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The Experimental Investigation on various additives used in Friction Stir Welded Joints of Aluminium and Copper Alloys

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Abstract

This paper presents an experimental investigation into the influence of different input parameters on FSW joints of copper and Aluminium alloys. An experimental investigation has been carried out into the effects of diverse input parameters on Friction Stir Welding of copper and aluminium alloys. The FSW process parameters encompassed the use of both cylindrical and threaded profiles of the welding tool, employing tilt angles of 2 and 3 degrees, tool speeds set at 1000 rpm and 1500 rpm. Twenty-four specimens, consisting of Cu and Al alloys plates were crafted for the experimentation. Employing a vertical milling machine, simple butt joints were fashioned in aluminium and copper alloys. The joints were fortified using a combination of five additives—aluminium oxide, boron carbide, zirconium oxide, zirconium bromide, and silicon carbide—in equal ratios to enhance the FSW joints.

The study tested the joints for a range of mechanical properties such as Tensile testing, Macrostructure, Hardness, as well as Bending testing. A comparative analysis among these joints was made to explain their mechanical performance. The findings of this experimental investigation provide valuable insights into how variations in input parameters, coupled with the use of specific additives.

Keywords: FSW, Mechanical, Alloys, Metals, Wear, Tools

1. Introduction

Friction Stir Welding (FSW) stands as a revolutionary welding process in contemporary manufacturing, offering a blend of speed, eco-friendliness, and exceptional joint performance. Patented by The Welding Institute in 1991, FSW represents a solid-state joining technique capable of uniting ferrous, nonferrous, and plastic materials that prove challenging for traditional fusion welding methods. This innovative process operates below the melting temperature of materials, facilitating superior mechanical properties and minimal heat consumption. Unlike conventional fusion welding, FSW requires no filler material or fusion line, making it an environmentally friendly and efficient technology. FSW's principle involves a rotating cylindrical welding tool with a shouldered, wear-resistant profile, which gradually makes contact with the joint line between workpieces, generating frictional heat to soften the material without reaching its melting point. The resulting solid-phase bond exhibits remarkable benefits such as low distortion, minimal shrinkage, and freedom from porosity. However, FSW also presents challenges, including exit holes upon tool withdrawal and geometric complexities due to clamping requirements. Despite its limitations, FSW finds diverse applications, including joining dissimilar materials and achieving enhanced mechanical properties. At the heart of FSW lies the friction stir tool, comprising the shank, shoulder, and probe, which significantly influence welding quality and performance. Through specialized tool designs and materials, FSW enhances mechanical and physical properties, addressing issues such as creep, fatigue, and corrosion resistance. In essence, FSW represents a transformative welding technology poised to revolutionize various industries with its efficiency, reliability, and versatility[1-11].

Friction Stir Welding (FSW) has garnered significant attention in recent years due to its potential for joining dissimilar materials and modifying microstructures. Anuradha and Reddy (2017) explored FSW on Aluminium alloy AA6061, paving the way for joining dissimilar materials like Aluminium and brass while minimizing intermetallic compounds [1]. Mehdi and Mishra (2017) highlighted the energy efficiency and versatility of FSW, focusing on microstructural modifications and mechanical properties [2]. Meyghani et al. (2017) discussed the complexity of experimental investigations in FSW and proposed Finite Element Methods (FEMs) to enhance accuracy and reduce costs

[3]. Oyedemi et al. (2017) investigated the process response of different tool-pin profiles for FSW of AA6082-T6 Aluminium, optimizing dwell time for stable welds [4]. Sahlot et al. (2017) quantitatively analyzed H13 steel tool wear during FSW of Cu-Cr-Zr alloy, offering insights for optimizing process parameters and improving tool life [5]. Mishra and Jeganathan (2017) successfully applied FSW to join copper alloy, observing defect-free weld zones and variations in grain structure and hardness [6]. Tarasov et al. (2017) explored the microstructural evolution of Aluminium alloy AA2195 in ultrasonic-assisted FSW, observing refined grain size and enhanced precipitation [7]. Tao et al. (2017) investigated fracture patterns in FSW joints of Al-Li alloy, emphasizing microstructural characteristics in different subzones [8]. Chen et al. (2017) examined the welding distortion in FSW of 2014 Aluminium alloy sheets, highlighting the influence of rotation speed and cooling methods [9]. Li et al. (2017) reviewed the macrostructure, microstructure, and mechanical properties of FSW joints in magnesium alloys, addressing the effects of welding parameters [10]. Mirjavadi et al. (2017) investigated the addition of TiO2 nanoparticles in FSW of AA5083 alloy, observing improved mechanical and tribological properties with increased number of passes[11].

