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Influence of MWCNTs and SiC/Al_2O_3/B_4C particulate reinforcements on mechanical properties of AA 6063 based composites

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Abstract: Aluminum Matrix composites are in high demand to fulfill the functional requirements of the automotive, military, aerospace, and electricity industries. To meet this need, composites have been developed by systematic integration of different particulate reinforcements at the micro and nano-scale. In this investigation, aluminum composites were developed by stir casting and designed to improve the mechanical properties of AA 6063 matrixed composite by systematically dispersing COOH functionalized MWCNTs as primary reinforcement with a constant weight of 0.5%. Further, Alumina (Al_2O_3), Silica (SiC), and Boron Carbide (B_FC) were reinforced individually in Aluminum alloy AA 6063 with sequential weight fractions equivalent to 2%, 4%, 6%, and 8% by weight of Aluminum Oxide, Silicon carbide, and Boron carbide. The study found a significant increase in strength by constant nano and varying micro particulate reinforcements in aluminum. Maximum improvement in Tensile strength and Young's modulus was observed at 6% wt. of microparticulate reinforcement of SiC, Al_2O_3, and B_4C. Compression strength and hardness improved proportionally with the quantity of reinforcement; more specifically, strength and hardness increased for maximum reinforcement of 8% wt. of alumina, silica, and boride respectively.

Keywords: AA 6063, MWCNTs, SiC, Al_2O_3, B_4C, Aluminum matrix hybrid nanocomposites, mechanical properties.

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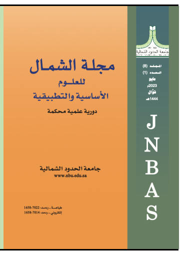

تأثير MWCNTs و SiC / Al_2O_3 / B_4C على الخواص الميكانيكية للمركبات القائمة علىAA 6063

بدر مشبب القحطاني

(قدم للنشر في 1444/8/9؛ وقبل للنشر في 1444/11/11هـ)

مستخلص البحث: هناك طلب كبير على مركبات مصفوفة الألومنيوم لتلبية المتطلبات العملية لمصانع السيارات والمعدات الحربية والفضاء والكهرباء. لتلبية هذه الحاجة ، تم تطوير المواد المركبة من خلال التكامل المنهجي لتعزيز الجسيمات المختلفة بحجم المايكرو والنانو. في هذه الدراسه ، تم تطوير مركبات الألومنيوم عن طريق صبها وتم تصميمها لتحسين الخواص الميكانيكية لمركب مصفوفة **AA 6063** عن طريق تشتيت COOH functionalized MWCNTsبشكل منهجي كتعزيز أولي بوزن ثابت 0.5٪. علاوة على ذلك ، تم تقوية الألومينا **(Al_2O_3)** والسيليكا **(SiC)** وكربيد البورون **(BFC)** بشكل فردي في سبيكة الألومنيوم **AA 6063** بأجزاء متتابعة من الوزن تعادل 2٪ و 4٪ و 6٪ و 8٪ من وزن أكسيد الألومنيوم ، كربيد السيليكون وكربيد البورون. وجدت الدراسة زيادة كبيرة في القوة من خلال التعزيزات الثابتة النانوية والجسيمات الدقيقة المتغيرة في الألومنيوم. كذلك أقصى تحسن في مقاومة الشد ومعامل يونغ لوحظ عند 6٪. لتقوية الجسيمات الدقيقة ل **SiC** و **Al_2O_3** و**B_4C** . تم تحسين قوة الضغط والصلابة بالتناسب مع كمية التعزيز ؛ وبشكل أكثر تحديدًا ، تمت زيادة القوة والصلابة للحصول على أقصى تقوية بنسبة 8٪. من الألومينا والسيليكا والبوريد على التوالي.

كلمات مفتاحية: AA 6063، MWCNTs، SiC، Al_2O_3، B_4C، مصفوفة الألومنيوم المركبة النانوية الهجينة، الخواص الميكانيكية.

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1. INTRODUCTION:

The development and manufacturing of composites are influenced by the high demand of industries in various applications. Various engineering applications require composites with high specific strength and durability (Miracle, 2005). The systematic engineering assortment of metallic matrix and ceramic reinforcements leads to the new material delivering exceptional characteristics than that of the conventionally available groups of materials. The new material offers high specific strength, enhanced endurance, resistance against corrosion, improved hardness, toughness, etc., and can further be tailored with the addition of nanoparticles/nanotubes to enhance mechanical, electrical, thermal, hygrothermal, and many other physical properties (Adamiak, 2006), (Aribo, Omotoyinbo, & Folorunso, 2011). Common microparticles such as silicon carbide (SiC), aluminum oxide (Al_2O_3), titanium oxide (TiO2), boron carbide (B_4C), and many other nitrides, borides, carbides, and oxides serve as eramic reinforcement in MMCs. The mechanical, tribological, and thermal properties of hard particulate reinforcement facilitate interfacial bonding with matrices and normalize the properties of elements to achieve a high modulus to density ratio in composites [Marin, Lekka, Andreatta, Fedrizzi, Itskos, Moutsatsou & Kouloumbi, 2012), (Koli, Agnihotri, & Purohit, 2015).

