Research Article

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Exploring the Influence of Stirring Temperature on the Fatigue and Mechanical Characteristics of AA5128/SiC Nanocomposites

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ABSTRACT

Aluminum is anticipated to continue being the primary material for various essential uses like aviation and automobiles. This is because of the great resistance to various climatic conditions, required and controllable mechanical qualities, and high fatigue resistance. Aluminum nanocomposites like AA5128/SiC can be produced by several liquid metallurgical techniques. The main challenges for this method in producing nanocomposites involve ensuring a consistent distribution of strengthening components and controlling any chemical interactions between the strengthening compositions and the matrix. Intended for structural use, specifically in the aircraft industry, developing cost-effective nanocomposites with operational and geometric flexibility poses a significant ongoing challenge. Various methods of producing AA5128/SiC nanocomposites yield distinct mechanical characteristics. Nine nanocomposites were synthesized in the current research by varying the stirring temperatures (810, 860, and 910℃) with different levels of SiC added at 0, 6, 8, and 10 wt %. The composite consisting of 10 wt % SiC and agitated at 860℃ showed improved characteristics in tensile, hardness, and fatigue tests. The composite containing 10 wt % SiC with a stirring temperature (ST) of 860℃ led to a 22.3% rise in tensile strength, a 16.2% rise in Vickers hardness number, and a 40.2% reduction in ductility compared to the sample without nanoparticles. At 810℃ (ST), the fatigue life at a stress level of 100 MPa raised by 18.5% compared to the 10 wt% nanocomposite.

Keywords: AA5128; SiC; Stirring temperature; Stir casting technique; Mechanical properties; Fatigue properties.

1. INTRODUCTION

In the past decades, advancements in materials have enhanced their usefulness, with new forms being crucial in the progress of science and technology (Cheng *et al.* 2015; Arab *et al.* 2020). Researchers all over the world have produced and managed materials to fulfill the requirements. However, when it comes to size reduction, an established association has not been determined between the properties of materials and their nanoscale size (Zou *et al.* 2018). Currently, researchers are continuously studying, exploring, and adapting to novel inventive materials in technology (Altinkok, 2016; Kamali *et al.* 2019). A scientific study has been conducted to enhance the mechanical characteristics of alloys by investigating factors such as stirring temperature (ST) and precise quantities of metal nanoparticles added (Zhang *et al.* 2019; Muralidhar *et al.* 2022).

Several research works investigated improving mechanical characteristics by analyzing variables including stirring time, stirring temperature, and particle dispersion, which could impact material characteristics. Nanocomposites have been synthesized using a process that evenly distributes nanoparticles in metal matrix composites (MMCs). The Young's modulus and hardness have witnessed a notable enhancement as a result of incorporating a little amount of nanomaterial (Jiang *et al.* 2015). The impact of incorporating SiC, TiO_2, and ZrO_2 nanoparticles, each measuring 40 nm, into an A356 aluminum cast alloy has been examined (Suresh *et al.* 2021; Singh *et al.* 2024). The A356 matrix was weight-mixed with fraction ratios ranging from 0% to 5%. At 600 and 700 °C, the stirring time was constant at one minute, and the speeds ranged from 270 to 2150 rpm (Girimurugan *et al.* 2022; Murugan *et al.* 2022). Results showed that the characteristics of nano-reinforced castings were enhanced by incorporating SiC, TiO_2, and ZrO_2 during the semi-solid-state process at 600 °C, with 2 wt. % SiC and 3 wt. % TiO_2 or ZrO_2 while stirring at 1500 rpm. An innovative method has been proposed to improve the characteristics of casting Al alloys through the incorporation of various nanoparticles (KHOSRAVI *et al.* 2014; Soltani *et al.* 2017). The research involved the use of several nanoparticles and considered factors such as mixing speed and duration.

Furthermore, the effect of reinforcing the metallic matrix on its mechanical characteristics has been investigated (Jayaraman *et al.* 2022). The main results of this study indicated that decreasing the size of reinforcement particles and increasing the reinforcement ratio greatly improve the characteristics of MMCs. Furthermore, the investigation of creep and wear resistance has been conducted as significant elements that are sometimes overlooked. Aluminium Matrix Composites (AMCs) have been shown to gradually lose fracture toughness as the SiC fraction increases. Introducing zirconia has been found to enhance the strength of AMCs. In addition, a 10 wt % concentration of SiC nanomaterial has been incorporated into AA5128 using the stir casting technique to fabricate nanocomposites (Chandra Kandpal *et al.* 2018). Researchers analyzed AA5128 metal matrix with 10 wt % SiC nanocomposites, which showed a 13.9% increase in fatigue strength at 10^7 cycles due to the addition of 10 wt % reinforcement. The fatigue life of the 10 wt % nanocomposite was found to be enhanced by 34.48% for low-high loading sequences and by 40.69% for high-low loads (Manikandan *et al.* 2023; Srinivasan *et al.* 2023). Results showed that fatigue life and cumulative/continuous fatigue durability were both enhanced by nanoparticle addition.

