El-Sayed M. Sherif[1], Osamah J. Al-Sareji[2], Sunil Kumar Shetty[3], Madeva Nagaral[4], Virupaxi Auradi[5], Pankaj Kumar Chauhan[6], Abhinav Kumar[7], A. Bhowmik[8], Abhishek Bhattacherjee[9], Raman Kumar[10], Rajendra P.[11]*

CERAMIC BORON CARBIDE MICRO-PARTICLES INFLUENCE ON THE MECHANICAL AND FRACTOGRAPHIC BEHAVIOUR OF Al2005 ALLOY COMPOSITES

UTICAJ KERAMIČKIH MIKRO ČESTICA BOR-KARBIDA NA MEHANIČKO FRAKTOGRAFSKO PONAŠANJE KOMPOZITNIH LEGURA Al2005

Originalni naučni rad / Original scientific paper
Rad primljen / Paper received: 10.01.2025
https://doi.org/10.69644/ivk-2026-01-0109

Adresa autora / Author's address:
[1] Mechanical Engineering Department, College of Engineering, King Saud University, Riyadh, Saudi Arabia
E.-S. M. Sherif https://orcid.org/0000-0003-2080-8552
[2] Sustainability Solutions Research Lab, Faculty of Engineering, University of Pannonia, Veszprem H, 8200, Hungary
[3] Department of Mechanical Engineering, Nitte (Deemed to be University), NMAM Institute of Technology, Karkala-574110, Karnataka, India
S.K. Shetty https://orcid.org/0000-0002-8939-8718
[4] Aircraft Research and Design Centre, Hindustan Aeronautics Limited, Bangalore 560037, Karnataka, India
M. Nagaral https://orcid.org/0000-0002-8248-7603
*email: madev.nagaral@gmail.com
[5] Department of Mechanical Engineering, Siddaganga Institute of Technology, Tumakuru 572103, Karnataka, India
V. Auradi https://orcid.org/0000-0001-6549-6340
[6] Department of Mechanical Engineering, Galgotia University, Greater Noida-203201, Uttar Pradesh, India
P.K. Chauhan https://orcid.org/0000-0002-0467-7823
[7] Department of Mechanical Engineering, Karpagam Academy of Higher Education, Coimbatore-641021, India
[8] Chitkara Centre for Research and Development, Chitkara University, Pinjore, Himachal Pradesh, India
[9] Department of Computer Science Engineering, Lovely Professional University, Punjab, India
[10] Department of Mechanical and Production Engineering, Guru Nanak Dev Engineering College, Ludhiana 141006, Punjab India
[11] Department of Mechanical Engineering, Ramaiah Institute of Technology, Bangalore, India

Keywords
- Al2005 alloy
- B_4C particles
- microstructure
- hardness
- tensile strength

Abstract

The current study involves the production of composites consisting of Al2005 alloy and B_4C using a liquid metallurgical technique. The Al2005 alloy is employed to fabricate composites with 4 and 8 weight percent of B_4C particles. The microstructure of the produced composites is examined utilising Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDS). The density, hardness, ultimate strength, yield strength, and elongation are assessed according to the ASTM E8 standard for tensile testing and the E10 standard for hardness testing. The consistent distribution of B_4C particles throughout the Al2005 alloy is validated by SEM. EDS analyses indicate the existence of B_4C particles within the Al2005 alloy. The incorporation of lighter B_4C particles into the matrix diminishes the density of aluminium alloy composites. The incorporation of particles results in an improvement in the hardness, ultimate tensile strength, and yield strength of the Al2005 alloy by 33.73 %, 36 %, and 41.84 %, respectively. The tensile fractured micrographs offer additional proof of the distinct fracture characteristics shown by the Al2005 alloy and its composites.

Ključne reči
- legura Al2005
- čestice B_4C
- mikrostruktura
- tvrdoća
- zatezna čvrstoća

Izvod

U ovom radu bavimo se istraživanjem proizvodnje kompozita od legure Al2005 i B_4C primenom metode metalurgije u tečnom stanju. Legura Al2005 se uvodi za izradu kompozita sa 4 i 8 težinskih procenata čestica B_4C. Mikrostruktura proizvedenih kompozita se ispituje skening elektronskom mikroskopijom (SEM) i energetskom disperzivnom rendgenskom spektroskopijom (EDS). Gustina, tvrdoća, zatezna čvrstoća, napon tečenja, i izduženje se određuju prema standardu ASTM E8 za ispitivanja zatezanjem i prema standardu E10 za ispitivanje tvrdoće. Nepromenljiva raspodela B_4C čestica unutar legure Al2005 se proverava SEM. Analize EDS ukazuju na postojanje B_4C čestica unutar legure Al2005. Uvođenjem lakih čestica B_4C u matricu se smanjuje gustina kompozita od legure aluminijuma. Prisustvo čestica dovodi do poboljšanja tvrdoće, zatezne čvrstoće, i napona tečenja legure Al2005 za 33,73 %, 36 % i 41,84 %, respektivno. Mikrosnimci prelomnih površina dobijenih zatezanjem pružaju dodatni dokaz za uočljive osobine loma kod legura Al2005 i njihovih kompozita.

INTRODUCTION

Composite materials are synthesised through the combination of two or more materials that possess separate properties and are incapable of dissolving into one another. Composite materials are created by mixing elements with distinct characteristics, resulting in a distinctive property that surpasses the individual properties of the constituent materials /1, 2/.

Constituents maintain their identity while also combining in a way that produces new traits that are superior to the sum of their individual parts. As technology continues to improve, there is an increased need for materials that are energy-efficient, lightweight, and affordable in the aerospace, defence, aviation, automation, and many other sectors /3-5/. Therefore, the principal applications revolve on reducing weight while simultaneously preserving improved mechanical and other tribological qualities, for which aluminium composites are best suited /6, 7/. Aluminium is suitable for usage because its resistance to corrosion is high as compared to magnesium and other alloys, especially for aerospace applications /8, 9/. When its surface reacts with air, it forms oxides that provide protection against erosion caused by rubbing between two surfaces in an application. Therefore, it is often utilised in aircraft applications where it lacks significant inherent wear resistance. Hence, there is a pressing want for substantial improvements on its properties /10-13/.

