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Physio-Mechanical Properties and Microstructural Characteristics of Friction Stir Welded Aluminium and Copper Plates Using Conical Unthreaded Tool

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Abstract

Friction Stir Welding (FSW) is a type of welding used to join materials for high strength applications. FSW is a well-liked solid-state welding technique for joining aluminum alloys and other non-ferrous materials in the aerospace, automotive, and marine industries. Pure copper and aluminum from the 6082 series were welded together using a specially designed milling machine. Tests for hardness, flexural rigidity, and impact are performed to assess the welding strength. Material flow and weld defects have been investigated by analyzing the microstructure of the weld junction. The modified vertical milling machine has been used to execute FSW of pure copper and aluminum plates. The aim is to explore the produced welded joints and to comprehend the difficulties encountered while utilizing milling machines as a FSW equipment. Similarly, to optimize the welding parameters in order to accomplish sound welding. FSW can be carried out on a milling machine because the flexural strength of a conical unthread thread tool is 108.58N/mm^2 and 92.16N/mm^2, respectively, at rotational speeds of 500 rpm and 1000 rpm with welding feed rates of 16 mm/min and 50 mm/min.

Keywords: *Friction Stir Welding, Heat Affected Zone (HAZ), Stir Zone (SZ), Thermo-Mechanical Affected Zone (TMAZ)*

1.0 Introduction

Setting up the right conditions is necessary to establish a welded junction with the right geometric dimensions, configuration, and other functional qualities to fuse diverse materials with limited mutual solubility and produce high-quality welded junctions. A second problem that emerges concurrently with the first is the prevention or suppression of chemical intermetallic compounds that exist in the welded joint under unfavourable formation conditions (lamellar, columnar, cellular) due to limited mutual solubility. These substances have low stability, high fragility, and hardness. The aforementioned makes it necessary to create methods and specifications for achieving defect-free weld junctions.

FSW is a solid-state joining method that attaches two work-pieces that are opposing, without causing the material to melt. According to study by Li *et al.*[2], the softened area surrounding the FSW tool is caused by heat produced by friction between the material of the workpiece and the revolving tool. As the tool advances along the joint line, the two pieces of metal are mechanically combined, and the tool's mechanical pressure forges the heated and softened metal. In

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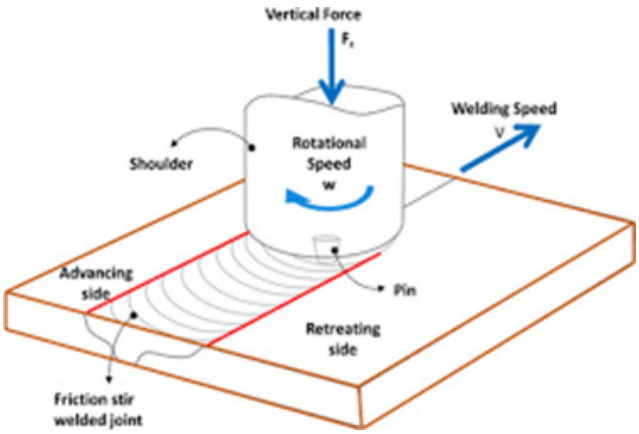


Figure 1. FSW process[1].

