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FRICTION STIR CASTING OF AL-COPPER ALLOY FOR WELD IMPROVEMENT IN AERO APPLICATIONS

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ABSTRACT

This study investigates the design and transient thermal analysis of TIG welded plates using a stir casting process, specifically focusing on Aluminum 6061 reinforced with Silicon Carbide (SiC) and Copper reinforced with Boron Carbide (B4C). The primary aim is to explore the effect of varying reinforcement percentages and processing conditions on the weld zone’s thermal behavior. Reinforcement materials were incorporated at varying concentrations of 6%, 8%, and 10% for SiC in aluminum, and 4%, 6%, and 8% for B4C in copper. Different processing temperatures and stir speeds were employed to determine optimal parameters. The experimental design follows the L9 orthogonal array from Taguchi's Design of Experiments (DOE), enabling systematic variation of the process parameters for optimal performance. Thermal analysis was conducted using the ANSYS software, employing the transient thermal module to evaluate the temperature distribution, heat flow, and thermal errors within the weld zone. Structural analysis was also performed to assess the total deformation and maximum stress under thermal conditions, ultimately offering insights into the effects of reinforcement and processing variables on the welded material's mechanical properties

Keywords: Friction stir casting, DOE, Taguchi L9, Thermal analysis, Aero applications

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1. INTRODUCTION

Welding is the process of joining two metals, either of the same or different types, by melting the metals together, with or without the use of pressure and filler metal. The welding process itself can cause metallurgical changes, quick solidification at the welding zone can cause a change in the material's hardness, materials can oxidize to varying degrees when exposed to air, and cracking is more likely to occur at the welding joint itself. Beginning in the so-called "Bronze Age" some two thousand years ago, welding became a widespread activity. During the Iron Age, however, Egyptians began welding the mechanical parts together. TIG welding, first demonstrated by Russell Meredith in 1930 for the aircraft industry's welding of magnesium and aluminum, is now widely utilized in modern industry. It is particularly favored for producing high-quality welds in materials such as titanium alloys, aluminum, stainless steel, and others. A high-quality weld and easy adjustment of welding parameters are two advantages of TIG welding.

1.1 Stir Casting

The primary commercial method for making aluminum-based composites is stir casting, which began in 1968 In this process, reinforcing powder is mixed with molten metal using mechanical stirring, as shown in Fig. 11 The main drawbacks of this method are the uneven distribution of reinforcement in the solidified composite and the fact that it tends to sink or float due to the density difference between the liquid metal and the reinforcement.

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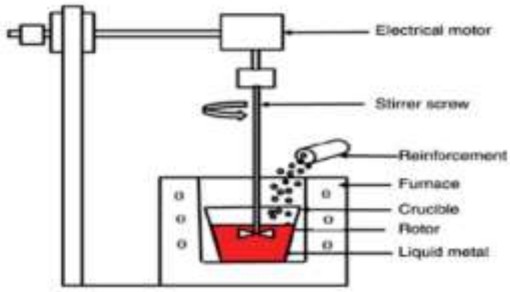

Figure 1: Mechanical stirring

To optimize the mechanical qualities, a uniform distribution of particles is ideal for the majority of applications. According to microstructure analysis found that particle clustering happened in some spots when stir duration and speed were reduced, and they also found some spots where SiC was not present. A more uniform dispersion of SiC in the Al matrix was achieved by adjusting the stirring duration and speed.

1.2 Introduction to Dissimilar Materials:

A multi-material hybrid structure may combine several materials to create an optimum, lightweight, and high-performance structure. This can also accommodate the trend of incorporating more functionalities into each section The desired product performance is attained by combining the various material qualities. As an example, this tendency is mentioned in the following sectors: Transportation Aeronautics Implants for Altering Clothes Renewable energy and maritime uses the combination of novel materials calls for a methodical strategy in choosing these components: Changes in production methods may be necessary due to the novel interactions that may emerge between these elements.

1.2.1 Problem Statement

Joining dissimilar aluminum alloys, such as Aluminum 6061 and Copper reinforced with Boron Carbide (B4C), using TIG welding presents challenges like the formation of brittle intermetallic compounds, uneven heat distribution, and the risk of defects such as cracking and porosity. These issues are exacerbated by varying reinforcement percentages and processing conditions like temperature and stir speed. This study aims to optimize TIG welding parameters for dissimilar aluminum alloys, focusing on minimizing defects and enhancing weld quality for high-performance applications.

