MATERIALS PHYSICS AND MECHANICS RESEACH ARTICLE

Submitted: November 27, 2023 Revised: December 18, 2023 Accepted: May 9, 2024

Synthesis and tensile behavior of Al7475-nano B_4C particles reinforced composites at elevated temperatures

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ABSTRACT

Materials with superior mechanical and wear properties, high strength, high stiffness, and low weight are necessary for modern technology. Mechanical characteristics of metal matrix composites are crucial to their potential use as structural materials. The current research focuses on the preparation of Al7475 alloy with 400 to 500 nm sized B_4C a composite using a liquid metallurgy technique. Al7475 alloy was used to make composites with 2, 4, 6, 8 and 10 wt. % of B_4C particles. Microstructural analysis was performed on the produced composites using SEM and EDS. Density, hardness, ultimate strength, yield strength, and elongation as a percentage were all measured as per ASTM norms. Further, tensile tests were conducted at room temperature, 50 and 100 °C elevated temperatures. SEM images showed that the boron carbide particles were evenly dispersed throughout the Al7475 alloy. EDS spectrums verified that Al7475 alloy contains boron carbide particles. By incorporating dual particles into the matrix, the density of Al alloy composites was lowered. Al7475 alloy with B4C composites exhibited superior tensile properties at room and elevated temperatures as compared to the base alloy.

KEYWORDS

Al7475 alloy • B_4C particles • microstructure • density • tensile behavior

Citation: Chandrasekhar GL, Vijayakumar Y, Nagaral M, Rajesh A, Manjunath K, Kaviti RVP, Auradi V. Synthesis and tensile behavior of Al7475-nano B_4C particles reinforced composites at elevated temperatures. *Materials Physics and Mechanics*. 2024;52(3): 44–57.
http://dx.doi.org/10.18149/MPM.5232024_5

Introduction

Similar to other composites, metal matrix composites (MMCs) consist of at least two chemically and physically different phases that are dispersed in a way that confers properties not present in either phase alone. Many scientists simply refer to these materials as "light metal matrix composites". Recent decades have seen significant progress in the development of light metal matrix composites, allowing for their deployment in the most critical applications. In a commercial setting, aluminium matrix composites (AMCs) perform admirably. Due to their low density, high strength, outstanding creep resistance, high damping capacity, and amazing dimensional stability, metal matrix nanocomposites of aluminium have been the topic of extensive research in recent years [1,2].

Aluminium and its derivatives are now in the mechanical generation stage of MMC production, having exceeded the previous lattice materials. The creation of low-cost Al-based MMCs that are reinforced with hard and delicate materials including SiC, Al_2O_3, ZrO_2, Graphite, and Mica have been a key focus of study. Boron carbide filaments and particles are widely recognized as being of exceptional quality [3]. Aluminium-ceramic multi-material composites produced using different methods are good examples of inexpensive, application-specific manufactured materials [4,5].

Metal matrix composites (MMCs) are a broad category of materials with the goal of improving many different characteristics. Although the grid can be constructed from any metal or alloy, research has focused mostly on the more easily modified mechanical properties of the lighter basic metals. Improvements in quality and reliability [6,7] have thus far been the driving forces for MMC development. By incorporating various filler components into metal grids, significant improvements can be made. As a result of these upgrades, the grids now have a higher damping limit, lighter segments, better wear resistance, warmer development, and higher temperature capacity. Metals are preferred due to their many useful qualities, including their low production cost, malleability, high heat and electrical conductivity, etc.

Since the properties of metal matrix composites (MMCs) may be modified by adding different reinforcements, they find widespread application in cutting-edge sectors including the aerospace and automotive industries. Particulate-reinforced metal composites have recently attracted attention due to their high specific strength and specific stiffness in either room temperature or increased temperature applications. Micro-structural factors of the reinforcement, such as form, size, orientation, distribution, volume, and weight, are known to have a major impact on the elastic properties of a metal matrix composite [8,9].

Aluminium alloys show great promise as matrix materials due to their high specific strength and stiffness. However, their short lifespan limits their applicability. The aerospace and automotive industries make extensive use of particulate reinforced aluminium matrix composites because of their superior mechanical and tribological properties in comparison to those of regular alloys. In order to develop high-quality, inexpensive MMCs [10,11], scientists are investigating Al-based compounds reinforced with hard and soft materials such as SiC, Al_2O_3, B_4C, ZrO_2, tungsten carbide, graphite, and mica.

