# SYNTHESIS OF A356 ALLOY-VARIABLE PARTICLE SIZED BORON CARBIDE COMPOSITES: INVESTIGATIONS ON MECHANICAL BEHAVIOUR AND TENSILE FRACTOGRAPHY

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**Abstract:**
Lightweight metal matrix composites made of aluminium are now essential in several fields, including aerospace and automotive. An important factor determining the quality and properties of the composite material is the ease or difficulty of evenly dispersing the reinforcement throughout the matrix. The goal of this research is to find out the impact of 40 and 90 µm varying-sized boron carbide ($B_4C$) particles in A356 alloy composites. Using the liquid stir casting technique and $K_2TiF_6$ as the wetting flux, A356 alloy with 9 wt.% of $B_4C$ composites were prepared. SEM and EDS images were used to study the material's microstructure. ASTM-approved methods were used to measure the material's mechanical properties. Scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) confirmed that $B_4C$ particles were evenly distributed throughout the A356 alloy. The addition of $B_4C$ reinforcement to the A356 alloy matrix increased the hardness, ultimate, yield, compression, and impact strength of composites with a reinforcement size of 40 µm. The hardness of A356 alloy was enhanced by 40.7% and 34.6%, respectively, when 9 wt. % of 40 and 90 µm $B_4C$ were added. Similarly, there was a 34% increase in ultimate strength and a 31% improvement in yield strength. Both cases showed a little decrease in the ductility of the composites. Scanning electron micrographs were used to examine the morphologies of tensile fractured surfaces.

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## 1. INTRODUCTION

The type of structural material known as a composite is made up of two or more elements that may or may not be identical. One of these elements serves as a matrix, while the other one serves as reinforcement. These components are macroscopically blended together but are insoluble in one another within the composite. The substance provides the foundation for the

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reinforcement [1-3] called a matrix. Adding reinforcing material to the matrix material enhances its mechanical properties compared to the base material. The attributes of metal matrix composites, such as hardness, strength, and bending stress, are enhanced compared to those of base metals [4]. Matrix reinforcement can take the form of a fiber, particle, flake, or whisker. Because they may be produced affordably using standard procedures, composites with discontinuous reinforcement, particularly particulate metal matrix composite (MMC), have found commercial uses [5]. Processing flexibility and low-density good strength have all drawn attention to Al alloy-based composites [6]. Ceramic particles with micron particle sizes or nanometers, such as SiC, $B_4C$, and $Al_2O_3$, are incorporated into an Al-alloy matrix to create aluminium metal composites (AMCs).

The automotive industry has recently demanded lightweight components to improve fuel economy and limit the effect of harmful pollutants on the environment, which are considered to contribute to ozone layer depletion, increased greenhouse gas emissions, and acid rain. Lightweight aluminium alloy-based knuckles have been used in passenger cars thanks to methods such as casting and forging that have not been applied to mass production because the products are unreliable, prices have grown, and an exorbitant initial investment has been required. Die casting, or the forming method of pouring molten metal into mould holes, provides benefits for the mass manufacture of thin objects with complicated geometries that need minimal mechanical strength. The method, however, is not suitable for creating high-strength components because flaws, for example, air entrapment and shrinking caused by turbulent flow, may occur when the melt flows into the mould cavities. Furthermore, since the shaping process comprises numerous phases, the forging process has various limits in terms of creating exact components and productivity. On the other hand, the mechanical qualities of the pieces seem consistent and stable. Nanoparticles and other ultra-fine particles minimize inter-particle space, resulting in improved mechanical characteristics. Nanoparticles have a high proclivity for forming agglomerates [7]. It's crucial to figure out the best size, reinforcing content, and manufacturing parameters for each process and matrix to reduce agglomeration.

Agglomeration may be caused by various factors, including particle sizes, density, geometries and flow. Mixing the matrix and reinforcement is an important stage in this procedure because it ensures an even distribution of particles in the matrix. Ceramic particles have become very interesting in academia and industry because they reduce stress concentration, making them more difficult to fracture [8].

In most cases, the wettability of the reinforcing ceramic particles by a liquid metal is negligible. Due to excellent wetting between the two, the right bonding of ceramic particles and liquid metals occurs during and after casting. Preparation and addition of ingredients such as Mg and Li to the matrix as active agents [9], coating or oxidizing the particles, ultrasonic cleaning of the particle surface, and other etching processes have all been explored to increase wettability. Among the several techniques available, stir casting is one of the approved commercial ways for producing MMC reinforced with ceramic particles. This method, on the other hand, requires meticulous parameter tuning. Neutron absorbers and armour plate materials are made from aluminium boron carbide composites. These materials are strong and resistant to wear.

This study used Stir casting to make the composites with 9 wt.% of 40 and 90 varying particles of $B_4C$ reinforced composites.

Including Silicon enhances silicon's influence on the casting and ripping resistance. As a result, castings are less prone to shrinkage faults since the amount of Si rises during solidification. Adding silicate to aluminium does not detract from the material's low weight since the density of aluminium is 2.7 g/cc, and that of silicate is 2.3 g/cc. While aluminium is soluble in silicate, silicate precipitates as almost pure Si, which is hard and increases the abrasion resistance. Adding Si to Al-Si alloys decreases their thermal expansion coefficient. With the addition of silicon, aluminum's machinability suffers. Uncertainty and imprecision are inherent in many fields, such as casting lightweight components. The usage of these cast alloys is currently restricted, even though casting would be a more cost-effective way of manufacture.

