



Structural and Mechanical Characterization of Aluminum Matrix Nanocomposites Reinforced with SiC and Al₂O₃ Nanoparticles

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ABSTRACT

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The mechanical and structural properties of aluminum matrix nanocomposites (AMNCs), such as hardness, toughness, and damping ratio, are critical for a wide range of engineering applications. In this study, Al 6061 was selected as the matrix material, with silicon carbide (SiC) and aluminum oxide (Al₂O₃) nanoparticles utilized as reinforcements. The AMNCs were fabricated through the stir casting method, with various weight ratios of nanoparticle reinforcement. The damping behavior, hardness, and toughness of the composites were evaluated at different reinforcement levels. It was found that the damping ratio of the AMNCs increased significantly relative to the base Al 6061, with the optimum enhancement observed at approximately 2% reinforcement. At this nanoparticle concentration, both the impact resistance and hardness were notably improved. The findings demonstrate that the incorporation of SiC and Al₂O₃ nanoparticles into Al 6061 leads to substantial improvements in the mechanical and structural properties of the composite, thus highlighting the potential of AMNCs for advanced applications requiring superior performance in terms of energy dissipation, strength, and durability.

1. INTRODUCTION

Nowadays, aluminum matrix composites (AMCs), as part of metal matrix composites (MMCs), are highly demanded materials in many engineering applications. AMCs have superior characteristics [1-2]. With the improvement of nanoscience and nanotechnology, MMCs reinforced by nanoparticles (MMnCs) are recently being considered worldwide because of their talented properties that fit a great number of functional and structural applications [3]. Choosing the processing method to produce this material is affected by many factors, including the type of reinforcement and matrix, the required mechanical and thermal properties, and the extent of microstructural integrity desired [1, 3, 4]. In this study, stir casting was chosen for performing the task. Annigeri and Kumar [5] gave a detailed description of stir casting and showed that this method is simple, flexible and low cost with mass production. The main drawback of this method is the difficulty to achieve a homogenous composite, which can be improved by the use of modified stir casting, nanosized particles or both. The modified methods include ultrasonic stir casting [6-8], vacuum stir casting [6], hot water treatment of the particles, squeeze casting [9], and powder metallurgy processes [10, 11]. On the other hand, the improvement can be gained by decreasing the size of particles because the use of nanosized particles has the tendency of agglomeration and

clustering, due to high surface energy, electrostatic, moisture adhesiveness and attractive Vander Waal's bonding, which affect its uniform distribution during processing [11]. The characteristics of final composites are affected by the mixing ratio, the processing parameters, the heat treatment schedule and other factors [12-18]. Enormous studies have treated the effect of different parameters on the performance and characteristics of AMCs and AMNCs [1-27]. Most of these studies have investigated the mechanical properties of composite material, with rare research concerning damping property conducted [19-27]. From those studies, it can be concluded that the research on determining the damping of nano reinforcement particulates in AMNCs is limited. This study investigates the effect of nano Al₂O₃ and nano SiC reinforcement on the damping and some other mechanical properties by focusing on the effect of the weight ratio of the particulate. This study aims to:

- fabricate many specimens of the aluminum matrix with different types of nanoparticles.
- compare nanoparticles in terms of their effect on mechanical proprieties.
- find the damping ratio for AMNCs.

In summary, this study aims to determine the effect of nanoparticles on mechanical and structural properties (fracture toughness, hardness and damping) of AMNCs.

2. EXPERIMENTAL METHOD

2.1 Materials

The matrix material used in this study is 6061 aluminum alloy. The physical, mechanical, electrical, thermal, and

processing properties and the composition of aluminum alloys are well-known. The nanoparticles (alumina and SiC) that were used as the reinforcement phase are also well-known. The detailed specifications and compositions of these materials are shown in Table 1 and Table 2.