1.2.2 Objectives

- To investigate the effects of varying reinforcement percentages of Silicon Carbide (SiC) in Aluminum 6061 and Boron Carbide (B4C) in Copper on the quality of TIG welded joints.
- To evaluate the influence of processing parameters such as temperature and stir speed on the thermal behavior and mechanical properties of the welded joints.
- To optimize TIG welding parameters using Taguchi’s Design of Experiments (DOE) methodology to minimize defects like porosity, cracking, and residual stresses in the weld zone.
- To analyze the microstructure and formation of intermetallic compounds (IMCs) at the weld interface and their impact on the mechanical strength and durability of the welded joints.
- To perform transient thermal analysis using ANSYS to predict the temperature distribution and assess the heat flow within the welded joint.

2. LITERATURE REVIEW

This review synthesizes recent studies on TIG welding of dissimilar aluminum alloys, focusing on process optimization, microstructural evolution, and mechanical properties. In recent years, considerable research works were carried out to study and optimize pulse TIG welding process parameters for welding of different metals Sreekumar and Sivakumar (2021) utilized Response Surface Methodology (RSM) to optimize TIG welding parameters for the dissimilar welding of AA7075-T6 and AA6061-T6 aluminum alloys. Rangasamy et al. (2024) explored the use of ultrasonic vibration during TIG welding of dissimilar aluminum alloys (AA7075 and AA6061). Their study found that ultrasonic vibration significantly reduced hot cracking and improved the mechanical properties, including microhardness and tensile strength. Kaba et al. (2021) investigated the microstructural changes during TIG welding of AA2024 T3 and AA7075 T6 aluminum alloys. They observed the formation of intermetallic compounds such as θ (Al_2Cu), which can lead to reduced mechanical properties and increased susceptibility to cracking. Zhang et al. (2020) examined the impact of the heat-affected zone (HAZ) on the strength of TIG welded joints between dissimilar aluminum alloys. Their study revealed that the HAZ exhibited lower hardness compared to the base materials, which contributed to reduced tensile strength and overall joint performance. Mishra et al. (2020) studied the effects of various filler materials in TIG welding of dissimilar aluminum alloys. They found that using Al 5356 filler rods led to improved weld integrity, while the use of composite fillers, such as Al 5356 reinforced with ZrB_2, further enhanced the microhardness and reduced the occurrence of hot cracking Xu et al. (2019) conducted a transient thermal analysis of TIG welded dissimilar aluminum alloys using finite element modeling. Their analysis revealed significant temperature gradients across the welded joint, which affected the cooling rates and solidification patterns. Ramesh et al. (2020) applied RSM to optimize TIG welding parameters for dissimilar aluminum alloys, focusing on the effects of welding speed, current, and heat input on weld quality. Dighe et al. (2019) investigated the role of welding speed in the TIG welding of dissimilar aluminum alloys. They found that higher welding speeds resulted in finer microstructures, leading to improved tensile strength and reduced susceptibility to hot cracking. Sharma et al. (2019) examined the microstructural evolution during TIG welding of dissimilar aluminum alloys. They noted that differences in the alloy compositions led to the formation of complex microstructures, including dendrites and eutectic phases, which affected the mechanical properties of the welded joint. Zhang and Li (2021) explored the use of laser-TIG hybrid welding for dissimilar aluminum alloy joints. They demonstrated that hybrid welding techniques could significantly improve joint quality by combining the strengths of both welding methods, such as better heat input control and enhanced penetration. Karan et al. (2020) reviewed the role of intermetallic compounds (IMCs) in dissimilar aluminum alloy welding, particularly focusing on the challenges posed by the formation of IMCs during TIG welding. Cheng et al. (2021) investigated the effect of filler alloy composition on the mechanical properties and microstructure of dissimilar TIG welded joints between aluminum and aluminum alloys. Liu et al. (2021) provided an overview of recent advancements in TIG welding of dissimilar aluminum alloys, including improvements in welding equipment, filler materials, and techniques. Singh et al. (2019) studied the microhardness and tensile strength of TIG welded dissimilar joints between aluminum alloys. Gupta et al. (2020) analyzed thermal residual stresses in TIG welded dissimilar aluminum alloys and the impact of these stresses on the performance of the welded joint.

3. METHODOLOGY

The main components of research work divided in to 4 steps, 1st one is stir casting of selected metal matrix composites and optimization with Taguchi prediction, 2nd pilot experiments for welding process with different electrodes at different currents, 3rd experimentation with selected electrodes and 4th is thermal and structural analysis with loading condition to find maximum stress distribution on weld component.

