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Optimizing Mechanical Properties of Al-6061 Alloy with Varied Nanoparticle Reinforcements: A Study Using Titanium Dioxide and Silicon Carbide Nanoparticles

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Abstract This study investigated the effect of the nano particle's addition on the mechanical characteristics of the aluminum 6061 alloy. The reinforcement particles used are silicon carbide (SiC), titanium dioxide (TiO2) nanoparticles and a blend of them. The fabrication method was completed by means of stir casting method. Different samples were fabricated and tested. The specimen's composition: pure Al-6061; Al-6061 with different weight percentages of SiC NPs and TiO2 NPs; or a combination of both nanoparticles of SiC and TiO2 at specific weight percentages. Scanning electron microscopy (SEM) was used to reveal the morphology of the nanoparticles used as Al 6061 reinforcements. Also, the morphology of MMCs was analyzed. Standardized tests evaluated the mechanical characteristics such as stiffness, flexural strength, and hardness of the specimens. The nanoparticle-reinforced samples showed significant improvement in mechanical properties compared to pure Al-6061. Further studies are needed to clarify the specific effects of TiO2 incorporation and the combined effect of TiO2/SiC nanoparticles.

Keywords: MMCS, SiC, TiO2, Stir casting method, SEM analysis, Tensile Strength, Flexural Strength, Hardness.

1 Introduction

Aluminum alloys have a variety of applications, combining lightweight, small particle sizes and high surface area. Nanoparticles give rise to a promising new class of materials called metal matrix composites (MMCs). These MMCs are particularly interesting for the aerospace, marine, and automotive industries, as they offer many advantages. One of the famous aluminums MMCs is Al-6061. It is known to be lightweight and robust, with better corrosion resistance than other MMCs [1–6]. Many researchers are investigating how the inclusion of even small nanoparticles affects the properties of these materials [7–8]. MMCs are usually winners in terms of resistance to corrosion, being lighter and stronger than their unreinforced counterparts [9–10]. The inclusion of ceramic nanoparticles as reinforcement not only improves their corrosion resistance but also their erosion resistance [11–12]. In the process of metal matrix fabrication, these nanoparticles are carefully mixed before curing the molten metal [13–16]. This superior property makes MMC popular across industries. Their impressive strength-to-weight ratio and overall performance make them a valuable choice for a variety of applications. Metal matrix composites (MMCs) stand out in comparison to traditional aluminum alloys due to their advanced mechanical characteristics. This makes MMCs sought-after for their tremendous aggregate of lightweight layout and more desirable elasticity. MMCs find tremendous use across numerous industries because of their precise abilities. Al6061-based composites and nanocomposites were fabricated by Sourabh K. et al. [17] with enhanced dispersion of reinforcing particles through ultrasonic-assisted melt stirring. The ultrasonic assistance resulted in superior mechanical properties, with up to 143.57% higher tensile strength and 74.25% higher microhardness compared to conventional melt stirring, displaying a significant enhancement in material performance. Rajkumar et al. [18] investigated the effect of silicon carbide (SiC) particle inclusion on the hardness of Al-Si composite parts produced by stir casting. Their study revealed a remarkable increase in hardness, which is due to the inherent hardness of the SiC particles acting as reinforcement in the steel matrix. This study is an example