AA 6063 contains Si and Mg as major alloying elements, which allows for its wide applicability. AA 6063's machinability, weldability, and formability produce high levels of strength (Thangarasu, Murugan, Dinaharan, & Vijay, 2014). By precisely engineering the material with the systematic integration of the right amount of reinforcements (Gangil, Maheshwari, & Siddiquee, 2018), (Ali, Kuppuswamy, Soundararajan, Ramkumar, & Sivasankaran, 2021), machining and manufacturing ease can be achieved by using AA 6063. SiC reinforced in aluminum alloy 6603 has shown significant improvement in tensile strength, density, and hardness, whereas particles of Al_2O_3 exhibit better mechanical properties and greater wear resistance compared to aluminium alloy 6603 (Chak, Chattopadhyay, & Dora, 2020), (Singh & Goyal, 2018). When blended with calcium carbide in AA 6063, boron carbide microparticles developed a composite that exhibited significant improvement in mechanical properties, including tensile strength and hardness of AA6063. Impact strength, however, deteriorated with the increase in the quantity of reinforcement (Madheswaran, Sugumar, & Elamvazhudi, 2015). In recent investigations, it was observed that nano reinforcement has improved the mechanical properties of AMCs at higher levels than the microparticle reinforcements.Nano reinforcement in AMCs has greatly improved the characteristics of materials in static and dynamic loading. More specifically, the interfacial bonding was seen significantly enhanced, thus reflecting enhanced properties due to quantum confinement and surface exposure in nanoparticles and nanotubes (Sharma, Kumar, & Joshi, 2019). It was recorded that microparticles generate micro cracks and voids in manufacturing. It was observed that if the weight fraction of ceramic reinforcement is increased above 30% in AMCs, the brittleness of material increases. This brittleness result in low tensile strength and toughness, but the problem can be overcome with the integration of nanoparticles/nanotubes in AMCs, which enriches the interfacial bonding and increases the strength and mechanical characteristics of AMCs (Sharma, Kumar, & Joshi, 2019), (Yang, Lan, & Li, 2004). It was noted that the compressive strength and impact strength of AA 7075+ SiC composites increased with an increase of SiC in AMC. This increase was produced by a liquid metallurgy solidification process. Solutionizing and artificially aging composites to T6 condition further improved the properties and reduced the deflection in 3 point bending. Further increase in SiC was achieved by reducing particle size has enhanced the microhardness but reduced the ductility of AMC in stir-assisted solidification (Das, Sharma, Samal, & Nayak, 2019). It is found that 11% wt. of B4C addition in AA 6061 (in two stages of addition) with 0.3x ratio of K2TiF6 salt in stir casting resulted in improved wettability and uniform dispersion in matrix, resulted in enhancement of UTS by 4.2% and hardness by

223% (Auradi, Rajesh & Kori, 2014). When the examination was done on the effect of nano reinforcement (CNTs) in AA 6063, they found that by using a hot extrusion process, 3% vol. of CNTs in composites resulted in a high Vickers hardness of 120 HV, recrystallization zone projected excellent hardness, strength, and ductility which is evidenced by dimples seen in microstructures (Kim, Park, Kim, Miyazaki, Joo, Hong, & Kwon, 2019). The hybrid nanocomposites based on aluminum alloy 6061 reinforced with different hybrid ratios of SiC (0.5, 1.0 and 1.5 vol. %) and B4C (fixed 0.5 vol. %) nanoparticles were successfully fabricated using ultrasonic cavitation-based solidification process. The fabricated cast specimens were characterized using SEM study with EDS analysis, hardness test, tension test and impact test. The results indicate that, Compared to the un-reinforced alloy, the room temperature hardness and tensile strength of the hybrid composites increased quite significantly while the ductility and impact strength reduced marginally. The combination of 1.0 volume percentage SiC and 0.5 volume percentage B4C gives the superior tensile strength. The major reason for an increase in the room-temperature mechanical properties of the hybrid composites should be attributed to the larger hybrid ratio of SiC and B4C nanoparticles, the coefficient of thermal expansion mismatch between matrix and hybrid reinforcements and the dispersive strengthening effects. (Poovazhagan, Kalaichelvan, Rajadurai, & Senthilvelan, 2013). When investigation was done on the mechanical properties of AA 6063 based composites reinforced with constant 1% Wt. of alumina and varying graphite with 3%, 6%, 9%, and 12% Wt. They found that hardness, compressive strength, flexural strength, and impact strength increased with an increase of reinforcement up to 6% of the weight. Further increase in reinforcement resulted in a decrease in these properties (Saravanakumar, Sasikumar, & Sivasankaran, 2014). It was observed that the significant advancements of mechanical properties such as UTS (ultimate tensile strength), compressive strength, and hardness in AMCs. With the integration of CNTs and graphenes, strength has increased by up to 5x (Khanna, Kumar, & Bansal, 2021). When the study was done on the influence of SiC and B4C particulate reinforcement in aluminum-based composites. They found that silica and boron carbide greatly enhanced the mechanical and physical properties, whereas TiB2 integration deteriorated in Al composites (Kumar, Dabade, & Wankhade, 2021). Aluminium alloy surface hybrid nanocomposite, reinforced with boron carbide (B4C), aluminium oxide (Al2O3), and Graphite (Gr) at different combination mixtures by weight ratio have been fabricated on Al7075-T6 aluminium plate by employing friction stir processing (FSP). The hybrid nanocomposite having a reinforcement mixture of 30 B4C+60 Al2O3+10 Gr exhibits a significant wear resistance than other combination ratios. This is endorsed by the enhancement in binding strength of the matrix and the pinning effect of hard reinforcements, which act against the applied shear force. (Gobikannan, Gopalakannan & Balasubramanian, 2022)

Tensile strength and Young's modulus are required in almost every mechanical investigation. To meet the functional requirements of the industry, aluminum composites with different types and grades of reinforcement (which exhibit varied strength and mechanical properties) have been developed. To design the material for specific applications, researchers must choose the right level of reinforcement.

In the present work an attempt is being made to process AA 6063 matrixed composite by systematically dispersing COOH functionalized MWCNTs as primary reinforcement with a constant weight of 0.5% by stir casting method. Further, Alumina (Al2O3), Silica (SiC), and Boron Carbide (BFC) were reinforced individually in Aluminum alloy AA 6063 with sequential weight fractions equivalent to 2%, 4%, 6%, and 8% by weight of Aluminum Oxide, Silicon carbide, and Boron carbide. The composites prepared were subjected to evaluation of mechanical properties and the improvement achieved is noted down.

2. EXPERIMENTAL METHODOLOGY:

2.1. Materials and Methods:

The selection of materials is a crucial task in any investigation. The prime objective of this study is to develop composites for wide applicability; high functionality; minimized cost of material; low density; high levels of durability, endurance, and machinability; improved thermal and/or electrical properties; and advanced static and dynamic load-sustaining capabilities. Aluminum often fulfills various structural and mechanical requirements because it is lightweight, easy to machine, and easy to fabricate. For these reasons, commercially available standard aluminum alloy 6063 was selected to matrix the composites. To reinforce the composites, silicon carbide, aluminum oxide, and boron carbide particulates were chosen as primary reinforcement. Additionally, to enhance the blend/mixture of matrix and reinforcements, carboxyl (COOH) functionalized multi-walled carbon nanotubes were used as secondary reinforcement. Nanotubes were selected because of their excellent interfacial bonding capabilities. Reinforcement particles were subjected to ball milling to minimize the particle size, which optimized the blend of matrix and reinforcements. The particles were resized to 15-50µm. SiC, Al_2O_3, and B_4C were reinforced individually in AA 6063 to study the effect of microparticulates in composites in the weight fractions of 2%, 4%, 6%, and 8% [with a constant weight fraction of 0.5% nano reinforcement (Multi-walled carbon nanotubes -MWCNTs) in each composition].