The use of contemporary materials with greater qualities in the automotive and aerospace industries has led to a steady advancement of metal composites /14, 15/. A metal composite is made up of reinforcements like ceramics and a matrix material like metal or an alloy. At the microscopic level, composites are heterogeneous, yet at the macroscopic level, they are homogeneous.

The crucial aspect is in the assessment of a material's macroscopic characteristic, wherein the components produced by these composites may be seen identified without the aid of magnification. At a macroscopic level, different types of materials are joined, such as alloys of metals. These materials appear to be homogeneous to the naked sight, meaning that their pieces cannot be distinguished and they clearly work together /16, 17/.

The fundamental benefit of composites is that a good design shows off the premium attributes of its constituent parts. Both naturally occurring and man-made composites exist. Among the former are wood, where lignin serves as the matrix and is reinforced by cellulose fibres. The human body is also made up of composites, with soft collagen being strengthened by bone-salt of calcium and phosphate ions.

Utilising a composite material by integrating two or more substances requires more effort compared to using conventional monolithic steel and aluminium components. Essentially, these metals and their alloys consistently fail to fulfil the demands of modern advanced technology. Required performance is achieved solely through the utilisation of diverse material combinations. Currently, the aircraft industries have experienced an increase in acceptability due to the use of new materials.

Due to their outstanding properties such as low ductility, good wear resistance, low thermal expansion, good thermal conductivity, good damping characteristics, and excellent thermal expansion, aluminium matrix composites (AMCs) /18-20/ have garnered a lot of attention in recent decades and are seen as the most promising materials to encounter the ever-increasing demands of current technology /21, 22/. For as long as composites have been around, aluminium and its alloys have been the go-to matrix material. Reasons for this include the inexpensive production cost of AMCs and the wide variety of excellent mechanical and thermal qualities already stated, /23, 24/.

The major reason to choose the boron carbide particles as a reinforcement particle in the present study is due to its compatibility with Al alloy matrix /25, 26/. The density of Al2005 alloy is 2.80 g/cm^3 and the density of B_4C is 2.52 g/cm^3, which is not too high or low as compared to the matrix. Further, with the addition of these particles density of composites will reduce. On the other hand, if one uses SiC or TiC, the density of these particles is high as compared to the Al2005 alloy, which causes wettability issues with the matrix /27, 28/. Further, the hardness and Young's modulus of B_4C are very high as compared to the base matrix alloy. This high hardness and modulus of the reinforcement particle helps in enhancing the hardness and tensile strength of the base material, /29, 30/.

The extant literature indicates that there has been little research on the use of B_4C particles in an Al2005 alloy matrix, specifically with particle sizes ranging from 80 to 90 microns. The B_4C metal matrix composite, based on aluminium, is fabricated using the stir casting technique. In the present research to improve the wettability between the Al2005 matrix and B_4C particles, a halide salt K_2TiF_6 is used. In order to avoid clumping together, B_4C particles are introduced into the aluminium melt in two separate phases. After being prepared, the AMMC is subjected to various mechanical testing.

EXPERIMENTAL DETAILS

Materials used

Al2005 can be processed in a subsequent operation. With a density of 2.80 g/cm^3 and a melting point of 660 °C, Al2005 is primarily alloyed with copper. Many industries, including transportation and aerospace, rely on the Al2005 alloy. When it comes to welding, Al2005 shines thanks to its excellent self-healing capacity, strong raised temperature strength, and excellent corrosion resistance. Table 1 shows the chemical composition of Al2005.

Table 1. Chemical composition of Al2005 alloy.

Elements	Si	Fe	Cu	Mg	Cr	Mn	Ti	Al
% wt.	0.8	0.70	4.80	0.20	0.10	0.90	0.10	bal.

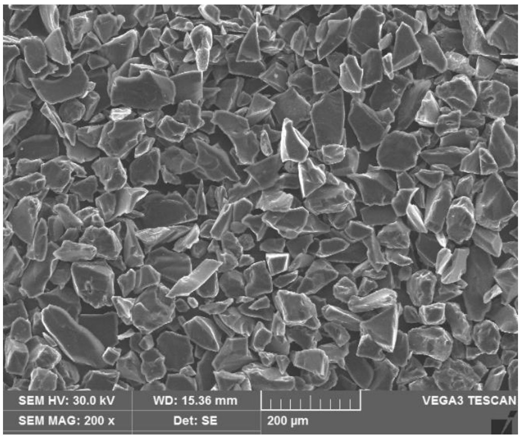


Figure 1. SEM micrograph of 80 to 90 micro sized B_4C particles.

Boron carbide, ranging in size from 80 to 90 μm, is acquired from Speedfam Chennai Ltd., India, and is used as a reinforcing material. Black is the colour of the reinforcement, having a melting point of 3300 °C and a range of hardness 3100-3600 kg/mm^2, the density of reinforcement particles is 2.52 g/cm^3 /31, 32/. Figure 1 shows the scanning electron micrograph of B_4C particles used to make the metal composites.

Composites preparation and testing

By using liquid metallurgy, Al2005 alloy with various weight rates of B_4C composites are created. Al2005 composite metal pieces weighing a certain amount are placed into the electric furnace and heated till liquid metal stage. The temperature of Al2005 compound liquid metal is raised to 750 °C. The correct thermocouples are used to measure and record the superheating and dissolving temperatures. For around three minutes, potassium titanium fluoride (K_2TiF_6) /33, 34/ is used to degas the superheated liquid metal in the crucible. To blend the metal in the liquid, a shaft stirrer is utilised in conjunction with a zirconium-coated steel rotor. For the purpose of creating vortices, the stirrer is spun at a speed of around 300 rpm while submerged in the crucible's liquid metal to a depth of approximately 65 %. The molten metal of Al2005 alloy with B_4C is stirred for 5 minutes. The process of blending is prolonged until the overall wettability of Al2005 composites with particles reaches a certain level at which interfacial strength is recognised. At that time, the cast iron moulds with the requisite dimensions are filled with the liquid metal mixture of Al2005 composite and B_4C particulates. Figure 2 indicates the Al2005-B_4C composites.

Figure 2. Al2005-B_4C composites prepared.

