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Research Article

Mechanical and fractography behavior of nano and micro boron carbide particles reinforced Al2014 alloy composites for aerospace applications

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Abstract

Nano- and micro particle-reinforced aluminum matrix composites are promising materials for the aerospace and automotive industries. These composites exhibit high strength and specific modulus with low density. In this study, the authors looked into how adding boron carbide (B4C) in nano and micron sizes altered the mechanical properties of Al2014 alloy composites. Using a novel two-stage casting method, composites of Al2014 alloy were synthesized with 3 and 6 wt.% of B4C, respectively, using particles with sizes of 200 nm and 25 microns. Microstructural analysis using SEM and EDS was performed on Al2014 alloy with nano- and micron-sized B4C composites. Additionally, studies of density, mechanical properties, and fractography were conducted to understand the impact of particle size on the behavior of the Al2014 alloy. Elemental presence was verified by EDS spectra, and microstructural analysis of the Al2014 alloy showed a regular distribution of particles. A minor reduction in elongation occurred, accompanied by enhancements in all other mechanical parameters with the addition of nano- and micron-sized B4C. Moreover, in comparison to micron-sized particle-reinforced composites, the Al2014 alloy containing 3 and 6 wt.% of 200 nm B4C exhibited markedly superior hardness, ultimate strength, yield strength, and compressive strength.

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1. Introduction

During For aircraft, automotive, civil development, and current gadget applications, high-quality, rigid materials are needed [1, 2]. This enabled composite material enhancement. Composite materials are macroscopic combinations of two or more materials having a comprehensible interface [3-5]. Composites are employed for many uses due to their mechanical, thermal, tribological, and other properties [5-8]. Modern materials seek towards property parity for a specific application. It is proposed that aluminum metal matrix composites (AMCs) replace monolithic general materials in a variety of applications [9, 10], including ferrous and nonferrous alloys and titanium (Ti) alloys. When designing systems for widespread implementation, AMCs are utilized as alternatives to conventional materials; therefore, the entire system must be updated in order to achieve weight and volume reductions [11]. Particle-reinforced aluminum matrix composites (PAMCs) incorporate ceramics in the form of oxides, carbides, or borides, including Al_2O_3, TiB_2, TiO_2, SiC, TiC, and B_4C, among others [12-15]. When compared to the unenhanced matrix, particle-reinforced metal composites demonstrate enhanced performance in terms of wear resistance, structural efficiency, and regulation of physical parameters including density and coefficient of thermal extension (CTE). These improvements ultimately lead to more effective implementation of design concepts [16]. PAMCs are attractive due to the aforementioned characteristics and the inexpensiveness of fortifications. In addition, extensive interfacial reactions, microstructural heterogeneity, fiber-to-fibre contact, and fibre degradation that are typical of MMCs can be circumvented. When comparing PAMCs to un-strengthened materials, isotropic properties such as increased strength and rigidity are observed. Al2014 is an alloy of moderate strength and low density. The alloy is fortified with B_4C particles measuring nanometers and micrometers in size in order to augment its oxidizing traits.

The specifications of MMC components are critical for their effective production, functionality, and characteristics. Considerable attention is devoted to the structure and behavior of the interface region in the fundamental study of MMCs. Numerous investigations employed powder metallurgy (PM), liquid state [17, 18], and semisolid state methodologies to fabricate a variety of Al alloy composites through the incorporation of SiC, Al_2O_3, B_4C, and graphite particles [19, 20]. Spray co-deposition, stir casting, squeeze casting, and liquid metal infiltration are a few of the innovative fabrication techniques that were utilized to create MMC materials [21, 22]. Stir casting, alternatively referred to as the vortex technique, is the most straightforward and economical among these methods due to its capacity to manufacture components with a high degree of flexibility and near-net shape at a minimal expense.

Moreover, the reinforcement's dimensions and configuration significantly impact the enhancement of the characteristics exhibited by metal matrix composites. Furthermore, ancillary operations such as rolling, forming, and extrusion contribute to the enhancement of the grain through refinement. Despite the fact that numerous Al alloys have been utilized as matrix ingredients, the literature review indicates that aluminum alloys continue to be the preferred option due to the aforementioned factors. Fork hinges, bulkheads, wing root connections, and mounting brackets are a few of the numerous aerospace applications for Al2014 alloy. The incorporation of B_4C particles at the nano-scale and micro-scale into Al2014 alloy can significantly enhance its strength, a critical attribute in aerospace applications where weight is invariably restrictive. In numerous applications, the condensed cross-sectional area of these high-tech metal composites provides an alternative material option. By decreasing the cross-sectional area of the component, its weight can be decreased, leading to improved efficiency [23].

Al-boron carbide composites play a significant role in advanced industrial applications where the demand for lightweight materials is increasing. Based on the aforementioned discoveries, Al2014 alloys containing B_4C composites measuring 200 nanometers and 25 microns in size were fabricated at weight percentages of variable 3 and 6 wt.%. Hardness, ultimate yield, ductility, and compressive strengths of Al2014 alloy were compared to those of nano and micro composite materials. In the present work, an attempt has been made to develop 3 and 6 wt.% of nano and micro boron carbide particles reinforced Al2014 alloy composites. To overcome the challenges about wettability and having proper distribution of nano and micro particles during development of metal composites using metal and ceramic reinforcements, a novel two stage stir casting method was adopted in the present study.

