatively higher than that of the Aluminium alloys. The density of Al 6061 is 2.7g/cm^3 whereas the density of commercial copper is 7.64g/cm^3. The material used for the tool is P20 steel. P20 steel has its own advantages and disadvantages when compared to the other traditional materials used for tools i.e., Tungsten Carbide or HSS. P20 has an Ultimate Tensile Strength in the range of 965-1030Mpa.

B. METHODS: Traditionally, there has been a problem when welding dissimilar materials as the properties of the materials differ. Aluminium and Copper mostly cannot be welded using the conventional fusion welding processes like Arc welding, Gas welding etc. It was proved that these materials could be efficiently welded by using the Friction Stir Welding process. FSW is a solid-state process when compared to the other conventional welding processes that are fusion-welding processes. FSW has various advantages over other welding processes like no hot cracking of the welded metals, no porosity, very less residual stresses, safe and environment friendly apart from others. After the materials were welded, various tests like Tensile strength test, Vicker's hardness test and the microstructure tests were conducted at the welded joint.

III. LITERATURE REVIEW

Aluminum and Copper and their alloys are two of the most widely used materials for different industrial and non-industrial purposes. The production of (Al-Cu) hybrid systems would enable the development of new engineering solutions combining Copper's improved mechanical, thermal and electrical properties with Aluminum's low specific weight and cost. The knowledge of the mechanical properties of the dissimilar friction stir welds between Aluminium and Copper is of importance to enhance their use in the industries. According to Xue et al [2], the hardness increased in the layered structure due to the strengthening effect of intermetallic compounds. Shukla and Shah [3] found that the maximum tensile strength of Al/Cu joint was low (62.2 Mpa) mainly due to the presence of intermetallic compounds. Also the increase in the rotational speed resulted in the tensile strength decreasing. In most of the work done on FSW, the tool geometry design is not disclosed which may be due to proprietary reasons. Akinlabi et al [4] successfully welded Al 5754 alloy with C11000 Cu by using the threaded and concave shoulder tool machined from H13 tool steel. Guerra et al [5] was able to join Al 6061 with a thin high purity Copper one-piece pin and shoulder from D2 tool steel heat treated to HRC62. Singh et al [6] found that in the horizontal hardness profiles, the values were found to be about 110 HV and 106 HV for copper and aluminium base metals respectively. Esmaeili et al [7] also suggested that the thickness of the intermetallic compound formation increases with an increase in the rotational speed, which results in the decrease of tensile strength, and increase in the hardness values. Various other researches had their own views and results. FSW could be the most used joining technique of dissimilar materials in the future; however more research needs to be done to improve the mechanical properties of the welds. Also, it is necessary to further investigate the effect of FSW tool geometry especially for dissimilar materials to improve the weld quality.

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IV. EXPERIMENTAL SETUP

The materials used in this study, i.e., Al 6061 alloy, Commercial Copper were procured in the form of cold rolled plates with their composition as shown in Table 1 (a) & (b).

Table I: Chemical composition of (a) Al 6061 (b) Commercial Copper

Al	Si	Fe	Cu	Mn	Mg	Cr	Others
Balance	0.4-0.8	0.7 max	0.15-0.4	0.2-0.8	0.8-0.12	0.15-0.35	0.5

(a)

Cu	Tin	Lead	Zinc
Balance	0.002	0.005	4.0-4.95

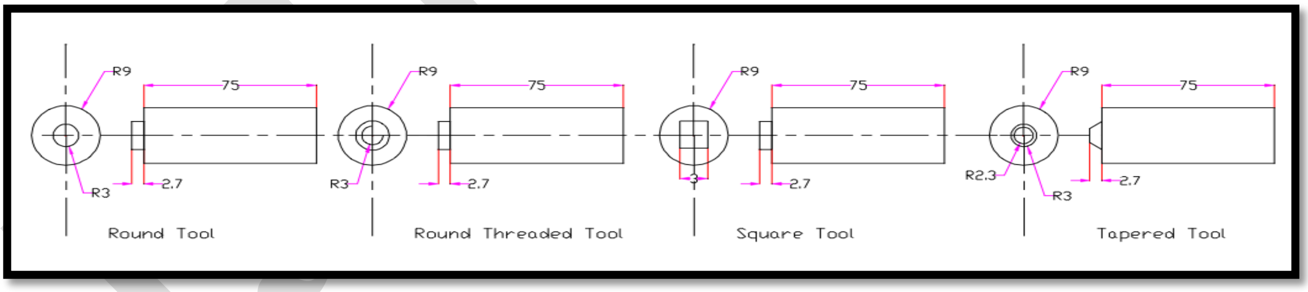
(b)

