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Experimental Investigation on Metallurgical and Mechanical Properties and Wear Behavior of Al5032/SiC Nanocomposites

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Aluminium metal matrix composites are highly dominated composites for various applications such as military, marine, aircraft, aerospace and automobile because of their corrosion resistance, tribological and mechanical properties. In this research, aluminium alloy 5032 composite reinforced with SiC_{np} (4, 8, 12 and 16 wt.%) was manufactured using stir casting method and subjected to various mechanical, metallurgical and wear tests. The novelty of this research lies in the fabrication and characterization of Al5032/SiC_{np} composites, which has been not done before. The Energy Dispersive X ray analysis (EDAX) was used to examine the presence of SiC in Al5032 matrix and Scanning Electron Microscope (SEM) was employed to examine the microstructure of the composite. Further micro hardness, wear resistance, tensile and impact tests were carried out. The aforesaid properties increases upto 12 wt.% addition of silicon carbide in Al5032 alloy and thereafter reduces. The nanocomposite Al5032/12wt.%SiC exhibits 98 HV, 256 MPa tensile strength, 19 MPa impact strength and 5 mg wear loss.

Keywords: *Aluminium alloy 5032, Silicon carbide, Nanocomposite, Stir casting, Pin on disc, Wear resistance.*

1. Introduction

Innovative materials are needed to suit the demands of application in industries that are rapidly developing, such as the marine, military, transportation, and automobile[1,2]. By combining two or more components, composites can give all the necessary properties in a single material[3]. Aluminium metal matrix composites (AMMCs) are very suitable materials in all kinds of mechanical utilization with their unique attributes like greater strength to less weight proportions, resistance to corrosion and increased tribological characteristics[4]. Numerous techniques, including powder metallurgy, centrifugal casting, additive manufacturing and stir casting are used to create aluminium-based nanocomposites[5,6].

The simplest, least expensive and most straightforward method for creating composites is stir casting[7]. To enhance the characteristics of matrix materials, a variety of reinforcements are used, such as boron carbide, titanium-di-oxide, titanium carbide, titanium-di-boride, silicon nitride, silicon carbide, and zirconium-di-oxide[8,9]. Silicon carbide is used more frequently to improve structural qualities compared to other reinforcing materials[10]. The Al2024 is strengthened with silicon carbide, and the outcomes show that doing so improves the mechanical properties of the composites[11]. Silicon carbide was added to the LM25-based composites in weight percentages of 1, 2, and 3 to increase their tensile strength and hardness[12]. The findings from microhardness tests revealed that, the silicon carbide and titanium additions in different weight percentages to strengthen aluminium alloy 7075, increased

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Table 1. Elements in Al5032 alloy.

Elements	Cr	Fe	Mg	Cu	Mn	Ti	Si	Al
Wt.%	0.23	0.3	2.48	0.02	0.03	0.02	0.09	Rem.

the microhardness and decreased the same at 15 wt.%[13]. The aluminium alloy 6061 was reinforced with SiC and B_4C (3, 6, 9 and 12 wt.%) through the use of powder metallurgy. In the above reinforcement combinations, aluminium alloy 6061 composite reinforced with 12 wt.% B_4C has a higher tensile strength[14]. The Al6061/SiC/Gr composites were made using the stir casting method. Al6061/10%SiC/10%Gr composite have greater tensile strength and microhardness when compared to other manufactured composites[15]. The wear resistance of aluminium alloy 7075 with ZrB_2 reinforcement is higher than that of the base alloy[16]. Different particle size of silicon carbide (63, 76 and 89) was incorporated into aluminium alloy 8011 and it has been found that the highest particle size of silicon carbide resulted a composite with lowest mechanical properties[17]. The addition of tantalum carbide (TaC) and niobium carbide (NbC) enhances the mechanical properties of Al2024[18]. The mechanical properties such as ultimate tensile strength, yield strength and microhardness of Al-Si metal matrix composite are enhanced by the addition of vanadium carbide (VC) and fly ash (FA) reinforcements[19]. The addition of tantalum carbide and boron nitride into the aluminium alloy 7075 enhances the compressive strength and microhardness of the resulting composite[20]. The addition of silicon carbide in aluminium matrix increases the mechanical properties[21]. The addition of zirconium di oxide enhances the mechanical properties and wear resistance of Al2024 based composites[22].

The Al5032 alloy has high temperature resistance and corrosion resistance. The characteristics of Al5032 based composites has not been examined so far and this is evident from the literature review. Therefore, the novelty lies in the fabrication and characterization of Al5032 based composites. In this investigation, SiC nanoparticles are added in different weight percentages to the Al5032 alloy to attain Al5032/SiC nanocomposites through stir casting method. Then the resulting metal matrix composites were examined for their wear behaviour along with metallurgical and mechanical properties.

2. Process Procedure of Specimen Fabrication

2.1. Materials

The aluminium alloy 5032 which is widely used for marine and aerospace structural applications[23] is chosen as matrix material and it has higher corrosion resistance than other series of aluminium alloy. The mechanical properties of aluminium alloy 5032 are low even though its corrosion resistance and temperature resistance are high. So enhancement of mechanical attributes of aluminium alloy 5032 is needed and the gas chromatography was utilized to conduct this test. Table 1 reveals the elements present in aluminium alloy 5032. Table 2 displays the mechanical characteristics of aluminium alloy 5032 and nano silicon carbide. The properties given in Table 1 and 2 are given by the vendor: Sigma Aldrich Chemicals Private Limited, Bengaluru, India. The silicon carbide has higher mechanical properties than other reinforcements[24]. Hence, the silicon carbide nanoparticle is chosen as reinforcement material in this experimental investigation to enhance the mechanical properties of Al5032.