Table 1. Composition of a 6061 aluminum alloy

Grade Designation			Composition (wt%)											
Aluminum Association	UNS No.	ISO No.	Si	Fe	Cu	Mn	Mg	Cr	Zn	V	Ti	Unspecified other elements		Al, min.
	R209											Each	Total	
6061	A96061	AlMg1SiCu	0.40-0.8	0.7	0.15-0.40	0.15	0.8-1.2	0.04-0.35	0.25	1	0.15	0.05	0.15	rem

Table 2. Mechanical properties of Al 6061, SiC and Al₂O₃

Properties	Al 6061	SiC	Al ₂ O ₃
Density ρ (g/cm ³)	2.73	3.217	3.95
Particle size (nm)	-	50-70	60-100
Elasticity modulus E (GPa)	68.9	380-410	330 (20°C) or 300 (1200°C)
Poisson's ratio ν	0.33	0.14	0.21
Melting Point (°C)	588	2700	2,072
Hardness (HB500)	30 (95 Brinell)	2800	1175
Thermal expansion coefficient (K ⁻¹ ×10 ⁻⁶)	23.2 (20-100°C)	8.2	4.5
Fracture toughness (MPa m ^{0.5})	25	4-5	

2.2 Preparation of composites

The following steps were conducted to produce the samples of AMNCs. The flow chart is shown in Figure 1.

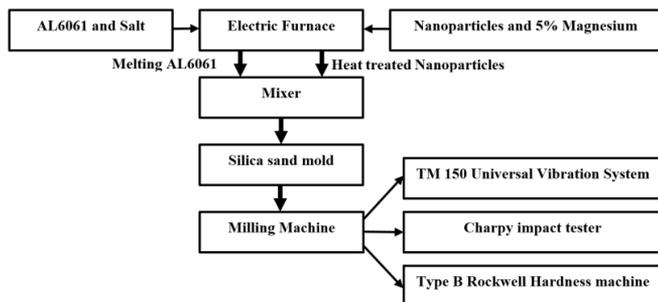


Figure 1. Flow chart for the sample preparation and testing

Step 1: A specific mixer was fabricated within certain conditions in order to be used in the stir casting process.

Step 2: A silica sand mold was prepared.

Step 3: Aluminum alloy (Al 6061) was melted in the electric furnace for two hours up to 800°C.

Step 4: The melting aluminum was poured in the mixer.

Step 5: Salt was added to the melting aluminum to remove Al₂O₃.

Step 6: The nanoparticles were heat treated in the electric furnace to improve wettability for seven minutes with a temperature of around 400°C. In this step, magnesium with a ratio of 5% was mixed with the particles in order to enhance the porosity and homogeneity of the final composite.

Step 7: The nanoparticles were added to the melting aluminum and then were mixed by the mixer for 15 minutes at a rotating speed of 500 rpm.

Step 8: The MMC was poured in the sand mold.

Step 9: The final product was cleaned, shaped and surface-finished by the milling machine.

Step 10: The samples were cut to the standard dimensions of the different testing devices.

2.3 Experimental testing

As mentioned above, the stir casting method was used for processing Al 6061 and reinforcing it with 0.5%, 1.5%, and 3% weight fractions of Al₂O₃ particles and 1.5% of SiC particles, respectively, as shown in Table 3.

Table 3. Reinforcement particle details of different samples

Sample No.	Reinforcement Particles	Weight Ratio (%)
1	SiC	1.50
2	Al ₂ O ₃	0.50
3	Non (pure)	0
4	Al ₂ O ₃	1.50
5	Al ₂ O ₃	3

Three types of experiments were performed in order to study the different factors affecting the performance of AMNCs. These tests include vibration damping, impact and hardness. The samples were prepared in accordance with the standard specifications and recommendations.

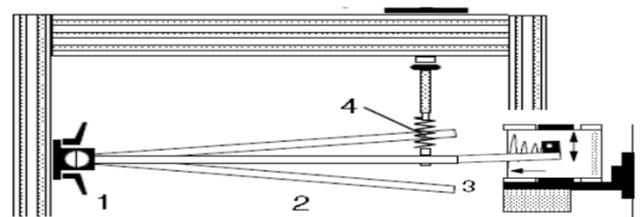


Figure 2. Vibration test set-up using the TM 150 universal vibration system

Note: 1. Fixed end; 2. Cantilever beam; 3. Drum plotter; 4. Helical spring.