These studies collectively contribute to our understanding of FSW processes, offering insights into parameter optimization, microstructural evolution, mechanical properties, and wear characteristics. Further research is warranted to address challenges and optimize FSW techniques for diverse industrial applications.

2. Experiment Set-up

Work piece Material

Al and Cu alloys are the most demanding in the market. But it is difficult to produce sound Al–Cu dissimilar joints by fusion welding due to their significant difference in chemical, physical and mechanical properties. So, the Friction stir welding method is best suited for this purpose. The workpiece material are Aluminium and copper alloy.

Tool material

High-speed steel, renowned for its exceptional heat and wear resistance, as well as its superior hardness compared to other steel variants, will be utilized as the primary material for tools in this project. Its capability to sustain a sharp cutting edge even during prolonged and demanding usage or when subjected to extreme temperatures makes it an ideal choice.

Additives

The joints were fortified using a combination of five additives—Aluminium oxide, boron carbide, zirconium oxide, zirconium bromide, and silicon carbide—in equal ratios to enhance the FSW joints.

Tool tilt angle

For this Research work the tool tilt angles are 2° and 3°

Tool Rotational Speed

- 1000 RPM
- 1500 RPM

Hence, all details are tabulated below, in table 1.

Table 1 Details of the Materials, Additives, and other Welding Parameters

Material	Aluminium		Copper	
Additives	B_4C	Al_2O_3	$ZrBr_4$	ZrO_2
Tilt Angle	2°		3°	
Tool Profile	Cylindrical		Threaded	
Tool Speed	1000 rpm			
Transverse Speed	30mm/min			

Research testing

In this research work following Mechanical testing will be applicable to

- Macrostructure Analysis
- Hardness Analysis
- Tensile Test
- Bending Test
- Fatigue

Welding Machine:

The welding process has been executed with the assistance of a vertical milling machine as shown in the figure 1 and description is shown in the Table 2.

Table 2 Details of Milling Machine used in FSW Process

Sr.No.	Parameter	Detail
1	Welding Machine Type	Vertical Milling Machine
2	Welding Machine ID	VM/2003/03
3	Welding Machine Make	JINWEI
4	Maximum RPM of Welding Machine	5000 RPM
5	Length of Bed of Machine	1.5 m

Fig. 1 Vertical Milling Machine used in FSW process

Welding Details

Following are the traceability of the Friction Stir Welding Joints in Figure 2 as 2(A) Placing of workpiece on machine 2(B) FSW Process 2(C) Welded workpiece and 2(D) Tensile samples. Table 3 is containing the various welding parameters.