Alloys' strength and hardness are heavily dependent on their microstructure; hence, castings of aluminium A356 alloy have been reworked to improve their mechanical qualities. These aluminium metal matrix composites (AMMC) may be used in the automotive and aerospace sectors because the dispersion hardening process boosts the mechanical characteristics of the matrix by strengthening ceramic particles. Lashgari et al. [10] investigated the effect of strontium on wear resistance in aluminium $B_4C$ stir cast composites with 10% reinforcement. They demonstrated that adding strontium to aluminum $B_4C$ composites improves wear resistance. Boron carbide enhances the mechanical properties of an Al-Si-Mg alloy by adding it to the matrix. The aluminium matrix included uniformly dispersed boron carbide particles. The impact of B4C particles (20 µm) with different weight fractions (2%, 4%, 6%, and 8 %) in AA6061 alloy was studied by Kalaiselvan et al. [11] using the stir casting process. According to the testing findings, the A356/$B_4C$ composites have a high hardness and tensile strength. Zeng et al. [12] carried out a thorough analysis of aluminium–silicon cast alloys, demonstrating the relationship between microstructural characteristics and mechanical performance. The lack of homogenization treatment results in a gradient in the distribution of alloying elements, precipitated phases, and the resulting mechanical characteristics. Kalangi et al. [13] conducted a thorough and precise examination of the microstructure of cast aluminium alloys, their principal morphologic properties, and the relationship between observed features and imposed operating parameters. To reinforce commercially available aluminium via the casting process, Kerti and Toptan [14] conducted experiments with $B_4C$ powders of varying particle sizes, finding that adding $B_4C$ with a bigger particle size resulted in a stronger microstructure with less agglomerated particles. Sharifi et al. [15] discovered that increasing the volume percent of hard phase and particle size reduces the wear rate of bulk Al–$B_4C$ nano composites during a research comprising the manufacture and characterisation of bulk Al–$B_4C$ nano composites. The mechanical behaviour of composites made by A356 with $B_4C$ and graphite composites were investigated by Annigeri et al. [16]. The A356 alloy with $B_4C$ exhibited superior tensile strength as compared to the base matrix alloy. Rohatgi et al. [17] investigated the ageing properties of aluminium alloy A356 and A356 with hollow spherical fly ash particles. Because the composite is lighter than the basic metal, its density is lower owing to the existence of hollow particles.

Researchers have shown that when $B_4C$ particles are utilized in metal composites, inhomogeneous dispersion occurs because the $B_4C$ particles are incompatible with the aluminium matrix. Creating metal matrix composites is challenging since the A356 alloy used in this work A356 alloy is a metal, and the boron carbide particles are ceramics. This makes it much more difficult to achieve a uniform distribution of the non-metal particles within the metal matrix. The A356 alloy matrix and the $B_4C$ particles were made more wettable in this study by using potassium titanium fluoride ($K_2TiF_6$) as a flux. The wettability is increased when $B_4C$ particles are embedded in an Al matrix. When it comes to mechanical qualities, particle size matters a lot. A356 alloy $B_4C$ reinforced composites with 40 and 90 µm sized particles were investigated for their mechanical properties and microstructure. In the present research, two different-sized particles are used to know the impact of the particle size on the mechanical behaviour of composites. The varying particle-sized $B_4C$ reinforced composites are tested for mechanical properties.

## 2. MATERIALS AND METHODS

### 2.1 Materials

The base material in this study was an aluminum-silicon based alloy called A356, and the reinforcing material was $B_4C$. The A356 alloy was designated for its great cast ability, increased strength, superior machinability, low weight, thermal characteristics, and wear resistance. $B_4C$ was selected as a reinforcing material because of its desirable features, which include low density, exceptionally high hardness, and excellent chemical stability. The densities of the A356 and $B_4C$ are 2.68 gm/cm$^3$ and 2.52 gm/cm$^3$, respectively. Table 1 indicates the chemistry of A356 alloy. Fig. 1 shows the SEM of 40 and 90 µm sized particles.

**Table 1.** Chemistry of A356 alloy

| Elements | Wt. % |
|---|---|
| Si | 6.78 |
| Mg | 0.34 |
| Fe | 0.11 |
| Ti | 0.15 |
| Cu | 0.01 |
| Ni | 0.012 |
| Zn | 0.014 |
| Sn | 0.006 |
| Mn | 0.006 |
| Al | Balance |