Another work achieved the production of a semi-solid metal slurry with particles as the main phase by using gentle electromagnetic stirring and raising the pouring heat temperature, resulting in decreased superheat pouring. To get the main phase to take on the same size and shape as the liquid, the pouring temperature was raised from 15 °C to 35 °C above the liquidus temperature and use gentle electromagnetic stirring. The research examined the impact of stirring the alloy combination compared to not stirring it, with a specific focus on stirring temperatures above other characteristics. The effects of pouring temperature and stirring speed on the characteristics of stir cast Al5128-Cu reinforced SiC MMC have been examined (Abed *et al.* 2021). An enhanced homogeneity was attained at a stirring speed of 400 rpm compared to speeds of 200 and 600 rpm, as observed through scanning electron microscopy (SEM) analysis (GUAN *et al.* 2011).

Research on the alloy's agitation speed revealed that, above a certain point, its mechanical properties drastically degrade rather than improve. In addition, researchers (IIZUKA *et al.* 2013) conducted a study focusing on optimizing pouring temperature and stirring speed to enhance the characteristics of aluminum MMCs. Various pouring temperatures were tested while maintaining a persistent pouring speed of 3 cm/s as input variables. The experiment showed that using a pouring temperature within the limits of 750 °C to 800 °C and stirring at speeds between 400 and 600 rpm improved mechanical characteristics. The analysis aimed to improve the mechanical characteristics by optimizing stirring speed, pouring speed, and pouring temperature. A research work has been conducted to determine the best conditions for creating composites strengthened with cast at 860 °C and 6 wt % nanoparticles. The research determined the best conditions for creating composites by experimenting with reinforced nanoparticles casting. The composites showed uniformity in microstructures and improved mechanical qualities, including hardness and tensile strength. The authors have observed that improvements occur up to a certain proportion, beyond which certain qualities change without further enhancement. A recent study (Firouz *et al.* 2020) used the solutions mixing technique and successfully vulcanized nanocomposites made of acrylonitrile butadiene rubber (NBR) and graphene nanoplatelets (GNP). The results showed that, in comparison to pure NBR, the crosslinking density of the vulcanized rubber increased to 42.3%. Improving the chemical properties relies heavily on making it more homogeneous, according to the study.

Previous research works suggest that using nanocomposite materials in specific ratios using scientific fabricating techniques enhances the overall mechanical qualities. This pattern is brought to light in the present investigation. In this study, three distinct nanocomposites were synthesized utilizing the stir casting technique at temperatures ranging from 810 to 910℃. The mechanical and fatigue characteristics of three type of composites were thoroughly analyzed, followed by a comparison with full discussions on the nanocomposites.

This study aims to examine how the stirring temperature affects the AA5128/SiC nanocomposite. Three different stirring temperatures were employed during the creation of nanocomposites from AA518 to enhance its mechanical properties, such as its tensile strength, hardness, and fatigue strength, and to ensure that the materials were evenly dispersed.

2. MATERIALS AND METHODS

AA5128 was used in this study due to its extensive applications in the transportation and aerospace sectors. The chemical composition of AA5128is as follows: Si - 0.14%, Fe - 0.26%, Cu - 0.03%, Mn - 0.43%, Mg - 4.18%, Zn - 0.02%, Ti - 0.02%, Cr - 0.06 % and balance as aluminium alloy. The SiC reinforcement nanomaterial had a particle size ranging from 20 to 30 nm and density of 3.62 g/cm^3.