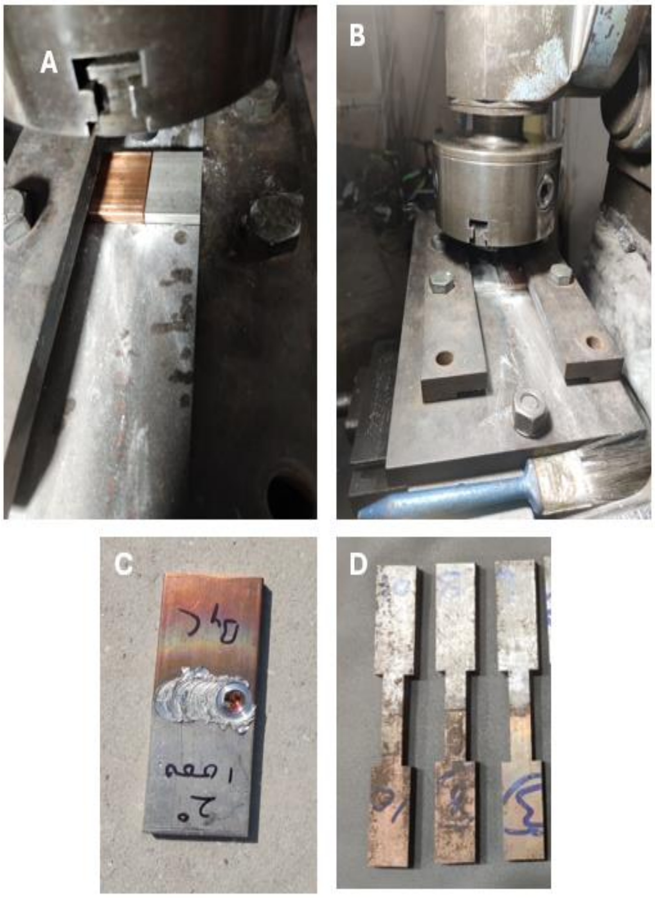


Fig. 2 (A) Placing of workpiece on machine (B) FSW Process (C) Welded workpiece (D) Tensile samples.

Table 3 Details of the Friction Stir Welding Joints

Joint ID	RPM of Tool	Feed Rate	Tool Tilt Angle	Sample Used For
Cu-Al-001	1000 RPM	25mm/ Minute	2°	Microstructure
Cu-Al-002	1000 RPM	25mm/ Minute	2°	Tensile
Cu-Al-003	1000 RPM	25mm/ Minute	2°	Bending
Cu-Al-004	1000 RPM	25mm/ Minute	2°	Macrostructure
Cu-Al-005	1000 RPM	25mm/ Minute	2°	Fatigue
Cu-Al-006	1000 RPM	25mm/ Minute	2°	Fatigue
Cu-Al-007	1000 RPM	25mm/ Minute	3°	Microstructure
Cu-Al-008	1000 RPM	25mm/ Minute	3°	Tensile
Cu-Al-009	1000 RPM	25mm/ Minute	3°	Bending
Cu-Al-010	1000 RPM	25mm/ Minute	3°	Macrostructure
Cu-Al-011	1000 RPM	25mm/ Minute	3°	Fatigue
Cu-Al-012	1000 RPM	25mm/ Minute	3°	Fatigue
Cu-Al-013	2000 RPM	25mm/ Minute	2°	Microstructure
Cu-Al-014	2000 RPM	25mm/ Minute	2°	Tensile
Cu-Al-015	2000 RPM	25mm/ Minute	2°	Bending
Cu-Al-016	2000 RPM	25mm/ Minute	2°	Macrostructure
Cu-Al-017	2000 RPM	25mm/ Minute	2°	Fatigue

Cu-Al-018	2000 RPM	25mm/ Minute	2°	Fatigue
Cu-Al-019	2000 RPM	25mm/ Minute	3°	Microstructure
Cu-Al-020	2000 RPM	25mm/ Minute	3°	Tensile
Cu-Al-021	2000 RPM	25mm/ Minute	3°	Bending
Cu-Al-022	2000 RPM	25mm/ Minute	3°	Macrostructure
Cu-Al-023	2000 RPM	25mm/ Minute	3°	Fatigue
Cu-Al-024	2000 RPM	25mm/ Minute	3°	Fatigue