Table 2. Mechanical properties of Al5032 alloy and $SiC_{np.}$

Material	Ultimate tensile strength, MPa	Vickers hardness, HV	Young's modulus, GPa
Al5032	228	68	69.2
SiC_{np}	2920	2700	417

The aluminium alloy 5032 and silicon carbide is chosen as round rod and powder form, respectively. The purity and density of Al5032 is 99.5% and 3.21 g/cm^3, respectively. The average particle size of silicon carbide is less than 150 nm (0.15 µm). The SEM picture of aluminium alloy 5032 and SiC_{np} is shown in Figure 1.

2.2. Fabrication of composites

The matrix material Al5032 is reinforced using silicon carbide nanoparticles with various weight percentages such as 4, 8, 12 and 16. The Al5032/SiC nanocomposites are manufactured with the support of stir casting process route. The purchased Al5032 round rod is cut into several pieces of round form to easily put into the electric crucible furnace. The silicon carbide nanopowder is preheated at 450° C for 30 minutes. The preheating is very useful for good bonding with Al5032 matrix material. The Al5032 pieces are heated to its melting temperature and then the preheated silicon carbide is fed into the molten Al5032 matrix material. The stirrer is rotated in the crucible furnace at a constant speed of 500 rpm for 20 minutes to obtain an even dispersion of nano silicon carbide powder particles in base matrix material of Al5032. The increasing of wettability between Al5032 matrix material and reinforcement nano silicon carbide is achieved by adding magnesium (1 wt.%) during stirring[25]. The molten Al5032/SiC nanocomposite is poured into the formed cavity for casting. The solidification is done at the atmospheric environment. The dimensions of the fabricated composites are 250 x 150 x 20 mm and used to obtain specimen for various testing. Figure 2 shows the stir casting equipment.

2.3. Testing of composites

The manufactured Al5032/SiC nanocomposites were subjected to mechanical, metallurgical and wear testing to study the corresponding properties and measure wear resistance. The mechanical, metallurgical and wear testing specimens were obtained by wire-cut electrical discharge

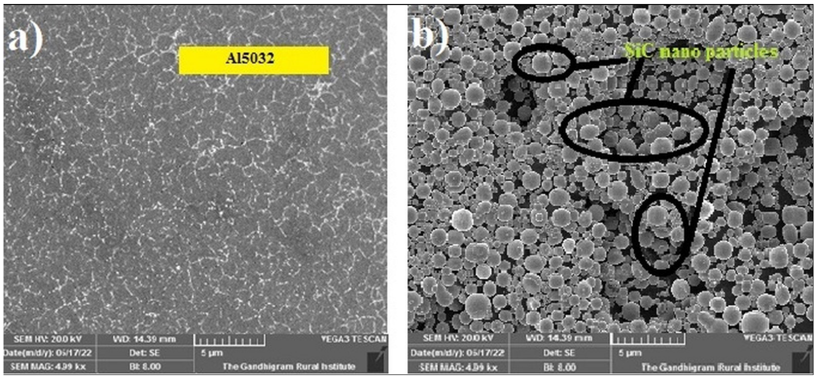

Figure 1. SEM picture of: a) Al5032 alloy and b) SiC nanoparticles.

machining (WEDM). The conventional cutting method cannot be used because nanoparticle reinforcements will be dislocated during cutting[26]. But the WEDM avoids the dislocation of particles in Al5032 nanocomposite during cutting of casted specimen into required shape[27]. The specimen was cut to ASTM standard as required for various testing.

The manufactured Al5032/SiC nanocomposites were subjected to Energy Dispersive X-ray Analysis (EDAX) to study the presence of processed matrix and nano SiC in the composites. Further, micrographs of the workpieces were obtained to examine their microstructure. The usage of antimicrobial agent enhanced the quality of the micrographs[28]. The different grit sheets were employed for surface polish of Al5032/SiC nanocomposites. The average surface roughness value of Al5032/SiC nanocomposites is 1μm[29]. The microhardness test for Al5032/SiC nanocomposites was done by using the Vickers hardness equipment (FIE,VM-50).

The Vickers microhardness investigation was carried out with ASTM E-384 standard. The Vickers hardness test on Al5032/SiC nanocomposites was done at the load of 350g for a duration of 15 seconds. The tensile strength of the nanocomposites was found by conducting tensile test (ASTM standard B557) using universal tensile testing machine (AGX-V series). The impact strength of the nanocomposites was found by conducting impact test (ASTM-E23 standard) using impact testing machine (ZwickRoell).

The pin-on-disc setup (Ducom) was used for studying the wear performance on Al5032/SiC nanocomposites. The chosen pin material was the manufactured composite and the wear test was carried out with required standard of ASTM G99-05[30]. The EN31 steel serves as disc material in the above test process. The three different combinations of wear test parameters, as given in Table 3, was utilized to investigate the wear behaviour. The surface of the wear test specimen was polished to 1 μm[31]. The wear loss of the specimen was examined by measuring the weight of the specimen prior and after finishing the wear test. The electronic weighing machine with accuracy of 0.0001 g was employed for calculating the wear loss.