AA5128 was cubed into 1 to 2 cm^3 pieces, rinsed with alcohol and then with distilled water five times. The cleaned components were dried with hot air at 100 °C and then heated to around 250 °C using an electric heater. The oven was filled with argon gas and heated to temperatures of 810, 860, and 910 °C while being stirred. Simultaneously, the SiC particles were heated to a temperature of 200 °C. A gas pump was used to inject nanomaterials into the molten aluminium alloy. The furnace temperature was originally raised to 810, 860, and 910 °C above the liquid temperature of aluminum. To melt the aluminum alloy completely, the first two samples were heated to 810 °C and 860 °C, respectively. The third sample was blended at 910±15 °C and cooled to just below 650 °C. A stirring speed of 450 rpm was used for a duration of 4 minutes. The molten mixture was heated in the furnace to 810 °C±15 °C before the SiC particles were added. An Al rod was cast from the liquid using molds. The finished product was a cylinder measuring 160 mm in length and 14 mm in outside diameter. Fig. 1 displays the apparatus used for the stir casting technique. Applying the rule of the combination to AA5128 as the metal matrix is shown in Table 1.

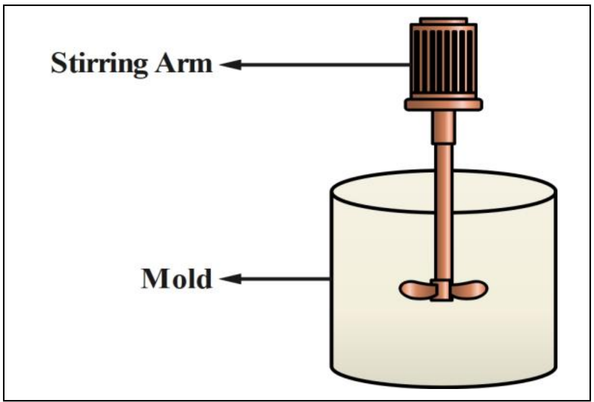

Fig. 1: Manufacturing of composites

Table 1. Rule of combination utilized in this study

SiC wt %	AA5128 (g)	SiC (g)	Total nanocomposite (g)
6 %	940	60	1,000
8 %	920	80	1,000
10 %	900	100	1,000

A WDW-100 tensile machine, capable of withstanding loads up to 100 kN, was used to conduct the tensile test. The 18 samples were employed from cylindrical rods that were made with a length (L) of 160 mm and a diameter (ϕ) of 10 mm. The deformations were documented using a measuring equipment and automated control systems. The tensile curves were plotted to predict how the material will behave under different loads.

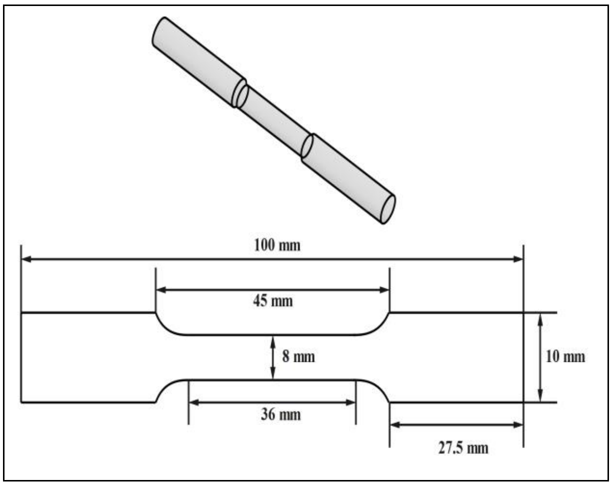

Fig. 2: Tensile sample prepared according to ASTM specification E8/E8M-09

The standard tensile specimens were fabricated following the guidelines of the ASTM E8, as shown in Fig. 2, with all dimensions measured in millimeters. This research conducted Vickers hardness numbers (VHN) on polished specimens at various ST (810, 860, and 910 °C). The fatigue tests were conducted using a rotating fatigue testing apparatus. The fatigue specimens for testing have been prepared in accordance with the DIN 50113 standard. All fatigue testing were conducted using a Schenck-type rotational bending fatigue tester.

3. RESULTS

The mechanical properties were measured at stirring temperatures of 810, 860, and 910 °C. Table 2 presents the mechanical characteristics data of AA5128 and nanocomposites with various weight percentages (wt %) of 0, 6, 8, and 10% SiC.