3. Result and Discussion

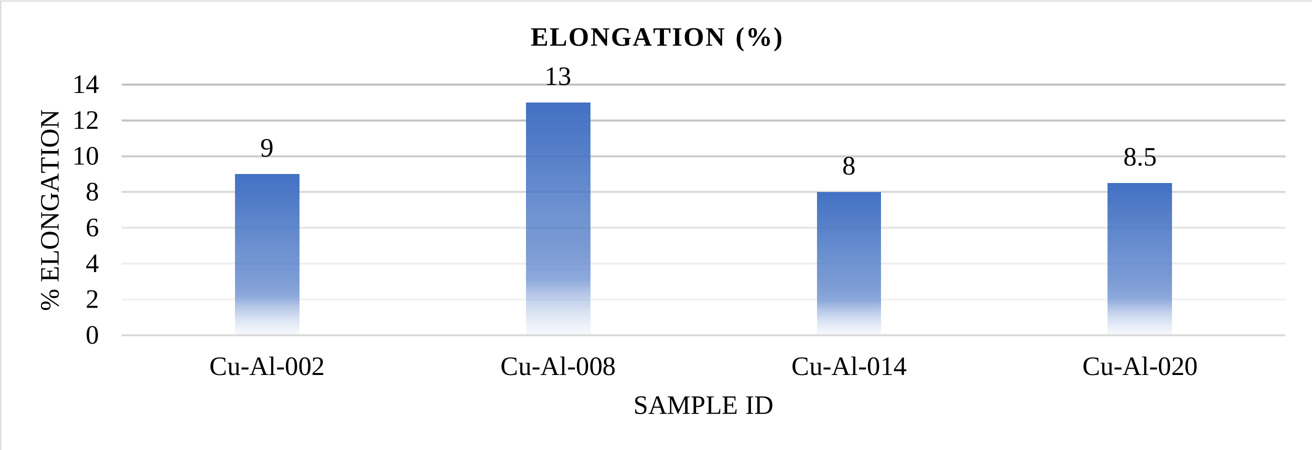
Following the welding process, all welded samples underwent a series of designated tests. Each test comprised four samples, each representing a distinct combination of input parameters. The results obtained from these tests were compared for each set of input parameters.

(UTS), and yield strength. Elongation ranged from 8% to 13%, while UTS varied between 191 MPa and 225 MPa. Notably, Sample ID Cu-Al-008, which corresponds to the combination of 1000 RPM and a 3-degree tilt angle,

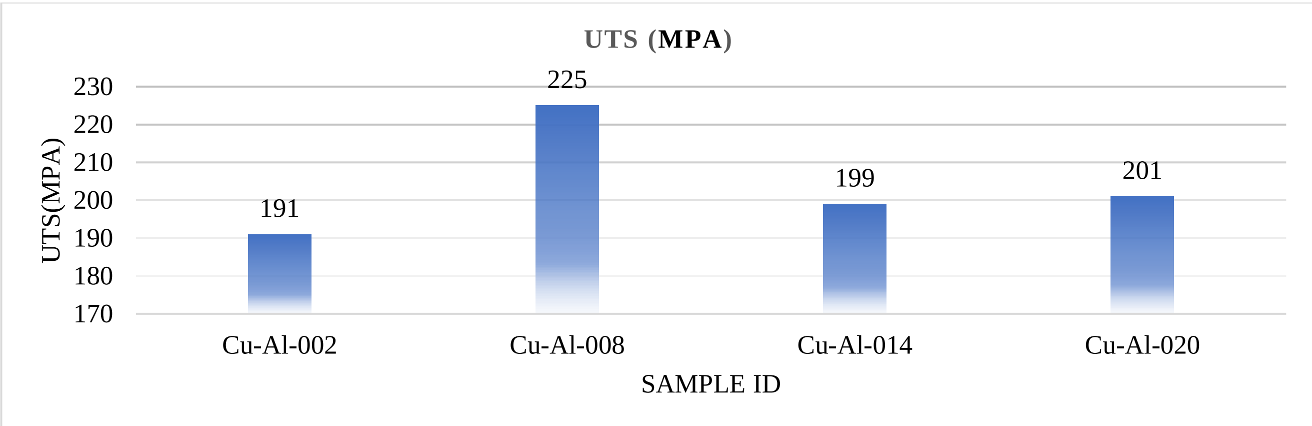
Tensile Test

The tensile tests were conducted using a Universal Testing Machine (UTM) with a capacity of 600KN. The provided graphs illustrate the variations in tensile test results across different sets of input parameters. Four samples underwent testing in the UTM to determine elongation, Ultimate Tensile Strength