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of the feasibility of ceramic filling dens that have been used to improve the mechanical properties of steel alloys. Nayaki and Det. [19] investigated the impact of heat treatment at the residences of aluminum matrix composites (AMCs) prepared by powder metallurgy. They centered on Al-SiC and Al-Al2O3 composites with various reinforcement volume and size probabilities. The studies discovered that thermal pressing progressed porosity, density, and hardness throughout all four composite kinds. Different researchers have explored Al6061 composites reinforced with TiO2 particles. By using stir casting and warmth forging, researchers observed enhancements in microhardness, distortion resistance, and ultimate tensile power (UTS) in comparison to the unreinforced Al6061 alloy. Ashok Kumar and Murugan enhanced the moisture content, ultimate tensile strength, yield strength, and microhardness of the Al6061 (T6)-AlNp composite by stir casting technique [20]. Xie et al. evolved SiCp/Aluminum composites and investigated the relationship between segment content, consolidation conduct, and mechanical properties of the composites. Their findings found that increasing the laser power density was more desirable for the hardness, material density, and resistance to friction of the SiCp/Al produced through selective laser melting (SLM), due to the higher temp. of the molten pool at elevated laser strength densities [21]. Aluminum alloy hybrid composites are fabricated through techniques like stir-casting, pressure casting, and powder processing. Stir-casting offers numerous advantages, including ease of use, flexibility, value-effectiveness, and the capacity to provide multifunctional, bulk-synthetic, and contoured composite additives devoid of unsafe reinforcing particles. Because of those extraordinary attributes, there has been a surge in efforts to create diverse composites using the stir casting method. However, the tensile, compression, and hardness properties of stir-forged aluminum hybrid composites with distinct reinforcements have received restricted testing to this point [22–29]. The goal of this work is to assess the influence of SiC and TiO2 nanoparticles on the mechanical behavior of Al-6061 alloy by means of stir casting to investigate the impact of different nanoparticle compositions on the reinforcement of mechanical performance, which would accomplish the objective of elucidating this relationship between these nanoparticles and the mechanical strength. Scanning electronic microscopy (SEM) was used to investigate the nanoparticle shapes within the matrix alloy. In addition, standardized mechanical tests were undertaken to assess elasticity, resistance, tensile strength, and yield strength.

2 Martial and Methods

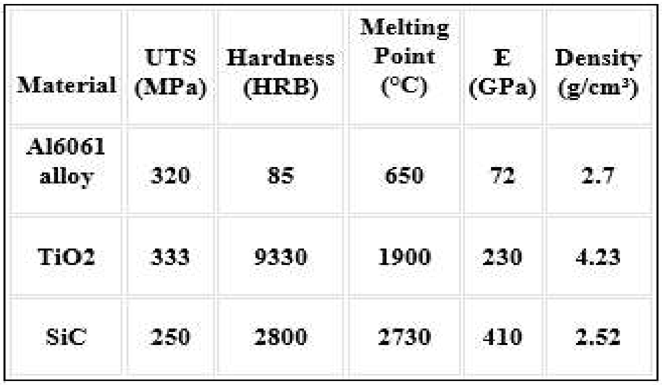
2.1 Material:

Al-6061 composites were processed in a refined and standardized stir casting furnace. The furnace was equipped with fine temperature controls as well as inert gas, which brought about the uniform inclusion of nano-additives into the molten alloy matrix. SiC and TiO2 nanoparticles are a very important components in the nanocomposite, and they were supplied by Sigma Aldrich. SiC with a particle size of 100 nm and a surface area of 215 m2/g. while, (TiO2) nanoparticles featured an average particle size of 21 nm and a surface area of 65 m2/g. Characterization, including particle size analysis and morphology identification was done by means of scanning electron microscopy (SEM). The nanoparticles were examined to determine their shapes and distribution. The chemical constitution of the Al-6061 alloy is stated in Table 1 below. The mechanical properties of the metal matrix and the used nanoparticles are illustrated in Table 2. Eight samples were chosen with different weight ratios or proportions of SiC and TiO2. These samples were chosen to investigate the influence of varying proportions of SiC and TiO2 nanoparticles on the properties of the alloy. The samples' weight percentage and composition are included in Table 3. Scanning electron microscopy (SEM) enables visualization of the exact nanofiller morphology, as shown in Fig. 1. The figure depicts SEM images of the nanoceramic powders, characterizing them as being coarse, with an irregular shape, and unevenly sized. Mechanical properties, among which are ultimate tensile strength (UTS), hardness, and modulus of elasticity, were examined on each sample. Descriptive statistics for designing study graphs, which may include mean values, standard deviations, and tests, were conducted to detect significant differences and patterns. The mechanical characteristics, such as hardness, strength, and stiffness, of the nanoparticle-reinforced alloys were also compared with those of the Al-6061 base alloy.