Table 2. Analysis of mechanical characteristics of AA5128 and nanocomposites at three distinct ST

SiC, wt %	Ultimate Tensile Strength (UTS)			Yield Stress (YS)			Vickers hardness numbers (VHN)			Ductility		
	MPa			MPa			VHN			%		
	810 °C	860 °C	910 °C	810 °C	860 °C	910 °C	810 °C	860 °C	910 °C	810 °C	860 °C	910 °C
0	156.36	162.23	150.93	143.54	146.42	129.73	98.42	104.21	94.48	18.12	17.52	18.74
6	174.95	186.98	181.78	150.65	153.58	145.23	111.93	113.28	108.12	17.16	15.77	17.68
8	184.21	196.41	182.53	155.74	161.63	156.84	114.38	116.84	112.96	14.13	13.08	16.44
10	190.78	200.79	187.41	161.36	170.97	166.65	118.52	125.69	115.87	12.63	11.96	13.71

The stirring temperature and weight percentage of SiC nanoparticles impact the mechanical characteristics of nanocomposites, as listed in Table 2. The outcomes of the UTS testing in this study using ST of 810 °C, 860 °C, and

910 °C are presented in Fig. 3 to 5, respectively. The UTS of the nanocomposites rises between 162 to 200 MPa, the yield stress rises between 146 to 170 MPa, and the Vickers hardness number (VHN) rises between 99 to 118. The ductility decreases from 17.52% to 11.96% at the optimal ST of 860 °C and with 10 wt% of SiC. An increase of 22.3% for UTS, 16.2% for YS, and 20.1% for VHN was seen, with a 40.2% improvement in ductility. AA7075/SiC nanocomposites were fabricated by the stir casting method at a ST of 860 °C, with SiC concentrations of 0, 2, 4 to 6 wt%.

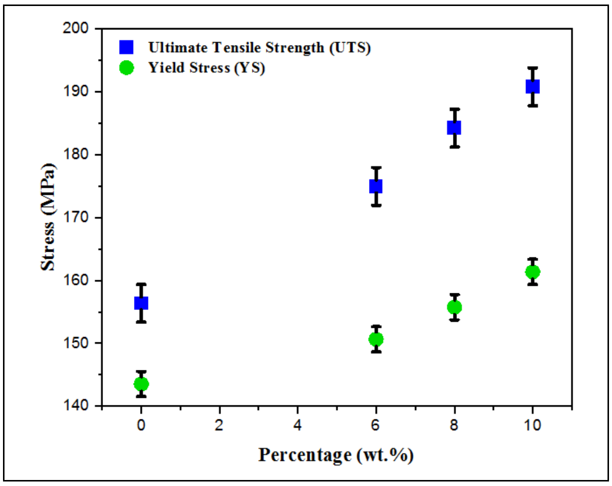

Fig. 3: UTS and yield stress (YS) at stir casting temperature of 810°C with the wt. % of SiC

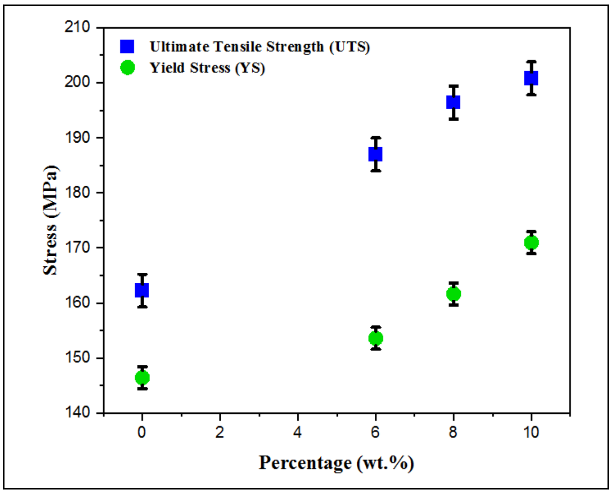

Fig. 4: UTS and yield stress (YS) at 860°C during stir casting, with the wt. % of SiC

The nanocomposite containing 10% SiC achieved an UTS of 200.79 MPa and a Yield Stress (YS) of 170.97 MPa at 860 °C with a stirring period of 4 minutes, as shown in Fig. 5. The UTS and yield stress (YS) have increased by 22.3% and 16.2%, respectively, related to the 0wt% of reinforcement. The even dispersal of silicon carbide (SiC) inside a matrix and the low porosity in the casting resulted in a high density of dislocations, which improved the mechanical properties. AA5128-based composites with 10% SiC exhibit superior mechanical characteristics. Every nanocomposite demonstrates enhanced hardness and ductility. The 10% SiC composite exhibits the most favorable enhancement in hardness and ductility at a ST of 860 °C. At 860 °C, the hardness of 10% SiC increased by 16.2% and the ductility improved by 40.2%. The results are consistent with a previous study (Girimurugan *et al.* 2022) that focused on creating and analyzing AA2024/SiC nanocomposites to enhance their mechanical properties.

