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Exploring the Mechanical Characterization and Microstructural Properties of the Varying Weight % of Nano Boron Carbide (nB_4C) Reinforced Al2024 composites using the Vacuum-Assisted Stir Casting Method

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Abstract

In this investigation the stir casting technique is utilized to fabricate Al2024-B_4C nano composites. The nanoB_4C particles used in the reinforcement material have a particle size of 50 nm and variable weight percentages. In Al2024 composites, boron carbide reinforcement is included at weight percentages ranging from 0% to 3%, with a 1% interval between each percentage addition. Following the casting process, the samples were prepared for microstructural and mechanical evaluation in accordance with the standards established by ASTM. Scanning electron microscopy, often known as SEM, is utilized for the purpose of analyzing the distribution of nanoparticles inside the matrix material as well as for the purpose of examining the morphology. As can be seen in the scanning electron microscope (SEM), there is a consistent distribution of nanoparticles across the entirety of the matrix, and there is a reduced amount of porosity that is left over. Stir casting with vacuum assistance is an effective method for producing aluminum composites because the reinforcement is distributed evenly throughout the casting process. In comparison to other samples, the composite Al2024 that contains 2 weight percent nB_4C demonstrates superior mechanical capabilities. These properties include its hardness, tensile strength, compressive strength, and impact strength scores. In nano particle-added composites, the hardness, maximum tensile strength, compression strength, and impact strength were measured to be 88 HV, 320 MPa, 511 MPa, and 25 J/cm^2 respectively.

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Keywords: Aluminium composite, Boron carbide, Nanoparticles, Tensile strength, Vacuum-assisted stir casting

1 INTRODUCTION

Over the past decade, the automotive and maritime sectors have been the primary consumers of low-density materials. Metal matrix composites are ideal for these applications because of their affordability and superior strength-to-weight ratio [1]. Aluminium is a lightweight substance, rendering it suitable for applications where weight minimisation is crucial, particularly in the aerospace, automotive, and transportation sectors [2]. Aluminium-based metal matrix composites (MMCs) reinforced with hard ceramic particles are highly desirable in the automobile, aerospace, and defence sectors due to their superior mechanical properties. These composites integrate the characteristics of metal alloys with those of hard reinforcement particles, resulting in enhanced mechanical performance [3]. Metal matrix composites are created by incorporating hard ceramic particulates such as Al_2O_3, SiC, TiB_2, and B_4C into an aluminium alloy matrix [4]. Among these, B_4C is the most promising ceramic reinforcement due to its superior attributes, including a low coefficient of thermal expansion, high hardness, strength, wear resistance, low density, and excellent chemical stability. Additionally, it exhibits exceptional bonding characteristics with aluminium alloys [5,6]. The rising surface-to-volume ratio has rendered particle aggregation a significant concern. Optimised process configuration and flexible processing can resolve this issue. Researchers have only lately commenced the investigation of composites that integrate nano-ceramic particles [7]. Incorporating certain ceramic particles enhances mechanical characterisation, corrosion resistance, and wear resistance. Factors like particle size, production methods, and the consistent distribution of reinforcing particles within the base material should be prioritised [8,9]. The application of stir casting to investigate aluminium and zinc composites with nano graphite (50 nm) ceramic particles was examined. With an increase in porosity, the densities of synthetic composites decreased [10]. There are few literatures reporting nanoscale research on boron carbide [11,12].

AA2024 reinforced with varying weight percentages (0.2%, 0.4% and 0.6%) of MWCNT and MgO was produced by the Stir casting method and its mechanical properties were assessed, AA2024 + 0.1%MgO + 0.1% MWCNT gives better mechanical properties [13]. NanoTiO_2 varying volume % (0,0.5,1) reinforced with AA2024 and assessed for Mechanical properties. The mechanical properties were drastically improved by adding nanoparticles in it [14]. AA2024 with varying wt % of TiB_2 (0 to 6wt%) with an interval of 2 produced by stir rheocasting, In this 4wt% TiB_2 with AA2024 exhibits better Hardness and Tensile strength compared to other compositions [15]. AA2024 with varying weight percentages of (4% and 5%) Hybrid nanocomposites of B_4C and SiC produced by stir casting, In this AA2024 with 4wt% of (B_4C +SiC) hybrid composites achieved better corrosion rates and AA2024 with 5wt% of (B_4C +SiC) hybrid composites reveals better hardness when compared to base material [16]. 10wt% Fly ash + 5 wt% graphite +AA2024 nanocomposites produced by manual stir casting and its mechanical properties and wear behaviours were assessed, the produced nanocomposites gives better mechanical properties and wear behaviour than base alloy [17]. AA2024 with varying wt % of WC (0,1,2 and 3) and Graphene nanoparticles (0,0.15,0.3) were produced by stir casting. The mechanical properties improved due to the addition of nanoparticles [18]. AA2024 with varying wt% (0.5,1.0, 2.5) of Al_2O_3 and SiC hybrid MMC produced by Stir casting, in this AA2024 + 0.5% Al_2O_3 + 0.5% SiC improved mechanical Properties [19]. From the above literatures, it is observed that in advanced casting methods like vacuum-assisted stir casting, ultrasonic-assisted stir casting, and Squeeze casting methods, lower nano concentrations are desirable for manufacturing composite materials.