2. Experimental Details

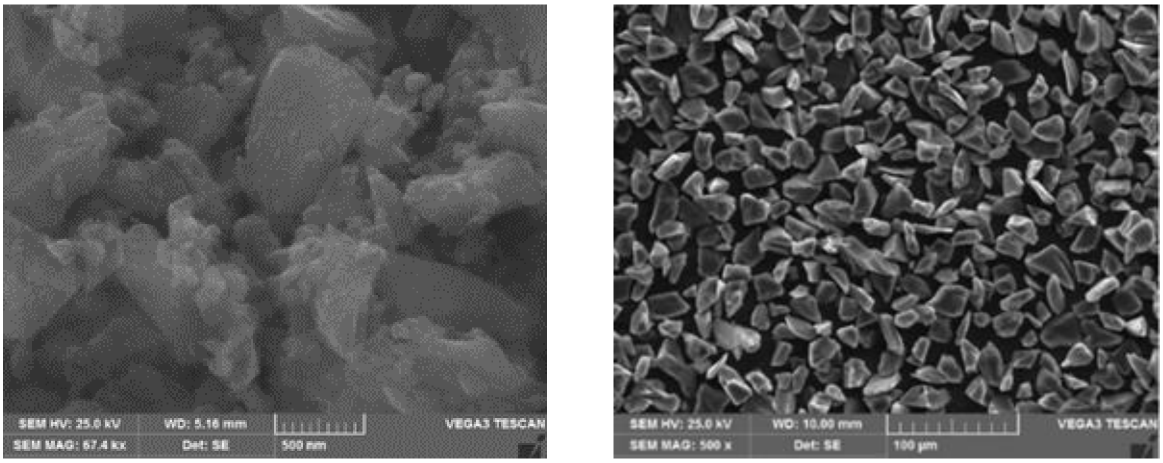
2.1 Matrix and Reinforcement Materials

The stir casting method was used to create nano- and micro-metal composites containing 3 and 6 weight percent of B_4C particles, respectively. As can be seen in Fig. 1 (a-b), an Al2014 alloy was used as the main material, and B_4C particles in two different sizes (200 nm and 25 m) were added as reinforcements. The elements and proportions that make up Al2014 are listed in Table 1.

Table 1. Chemistry of Al2014 alloy by weight %

Zn	Mg	Si	Fe	Cu	Ti	Mn	Cr	Al
0.19	0.64	0.72	0.20	4.50	0.06	0.83	0.01	Balance

The synthesis of Al2014 alloys containing B_4C composites containing 3% by weight of 200 nanometer particles was accomplished via liquid metallurgy. For liquefaction, a specific quantity of Al2014 compound ingots is inserted in the furnace. Aluminum alloys have a melting point of 660 °C. The temperature at which the substance liquefied was raised to 750 degrees Celsius. The liquid is subsequently degassed using solid hexachloroethane (C_2Cl_6) [24] for three minutes. In order to generate a vortex, the liquid metal is mixed using a Zr-coated impeller made of tempered steel. At 300 revolutions per minute, the impeller will be plunged to a depth of sixty percent of the liquid metal's height as seen from the exterior of the liquefy.



(a) (b)

Fig. 1. SEM micro-photographs of (a) 200 nano-meter (b) 25-micron sized B_4C particles

Additionally, 3% by weight of B_4C particulates were heated to 500°C in a heater prior to introduction into the vortex. Until the interface communications between the support particles and the network reach a state of equilibrium, stirring will continue. Subsequently, the Al2014 - 3 weight percent B_4C composite is shaped into a durable cast iron object measuring 120 mm in length and 15 mm in diameter. In a comparable fashion, composites were produced that were reinforced with B_4C particles, including nanocomposite at 6% by weight and 25 micron-sized composites at 3% and 6% by weight. Furthermore, based on the microstructural analysis, mechanical properties were assessed in accordance with ASTM standards. In the present research composites were produced by a novel two stage casting method, in this process the particles are included in the molten metal two times rather than including at a time. This helps in improving the wettability between the matrix and particles by avoiding agglomeration.

The cast specimen is subjected to microstructural analysis using a TESCAN VEGA 3 LMU instrument (Czech Republic) to determine the uniform distribution of reinforcing particles within the Al2014 alloy. The structures of Al2014 alloy and Al2014-reinforced composites containing 3% and 6% B_4C by weight are visualized via micrographs. The microstructure specimen has the following dimensions: 15 mm in diameter and 5 mm in height. Specimen surface polishing is performed with grain papers of 240, 600, and 800. Distilled water is used to remove any residual dirt or contaminants from the samples following the polishing process. Keller's reagent [25] is used to etch the specimens, imparting a unique and discernible surface.

Fig. 2. Al-Boron Carbide composites

Fig. 3. Tensile test specimen

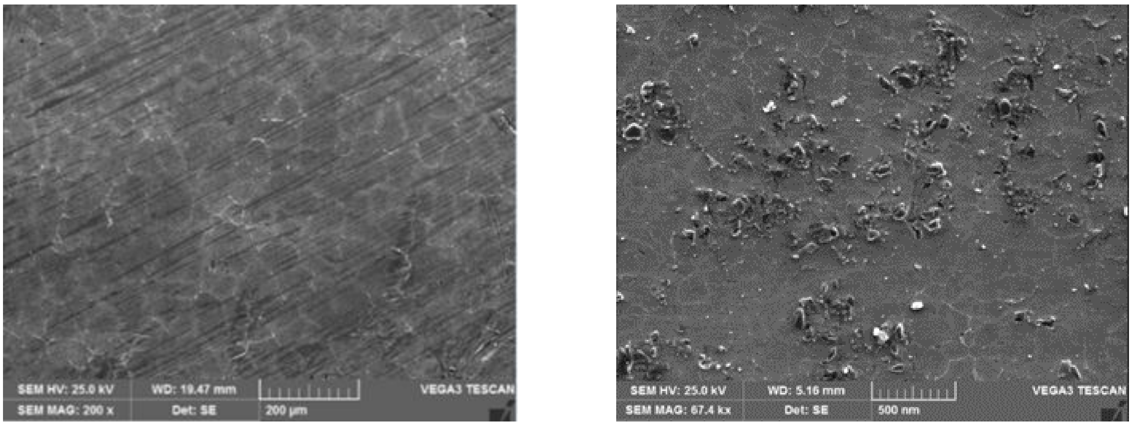
The densities of Al2014 alloy and B_4C composite were measured. Density estimations were calculated using the conventional weight process and the law of mixture and then compared to experimental densities. To perform the hardness test, the specimen must be machined in compliance with ASTM standard E10 [26]. A Brinell hardness tester is used to assess the material's hardness (Krystal Industries, Ichalkaranji). After polishing, the specimen's surface is as good as new. A 5 mm ball indenter loaded with 250 kg creates a depression.

