High-Temperature Performance of Al-Si Nanocomposites Developed by Ultrasonic Cavitation-Assisted Casting Method

Surender Kumar[1], Anant Krishan Pun[1], Akant Kumar Singh[1]

[1]Department of Mechanical Engineering, Chandigarh University, Mohali, Punjab, 140413, India

Abstract. Aluminum-silicon (Al-Si) nanocomposites have emerged as promising materials for applications at higher-temperatures as they have superior mechanical properties and thermal stability. Present study examines the high-temperature performance of Al-Si nanocomposites fabricated by casting method assisted by ultrasonic cavitation. This ultrasonic cavitation-assisted casting improves nanoparticle dispersion, minimizes agglomeration, and improves bounding of matrix-reinforcement. The developed composites enhanced hardness, tensile strength, and thermal stability at elevated temperatures. The paper puts forward a complete analysis of the thermal performance of composites under high-temperature conditions, mechanical behaviour, demonstrating the potential of ultrasonic processing in the development of advanced nanocomposites.

Keywords : Ultrasonic, Nanocomposites, Mechanical Properties, High Temperature

1 Introduction

Aluminium matrix composites (AMCs) with ceramic nanoparticles such as Al_2O_3, SiC and B_4C as reinforcement have attracted major attention for applications in automotive, aerospace, and structural components as they have favourable specific strength and excellent thermal properties. Among these reinforcement, Al-Si-based nanocomposites are particularly remarkable due to inherent qualities of SiC nanoparticles, like low density, resistance to wear, good cast ability and good compatibility with aluminium.

At elevated temperature service conditions, materials are required to maintain their mechanical properties, resist creep and fatigue. Traditional aluminium alloys, though lightweight and easy to develop, does not work well in high-temperature condition. The addition of nanoparticles into the matrix improves not only the mechanical properties but knowingly contributes to better performance at high-temperature through mechanisms like load transfer, grain boundary pinning, and thermal mismatch strengthening. However, attaining uniform nanoparticles dispersion within the Al matrix remains a major job due to issues like nanoparticle poor wettability and agglomeration. Ultrasonic cavitation-assisted casting has developed as a sustainable method to overcome these challenges by generating high-energy acoustic waves that help in breaking up nanoparticle clusters and encouraging homogeneous distribution. Previous studies have established that nanoparticle-reinforced Al-based composites exhibit superior mechanical and thermal characteristics compared to their microcomposite [1][2]. Prasad et al. [3] reported the use of Al_2O_3 nanoparticles in an Al matrix improved hardness and tensile strength significantly. Similarly, Zhao et al. [4] emphasized the significance of dispersion techniques, presenting that ultrasonic action reduces agglomeration and improves interfacial bonding. A detailed review by Suryanarayana [5] on nanocomposite development techniques emphasized that ultrasonic processing is particularly effective in creating uniform particle distribution in metallic matrices.

Provenzano and Holtz [6] developed both micro and nanocomposites for study of high temperature application. They found very good performance of nanocomposites at high temperature as compare to micro composites. Malaki [7] worked on advanced nanocomposites for improvement its performance at elevated temperature conditions. They conclude that performance of nanocomposites can be improved by maintaining the good microstructure of the nanocomposites. Kumar et al [8] probed the performance at high temperature of aluminium matrix nanocomposites as single reinforced and hybrid reinforced composites. Wear performance of developed composites showed a decreasing trend with an increase in temperature but hybrid composites retained their wear performance due to existence of MoS_2 particles (solid-lubrication). Microstructure of wear out surface confirm abrasive wear in mono reinforced while lubrication layer in case of hybrid reinforce composites. Martin [9] worked on improve of wear performance of aluminium at elevated temperature by using graphene nanoplatelets (GNPs). High temperature wear performance has been analysed from room temperature to 300 °C. The developed nanocomposites exhibit improved hardness and wear resistance. Yang et al. [10] fabricated Al 2024 –TiCp nanocomposites and tested their mechanical properties at high temperature. The tensile strength