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3.1 Stir casting model DOE using TAGUCHI

A total of 15 samples taken as pilot experimentation to check the best possible bonding of casted samples at different RPM- 800 and temperature 800 and 1000^{0}C as shown in tables

Table 1: Pilot experiments for stir casting with AL+ SiC mixtures (All in gms)

S. No	SiC	Mg	Zn	AL	Total(gms)
1	0	122	150	4728	5000
2	100	140	300	4460	5000
3	150	300	300	4250	5000
4	250	50	100	4600	5000
5	400	100	100	4400	5000

Table 2: Pilot experiments for stir casting with Cu+ B4C mixtures (All in gms)

S. No	B_4C	Mg	Zn	Cu	Total(gms)
1	0	100	200	4700	5000
2	100	100	300	4500	5000
3	150	250	300	4300	5000
4	250	50	100	4600	5000
5	400	150	50	4400	5000

After the pilot checking of samples to avoid cost for maximum samples preparation we adopted Taguchi method of L9 orthogonal array for two sets followed by stir casting. The current sample preparation takes into account a L9 orthogonal array as per the Taguchi studies. In the present study, we prepared composite castings using various percentages of SiC (Silicon Carbide) and B_4C (Boron Carbide), as well as Cu (Copper) and Al 6061 (Aluminum 6061), through the stir casting process. B_4C was added to copper in concentrations of 4%, 6%, and 8%, while SiC was added to aluminum in concentrations of 6%, 8%, and 10%.

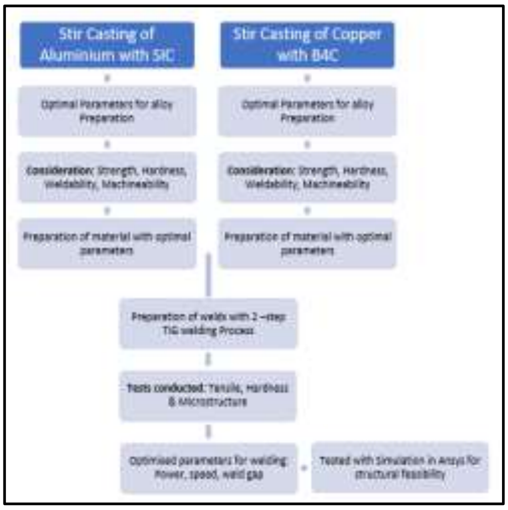

Figure 2: Stir Casting Experimental Flow Chart

3.2 Preparation of Aluminum casting and procedure with Centering SIC

The stir casting technique was used to fabricate the aluminum alloy 6061 hybrid composites reinforcement mixed with preheating SIC The schematic representation of stir casting machine setup has shown in the Figure the AA6061 has heated and melt in the crucible furnace 660^{0}C, in which the stirrer used to create a uniform vortex. The ceramic reinforcement built-in the molten metal of vortex

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and mixed uniformly than permitted to the solidification process. Addition Mg and other reinforcements are mixed uniformly and improving the wettability behavior due to the mechanical forces provided the stirring action as shown in the figure 3.3

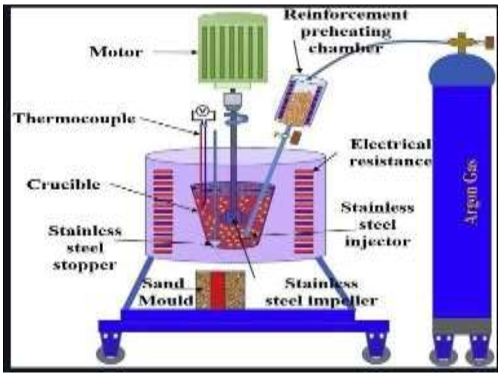

Figure 3: Stir Casting Machine Components ((Warren, H., and Hunft 2004)

The stirring action has been prevented the suspension of the dispersed particle. The literature surveys suggested the stir casting technique for low economical purposes up to the volume fraction 30% of reinforcements on aluminium matrices preheated the SIC and reinforcements mixed into the molten metal and flow into the permanent rectangular mound of dimension (150x150) mm, it can be allowed to preheat. The solid dry Hexacholoro ethane was included into the molten metal by producing the gas for avoiding the porosity during the solidification process. The preparation of samples was implemented to analyzing the characterization of the hybrid composites.

3.3 Copper centering B_4C By stir casting

The distribution of B_4C particulate reinforcement and graphite particles in the aluminium matrix is analysed using optical and scanning electron microscopy after casting specimens with varying volume fractions of B_4C particulate reinforcement (SEM) the dispersion of the particles in the aluminium metal matrix, which contains fine eutectic particles of Al- B_4C particles, for reinforcements of 4%, 6%, and 8% B_4C.

By considering the latest literature on Aluminium and Copper stir casting most of the experimental articles concluded that the mechanical properties are good between the temperatures 800°C to 1400 °C and Stir velocity 600 to 1000 rpm for Aluminium and 800°C to 1400°C for copper.