Tensile specimens assessed according to ASTM standard E8 [27, 28] evaluate Al2014 alloy and Al2014 with varied nano and micro B_4C composite percentages. Tensile strength, Al2014 alloy-reinforced composite behavior under unidirectional tension, and uniform distribution were assessed using an Instron computer-measured tensile machine. Total length is 104 mm, gauge length is 45 mm, and gauge diameter is 9 mm. Tensile testing evaluates composites and cast alloys under stress. The standard compression strength test is ASTM E9 [29]. Figure 3 shows the tensile specimen.

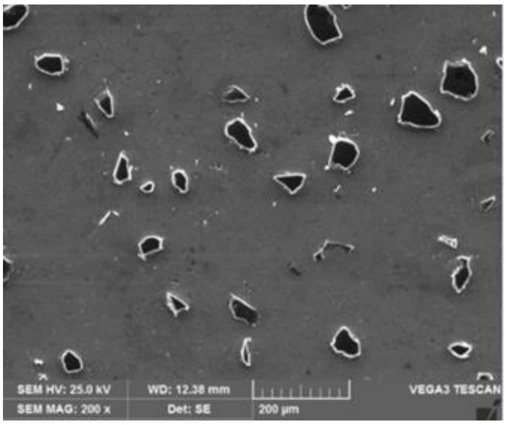
3. Results and Discussion

3.1 Microstructural Characterization

Figure 4 (a) shows the as-cast Al2014 alloy microstructure without B_4C particles. Scanning Electron Microscope (SEM) images 4b and 4c shows Al2014 alloys with 6% 200 nm B_4C and 6% 25-micron B_4C particles reinforced composites. The grain boundaries in Al2014 are clean and easily visible. If the micrograph shows a smooth, pore-free surface, casting is a suitable method for producing composites. These images show a clear and consistent dispersal of particles. The micrographs all show that the B_4C particles are firmly adhered to the Al2014 alloy. The enhanced properties of composites made from the Al2014 alloy benefit from this strong bonding. The distribution of particles plays an important role on the properties metal composites.



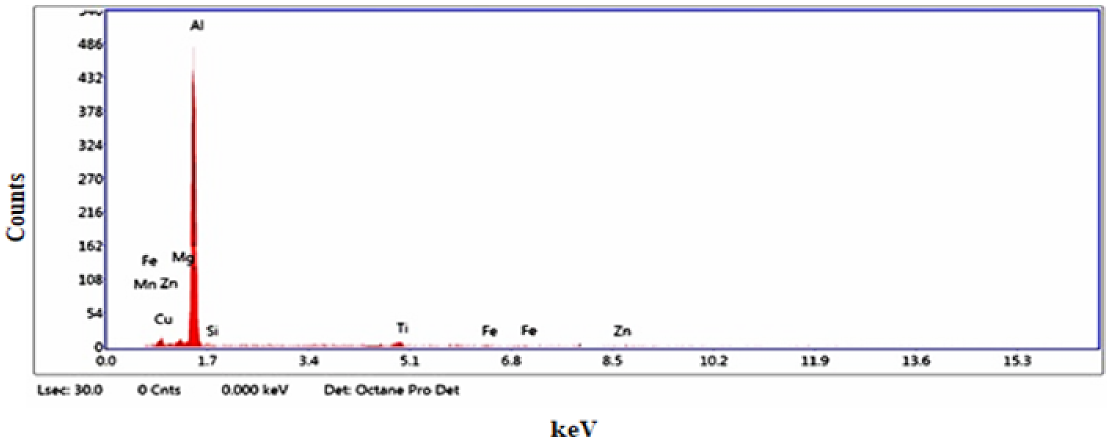
(a) (b)



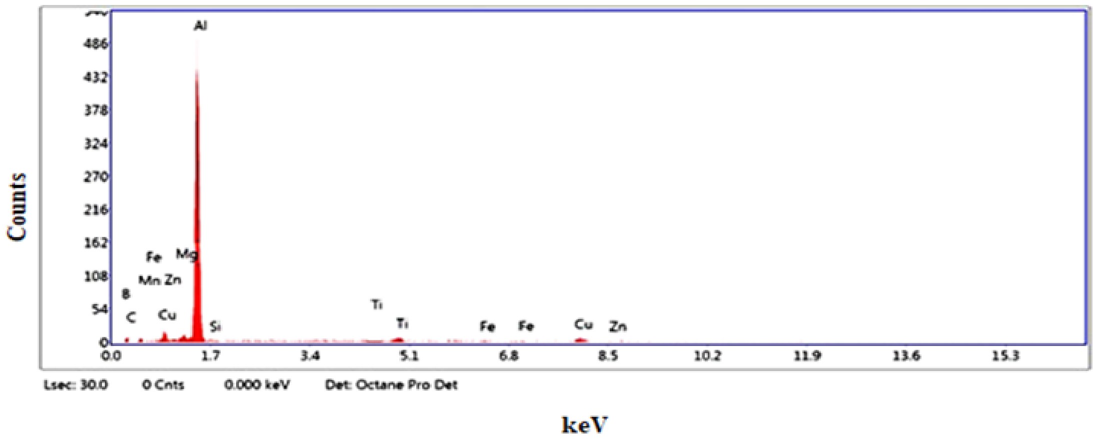
(c)

Fig. 4. (a-c) SEM of (a) Al2014 metal (b) Al2014-6 wt.% of 200 nm B_4C (c) Al2014-6 wt.% of 25 micron B_4C composites

The distribution helps in load transfer from the matrix to the particles, thus particles act as a barrier for the material deformation and reduces the strain development. Fig. 5 shows energy dispersal spectra for pure Al2014 and Al2014 doped with 6 wt. % 200 nm B_4C. (a, b). Fig. 5 (a) shows the principal Al and Cu alloying elements in aluminum 2XXX series alloys. In Fig. 5 (b), boron (B) and carbon (C) atoms appear alongside the Al peaks, showing B_4C in the produced Al2014 alloy with B_4C composites.