In order to determine whether the Al2005 alloy contains a uniform distribution of reinforcing B_4C particles, a SEM analysis is performed on the specimen after casting. Al2005 alloy and Al2005-B_4C composites have their microstructures photographed. The microstructure specimen has a 15 mm diameter and a 5 mm height. Paper with grits ranging from 300 to 1000 is used to grind the surface of the sample. After that, the surface is polished using polishing paper with a thickness of 3 μm to get an even smoother finish on the polishing machine.

To conduct the hardness test, the specimen is prepared by grinding it in line with the ASTM standard E10 /35, 36/. A Brinell hardness tester is employed for the purpose of quantifying hardness. The sample exhibits a smooth and impeccable surface. Upon exerting a force of 250 kg on the specimen, a 5 mm depression is created by a ball. The specimen's surface exhibits five depression marks which are subsequently analysed.

The optical microscope is used to inspect the specimens' indent marks in order to calculate their hardness values using the given relation.

$$\mathrm{BHN}=\frac{2P}{\pi D(D-\sqrt{D^2-d^2})},$$

where: P (kg) is load; D (mm) is diameter of steel ball; and d is size of indent.

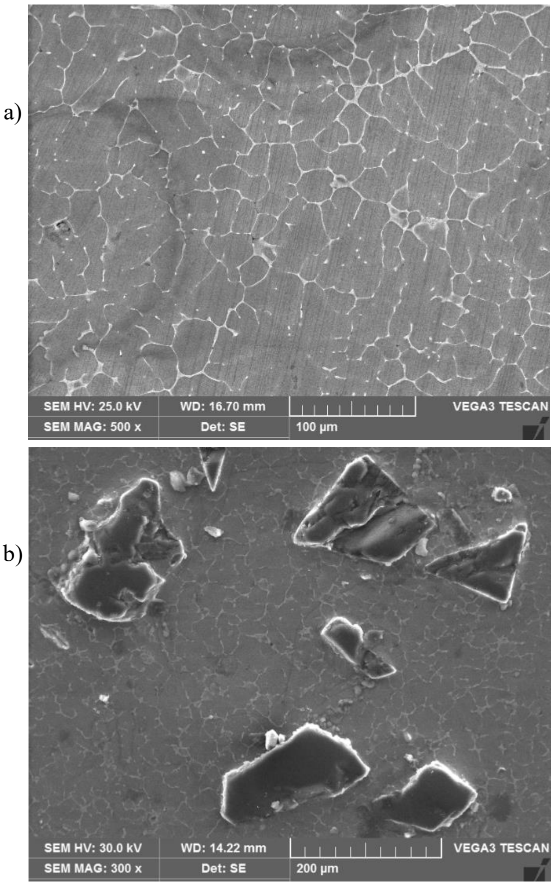
To analyse tensile properties of Al2005 alloy and B_4C reinforced composites, it is necessary to use specimens prepared following the guidelines specified in ASTM standard E8 /37, 38/. To obtain the most accurate findings, the tensile strength is tested by using three specimens. In order to examine the response of Al2005-B_4C composites to unidirectional tension, assess the influence of uniform distribution, and determine the tensile strength, a computer-controlled tensile machine is utilised. The tensile sample is 104 mm in total length, with gauge length of 45 mm and gauge diameter of 9 mm. The tensile test is used for evaluating the maximum, yield, and elongation strengths of cast alloys and composites. Figure 3 exhibits the tensile test specimen.

Figure 3. Tensile test specimen.

RESULTS AND DISCUSSION

Microstructural analysis

SEM microphotographs in Fig. 4a-c display composites that have been strengthened with 4 to 8 wt.%. B_4C particles. Figure 4a displays a SEM of the Al2005 alloy. The lack of particles is indicated by pristine grain boundaries. The micrograph does not exhibit any discernible voids or casting defects. Figures 4, b and c, display microphotographs of composites containing Al2005-4 % B_4C and Al2005-8 % B_4C, in respect.



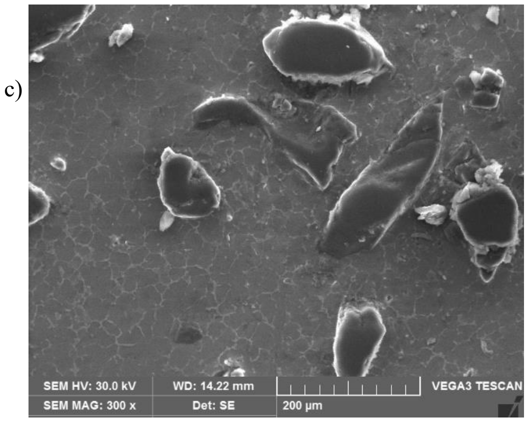


Figure 4. SEM microphotographs of: a) Al2005 alloy; b) Al2005, 4 wt.% of B_4C; c) Al2005, 8 wt.% of B_4C composites.

The micrographs clearly show that B_4C particles are present in reinforced composites at 4 and 8 wt.%. The innovative two-step casting method used to create the composites ensures that the particles do not clump together or agglomerate. In addition, the microstructure surface of Al2005 composites with 8 wt.% B_4C comprises a greater number of B_4C particles dispersed throughout the matrix Al2005 alloy.

Figure 5 displays the EDS analysis of composites that are reinforced with Al2005 alloy and include 8 wt.% of B_4C particles. Figure 5 (top) clearly illustrates that Cu is a prominent alloying element in the Al2005 alloy, along with Fe, Mn, and Zn. Additionally, Figure 5 (bottom) displays EDS spectra of composites strengthened with Al2005 and 8 wt.% B_4C particles. The existence of boron and carbon particles in the Al2005 alloy is identified using the spectrum of EDS. The presence of B and C elements, along with Zn, Fe, Cu, Mn, and Si, confirms the integrity of the casting procedure employed in the production of the composites.