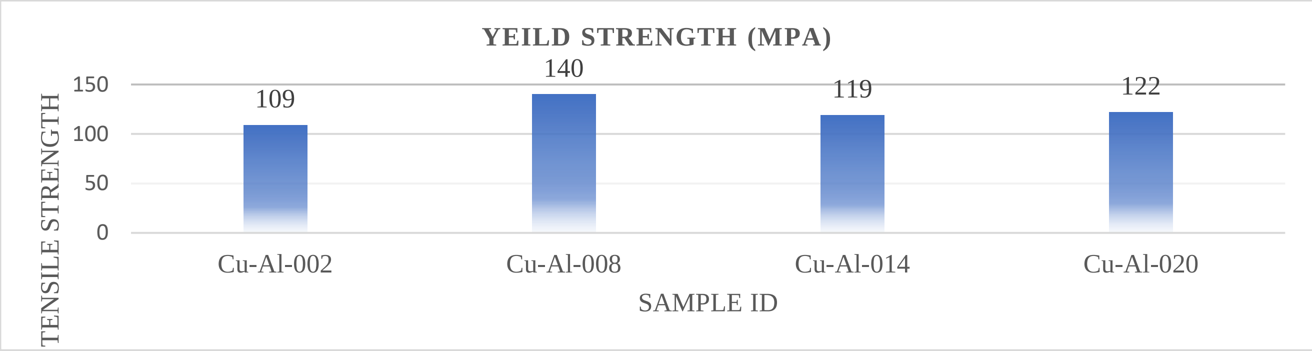
exhibited comparatively superior results compared to the other samples. The camparisons of Elongation, UTS, Yield Strength of Tensile tested Samples shown in graphs 1, graph 2, graph 3, and graph 4.



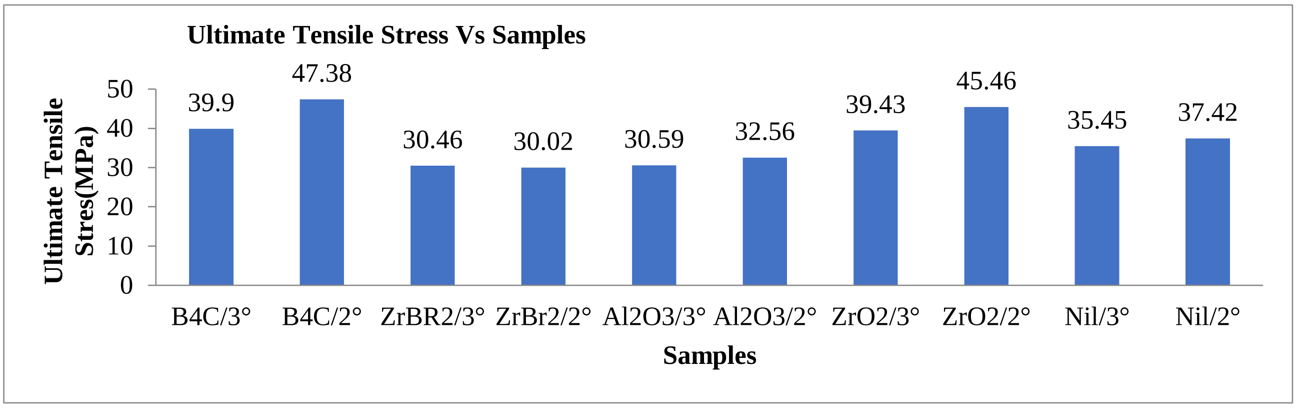
Graph 1 Comparison of elongation of Tensile tested Samples