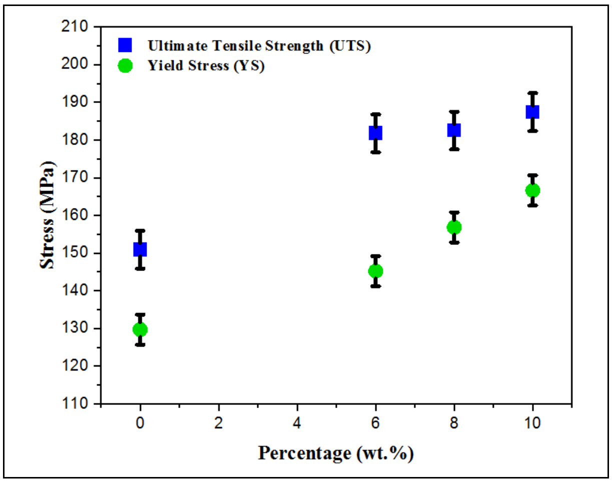

Fig. 5: UTS and Yield Stress (YS) at the stir casting temperature of 910°C with the wt. % of SiC

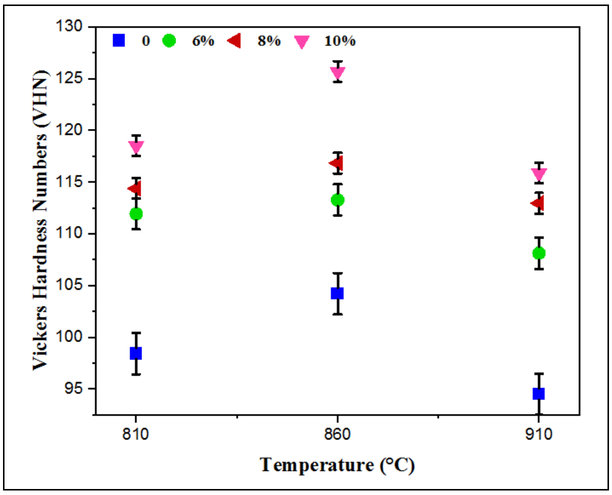

Fig. 6: Vickers hardness

Fig. 6 displays the VHN hardness results of the matrix. Significant advancements in mechanical characteristics and hardness were seen by including SiC into the matrix. The SiC particles hinder the movement of dislocations and serve as an obstacle to fracture initiation and slip band formation (Shin *et al.* 2010; Mamoon *et al.* 2020). SiC particles improve the mechanical properties and VHN of composites because they are stronger than the base metal. The mechanical properties of the composites were improved by the uniformly distributed SiC particles (Rutecka *et al.* 2011).

Increased SiC content results in decreased ductility, as indicated by ductility tests. The greatest reduction was seen in the composite containing 10 wt % SiC at a stirring temperature of 860°C. The finding is once again validated by reference (Yu *et al.* 2022), which demonstrates that enhancing the quantity of SiC enhances UTS and Vickers Hardness Number (VHN). However, ductility decreases as the silicon carbide content increases, reaching its peak reduction at 6 wt % SiC with a stirring temperature of 860 °C. Fig. 7 shows that the ductility of all composites diminishes as the amount of SiC is raised compared to the matrix material, with the most significant decrease observed in the composite fabricated at a ST of 860 °C. The temperature gradient between the base metal and SiC particles might explain why mechanical properties and hardness increase while ductility decreases (Al- Jaafari *et al.* 2021; Wei *et al.* 2024).