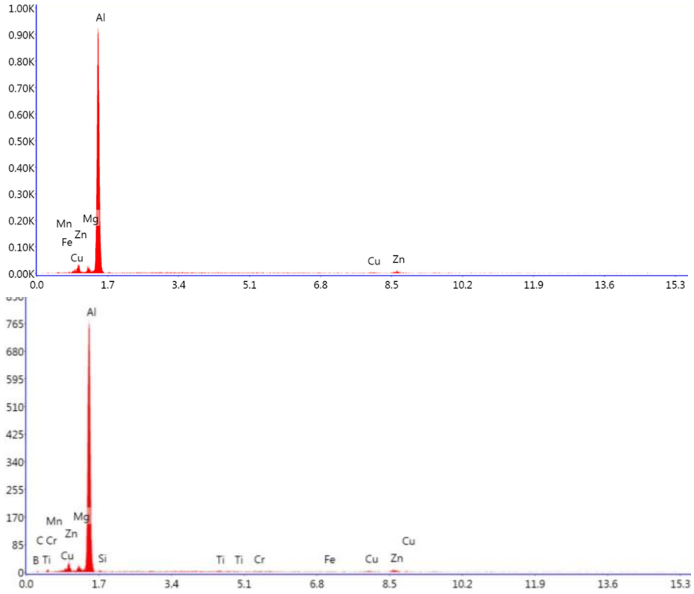


Figure 5. EDS analysis of Al2005 alloy (top); Al2005, 8 wt.% of B_4C composite (bottom).

Hardness measurements

Table 2 and Fig. 6 show hardness values of Al2005 alloy, Al2005- 4, and 8 wt.% of B_4C reinforced composites. As the plot shows, the hardness of Al2005 alloy improves from 4 to 8 wt.% B_4C particles. The hardness of the Al2005 is 67.77 BHN, but it increases to 80.36 and 90.18 BHN after adding 4 and 8 wt.% of B_4C particles, in respect. A hardness enhancement of 24.85 % is seen in B_4C composites with an Al2005 alloy content of 8 wt.%. Because of the hard B_4C particles present in the flexible matrix, the hardness of Al2005 alloy is enhanced. Incorporating B_4C particles of 3500 BHN into a soft matrix helps to increase the hardness. As a result of dislocation density caused by the thermal coefficient mismatch between Al2005 alloy and B_4C particles, this procedure also increases straining in the composites /39, 40/. The composites get harder due to the strain hardening.

Table 2. Hardness of Al2005-B_4C composites.

Sl No.	Materials	BHN with standard deviation	Improvement (%)
1	Al2005 alloy	67.77 ± 1.38	---
2	Al2005 - 4 wt.% B_4C	80.36 ± 0.98	15.66
3	Al2005 - 8 wt.% B_4C	90.18 ± 0.89	24.85

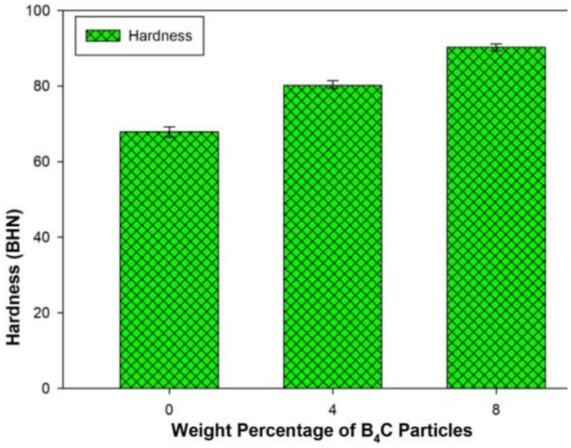


Figure 6. Hardness of B_4C reinforced Al2005 alloy composites.

Tensile properties

Figure 7 and Table 3 show the consequence of B_4C on strength of Al2005 alloy. The strength is upgraded as the wt.% of B_4C particles in the soft Al2005 matrix increases, as shown in Fig. 7. Al2005 alloy has an ultimate tensile strength (UTS) of 207.2 MPa. In addition, the UTS of composites of Al2005 with 4% B_4C is 247.7 MPa, and with 8% B_4C is 272.8 MPa, in respect. The addition of 8 wt.% B_4C

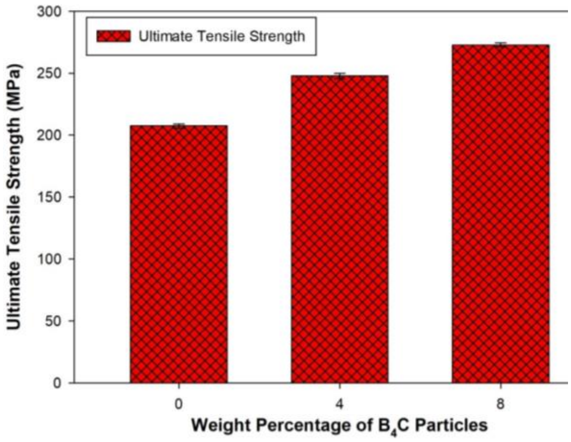


Figure 7. UTS of boron carbide reinforced Al2005 alloy composites.

particles ranging in size from 80 to 90 microns improves the UTS of Al2005 alloy by 24 %.

Table 3. Ultimate strength of Al2005-B₄C composites.

Sl No.	Materials	UTS (MPa) with standard deviation	Improvement (%)
1	Al2005 alloy	207.20 ± 1.73	---
2	Al2005 - 4 wt.% of B_4C	247.71 ± 2.01	16.35
3	Al2005 - 8 wt.% of B_4C	272.84 ± 1.60	24.05

In Fig. 8 and in Table 4 are the effects that B_4C particles have on the yield strength of Al2005. Figure 8 shows that the strength of Al2005 is enhanced with an increase in the wt.% of B_4C particles in the Al matrix. At 173.3 MPa, the Al2005 alloy yields its full strength. In addition, the YS of composites made with Al2005 and 4 wt.% B_4C is 212.8 MPa, while that of composites made with 8 wt.% B_4C is 237.9 MPa. The addition of 8 wt.% of B_4C particles ranging in size from 80 to 90 μm improves the YS of Al2005 alloy by 27.14 %.