Table 1: Composition of Al-6061

Element	**Mg**	**Si**	**Fe**	**Mn**	**Cu**	**Cr**	**Zn**	**Ni**	**Ti**	**Al**
Wt.%	**0.95**	**0.60**	**0.24**	**0.21**	**0.25**	**0.04**	**0.06**	**0.02**	**0.01**	**Balance**

Table 2: Mechanical properties of base alloy and its reinforcements (TiO2 and SiC)



Material	UTS (MPa)	Hardness (HRB)	Melting Point (°C)	E (GPa)	Density (g/cm³)
Al6061 alloy	320	85	650	72	2.7
TiO2	333	9330	1900	230	4.23
SiC	250	2800	2730	410	2.52

Table 3: Samples composition in wt.%

Specimen	Al 6061 (%)	SiC (%)	TiO2 (%)
S1	100	0	0
S2	96	4	0
S3	94	6	0
S4	92	8	0
S5	96	0	4
S6	94	0	6
S7	92	0	8
S8	86	6	8

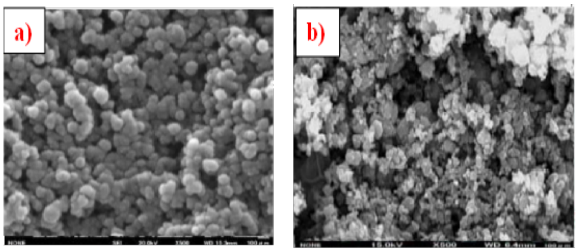


Fig. 1 SEM micrographs (a) TiO2, (b) SiC

2.2 Specimen preparation

In this research, the experimental fabrication of the composites was completed through the application of the stir casting method. TiO2 and SiC and a blend of both with different weight ratios were incorporated into the Al-6061 composite; the setup of the stir casting process is shown in Fig. 2. As for casting technique, argon gas was used during casting, and oxide formation had been inhibited through the recommendation found in [30]. In the experiment, the Al-6061 matrix was reinforced using 4, 6, and 8 wt% SiC nanoparticles. Also, another set of samples was produced by the inclusion of TiO2 nanoparticles at varied weight fractions: 4, 6, and 8 wt%. After that, an Al 6061 composite with an alloy of SiC and TiO2 was formed. For better wettability, a K2TiF6 filler was additionally engaged. Thereafter, nanoparticles were heated to 360°C in a different heater. The temperature of the composites was raised from room temperature to 350 °C in the furnace. Subsequently, the blower furnace melted the composites at about 840 °C to ensure that every part was completely melted. After the preheating process, the nanofiller powder was added in half the amount, and the motor stirred the molten mixture at 1300 rpm. The rest of the reinforcements were added, and the stirring was for 8 minutes. To prevent the influence of moisture contamination, the temperature was set at 850°C. Afterwards, the metal was poured into pre-heated steel molds to ensure proper cooling and to avoid “flash” defects. Data and parameters of the composite casting process were obtained as presented in Table 4.

