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Technical Note

Influence of B₄C particle size on the mechanical behavior of A356 aluminium composites

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Abstract

The influence of adding B₄C particulates with a 40 and 90 μm sizes on the compressive strength, tensile strength and impact toughness of the A356 alloy is being studied. In the Al alloy matrix, 40 and 90 μm -sized micro B₄C particulates are employed as reinforcements. In the A356 alloy, composites are created utilizing the liquid melt process in increments of 3 and 6 weight percent. Using an energy dispersive spectroscopy (EDS) and a scanning electron microscope (SEM), samples are examined for microstructural characterization. According to ASTM standards, mechanical characteristics including tensile, hardness, compression, and toughness are assessed. The consistent distribution of B₄C particles in the A356 alloy is seen in SEM micrographs, and this is supported by EDS analysis. Additionally, the inclusion of B₄C reinforcement improves the compression and impact strength of the base matrix A356 alloy, which is especially noticeable in the case of reinforced composites that are 6 wt. % of 40 μm B₄C in size.

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1. Introduction

Due to its beneficial qualities, such as light weight, corrosion resistance, high stiffness, and cost efficiency when compared to currently utilized metals, aluminum is extensively employed in aerospace, automotive, and structural applications. Aluminum has a density that is around one-third that of iron and copper, and its corrosion resistance negates the need for protective coatings. Recent growth in research suggests that there is still more room for advancement in the use of aluminum. Utilizing aluminum with increased characteristics will satisfy both economic and environmental needs [1].

Aluminum metal matrix composites (AMMC) may be treated in a number of ways, including liquid metallurgy, solid metallurgy, in situ procedures, etc. However, liquid metallurgy is preferred owing to its cheap cost, ease of processing, and superior characteristics. The primary issue with processing AMMC is the wettability of the ceramic particles, which may be solved by coating the reinforcement, which is one of the methods to improve wettability [2]. Ti coating has shown superior results for improving the wettability of B₄C. By creating a thin coating of Ti around the B₄C particles, the K₂TiF₆ halide salt, which is evenly mixed with B₄C during casting, has improved the bonding between Al and B₄C and the mechanical characteristics of the material. Aluminum is combined with B₄C and graphite using a mechanical stirrer. The homogenous dispersion of particles in the metal matrix is facilitated by the use of a mechanical stirrer and

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vigorous stirring. In liquid metallurgy, reinforcing particles are added in two steps, assisting with homogenous distribution and preventing particulate aggregation [3].

In general, aluminum-based MMCs provide a significant improvement in elasticity modulus, strength, and wear resistance compared to unreinforced alloys. The reinforcing particle size, shape, and volume fraction, the matrix material, and the response at the interface all have an impact on the properties of composites. Hard ceramic particles such as SiO₂, SiC, Al₂O₃, TiB₂, B₄C, etc. may be added to the Al matrix to reinforce it and increase its characteristics [4]. Al₂O₃ and SiC ceramic particles are the most often utilized materials for aluminum reinforcement. Due to its great hardness it is the third hardest substance after diamond and boron nitride boron carbide (B₄C) might be used as a replacement to silica and aluminum oxide [5]. High strength, low density, exceptionally high hardness, strong wear resistance, and good chemical stability are some of B₄C's appealing qualities. As a result, B₄C particle reinforcement of aluminum results in increased specific strength, elastic modulus, wear resistance, and thermal stability [6].

According to the literature review, SiC and Al₂O₃ particle reinforcements are the focus of the majority of investigations on aluminum-based MMCs. TiC particulate reinforcement of aluminum matrix is, however, comparatively underutilized. Despite the fact that powder metallurgy gives MMCs higher mechanical characteristics, liquid state processing offers certain significant benefits. Better matrix-particle bonding, simpler matrix structure management, cheap processing costs, closer net form, and a broad range of material options are a few of them. There are two techniques for manufacturing MMCs in a liquid state, and they are both dependent on the temperature at which the particles are added to the melt. The vortex is utilized to introduce reinforcement particles in both processes. Micro-particles are particularly cost-effective due to their cheap cost and simplicity of dispersion during manufacturing.

Stir casting is considered as the most effective and cost-effective technique out of all of them. However, this technique has always resulted in a large number of structural flaws in composite materials. Some significant structural flaws of stir cast composites include poor wettability, uneven distribution of reinforcement particles, segregation and agglomeration of reinforcement [7]. The compressive and impact characteristics of the A356 reinforced with micron B₄C particles MMC's manufactured by stir casting technique, however, are little understood. Aluminum-boron carbide composites are crucial, particularly in the aerospace industry, where there is a growing need for lightweight materials. The development of A356 micron B₄C composites with different particle sizes and weight percentages of B₄C particulates is suggested in light of the aforementioned findings.