Chularis *et al.*'s[3] research, the microstructure, mechanical properties, and phase components of the welded joints created by the FSW were investigated by a variety of metal physics techniques, including X-ray diffraction, mechanical tensile and bending tests, and more. When the Welding Speed (WS) is 25 mm/min and the resistance is 900 min^{-1}, the outcome demonstrates outstanding quality welding. Ramesh *et al.*'s[4] work focuses on solid-state combustion welding for aluminium alloys, specifically Al 6082, and examines a number of parameters, including feed, axial strength, and rotational speed. It focuses on how important performance evaluation is for welding specifications in order to minimise weld distortion and increase output. In their investigation, Khodir *et al.*[5] examined the impact of RS on the mechanical properties of intermetallic compounds and Al/Cu FSWed joints. Intermetallic compounds were more prevalent and formed intricate multilayer structures at faster rotation rates. At the fracture surfaces, joint tensile strength was unaffected by brittle intermetallic compounds. Wally *et al.*[6] The intention of the research is to determine the ideal rotating and welding rates for an Al/Cu butt joint that will use FSW. The study examines FSW at various welding rates (16 mm/min, 29 mm/min, and 44 mm/min) and rotating speeds (910 rpm, 1280 rpm, and 1700 rpm). The findings demonstrate that whereas lower welding speeds and higher rotating speeds are linked to voids and faults, greater rotational speeds and lower welding rates result in enhanced welding force and improved structural integrity. The results of Peng *et al.*[7] emphasise how crucial it is to choose the best rotational and welding speed combination in order to achieve the necessary mechanical and micro-structural characteristics in Al-Cu welded joints. Examined the formation process of inter-metallic compounds and how it affects joint strength by the use of Friction Stir Lap Welding (FSLW), dissimilar connections between Al–Zn–Cu–Mg and AZ31 Mg alloys. Baghel *et al.*[8] The FSW method for joining copper and AA7075 plates is the focus of an experiment in the paragraph. The research looks at the effects of the tool traverse and rotational speed on the microstructure, micro-hardness, and tensile strength of the joint. The major form of flaws observed in material flow patterns, such as swirl and vortex, is a ductile failure.

The primary objective of these findings is to maximise welding feed and Rotation Speed (RS) by utilising variety of parameters and the bending, impact, and tensile strengths as a point of reference. In FSW, microstructure analysis is used to study the organisation and behaviour of metal phases, grains, and flaws in the weld zone. It aids in assessing the joint's quality and integrity, comprehending the material's reaction to welding, and spotting any micro-structural alterations that might have an impact on the mechanical characteristics of the joint. To obtain strength close to that obtained with a FSW machine, it is required to examine the FSW of copper and aluminium, as well as their capacity to weld using ordinary milling equipment.

2.0 Experimental Setup

The stages listed below are included in both the modification of the milling machine and the welding procedure[9]. After obtaining the welded samples, the procedure is optimized using the learning's from each attempt. The samples that are believed to have the best weld for that specific alloy are then put through a strength test.

After completing the welding operation along the entire length of the plates, the tool is elevated at the end. The possible rotational speeds on this particular arrangement were 500 rpm, 710 rpm, 1000 rpm, and 1200 rpm, respectively[10-13]. Aluminium should be placed on the advancing side, which corresponds to the direction in which the tool will be turning, as it has the lowest hardness. The trials that were conducted for the welding method are listed below.



Figure 2. Modified Milling Machine with base plate attachment.