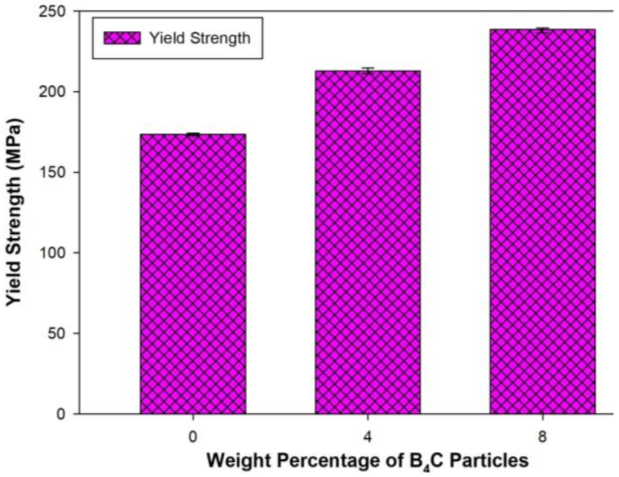


Figure 8. YS of B_4C reinforced Al2005 alloy composites.

Table 4. Yield strength of Al2005-B₄C composites.

Sl No.	Materials	Yield strength (MPa) with standard deviation	Improvement (%)
1	Al2005 alloy	173.33 ± 0.80	---
2	Al2005- 4 wt.% B_4C	212.80 ± 1.76	18.57
3	Al2005- 8 wt.% B_4C	237.91 ± 1.64	27.14

Plots 7 and 8 demonstrate that the inclusion of 4 and 8 wt.% of minuscule B_4C particles into the Al2005 alloy result in an increase in its ultimate and yield strengths, respectively. Incorporating B_4C into the matrix enhances the tensile strength of the Al alloy. Due to the particle's hardness, the matrix material becomes more fragile and is able to endure higher directed loads. Within the realm of composites, these resilient particles function as load-bearing elements, hence enhancing the strength of the composites. Furthermore, as per the Hall-Petch strengthening mechanism, the incorporation of minuscule particles into the aluminium matrix leads to a decrease in grain size. Consequently, the strength of the composites is enhanced. The presence of density dislocations in the Al2005 alloy is attributed to the significant difference in expansion coefficients between the alloy and B_4C particles, as explained by the Orowan principle /41, 42/. Strain hardening takes place in the Al-B_4C melt due to the presence of density dislocations, resulting in enhanced strength.

Figure 9 shows the ductility of Al2005 and Al2005 alloy composites reinforced with 4 and 8 wt.% of B_4C particles, respectively. The graph shows that the ductility of the matrix drops as the percentage of B_4C particles rises. The presence of hard B_4C particles in the matrix is responsible for the decrease in ductility. The material is able to resist further elongation due to the significant multidirectional stresses at the interface of the Al2005 alloy and B_4C. Thanks to the strong bonding between Al and B_4C particles, the applied load is effectively transferred to the evenly distributed micro B_4C particles, and the overall performance is improved. All things considered, the Al2005 alloy-8 wt.% B_4C composites exhibit lower elongation than the base amalgam and 4 wt.% B_4C particle reinforced composites.

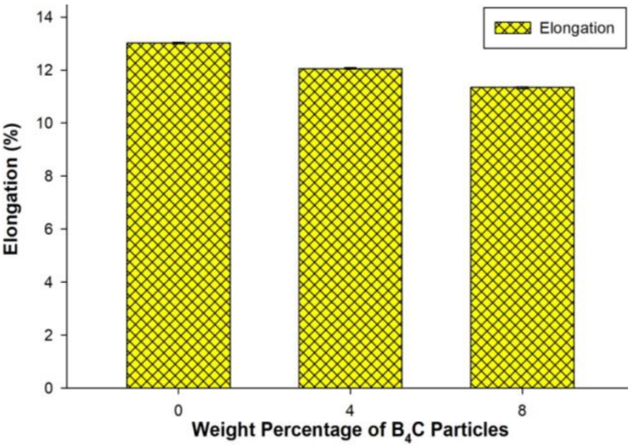


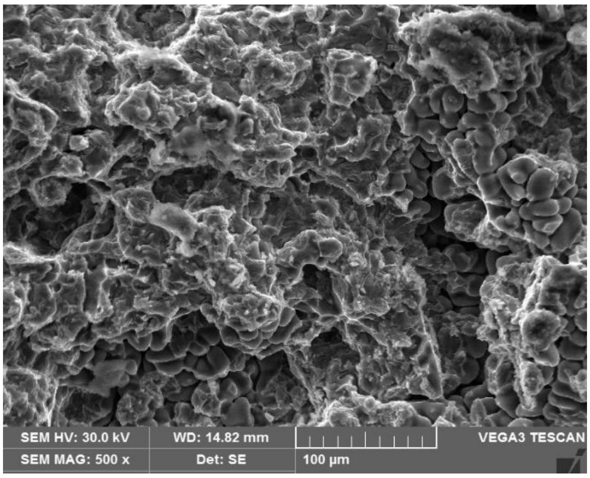
Figure 9. Elongation (%) of B_4C reinforced Al2005 alloy composites.

Tensile fractography

The SEMs of fractured surfaces of Al2005 and Al2005 with 4 and 8 wt.% B_4C composites are shown in Fig. 10a-c. The tensile fracture micrographs show that the matrix alloy and B_4C reinforcement are well-bonded. Figure 10a shows the fractured surface of Al2005 alloy taken at 500× magnification. The visible grains on the cracked surface of the cast alloy indicate a ductile fracture.

Also, the fractured surfaces of Al2005- 4 wt.% B_4C and Al2005- 8 wt.% B_4C composites can be seen in Fig. 10b-c. The micrographs show that the composites become more brittle with increasing amounts of B_4C reinforcement. The surface of tensile fractured Al2005- 4 wt.% B_4C composites

a)