In this work, the mechanical characteristics of A356 alloy-based composites containing 40 and 90 μm sized B₄C particles were examined utilizing the liquid metallurgical process at different weight percentages (3 and 6 wt. % B₄C). Based on the literature, smaller particles create agglomeration in the prepared composites, whereas larger particle addition creates de-bonding particles from the matrix. Hence, an attempt was made to develop an A356 alloy with varying boron carbide particle-reinforced composites and investigate the effect of the optimum reinforcing particle size on the mechanical properties of the composites.

2. Experimental Details

By using liquid metallurgy, metal matrix composites with 3 and 6 wt. % of B₄C particles and size of 40 and 90 μm are created. A356 alloy is employed as the matrix material and B₄C particles with an average size of 40 μm are used as reinforcements in the fabrication

of MMCs. Table 1 is showing chemical composition of A356 alloy and Table 2 is representing chemistry of B₄C particles.

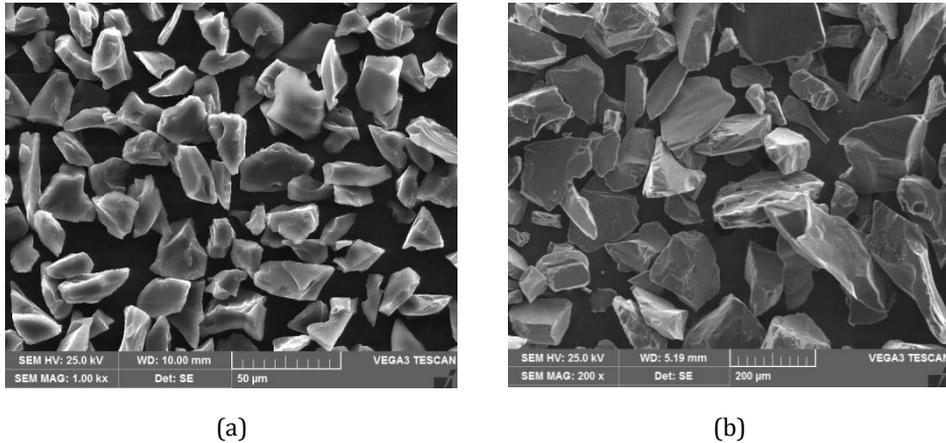


Fig.1 SEM images of (a) 40 µm B₄C (b) 90 µm B₄C particles

Table 1. Chemical Composition of A356 Alloy

Element	Symbol	Wt %
Silicon	Si	6.98
Magnesium	Mg	0.35
Iron	Fe	0.10
Titanium	Ti	0.15
Copper	Cu	0.01
Nickel	Ni	0.013
Zinc	Zn	<0.015
Tin	Sn	<0.005
Manganese	Mn	<0.005
Aluminum	Al	Balance

Table 2. Chemical composition of B₄C

Total Boron	Total Carbon	Total Iron	Total Boron + Carbon
77.5%	21.5%	0.2%	99.8%

2.1. Preparation of Composites

A356 alloy with 40 and 90 micron sized B₄C particles reinforced composites were created using the liquid metallurgical approach. An A356 alloy ingots were charged into the furnace by taking calculated quantity to melt. A356 alloy has a 660°C melting temperature. The maximum melting temperature of 750°C was used to melt the A356 alloy. A chromel-alumel thermocouple was used to measure the temperature. Hexachloroethane (C₂Cl₆) in solid form was then used to degas the liquid metal or remove the unwanted gases from the molten metal. The molten metal was stirred to form a vortex using a zirconium-coated stainless-steel impeller. The impeller was immersed 60 % below the height of the molten metal from the melt's surface and the stirrer rotates at a speed of 300 rpm. The pre-heated B₄C particles were added to the vortex. The A356 alloy with 3 weight percentage of B₄C composites were then placed into a permanent cast

iron mould with dimensions of 120 mm in length and 15 mm in diameter [8]. Similarly, A356 alloy with 6 wt. % of boron carbide particles reinforced composites were synthesized in the similar way. Further, based on the microstructural analysis, the tensile strength, hardness, compressive strength and impact toughness of the A356 alloy of 40 and 90 μm sized B_4C reinforced composites were evaluated and compared with the as-cast A356 alloy. Figure 2 shows cast aluminum specimen.



Fig. 2 Cast aluminum specimen

2.2. Testing of Composites

The microstructural specimens were polished using 220 to 1000 grit emery sheets before being subjected to diamond paste polishing and microstructural examination by SEM and EDS [9]. The specimens were etched with Keller's reagent. According to ASTM E10 standard, the hardness test was performed using Brinell hardness testing equipment. ASTM E8 and E9 standards were used to conduct the tensile and compression tests. According to ASTM E23 standard, the Charpy impact test was performed using an impact test machine.