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improved at high temoeratre as compare to unreinforced aluminium alloy. He et al. [11] developed in-situ $(Al_3Zr+ZrB_2)$/AA6016 AMCs. The wear experiment has been performed at elevated temperature. The wear resistance found better as compareds to the unreinforenced alloy at high temperatures. Sharath et al. [12] produced hybrid metal matrix composites (HMMCs) using simple stir casting technique. Tensile strength of composites material has been examined at temperatures ranging from 50-300°C. The developed compoites exhibits high tensile strength as compare to aluminium alloy Al2618. Sahoo el al. [13] examined sliding wear behaviour at high temperature of *in-situ* sub-micron sized TiB_2 reinforced ZE41 composite. The performance of composites was found better in comparison to unreinforced alloy. Further more wear mechanism has been analysed at high temperature. Zhuang et al. [14] studied of Al-6061/NiTi composite's tensile strength at 150, 200, and 250°C. Results reveals that tensile strength found more for developed composites as compared to Al6061 alloy. Lattanzi et al. [15] worked on Al-Sic composites for high-temperature wear as brake pad materials. The tests for wear were performed at NTP and also at elevated temperatures of 250 and 400 °C. The experiments were performed at high temperature on a pin on disc tribometer. Results reveal that brake pad material of Al-SiC has a lower wear rate and a longer lifespan. Senthilkumar et al. [16] examined novel LM25 aluminium alloy/Silicon Carbide foam (SiC_f)- IPCs developed, for wear and friction behaviour at elevated temperatures. Pin on disc tribometer was used to examine the tribological properties. The study testified that wear rate decreased with increase in refinforcement quantity. Kumar and sood [17] developed aluminium matrix nanocompoistes and performed wear tests at elevated temperature on pin on disc tribometer. The result reveals that performance of developed composites improved wear perforamce at high temperature. Present study delves into the mechanism of ultrasonic cavitation, its impact on nanoparticle dispersion, and the resulting increment in mechanical and thermal performance of Al-Si nanocomposites. Conversely, insufficient studies have concentrated on high-temperature performance, which is critical for aerospace applications and automobile applications.

2 Materials and Methods

2.1 Materials

In our study base matrix used is Al7075. The majour alloying elements of Al7075 are Zink (Zn), Magnesium (Mg) and copper (Cu). Some important properties of Al7075 are the density of Al7075 material (2.81 g/cm^3), the melting point (650°C), and the thermal conductivity (130-160 W/mK). Reinforcements included nano-sized particles of silicon carbide (SiC) selected. The thermal stability and mechanical reinforcement capatebility with aluminium alloy is main reason for selection of both as matrix and filler materials. These nanoparticles have average sizes ranging between 40 nm to 50 nm. These materials have excellent hardness and high melting points, which contribute significantly to the thermal endurance of the composite.

2.2 Ultrasonic Cavitation-Assisted Casting

The casting process involved melting the Al 7075 alloy at around 760°C in a graphite crucible under an inert argon atmosphere to prevent oxidation. Fig. 1 shows the setup of ultrasonic cavitation assisted casting technique. Nanoparticles were preheated to 400°C to remove moisture and enhance wettability. Ultrasonic cavitation was introduced using a titanium alloy sonotrode operating at 20 kHz and 1 kW power for 5 minutes. The ultrasonic prove was immersed into the molten metal to create localized high-pressure zones, resulting in cavitation bubbles that collapsed violently. This collapse generates shock waves and microjets, aiding in the uniform distribution of nanoparticles and the breakdown of any agglomerated clusters. Stirring was continued for an additional 5 minutes post-ultrasound to ensure complete mixing of nanoparticles with aluminium alloy.

Fig. 1. Ultrasonic Cavitation assisted casting technique setup

2.3 Wear and Mechanical Testing

The developed composites has been tested for both mechanical and tribological performance. For analyzing rate of wear, high temperatue pin on disc tribometer make: DUCOM, ASTM G-99 standards was used as shown in Fig. 1. During tests sample holder held the pin firmly while the cylindrical samples were kept stationary and disc of EN31 (HardnessHRC65) with roughness Ra 1.21 has been rotated during experimentation. The track diameter of rotation of sample kept at 65 mm. The wear rate calculations were done by weight loss method formula given in equation (1)

$$WR = \Delta m/\rho d \tag{1}$$

Where Δm: weight loss in grams, ρ: density of fabricated composites and d: sliding distance in meters. Weight loss has been calculated initial and final weight of sample befour testing and after testing. Density (ρ) has been calculated as accurately mass per unit volume of developed composites. Average of three different readings has been taken for final calculation. Sliding distance is same for all experiments its value is 1200m. Tensile strength and hardness of nanocomposites has been investigated on UTM machine and Rockwell hardness tester. Tensile strength and hardness of developed composites were investigated as per ASTM E8 and ASTM D785-89 standards respectively.