(a)



(b)

Fig. 5. (a-b) EDS of (a) Al2014 (b) Al2014-6 wt. % of 200 nm B_4C composite

3.2 Density Measurements

Fig. 6 compares predicted and experimental densities of Al2014 and Al2014 with 3–6% 200 nano-meter and 25-micron B_4C composites. Figure 6 illustrates that as weight percentages increase and boron carbide particle sizes decrease, the curve for both theoretical and experimental density of the composites decreases linearly. B_4C particles are lighter than Al2014 alloy, reducing composite density. In contemporary investigations, particle size decreases increase densities, which are closer to theoretical values. This may indicate good composite castings. Al2014 and Al22014 with 6% by weight of 200 nm and 25-micron B_4C composites have experimental densities of 2.692 and 2.682 g/cm^3, respectively.

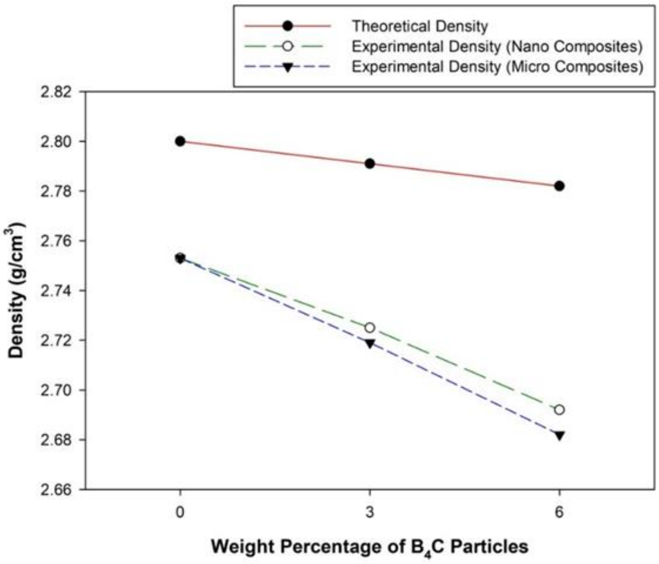


Fig. 6. Comparison of densities of Al2014 alloy with nano and micro B_4C composites

3.3 Hardness Measurements

In this study, Brinell hardness of Al2014 with micro and nano B_4C at 3 and 6 wt.% were studied. Each sample has three trials, and Fig. 7 shows the average values. Fig. 7 shows that composite hardness increases linearly with B4C concentration. BHN is 63.89 for a conventional Al2014 alloy, but 85.62 and 81.49 for alloys with 6 wt. % 200 nm and 25-micron B4C reinforced composites.

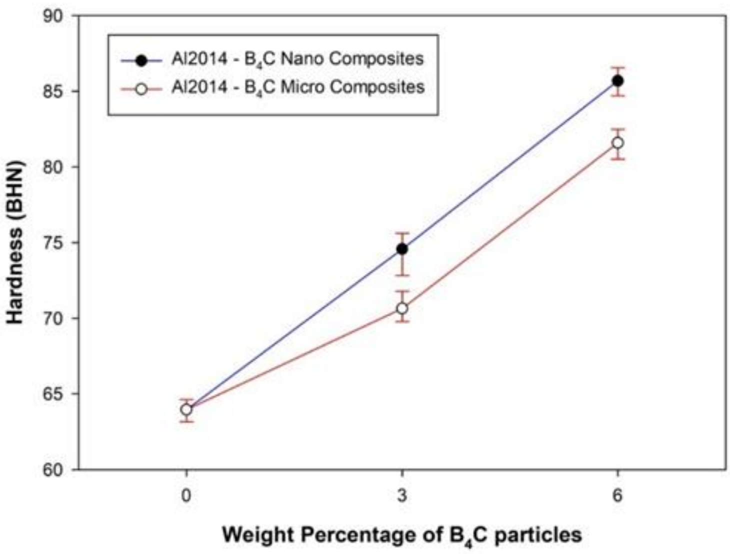


Fig. 7. Comparison of hardness of Al2014 alloy with nano and micro B_4C composites

Hardness of composites increases by 34% and 27.5% at 200 nm and 25 µm, respectively. As B_4C composites shrink, hardness increases, with the Al2014 alloy with 6% 200 nm composites improving the most. B_4C makes Al2014 matrix harder. Strengthening particles distribute alumina particles throughout the matrix, making it stronger and stiff. Milling down the particle size increases the reinforced composite's hardness (Fig. 7). Many factors contribute to this toughness. Most notably, 200 nm particles have a greater interface than 25-micron reinforced particles, increasing toughness. Smaller particles have a higher surface area than 25-micron particles in a composite. There are different perspectives on this situation. Smaller particles reinforced composites interact better than 25-micron ones. Compared to bigger particles, smaller particles provide more surface area in the composite they reinforce.

3.4 Tensile Properties

Tensile tests on the base Al2014 alloy and Al2014 reinforced with B_4C composites of 3 and 6 weight percent, respectively, with 200 nm and 25-micron B_4C particles, assess UTS, YS, and elongation as a percentage. Fig. 8 indicates that Al2014 alloy composite UTS increases linearly with B_4C content by decreasing particle sizes. The graph clearly indicates that hard B_4C particles reinforce the Al2014 matrix, increasing UTS. The UTS for pure Al2014 alloy is 205.97 MPa, however with 6 wt. % of 200 nm and 25-micron B4C reinforced composites, it rises to 267.65 and 258.33 MPa. The UTS of composites improved by 200 nm nano composites is 29.94%, whereas 25 µm improves it by 25.42%. UTS are maximum in Al2014 alloy doped with 6% 200 nm B_4C composites. Reinforcing particles boost a base alloy's tensile strength, making it more stress-resistant. Since B_4C particles are stiffer than Al2014 matrix, they first experience a lot of stress. The reinforcement's geometric limitations improve composite work hardening when B_4C particles are added to the matrix alloy [30, 31]. Orwan effect, where dislocations interact with non-shear-able B_4C, increases B_4C reinforced composite strength. As revealed by hardness data, particle addition gradually strengthens, therefore expected tensile strength increases should be represented as weight percentages [32].