Figure 2. Stir casting equipment used in this investigation.

3. Results and Discussion

3.1. Testing of metallurgical properties

Al5032 composites, reinforced with SiC_{np} (4, 8, 12 and 16 wt.%), were analyzed through EDAX to find the presence of constituent elements. The EDAX test results are shown in Figure 3 and it confirms the presence of each element's concentration. Aluminium alloys are bound to show the presence of oxygen, especially if the casting is done in the air. The presence of oxygen is not revealed in the EDAX as its accuracy limit is to show the elements with more than 1 wt.%.

The SEM test was conducted to examine the microstructure of the nanocomposites under investigation. The SEM picture of Al5032/SiC nanocomposites are shown in Figure 4. The silicon carbide nano reinforcements meant for strengthening are

Table 3. Wear test input parameters.

Wear test input parameters		
First combination for wear test	Second combination for wear test	Third combination for wear test
Constant applied load = (24 N)	Constant applied load (24 N)	Constant sliding velocity (2.4 m/s)
Constant sliding distance (1600 m)	Constant sliding velocity (2.4 m/s)	Constant sliding distance (1600 m)
Varying sliding velocity from 0.6 to 2.4 m/s instep of 0.6 m/s	Varying sliding distance from 400 to 1600 m instep of 400 m	Varying applied load 6 to 24 N in step of 6 N

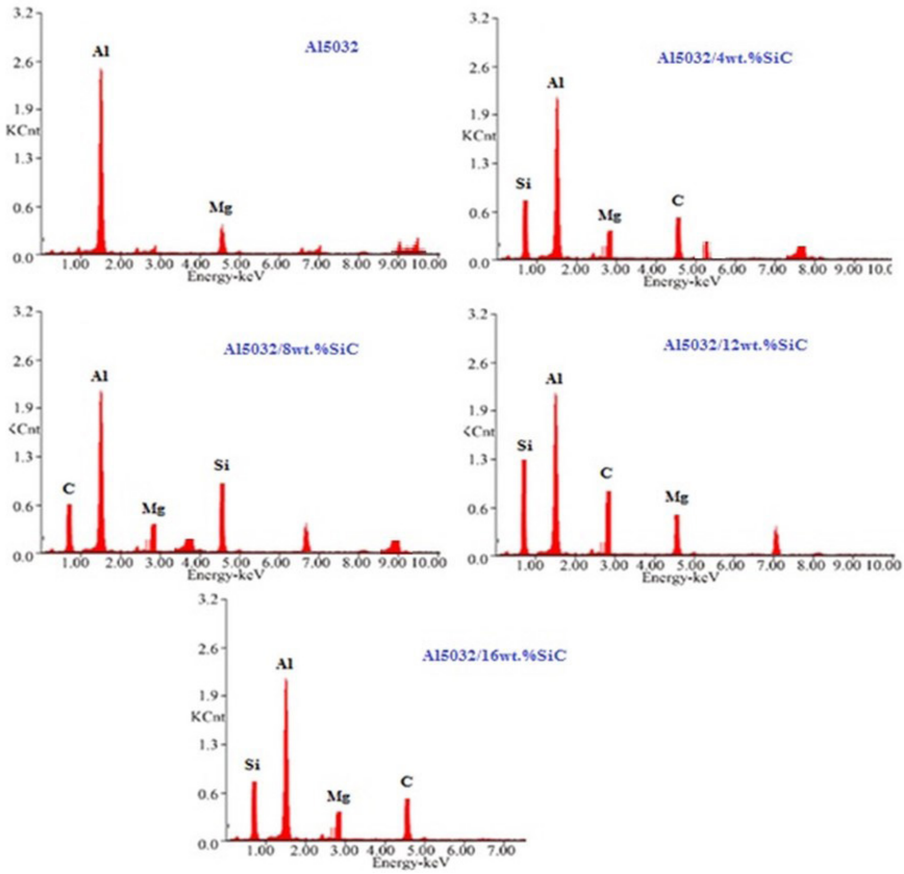

Figure 3. EDAX test results of Al5032/SiC nanocomposites.

dispersed evenly in the Al5032 matrix and it is justified through the SEM images. At the same time, it is evident that cluster of reinforcements happened at higher weight percentage addition of SiC. The oxide has occurred in some places on surface of the Al5032 nanocomposites, because of significant amount of humidity in cooling atmosphere[32].

3.2. Testing of mechanical properties

The Al5032 alloy without strengthening particles results in inferior mechanical properties[33]. Table 4 presents the average mechanical properties of Al5032 alloy and Al5032 reinforced with different weight percentages of SiC. The Vickers hardness of Al5032 alloy has got enhanced by the incorporation of silicon carbide nanoparticles. It has been observed that increase in wt.% of SiC_{np} has increased the Vickers hardness of the resultant composite and the aforesaid holds valid only upto 12 wt.% of SiC_{np} addition. The Vickers hardness of the specimen decreased at 16 wt.% of SiC_{np} addition. Similar results have been witnessed in peers work[13,17]. This can be attributed to the enhanced bonding strength between SiC_{np} and Al5032 matrix, as the reinforcement is uniformly distributed upto 12 wt.% addition of SiC_{np} (Figure 4). But, at 16 wt.% of SiC_{np} addition, the bonding strength of SiC_{np} with Al5032 matrix material might have gone below due to agglomeration of reinforcement particles, which is evident from Figure 4 and this may be the reason for reduced Vickers hardness. The bonding strength prevents the dislocation of reinforcement particles and thereby enhanced hardness.