In this research, varying weight percentages of B_4C (0%,1%,2%,3%) reinforced with Al2024 nanocomposites produced by vacuum-assisted stir casting with a speed range of 350 rpm to 600 rpm and totally the composites was stirred for 35 minutes and we attempt to characterize their microstructural and mechanical properties (Hardness, Tensile, Compression and Impact strength) .

2 MATERIALS AND METHODS

2.1 Matrix and Reinforcement Particles

The reinforcement particle used in this research work is nano Boron carbide (nB_4C – 2.25g/cm^3), purchased from Merck, Germany with a particle size of 50nm. Figure 1 illustrates the scanning electron microscopy (SEM) picture of nB_4C. The morphology of Boron carbide is seen as needle-like structure which is seen in SEM image and the powder particles are similar in size

Al2024 is used as a matrix material, which is procured locally from Hyderabad. The chemical combination of Al2024 is shown in Table 1. This alloy is light in weight. Its physical properties are better when compared to other aluminium alloys.

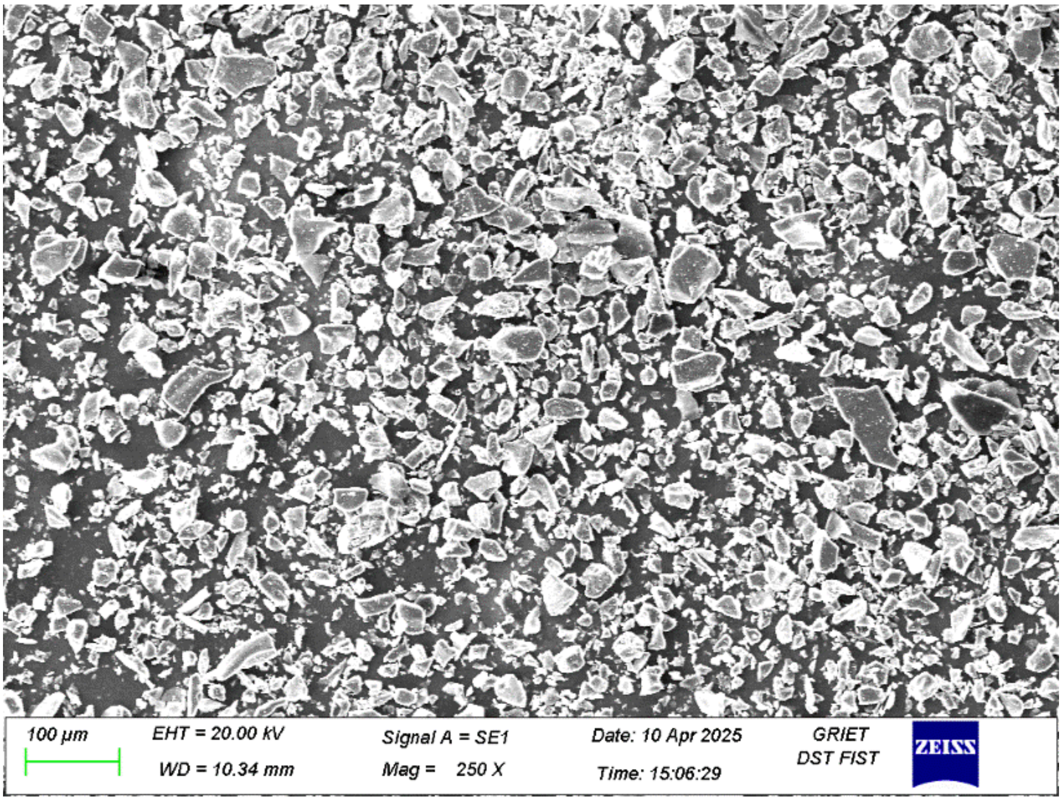

Figure 1. SEM Image of nB_4C.

Table 1. Chemical combination of Al2024 wt%.