Graph 2 Comparison of UTS of Tensile Tested Samples



Graph 1 Comparison of yield Strength of Tensile tested samples

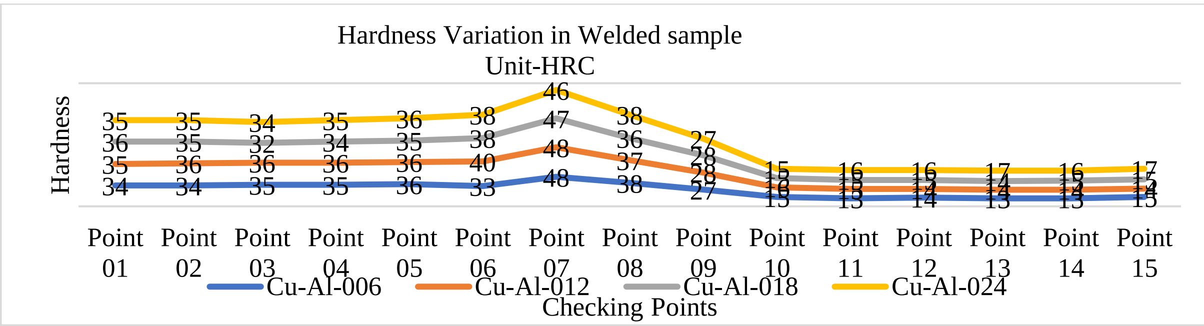


Graph 4 Comparison of UTS of Tensile tested Samples with additives combinations

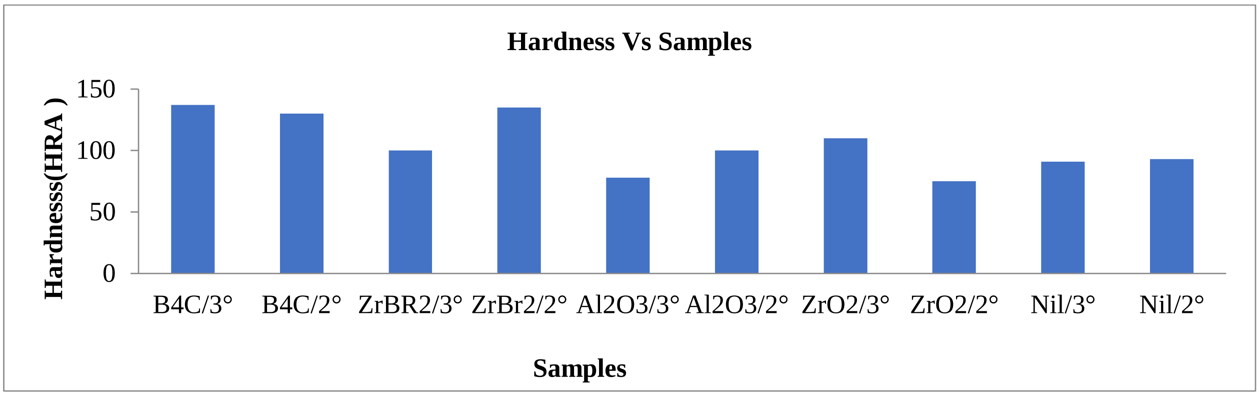
Hardness Analysis

To ascertain hardness levels, 15 points were meticulously designated, starting from the copper end, with each point positioned 5 mm apart. Notably, at the welded location, specifically points 6 through 9, the hardness values exhibited a discernible elevation compared to the parent material. The Hardness measurement points mentioned in the figure 3. The Hardness distribution is shown by the praph 5. A comparion of Hardness of the test material is shown in the graph 6.

Figure 3 Hardness measurement points in Cu and Al alloys



Graph 5 Hardness distribution graph



Graph 6 Comparision of Hardness of Hardness tested samples

Micro Structure Test

Figure 4 shows the Micro-Structure test results with complete details.