For the vibration test, the damping of the samples was

determined using the cantilever beam standard machine (TM 150 Universal Vibration System). In addition to computerized modeling, there are two experimental ways by which damping measurements can be made: time- and frequency-response methods. The test was performed with a time-response approach. The dimensions of the testing samples are shown in Table 4. The beam was fixed from one end and served as a damper for the helical spring ($k=3000$ N/m) at the other end. The time responses of the free end were recorded by a rotary chart plotter (a feed rate of 20 mm/s and a chart width of 100 mm) and a pointed pin (Figure 2).

The Charpy impact tester was used for computing the toughness of the samples.

Table 4. Geometry dimensions of the vibration sample

L : Length (m)	0.37
b : Width (m)	0.025
h : Thickness (m)	0.012
A : Area (m^2)	0.0003
I : Area moment of inertia (m^4)	3.6×10^{-9}

The hardness of the samples was found using the standard hardness machine. The Type B Rockwell (HRB) hardness testing machine was used for conducting the hardness test. Metallographic finish was provided to the samples using different grit-size emery papers to ensure precise measurement of the hardness. For testing, a 2.5 mm diameter indenter ball was used with a load of 175 kg and a dwell time of 10 s. Five readings were analyzed at different points on the sample. The arithmetic average value of the accumulated five test points was found and used as the final value of the hardness testing on each test specimen.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Vibration tests

The damping coefficient of the composite cantilever was calculated according to the amplitude attenuation ratio of the free vibration attenuation curve. The logarithmic decrement (δ) for underdamped free vibrations on n cycles was found from the following equation:

$$\delta = \frac{1}{n} \ln \left(\frac{x(t)}{x(t+nT_d)} \right) \quad (1)$$

The equivalent damping ratio was then determined from the following equation:

$$\zeta = \frac{\delta}{\sqrt{1-\delta^2}} \quad (2)$$

The logarithmic decrement was measured graphically by

Table 5. Vibration test results of different samples

Sample No.	Vibration-Measured Data						Vibration Parameters	
	Peak Values (mm)						Delta (δ)	Zeta (ζ)
	X_1	X_2	X_3	X_4	X_5	X_6		
1	22.0	20.5	19.5	18.5	16.0	15.0	0.077	0.012
2	25.0	23.0	20.0	19.0	17.0	15.0	0.102	0.016
3	11.0	9.0	7.0	6.0	5.0	3.5	0.229	0.036
4	30.0	25.0	20.0	14.0	9.0	4.0	0.403	0.064
5	17.0	15.0	13.0	10.0	7.0	4.5	0.266	0.042

experiment for many cycles in order to get more accurate results (Figure 3). The results of the tests are shown in Table 5 and Figures 3 and 4.

In such an experiment, results can be affected by many factors like the length and other dimensions of the beam, the distance between the spring and the support point, the stiffness of the spring and the material of the beam. All of these factors were kept constant except the material composition.

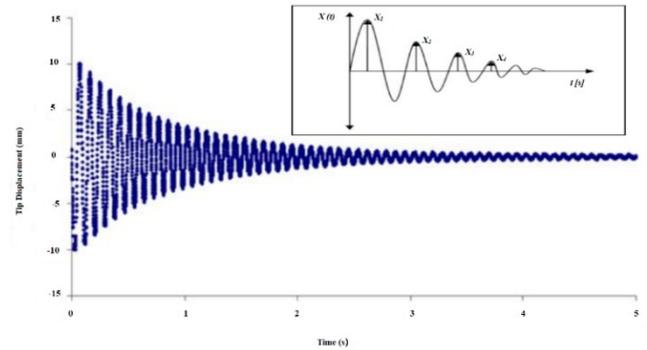


Figure 3. One example of time-response used for damping calculation with the logarithmic decrement method