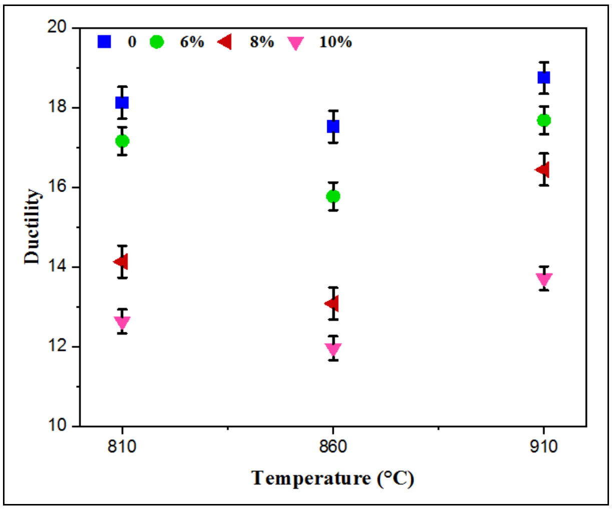

Fig. 7: The ductility varies with ST at various weight percentages of SiC

Since the sample is shaped like a circle, it is subject to the load that is applied along the vertical axis to the right side of the workpiece, which causes the bending moment to increase. Consequently, as the workpiece spins, the surface undergoes compression stress as well as tension stress. Each stress level was examined with three samples. The findings indicated that the specimen produced at 860 °C (stirring temperature) exhibit a superior fatigue life compared to the other samples, as presented in Table 3. These results can be used to examine the relationship between the fatigue life cycles and the applied stresses.

The S-N curve was plotted using data obtained from fatigue equations at three distinct stirring temperatures (810, 860, and 910 °C) shown in Fig. 8.

Table 3. Comparing fatigue test results

Stress level (MPa)	Stirring Temperature		
	810 °C	860 °C	910 °C
100	202,000	244,367	208,000
120	165,000	152,110	170,000
140	95,000	85,900	92,800
160	43,800	36,933	34,600
180	11,200	15,366	12,000

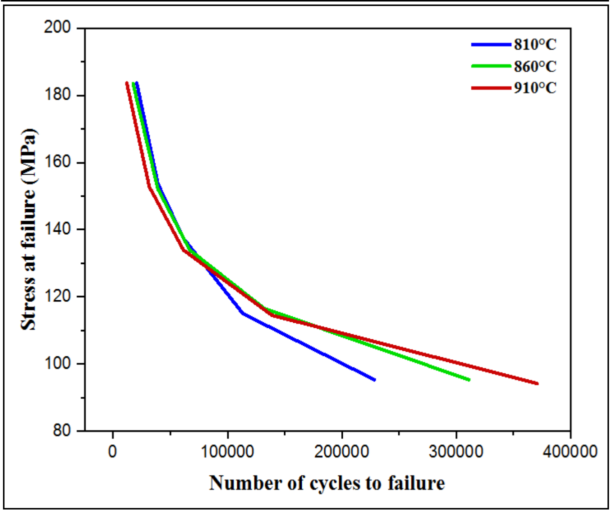

Fig. 8: Stress curvatures at three different stirring temperatures: 810 °C, 860 °C, and 910 °C

4. DISCUSSION

The study indicates that the SiC nanoparticles enhanced the characteristics by acting as barriers to dislocations, resulting in improved fatigue behavior and mechanical properties. The proposed method enhance the properties of the composites. One can notice a notable rise in UTS and YS. Fig. 6 shows a 16.2% increase in hardness (VHN) of the matrix, while Fig. 7 indicates a 40.2% increase in ductility. The composite exhibits the most improvement in UTS, YS, hardness, and ductility when 10 wt % of the nanocomposites is added to a mixture at 860 °C.

This approach is highly advantageous for enhancing mechanical properties. The characteristics, quality, and expense of nanomaterials are the crucial factors. To acquire pure and inexpensive nanomaterials, further studies are required. The limits of this method arise from the challenge of achieving a uniform distribution of nanomaterials without a thorough investigation of the molecular structure, which improves the obtained results.

Inhalation exposure is a significant drawback associated with nanoparticles. Studies in humans indicate that nanoparticles can have harmful effects on the lungs, leading to this concern. Thus, it is advisable to exercise caution when carrying out studies.

The research is valuable since the results provide significant insights for enhancing various attributes in comparison to the untreated alloy. This enhancement allows for the utilization of this alloy in various applications that require AA5128. This study is built upon previous research that has explored several nanomaterials in varied ratios and through various preparation techniques. Improving the mechanical characteristics of aluminium alloys was the primary goal of the research. As this technique develops, it will be possible to improve the mechanical and fatigue properties of a wide range of aluminum alloys by adding nanomaterials in varying concentrations; the exact amount needed will depend on the interplay between the nanoparticle ratio and the Al alloys themselves.

5. CONCLUSIONS

The study showed that using a stirring temperature of 860 °C with 10 wt % SiC composites results in superior mechanical properties, hardness, and fatigue properties compared to stirring temperatures of 810 °C and 910 °C. The stirring temperature significantly impacts these properties. The composite containing 10 wt % SiC, stirred at 860 °C, demonstrates the maximum hardness and lowest elongation when compared to composites stirred at other temperatures.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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