2.2. Fabrication and processing:

AMCs were fabricated using a stir casting melting technique. Stir casting setup as shown in (Figure 1), consist of a furnace, reinforcement feeder and mechanical stirrer. It is the most suitable process for metal matrix composites, because it allowed experimenters to blend hard/light particles in molten metal and disperse them using a stirrer for the weight fractions of reinforcements up to 30%. The mechanical stirrer used in this investigation rotated at a speed of 600RPM. The matrix was heated to 730ºC. Particulate reinforcement was added to matrix by preheating to 300ºC for 5 minutes. This heating improved the wettability of MWCNTs at room temperature. Now, the molten AMCs composites are poured into the mold and allowed to solidify. The moulds are taken out after solidification from the moulding box (Figure 2).

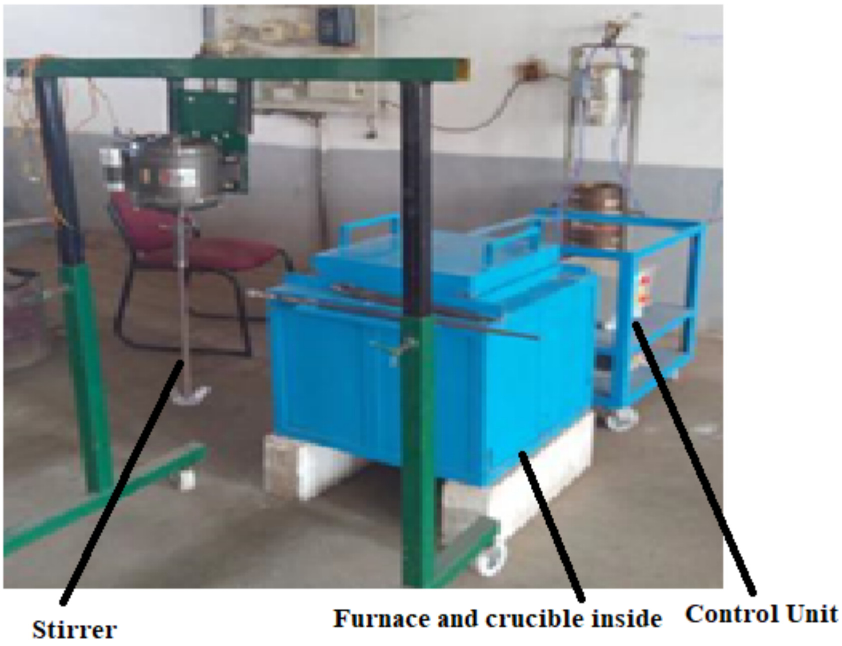

Figure 1: Stir casting furnace

Removal of Moulds from Moulding box

Figure 2: Post casting aluminum composite molds

2.3. Testing and Validations:

After casting was complete, AMC molds were machined and specimens were drawn for mechanical testing according to the geometries and testing standards described by ASTM viz, E8 for Tensile Testing (Figure 3a), E9 for Compression testing (Figure 3b), and E384 for Vickers Hardness (Figure 3c).

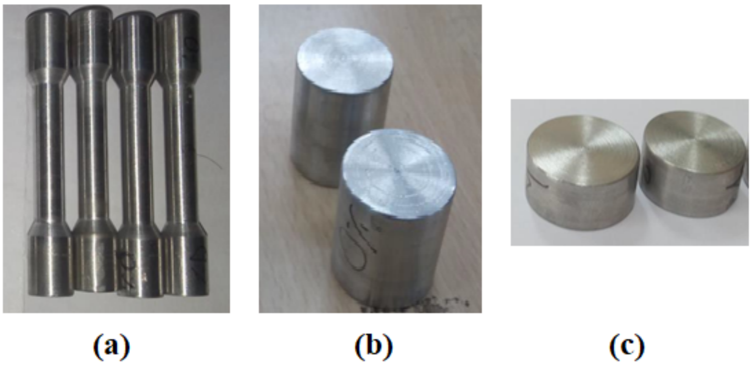

Figure 3: Specimens for (a) Tensile Test; (b) Compression Test; and (C) Hardness Test and Morphology

Tensile Test: A uniaxial tensile test was performed on an electromechanically operated, computer-controlled universal testing machine at room temperature at a loading rate of 10 MPa per second (following ASTM E8- M91 standards). The load vs. displacement and stress-strain curve generated was used to analyze the mechanism of fracture.

Compression Test: A uniaxial compression test was performed using AMCs in a computerized UTM to study the effect of axial compression on material and failure under compression (following ASTM E9 standards).

Hardness Measurement: Composites samples were carefully polished using various emery papers. Samples were also velvet-buffed and etched when required to achieve a clear surface. Following ASTM E384 standards, samples were then subjected to microindentation for hardness measurement. A Vickers microhardness test was carried out using diamond indentor.

Morphology: Composites samples were ground using various grid-sized emery papers in sequence from lower numbers to up to 2000 grids. The surface was buffed with cotton, then polished using velvet, alumina powder, and diamond powder. Finally, the carefully polished surface was etched using HNO_3 and HCL to normalize the micropeaks on the surface of the samples. After ensuring that the surface was fully polished, the surface microstructure, grains, inclusions, and surface properties were studied using an inverted metallurgical microscope in various magnifications up to 1600X.