Fig. 9 shows how increasing the weight percent of B_4C and decreasing the particle sizes leads to a linear increase in the YS of the Al2014 alloy composites. The graph shows that YS is enhanced in the Al2014 matrix following reinforcement with hard B_4C particles. A standard Al2014 alloy has a YS of 167.93 MPa, while the same alloy with 6 wt.% of 200 nm and 25-micron sized B_4C reinforced composites has YS values of 227.71 MPa and 219.10 MPa. Composites with particles of 200 nm and 25 µm show a 35.73 percent and 30.47 percent increase in yield strength, respectively. Al2014 alloy containing 6 wt. % of 200 nm sized B_4C composites shows the highest YS.

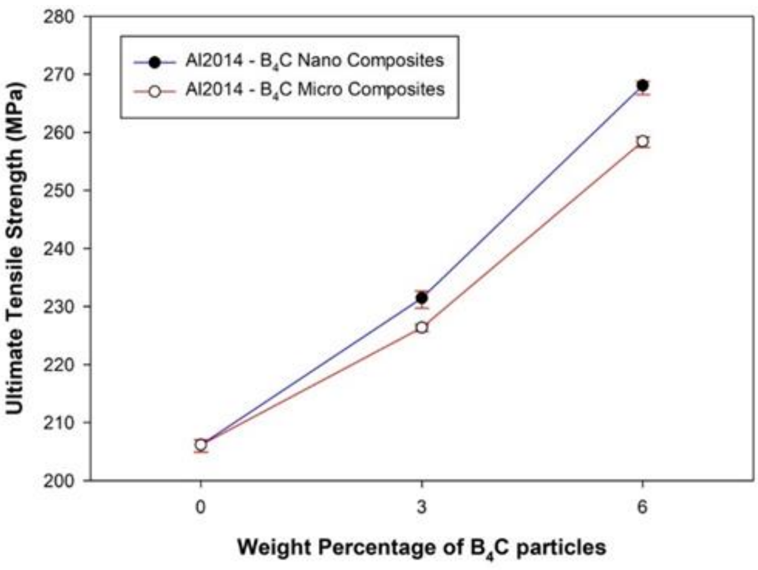


Fig. 8. Al2014 alloy ultimate strength vs nano and micro B_4C composites

Figures 8 and 9 illustrate the ultimate tensile strength (UTS) and yield strength (YS) of composites containing 3 and 6 wt.% B_4C, as well as the influence of particle size on these properties. Figures 8 and 9 illustrate that an increase in B_4C weight percentage results in a reduction of composite particle size, while enhancing ultimate tensile strength (UTS) and yield strength (YS). Composites with diverse compositions and 25 µm variable particles demonstrated that the composite containing Al2014 with 6 wt.% B_4C particles of 200 nanometer size had the highest tensile strength. A molecular-level elucidation of the matrix and the robust cohesion of particles. It seems that minuscule particles are closely associated with the matrix. Fig. 10 shows that composites with more B_4C by weight had better elongation throughout particle sizes. The graph demonstrates that the composite's elongation falls linearly as B_4C weight increases compared to the cast Al2014 matrix. The inclusion of hard particles in the soft matrix reduces the ductility and makes the materials as brittle. This brittle behavior of materials is not good for industrial applications, however with increased strength and ductility up to 9% are suitable for industrial applications.