Al	Cu	Mg	Mn	Si	Fe	Cr	Zn
93.38	4.1	1.4	0.6	0.2	0.3	0.01	0.01

Vacuum–Assisted Stir Casting

This study employed the vacuum-assisted stir casting technique to fabricate aluminium alloy nanocomposites as shown in Figure 2 and casted samples in Figure 3. A sliced Al2024 bar is rinsed with acetone to remove moisture and dust particles from its surface and then dried for 1 hour. The reinforcement material Nano boron carbide was preheated separately to 500°C for 30 minutes in order to eliminate the unknown moisture content and to improve the Matrix adhesion. A resistive heating electric furnace melted the Al2024 alloy in 10 minutes at 720°C. Stirring speed was maintained at 350 rpm to ensure complete melting of the alloy. At 750°C, 1.5 kg of raw materials were melted in the crucible. After melting 2024 aluminium alloy materials at 730 °C, argon gas bubbling for 5 min refined and removed slag, and a slagging spoon removed surface scum. Ceramic reinforcing particles were injected via an external sprue at 770°C. The liquid mixture is rapidly stirred at 500 rpm to prevent particle agglomeration. Interaction between matrix and reinforcement particles disintegrates particles, forming a vortex that prevents nanoparticle accumulation. It impacts the uniform distribution of reinforcement in the molten slurry. Raising the temperature of the molten metal to 800°C reduced the viscosity of the composite slurry, resulting in the ceramic reinforcement particles rising to the surface during stirring. The agitation rate was elevated to 600 revolutions per minute (rpm) and the duration was extended to 15 minutes. The addition of nano boron carbide (3 wt %) in the composites leads to agglomeration, despite the use of efficient processing procedures. Consequently, the maximum limit was maintained at 3 wt %. The die was heated to eradicate any trapped gas and reduce the porosity level in the matrix before the molten slurry was poured into the EN 8 die cavity. At ambient temperature, the liquid combination in the die cavity solidified. The aluminium alloy composite's efficiency was assessed by ASTM standards.

Figure 2. Experimental setup – Vacuum Assisted Stir Casting.


Figure 3. Casted Samples.

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The Hardness, tensile strength, compression strength and impact strength of aluminium alloy nano composites were assessed as per the ASTM Standards (E384, E8, E9, E23).

RESULTS AND DISCUSSION

Morphological Analysis

The morphology of reinforcing particles in the matrix alloy was analysed using a ZEISS Sigma 360VP scanning electron microscopy (SEM) model and an optical microscope.

The nB_4C particulates maintain contact with the matrix microscopically due to a robust particle-matrix interfacial bond, as demonstrated by the SEM and microscopic images. The polished matrix of stir-cast Al 2024 with the addition of 1% nB_4C is shown in Figure 4 & 2% nB_4C is shown in Figure 5.

The micrograph shows the distribution of composite particles of silicon carbide. The particles are evenly distributed with even spacing in the matrix. The microstructure of stir-cast aluminium alloy Al 2024 with the addition of 3wt% nano boron carbide composite particles is shown in Figure 6.

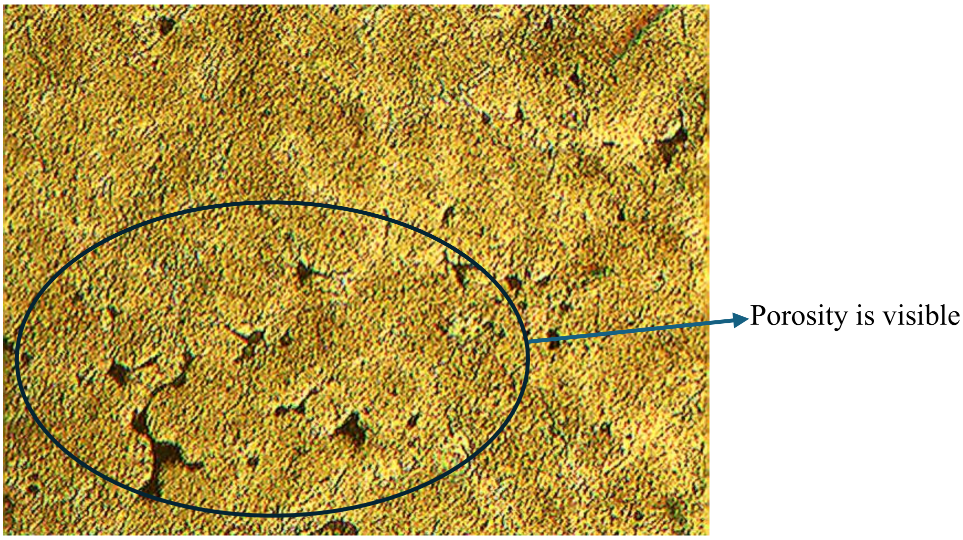

Figure 4. Microscope image of Polished matrix of Al2024+1wt% nB_4C.