Density Measurement: Density measurements were performed to determine porosity in the composites. Porosity is a defect at the micro level, so it can be calculated by comparing the theoretical and experimental density of the composites. The composite samples were weighed using a high-precision scale having that measures down to the thousandth of a gram. Theoretical density (ρ_{Th}) of the composite can be calculated by:

Density of Composite = (Volume fraction of AA 6063 x Density of AA 6063) + (Volume fraction of MWCNTs x Density of MWCNTs) + (Volume fraction of reinforcement 2 x Density of reinforcement 2)

$$\rho_{Comp\ 1} = (Vol_{AA\ 6063}\ X\ \rho_{AA\ 6063}) + (Vol_{MWCNTs} X \rho_{MWCNTs}) + (Vol_{SiC}\ X\ \rho_{SiC}) \quad \ldots\ldots.\ (1)$$

$$\rho_{Comp\ 2} = (Vol_{AA\ 6063}\ X\ \rho_{AA\ 6063}) + (Vol_{MWCNTs} X \rho_{MWCNTs}) + (Vol_{Al2O3}\ X\ \rho_{Al2O3}) \ldots.\ (2)$$

$$\rho_{Comp\ 3} = (Vol_{AA\ 6063}\ X\ \rho_{AA\ 6063}) + (Vol_{MWCNTs} X \rho_{MWCNTs}) + (Vol_{B4C}\ X\ \rho_{B4C}) \quad \ldots\ldots.\ (3)$$

Experimental density (ρ_{Exp}) can be obtained by precise measurement of sample weight divided by the volume of the sample

Porosity can be calculated by:

$$\%\ Porosity = \frac{(\rho Th - \rho Exp)}{\rho Th} \text{ x } 100 \quad \ldots\ldots\ (4)$$

3. RESULTS AND DISCUSSIONS:

3.1. Morphology and crystallography

The surface characteristics of composites influence several physical and mechanical properties. As a result, studying surface topography and microstructure is important for characterizing the materials.

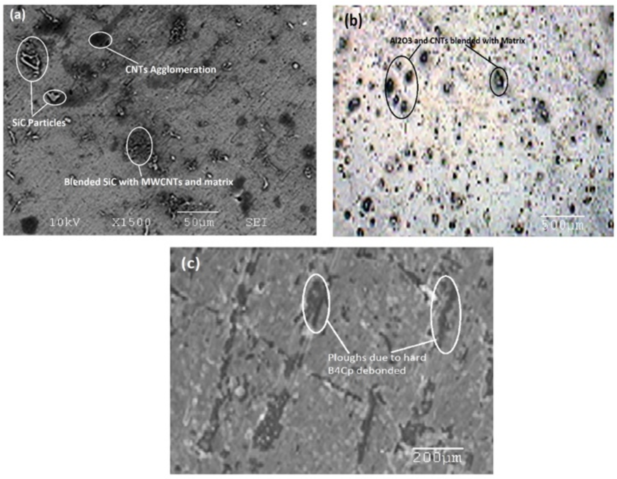

Figure 4: Microstructure of Al 6063 based composites surface for (a) 6% wt. SiC; (b) 6% wt. Al_2O_3; and (C) 6% wt. B_4C

Silicon Carbide was found in aluminum in the form of microflakes and is the cause of improper homogenization of reinforcement elements. The graphs thus show an artificial doping mechanism of SiC in Al 6063 as the carbon atoms form effective interstitially, which subsequently enhances the compressive strength. It was also found that MWCNTs act as interfacial bonds between the SiC and Al matrix, with adequate consistency in the formation of composites. The micrographs (Figure 4a) depict the greater influence of MWCNTs over SiC in bonding with the Al matrix. The material is expected to be hard, brittle, and highly resistant to wear.

Alumina particles can be seen clearly in the microstructure (Figure 4b). There is a nearly uniform distribution of reinforcement in the Al matrix. Al_2O_3 was reinforced into Al 6063 with an 8% weight fraction and also with 0.5%wt. of the composite, resulting in optimum doping of alumina particles and CNTs into a metallic matrix. This improved the dispersion and bonding of ceramic particulate and Al matrix, thus enhancing the mechanical and tribological characteristics of the material.

Boron carbide with MWCNTs integration in Al 6603 has substantially homogenized and exhibited atomic influence of matrix materials. Figure 4c illustrates its substitution in Al crystals. It was found that excessive reinforcement of B_4C leads to more general wettability issues due to its lower density. But in micrograph light, plough marks are seen and effective substitution of reinforcement is attributed to MWCNTs. However, the microstructure shows an obvious effect of particulate/atomic slip in matrix crystals due to the hardness and lightness of B_4C.

3.2. Density and Porosity

Density measurement of the composites is a practical approach to evaluating porosity, which is a common defect found in composites due to the fundamental heterogeneity of elements of composites. Effective engineering is needed in order to develop the composites with maximum blend efficiency. The conventional way of determination of density (by geometrical means and using the mass/volume method) was adopted and compared with the theoretical evaluation of density. The difference between theoretical and experimental density determines the porosity in composites.

Table 1: Density and Porosity of Composites with Varied Particulate Reinforcements

Composites	Theoretical Density (ρ_{Th})	Experimental Density (ρ_{Exp})	% Porosity
0%	2656.43	2643.27	1.317
2% Al_2O_3	2662.79	2647.24	1.556
4% Al_2O_3	2669.15	2650.78	1.837
6% Al_2O_3	2675.51	2660.25	1.526
8% Al_2O_3	2681.87	2653.26	2.861
2% SiC	2659.64	2628.28	3.136
4% SiC	2662.84	2637.67	2.5176314
6% SiC	2666.05	2637.32	2.8730046
8% SiC	2669.25	2640.13	2.9123779

2% B_4C	2655.06	2647.73	0.7331177
4% B_4C	2653.68	2641.23	1.2453505
6% B_4C	2652.30	2643.23	0.9075832
8% B_4C	2650.92	2638.27	1.265816

Table 1 shows the theoretical and experimental densities of the composites. By varying the quantity of different particulate reinforcements, we can notice the volume void fraction of the composite termed as porosity in composite blocks.