Table 3: Stir casting process conditions and parameters

Parameter	Value
Temperature	800°C, 1000ºC, 1200°C
Stir velocity	600 RPM, 800 RPM,1000 RPM
Mold type	30mm square with 150mm length
Stirring time	30 min
Cooling time in mold	3hrs
Gasious release	Hexa- choloro methane tablets (1%)
Blade angle	5°
Mg addition	1%

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Table 4: Stir casting parameters for Aluminium

S. No	Parameter - 1	Parameter-2	Parameter-3	% SiC	Speed (rpm)	Temperature (°C)
1	1	1	1	6	600	800
2	1	2	2	6	800	1000
3	1	3	3	6	1000	1200
4	2	1	2	8	600	1000
5	2	2	3	8	800	1200
6	2	3	1	8	1000	800
7	3	1	3	10	600	1200
8	3	2	1	10	800	800
9	3	3	2	10	1000	1000

Table 5: Stir casting parameters for copper

S.no	Parameter -1	Parameter-2	Parameter-3	% B4C	Speed (rpm)	Temperature (°C)
1	1	1	1	4	600	800
2	1	2	2	4	800	1000
3	1	3	3	4	1000	1200
4	2	1	2	6	600	1000
5	2	2	3	6	800	1200
6	2	3	1	6	1000	800
7	3	1	3	8	600	1200
8	3	2	1	8	800	800
9	3	3	2	8	1000	1000

3.4 Parametric study on TIG welding process

For welds – Each sample differing power and total of 9 samples done for different combinations. Pilot experiments with Tungsten copper rod also initiated for the experiment to check the failure of composite alloys welding Further the lower defected samples identified and the work focused on the best power ratios with 2 step weld process with selected aluma-steel rods. Among them we compared the samples with previous regular weld, The final six samples of each composition sent for testing.

Cu+ B4C (1) + Al 6061(1)- 3 samples- 60A, 70A, 80A

Cu+ B4C (1) + Al 6061(2)-3samples- 3 samples- 60A, 70A, 80A

Cu+ B4C (1) + Al 6061(3)-3 samples- 3 samples- 60A, 70A, 80A

Tests for Tensile, SEM, EDS, chemical forming at all zones of HAZ (heat affected zone), EDS were conducted.

4. EXPERIMENTATION RESULTS

Experimentation with DOE involves carefully selecting and arranging the factors and levels in order to minimize the effects of variations and maximize the quality of the results.

4.1 Sample preparation with Taguchi DOE

This method is particularly useful in identifying the optimal combination of factors for the desired outcome. Taguchi DOE can help reduce variability and improve the overall quality of the samples.

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Figure 4: Stir casting Experimental setup

Figure 5: Casted samples aluminium

With varying percentage of SiC mixtures to aluminium castings were prepared as shown in figure to check the mechanical and weld feasibility after machining the casted sample. Additionally, the friction stir casting process offers improved mechanical properties and enhanced fatigue resistance compared to conventional casting methods, making it a preferred choice for industries that require high-performance Aluminum +SiC castings.

Table 6: Aluminum 6061 as base metal the results of hardness and tensile

S.NO	%SiC	RPM	Temperature (0^0C)	Tensile UTS (MPa)	Hardness (HV)
1	6	600	800	169.33	70.6
2	6	800	1000	188.55	61.2
3	6	1000	1200	164.7	78.1
4	8	600	1000	125.3	65.8
5	8	800	1200	164.27	55.9
6	8	1000	800	98.05	50.8
7	10	600	1200	175.3	58.9
8	10	800	800	179.94	53.6
9	10	1000	1000	98.46	47.9

Table 7: Copper alloy as base metal casted sample result for tensile and hardness

S.NO	%B4C	RPM	Temperature (0^0C)	Tensile UTS(MPa)	Hardness (HV)
1	4	600	800	167.47	70.5
2	4	800	1000	188.51	61.8
3	4	1000	1200	164.80	78.4
4	6	600	1000	165.4	65.8
5	6	800	1200	186.32	55.9
6	6	1000	800	171.66	50.5
7	8	600	1200	188.90	58.9
8	8	800	800	179.94	53.6

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9	8	1000	1000	176.75	47.6

Copper matrix given better results compare with the Al matrix for selected temperatures, the maximum value found at sample 7 for tensile at a value of 188.9 at temperature 1200^0C. and even for hardness it is 78.4 for sample 3 at lower composition of 4%. There is a gradual variation between 800°C and 1000°C with a 6% addition of B4C. For better clarity on the optimal input parameters, the results presented.