The friction stir welding has been carried out by using a properly designed setup of the clamping fixture that allows the user to fix the two sheets (100mmx55mmx3mm) to be butt welded on a CNC vertical milling machine. The CNC Milling machine provides an alternative way to produce friction stir welds when the actual FSW machine is not available.

V. METHODOLOGY

In the current study, the four types of tool profiles were designed and applied; namely,

- Plain Circular or round tool profile
- Circular with Threaded tool profile
- Square tool profile
- Taper tool profile



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

Fig. 2:Tool Profile (a) Round (b) Round with Threaded (c) Square (d) Taper

The Fig. 2 represents the 2D diagrams of the tool profiles which have been created using AutoCAD. The length of the tool is 75mm whereas the height of the tool probe is less than the thickness of the materials, i.e., 2.7mm. Initially a long Aluminum plate was taken and sectioned according to the required dimensions (100x55x3mm). After the sectioning, the plates were properly clamped in the designed fixture setup for the welding operation. Subsequently, the tool (P20 steel material) was used and the welding process was completed at three different speeds while maintaining a constant feed.

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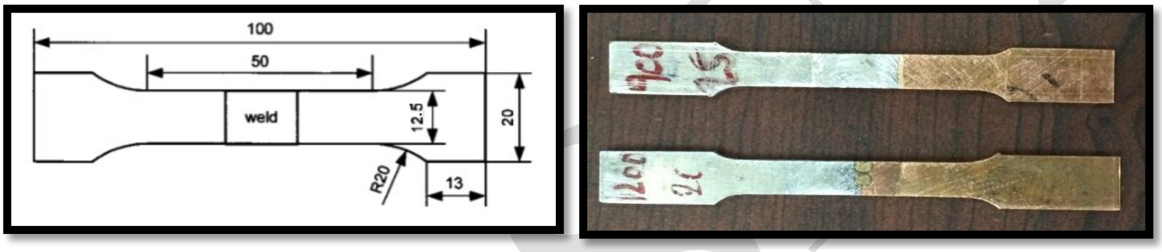
Fig. 3: Welded Al & Cu plate

The welded plates can be seen in the above Fig. 3 which was welded using the threaded tool at 900rpm with a feed of 25mm/min. The welded plates were first sectioned according to the tensile specimen test dimension standards as shown in the Fig. 4 and the tensile strength test was conducted on the Universal Testing Machine (UTM).



(a) (b)

Fig. 4:(a) Tensile Test Specimen Standards (b) Tensile Test Specimens

Fig. 4(a) represents the tensile test specimen standards whereas the Fig. 4(b) shows the specimens, which have been sectioned as per the standards. The gauge taken was 50mm with an arc of R20 and width 12.5mm.

Microstructure test:

A carefully prepared specimen and magnification are needed for microscopic examination. Proper preparation of the specimen and the material's surface requires that a rigid step-by-step process be followed. The first step is carefully selecting a small sample of the material to undergo microstructure analysis with consideration given to location and orientation.It is followed by sectioning, mounting, grinding, polishing and etching to reveal accurate microstructure and composition The etchant used was **2% HF** and **K_2CrO_7+HNO_3**. A magnification of **100X** was used fordetailed viewing of samples using a metallurgical microscope.