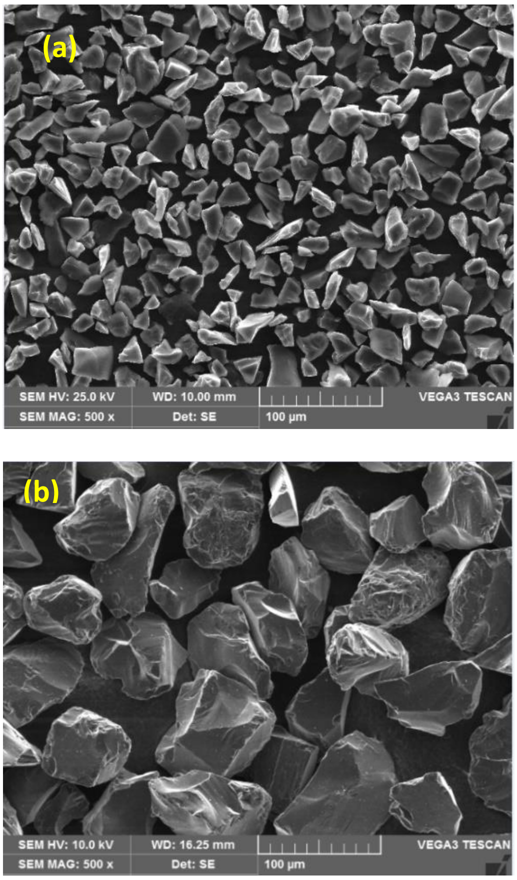



**Fig. 1.** SEM images of (a) 40 μm $B_4C$ (b) 90 μm $B_4C$ particles

## 2.2 Preparation of Composites

The stir casting process was used to combine the aluminium A356 alloy with $B_4C$ powder of 9 wt.% as shown in Fig. 2. The reinforcing material was boron carbide powder (40 and 90 μm) aluminium composites were manufactured using the stir casting process. The induction furnace and mechanical stirrer are the major components of this apparatus. The matrix material was first injected and heated at 725°C into the crucible to obtain a molten condition. Boron carbide particles were warmed to a temperature of 300°C to increase the bonding and wettability of the reinforcing material. The preheated reinforcement was gently adding metal to the melting metal in two steps, which helped to improve the wettability of particles with the A356 alloy matrix and swirled constantly at a speed of 350 rpm for 3 minutes to achieve homogenous dispersion of reinforced $B_4C$ particles in molten metal. A356 alloy, A356 with 9 wt. % of 40 μm $B_4C$, and A356 with 9 wt. % of 90 μm $B_4C$ were manufactured into three samples. A similar process was used to make composites. In this study, the key impacted process parameters used in the stir casting process include reinforcement weight percent.

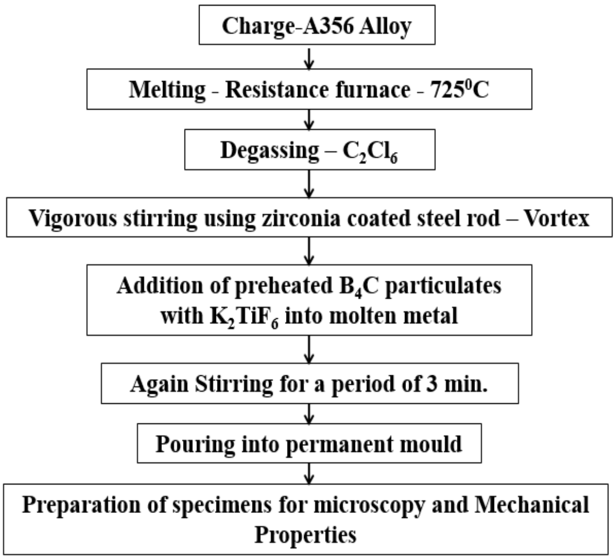



**Fig. 2.** Process flow chart of preparation of composites

Abrasive paper grades of 200 - 1000 were used to polish the metallographic samples of the composites that were made, and Keller's etchant was used for etching. A scanning electron microscope was utilized to conduct the metallographic evaluation. The tensile test of cast samples was produced in compliance with the ASTM E8 standard, as demonstrated in Fig. 3 (a), using Instron-made testing with a 20 kN to 60 kN load range. It was possible to forecast tensile strength and percent elongation with the help of standardized, computerized testing equipment. The American Society for Testing and Materials (ASTM) developed two standards: E9 for compression and E23 for impact. In Fig. 3 (b), it can be seen that the specimen was sent for the impact test.

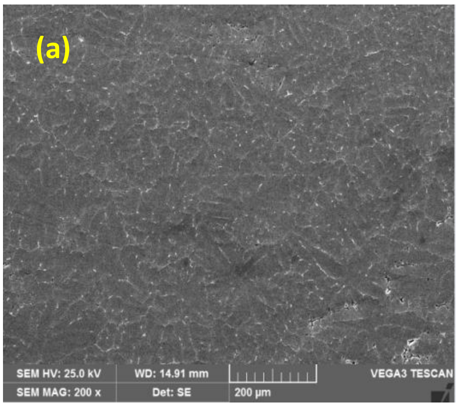

**Fig. 3.** (a) Tensile test specimen sample of A356-9wt.% of 40 μm $B_4C$ composite (b) Impact test specimen sample of A356-9wt.% of 40 μm $B_4C$ composite

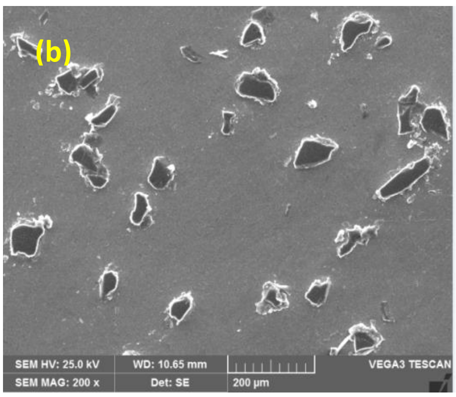
## 2. RESULTS AND DISCUSSIONS

### 3.1. Microstructure Studies

The microstructures of the sample were displayed at 200x magnification. The $B_4C$ particles were equally spread across the matrix, as seen in Fig. 4 (a-c). Casting characteristics such as the consistent stirring temperature of 720°C, preheating of reinforcement 300°C, stirring speed of 350 rpm, stirring duration of 3 min, preheating of the mould 250°C, and high fluidity behaviour of A356 aluminium alloy contributes to this homogenous distribution. The composites are also free of aggregation and other flaws. Composites containing A356 alloy 9 wt. % of 90 µm $B_4C$ particles separate uniformly during solidification due to differences in density. Based on its microscopic structure, $B_4C$ appears to have a higher particle concentration, which should translate to increased strength.

Fig. 4(b) shows the microstructure of the A356 with 90 wt. % of 40 µm $B_4C$ composites, Fig. 4(c) shows the microstructure of the same alloy with 9 wt.% of 90 µm sized $B_4C$ composites. Fig. 4 (b, c) shows a scanning electron micrograph showing the uniform dispersion of boron carbide particles throughout the matrix. The matrix of A356 alloy benefits from these evenly dispersed secondary particles because of their increased strength.