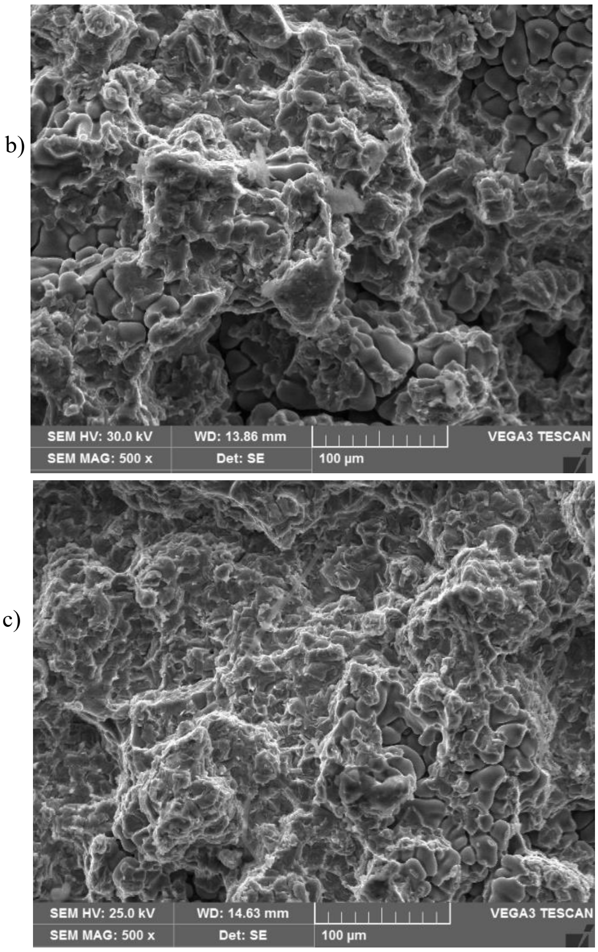


Figure 10. SEM images of tensile fractured surfaces: a) Al2005 alloy; b) Al2005, 4 wt. % B_4C; c) Al2005, 8 wt. % B_4C composites.

shows this increased brittleness clearly. This brittle fracture also occurs in tandem with the composites' elongation. There is a decline in composite ductility with increasing wt.% of B_4C particles, as mentioned in the elongation section.

Compression strength

Figure 11 and Table 5 show the compression strength of Al2005 and Al2005 composites with 4 and 8 wt.% B_4C, in respect. The plots show that the compression strength of Al2005 is strengthened by the hard particle phase, and that this enhancement continues as the weight percentage of B_4C particles grows. Compressive strength is a reliable indicator of the strength of carbide or oxide particles in ceramics because of their naturally hard character, /43, 44/. Because of the addition of B_4C particles, which greatly refine the grains, the presence of uniformly distributed tougher components, and the dislocations caused by modulus mismatch and thermal expansion coefficient, Al-B_4C composites are very strong. Findings from Fig. 11 show that compressive strength is significantly affected by the B_4C content. This proves what is already known: that B_4C particles enhance Al-B_4C composites.

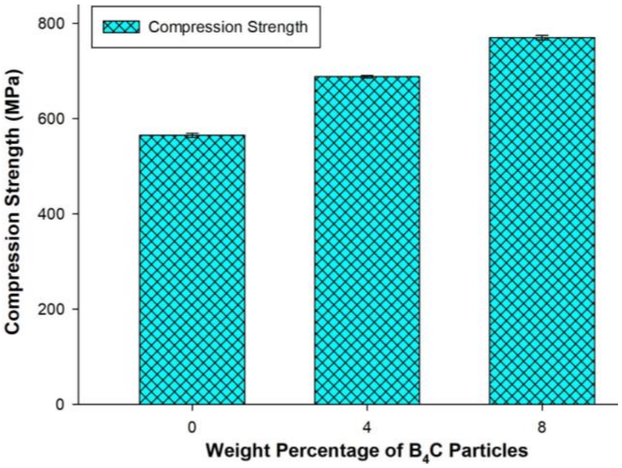


Figure 11. Compression strength of boron carbide reinforced Al2005 alloy composites.

Table 5. Compression strength of Al2005-B_4C composites.

Sl No.	Material	Comp. strength (MPa) with standard deviation	Improvement (%)
1	Al2005 alloy	565.06 ± 4.69	---
2	Al2005- 4 wt.% B_4C	688.32 ± 3.00	17.91
3	Al2005- 8 wt.% B_4C	770.35 ± 4.41	26.65

CONCLUSIONS

Al2005 alloy with 4 and 8 wt.% of B_4C composites are produced by stir casting and the following conclusions are made.

Microstructures of the produced Al2005 and Al2005 composites with 4 and 8 wt.% B_4C are examined by SEM and EDS.

SEM micrographs and EDS confirm the presence and distribution of B_4C micro particles in the Al2005 alloy.

The Al2005 alloy with 8 wt.% B_4C composites has a 24.85 % increase in hardness.

In addition, the ultimate, yield, and compression strengths of Al2005 alloy are increased by 24 %, 27 %, and 26.6 %, respectively, with the addition of 8 wt.% of carbide particles.

By adding 4 and 8 wt.% of carbide particles, the ductility of the aluminium alloy is reduced.

Ductile mode fracture is seen in Al2005 material on fractured surfaces of tensile specimens. Additionally, brittle mode of fracture is noted in the composites as the reinforcing amount increases to 8 wt.%.

REFERENCES

1. Ali, Z., Muthuraman, V., Rathnakumar, P., et al (2022), *Studies on mechanical properties of 3 wt% of 40 and 90 μm size B_4C particulates reinforced A356 alloy composites*, Mater. Today: Proc. 52(Part 3): 494-499. doi: 10.1016/j.matpr.2021.09.260
2. Harti, J.I., Prasad, T.B., Nagaral, M., et al (2017), *Microstructure and dry sliding wear behaviour of Al2219-TiC composites*, Mater. Today: Proc. 4(10): 11004-11009. doi: 10.1016/j.matpr.2017.08.058
3. Dayanand, S., Boppana, S.B., Auradi, V., et al. (2021), *Evaluation of wear properties of heat-treated Al-AlB$_2$ in-situ metal matrix composites*, J Bio- Tribo-Corr. 7(40): 1-11. doi: 10.1007/s40735-021-00476-w
4. Nagaraj, N., Mahendra, K.V., Nagaral, M. (2018), *Microstructure and evaluation of mechanical properties of Al-7Si-fly ash composites*, Mater. Today: Proc. 5(1)(Part 3): 3109-3116. doi: 10.1016/j.matpr.2018.01.116
5. Ali, Z., Muthuraman, V., Rathnakumar, P., et al. (2020), *Investigation on the tribological properties of copper alloy reinforced*

with Gr/ZrO$_2$ particulates by stir casting route, Mater. Today: Proc. 33(Part 7): 3449-3453. doi: 10.1016/j.matpr.2020.05.351