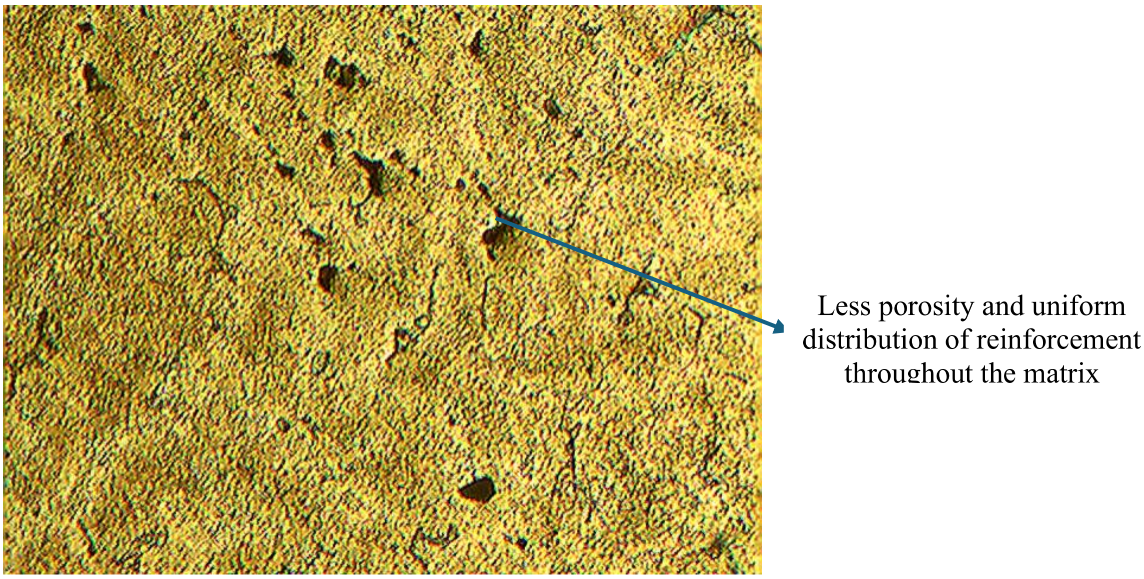

Figure 5. Microscope Image of 2 wt% nB_4C-reinforced Al2024 nanocomposites.

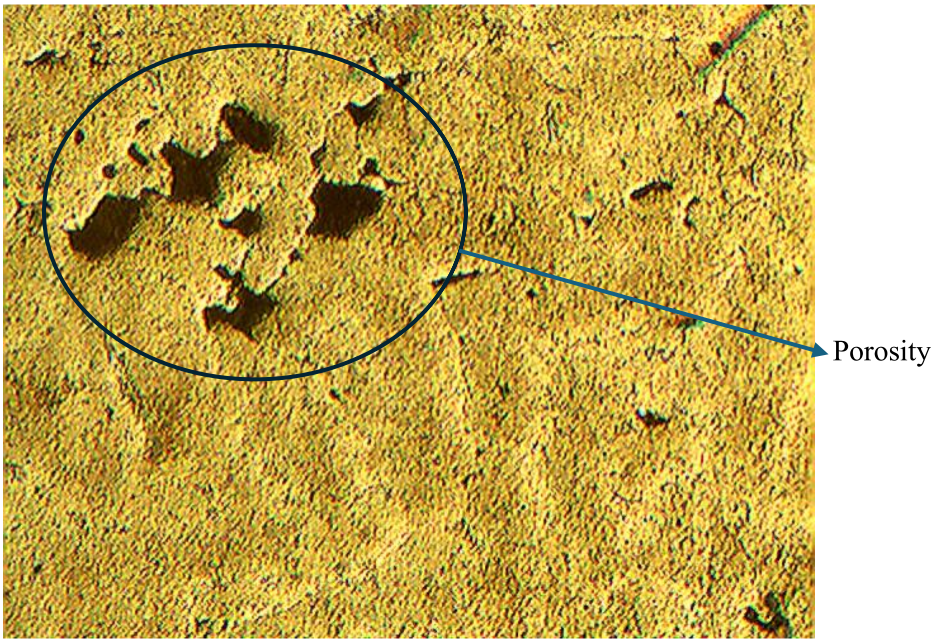

Figure 6. Microscope Images of Al2024+ 3wt% nB_4C composites.