3. Results and Discussion

3.1. Microstructural Study

The microstructure of the cast A356 aluminum alloy is seen in Fig. 3(a). A356 composites with 40 and 90 μm sized particles of 3% and 6% wt.% B_4C content are shown in Fig. 3(b-e). As shown in figures, the SEM micrographs show a very equal distribution of B_4C particles throughout the matrices (Fig. 3b-e). The porosity of the MMC is decreased by uniformly dispersed particles, which also improve overall strength and other qualities. From the micrographs it is revealed that the boron carbide particles distributed uniformly in the matrix material. The bonding between the A356 alloy and boron carbide particles is strong and helps in enhancing the properties.

Energy dispersive spectrographs (EDS) of the cast A356 aluminum alloy is seen in Fig. 4 (a) A356-3 wt.% of 40 and 90 μm sized B_4C particulates reinforced composites, and A356-6 wt. % of 40 and 90 μm sized B_4C particulates reinforced composites are shown in Fig. 4 (b-e). The B (Boron) and C (Carbon) components in the composites help to identify the presence of B_4C particles.

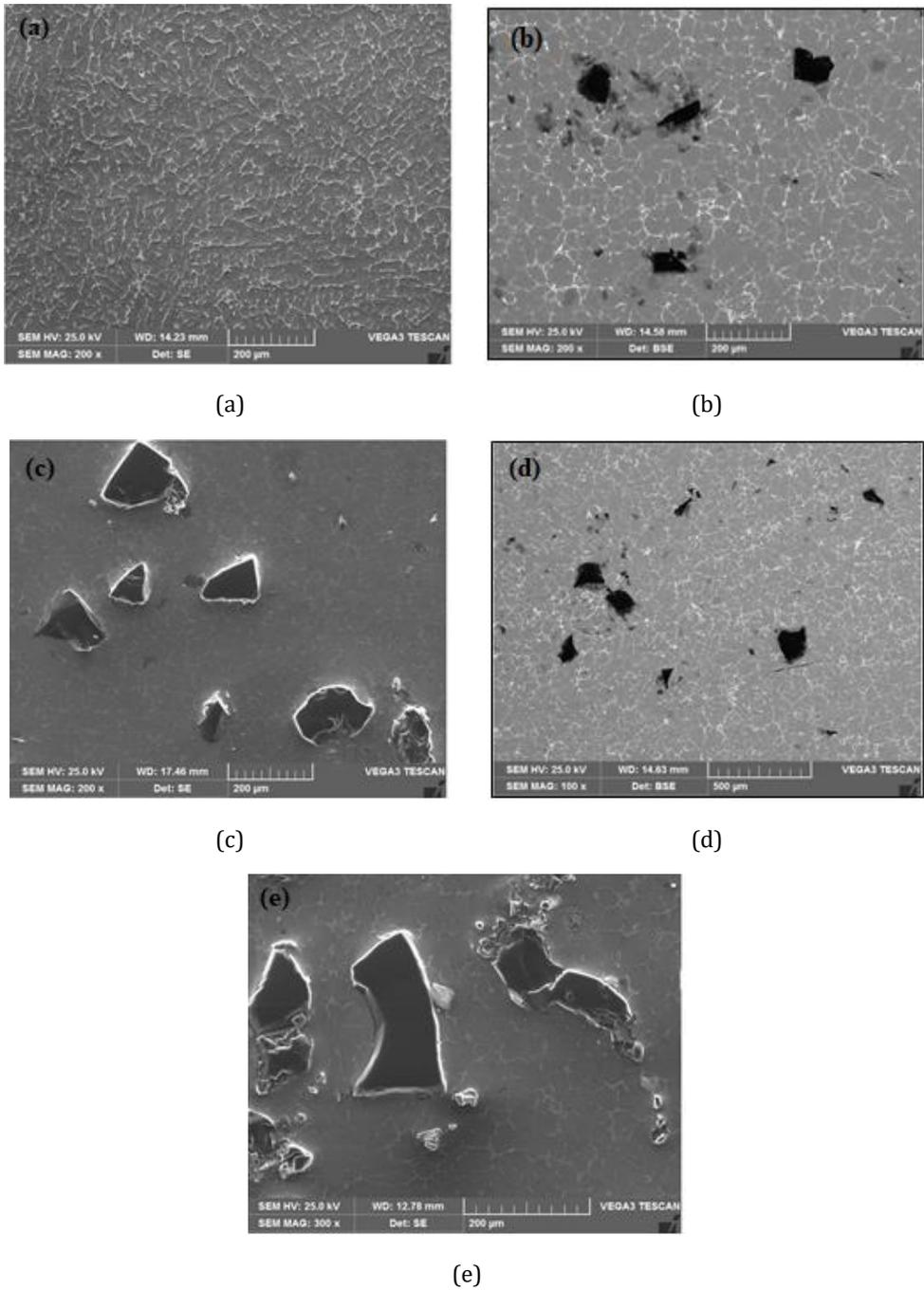
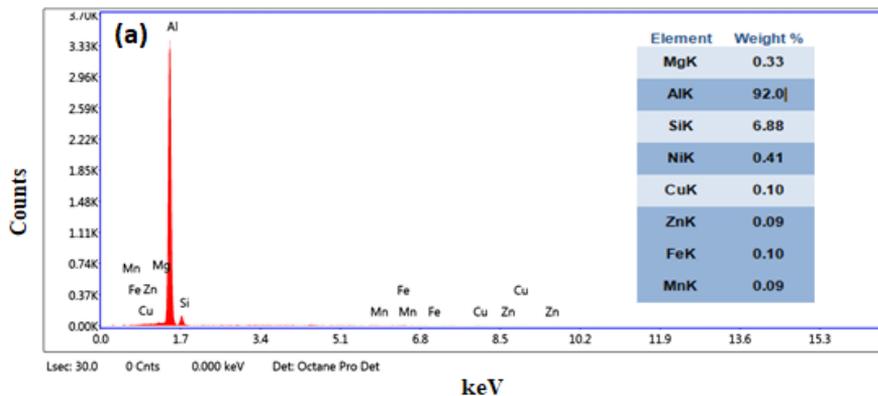
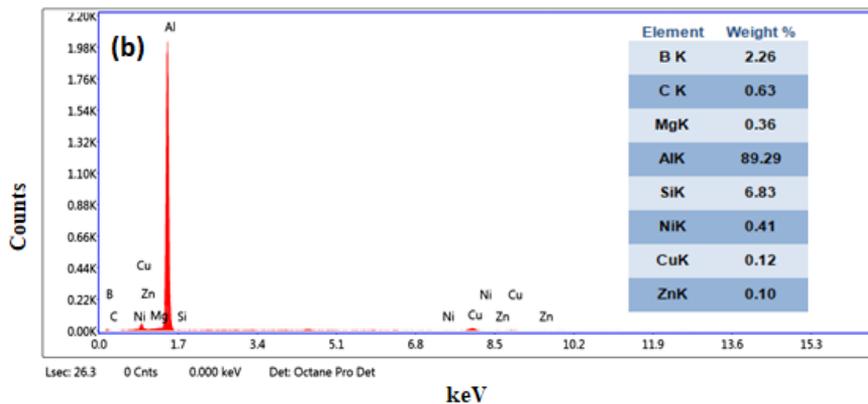