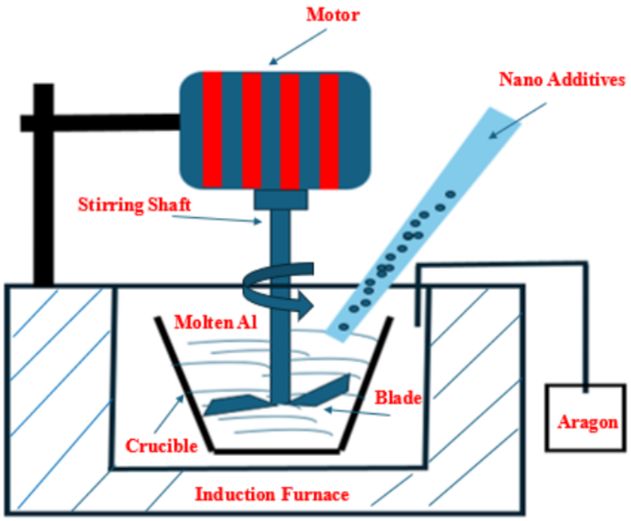
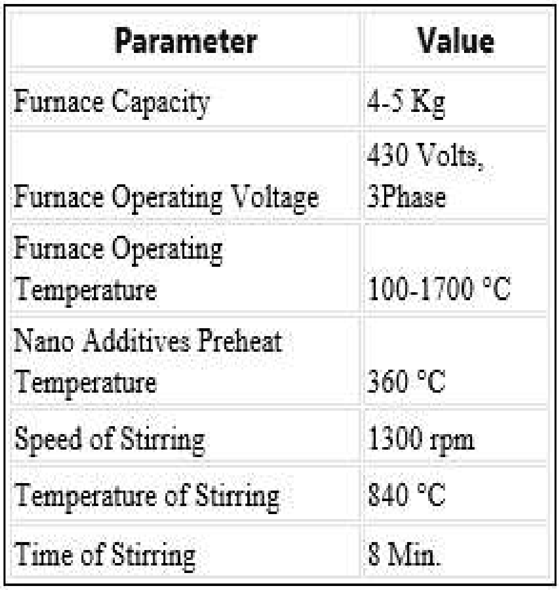


Fig. 2 Stir casting furnace setup

Table 4 Composites casting data.



Parameter	Value
Furnace Capacity	4-5 Kg
Furnace Operating Voltage	430 Volts, 3Phase
Furnace Operating Temperature	100-1700 °C
Nano Additives Preheat Temperature	360 °C
Speed of Stirring	1300 rpm
Temperature of Stirring	840 °C
Time of Stirring	8 Min.

2.3. Mechanical properties

Mechanical properties, including surface hardness, bending strength, and tensile strength, were examined. Hardness test specimens were cut into 63 mm x 63 mm x 13 mm, and then an average value was calculated with the results recorded from four different positions. Tensile test specimens were prepared according to ASTM E8M standards and tested on a computer universal testing machine model (320 kN, Zhejiang Jingyuan Mechanical Equipment Co., Ltd., Jinhua, China). Also, WAW-301B was used to determine the flexural strength with an equal strain rate of 6 mm/min.

3. Results and Discussion

3.1 Hardness

For a duration of 15 seconds, the Brinell hardness tests were conducted according to the ASTM E10 standard method using a 50-gram load. Figure 3 illustrates the distinct hardness profiles of different composite materials. The hardness test done on the Al-6061 alloy samples with SiC and TiO2 nanoparticles as reinforcement agents display an amazing enhancement of material properties for the Al-6061 alloy. Initially, the pure Al-6061 alloy accounted for the baseline, and its hardness was 108.63, thus it was allowed to have a comparative analysis. On the next step of sample manufacture, SiC nanoparticles increased in hardness progressively. 4% SiC nanoparticles were mixed, which led to a hardness of 124.44, which was used as the basis for the study and further extended to a hardness of 128.71 using 6% SiC nanoparticles. When 8% of SiC nanoparticles were inserted in the alloy matrix, the hardness of the alloy dropped to 125, although the reason for it could be related to the nanoparticle's dispersion within the alloy matrix, which differs from the sharp bonds between the Al/SiC nanoparticles in the previous case. On the contrary, the application of nanoparticle TiO2 offered the same outcome in terms of hardness as well. The 133.31, 137.37, and 139.45 hardness values, corresponding to the 4%, 6%, and 8% TiO2-incorporated ceramics, were in increasing order, meaning that every sample presented a higher hardness than the previous one. The accompanied interaction between SiC and TiO2, which manifests in the formation of the ternary complex, is also worth mentioning. The composite made of 6% SiC and 8% TiO2 is visibly outperforming all the nanocomposites. The hardness of this nanocomposite reached 162.36, which is higher than the individual nanoparticle-reinforced ones. As a result of such experimentation, the values indicate the ability of nanomaterials to drastically improve the hardness characteristic of the Al-6061 alloy. Such improvements opened an interesting field of applications in industry demanding exactly those features, like increased wear resistance and mechanical resilience. Yet, this study emphasizes the likelihood that finding the best material mixture to obtain the desirable properties requires further research. Therefore, components should be thoroughly researched, and different mixtures of nanoparticles and their effects on the properties of the composites could be found. The results obtained closely correspond to those in [31–35], which explore the impact of nanoparticle incorporation on enhancing the properties of Al-based materials.