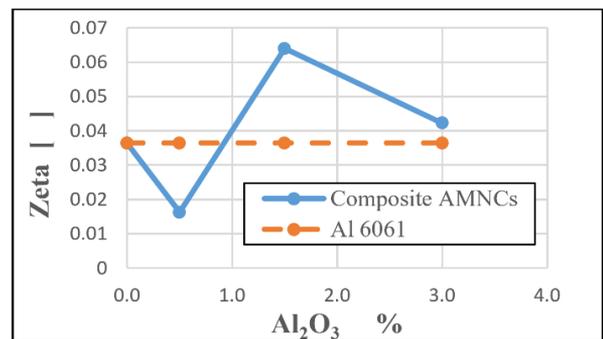


Figure 4. Plot of the average damping ratio (Zeta) for different weight ratios of Al_2O_3

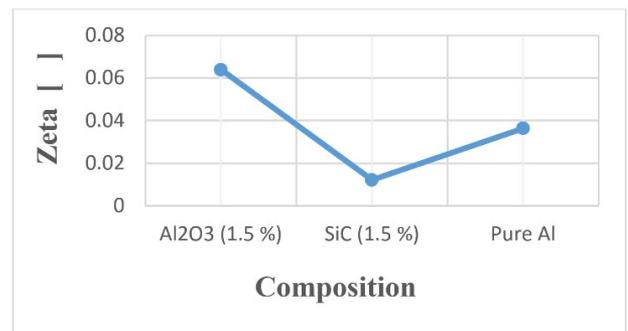


Figure 5. Plot of the average damping ratio (Zeta) for different materials

The experimental damping ratio (ζ) values ranged between 0.01 and 0.07, which are the same as those in the literature. Figure 4 shows the effect of the Al₂O₃ weight ratio on the beam damping. At a low ratio (less than 1%), the damping was lower than that of Al 6061 and this negative effect can be referred to poor manufacturing. After that ratio, the damping of the AMNCs became higher than the origin and reached the best value (about twice of the Al 6061) at the ratio of around 2%. As indicated in several studies [10, 25], the reinforcement weight fraction increased beyond a limit, and the composite showed a decline in characteristics due to the clustering and agglomeration of nanoparticles. The method must be improved in order to reduce the porosity and increase the homogenous distribution of nanoparticles.

This study compares between Al₂O₃ and SiC as nanoparticle reinforcement of Al 6061 with the same ratio (1.5 weight %), as shown in Figure 5. The Al₂O₃ obtained a higher damping ratio than SiC.

3.2 Hardness tests

Five readings were used for each sample composition at different positions in order to give more realistic values. Their average values were found and recorded. The coefficient of variation (CV), sometimes called relative standard deviation, of the five readings was calculated and found to be acceptable. As a general guideline, a CV less than 100% reflects low variability, while values greater than 100% reflect high variability. The results of these tests were shown in Table 6.

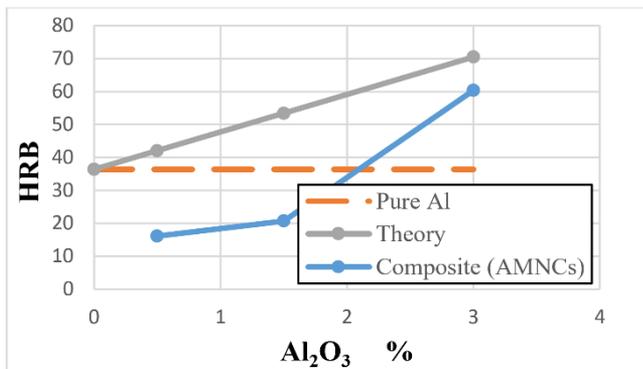


Figure 6. Plot of the average surface hardness (HRB) for different weight ratios of Al₂O₃ particulates