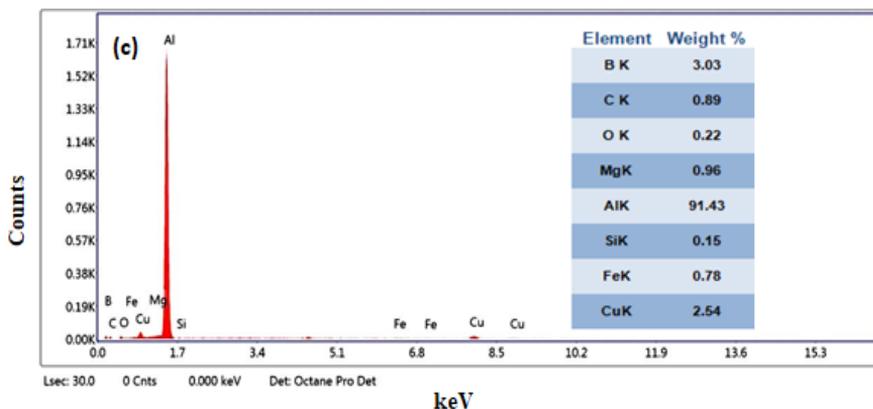
Fig. 3 SEM image of a) A356 alloy b) 3 wt.% 40 μm B₄C c) 3 wt.% 90 μm B₄C d) 6 wt.% 40 μm B₄C e) 6 wt.% 90 μm B₄C