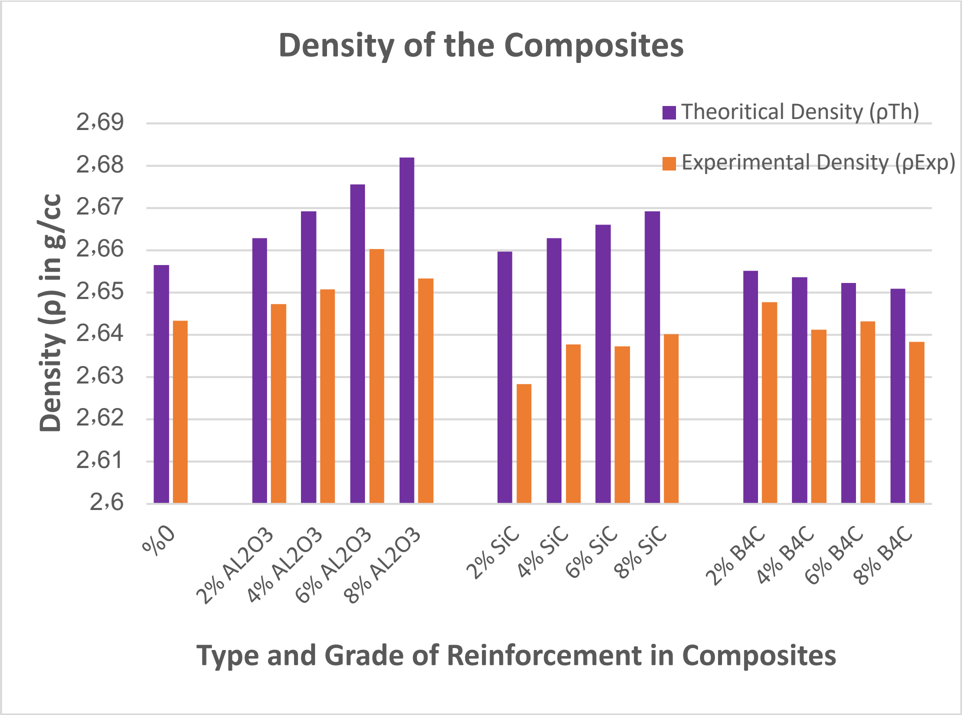

Figure 5: Theoretical and Experimental Densities of Composites with Different Weight Fractions of Particulate Reinforcements SiC, Al_2O_3, and B_4C

Figure 5 compares the theoretical and experimental densities of composites. It was found that the density of composites increased in SiC reinforcement and that it increased linearly with the number of reinforcements because SiC is denser than the AA 6063 alloy. In alumina and B_4C reinforcements, theoretical and experimental densities were reduced due to the fineness and lowered density of the reinforcing agent. Furthermore, in the B_4C reinforcement, the density was lower than base AA 06063. The density of B_4C reinforcement is lower than that of the matrix element, and with the rise in weight fraction of reinforcements, there is an overall reduction of densities in composites.

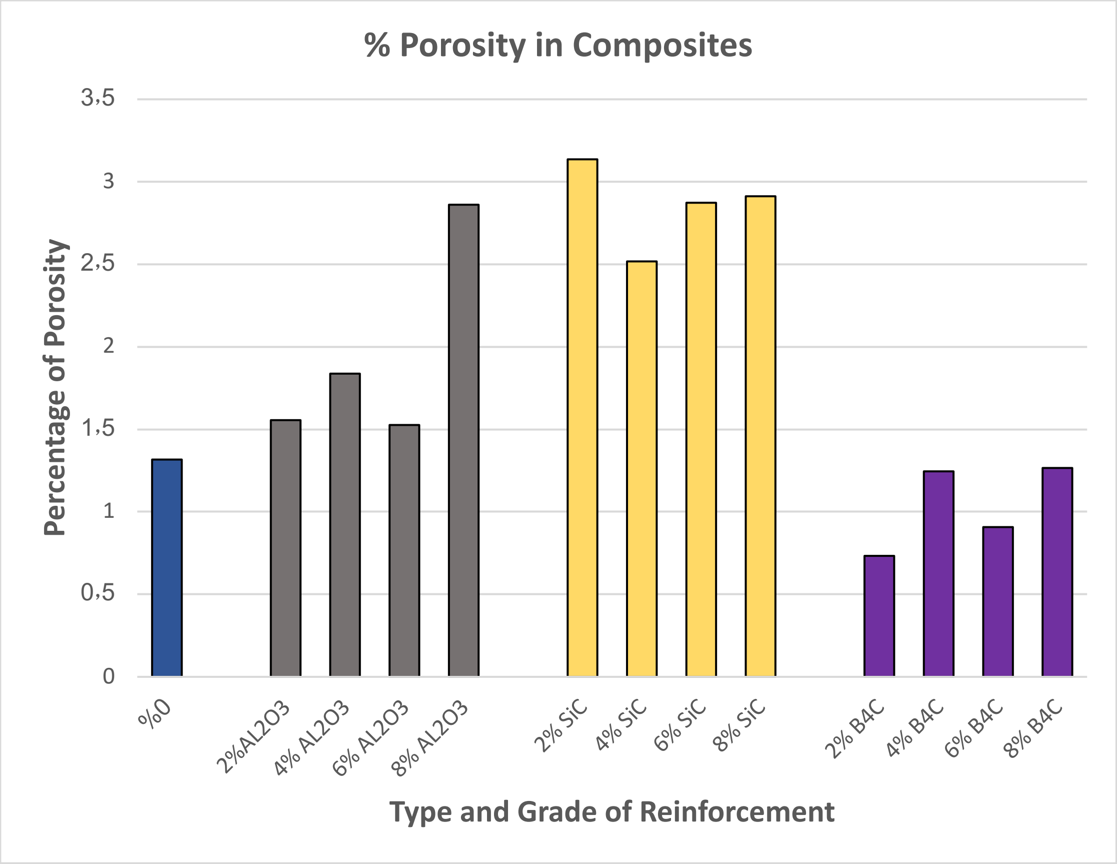

Figure 6: Volume Void Fraction or Porosity of Composites with Different Weight Fractions of Particulate Reinforcements SiC, Al_2O_3, and B_4C

Experimental density decreased due to the blend of two distinctly characterized materials, resulting in void volume or porosity in composites (Fig 6). The change in atomic arrangement and mechanical crystal structure caused atomic vacancies, substitutional deficiencies, and improper interfacial bonds. This contributed to the formation of microcracks and gaps between the Al matrix and non-homogenized particles of composites. B_4C-reinforced composites reacted more with MWCNTs in forming an effective blend and a reinforcement bond with the Al matrix. Reduction of porosity was largely attributed to the functionalized CNTs, which fill the micro /nano gaps and act as agents in reinforcing the composites' bond.

3.3. Tensile Test

The tensile strength of Al 6063 matrix composites with SiC, Al_2O_3, and B_4C reinforcements was measured by maintaining a constant 0.5% weight fraction of MWCNTs and varying microparticulate reinforcement by weight at 2%, 4%, 6%, and 8%. Table 2 shows the tensile properties of composites and the enhancement of tensile strength and modulus by integration of reinforcements in aluminum alloy AA 6063.