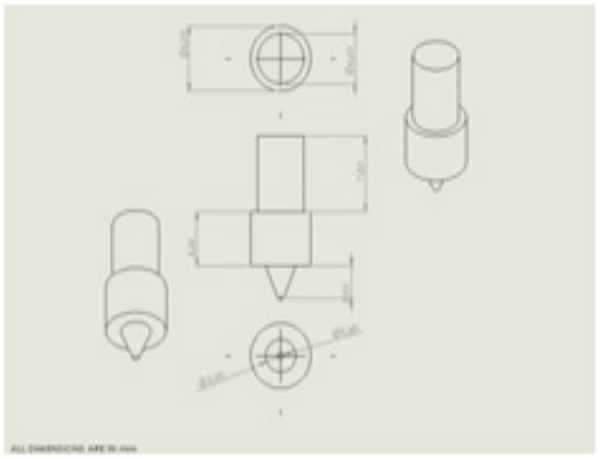


Figure 2(a). Tool with conical pin shape with EN24 material

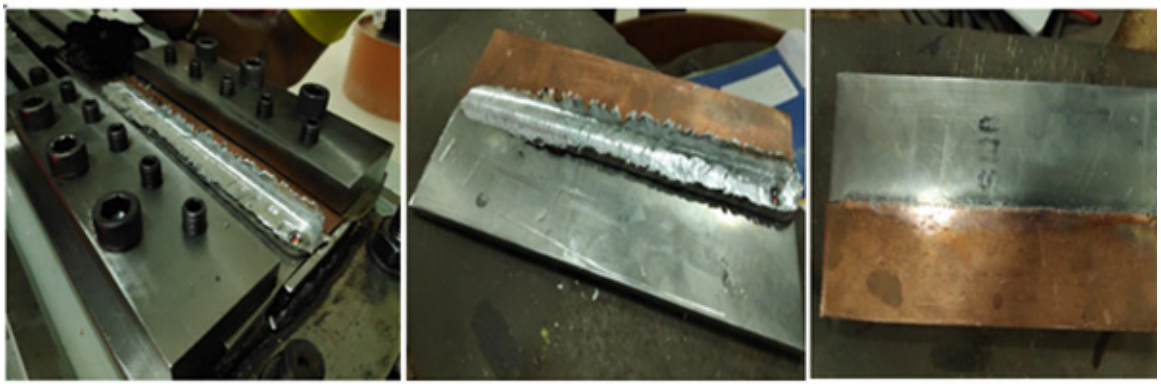


Figure 3. Welded sample (a) with attachent (b) Top view (c) Bottom view.

3.0 Result and Discussion

The ASTM standard was followed in the preparation of all testing specimens. Flexure, hardness, Microstructure, and impact tests were performed on three samples from each category. Tables 1-3 and Figures 4-5 show the outcomes, correspondingly.

3.1 Flexural Strength

Table 1. Bending test for conical unthreaded

Sl./No	RPM	Feed Rate (mm/min)	Load (in KN)	Elongation at Peak (in mm)	Tensile Strength (TS) (N/mm^2)
1	500	16	2.56	2.832	25.6
2	500	25	3.467	3.258	34.67

3	500	50	3.582	2.419	35.82
4	710	16	3.12	2.921	31.2
5	710	25	4.258	3.258	42.58
6	710	50	3.582	2.419	35.82
7	1000	16	6.376	3.581	63.76
8	1000	25	8.164	4.283	91.64
9	1000	50	11.455	3.925	114.55
10	1200	16	2.657	2.183	26.57
11	1200	25	2.361	1.381	43.61
12	1200	50	2.099	3.451	63.99

3.2 Micro-Hardness

The Stir zone is harder than the base metal, as shown by the hardness versus rotational speed graph. The SZ will contain inter-metallic compounds, which make it more brittle than any other zone. In TMAZ and HAZ, the hardness is lower.

3.3 Impact Test

At 16 mm/min, it is noticed that the impact strength

Table 2. Hardness at joints

	Sample	**Hardness (VH 5)**			**Mean Hardness (VH 5)**
		SZ	TMAZ	HAZ	
Conical Threaded	500 rpm,16 mm/min	78.4	77.5	77.9	77.93
	710 rpm,16 mm/min	79.3	79.2	78.4	79
	710 rpm,16 mm/min	77.5	76.6	77.7	76.86

Table 3. Impact strength for conical unthreaded

Tool	**Sample**	**Energy (Joule)**	**Strength (J/mm^2)**
Conical Unthreaded	1000 rpm,16 mm/min	2	0.2
	1000 rpm,16 mm/min	2	0.2
	1000 rpm,16 mm/min	2	0.2

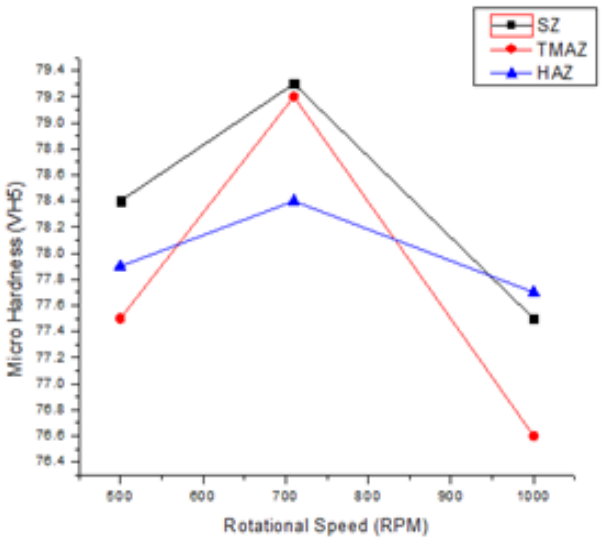


Figure 5. Graph shows rotational speed vs hardness at weld zone.

is similar in all samples and indicated that the weld is sufficient and 90% stronger than the Al base metal.