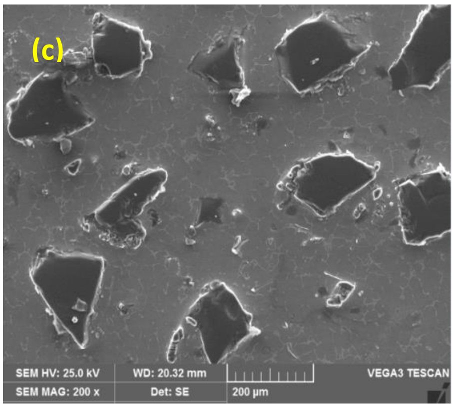




**Fig. 4.** SEM micrographs of (a) A356 alloy (b) A356 – 9 wt. % of 40 µm sized $B_4C$ composite (c) A356 – 9 wt.% of 90 µm sized $B_4C$ composite

In Fig. 5, we can see the energy dispersive spectra of three different composites made of A356 alloy: one with a weight percent of 40 µm sized $B_4C$ particles (Fig. 5b), and another with a weight percent of 90 µm sized boron carbide (Fig. 5c). Carbon and Boron were able to verify that the composites did, in fact, contain $B_4C$ particles.

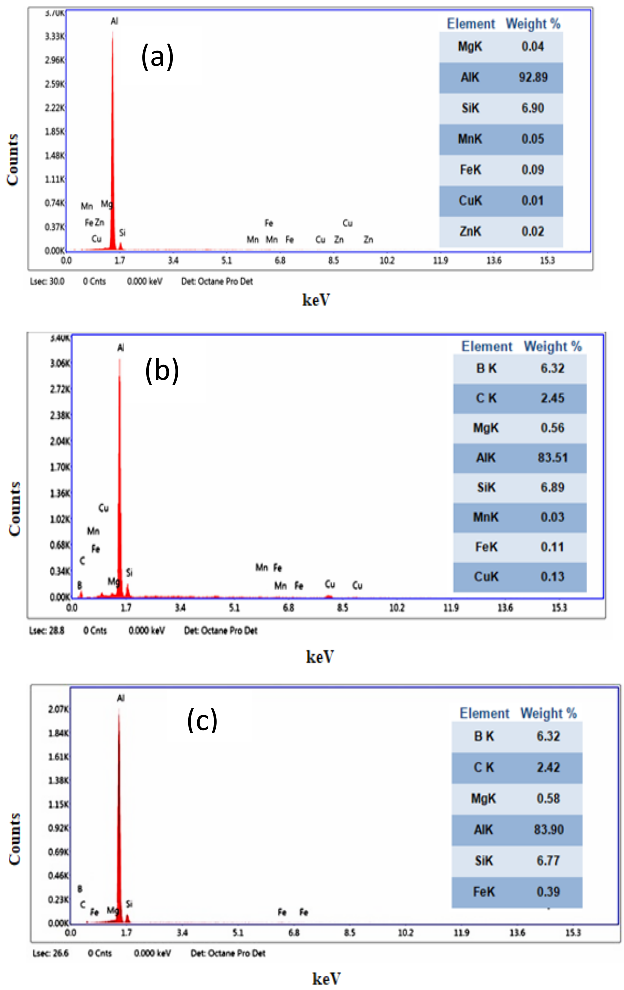



**Fig. 5.** EDS micrographs of (a) A356 alloy (b) A356 – 9 wt.% of 40 µm sized $B_4C$ composite (c) A356 – 9 wt.% of 90 µm sized $B_4C$ composite

### 3.2. Hardness

In the Figs. 6, 7, 8 and 9, the following notations are used to identify the as cast A356 alloy and $B_4C$ composites: A is as cast A356 alloy, B is the A356 alloy with 9 wt.% of 40 µm sized $B_4C$ reinforced composites, and C is the A356 alloy with 9 wt.% of 90 µm sized $B_4C$ reinforced composites.

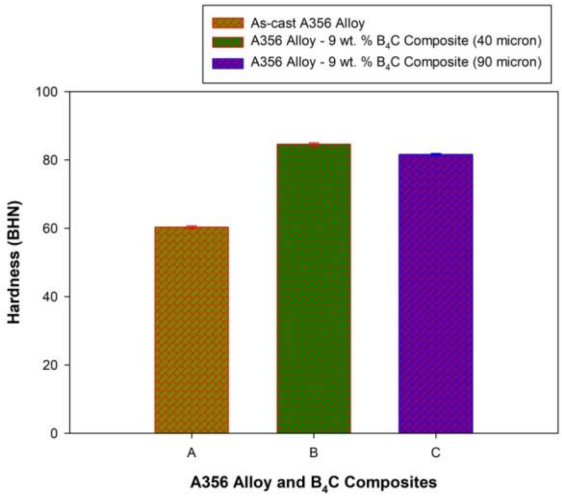



**Fig. 6.** Hardness of A356 with $B_4C$ composites

Fig. 6 compares the hardness of reinforced composites manufactured with boron carbide particles of sizes 40 and 90 µm. The graph makes it quite evident that when the reinforcing particle size decreases from 90 to 40 µm, the hardness of A356 alloy composites goes up. Moreover, the hardness values of $B_4C$ composites with a 40 µm size were higher compared to those with a 90 µm size. Adding 9 weight percentages of $B_4C$ particles with a 40 µm raises the hardness of base matrix A356 alloy from 60.3 BHN to 84.9 BHN. Similarly, for A356 aluminium composites supplemented with $B_4C$ particles of 90 µm size, it is 81.3 BHN regardless of the weight percentage. According to the results, $B_4C$ composites with a 40 µm measurement have a higher hardness than $B_4C$ composites with a 90 µm measurement. The high wettability of the particles in the A356 alloy matrix is responsible for the substantial improvement in hardness observed in composites augmented with smaller particles [18]. Microstructural investigations have also confirmed this. The bond between the reinforcement and matrix alloy becomes stronger as the particle size decreases.