Similar trend is observed for the properties namely, tensile strength and impact strength. The visual comparison of Vickers hardness, tensile strength and impact strength is shown in Figures 5, 6 and 7, respectively. The addition of

Table 4. Properties of the investigated specimens.

S.No	Material	Hardness (HV)	Tensile strength (MPa)	Impact strength (MPa)
1	Al5032	75	228	12
2	Al5032/4wt.%SiC	82	232	14
3	Al5032/8wt.%SiC	89	241	17
4	Al5032/12wt.%SiC	98	256	19
5	Al5032/16wt.%SiC	92	245	18

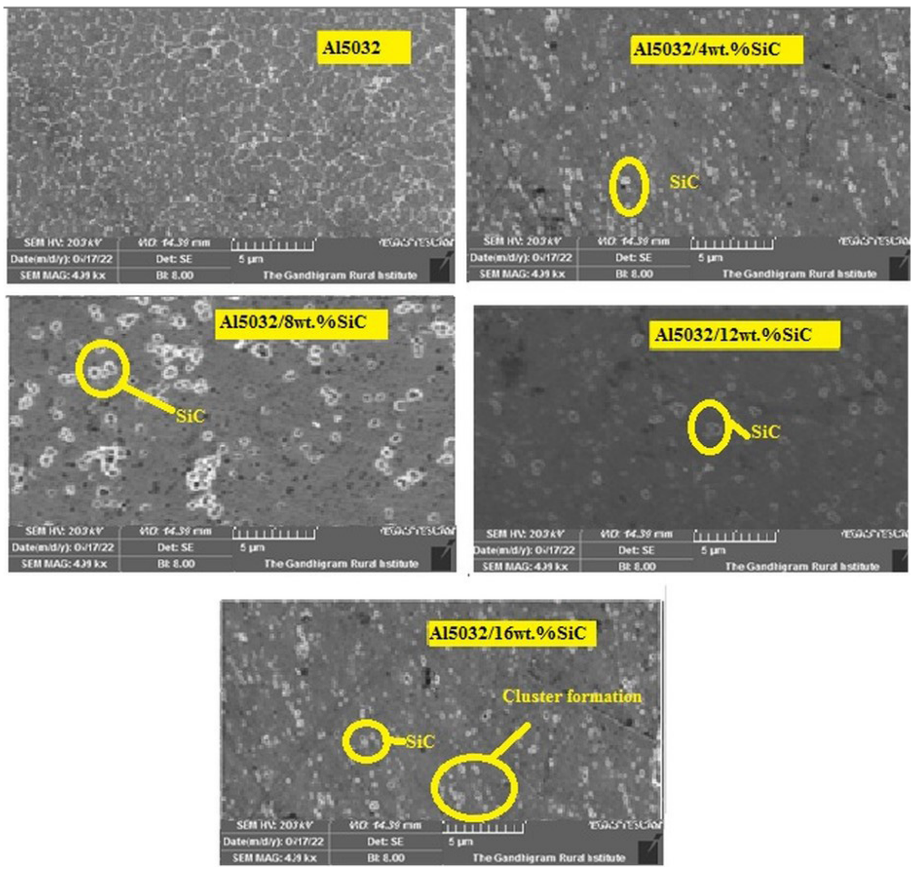

Figure 4. SEM picture of Al5032 based nanocomposites.

SiC_{np} to the Al5032 alloy transfers the resulting composite from ductile nature to brittle nature. This is the reason for increase in tensile strength with respect to the increase in wt.% of SiC_{np} addition. The observed trend in the investigated properties shows that there is a linear relation between hardness and tensile strength. Impact strength is a function of both tensile strength and fracture toughness. Hence impact strength cannot be correlated with tensile strength only. Therefore the fracture surface of the tested specimens were investigated. The fracture surface of tensile and impact tested specimen is shown in Figure 8a and 8b, respectively. Figures 8a and 8b, shows that the fracture has occurred in the matrix material near the bonding region of SiC_{np} with Al5032 matrix. Hence it can be concluded that the impact strength of the investigated specimens increased upto 12wt.% addition of SiC_{np} due to increased bonding strength and further addition of reinforcement lead to decrease in impact strength due to less bonding strength caused by the agglomeration of reinforcement particles. Therefore in the composite Al5032/SiC_{np} a linear relation between hardness, tensile strength and impact strength exists.

3.3. Investigation of wear behaviour

The prepared Al5032/SiC nanocomposite specimens wear subjected to wear test as per the three different combinations of wear test input parameters (Table 3) and the results were given by considering the average values. The first combination for wear test is meant to identify the loss of wear in connection with varying sliding velocity. The functional applied load (24 N) and distance of slide (1600 m) were kept constant with varying sliding velocity of 0.6 to 2.4 m/s in step of 0.6 m/s. The aforesaid wear test outcomes are tabulated in Table 5. The results of wear test with the first combination of parameters exhibit that enhancement of sliding velocity decreases the wear loss and this is similar to the findings of peers[34]. The wear loss is increased by enhancing the pin and counter disc material contact duration. The time duration of contact of pin with counter disc material is increased while decreasing the sliding velocity. Hence, the increasing of sliding velocity reduces the wear loss. The wear loss is low at 2.4 m/s sliding velocity in the above test. The comparison of wear loss with varying sliding velocity is shown in Figure 9a. The comparison of coefficient of friction (COF) with varying sliding velocity is given in Table 6 and visually presented as Figure 9b. The increase in sliding velocity decreases the COF and this is due to decrease in the duration of contact. From the worn surface of the composite Al5032/12wt.%SiC at 0.6 m/s sliding velocity, it can be inferred that the wear mechanism occurred is abrasion (Figure 9c).