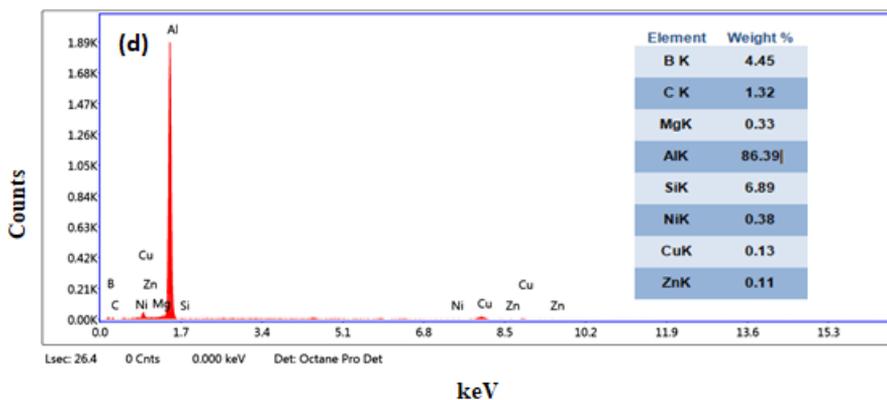
(a)



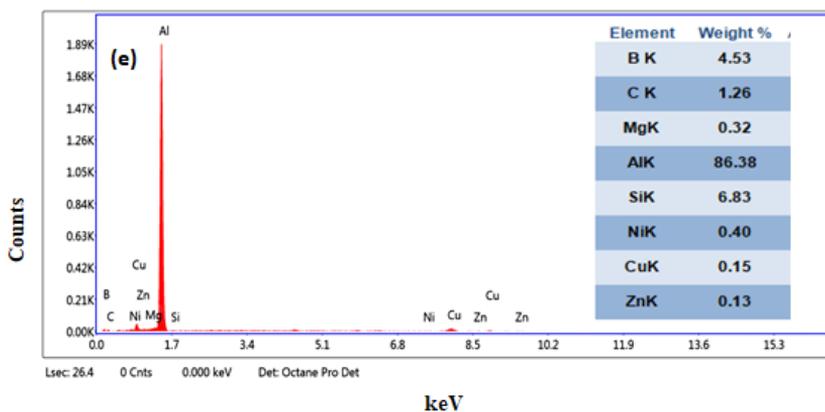
(b)



(c)



(d)



(e)

Fig. 4 SEM image of a) A356 alloy b) 3 wt.% 40µm B₄C c) 3 wt.% 90µm B₄C d) 6 wt.% 40µm B₄C e) 6 wt.% 90µm B₄C

3.2. Tensile Properties

To analyze tensile parameters such as ultimate tensile strength and yield strength, the tensile behavior of all the composite sample preparations is determined. The computerized universal testing apparatus received the specimens by hydraulic loading. The weights that caused the specimen to break and reach the yield point were noted. Fig. 5, 6 and Table 3 depicts how adding B₄C particles of 40 and 90 µm in size affected the samples' ultimate tensile strength and yield strength. In a nutshell, both direct and indirect strengthening plays a significant role in the strengthening [10]. With the addition of 6 wt. % 40 and 90 µm size B₄C, the ultimate tensile strength and yield strength both exhibit an improvement. This improvement is mostly attributable to an increase in dislocation density and their accumulation behind the uniformly dispersed B₄C. The changes in the matrix microstructure brought on by the presence of reinforcement particles lead to indirect strengthening. The mismatch in the coefficient of thermal expansion between B₄C and A356 alloy causes an increase in dislocation density in the A356- B₄C composites, which leads to indirect strengthening [11]. As the weight

percentage of B₄C rises, so does the density of these thermally generated dislocations, increasing the indirect strengthening contribution as well. On the other hand, work hardening behavior seems to be the cause of this progressive improvement.

Table 3. Tensile properties of A356 alloy and its B₄C composites with standard deviation

Material Composition	B ₄ C Particle Size (micron)	Ultimate Tensile Strength (MPa)	Yield Strength (MPa)
A356 Alloy	--	162.5 ± 0.95	126.4 ± 1.11
A356 - 3 wt. % B ₄ C	40	183.2 ± 0.75	151.4 ± 1.02
A356 - 6 wt. % B ₄ C		206.4 ± 1.10	182.0 ± 0.72
A356 - 3 wt. % B ₄ C	90	179.2 ± 1.01	148.2 ± 1.15
A356 - 6 wt. % B ₄ C		198.4 ± 1.07	168.7 ± 0.76

± - SD (Standard Deviation)