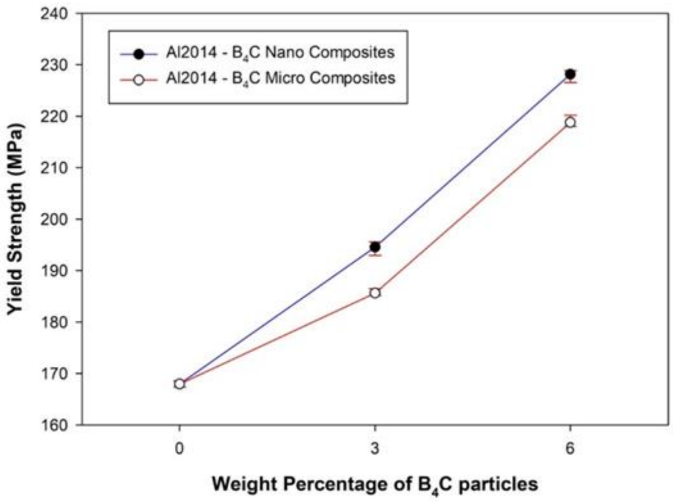


Fig.9. Al2014 alloy yield strength vs. nano and micro B_4C composites

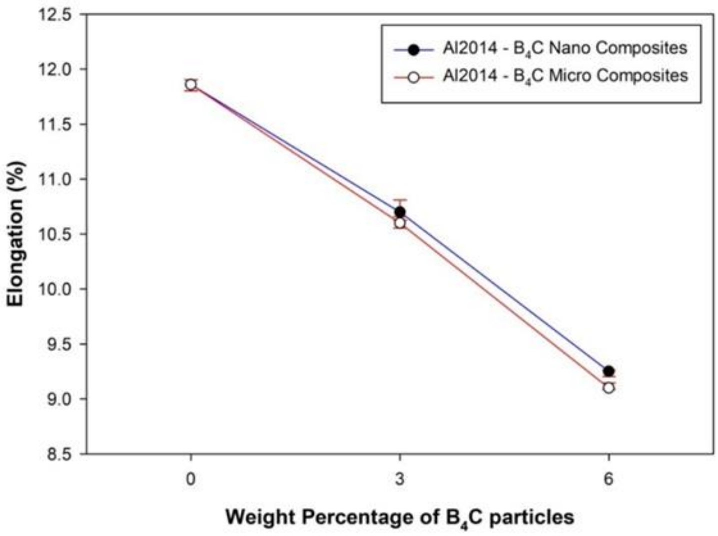


Fig. 10. Comparison of ductility of Al2014 with B_4C composites

3.5 Compression Strength

Al2014 alloys with 3 and 6 weight percent B_4C reinforcement and 200- to 25-micron particles are tested for compression strength. Fig. 11 shows that Al2014 alloy composite compressive strength rises linearly with B_4C wt.% at decreasing particle sizes. The graph shows that hard B_4C particles boost compression strengths in an Al2014 matrix. Al2014 alloy with 6 wt.% 200 nm and 25-micron B_4C reinforced composites has compression strengths of 775.04 MPa and 730.64 MPa, respectively, while its strength is 568.26 MPa. Nano and micro particles increase composite compressive strength by 36.38 and 28.57 percent. Compression strength is highest in Al2014 alloy doped with 6 wt.% nano B_4C composites. A composite composed of fine particles has superior compression strength compared to one with intermediate particle sizes or an unreinforced alloy. The augmentation of particle quantity and the reduction of inter-particle spacing at varying weight percentages of B_4C, when particle size is significant, may elucidate this phenomenon [35]. With more particles blocking dislocations, hardening is faster and compression plastic deformation is reduced [36].

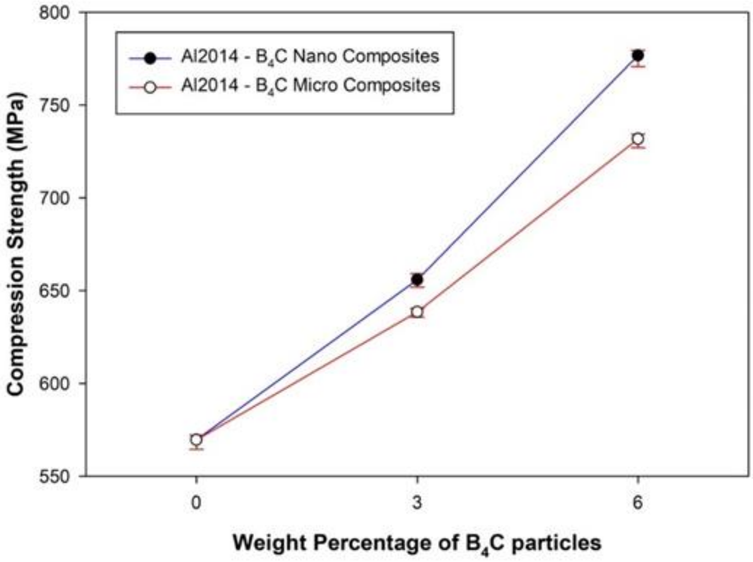
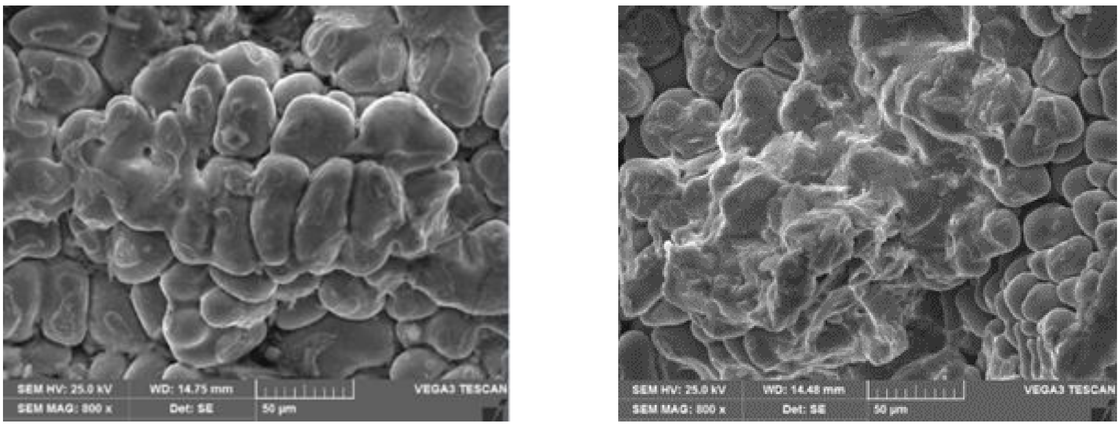


Fig.11. Al2014 alloy compressive strength vs. nano and micro B_4C composites

3.6 Tensile Fractography

Tensile fracture studies were done to elucidate the alterations in the composite's fracture behavior following reinforcement with B_4C particles. The fractures in Fig. 12 (a) of the Al2014 are larger and more homogeneous, indicating its malleability. The fracture of a composite containing 6 wt.% B_4C nano-composites of 200 nm and 25-micron sizes is depicted in Fig. 12 (b, c). The presence of minor ductile dimples in the matrix alloy indicates that minimal plastic deformation has transpired following the incorporation of B_4C particles. Additionally, particle de-cohesion between the Al and particle was evident in scanning electron micrographs of the fracture surfaces of 200 nm B_4C composites. The incorporation of hard particles into the Al matrix converts the ductile mode fracture to the brittle mode. Further, this brittle fracture is more in the case of micron sized particles reinforced composites compared to the nano sized particles.



(a) (b)

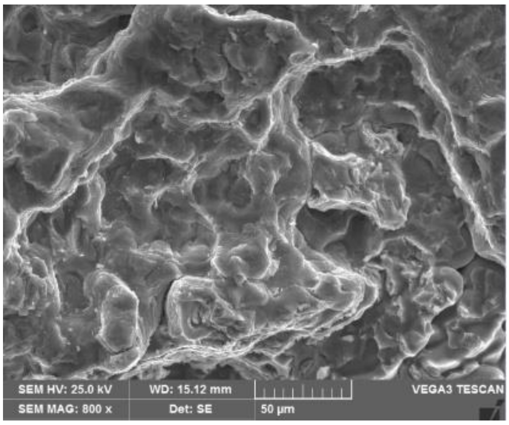


Fig. 12. Tensile fractured surfaces (a) Al2014 alloy (b) Al2014 – 6 wt. % of 200 nm B_4C (c) Al2014 – 6 wt. % of 25 micron B_4C composites

4. Conclusions

The current study has resulted in the following conclusions:

- The Al2014 alloy, incorporating nano and micron-sized B_4C particles in metal matrix composite at 3 and 6 wt. percent, was effectively produced using the stir casting method.
- The SEM micrographs demonstrate that the B_4C particles are evenly distributed throughout the Al2014 alloy. The EDS analysis revealed the presence of B_4C particles in engineered composites.
- UTS, YS, and compression strength, as well as hardness, have all increased in B_4C reinforced composites, while ductility has decreased slightly.
- The hardness, tensile, and compressive behaviors of Al2014 alloy reinforced with 200 nm B_4C nanoparticles were significantly superior to those of 25-micron B_4C reinforced composites.
- Fractographic analysis of surfaces using a SEM demonstrated the distinct fracture mechanisms of the base Al2014 alloy and its resultant composites.
- A composite made from Al2014 with 6% nano B_4C particles exhibited 29.9% and 35.7% increases in ultimate and yield strengths, respectively, compared to the original Al2014 alloy. Thus, these composites can reduce weight and cross-sectional area in the manufacture of aeronautical components.

References

[1] Suresh S, Moorthi NSV, Vettivel SC, Selvakumar N, Jinu GR. Effect of graphite addition on mechanical behavior of Al6061-TiB2 hybrid composites using acoustic emission. Mater Sci Eng A. 2014;612:16-27. https://doi.org/10.1016/j.msea.2014.06.024

[2] Kumar NGS, Shivashankar GS, Basavarajappa S, Suresh R. Some studies on mechanical and machining characteristics of Al2219/n-B4C/MoS2 nano hybrid metal matrix composites. Measurement. 2017;107:1-11. https://doi.org/10.1016/j.measurement.2017.05.003

[3] Krishna UB, Vasudeva B, Auradi V, Nagaral M. Effect of percentage variation on wear behaviour of tungsten carbide and cobalt reinforced Al7075 matrix composites synthesized by melt stirring method. J Bio Tribo-Corros. 2021;7(3):1-8. https://doi.org/10.1007/s40735-021-00528-1

[4] Kumar GBV, Chowdary GV, Vamsi MS, Reddy KJ, Nagaral M, Naresh K. Effects of addition of titanium diboride and graphite particulate reinforcements on physical, mechanical and tribological properties of Al6061 alloy based hybrid metal matrix composites. Adv Mater Process Technol. 2021:1-18. https://doi.org/10.1080/2374068X.2021.1904370

[5] Zheng R, Chen J, Zhang Y, Ameyama K, Ma C. Fabrication and characterization of hybrid structured Al alloy matrix composites reinforced by high volume fraction of B4C particles. Mater Sci Eng A. 2014;601:20-8. https://doi.org/10.1016/j.msea.2014.02.032

[6] Bharath V, Auradi V, Nagaral M, Boppana SB. Experimental investigations on mechanical and wear behaviour of 2014Al-Al2O3 composites. J Bio Tribo-Corros. 2020;6(2):1-10. https://doi.org/10.1007/s40735-020-00341-2