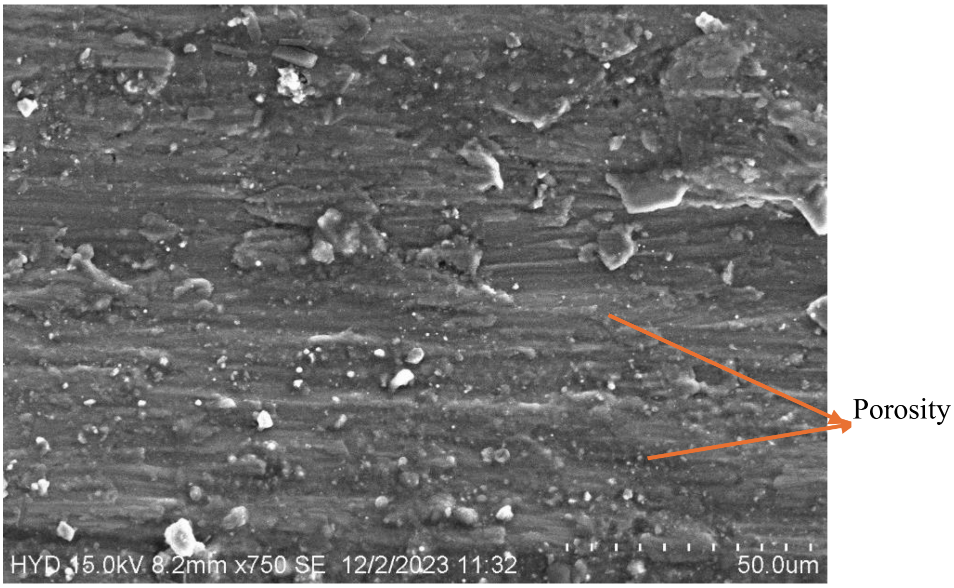

Figure 7. SEM Image of 1 wt% nB_4C reinforced Al2024 Composites.

The lower addition of the composite shows a lower distribution density distribution. The grain boundaries also show the precipitated particles of the eutectic constituents of the alloy. Some eutectic particles were also observed inside the grains of the primary aluminium solid solution.

The scanning electron microscopy (SEM) image of the 1 wt% nB_4C reinforced aluminium composites reveals that the strengthening particles are evenly distributed throughout the matrix and porosity is visible in Figure 7.

Nanoparticles are uniformly dispersed throughout the matrix material, exhibiting reduced porosity, and a Hexagonal platelet-like shape [20] shown in Figure 8. As the nanoparticle concentration is elevated to 3 wt%, the SEM images reveal the formation of clusters or accumulations in particular areas of the composite, resulting in nanoparticle agglomeration, as illustrated in Figure 9.

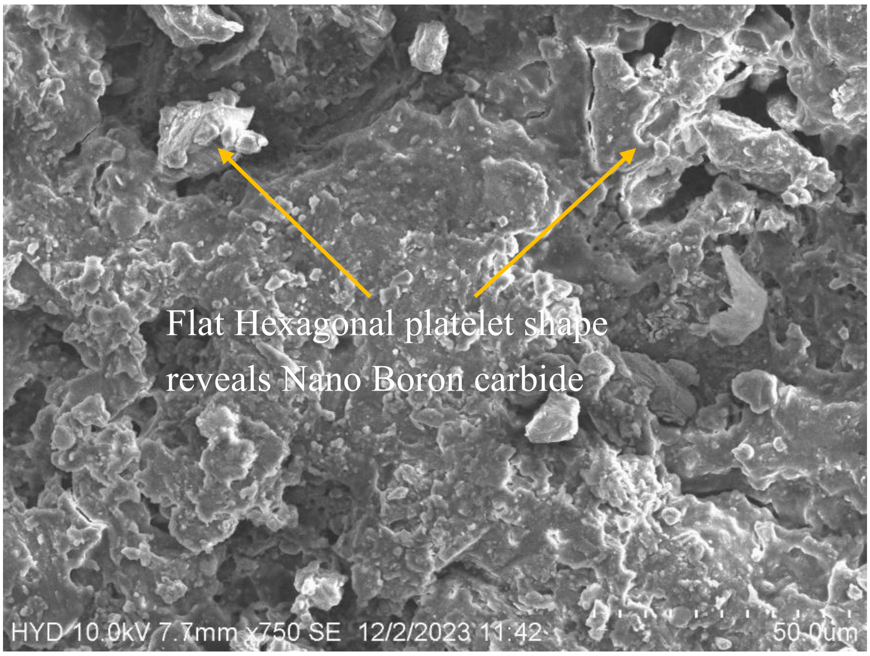

Figure 8. SEM Image of 2 wt% nB_4C reinforced Al2024 Composites.