Table 6. Hardness test results of different samples

Sample No.	HRB Value					Average	CV (%)
	X ₁	X ₂	X ₃	X ₄	X ₅		
1	14.4	22.3	27.4	54.8	40.9	31.96	50
2	14.1	6.6	13.8	25.3	21.0	16.16	45
3	29.0	24.6	50.6	46.7	30.8	36.34	32
4	35.4	15.2	19.3	16.1	17.5	20.70	40
5	77.8	80.5	60.6	51.7	31.4	60.40	33

* CV = Standard deviation / Average * 100%

Figure 6 shows the results of hardness tests conducted on the Al 6061 alloy and the AMNCs containing different weight percentages of Al₂O₃ particles. The hardness increased when more particles were added, clearly indicating that the presence of particulates in the matrix can improve the hardness of the composites. This agrees with the theory because the ceramic particles are harder than aluminum. When the AMNCs were compared with the pure material, the hardness values were less

than those of the pure material until the weight ratio reached around 2%. After this ratio, the hardness of the AMNCs became higher than that of the Al 6061. According to the theoretical expectations, the hardness of the AMNCs must be higher than the original material in all ranges, but some practical errors reduced these values. Most of these errors belonged to the different parameters and techniques of the stir casting method.

Figure 7 shows a comparison between SiC and Al₂O₃ as nanoparticle reinforcement of Al 6061 with the same weight ratio (1.5%). As observed, the SiC composite exhibits higher hardness than the Al₂O₃ composite. However, both composites demonstrate lower hardness values compared to pure Al 6061, as previously discussed.

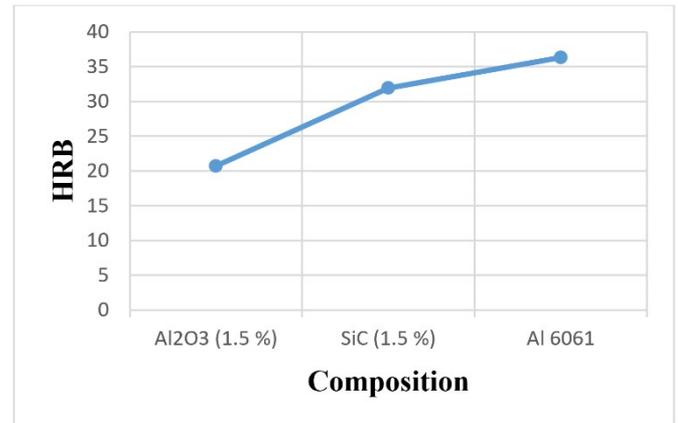


Figure 7. Plot of the average surface hardness (HRB) for different materials

3.3 Impact strength tests

The Charpy impact test was used to assess the toughness and notch sensitivity of the samples. The energy absorbed by the material during fracture was measured, with brittle materials absorbing minimal energy and ductile materials absorbing a significantly higher amount before fracture.

Five different samples were used for each sample composition and their averages were found. The CV of the five readings around the averages was computed and found to be satisfactory. The results of the tests were shown in Table 7.

Table 7. Charpy impact test results of different samples

Sample No.	Toughness Value (J)					Average	CV (%)
	X ₁	X ₂	X ₃	X ₄	X ₅		
1	0.8	0.7	0.7	0.7	0.6	0.70	10
2	0.5	0.5	0.5	0.6	1.0	0.62	35
3	9.0	9.5	2	5	2.2	5.54	65
4	0.6	0.7	0.6	0.8	0.5	0.64	18
5	1.0	1.4	1.4	1.2	1.3	1.26	13

* CV = Standard deviation / Average * 100%

Figure 8 shows the toughness values for different ratios of Al₂O₃. The toughness increased slightly with the increase of the weight ratio. The toughness value of AMNCs was less than that of the pure material, which comes to an agreement with the role of mixture and the theoretical expectations. The degree of reduction is more than theory, which proves that the samples with reinforced particles become more brittle due to porosity formation. Well-controlled production can improve this drawback. The properties of AMNCs are also dependent

on both the sintering temperature and time. Several studies have suggested that ultrasonic-assisted stir casting followed by squeeze casting can effectively reduce the porosity and increase the homogenous distribution of nanoparticles [6-8, 25]. One more problem is the relatively poor wettability of nanoparticles. This has been partially solved by heating the nanoparticles to high temperatures before mixing. Further improvements happened when the wetting agent was used.