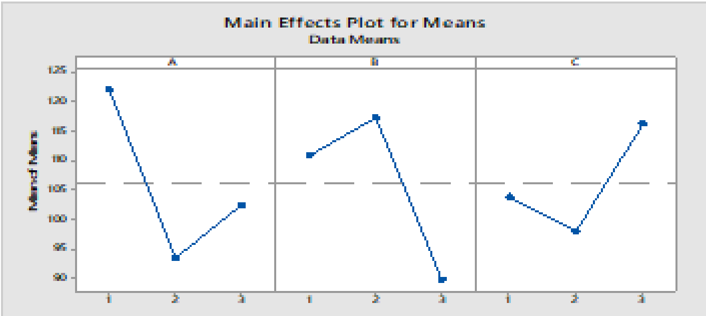

Figure 6: (a) Responses of Data means

By analyzing the mean plots it is observed that the percentage addition of silicon carbide yields favorable results, while stirring speed and temperature exhibit an inverse relationship. The parameters of 10% SiC at 600°C and 600 RPM are closest to the mean value compared to other samples,

Figure 7: (b) Responses of S/N ratios

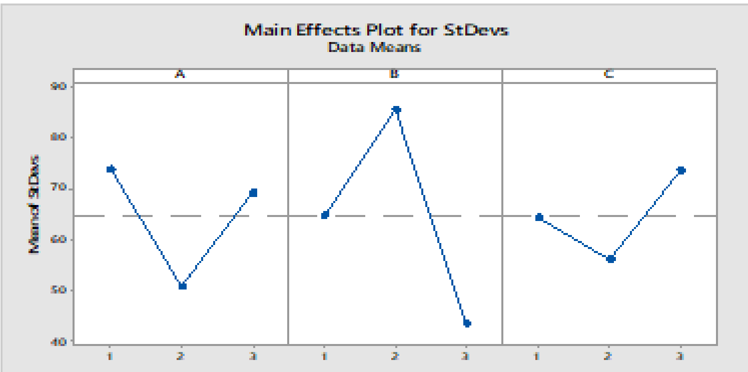

Figure 8: (C): main effects plot for StDevs

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Table 8: Taguchi prediction for AL stirs casted samples

S.NO	%SIC	RPM	TEMP(^{0}C)	S/N	MEAN	St.Dev	Ln. St.Dev
1	6	600	800	39.617	124.816	73.593	4.295
2	6	800	1000	38.675	125.336	85.972	4.463
3	6	1000	1200	39.290	116.088	61.532	4.102
4	8	600	1000	37.625	90.237	42.369	3.726
5	8	800	1200	37.809	114.936	80.409	4.388
6	8	1000	800	36.459	74.886	29.333	3.472
7	10	600	1200	38.313	117.561	78.229	4.373
8	10	800	800	36.532	111.458	89.632	4.479
9	10	1000	1000	36.021	78.031	39.532	3.625

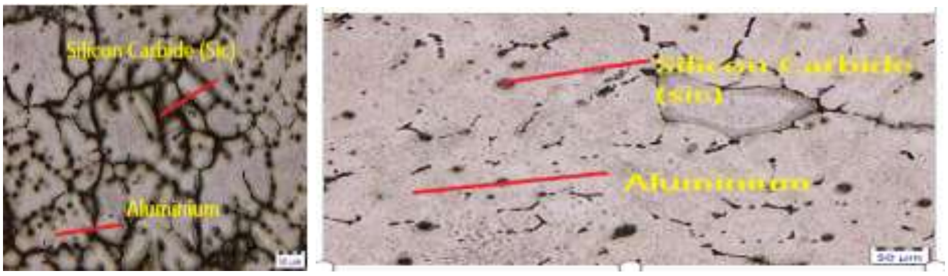

Figure 9: Al & Sic, Micro-structure at 800^{0}C

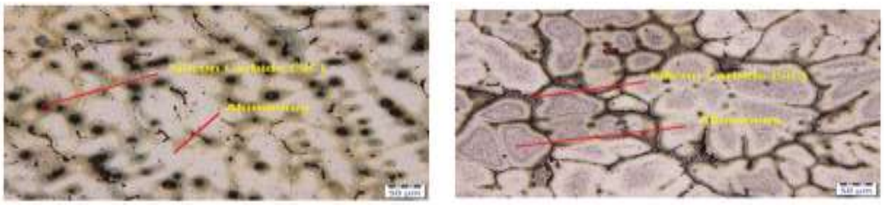

Figure 10: Al & Sic, Micro-structure at 1000^{0}C

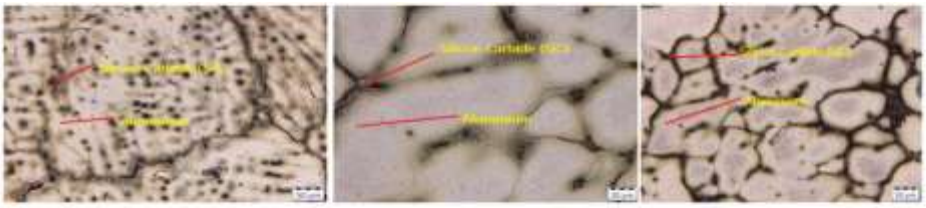

Figure 11: Al & Sic, Micro-structure at 1200^{0}C

- At lower temperature i.e. 800^{0}C the mixing of SiC is little bit typical, microlevel cracks observed at higher magnification.
- At a temperature of 1000^{0}C no wider cracks are formed but the silica deposited as fine bonding agent when observed the structure.
- At a temperature of 1200^{0}C SiC particle depositions are distributed with linear formation which can yield to some ductile nature.