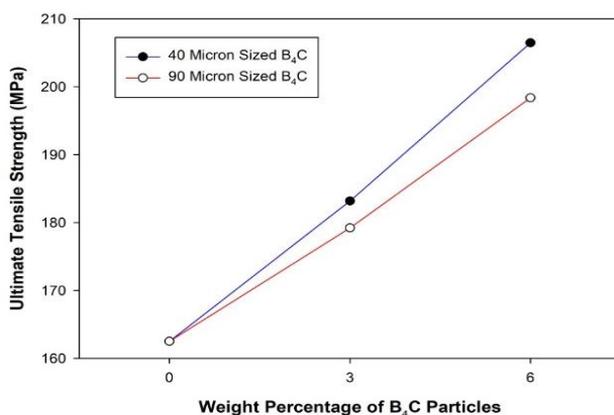


Fig. 5 Ultimate tensile strength of A356 with B₄C composites

In composite materials, the presence of a larger weight percentage of B₄C boosted the strengthening effect and load absorption. When compared to the unreinforced A356 alloy, the aluminum alloy containing reinforcement particles such boron carbide reinforcement supplied the highest tensile strength, according to earlier study findings [12]. Particle reinforcement increased strength and provided greater resilience to tensile stresses. The highest tensile strength of composites is provided through load transmission from the matrix to the reinforcing particles.

If an applied stress at which considerable internal damage (particle fracture and/or interfacial failure) occurs is taken into account, the impact of reinforcement as a function of matrix yield stress and tensile strength may be somewhat rationalized. The distribution of residual tension and the size of the particles are two important variables that will affect this stress. The impact of particle size is significant since the average fracture stress of the B₄C particles decreases as particle size rises. Therefore, in composites reinforced with big particles, particle breakage will occur at lower applied stress levels and therefore, will be reduced. Additionally, the overall interfacial area will shrink as particle size rises. Particle size is unlikely to have a significant impact on the interfacial strength. Therefore, when the particle size rises, the percentage of particle damage caused by particle breakage is anticipated to rise.

The uniformity of the particle dispersion may have an impact on the tensile characteristics of these materials. These have been shown to be quite homogenous in the current situation (Fig. 3b-e), and it is thought that they will not significantly affect the trends of the current work. The presence of any clusters, however, may impair strength and ductility by causing localized damage. Such clusters might be seen in this context as areas of potential harm that exist before loading. It should be emphasized that composites reinforced with small particulates, which seem to have more strength and ductility than materials containing coarse particles, are often more prone to have any such clustering. It is obvious that any such zones of clustering must be minimized if optimal performance is sought, particularly for the tiny particle reinforced composites.

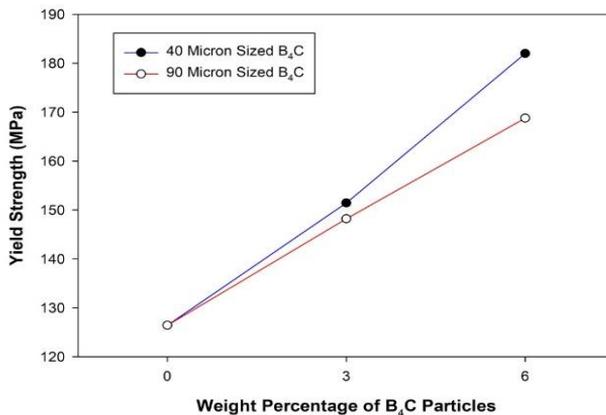


Fig. 6 Yield strength of A356 with B₄C composites

3.3. Hardness Measurements

Brinell hardness tester was used to measure the composites' hardness. Test specimens were carved out of each composite composition and polished before testing in order to achieve a flat and smooth surface finish. Brinell hardness is assessed by pressing a hard steel or carbide sphere with a certain diameter into a material's surface under a predetermined force for a predetermined amount of time, then measuring the diameter of the indentation that remains after the test. By dividing the applied force, in kilograms, by the actual surface area of the indentation, in square millimeters, one may get the Brinell hardness number. For aluminum castings, a 500 kilograms load is applied for 30 seconds. Each sample underwent several hardness tests, with the average result used to calculate the specimen's hardness.

Fig. 7 and Table 4 compares the hardness of A356 alloy with composites supplemented with 40 and 90 μm sized B₄C particulates at 3 and 6 weight percentages. The graph clearly shows that the hardness of the A356 alloy in both 40 and 90 μm of 3 and 6 wt. percent sized composites rises as the weight percentage of reinforcing particles increases [13, 14]. The basic matrix A356 alloy has a hardness of 60.3 BHN. The hardness of A356 alloy is 65.4 BHN with 3 wt. percent of 40 μm B₄C particle reinforced composites, and it is 76.3 BHN with 6 wt. percent of 40 μm B₄C particle reinforced composites. Similarly, in the case of 3 and 6 weight percentages of 90 μm sized B₄C particulates reinforced A356 alloy composites it is 64.1 and 73 BHN respectively.