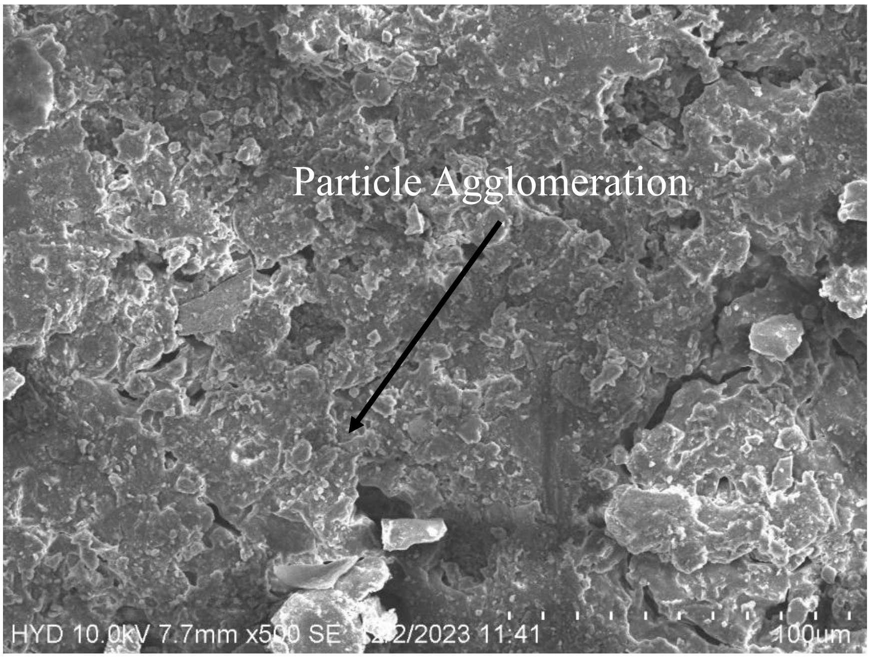

Figure 9. SEM image of 3% nB_4C reinforced Al2024 composites.

Mechanical Characterization

Hardness

Hardness measurements were carried out on a Vickers hardness testing apparatus Wilson MICI with a load range of 1kg with a diamond pyramid as indenter for a dwell period of 15s. The mean values of 5 different areas in a sample was taken. Each composition 5 samples made for testing the hardness and the average was taken for consideration.

Composite material with 2 wt% nB_4C reinforced with AA2024 shows good improvement which is 4.34% more than the base alloy Al2024. Meanwhile, the composites with Al2024+1% nB_4C, Al2024+ 3% nB_4C also shown better results than the base alloy and their values are shown in Figure 10.

Ultimate Tensile Strength

The universal testing machine with a maximum load of 10 tonnes, and the crosshead rate of 0.5mm/min. was employed to evaluate the tensile properties of base alloy and Aluminum nano composites at room temperature as per the ASTM E8 standard. Composites with 2 wt% nB_4C with Al2024 exhibit a higher tensile strength of 20.31% compared to specimens with Al2024+0 (Base Material).

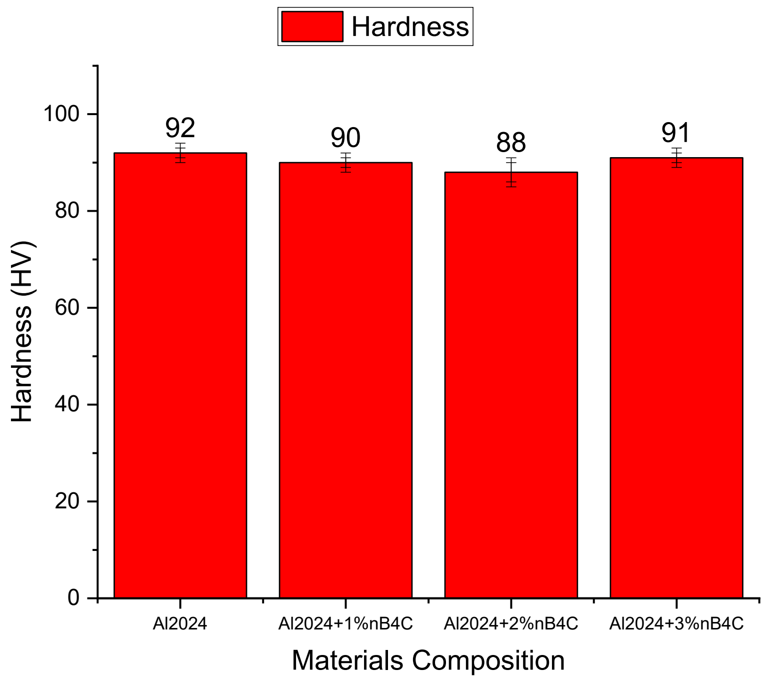

Figure 10. Micro Vickers Hardness.