Vickers Hardness Test:

The Vickers hardness test method consists of indenting the test material with a diamond indenter as shown in Fig. 5, in the form of a right pyramid with a square base and an angle of 136 degrees between opposite faces subjected to a load of 1 to 100 kgf. The full load is normally applied for 10 to 15 seconds. The two diagonals of the indentation left in the surface of the material after removal of the load are measured using a microscope and their average calculated. The area of the sloping surface of the indentation is calculated. The Vickers hardness is the quotient obtained by dividing the kgf load by the square mm area of indentation. The load applied was 5kg.

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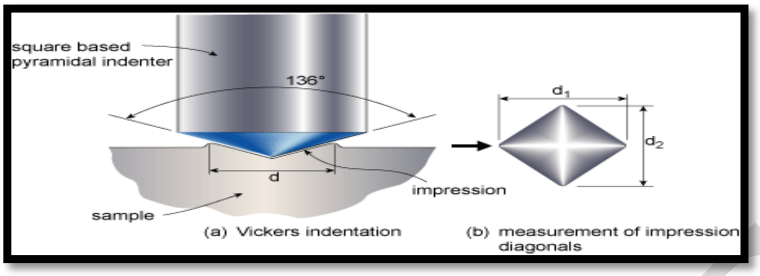

Fig. 5:Vickers hardness principle

VI. RESULTS AND DISCUSSIONS

Tensile Test Results:
In the present work, different butt welds were obtained by varying the speed with constant feed and the results were tabulated in table II.

Table II:Tensile test results

Sample No.	Rpm	Feed (mm/min)	Tensile Strength (N/mm^2)	Tool Profile
1	900	25	81.073	Threaded
2	900	25	78.222	Taper
3	900	25	----	Round
4	900	25	----	Square
5	1200	25	62.715	Threaded
6	1200	25	52.571	Taper
7	1200	25	----	Round
8	1200	25	----	Square
9	1500	25	54.674	Threaded
10	1500	25	47.334	Taper
11	1500	25	40.323	Round
12	1500	25	----	Square

In the Table II, the highest tensile strength of 81.073 $N/mm^2$is observed while operating at 900 rpm and feed of 25mm/min with the threaded tool profile. Under similar operating conditions, the second highest strength of 78.222 N/mm^2 was achieved with the taper tool. The lowest strength came with the round tool profile and it was 40.323 N/mm^2. The welding could not be carried out at 900rpm, 1200rpm and 1500rpm using the Square tool and the Round tool because the axial load was exceeding the CNC machine's capacity, which was 200bar. Overall, the results obtained for the tensile strength were satisfactory.

Vicker's Hardness Test:
The Vicker's hardness test was performed on the welded joints. Three impressions on the joints were taken i.e., the starting position of the weld, the middle position and the end position of the weld. Averages of all the three positions were calculated and the hardness numbers were noted down.

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Table III:Vicker's hardness results

Sample No.	Identification		Location	Impression 1 (HV5)	Impression 2 (HV5)	Impression 3 (HV5)	Average (HV5)	Tool Profile
	Rpm	Feed mm/min						
1	900	25	On weld	160	153	156	156.33	Threaded
2	900	25	On weld	165	167	165	165.67	Taper
3	900	25	On weld	____	____	____	____	Round
4	900	25	On weld	____	____	____	____	Square
5	1200	25	On weld	200	201	201	200.67	Threaded
6	1200	25	On weld	254	257	254	255	Taper
7	1200	25	On weld	____	____	____	____	Round
8	1200	25	On weld	____	____	____	____	Square
9	1500	25	On weld	257	259	256	257.33	Threaded
10	1500	25	On weld	261	263	260	261.33	Taper
11	1500	25	On weld	268	265	268	267	Round
12	1500	25	On weld	____	____	____	____	Square

The results are tabulated as shown in the Table III.The highest hardness number is achieved for the circular/round tool, which is 267 HV. On the other hand, the lowest hardness number was achieved for the threaded tool, which in turn had the highest tensile strength. This shows that it is not necessary that a weld joint having the highest tensile strength should also have the highest hardness number. The second highest hardness value was achieved when taper tool was used i.e., 261.33. Overall, the results obtained from the Vicker's hardness were satisfactory.