The mechanical and other qualities of aluminium alloy can be improved by using ceramic particles as reinforcement, and this has been demonstrated. Most of the time, ceramics are used for the reinforcement in MMCs, and these reinforcements can be broadly classified as either continuous or discontinuous. They are known as continuous (fibre) reinforced composites and discontinuous (non-fiber) reinforced composites, respectively, for the MMCs they yield. Continuous fibres, short fibres (chopped fibres, not always the same length), whiskers, particle, and wire (only for metal) are the five main groups into which they can be further classified [12,13]. With the exception of wires, most reinforcing materials are ceramics, specifically oxides, carbides, and nitrides. These are put to use because they combine excellent strength and stiffness in both cold and hot conditions.

Mechanical properties of Al7475 MMCs reinforced with nano B_4C particles manufactured through the stir casting method are poorly understood, however. Aluminium boron carbide composites are becoming increasingly significant as lightweight materials are required for new industrial applications. In light of these findings, it is suggested that Al7475 nano B_4C composites with different concentrations of B_4C particles be developed. The goal of this research is to use the liquid metallurgy method to develop Al7475 alloy with 2 to 10 wt. % of B_4C composites and examine the mechanical properties of composites. Tensile characteristics are analyzed between a 50 and 100 °C temperature range. In the present research an attempt has been made to develop Al7475 alloy with 400 to 500 nano sized B_4C composites using advanced novel two stage stir casting process. In the preparation of metal composites using oxide, carbide or nitride ceramic particles in the metal, always wettability between matrix and reinforcement is a major concern. This novel two stage melt stir method helped to develop uniformly distributed particles in the matrix.

Experimental details

Materials used

The main alloying element in 7475-alloy is zinc, making it a precipitation hardening aluminium alloy. 7475-O (annealed) and 7475-T6 (solutionized and artificially aged) are two popular pre-tempered grades, and 7475-T651 (solutionized, stress-relieved stretched and artificially aged) is another. In Table 1, we can see the Al7475 ingot that was analyzed here.

Table 1. Chemical composition of the Al7475 alloy used in the present study

Elements	Zn	Mg	Si	Mn	Cu	Fe	Cr	Ti	Al
Weight, %	5.70	2.50	1.50	0.06	1.20	0.12	0.22	0.06	Bal

As a wrought product and primary matrix material, Al7475 belongs to the 7000 class of aluminium alloys and features a high zinc and magnesium content. Al7475 is favored among aluminium alloys due to its low density (2.8 g/cm^3) and great machinability (it can be formed into many shapes, such as jet engine components, structural components, and tubing). Age hardenable, strength, corrosion resistance, and superior weldability are all benefits of the materials with high zinc and magnesium content. The elements that make up Al7475 alloy are shown in Table 1.

The nanoB_4C employed here is a secondary reinforcement particle with a diameter of 400 to 500 nm. It was purchased from Reinste Delhi. Nano B_4C is a popular material among scientists and engineers because of its high mechanical and tribological qualities, as well as its other unique traits, such as its hardness, its ability to support a catalyst, and its use as a neutron absorber. B_4C is used to reinforce aluminium because of the metal's low density (it's lighter than the matrix material, thus it helps save weight) and because B_4C has a high melting point (up to 2950 °C) and good chemical and thermal stability. As a result, the low-cost stir casting technology has gained popularity among consumers interested in B_4C reinforced aluminium matrix composites.

Table 2. Physical properties of boron carbide [14]

Physical property	Specification
Crystallography	Rhombohedral
Color	Black
Specific gravity	2.52
Knoop100 hardness	2800
Melting point, °C	2950

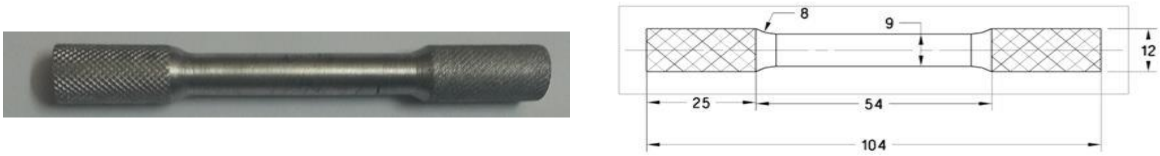
Particles of boron carbide have unusually high hardness, low density, and good wear resistance. Carbon and boron oxide are reduced in an electric furnace to form boron carbide. The black powder is first ground into a fine powder and then pressed at temperatures above 2000 °C to solidify it. Tables 2 and 3 list the material and mechanical properties of boron carbide, respectively.