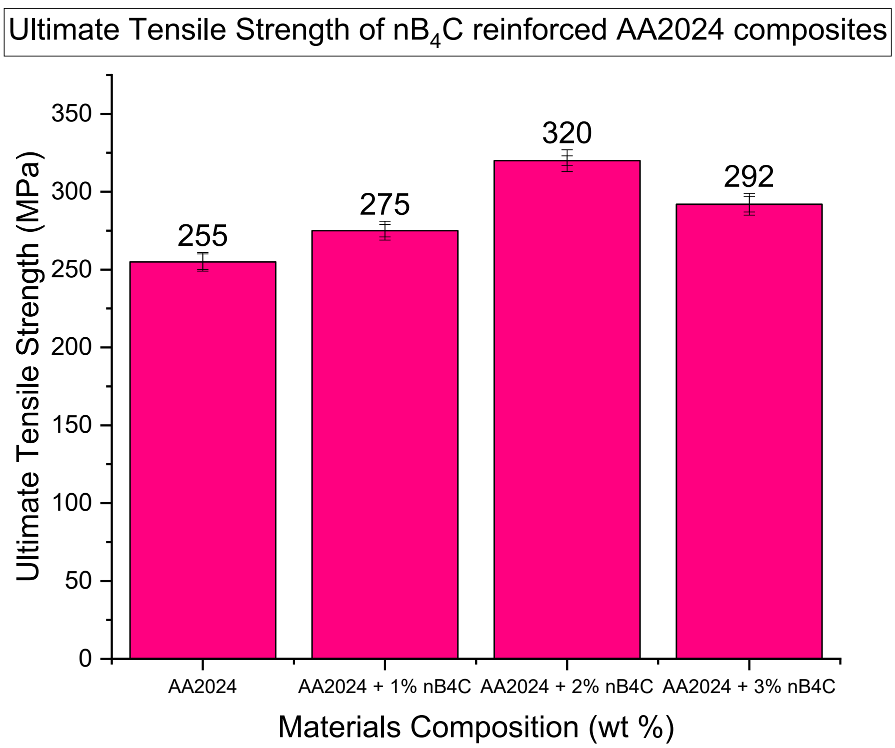

Figure 11. Ultimate Tensile Strength of Al2024 with varying weight percentages of nB_4C.

Similarly, Al2024+1% nB_4C, Al2024+3% nB_4C improved by 7.27%, 12.67% than base material are shown in Figure 11. The reason could be that Al2024 and nano Boron carbide strengthened particles had higher tensile strength with homogeneous reinforcement dispersion. Intermetallic bonding was enhanced in solid phases shielded by reinforced materials in Al2024 and nB_4C. The nanoparticles are distributed uniformly throughout the composite material with less porosity, which produces low defective materials. Due to this, the tensile strength is improved, When nanoparticles are scattered in a composite, they can serve as nucleation sites when the material solidifies. The result is the metal forming finer granules that are smaller in size. Orowan strengthening occurs when nanoparticles in a metal matrix prevent dislocation movement. Due to this, there is a drastic improvement in tensile strength.

Compression Strength

Figure 12 displays the compression characteristics of stir-cast Al2024 and Al2024 with different weight percentages of nano B_4C. Nano B_4C particles promote grain refinement during processing, which enhances strength. The nanoparticles are uniformly distributed within the composite material, with less porosity and fewer defects, enhancing the compressive strength. Composites with Al2024+1% nB_4C, 2 wt% nB_4C with Al2024, and Al2024+3% nB_4C exhibit higher compressive strength of 5.43 % , 9.98 % , and 6.5% compared to Al2024+0 wt% nB_4C

The compressive strength of Al2024 alloy nano composite material is significantly enhanced due to the introduction of ceramic reinforcing particles that are more durable.

Impact Strength

An impact test was conducted using the FIT 300N impact testing apparatus, characterized by a Charpy specification of 300J, a least count of 2J, and a drop angle of 140 degrees. The degree of a material's impact resistance and overall toughness was assessed. The impact strength of Al2024, Al2024 with varying weight % of nano ceramic strengthening particulates is assessed according to the ASTM E23. During the fracture, the amount of energy absorbed by the material was measured; ductile materials absorbed more energy than brittle materials due to the uniform distribution of ceramic strengthening particulates in the matrix alloy, the reduction in porosity attained through the Vacuum-assisted stir casting process, the improvement of ductility through the increase in yield strength of composites, and the presence of the Mg2Si interface in the composites. The Impact strength of Al2024, varying weight percentages of nano Boron carbide is illustrated in Figure 13.