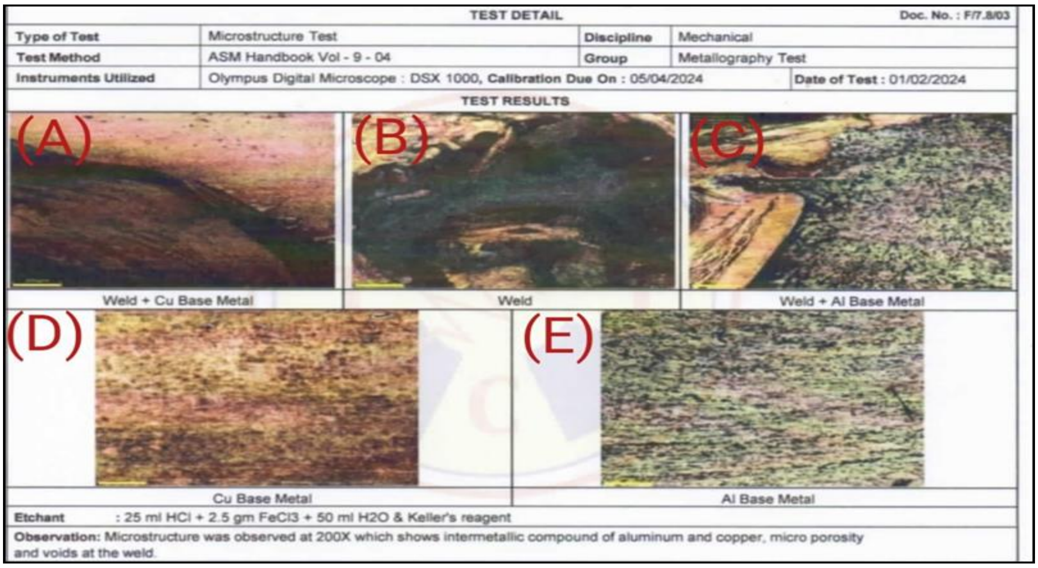


Figure 4 Micro-Structure Test Results with Complete details as: (A) Micro Structure of Weld + Cu base Metal (B) Micro Structure of Weld (C) Micro Structure of Weld + Al base Metal (D) Micro Structure of Cu base Metal (E) Micro Structure of Al base Metal.

Bend test

To assess the bending characteristics of the sample, a bend test was conducted using a 3-point bend test machine as shown in figure 5, employing a comprehensive set of parameters. The table 4 presented below encapsulates the summary of the bend test report.