Table 3. Mechanical properties of boron carbide [14]

Density, gm /cm^3	2.52
Melting point, °C	2445
Young's modulus, GPa	450 – 470
Thermal conductivity (at 25 °C), W/m-K	30 – 42
Hardness (Knoop 100g), kg/mm^2	2900 – 3580

Because of its low cost and suitability for mass manufacturing, the stir casting technique is used to manufacture metal matrix nano composites. Stir casting was used to create nano-composites with 2, 4, 6, 8, and 10 wt. % of B_4C particles, respectively. The necessary quantity of B_4C and the cast iron die are initially warmed to 500 °C. However, the Al7475 was heated to 750 °C in an electric furnace after being weighed and deposited in a graphite crucible. After the Al7475 alloy has melted completely, a degassing powder called solid hexachloroethane (C_2Cl_6) [15] was added to the molten melt in order to expel the undesirable adsorbed gases. A zirconium-coated mechanical stirrer is dipped into the hot melt, creating a visible vortex while the stirrer spins at 300 revolutions per minute. The nano ceramic particles and the right amount of K_2TiF_6were fed into the vortex at a consistent rate once the melt has reached the suitable temperature. The nano B_4C and K_2TiF_6 combination was stirred continuously before and after each pouring stage to ensure that the nano particles are evenly dispersed throughout the melt without cluster. The molten metal was put into a cast iron die that had been preheated, and then stirred for a while.

To prepare the metal matrix composites usually ceramic reinforcements in the form of oxides, nitrides and carbides are used. The maximum 15 wt. % of reinforcement can be used to synthesize the metal base composites, beyond this is very difficult to have good wettability between the matrix and reinforcement. So, one can use any combination of weight percentage below 15 wt. % to fabricate the composites, it may be 2, 4, 6, 8 and 10 or 4 and 8 or 3, 6, 9 and 12 wt. %. In the present study, it is considered 2 to 10 wt. % in steps of 2 wt. %. Al7475 - 10 wt. % of B_4C composites exhibited lesser ductility as compared to 8 wt. % of B_4C reinforced composites; hence in this study 10 wt. % was used as a maximum wt. % to fabricate the Al7475 alloy composites. Rashmi et al. [16] studied the impact of 4 and 8 wt. % of nano and micron particles of B_4C composites. Al7075 alloy with 8 wt. % of nano B_4C composites shown improved properties with slight decrease in the ductility, if more wt. % of boron carbide content in the matrix, decreases the ductility of the composites. Angadi et al. [17] investigated the various properties of 2.5 to 5 wt. % of B_4C reinforced Al2011 composites. Al2011 with 5 wt. % of boron carbide composites once again exhibited high properties with slight reduced elongation. Hence, the higher weight percentage of carbide particles reduces the ductility of the composites. Ductility is an important property of materials it should not be lesser.



(a) (b)

Fig. 1. Photograph (a) and dimensions (in mm) of a tensile test specimen

For the purpose of characterization, the synthesized Nano composites were machined to ASTM standards. After confirming the presence of B and C components and the homogeneous distribution of particles in the matrix using SEM, the mechanical behavior of as cast Al7475 alloy and its nano composites is evaluated using ASTM standards. Figure 1(a) shows the tensile test specimen used as per ASTM E8 standard. Figure 1(b) demonstrates the block diagram of the tensile test specimen with dimensions as per ASTM E8 standard.

Results and Discussion

Microstructural studies

The manufactured nano composite's reinforcing pattern and uniform distribution of nano particles are inspected using a scanning electron microscope. Emery papers of progressively finer grits (starting with 220 grit SiC paper) were used to smooth up a segment of the casted specimen's cut section. Keller's reagent (HCL+ HNO_3+HF+Water) was used to etch the samples after they were manually polished to better highlight the microstructure [18,19].