Table 2: Tensile Properties of Composites with Varied Reinforcements

Composites	Young's Modulus *(N/mm^2)*	Ductility/ Elongation *(%)*	UTS Improvement *(%)*	Modulus Improvement *(%)*
0%	336.12	32.48	--	--
2% Al_2O_3	1016.64	31.58	43.58	202.46
4% Al_2O_3	724.11	26.90	50.76	115.43
6% Al_2O_3	1277.19	18.39	77.96	279.97
8% Al_2O_3	871.14	27.67	59.60	159.17
2% SiC	751.26	28.44	46.43	123.51
4% SiC	626.31	25.65	48.54	86.332
6% SiC	1458.7	20.07	65.26	333.98
8% SiC	537.33	19.42	52.53	59.86
2% B_4C	1043.46	18.89	74.63	210.44
4% B_4C	3133.95	18.74	133.91	832.38
6% B_4C	2546.17	15.52	232.91	657.51
8% B_4C	1649.97	18.79	164.36	390.88

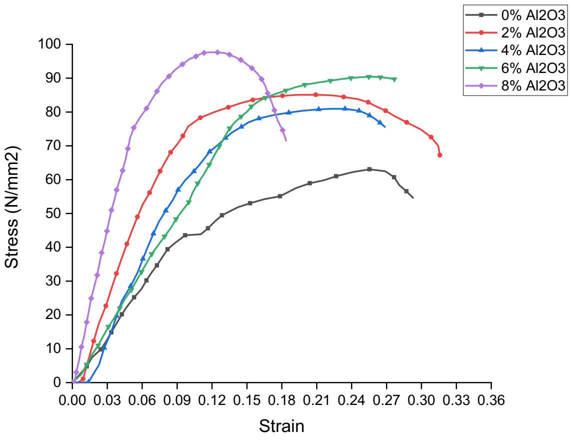

Figure 7: Stress-Strain curves of AA 6063+ 0.5% MWCNTs + Al_2O_3 Composites tested under tension with variable alumina quantity by 2%, 4%, 6%, and 8% wt.

Figure 7 shows the stress-strain curves of Al matrix composites with different grades of alumina-reinforced composites. It was observed that the composites showed improved strength with micro and nano-reinforcements up to the critical reinforcement of 6% by weight, beyond which the tensile strength decreased. Furthermore, the strain or extension at 6% of Al_2O_3 reinforcement is lower, which indicates embrittlement of material and improper placement of atoms in crystals. This embrittlement results in microcracks and improper bonding of alumina particles with AA 6063. Overall performance of the composites under tension improved with the addition of reinforcements. It was observed that the maximum UTS is improved by 78% for 6% of Al_2O_3 and 0.5% of MWCNTs. The subsequent elastic modulus was improved by 2.8x. The ductility of the composites was compromised with the integration of Alumina. Ductility decreased with increases in the amount of reinforcement and for 6% of alumina, it was reduced by 43%.

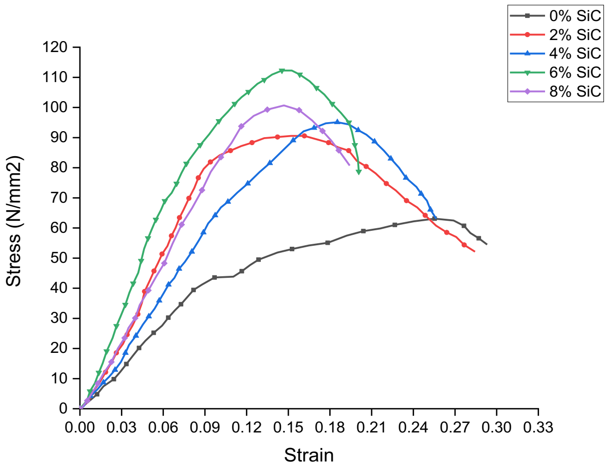

Figure 8: Stress-Strain curves of AA 6063+ 0.5% MWCNTs + SiC Composites tested under tension with variable Silica quantity by 2%, 4%, 6%, and 8% wt.

In Figure 8, characteristic curves of stress-strain under tension were observed. In SiC reinforcement with MWCNTs, the tensile strength significantly improved and was highest at 6% wt. of SiC, while the corresponding strain was enhanced at lower levels. The elastic modulus reduced the elongation/ductility of the composite. In the composition, tensile strength was ultimately enhanced by 65% and modulus by 3.3x for 6% wt. of SiC with 0.5% wt. of MWCNTs.

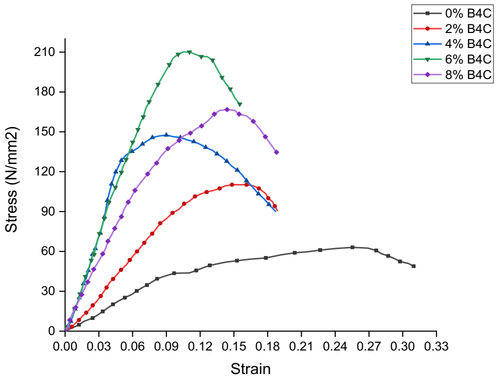

Figure 9: Stress-Strain curves of AA 6063+ 0.5% MWCNTs + B_4C Composites tested under tension with variable Boron carbide quantity by 2%, 4%, 6%, and 8% wt.

Figure 9 shows the stress-strain curve, projecting tensile characteristics of B_4C-reinforced Al composites. The B_4C reinforcement substantially reduced the total extension/elongation of the composites, but it significantly enhanced the strength. This is due to B_4C having a lower density than the Aluminum alloy. The lower density makes the homogenization of the matrix reinforcement mixture more difficult, but the integration of MWCNTs improved the wettability issues, which enhanced interfacial bonding and aided in effective doping of reinforcing atoms in the Al matrix. In the composites, tensile strength increased linearly with increases in reinforcement but began to deteriorate after 6% integration of B_4C by weight. The UTS was enhanced by 2.3x, the elastic modulus by 6.5x, and subsequent elongation was reduced by 42%.