[7] Sekar K, Allesu K, Joseph MA. Effect of heat treatment in tribological properties of A356 aluminium alloy reinforced with Al2O3 nano particles by combination effect of stir and squeeze casting method. Appl Mech Mater. 2014;592-594:968-71. https://doi.org/10.4028/www.scientific.net/AMM.592-594.968
[8] Umanath K, Selvamani ST, Palanikumar K, Raphael T, Prashanth K. Effect of sliding distance on dry sliding wear behavior of Al6061-SiC-Al2O3 hybrid composite. In: Proc Int Conf Adv Mech Eng. 2013. p. 749-75. https://doi.org/10.1016/j.compositesb.2013.04.051
[9] Ramchandra M, Abhishek A, Siddeshwar P, Bharathi V. Hardness and wear resistance of ZrO2 nanoparticle reinforced Al nanocomposites produced by powder metallurgy. Procedia Mater Sci. 2015;10:212-9. https://doi.org/10.1016/j.mspro.2015.06.043
[10] Nagaral M, Kalgudi S, Auradi V, Kori SA. Mechanical characterization of ceramic nano B4C-Al2618 alloy composites synthesized by semi solid state processing. Trans Indian Ceram Soc. 2018;77(3):1-4. https://doi.org/10.1080/0371750X.2018.1506363
[11] Dhanalakshmi P, Mohansundararaju N, Venkatkrishnan PG. Preparation and mechanical characterization of stir cast hybrid Al7075-Al2O3-B4C metal matrix composites. Appl Mech Mater. 2014;592-594:705-10. https://doi.org/10.4028/www.scientific.net/AMM.592-594.705
[12] Devnani GL, Sinha S. Effect of nano fillers on the properties of natural fiber reinforced polymer composites. Mater Today Proc. 2019;18(3):647-54. https://doi.org/10.1016/j.matpr.2019.06.460
[13] Narimani M, Lotfi B, Sadeghian Z. Evaluation of the microstructure and wear behavior of AA6063-B4C/TiB2 mono and hybrid composite layers produced by friction stir processing. Surf Coat Technol. 2016;285:1-10. https://doi.org/10.1016/j.surfcoat.2015.11.015
[14] Pakdel A, Witecka A, Rydzek G, Awang Shri DN, Nicolosi V. A comprehensive analysis of extrusion behavior, microstructural evolution and mechanical properties of 6063 Al-B4C composites produced by semisolid stir casting. Mater Sci Eng A. 2018;721:28-37. https://doi.org/10.1016/j.msea.2018.02.080
[15] Murthy IN, Rao DV, Rao JB. Microstructure and mechanical properties of aluminium fly ash nano composites made by ultrasonic method. Mater Des. 2012;35:55-65. https://doi.org/10.1016/j.matdes.2011.10.019
[16] Shashidhar S, Kumar PV, Shivananda HK, Nagaral M. Processing, microstructure, density and compression behavior of nano B4C particulates reinforced Al2219 alloy composites. Int J Adv Technol Eng Explor. 2018;5(46):350-5. https://doi.org/10.19101/IJATEE.2018.546015
[17] El-Kady O, Fathy A. Effect of SiC particle on the physical and mechanical properties of extruded Al matrix composites. Mater Des. 2014;54:348-53. https://doi.org/10.1016/j.matdes.2013.08.049
[18] Ramnath BV, Elanchezhian C, Jaivignesh M, Rajesh S, Parswajinan C, Ghias ASA. Evaluation of mechanical properties of aluminium alloy-alumina-boron carbide metal matrix composites. Mater Des. 2014:332-8. https://doi.org/10.1016/j.matdes.2014.01.068
[19] Matti S, Shivakumar BP, Shashidhar S, Nagaral M. Dry sliding wear behavior of mica, fly ash and red mud particles reinforced Al7075 alloy hybrid metal matrix composites. Indian J Sci Technol. 2021;14(4):310-8. https://doi.org/10.17485/IJST/v14i4.2081
[20] Ali Z, Muthuraman V, Rathnakumar P, Gurusamy P, Nagaral M. Studies on mechanical properties of 3 wt% of 40 and 90 μm size B4C particulates reinforced A356 alloy composites. Mater Today Proc. 2022;52:494-9. https://doi.org/10.1016/j.matpr.2021.09.260
[21] Kumar R, Deshpande RG, Gopinath B, Harti J, Nagaral M, Auradi V. Mechanical fractography and worn surface analysis of nanographite and ZrO2-reinforced Al7075 alloy aerospace metal composites. J Fail Anal Prev. 2021;21:525-36. https://doi.org/10.1007/s11668-020-01092-5
[22] Bharath V, Ajawan SS, Nagaral M, Auradi V, Kori SA. Characterization and mechanical properties of 2014 aluminum alloy reinforced with Al2O3p composite produced by two-stage stir casting route. J Inst Eng India Ser C. 2019;100:277-82. https://doi.org/10.1007/s40032-018-0442-x
[23] Prasad GP, Chittappa HC, Nagaral M, Auradi V. Influence of B4C reinforcement particles with varying sizes on the tensile failure and fractography of LM29 alloy composites. J Fail Anal Prev. 2020;20(6):2078-86. https://doi.org/10.1007/s11668-020-01021-6
[24] Nagaraj N, Mahendra KV, Nagaral M. Microstructure and evaluation of mechanical properties of Al-7Si-fly ash composites. Mater Today Proc. 2018;5(1):3109-16. https://doi.org/10.1016/j.matpr.2018.01.116
[25] Dama K, Prashanth L, Nagaral M, Mathapati R, Hanumantharayagouda MB. Microstructure and mechanical behavior of B4C particulates reinforced ZA27 alloy composites. Mater Today Proc. 2017;4(8):7546-53. https://doi.org/10.1016/j.matpr.2017.07.086
[26] Hanumantharayappa AKB, Prasanna C, Ragavendra CC, Beekam CS, Boluvar LS, Nagaral M, et al. Synthesis and mechanical characterization of Si3N4 reinforced copper-tin matrix composites. J Mech Behav Mater. 2021;30(1):199-206. https://doi.org/10.1515/jmbm-2021-0020
[27] Kumar HSV, Kempaiah UN, Nagaral M, Auradi V. Impact, tensile and fatigue failure analysis of boron carbide particles reinforced Al-Mg-Si (Al6061) alloy composites. J Fail Anal Prev. 2021;21(6):2177-89. https://doi.org/10.1007/s11668-021-01265-w

[28] Nagaraj N, Mahendra KV, Nagaral M. Investigations on mechanical behaviour of micro graphite particulates reinforced Al-7Si alloy composites. IOP Conf Ser Mater Sci Eng. 2018;310(1):012131. https://doi.org/10.1088/1757-899X/310/1/012131
[29] Venkataraman V, Nagaral M. Mechanical characterization and wear behavior of aerospace alloy AA2124 and micro B4C reinforced metal composites. J Met Mater Miner. 2020;30(4):97-105. https://doi.org/10.55713/jmmm.v30i4.641
[30] Murthy BV, Auradi V, Nagaral M, Vatnalmath M, Namdev N, Anjinappa C, et al. Al2014-alumina aerospace composites: particle size impacts on microstructure, mechanical, fractography, and wear characteristics. ACS Omega. 2023;8(14):13444-55. https://doi.org/10.1021/acsomega.3c01163
[31] Kumar HSV, Revanna K, Kumar N, Sathyanarayana N, Madeva N, Manjunath GA, et al. Impact of silicon carbide particles weight percentage on the microstructure, mechanical behaviour, and fractography of Al2014 alloy composites. 2022;Article ID: 2839150. https://doi.org/10.1155/2022/2839150
[32] Bharath V, Ashita DH, Auradi V, Nagaral M. Influence of variable particle size reinforcement on mechanical and wear properties of alumina reinforced 2014Al alloy particulate composite. FME Trans. 2020;48(4):968-78. https://doi.org/10.5937/fme2004968B
[33] Basavaraja P, Nagaral M, Auradi V, Vidyashankar. Evaluation of mechanical properties of Al2219-SiC-Graphite reinforced hybrid composites. Int J Appl Eng Res. 2015;10(9):9300-3.
[34] Boppana SB, Dayanand S, Murthy BV, Nagaral M, Telagu A, Kumar V, et al. Development and mechanical characterisation of Al6061-Al2O3-graphene hybrid metal matrix composites. J Compos Sci. 2021;5(6):155. https://doi.org/10.3390/jcs5060155
[35] Fazil N, Venkataramana V, Nagaral M, Auradi V. Synthesis and mechanical characterization of micro B4C particulates reinforced AA2124 alloy composites. Int J Eng Technol UAE. 2018;7(2.23):225-9. https://doi.org/10.14419/ijet.v7i2.23.11954
[36] Manjunatha TH, Basavaraj Y, Nagaral M, Venkataramana V, Harti JI. Investigations on mechanical behavior of Al7075-nano B4C composites. IOP Conf Ser Mater Sci Eng. 2018;376(1):012091. https://doi.org/10.1088/1757-899X/376/1/012091