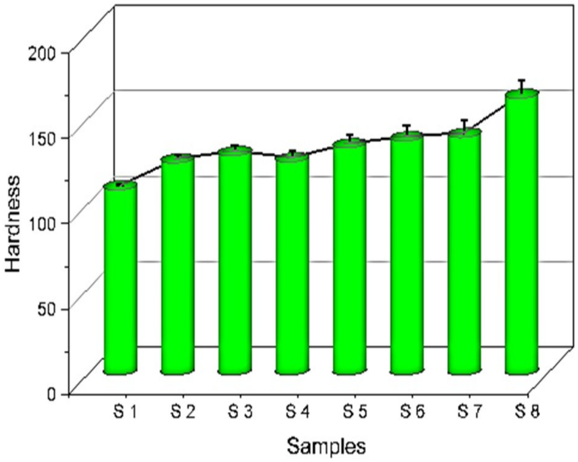


Fig. 3 illustrates a comparison of hardness among all metal matrix composites.

3.2 Tensile strength

The data in Figure 4 shows the change in tensile strength with the incorporation of nanoparticles into the metal matrix composites, as the tensile strength of the nanocomposites had been assessed based on the procedure described in the ASTM E8M standard. The assessed tensile strength data, especially, throws a glimpse into mechanical capabilities that can probably be obtained with nanoparticles reinforcing the matrix of an aluminum alloy, Al-6061. The initial tensile strength of the AL6061/0wt% alloy is the most important reference point for addressing the effect that introducing nanoparticles has on their properties. Consequently, the addition of 4% SiC nanoparticles manifest an excellent enhancing effect as the strength of the superposition is 220.63 MPa, which reveals the reinforcing effect of these nanoparticles. The kind of improvements that the tensile strength reaches as nanoparticle content elevates, with 6% SiC nanoparticles achieving a tensile strength of 255.04 MPa, Although the smallest decrease happens to the alloy with 8% (S4), the increase to 245 MPa of tensile strength compared to a neat alloy is still impressive. In the context of the above results, it is also shown that the incorporation of TiO2 nanoparticles brings about a significant increase in tensile strength. Samples that contain 4%, 6%, and 8% TiO2 nanoparticles (S5, S6, and S7) present increasingly extensive tensile strengths of 265.67 MPa, 270.32 MPa, and 274.41 MPa, respectively, which correspond well with the strengthening character of these nanoparticles in an alloy compound. What is special about the nanocomposite with SiC/TiO2 particles (S8) is that it possesses the best tensile strength ability among all the evaluated composite samples at 302.32 MPa. This illustrates the potential for individualized nanoparticle constituents to obtain better mechanical performance in composite materials among all the qualities that nanoparticle compositions have. Not only do the outcomes of the research stress the influence of this technology on increasing the tensile strength of the Al-6061 alloy, but they also point the way to further optimization and involve additional efforts in nano-reinforcement as a part of metal engineering. They indicate the general capabilities of the new materials for areas such as machine industries and mechanical performance.