### 3.3 Ultimate tensile strength and Yield Strength

Figs. 7 and 8 show a comparison of the A356 alloy reinforced composites' ultimate tensile strength (UTS) and yield strength (YS) when 9 weight percentages of 40 and 90 µm sized $B_4C$ particles are included. The graph clearly shows that the ultimate and yield strengths of A356 alloy composites rise when the reinforcing particle size reduces from 90 to 40 µm. A356 alloy strength is increased due to the addition of carbide particles, leading to a higher resistance to the tensile stresses and enhancement in the overall tensile strength [19, 20].

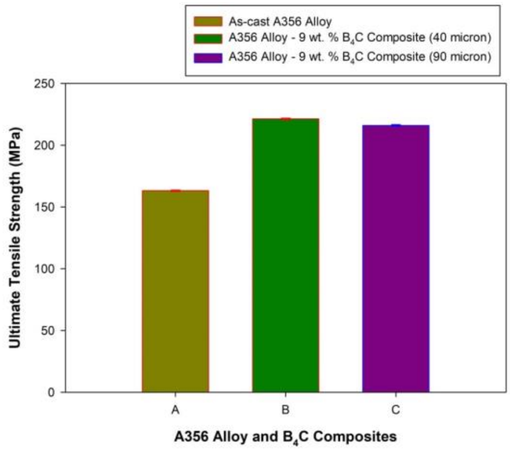



**Fig. 7.** Ultimate tensile strength of A356 with $B_4C$ composites

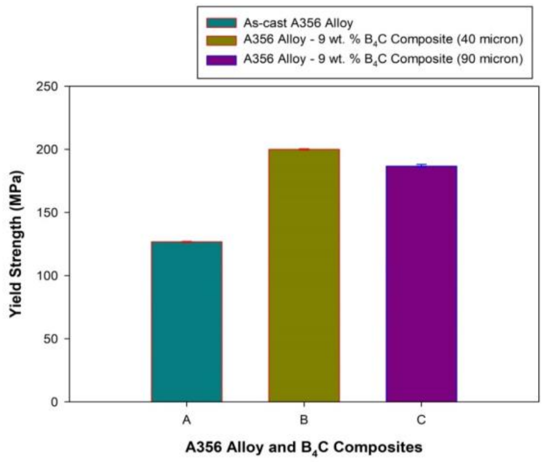



**Fig. 8.** Yield strength of A356 with $B_4C$ composites

Furthermore, compared to $B_4C$ composites with a 90 µm size, those with a 40 µm size demonstrated superior ultimate and yield strength values. After incorporating 9 weight percentages of 40 µm sized $B_4C$ particles, the maximum strength of the basic matrix A356 alloy increases to 221.3

MPa from 163.18 MPa. For A356 aluminium composites reinforced with 9 weight percent $B_4C$ particles of 90 µm in size, the corresponding value is 216.7 MPa.

The yield strength of the A356 base alloy is 126.7 MPa, and as shown in Fig. 8, it increases to 199.5 MPa after adding 9 weight percentages of $B_4C$ particles sized 40 µm. A similar strength of 186.7 MPa is achieved in A356 alloy composites that contain 9 weight percent of $B_4C$ particles sized 90 µm.

The research indicates that $B_4C$ composites with a size of 40 µm exhibit greater ultimate and yield strength compared to $B_4C$ composites with a size of 90 µm. Composites with smaller particles have greater ultimate and yield strengths because the particles are very wettable in the A356 alloy matrix. This has also been demonstrated by microstructural analyses. Reinforcement and matrix alloy bond strength improves with decreasing particle size.

Ultimate and yield strengths were higher in the A356 alloy and 40 µm $B_4C$ particle composites compared to the 90 µm $B_4C$ particle composites. Figs. 7 and 8 show that reducing the boron carbide particle size improves the composites' ultimate and yield strengths. This character has several possible interpretations. One benefit of using smaller boron carbide particles in composites is an increase in contact strength compared to larger particle sizes [21]. Second, smaller $B_4C$ particles have a substantially larger surface area than coarse or larger particles, which is an important consideration. The suppression of dislocation movement in response to tensile loading is enhanced in composites with boron carbide particles 40 µm in size [22].

### 3.4 Percentage of Elongation

The correlation between the percentage of AMCs that are elongated and the 9 weight % of $B_4C$ particles is seen in Fig. 9. While increasing the proportion of $B_4C$ in the aluminium matrix resulted in a decrease in percentage elongation. The use of $B_4C$ as a reinforcement reduced the ductility of the composites and increased their brittleness because $B_4C$ is a brittle material. So, the brittleness of $B_4C$ particles is a major factor in reduced ductility. The composites' percentage elongation drops due to reduced flow ability and lower ductile matrix content caused by increasing the quantity of $B_4C$ particles to 9 wt. %. With increasing reinforcement in the aluminium matrix, the percentage of elongation decreased [23].