The second combination for wear test is meant to identify the loss of wear in connection with varying sliding distance. The functional applied load (24 N) and sliding velocity (2.4 m/s) were kept constant with varying sliding distance of 400 to 1600 m in step of 400 m. The aforesaid wear test outcomes are tabulated in Table 7. The results of wear test with the second combination of parameters exhibit that enhancement of sliding distance increases the wear loss. The wear loss is increased due to increase in the duration of the force acting on the pin material while increasing the sliding distance. Hence, increasing of sliding distance increases the wear loss. The wear loss is low at 400 m sliding distance in the above test. The comparison of wear loss with varying sliding distance is shown in Figure 10a. The comparison of coefficient of friction (COF) with varying sliding distance is given in Table 8 and visually presented as Figure 10b. The increase in sliding distance increases the COF and this is due to increase in the duration of contact. From the worn surface of the composite Al5032/12wt.%SiC at 400 m sliding distance, it can be inferred that the wear mechanism occurred are abrasion and delamination (Figure 10c).

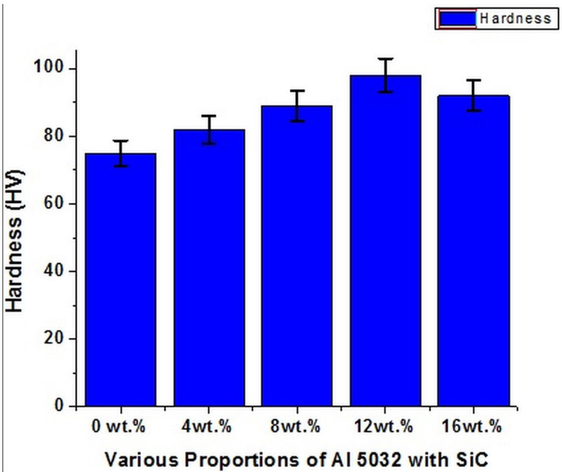

Figure 5. Comparison of Vickers hardness among the investigated specimens.

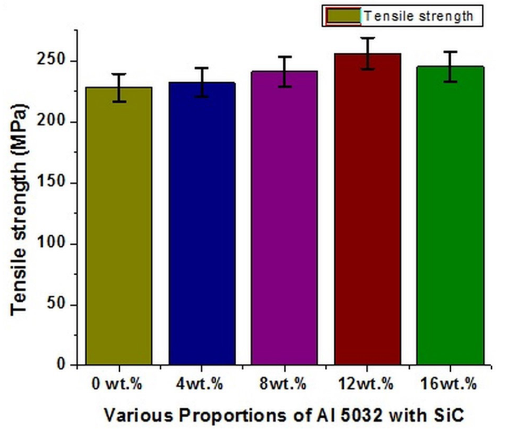

Figure 6. Comparison of tensile strength among the investigated specimens.

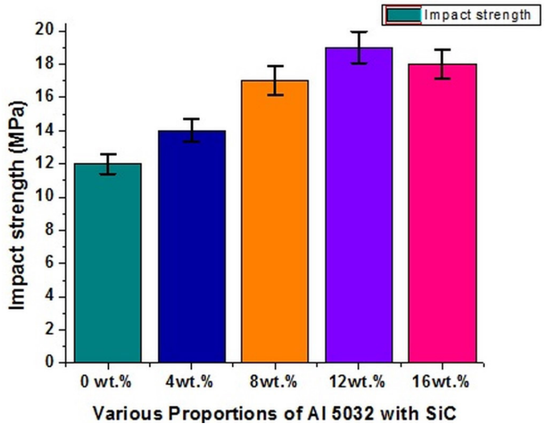

Figure 7. Comparison of impact strength among the investigated specimens.

Table 5. Results for wear loss at 24 N applied load, 1600 m sliding distance and with varying sliding velocity.

S. No	Material	Wear loss (mg)			
		0.6 m/s	1.2 m/s	1.8 m/s	2.4 m/s
1	Al5032	45	39	36	31
2	Al5032/4wt.%SiC	38	32	28	25
3	Al5032/8wt.%SiC	34	31	26	21
4	Al5032/12wt.%SiC	26	22	18	14
5	Al5032/16wt.%SiC	31	27	23	18