6. Prasad, G.P., Chittappa, H.C., Nagaral, M., Auradi, V. (2020), *Influence of B$_4$C reinforcement particles with varying sizes on the tensile failure and fractography of LM29 alloy composites*, J Fail. Anal. Prevent. 20(6): 2078-2086. doi: 10.1007/s11668-020-01021-6
7. Bharath, V., Auradi, V., Nagaral, M., Bopanna, S.B. (2020), *Influence of alumina percentage on microstructure, mechanical and wear behaviour of 2014 aluminium-alumina metal matrix composites*, Jurnal Tribologi, 25(1): 29-44.
8. Fazil, N., Venkataraman, V., Nagaral, M. (2020), *Mechanical characterization and wear behavior of aerospace alloy AA2124 and micro B$_4$C reinforced metal composites*, J Met. Mater. Miner. 30(4): 97-105. doi: 10.55713/jmmm.v30i4.641
9. Manjunatha, T.H., Basavaraj, Y., Nagaral, M., et al (2018), *Investigations on mechanical behavior of Al7075-nano B$_4$C composites*, IOP Conf. Ser.: Mater. Sci. Eng. 376(1): 012091. doi: 10.1088/1757-899X/376/1/012091
10. Kumar, H.S.V., Kempaiah, U.N., Nagaral, M., Auradi, V. (2021), *Impact, tensile and fatigue failure analysis of boron carbide particles reinforced Al-Mg-Si (Al6061) alloy composites*, J Fail. Anal. Prevent. 21(6): 2177-2189. doi: 10.1007/s11668-021-01265-w
11. Murthy, B.V., Auradi, V., Nagaral, M., et al. (2023), *Al2014-alumina aerospace composites: particle size impacts on microstructure, mechanical, fractography, and wear characteristics*, ACS Omega, 8(14): 13444-13455. doi: 10.1021/acsomega.3c01163
12. Bharath, V., Auradi, V., Veeresh Kumar, G.B., et al. (2022), *Microstructural evolution, tensile failure, fatigue behavior and wear properties of Al$_2$O$_3$ reinforced Al2014 alloy T6 heat treated metal composites*, Materials, 15(12): 4244. doi: 10.3390/ma15124244
13. Priyankar, D., Ali, Z., Nagaral, M., et al. (2023), *Microstructure and evolution of mechanical properties of Cu-Sn alloy with graphite and nano zirconium oxide particulates*, Mater. Today: Proc. 52(Part 3): 296-300. doi: 10.1016/j.matpr.2021.08.300
14. Shetty, R.P., Mahesh, T.S., Ali, Z., et al. (2022), *Studies on mechanical behaviour and tensile fractography of boron carbide particles reinforced Al8081 alloy advanced metal composites*, Mater. Today: Proc. 52(Part 3): 2115-2120. doi: 10.1016/j.matpr.2021.12.397
15. Chandrasekhar, G.L., Vijayakumar, Y., Nagaral, M., Anilkumar, C. (2021), *Microstructural evaluation and mechanical behaviour of nano B$_4$C reinforced Al7475 alloy metal composites*, Int. J Veh. Struct. Syst. 13(5). doi: 10.4273/ijvss.13.5.24
16. Nagaraj, N., Mahendra, K.V., Nagaral, M. (2018), *Investigations on mechanical behaviour of micro graphite particulates reinforced Al-7Si alloy composites*, IOP Conf. Ser.: Mater. Sci. Eng. 310(1): 012131. doi: 10.1088/1757-899x/310/1/012131
17. Vasanth Kumar, H.S., Revanna, K., Kumar, N., et al. (2022), *Impact of silicon carbide particles weight percentage on the microstructure, mechanical behaviour, and fractography of Al2014 alloy composites*, Adv. Mater. Sci. Eng. 2022(1): 2839150. doi.org/10.1155/2022/2839150
18. Somayaji, A., Nagaral, M., Anjinappa, C., et al. (2023), *Influence of graphite particles on the mechanical and wear characterization of Al6082 alloy composites*, ACS Omega, 8(30): 26828-26836. doi: 10.1021/acsomega.3c01313
19. Raksha, M.S., Adaveesh, B., Nagaral, M., et al. (2023), *Impact of boron carbide particles and weight percentage on the mechanical and wear characterization of Al2011 alloy metal composites*, ACS Omega, 8(26): 23763-23771. doi: 10.1021/acsomega.3c02065
20. Shetty, R.P., Raju, T.H., Nagaral, M., et al. (2024), *Effect of B$_4$C particles addition on the mechanical, tensile fracture and wear behavior of Al7075 alloy composites*, J Bio- Tribo-Corr. 10(2): 32. doi: 10.1007/s40735-024-00841-5
21. Preethi, K., Raju, T.N., Shivappa, H.A., et al. (2023), *Processing, microstructure, hardness and wear behavior of carbon nanotube particulates reinforced Al6061 alloy composites*, Mater. Today: Proc. 81(Part 2): 449-453. doi: 10.1016/j.matpr.2021.03.608
22. Matti, S., Shivakumar, B.P., Nagaral, M., et al. (2022), *Mechanical and tribological behavior of flyash, red mud and mica particles reinforced Al7075 alloy hybrid metal composites*, Manuf. Rev. 9(11). doi: 10.1051/mfreview/2022009
23. Ganiger, S.S., Sakri, M., Nagaral, M., et al. (2021), *Microstructural evolution and mechanical behavior of 90 micron sized B$_4$C particulates reinforced Al2219 alloy composites*, Mater. Today: Proc. 45(Part 7): 7138-7142. doi: 10.1016/j.matpr.2021.02.026
24. Shashidhar, S., Vijaya Kumar, P., Shantharaja, M., et al. (2018), *Processing, microstructure and tensile behavior of nano B$_4$C particulates reinforced Al2219 alloy composites*, Mater. Today: Proc. 5(11)(Part 3): 25158-25164. doi: 10.1016/j.matpr.2018.10.317
25. Veeresha, G., Manjunatha, B., Bharath, V., et al. (2022), *Synthesis, microstructural characterization, mechanical, fractographic and wear behavior of micro B$_4$C particles reinforced Al2618 alloy aerospace composites*, Frattura ed Integrità Strutturale, 16(62): 385-407. doi: 10.3221/IGF-ESIS.62.27
26. Dharshan, K., Raju, T.N., Nagaral, M., et al. (2022), *Microstructure, tensile and impact behaviour of Si$_3$N$_4$ particles reinforced Al2024 matrix composites*, Mater. Today: Proc. 52(Part 3): 1499-1503. doi: 10.1016/j.matpr.2021.11.224
27. Nagaral, M., Pai, R.K., Auradi, V., et al. (2021), *Effect of micro graphite particles on the microstructure and mechanical behavior of aluminium 6061 (Al-Mg-Si) alloy composites developed by novel two step casting technique*, J Metals, Mater. Miner. 31(2): 38-45. doi: 10.55713/jmmm.v31i2.1046
28. Balaraj, V., Kori, N., Nagaral, M., Auradi, V. (2021), *Influence of Al$_2$O$_3$ and B$_4$C particles addition on the mechanical characterization of Al6061 alloy hybrid metal composites*, Int. J Veh. Struct. Syst. 13(5): 1-8. doi: 10.4273/ijvss.13.5.14
29. Harti, J.I., Prasad, T.B., Nagaral, M., et al. (2021), *Microstructure, mechanical behavior and tensile fractography of 90-micron-sized titanium carbide particles reinforced Al2219 alloy die cast metal composites*, J Fail. Anal. Prevent. 21(3): 631-639. doi: 10.1007/s11668-020-01107-1
30. Nagaral, M., Shivananda, B.K., Jayachandran, et al. (2016), *Effect of SiC and graphite particulates addition on wear behaviour of Al2219 alloy hybrid composites*, IOP Conf. Ser.: Mater. Sci. Eng. 149(1): 012108. doi: 10.1088/1757-899X/149/1/012108
31. Raksha, M.S., Basavalingappa, A., Nagaral, M., et al. (2024), *Impact of micro graphite particles addition on the mechanical behavior of Al2011 alloy metal composites*, Eng. Rep. 6(4): e12746. doi: 10.1002/eng2.12746
32. Namdev, N., Vishwanathaiah, M.K., Nagaral, M., et al. (2024), *A review on processing and properties of aluminum based metal matrix composites*, Braz. J Devel. 10(5): e69389. doi: 10.34117/bjdv10n5-009
33. Kumar, N., Vasanth Kumar, H.S., Hemanth Raju, T., et al. (2022), *Microstructural characterization, mechanical and Taguchi wear behavior of micro-titanium carbide particle-reinforced Al2014 alloy composites synthesized by advanced two-stage casting method*, J Bio- Tribo-Corr. 8(4): 109. doi: 10.1007/s40735-022-00709-6
34. Veeresha, G., Manjunatha, B., Nagaral, M., et al. (2022), *Synthesis and wear behavior of varying particle sized B$_4$C rein-*