3.4 Microstructure

FSW of copper and aluminium exhibits a defined and homogenous microstructure. The formation of inter metallic compounds is observed, indicating the metallurgical bonding between two materials. The absence of defects such as porosity or cracks confirms the successful weld quality.

The pure copper specimen has been placed on the retreating side and the aluminium specimen on the advancing side. In the below SEM photographs, we could see both an unetchant view and an etchant specimen. In un-etchant SEM photographs, it is quite evident that materials have flowed each other due to the friction heat generated between the tool and the specimen. Due to

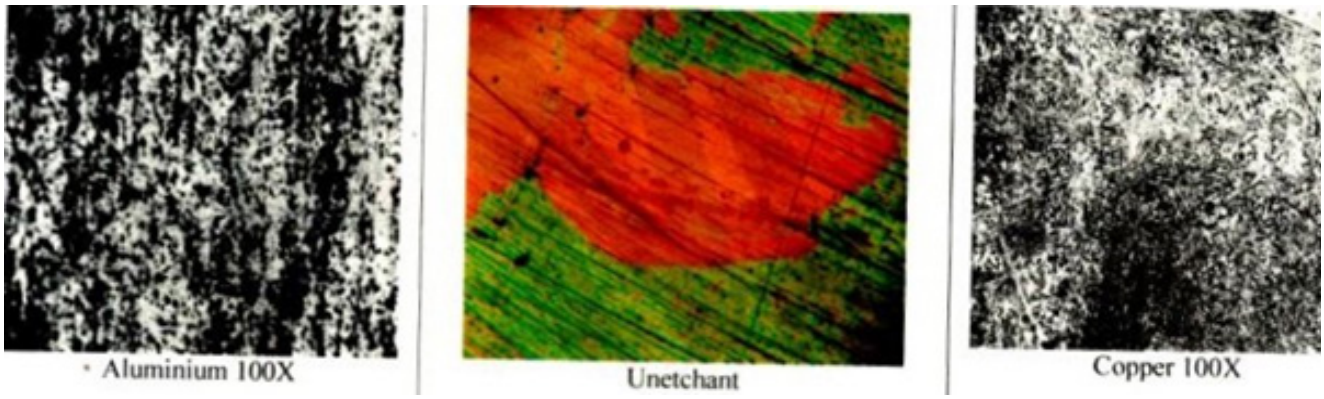


Figure 6. Sample - 11, (500 rpm, Feed rate- 25 mm/min conical unthreaded).

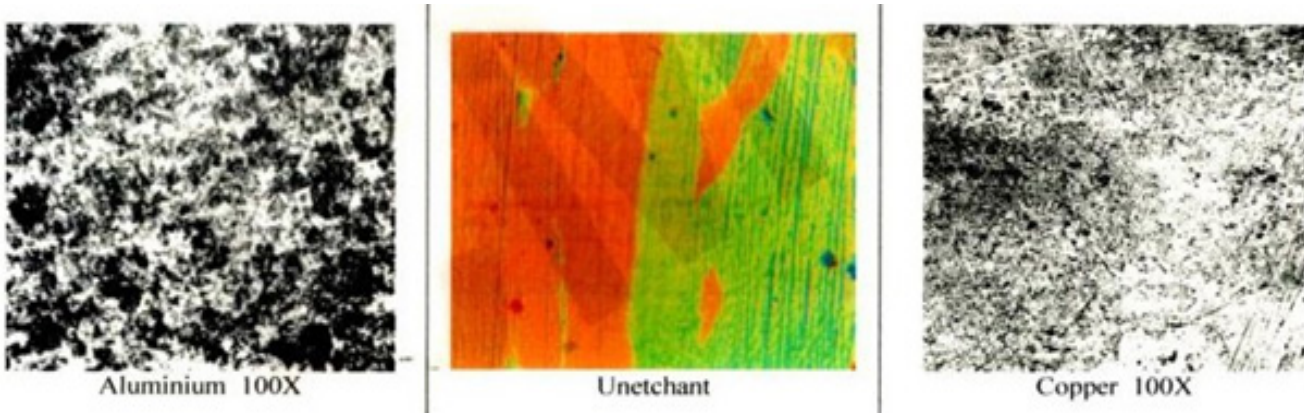


Figure 7. Sample - 12, (500 rpm, Feed rate- 50 mm/min conical unthreaded).