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Figure 12: Welded plates

Tensile Test:

Tensile testing is essential for determining a metal's tensile strength, yield strength, ductility, and other mechanical properties. It measures the extent to which a composite or plastic specimen can stretch before breaking and the force required to do so. Composite materials are typically tested under standard procedures using basic tension or flat-sandwich tension methods.

Figure 13: Tensile test samples

Table 9: Tensile Test results

SAMPLE NO	Weld strength (MPa)
SAMPLE-1	174.5
SAMPLE-2	162.37
SAMPLE-3	181.2
SAMPLE-4	274.3
SAMPLE-5	305.5
SAMPLE-6	145.8

Hardness Test:

Material hardness testing assesses a material's resistance to penetration to estimate its strength. Hardness test results are especially useful when selecting materials, as they indicate the material's manufacturability, precision, and wear resistance. Metal hardness testing is typically conducted to evaluate the effectiveness of treatments and coatings.

Table 10: Hardness Results at different zones

SAMPLE NO	ALBM	AL HAZ	Weld	CU HAZ	CU BM
SAMPLE-1	66.6	63.9	134.7	123.2	124.7
SAMPLE-2	63.4	53.6	141.2	74.9	124.7
SAMPLE-3	61.5	56.3	145.5	111.5	123.6
SAMPLE-4	62.9	56.4	144.3	97.6	122.8
SAMPLE-5	67.1	61.1	157.2	114.9	117.3
SAMPLE-6	59.2	55.9	109.3	105.2	111.5

5. SIMULATION RESULTS

Ansys workbench temperature and power simulation of a weld was performed to verify the ultimate deformation of two metals, using experimentally determined characteristics and boundary conditions to measure thermal stress in the weld zone and HAZ.

Transient thermal analysis:

This approach evaluates a system's response to both static and dynamic boundary conditions. It also determines the time required to reach steady-state temperature and the time to reach the threshold temperature under specified boundary conditions.

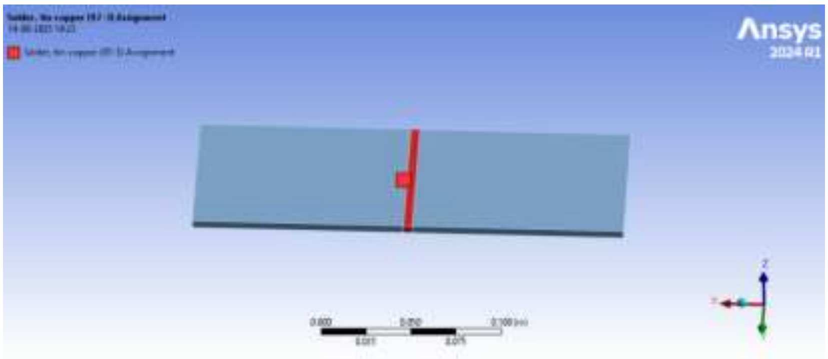

Figure 14: Material Assignment copper

The material assignment in Ansys for transient thermal analysis is used to determine the temperature distribution in a structure. It is important to accurately assign the material properties to the structure to ensure that the thermal response is accurate.

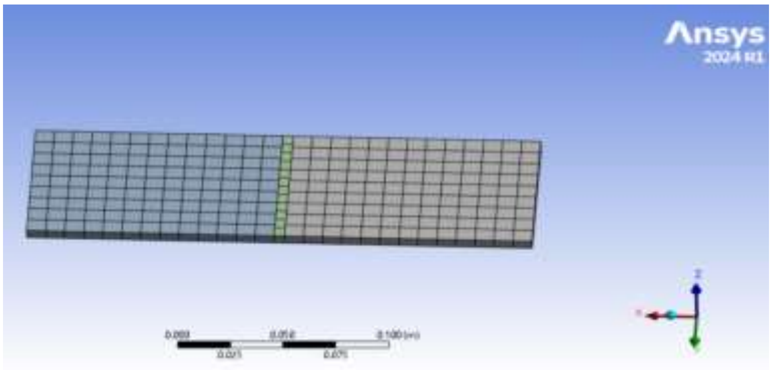

Figure 15: Meshed view

This study investigates the distribution of thermal stress on a 10-millimeter fixed segment using experimental boundary conditions with high-strength samples. Weld mobility can be monitored through heat-affected zone (HAZ) contours.