Scanning electron microscopy (SEM) images of as cast Al7475 alloy are displayed in Fig. 2(a). Figure 2(b–f) demonstrates 2 to 10 wt. % of nanoB_4C reinforced composites. SEM images show that secondary phase nanoparticles are dispersed uniformly throughout the Al7475 alloy matrix with no evidence of agglomeration. Furthermore, the characteristics of Al7475 alloy are improved by the excellent interfacial bonding between the B_4C and the alloy matrix.

Figure 3(a) displays EDS spectra of as cast Al7475 alloy, while Fig. 3(b–f) displays EDS spectra of Al7475 alloy reinforced with 2 to10 wt. % of nano B_4C particulates. Elements such as Zn, Fe, Mg, Cu, Si, Cr, and Ti are depicted in an Al matrix in Fig. 3(a). Energy dispersive spectroscope spectra of Al7475 alloy with 2, 4, 6, 8, and 10 wt. % B_4C nano composites are shown in Fig. 3(b–f). All of the spectra show that boron (B) and carbon (C) are present in the Al7475 alloy, in addition to the expected Al, Zn, Cu, and Si.

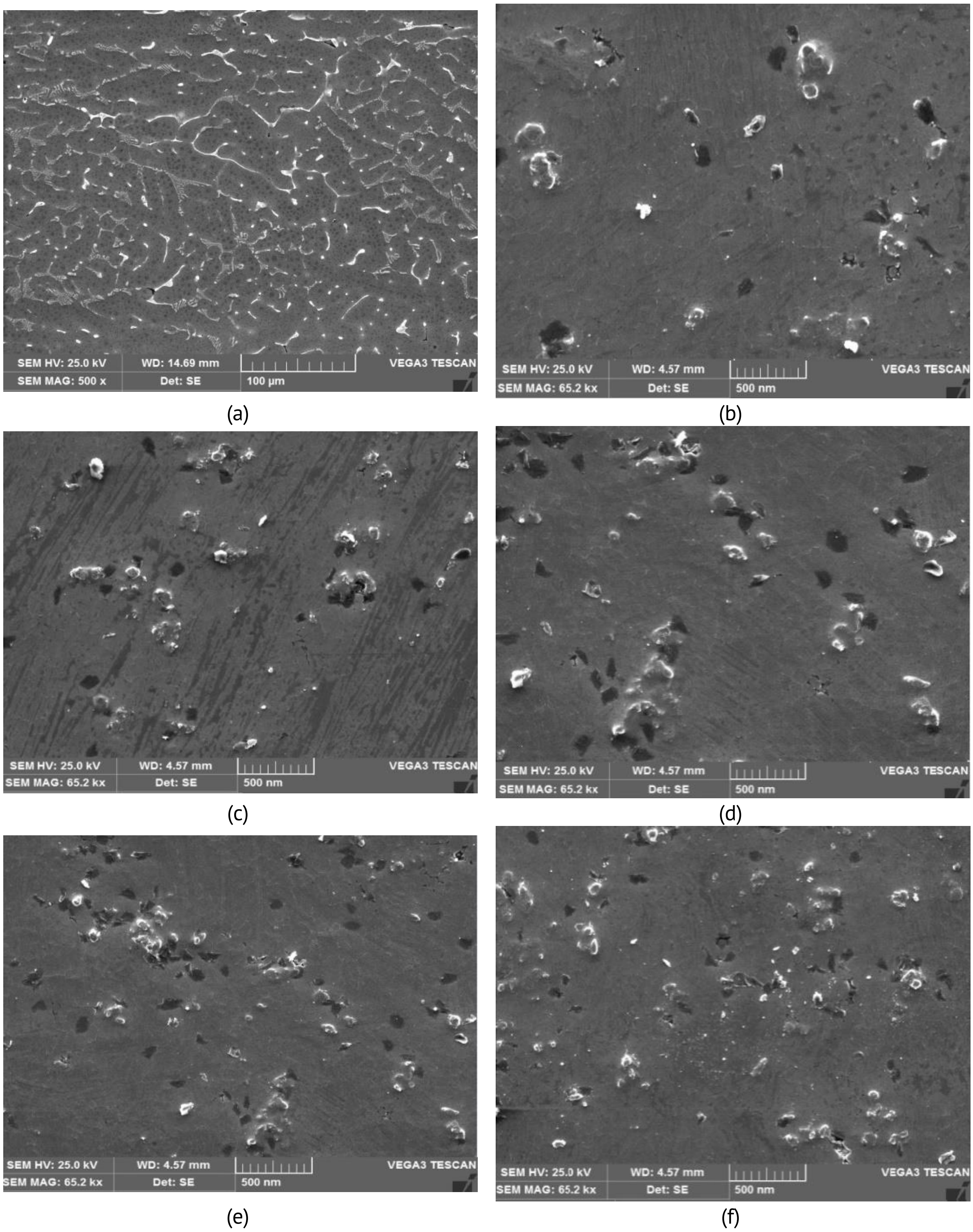


Fig. 2. SEM images of (a) As cast Al7475 alloy, (b) Al7475-2% B_4C, (c) Al7475-4% B_4C, (d) Al7475-6% B_4C, (e) Al7475-8% B_4C, (f) Al7475-10% B_4C nano composites

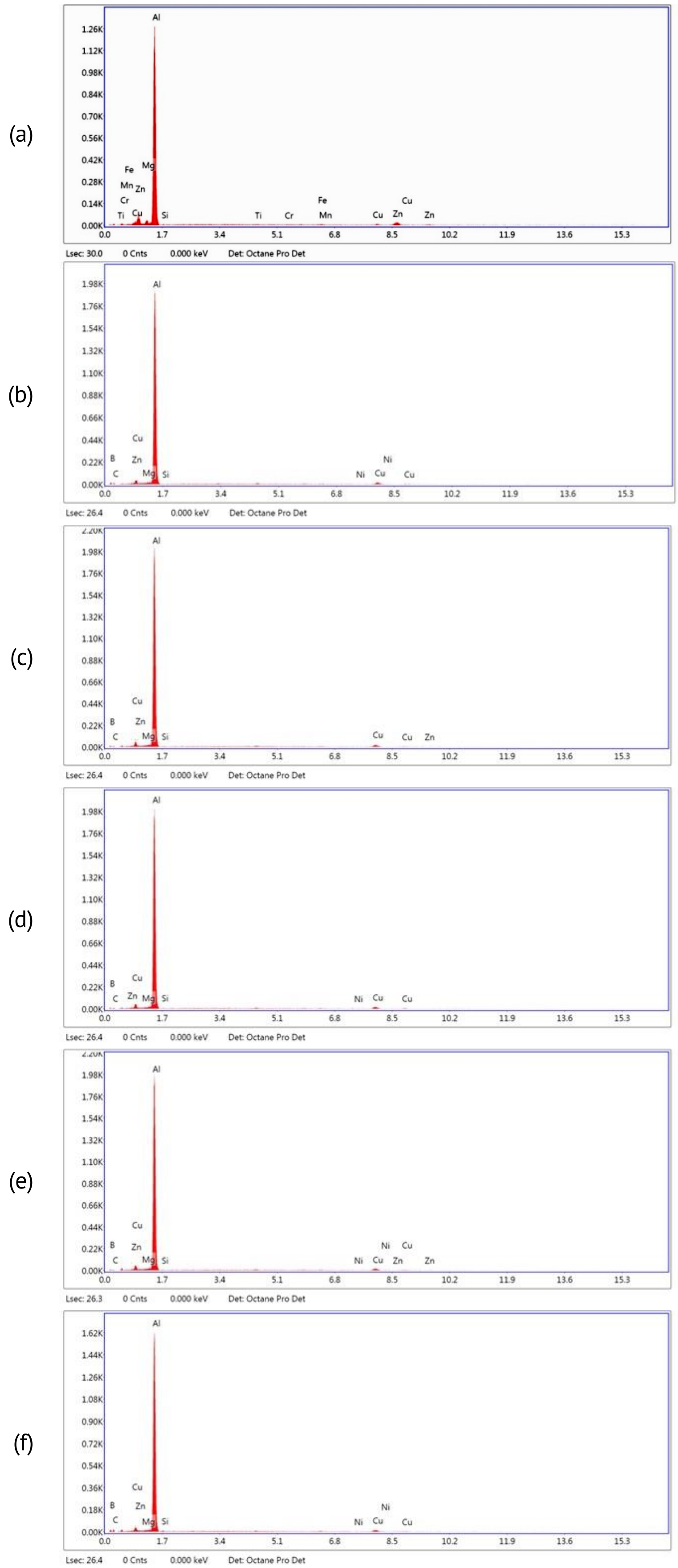


Fig. 3. EDS spectrums of (a) as cast Al7475 alloy, (b) Al7475-2% B_4C, (c) Al7475-4% B_4C, (d) Al7475-6% B_4C, (e) Al7475-8% B_4C, (f) Al7475-10% B_4C nano composites