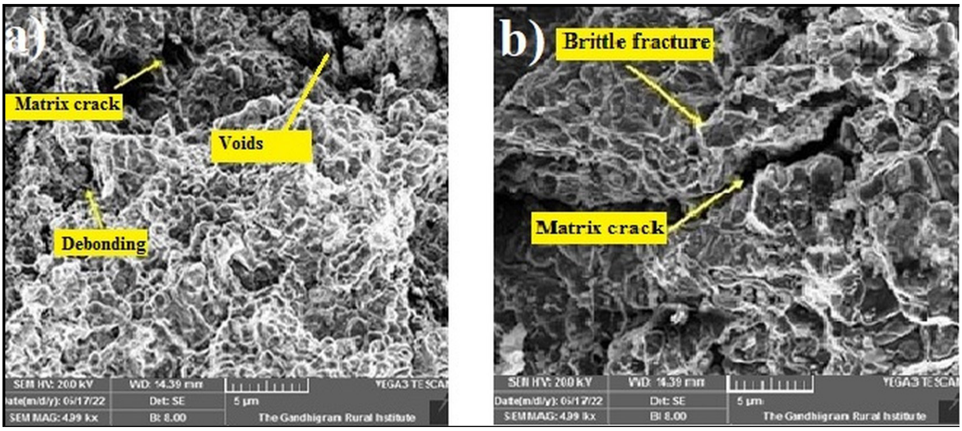

Figure 8. Fracture surface of nano specimen (Al5032/12wt.% SiC) subjected to: a) tensile test b) impact test.

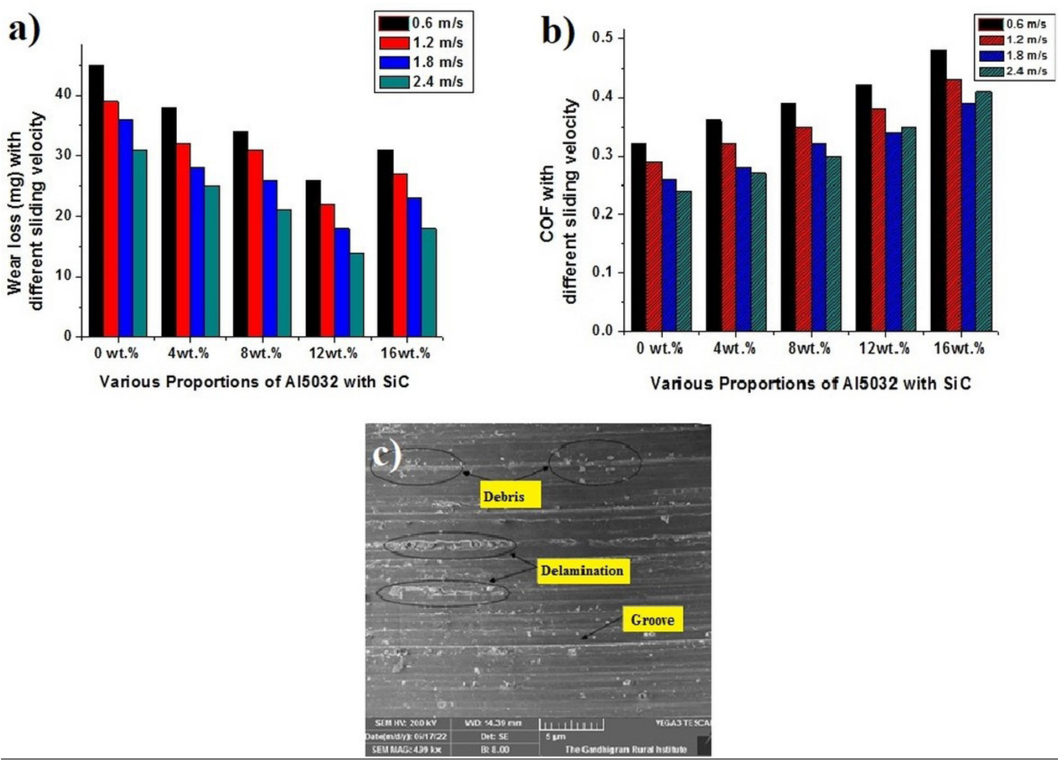

Figure 9. Under first combination for wear test: a) wear loss at varying sliding velocity b) COF at varying sliding velocity c) worn surface of Al5032/12wt.%SiC at 0.6m/s sliding velocity.

Table 6. Results for COF at 24 N applied load, 1600 m sliding distance and with varying sliding velocity.

S. No	Material	COF			
		0.6 m/s	1.2 m/s	1.8 m/s	2.4 m/s
1	Al5032	0.32	0.29	0.26	0.24
2	Al5032/4wt.%SiC	0.36	0.32	0.28	0.27
3	Al5032/8wt.%SiC	0.39	0.35	0.32	0.30
4	Al5032/12wt.%SiC	0.42	0.38	0.34	0.35
5	Al5032/16wt.%SiC	0.48	0.43	0.39	0.41

The third combination for wear test is meant to identify the loss of wear in connection with varying applied load. The sliding velocity (2.4 m/s) and sliding distance (1600 m) were kept constant with varying applied load of 6 to 24 N in step of 6 N. The aforesaid wear test outcomes are tabulated in Table 9. The results of wear test with the third combination of parameters exhibit that enhancement of applied load increases the wear loss. The increase in applied load increases the force acting on the surface and therefore leads to high wear loss. The later is in agreement with the

Table 7. Results for wear loss at 24 N applied load, 2.4 m/s sliding velocity and with varying sliding distance.

S. No	Material	Wear loss (mg)			
		400 m	800 m	1200 m	1600 m
1	Al5032	21	24	28	31
2	Al5032/4wt.%SiC	19	20	23	25
3	Al5032/8wt.%SiC	11	14	18	21
4	Al5032/12wt.%SiC	9	10	12	14
5	Al5032/16wt.%SiC	10	13	16	18

Table 8. Results for COF at 24 N applied load, 2.4 m/s sliding velocity and with varying sliding distance.