Figure 9 shows a comparison between SiC and Al₂O₃ as nanoparticles reinforcement of Al 6061 with the same weight ratio (1.5%). As indicated in the figure, the toughness of the SiC composite is higher than that of the Al₂O₃ composite. However, it should be noted that the toughness values of both composites are significantly lower than that of the pure Al 6061.

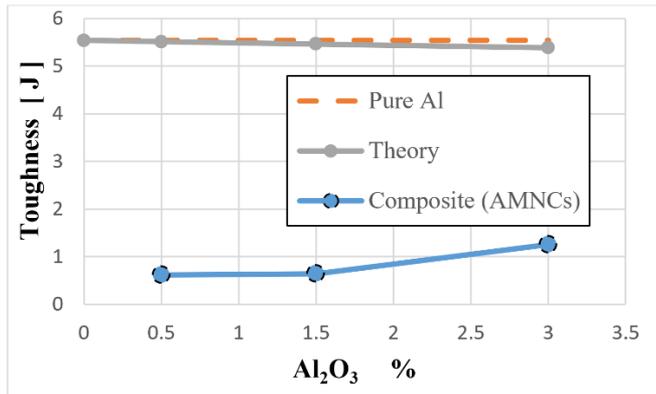


Figure 8. Plot of the average surface roughness for different weight ratios of Al₂O₃

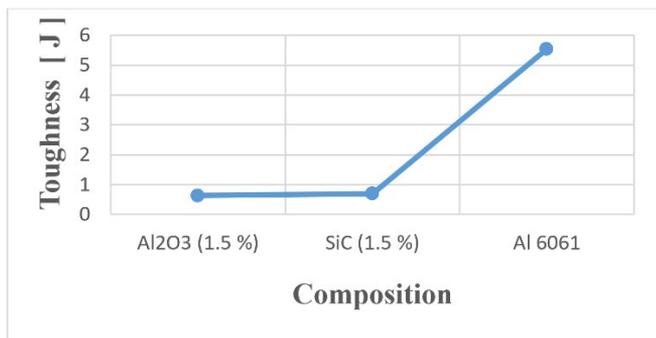


Figure 9. Plot of the average surface roughness for different materials

The test results showed that the impact energy of Al/Al₂O₃ and Al/SiC composites were mainly depended on the distribution of the particles in the matrix.

The presence of the ceramic particles in the alloy negatively affected the toughness value in which the composite became brittle. However, with the increasing percentage of the ceramic particles, the behavior of the composite changed in which the toughness value increased along with the particles, but it was still less than the desirable value and was still brittle.

4. CONCLUSIONS

This study systematically investigated the structural and mechanical properties of different types of nanoparticle reinforced AMCs. In addition, the effects of variations in

Al₂O₃ nanoparticles in Al 6061 were also investigated. The experimental results were discussed, and the important conclusions were drawn below. The damping and hardness increased significantly with the addition of nanoparticles in the matrix. The 2% Al₂O₃ nanoparticles in the composite were found to be the optimal weight fraction of added nanoparticles that produced a higher damping ratio. The addition of nanoparticles showed adverse effects in the toughness performance of the composite due to its higher brittleness. Compared with different theoretical and experimental models from previous studies, the results worked very well.

Although stir casting is regarded as a straightforward production technique, its results can be significantly enhanced by the precise control of processing parameters, the incorporation of auxiliary methods such as ultrasonic assistance, and the addition of improvement agents. In further experiments, more investigations of those factors of this operation could be performed in order to get a more accurate picture.

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