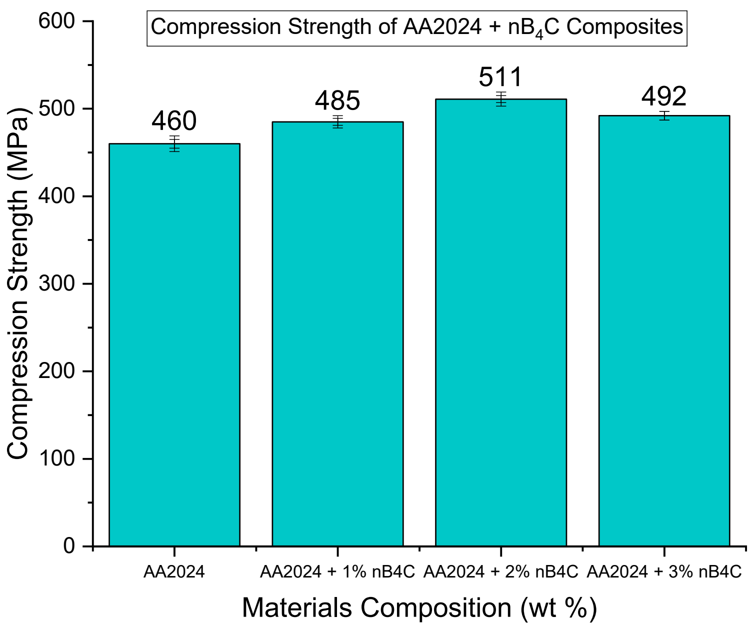

Figure 12. Compression Strength of nB_4C reinforced Al2024 Composites.

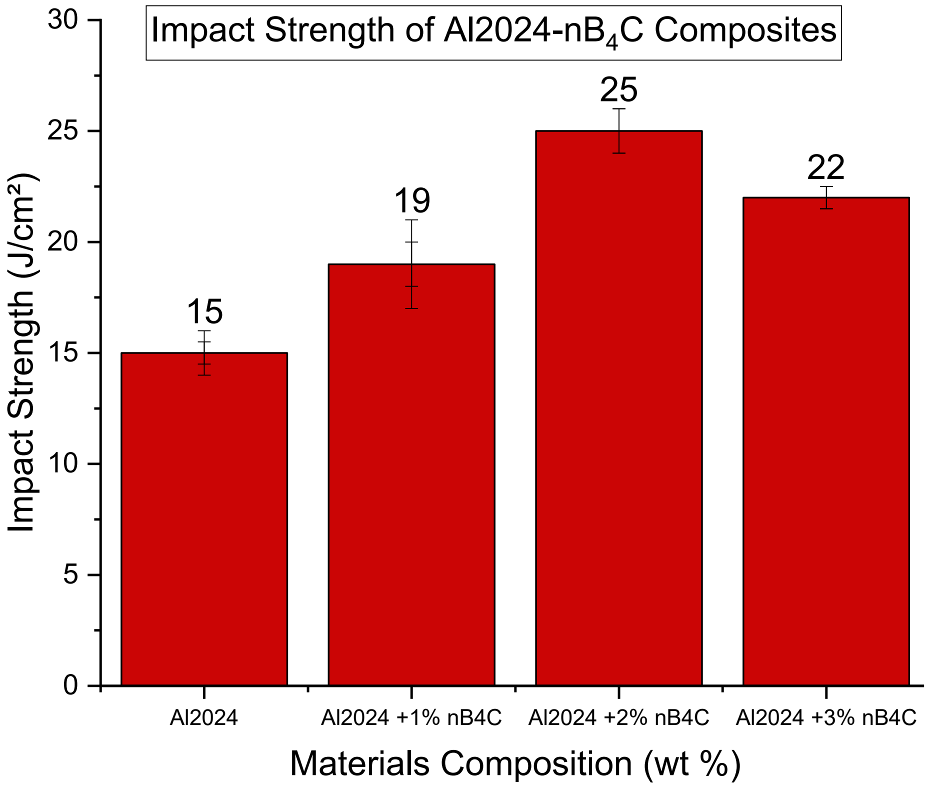

Figure 13. Impact Strength of Al2024-nB_4C Composites.

CONCLUSION

- Vacuum-assisted stir casting of varying weight percentages of nB_4C-reinforced Al2024 composite material was successfully produced.
- Scanning electron microscopy images revealed a uniform distribution of nanoparticles throughout the matrix material. SEM shows that the nano boron carbide particles are insoluble because of their high thermal properties.
- Nanoceramic reinforcing particles are evenly dispersed in base materials with less porosity. However, agglomeration happens when the weight percentage of ceramic particles increases to 3%.
- Hardness value of Al2024 with 2wt% nB_4C reinforcement shows 19.29% higher than the Al2024 base alloy
- The Ultimate tensile strength of the 2wt % nB_4C reinforced Al2024 composites is 20.31% higher than that of the original Al2024 alloy.
- Similarly, the Compression strength and Impact strength of the 2 wt% nB_4C-reinforced Al2024 composites are 9.98 % and 40% higher than the base material.

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Conflict of Interest

There are no conflicts of Interest.

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