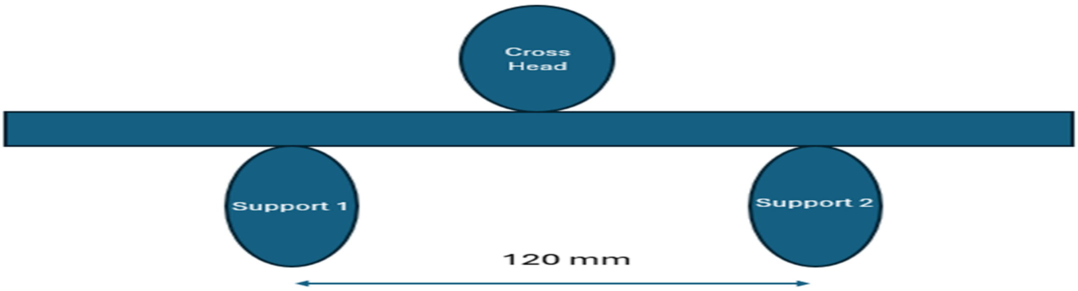


Fig. 5 Bend Test Set up

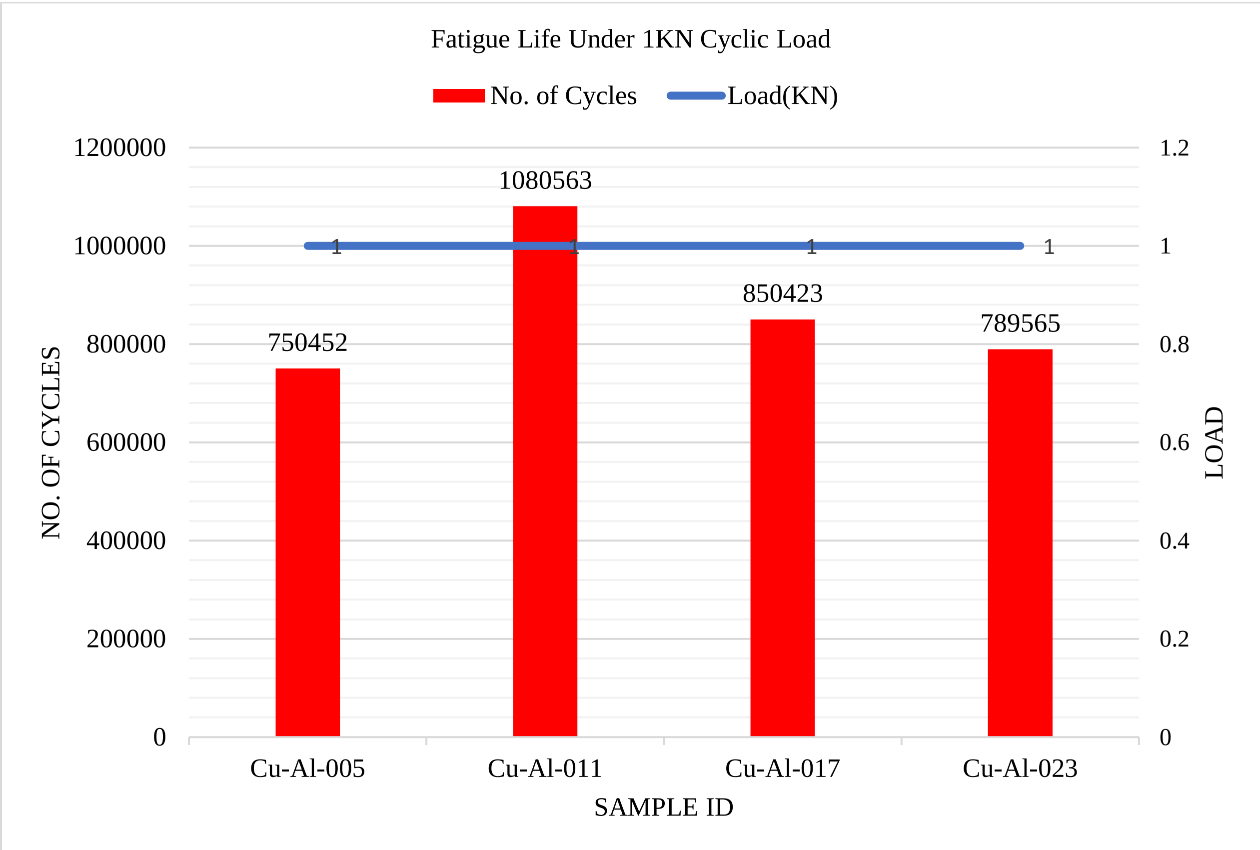
In sample ID Cu-Al-003, the maximum load peak and crosshead travel were observed. This particular sample corresponds to a combination of 1000 RPM and a 3-degree tilt angle.

Table 4 Point Bend Test Report

3-Point Bend Test Report			
SN	Sample ID	Cross head travel at Peak	Load Peak
01	ID-Cu-Al-003	12 mm	2.6 KN
02	ID-Cu-Al-009	18 mm	3.5 KN
03	ID-Cu-Al-015	13 mm	2.7 KN
04	ID-Cu-Al-021	15 mm	3.0 KN

Fatigue Test Result

The fatigue test was conducted with consistent cyclic loads applied across all sets of input parameters. The analysis aimed to determine the endurance limit of the test specimen under the prescribed load conditions. In sample ID Cu-Al-011, the maximum life cycle observed as shown in graph 7. This sample corresponds to a combination of 1000 RPM and a 3-degree tilt angle



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Graph 7 Fatigue test report

Macroscopic Analysis

In Macroscopic analysis it observed that in all sample the width of welded upsets is found 15-17 mm. Negligible zone observed in any sample.

At the beginning point of friction stir welding a undesirable notch absorbed. On butt surface the depth of upset was 2 mm below the top surface and upset height 3 mm above the top surface.

4. Conclusion

Friction stir welding was conducted using 24 different sets of input parameters, with rotational speed and tool tilt angle as variables while maintaining the transverse speed, tool geometry, and additive consistent across all parameters. Subsequently, mechanical properties were investigated across all welded samples, and comparisons were drawn among them.

It was noted that macro-structural properties influenced by all four sets of variables exhibited substantial similarity. Furthermore, the distribution of hardness was observed across all variable sets, with the hardness of the welded zone consistently on the higher side.

Noteworthy mention is the combination of 1000 tool RPM and a 3-degree tool tilt angle, which displayed the highest tensile strength among all combinations. Similarly, this combination demonstrated the longest endurance under a fixed cyclic load of 1 KN, outperforming other combinations.

In bending tests, the same combination of 1000 tool RPM and 3-degree tool tilt angle exhibited the highest crosshead travel and peak load, indicating superior performance in bending characteristics compared to alternative combinations.

This friction stir welding will help industry by providing high strength joints at lesser cost. By adjusting the tool tilt angle an tool RPM gives better result which can be optimize the product requirements.

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