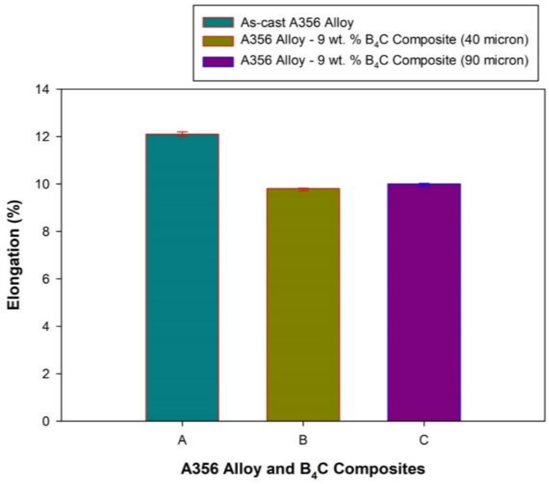
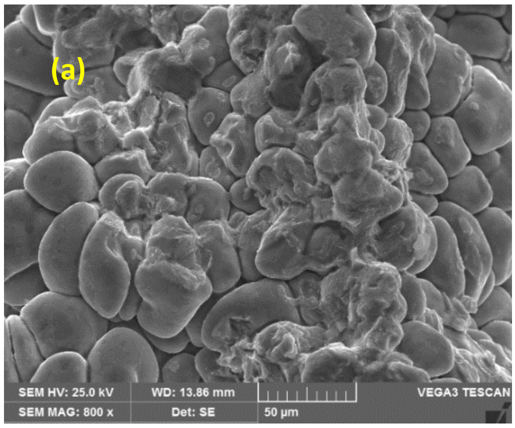



**Fig. 9.** Elongation of A356 with $B_4C$ composites

### 3.5 Tensile Fractography

The surfaces of the A356 alloy show signs of fracture when it is in as cast (Fig. 10a), A356 alloy with 9 weight percent of 40 µm sized $B_4C$ composites (Fig. 10b), and A356 with 9 weight per cent of 90 µm sized $B_4C$ composites (Fig. 10c).

Metal composites with particles as reinforcements fail for a variety of reasons, including interface decohesion of the A356 alloy, reinforcement $B_4C$ fracture, and matrix failure. In the case of the as-cast A356 alloy, scanning electron microscopy shows a dimpled fracture surface, which is characteristic of ductile fracture. In contrast, the reinforced A356 alloy, which contains 9 weight percent of 40 µm sized $B_4C$ material, shows a pattern of brittle fracture, which is characterized by an uneven distribution of small dimples connected by pieces of smaller dimples [24,25]. Fig. 10c further shows that the A356 alloy matrix exhibits a mixed ductile and brittle mode of fracture due to the presence of larger particles (90 µm in size).



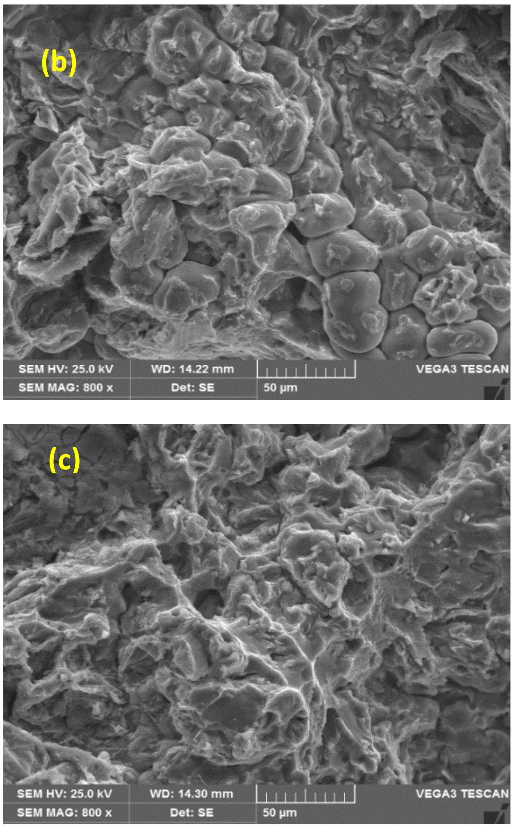



**Fig. 10.** Tensile fractured SEM micrographs of (a) A356 alloy (b) A356 – 9 wt. % of 40 μm sized $B_4C$ composite (c) A356 – 9 wt.% of μm sized $B_4C$ composite

### 3.6 Compression Strength

Compared to as cast A356 alloy, A356-$B_4C$ composites have increased compression strength, Fig. 11.

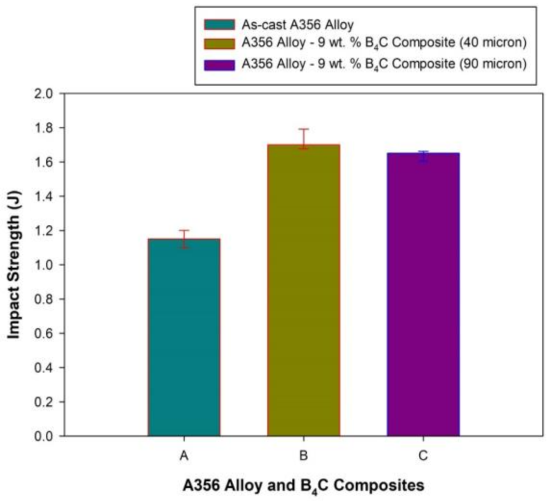



**Fig. 11.** Compression strength of A356 with $B_4C$ composites

A356 alloy with 40 μm $B_4C$ composite values are 35.85% higher than A356 cast aluminium alloy values (Fig. 11). The compression strength is improved by the $B_4C$ particles' strong binding capabilities, and the pores are reduced by the pressure used. The boron carbide particles stop the matrix's dislocation from moving. Due to the applied compressive force, porosity won't affect the material's compressive strength.