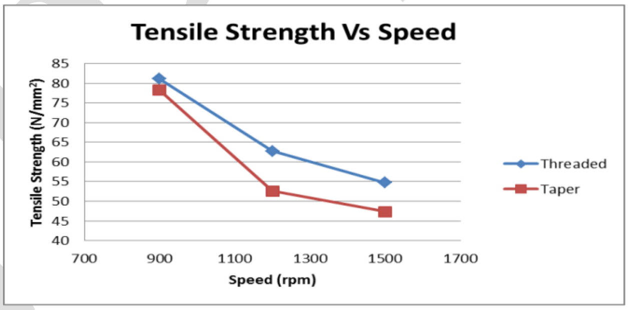

Fig. 6:Graph showing Tensile strength vs. Speed

Fig. 6 represents a graph showing the result, Tensile Strength vs. Speed. It can be seen that, as the speed increases from 900 to 1500rpm, the tensile strength decreases.

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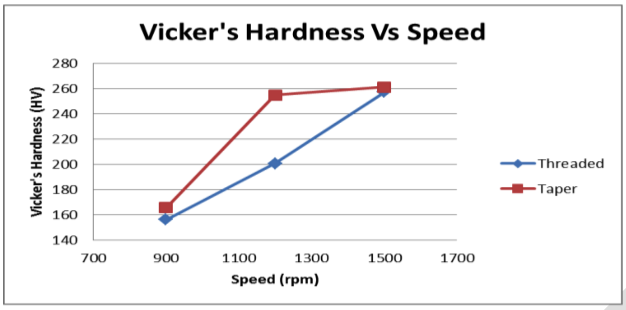

Fig. 7: Graph showing Vicker's Hardness vs. Speed

Fig. 7 represents the variation of Vicker's Hardness number with respect to speed. It can be seen that, as the speed increases from 900 to 1500rpm, the Vicker's Hardness value increases satisfying the general relationship between hardness and tensile strength.

Microstructure Results:

The microstructure test was conducted on three welded plates on the joint area by randomly selecting them.The plates are randomly selected one from each of the tool profiles (threaded, taper, round) with speeds of 900, 1200 and 1500 rpm respectively. The test was conducted as per the ASME guidelines and was free from cracks and voids. The slag and inclusions level were found to be satisfactory.

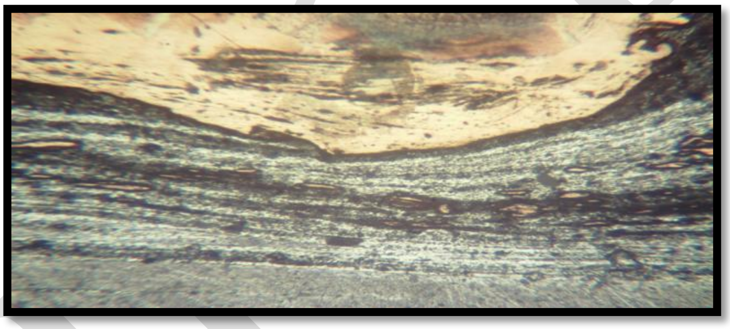

Fig. 8: Sample-900, 25-Threaded tool

Fig. 8 represents the microstructure of the welded joint, when welded at 900rpm with feed 25mm/min using the Threaded tool. The first step is carefully selecting a small sample of the material to undergo the microstructure analysis with consideration given to location and orientation. This step is followed by sectioning, mounting, grinding, polishing and etching. The black/silverish regions are etched aluminium rich while the golden yellow being copper rich regions. The joint interfaces are characterized by mixed layers of aluminium and copper as evident in the microstructures resulting from the heat input into the welds by the stirring of the tool during the FSW process.

VII. Conclusions

The maximum tensile strength achieved was 81.073 MPa while welding at 900rpm with 25mm/min feed using the threaded tool. The maximum hardness value achieved was 267HV while welding at 1500rpm, 25 mm/min feed using the round tool. The microstructure results obtained were found free from cracks, voids and non-metallic inclusions and slags levels were found satisfactory. It can hence be concluded that use of threaded and taper tool profiles yield better results than that of the round and square tool profiles.

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