3.3 The flexural strength

The flexural strength of Al-6061 nanocomposites can be determined using the following formula:

$$\sigma=3F/ 2b \text{ x } L/d^2$$

Here, σ is the stress in incognito of the pressure corresponding to the flexural strength in Pascals (Pa), F is the force in even darker incognito of the pressure applied on the material in Newton (N), L stands for the dimension or designer of the material within the span length in meters (m), b is the dimension or width of the material in meters (m), and d is the thickness of the tested specimen in meters (m). Figure 5 below shows the way the basic flexural strength of Al-6061 nanocomposites is affected by the nano-additives, as shown by their weight percent incorporation. Out of all the data that was acquired in this study, the flexural strength of the Al-6061 alloy loaded with SiC and TiO2 nanoparticles gives explanations on how nanoparticle integration boosts the strength and mechanical properties. The value of flexural strength of the neat Al-6061 alloy (S1) is considered the most empirical value for referencing its impact after nanoparticles have been incorporated into the alloy. At 256.52 MPa, the strength of aluminum alloy is established, which becomes one of the building blocks for understanding mechanical behavior. Adding 4% SiC nanoparticles (S2) lead to a value of 293.36 MPa in flexural strength. This addition reflects a rise of about 14.34% and presents the tendency of the effect of SiC nanoparticles. The interaction of nanoparticles with the microstructure of the metallic matrix is complex but interesting. Although small increases in SiC nanoparticle content yield reductions in bent strength, the resultant behavior is continuous and increasingly advantageous. Samples that have 6% SiC nanoparticles (S3) show a greater across-the-board increment, gaining 300.074 MPa as compared to a baseline, which is approximately 16.86% improvement. Although as little as 8% of SiC nanoparticles do produce a decline in ductility, the value of the composite is higher than that of the original alloy, which speaks volumes to the additional strengthening potential of nanoparticle additions. A comparable situation applies to the addition of TiO2 nanoparticles, which also leads to a marked increase in flexural strength. The specimens with the 4%, 6%, and 8% of the TiO2 nanoparticles (S5, S6, and S7) have a flexural strength of 342.14 MPa, 361.67 MPa, and 367.24 MPa; these improvements represent percentage increases of approximately 33.07%, 40.77%, and 43.16%, respectively, compared to the baseline. The fraction made up of nano SiC and nano TiO2 particles (S8) has shown a superior stiffness of 410.25 MPa, which implies an incredible increase of 59.88% over the unfilled matrix.

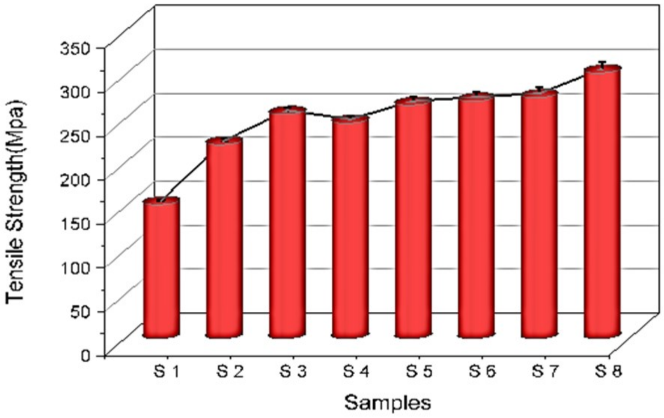


Fig. 4 depicts the tensile strength of Al-6061 nanocomposites.

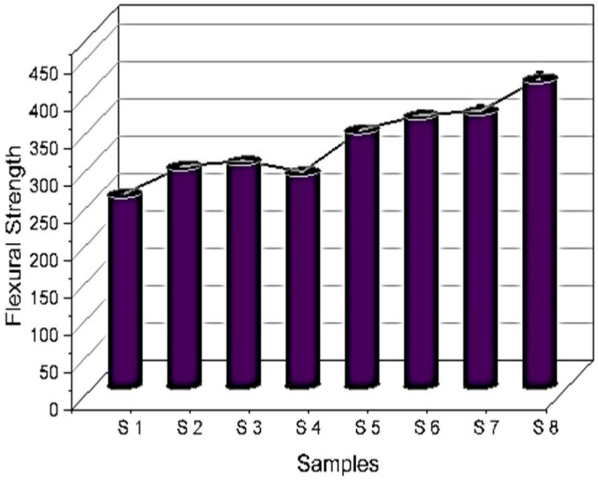


Fig. 5 shows the variation in flexural strength across all Al-6061 nanocomposites.