### 3.7 Impact Strength

The impact strength of A356-$B_4C$ composites is higher than that of cast A356 alloy, as in Fig. 12. A356 alloy with 40 μm boron carbide composites is 10% higher than the base matrix. The $B_4C$ particles' excellent binding properties make them more impact-resistant. The fact that smaller particles are more resistant to de-bonding when subjected to impact loading is the main reason why composites reinforced with $B_4C$ particles sized 40 μm show an improvement in impact toughness. When subjected to an impact force, composites with relatively larger particles are more likely to de-bond, resulting in reduced impact toughness as compared to particles of a smaller size.

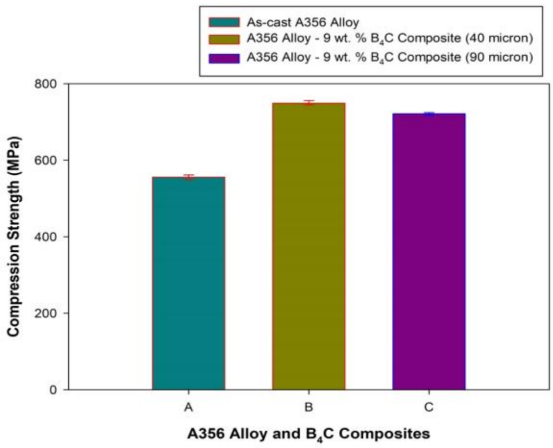



**Fig. 12.** Impact strength of A356 with $B_4C$ composites

## 4. CONCLUSIONS

Metal composites of A356 alloy with $B_4C$ particles of 40 and 90 μm sizes are efficiently produced by the stir cast technique. The scanning electron micrographs reveal a uniform distribution of $B_4C$ particles throughout the A356 alloy. The presence of $B_4C$ particles in the composites was determined by the EDS analysis. A356 alloy with 40 μm sized $B_4C$ particles composites achieve an even higher level of hardness compared to unreinforced A356 alloy. The hardness of A356 alloy improved by 40.9% by adding 9 wt.% of 40 μm $B_4C$ particles. The ultimate yield strength of A356 alloy has been enhanced with the inclusion of carbide particles. A356 alloy with 9 wt.% of 40 µm boron carbide particles composites showed more tensile strength compared to cast A356 and 90 µm sized carbide particles composites. In addition, the A356 alloy that was reinforced with 40 µm $B_4C$ demonstrated higher compressive strength when contrasted with $B_4C$ composites that had a particle size of 90 µm. In addition, the impact toughness of the A356 alloy with $B_4C$ particle-reinforced composites of 40 µm sized was found to be better than that of 90 µm sized composites. Tensile fractures surfaces indicated a ductile mode of fracture in the A356 alloy and brittle fracture in the boron carbide-reinforced composites.

**Conflicts of Interest**

The authors declare no conflict of interest.

**REFERENCES**


[1] H.S. Chen, W.X. Wang, Y.L. Li, P. Zhang, H.H. Nie, Q.C. Wu, The design, microstructure and tensile properties of $B_4C$ particulate reinforced 6061Al neutron absorber composites. *Journal of Alloys and Compounds*, 632, 2015: 23-29. https://doi.org/10.1016/j.jallcom.2015.01.048

[2] Y. Yong, L. Jie, L. Xiaochun, Study on bulk aluminum matrix nano-composite fabricated by ultrasonic dispersion of nano-sized SiC particles in molten aluminum alloy. *Materials Science and Engineering: A*, 380(1-2), 2004: 378-383. https://doi.org/10.1016/j.msea.2004.03.073

[3] T. Rajmohan, K. Palanikumar, S. Ranganathan, Evaluation of mechanical and wear properties of hybrid aluminium matrix composites. *Transactions of Nonferrous Metals Society of China*, 23(9), 2013: 2509-2517. https://doi.org/10.1016/S1003-6326(13)62762-4

[4] K. Sekar, A. Kanjirathikal, M.A. Joseph, Effect of T6 Heat Treatment in Tribological Properties of A356 Aluminum Alloy Reinforced with $Al_2O_3$ Nanoparticles by Combination Effect of Stir and Squeeze Casting Method. Applied Mechanics and Materials, 592-594, 2014: 968-971. https://doi.org/10.4028/www.scientific.net/amm.592-594.968

[5] M. Ravikumar, H.N. Reddappa, R. Suresh, Y.S. Rammohan, E.R. Babu, C.R. Nagaraja, Machinability study on Al7075/$Al_2O_3$-SiC hybrid composites. *Metallurgical and Materials Engineering*, 28(1), 2022: 61-77. https://doi.org/10.30544/749

[6] S. Dhanalakshmi, N. Mohansundararaju, P.G. Venkatkrishnan, Preparation and mechanical characterization of stir cast hybrid Al7075-$Al_2O_3$-$B_4C$ metal matrix composites. *Applied Mechanics and Materials*, 592-594, 2014: 705-710. https://doi.org/10.4028/www.scientific.net/amm.592-594.705

[7] M. Li, K. Ma, L. Jiang, H. Yang, E.J. Lavernia, L. Zhang, J.M. Schoenung, Synthesis and mechanical behavior of nanostructured Al 5083/n-$TiB_2$ metal matrix composites. *Materials Science and Engineering: A*, 656, 2016: 241-248. https://doi.org/10.1016/j.msea.2016.01.031

[8] L. Kumar, S.N. Alam, S.K. Sahoo, M.B.K. Teja, Mechanical Properties of Cu-MWCNT Composites Developed by Powder Metallurgy Route. *Materials Today: Proceedings,* 5(9), 2018: 19883-19892. https://doi.org/10.1016/j.matpr.2018.06.353