S. No	Material	COF			
		400 m	800 m	1200 m	1600 m
1	Al5032	0.16	0.18	0.21	0.24
2	Al5032/4wt.%SiC	0.19	0.22	0.24	0.27
3	Al5032/8wt.%SiC	0.21	0.24	0.27	0.30
4	Al5032/12wt.%SiC	0.26	0.29	0.32	0.35
5	Al5032/16wt.%SiC	0.31	0.34	0.37	0.41

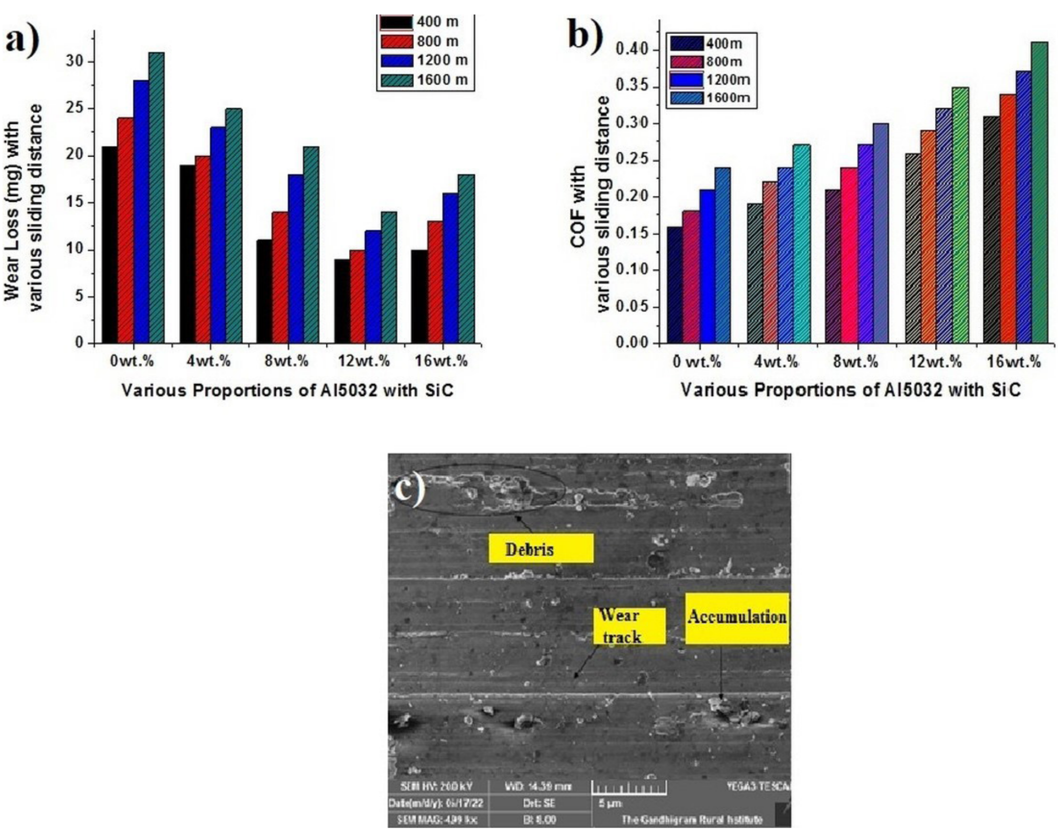

Figure 10. Under second combination for wear test: a) wear loss at varying sliding distance b) COF at varying sliding distance c) worn surface of Al5032/12wt.%SiC at 400 m sliding distance.

findings of peers[35-37]. The wear loss is low at 6 N applied load in the above test. The comparison of wear loss with varying applied load is shown in Figure 11a. The comparison of coefficient of friction (COF) with varying applied load is given in Table 10 and visually presented as Figure 11b. The increase in applied load increases the COF and this is due to increased force acting on the surface. From the worn surface of the composite Al5032/12wt.%SiC at 6 N applied load, it can be inferred that the wear mechanism occurred is abrasion (Figure 11c).

Table 9. Results for wear loss at 2.4 m/s sliding velocity, 1600 m sliding distance and with varying applied load.

S. No	Material	Wear loss (mg)			
		6 N	12 N	18 N	24 N
1	Al5032	16	20	24	31
2	Al5032/4wt.%SiC	13	16	22	25
3	Al5032/8wt.%SiC	10	14	17	21
4	Al5032/12wt.%SiC	5	7	11	14
5	Al5032/16wt.%SiC	7	11	15	18

Table 10. Results for COF at 2.4 m/s sliding velocity, 1600 m sliding distance and with varying applied load.