forced Al2618 alloy composites, Mater. Phys. Mech. 50(3): 373-387. doi: 10.18149/MPM.5032022_2

35. Ganiger, S.S., Sakri, M., Nagaral, M., Auradi, V. (2023), *Microstructural characterization and wear behavior of varying weight percentages of boron carbide reinforced Al2219 alloy composites*, J Mines, Metals Fuels, 71(12A): 291-296. doi: 10.18311/jmmf/2023/43188
36. Bharath, V., Auradi, V., Nagaral, M., et al. (2021), *Impact of alumina particulates addition on hardness and wear behaviour of 2014 Al metal matrix composites by vortex method*, IOP Conf. Ser.: Mater. Sci. Eng. 1013(1): 012018. doi: 10.1088/1757-899X/1013/1/012018
37. Mydur, K., Kumar, M., Nagaral, M., et al. (2023), *Microstructure, physical, tensile and wear behaviour of B_4C particles reinforced Al7010 alloy composites*, Manuf. Rev. 10: 3. doi: 10.1051/mfreview/2023001
38. Anjan Babu, V.A., Saravanan, R., Raviprakash, M., et al. (2022), *Microstructural characterization and wear behavior of 12 wt% of boron carbide reinforced Al2030 alloy composites*, Mater. Today: Proc. 52(Part 3): 439-444. doi: 10.1016/j.matpr.2021.09.098
39. Ali, Z., Muthuraman, V., Rathnakumar, P., et al. (2023), *Influence of B_4C particle size on the mechanical behavior of A356 aluminium composites*, Res. Eng. Struct. Mater. 9(2): 527-540. doi: 10.17515/resm2022.542ma1004tn
40. Kambaiah, R., Suresh, R., Nagaral, M., et al. (2024), *Mechanical-wear behavior and microstructure analysis of Al2214 alloy with B_4C and graphite particles hybrid composites*, Eng. Rep. 6 (10): e12876. doi: 10.1002/eng2.12876
41. Madhu, D., Patil, S., Nagaral, M., et al. (2024), *Synthesis and tensile characterisation of B_4C particles reinforced Al7475 (Al-Zn) alloy composites*, J Mines, Metals Fuels, 72(3): 251-262. doi: 10.18311/jmmf/2024/43745
42. Angadi, S.B., Kumar, S., Nagaral, M., et al. (2025), *Effect of ceramic boron carbide particles addition on the mechanical and microstructural characteristics of Al7020 alloy composites*, Mech. Adv. Compos. Struct. 12(1): 169-180. doi: 10.22075/macs.2024.33857.1655
43. Krishnappa, A., Ramesh, S., Bharath, V.M., et al. (2025), *Effect of hybrid nano particle reinforcements on fractographic, mechanical and wear behavior of Al6061 alloy composites, developed by ultrasonic assisted stir casting technique*, Frattura ed Integrità Strutturale, 19(71): 285-301. doi: 10.3221/IGF-ESIS.71.21
44. Shetty, S.K., Kumar, V.R., Nayak, M., et al. (2024), *Influence of electroless copper coated B_4C particles addition on the hardness, density and wear behavior of Al2025 alloy composites*, J Bio- Tribo-Corr. 10(4): 111. doi: 10.1007/s40735-024-00916-3