[9] M. Ramchandra, A. Abhishek, P. Siddeshwar, V. Bharathi, Hardness and wear resistance of $ZrO_2$ nano particle reinforced Al nano composites produced by powder metallurgy. *Procedia Materials Science,* 10, 2015: 212-219. https://doi.org/10.1016/j.mspro.2015.06.043

[10] H.R. Lashgari, A.R. Sufizadeh, M. Emamy, The effect of strontium on the microstructure and wear properties of A356–10% $B_4C$ cast composites. *Materials & Design*, 31(4), 2010: 2187-2195. https://doi.org/10.1016/j.matdes.2009.10.049

[11] K. Kalaiselvan, N. Murugan, S. Parameswaran, Production and characterization of AA6061–$B_4C$ stir cast composite. *Materials & Design*, 32(7), 2011: 4004-4009. https://doi.org/10.1016/j.matdes.2011.03.018

[12] L. Zeng, J. Sakamoto, A. Fujii, H. Noguchi, Role of eutectic silicon particles in fatigue crack initiation and propagation and fatigue strength characteristics of cast aluminum alloy A356. *Engineering Fracture Mechanics*, 115, 2014: 1-12. https://doi.org/10.1016/j.engfracmech.2013.11.016

[13] C. Kalangi, V. Bolleddu, H.L. Allasi, Tribological characteristics of carbon nanotubes-reinforced plasma-sprayed $Al_2O_3$-$TiO_2$ ceramic

coatings. *Advances in Materials Science and Engineering*, 2021(1), 2021: 8094640. https://doi.org/10.1155/2021/8094640

[14] I. Kerti, F. Toptan, Microstructural variations in cast $B_4C$-reinforced aluminium matrix composites (AMCs). *Materials Letters*, 62(8-9), 2008: 1215-1218. https://doi.org/10.1016/j.matlet.2007.08.015

[15] E.M. Sharifi, F. Karimzadeh, M.H. Enayati, Mechanical assisted synthesis of $B_4C$ nanoparticles. *Advanced Powder Technology*, 22(3), 2011: 354-358. https://doi.org/10.1016/j.apt.2010.05.002

[16] U. Annigeri, S.C. Simha, Study of stir casting and microstructure of Al-$B_4C$ MMCs. *Materials Science Forum*, 1112, 2024:27-32. https://doi.org/10.4028/p-1Py2E1

[17] P.K. Rohatgi, B.F. Schultz, J.B. Ferguson, Synthesis and properties of metal matrix nanocomposites (MMnCs), syntactic foams, self-lubricating and self-healing metals. *In Proceedings of the 8th Pacific Rim International Congress on Advanced Materials and Processing*, Springer, Cham, 2013: 1515-1524. https://doi.org/10.1007/978-3-319-48764-9_191

[18] V. Nishant, S.C. Vettivel, Characterization and experimental analysis of boron carbide and rice husk ash reinforced AA7075 aluminium alloy hybrid composite. *Journal of Alloys and Compounds*, 741, 2018: 981-998. https://doi.org/10.1016/j.jallcom.2018.01.185

[19] F.A. Essa, Q. Zhang, X. Huang, M.K.A. Ali, A. Elagouz, M.A.A. Abdelkareem, Effects of ZnO and $MoS_2$ Solid Lubricants on Mechanical and Tribological Properties of M50-Steel-Based Composites at High Temperatures: Experimental and Simulation Study. Tribology Letters, 65, 2017: 97. https://doi.org/10.1007/s11249-017-0880-2

[20] H.S.V. Kumar, K. Revanna, N. Kumar, N. Sathyanarayana, N. Madeva, G.A. Manjunath, H. Adisu, Impact of Silicon Carbide Particles Weight Percentage on the Microstructure, Mechanical Behaviour, and Fractography of Al2014 Alloy Composites. *Advances in Materials Science and Engineering*, 2022(1), 2022: 2839150. https://doi.org/10.1155/2022/2839150

[21] T. Senthilnathan, K. Balachandar, Mechanical and microstructure evaluation of novel hybrid $TiB_2/B_4C$ aluminium metal matrix composite. *Materials Research Express*, 10(6), 2023: 066509. https://doi.org/10.1088/2053-1591/acda18

[22] G. Veeresha, B. Manjunatha, M. Nagaral, V. Auardi, V. Bharath, Synthesis and wear behavior of varying particle sized $B_4C$ reinforced Al2618 alloy composites. *Materials Physics and Mechanics*, 50(3), 2022: 373-387. https://dx.doi.org/10.18149/MPM.5032022_2

[23] G.B. Veeresh Kumar, M.S. Kiran, S.M. Khalid, B. Jaswanth, B. Dileep, Mechanical and tribological studies of boron carbide reinforced Al7150 MMCs. *AIP Conference Proceedings*, 2408(1), 2021: 020019. https://doi.org/10.1063/5.0072646

[24] M. Nagaral, V. Auradi, K.I. Parashivamurthy, S.A. Kori, B.K. Shivananda, Synthesis and characterization of Al6061-SiC-graphite composites fabricated by liquid metallurgy. *Materials Today: Proceedings*, 5(1), 2018: 2836-2843. https://doi.org/10.1016/j.matpr.2018.01.073

[25] V. Bharath, V. Auradi, M. Nagaral, Fractographic characterization of Al2O3p particulates reinforced Al2014 alloy composites subjected to tensile loading. *Frattura ed Integrità Strutturale*, 15(57), 2021: 14-23. https://doi.org/10.3221/IGF-ESIS.57.02