Table 4. Hardness of A356 alloy and its B₄C composites with standard deviation

Material Composition	B ₄ C Particle Size (micron)	Hardness (BHN)
A356 Alloy	--	60.33 ± 1.22
A356 – 3 wt. % B ₄ C	40	65.43 ± 0.80
A356 – 6 wt. % B ₄ C		76.30 ± 1.05
A356 – 3 wt. % B ₄ C	90	64.13 ± 1.00
A356 – 6 wt. % B ₄ C		73.03 ± 0.77

± - SD (Standard Deviation)

The data show that the hardness of B₄C composites with a 40 μm size 6 wt. % is greater than that of B₄C composites with 3 wt. %. The improvement in hardness is more pronounced in composites supplemented with smaller particle and larger in quantity. This enhancement is caused by the particles' excellent wettability in the matrix of the A356 alloy and is also evident from microstructural tests. The bonding between the reinforcement and the matrix alloy increases as particle size decreases [15, 16].

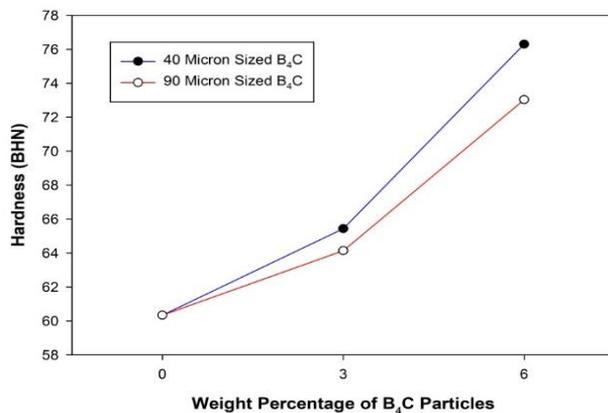


Fig. 7 Hardness of A356 with B₄C composites

3.4. Compression Strength

The Universal Testing Machine does compression testing (UTM). On the UTM's base plate is affixed the cylindrical test specimen. The specimen being utilized has a diameter that is equal to its height. The specimen is progressively loaded until it has been crushed by 50% (height). When applying higher weights, displacement also rises up to a certain point before abruptly falling till it reaches a height beyond which it can no longer be squeezed.

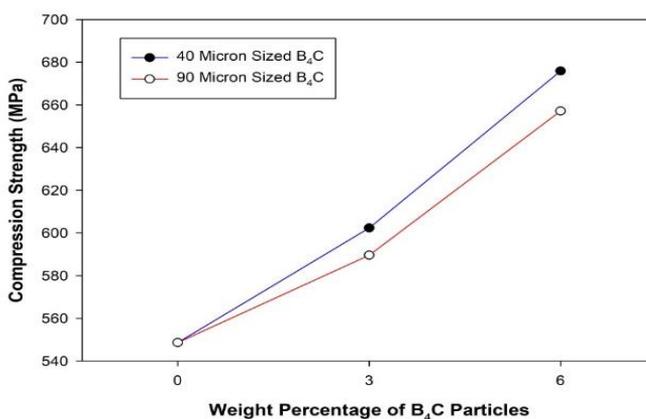
Fig. 8 and Table 5 compares the compressive strength of composites reinforced with 3 and 6 weight percent of 40 and 90 μm B₄C particles with that of A356 alloy. When B₄C particles with sizes of 40 and 90 μm are added, the compressive strength of the A356 alloy rises. Furthermore, as compared to composites reinforced with 40 μm sized B₄C particulates exhibit better compressive strength. The basic matrix of the A356 alloy has a compressive strength of 548.6 MPa.

Table 5. Compression strength of A356 alloy and its B₄C composites with standard deviation

Material Composition	B ₄ C Particle Size (micron)	Compression Strength (MPa)
A356 Alloy	--	548.60 ± 2.36
A356 – 3 wt. % B ₄ C	40	602.33 ± 3.51
A356 – 6 wt. % B ₄ C	40	675.87 ± 3.25
A356 – 3 wt. % B ₄ C	90	589.57 ± 3.10
A356 – 6 wt. % B ₄ C	90	657.13 ± 4.17

± - SD (Standard Deviation)

The compressive strength of A356 alloy is 602.3 MPa with 3 wt. percent of 40 μm B₄C particle reinforced composites, and it is 675.9 MPa with 6 wt. percent of 40 μm B₄C particle reinforced composites. Similarly, in the case of 3 and 6 weight percentages of 90 μm sized B₄C particulates reinforced A356 alloy composites it is 589.6 and 657.1 respectively. This improvement is the result of the matrix's hard B₄C particles, which have a higher compressive strength [17, 18]. Additionally, the higher resistance of crushing 40 μm 6 wt. % B₄C particles is the reason for the increased strength in 40 μm sized particle reinforced composites as compared to 3 wt. % reinforced composites.