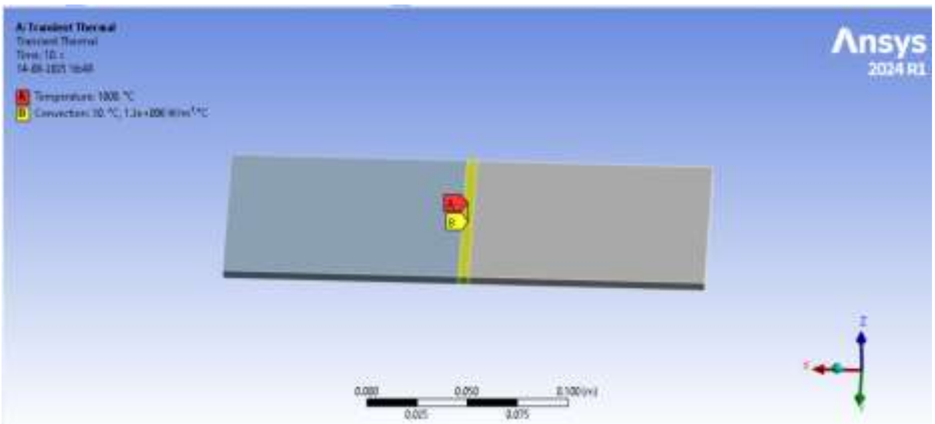

Figure 16: Apply boundary conditions

This image depicts the setup for a transient thermal analysis of a TIG weld plate in ANSYS. Boundary conditions are applied where surface A is heated to 1000°C, simulating the welding process, while surface B experiences convective cooling with a heat transfer coefficient of 30°C and a convection coefficient of 1.2e+006 W/m²°C.

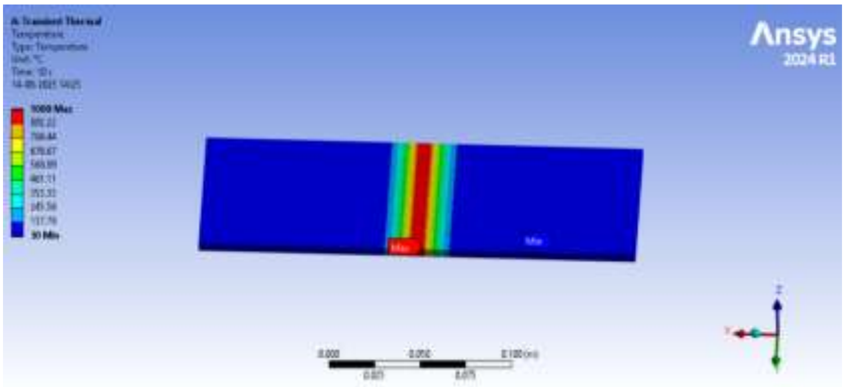

Figure 17: Temperature

This image shows the temperature distribution in the TIG weld plate after 10 seconds of a transient thermal analysis in ANSYS. The color scale on the left indicates the temperature range, with red representing the maximum temperature of 1000°C and blue representing the minimum temperature of 137.78°C.

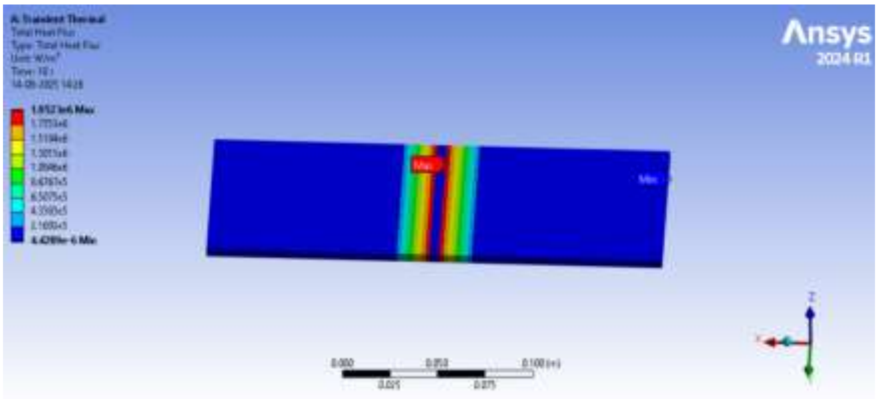

Figure 18: Total Heat flux

This image shows the total heat flux distribution across the TIG weld plate after 10 seconds of a transient thermal analysis in ANSYS. The color scale on the left represents the heat flux in units of W/m², with red indicating the maximum heat flux of 1.9523e6 W/m² at the center (near the weld zone) and blue indicating the minimum heat flux of 4.4289e-6 W/m² at the edges.