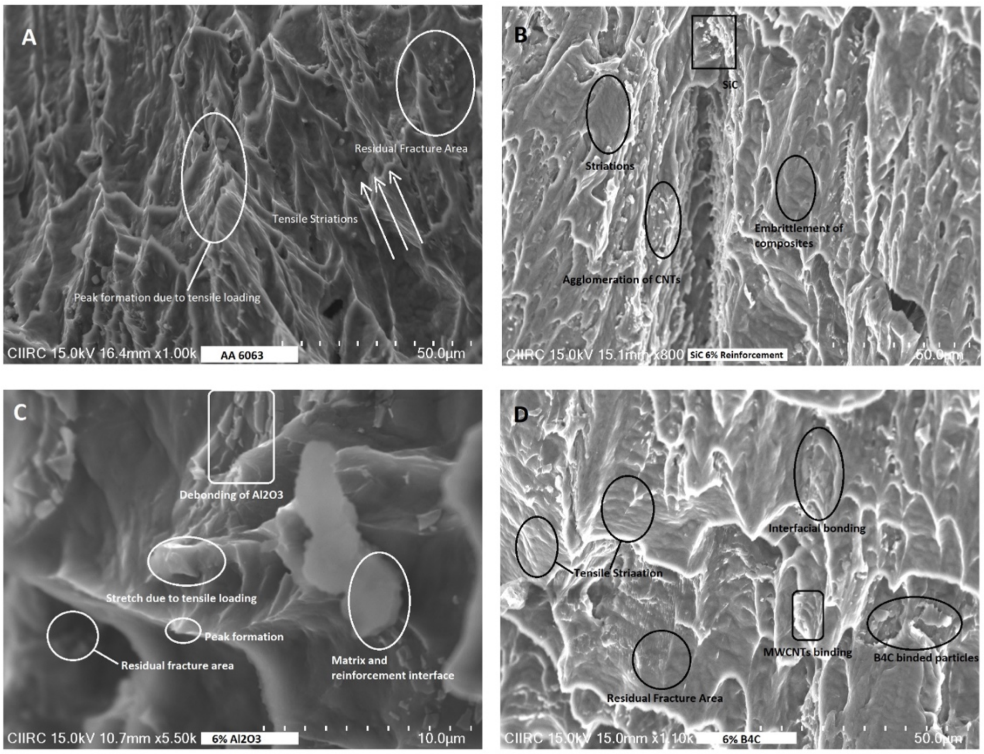

Figure 10. SEM fractographs of (A). Al 6063 with no reinforcements and composites with constant 0.5% wt. MWCNTs; at (B) 6% wt. SiC; (C) 6% wt. Al_2O_3; and (D) 6% wt.

The fracture mechanism of AA 6063-based composites is as shown in figure 10. The fractpographs in Figure A indicate that aluminum alloy 6063 exhibits more tensile striations due to the highly ductile nature whereas, in reinforced composites, striations are considerably lowered. This indicates that brittleness is introduced along with the introduction of hard ceramic particles. Figure B shows the agglomeration of MWCNTs in some areas, but nanotubes greatly influenced SiC particles' bonding with aluminum. Figure C illustrates the fine Al_2O_3 particles bonding effectively due to the mutual atomic doping and diffusion. This doping and diffusion cause atomic transfusion with base aluminum and mixes with it at high temperature. However, formation of alumina clusters was observed in some areas. Furthermore, MWCNTs enhanced the interfacial bonding of alumina with based aluminum. In Figure D, B_4C particles (which are significantly harder and has lower density than AA 6063) bonded moderately, causing the increase in hardness and brittleness of the material. AA 6063 was force blended and followed by CNT's bonding effect. As a result, striations can be seen in the areas of partial mixture, whereas CNT's influence on matrix reinforcement binding was observed. The strongest composite was observed with reduced elongation and enhanced hardness.

3.4. Compression Test

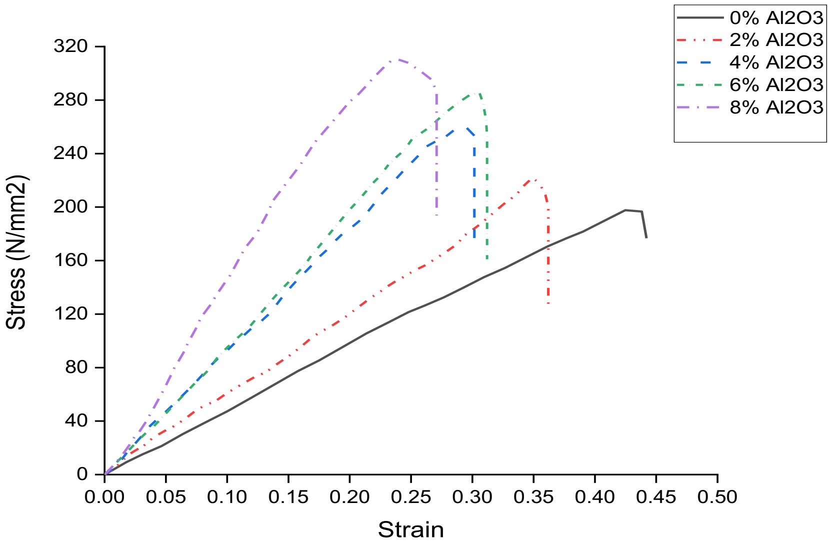

Figure (11a)

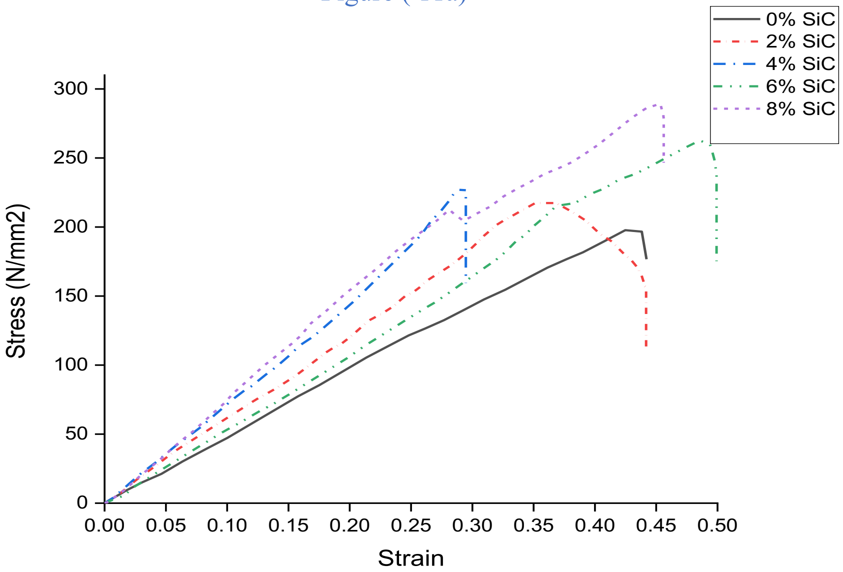

Figure (11b)