Fig. 8 Compression strength of A356 with B₄C composites

3.5. Impact Strength

Fig. 9 and Table 6 compares the impact toughness of A356 alloy with 40 and 90 μm sized B₄C reinforced composites. In reinforced composites with 40 and 90 μm sized particle sizes, the impact toughness of the A356 alloy is enhanced by 3 and 6 weight percent. A356 alloy with 6 weight percent Boron carbide in 40 μm composites demonstrate greater impact toughness than composites with 3 weight percent B₄C particles. The greater resistance of smaller particles to debonding during impact loading accounts for the majority of the improvement in impact toughness in 40 μm B₄C composites.

There is no void formation or debonding at the interface of the matrix and the particle reinforcements, indicating improved interfacial bonding between the matrix and the reinforcements [19, 20]. The uniformity produced by the homogeneous dispersion of B₄C particles in the matrix improves the matrix-reinforcement bonding as well as the impact

strength of composites. Under the impact loading, the homogeneous particles could clearly be distinguished. The SEM analyses in figure 3 lend credence to this hypothesis.

As a result, particle cracking dominates the failure mechanism. This outcome is consistent with the literature, which states that particle breakage occurs when the contact is stronger than the individual particles. Therefore, it seems that the failure results from an accumulation of internal damage brought on by particle breakage and matrix material deformation [21, 22].

Table 6. Impact strength of A356 alloy and its B₄C composites with standard deviation

Material Composition	B ₄ C Particle Size (micron)	Impact Strength (J)
A356 Alloy	--	1.10 ± 0.1
A356 – 3 wt. % B ₄ C	40	1.45 ± 0.05
A356 – 6 wt. % B ₄ C		1.90 ± 0.03
A356 – 3 wt. % B ₄ C	90	1.35 ± 0.04
A356 – 6 wt. % B ₄ C		1.88 ± 0.02

± - SD (Standard Deviation)

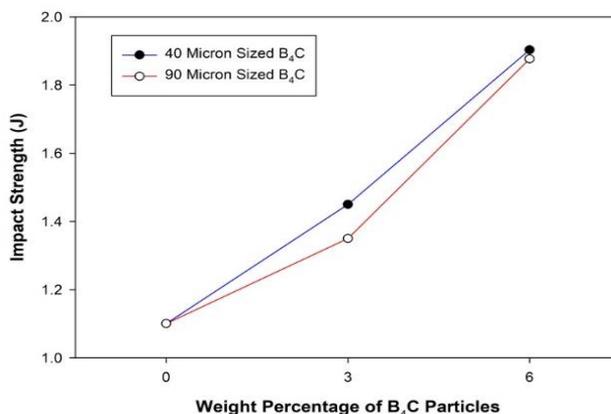


Fig. 9 Impact strength of A356 with B₄C composites

4. Conclusions

The following general findings are drawn from this study on the synthesis and characterization of composites reinforced with B₄C particles of various sizes made of the A356 alloy:

- Stir casting is an effective method for producing reinforced composites made of A356 alloy that include 3 and 6 weight percent of B₄C particulates that are 40 and 90 μm in size.
- Energy dispersive analysis (EDS) confirms the existence of B₄C particles in the form of C elements in composites made of A356 and B₄C that are 40 and 90 μm in size.
- SEM micrographs show a very equal distribution of B₄C particles throughout the matrix.
- The inclusion of 40 and 90 μm sized B₄C particles enhances the tensile properties of A356 composites with 3 and 6 wt.%B₄C. Additionally, as cast A356

alloy and composites reinforced with 6 wt.% percent 40 μm sized B_4C particles exhibit better tensile properties than composites reinforced with 3 wt.% B_4C . The inclusion of 40 and 90 μm sized B_4C particles enhances the hardness of A356 composites with 3 and 6 wt.% B_4C . Additionally, as cast A356 alloy and composites reinforced with 6 wt.% percent 40 μm sized B_4C particles exhibit better hardness than composites reinforced with 3 wt.% B_4C . The addition of B_4C particles results in an increase in the compressive strength of the A356 matrix. Furthermore, compared to 3 wt. % B_4C composites, the A356 alloy with 6 wt. % 40 μm sized B_4C particle reinforced composites show greater compressive strength.

- The inclusion of B_4C particles increases the impact toughness of the A356 matrix. Furthermore, compared to 3 wt. % 40 μm sized B_4C composites, the A356 alloy supplemented with 6 wt.% percent 40 μm sized B_4C particle demonstrates greater impact toughness.

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