Fig. 2. High temperatures Tribometer pin on disc: DUCUM Make

3. Results and Discussion

3.1. Mechanical Properties

The hardness of nanocomposites increased by 30% approximately as compared to unreinforced alloy due to presence of hard nano-reinforcements and refined grains. Tensile strength at room temperature showed a significant improvement, with values increasing from 187 MPa (S-1) to 246 MPa (S-3). Similarly the values of hardness increase form 65 HRB (S-1) to 79 HRB (S-3). The mechanical enhancement is attributed to several synergistic strengthening mechanisms: Orowan looping around nano-sized reinforcements, load transfer due to stiff particles, and thermal mismatch-induced dislocation generation. These mechanisms are particularly effective in nanocomposites where the surface area-to-volume ratio of the reinforcement is high.

Table 1. Hardness and Tensile strength of fabricated composites

Sr. No.	Samples Designations	Tensile Strength (MPa)	Hardness(HRB)
1.	S 1.00 [Al705+1%SicP]	187	65
2.	S 2.00 [Al705+2%SicP]	236	71
3.	S 3.00 [Al705+3%SicP]	246	79

3.2 Wear performance

Thermogravimetric analysis revealed negligible wear of nanocomposites up to 120°C. indicating excellent thermal stability. The analysis showed higher heat absorption capacity and resistance to thermal softening, attributed to the thermal stability of the reinforcements and the strong interfacial bonding achieved through ultrasonic processing of melt. This suggests potential applicability in engine components, break pads, heat exchangers, and other high-temperature condition.

The improved thermal performance is a result of the thermal barrier effect introduced by the reinforcements, which retard heat flow and reduce matrix softening. Furthermore, the nanoparticles hinder atomic diffusion, thereby suppressing creep and grain boundary sliding, which are dominant at high temperatures. The reponse surface methodology (RSM) use for experimetns design. The parameters for finding the performance of nanocomposites has been given in Table 2. Table 3. signifies the values of wear rate at different combination of experiments.

Table 2. Parameters and their level

Parameters	Notation	level-1	level-2	level-3
Pin Temperature (°C)	A	75	150	225
Normal Load (N)	B	8	16	24
Sliding Velocity (m/s)	C	1.00	2.00	3.00
Reinforcement Percentage (%)	D	1	2	3

Table 3 Experiments details values of wear rate

Sr. No	Pin Temperature (°C)	Normal Load (N)	Sliding Velocity (m/s)	% Reinforcement	(Wear Rate) × 10^{-4} (mm^3/m)
1	150	8	3	2	3.143
2	150	16	2	2	3.9838

3	225	24	2	2	6.0073
4	150	16	1	3	3.0142
5	225	16	3	2	6.4214
6	150	16	2	2	4.1257
7	150	16	2	2	4.1612
8	150	24	3	2	5.6145
9	150	8	2	1	3.1654
10	150	8	2	3	2.5265
11	225	16	2	1	6.0931
12	150	8	1	2	2.5022
13	75	16	3	2	3.3125
14	225	16	1	2	4.1105
15	150	16	2	2	3.9921
16	150	16	3	1	5.4521
17	75	8	2	2	1.7247
18	150	24	1	2	4.5157
19	150	24	2	1	5.0624
20	150	24	2	3	3.4244
21	75	16	2	1	2.8571
22	150	16	3	3	4.4421
23	75	16	1	2	1.8923
24	150	16	1	1	3.3625
25	75	24	2	2	3.0512
26	75	16	2	3	2.0256
27	150	16	2	2	3.9814
28	225	16	2	3	4.5625
29	225	8	2	2	4.1514

All the four parameter has been analysed for the wear rate. The variation of each parameter has been shown in Fig. 3. The parameter ‘A’ is significantly affect the wear rate and subsequently B & C. These parameters signify increased wear rate with rise in normal load, sliding speed and pin temperature. The parameter ‘D’ signifies that wear rate decreased with rise in quanity of nanoparticles in aluminium alloy. It shows that addition of nanoparticles in aluminium alloy significantly reduce wear rate of nanocomposites.