S. No	Material	COF			
		6 N	12 N	18 N	24 N
1	Al5032	0.17	0.19	0.21	0.24
2	Al5032/4wt.%SiC	0.19	0.21	0.25	0.27
3	Al5032/8wt.%SiC	0.22	0.25	0.27	0.30
4	Al5032/12wt.%SiC	0.26	0.29	0.32	0.35
5	Al5032/16wt.%SiC	0.33	0.36	0.39	0.41

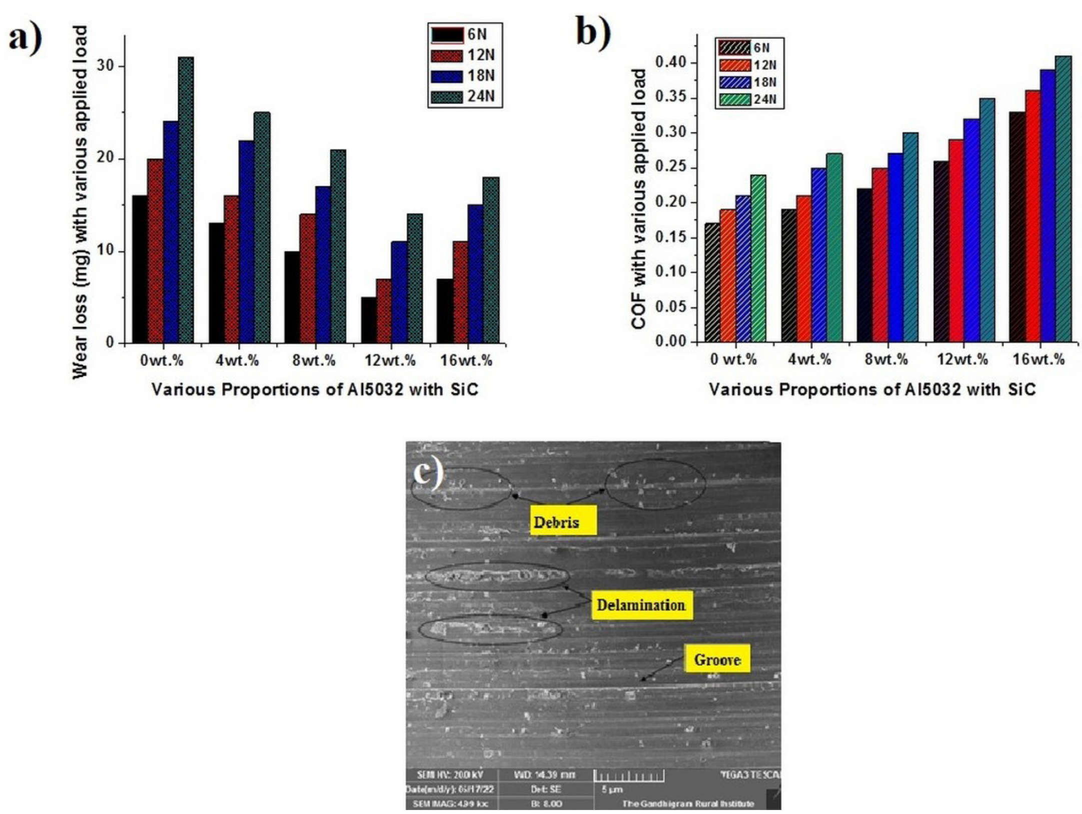

Figure 11. Under third combination for wear test: a) wear loss at varying applied load b) COF at varying applied load c) worn surface of Al5032/12wt.%SiC at 6N applied load.

From the above three combinations for wear test in the composite specimens Al5032/SiC_{np}, the following can be derived: In the first combination for wear test, minimum wear loss (14 mg) occurred at 24 N load, 1600 m sliding distance and 2.4 m/s sliding velocity. In the second combination for wear test, minimum wear loss (9 mg) occurred at 24 N load, 400 m sliding distance and 2.4 m/s sliding velocity. In the third combination for wear test, minimum wear loss (5 mg) occurred at 6 N load, 1600 m sliding distance and 2.4 m/s sliding velocity. It is found that minimum wear losses occurred in the nanocomposite Al5032/12wt.%SiC and this substantiates that 12wt.% addition of SiC_{np} in Al5032 alloy is optimum. Therefore, within the investigation limits, it can be concluded that at constant sliding velocity, applied load is more influential followed by sliding distance in attaining minimum wear loss.

4. Conclusion

In this investigation, through stir casting method Al5032/SiC_{np} composites were attained with different weight percentages (4, 8, 12 and 16) of SiC_{np}. Then the resulting metal matrix composites were examined for their wear behaviour along with metallurgical and mechanical properties, which resulted to the following findings:

- Upto 12 wt.% of SiC_{np} addition, the bonding strength of SiC_{np} with Al5032 matrix material increases and thereafter the bonding strength decreases.
- Increase in wt.% of SiC_{np} has increased the mechanical properties (Vickers hardness, tensile strength and impact strength) and decreased the wear loss of the resultant composite and the aforesaid holds valid only upto 12 wt.% of SiC_{np} addition to the Al5032 alloy matrix. Further addition of SiC_{np} to the Al5032 alloy matrix gives vice versa results due to agglomeration of reinforcements in the matrix.
- The nanocomposite Al5032/12wt.%SiC exhibits 98 HV, 256 MPa tensile strength and 19 MPa impact strength.
- In the composite Al5032/SiC_{np} a linear relation between Vickers hardness, tensile strength and impact strength exists.
- The increase in sliding velocity decreases both, wear loss and COF.
- The increase in sliding distance and applied load increases both, wear loss and COF.
- At constant sliding velocity, applied load is more influential followed by sliding distance in attaining minimum wear loss.
- Within the tested range of parameter levels and composite specimens, minimum wear loss (5 mg) occurred in the nanocomposite Al5032/12wt.%SiC at 6 N load, 1600 m sliding distance and 2.4 m/s sliding velocity.

5. Data Availability

The data used to support the findings of this study are included within the article.

6. References

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