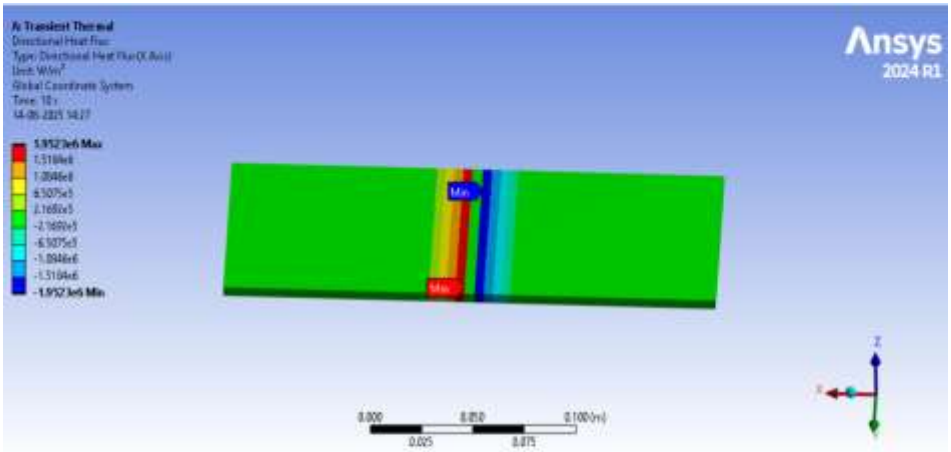

Figure 19: Directional Heat flux

This image shows the directional heat flux (along the X-axis) distribution across the TIG weld plate after 10 seconds of transient thermal analysis in ANSYS. The color scale on the left represents the heat flux values in W/m², with red indicating the maximum directional heat flux of 1.9523e6 W/m² and blue indicating the minimum directional heat flux of -1.9523e6 W/m².

6. CONCLUSION

In this study, the friction stir casting process was employed to investigate the welding behavior and performance of Al-Copper alloy plates reinforced with SiC (Silicon Carbide) and B4C (Boron Carbide) for aerospace applications. The primary focus was on understanding how varying reinforcement percentages and processing conditions influence the thermal and mechanical behavior of the weld zone. The inclusion of SiC in aluminum and B4C in copper enhanced the overall strength and thermal stability of the welded material, making it more suitable for high-performance aerospace applications where material integrity under extreme conditions is crucial. The thermal analysis using the ANSYS software revealed that the distribution of heat flow within the weld zone was significantly affected by the reinforcement material and processing parameters, such as stir speed and processing temperature. The optimal processing conditions were determined based on the temperature distribution and maximum stress evaluation, leading to improved welding efficiency and enhanced material properties. The L9 orthogonal array from Taguchi's Design of Experiments (DOE) approach proved effective in systematically varying parameters to achieve the best performance for weld quality and material stability.

1. Copper-reinforced composites have the maximum compressive strength at 8% reinforcement, and this 7% improvement in compressive strength is 79.1 percent significant.
2. This indicates that the addition of SIC and B_4C not only enhances the strength but also significantly improves the hardness of the composites. Consequently, these materials become more suitable for applications requiring high durability and resistance to wear.
3. The maximum values for density Cu reinforced composites were obtained at 8% reinforcement with a percentage increase of 2.76 percent.
4. The micro structural images show that copper contains a variety of particles of various shapes and sizes. Copper has an average pore size of 290 nanometres (nm), according to research.
5. Stir-casting method is a prominent process to get good mechanical properties after fabrication. Regular weldment of similar metals by GTAW (known as TIG) will give promising results of its same physical, mechanical and thermal properties, composite material welds in the present study given equal result by fastening it with special copper electrodes namely Aluma steel.
6. This is because the SIC and B_4C particles act as a reinforcement to the matrix material, increasing the strength and hardness of the material. The increased strength and hardness of the composites allows them to withstand greater forces and resist wear better than composites without SIC and B4C.

In conclusion, the study demonstrated that the use of friction stir casting for Al-Copper alloy welding, coupled with SiC and B4C reinforcements, enhances the thermal conductivity, mechanical strength, and durability of the welded material. This process and the optimal parameters identified in this research are highly applicable to aerospace applications, where high-strength, thermally stable, and lightweight materials are required for improved performance under extreme operational conditions. The results provide valuable insights for the future development and application of advanced welding technologies in critical industries like aerospace.

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Future recommendations/ Suggestions

1. Present work focused on the composite plate welding of dissimilar materials made of copper and aluminium, alloy combinations of tungsten is recommended in the same procedure.
2. The results from these simulations provide critical insights into the performance and durability of the welds under operational conditions. This helps in optimizing the welding process to ensure reliability and longevity in aerospace applications.
3. Thermal flow simulation in HAZ criteria with different combination of alloys as a computational work as a scope.
4. SiC and B4C can added with tungsten composite as supplementary addition as a new approach.
5. Therefore, the outcome of this study is of immense importance for aerospace and satellite engineering.

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