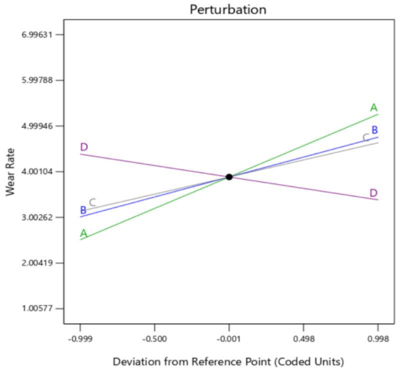

Fig. 3. Perturbation for each parameters on same platform.

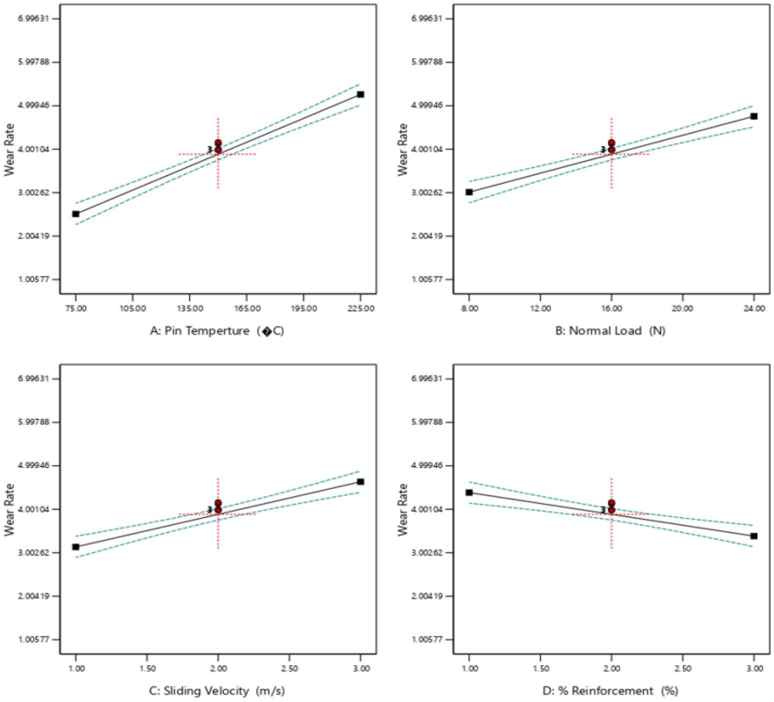

Fig. 4. Variation of each parmeter with wear rate on individual platform

The Fig. 4. shows that variation on each paramter starting form A –D on individual graphs. The graphs dipicts the variation on paramters are in acceptance range as variation lies within green boundry lines.

4. Conclusion

Nanocomposites successfully developed with help od ultrasonic cavitational assistant casting technique. All the sample has been manufacures as per ASTM standard for investigations. Following the important conclusion drawn form present investigations.

- Ultrasonic cavitation-assisted casting proves to be an effective technique for fabricating Al-Si nanocomposites with enhanced high-temperature wear performance.
- The mechanical properties improve with inclusion of nanoparticles and good interfacial bondings. Significant rise in tensile strength and hardness of nanocomposites was observed with addition of nanoparticles.
- High temperature performance of developed composites is excellent for developed nanocomposites. Wear performance decreased with an increase in sliding speed, sample temperature and Normal load, while wear performance increased with rise in weight percent of filler materials.
- These findings suggest that such nanocomposites are suitable for applications requiring high strength and reliability at elevated temperatures, including aerospace, automotive, and thermal management systems.

5 Future Work

Further investigations are recommended to explore hybrid reinforcement systems combining multiple nanoparticles. Long-term thermal cycling experiments and fatigue behavior assessments under high-temperature environments are essential to confirm the durability of these composites in service. Additionally, optimizing the parameters of ultrasonic treatment—such as duration, frequency, and energy input—can lead to even better mechanical and thermal outcomes.

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