Figure 8. Sample – 13, (710 rpm, Feed rate- 16 mm/min conical unthreaded).

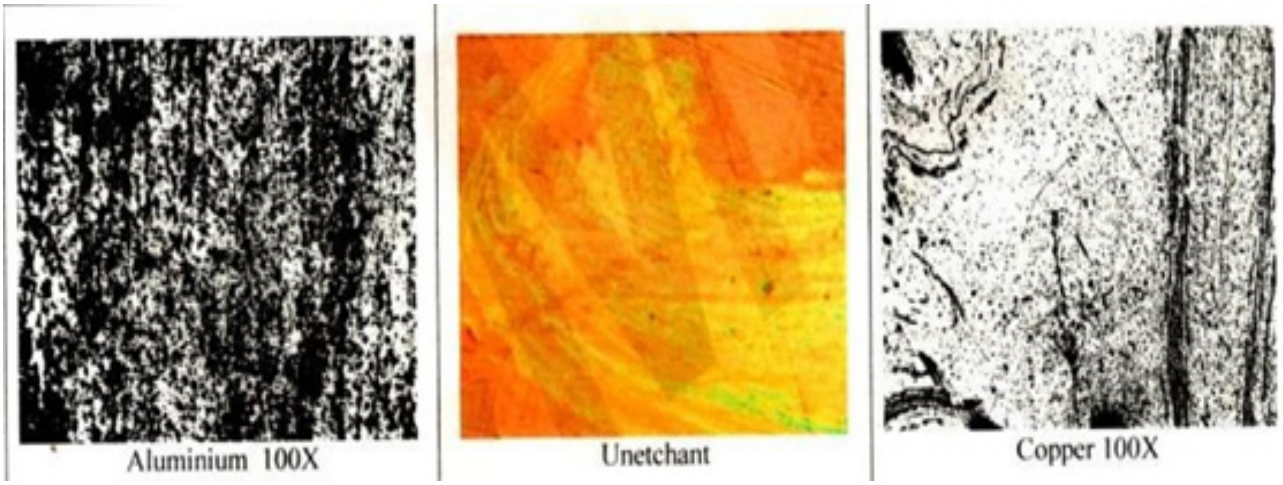


Figure 9. Sample – 16, (1000 rpm, Feed rate- 16 mm/min conical unthreaded).

this, there is bonding of Al and Cu in the plastic state. Al inclusion is greater as it is softer than Cu, and the same has been observed during the welding process as well.

When it comes to etchant specimens of both Al and Cu and copper sides starting from the nugget region, it is quite evident that the grain refinement has taken place because of the friction stirring process. In Figure 6 sample with 1000 rpm, there is fine grain[14-16] refinement compared to 710 rpm sample, and the Al-Cu intermediate compound has formed a Cu side, causing more Al metal to flow towards Cu metal in Figure 7. The 500 rpm sample resembles the 1000 rpm and 710 rpm[17-20] samples in terms of material flow. The tool moves very slowly, producing more heat than in the other 2 examples, which disturbs the grain boundaries (Figure 6-9).

4.0 Conclusion

Friction stir technology has the potential to join copper and aluminium alloy components. Because the pin shapes of FSW tools influence the characteristics of welded joints, conical threaded tools were used in this instance. Conical unthreaded FSW joints showed higher elongation and flexure strength percentages than joints

made with other profile instruments. The hardness and impact strength of joints created with conical threaded tools demonstrated better properties than joints created with other profile FSW tools; as a result, the optimal welding parameters were RS of 500 rpm and 1000 rpm and Welding Speed (WS) of 16 mm/min and 50 mm/min, which produced joints with flexural strength, is 108.58 N/mm^2 and 92.567 N/mm^2, respectively. The results of the bending test showed the exceptional ductility of the welded connections, and the failure occurred in the foundation material rather than the weld zone. The Charpy impact test depicts that the joints had a high degree of hardness and fracture resistance. The welded zone had a precisely adjusted and uniform grain structure, according to the microstructure study. It is determined that employing conical threaded tools and specially designed milling machines, sound FSW of incompatible metals such as Al6082 and pure copper alloys is possible.

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