4 SEM Investigations

The SEM photos depicted in Figure 6 illustrate the morphological fractures found across various samples, beginning with the pure Al-6061 alloy as depicted in Figure 6(a). This alloy exhibits a regular distribution of voids. Upon the creation of nanofillers to the pure Al-6061, there may be a noticeable discount within the void's ratio, as visible in Figures 6(b-d). Figures 6(a-c) show three morphologies indicative of ductile fracture, with the pure Al-6061 alloy demonstrating greater suggested ductility in comparison to Al-6061 reinforced with SiC and TiO2 composite. This decline in ductility and elongation percent is attributed to the hardness of SiC and TiO2 debris. Figures 6(b-d) show the morphological fractures of Al-6061 following tensile testing of Al-6061/hybrid nanocomposites. These show a ductile fracture mode characterized by means of reinforcing decohesion debris, resulting in fracture and particle pull-out, which lead to microvoid formation. However, Al-6061 nanocomposites strengthened with the aid of TiO2 particles exhibit progressed maintenance, indicating stronger bonding between the matrix and nanofiller debris. Although the presence of ductile fracture is more suggested in the natural Al-6061 alloy compared to nanocomposites, nanoparticles continue to be intact in numerous locations, ensuring reliability and facilitating advanced bonding between the aluminum matrix and nanofiller debris, especially in the case of Al/SiC/TiO2.

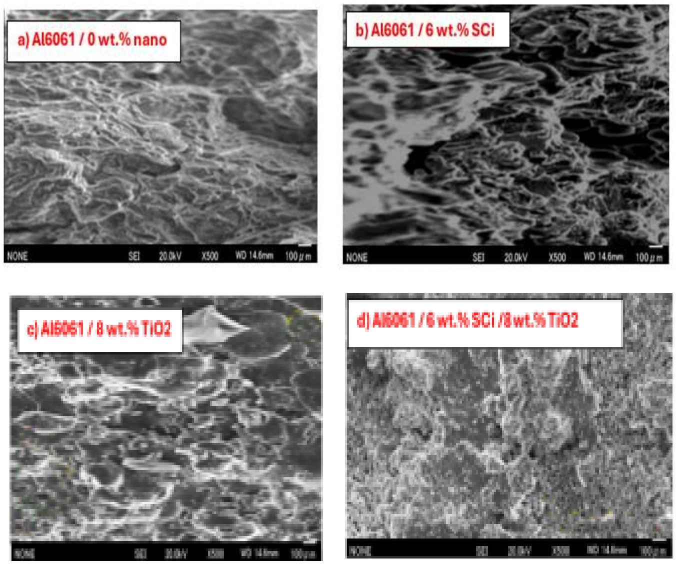


Fig. 6. (a-d) SEM photographs of tensile fracture surface

5 Conclusions

The study demonstrates a notable enhancement in the mechanical properties of the investigated Al 6061 alloy, which has been reinforced with different concentrations of silicon carbide (SiC) and titanium dioxide (TiO2) nanoparticles via stir casting. Those nanoparticles jumping on with an experimentation and studying got the final breakdown as immensely in big areas related to several parameters. Firstly, increasing the nanoparticle content notably enhances the mechanical characteristics of the metal matrix alloy. The combination of SiC and TiO2 alloy proved to be the best admixture overall, being able to increase the hardness and tensile strength indices by 24% to 39% compared to the unreinforced alloy. On the other hand, the MMCs had a significant improvement in the stiffness of the alloy upon the nanoparticle's incorporation. Additionally, the study found that the flexural strength value improved after combining SiC and TiO2, which achieved an approximate 60% increment from the base alloy.

SEM evaluation of the composites proved increased bonding at the level of the matrix against nanoparticles, suggesting the high degree of mechanical reinforcement of the composite material.

To sum up, the findings show the significant potential of nanoparticle-integrated composites to be good candidates for applications that withstand impact and provide high strength and durability. Despite that, special research is a prerequisite to the achievement of the optimum nanoparticle configurations and processing conditions needed for unique industrial requirements.

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