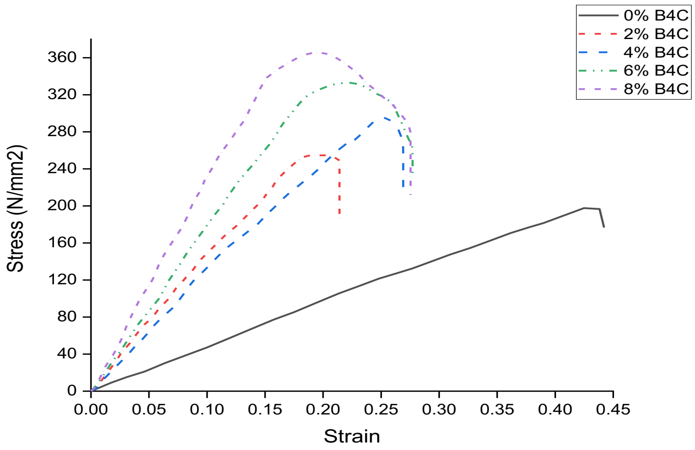

Figure (11c)

Figure 11: Stress-Strain diagrams of AA 6063 based composites under compression with constant 0.5% MWCNTs and variable micro particulate reinforcements of (a) Al_2O_3; (b) SiC; and (c) B_4C with variable quantity by 2%, 4%, 6%, and 8% wt.

Figure 11 shows characteristic curves of stress vs strain of the Al matrix composites with variable micro and fixed nanoreinforcements. In the graphs, it was observed that the compression strength of composites was significantly increased with the increase in the number of reinforcements. Because the density of composites was also enhanced, the load-carrying capacity of the composites under compression was improved. Here, B_4C reinforcement has shown a substantial increase in strength, followed by alumina and silica. Silica-reinforced composites exhibited a strength enhancement of 46%, alumina reinforced composites by 57%, and boron carbide reinforced composites by 85% (each for 8% weight fraction of composites).

3.5. Hardness Test

Measurement of the composites' hardness is crucial for determining composites' machinability and surface reliability under the influence of abrasion/erosion or indentation. The compositions' hardness was measured using Vicker's hardness test.

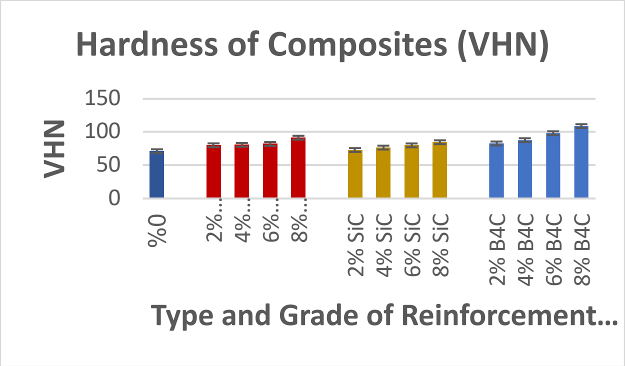

Figure 12: Hardness of the Al matrix composites with variable reinforcements

Figure 12 illustrates the hardness of composites in HV for various compositions. The hardness is commensurate with the mean of hard reinforcing particles. The trend of the hardness is proportional to the hardness of the particulate, and it improved proportionally with the increase in the amount of reinforcement. For the 8% weight fraction of micro particulate inclusion, maximum hardness in alumina reinforced composites was enhanced by 28.5%, by 19% for silica reinforcement, and by 53% for boron carbide.

4. CONCLUSION

Aluminum Alloy AA 6063 based composites were produced by the liquid fabrication method. Stir casting technique and composites were made by nanoreinforcement, with the addition of 0.5% wt. of functionalized MWCNTs constantly in all compositions. The composites were further reinforced by different microparticulates by varying the quantity of SiC, Al_2O_3, and B_4C, each of which was reinforced in AA 6063 at 2%, 4%, 6%, and 8% by wt. in order to study the effect of microparticulate reinforcement on the mechanical properties of composites. The following conclusions have been drawn:

1. MWCNTs enhance the interfacial bonding of reinforcement and matrix by an effective doping mechanism, thus improving the mechanical and physical characteristics of the composites.
2. The surface topography of the composites had an equal and nearly uniform distribution of reinforcement and MWCNTs acted as binding agents by filling the microgaps between solid reinforcement particles and matrix crystals. This improved the composites' ductile properties and reduced brittleness.
3. In the density evaluation, it was noted that the porosity of the composites was significantly reduced with the integration of MWCNTs in composites. With the increase in the amount of particulate reinforcement, porosity also increased. The porosity of SiC reinforced composites exhibited higher porosity than that of B_4C and Al_2O_3 composites. Hardness was enhanced proportionally with volume of reinforcements, as seen that 8% wt. fraction. Hardness was improved by 57%, 46%, and 85% for the Al_2O_3, SiC, and B_4C reinforcements, respectively.
4. Tensile strength improved with the increase in the amount of reinforcement. The highest σt was observed at 6% wt. of particulate reinforcements, beyond which it deteriorates. UTS improved by 78%, 65%, and 232% for an Al_2O_3, SiC, and B_4C reinforcements, respectively
5. Compression strength and hardness increased linearly, with the highest levels found at 8% wt. of reinforcement and enhancement in σ_c. Hardness levels were 57%, 46%, and 85% for Al_2O_3, SiC, and B_4C reinforcements, respectively.
6. SEM micrographs showed the fracture mechanism of the tensile test in composites. It was found that stretch due to axial pull had peak formation and partial tensile striations due to the uniform dispersion of reinforcements. The fracture is caused by instant crack and failure. The microstructure at residual fracture area clearly shows the distribution and bonding between the ceramic particles and the Al matix. In some areas, agglomeration of MWCNTs embrittled the material and resulted in the rapid disengagement of reinforcing particles. Overall, the dispersion of particulates was effective on composites.

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