Density measurements

Figure 4 shows a comparison of the theoretical and experimental densities of as cast Al7475 alloy to Al7475 alloy with 2, 4, 6, 8, and 10 wt. % of nano sized B_4C composites. The density of Al7475 is 2.82 g/cm^3, while that of boron carbide is 2.52 g/cm^3. When Al7475 is reinforced with 2 wt. % nano B_4C, the composite's overall density decreases because the B_4C density is lower than the Al7475 alloy. When 4, 6, 8, or 10 wt. % of B_4C particles are added to Al7475 alloy, the composite typically has a lower density than the original/base aluminium alloy. Furthermore, the difference between the theoretical and experimental densities can be seen to be smaller than expected [20,21]. Boron carbides' ability to reduce material density agrees with findings from competing studies.

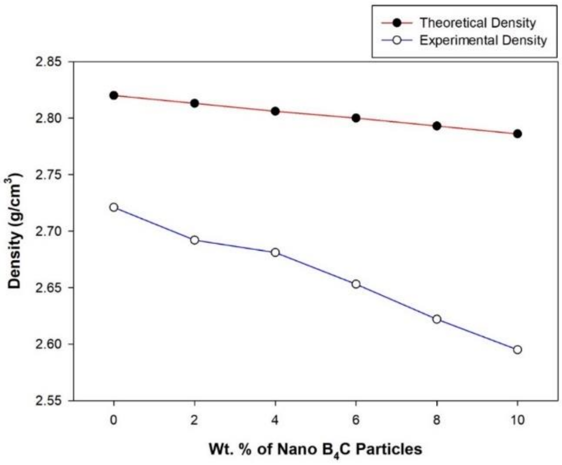


Fig. 4. Theoretical and experimental densities of Al7475 alloy with nano B_4C composites

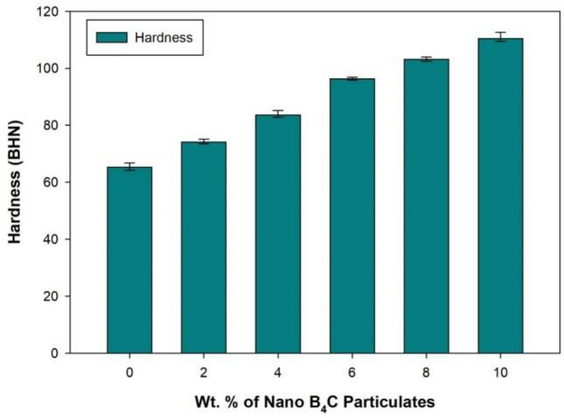


Fig. 5. Hardness of Al7475 alloy and its nano B_4C composites

Hardness measurements

One way to characterize a material's hardness is by measuring its resistance to plastic deformation. The hardness of as cast Al7475 alloy and Al7475 alloy with nanoB_4C composites containing 2, 4, 6, 8, and 10 wt. % is measured using a Brinell hardness testing machine equipped with a 5 mm ball indenter, an applied force of 250 kgf, and a dwell period of 30 seconds for each sample at different locations. As can be seen in Fig. 5, the durability of composites greatly exceeds that of their as-cast counterparts as the percentage of nano B_4C in the composites increases. The increasing trend in hardness can be attributed to the B_4C particles, which are dispersed uniformly and add to the hardness of the composite by blocking the progress of dislocations within the matrix. The findings are consistent with those of other researchers, which may be due in large part to the intrinsic link between the matrix and reinforcement [22,23].

Tensile properties

Figures 6–8 show the ultimate tensile strength of unreinforced Al7475, Al7475 reinforced with 2 wt. % B_4C, Al7475 reinforced with 4 wt. % B_4C, Al7475 reinforced with 6 wt. % B_4C, Al7475 reinforced with 8 weight percent B_4C, and Al7475 reinforced with 10 wt. % B_4C at room temperature and at 50 and 100 °C, respectively.

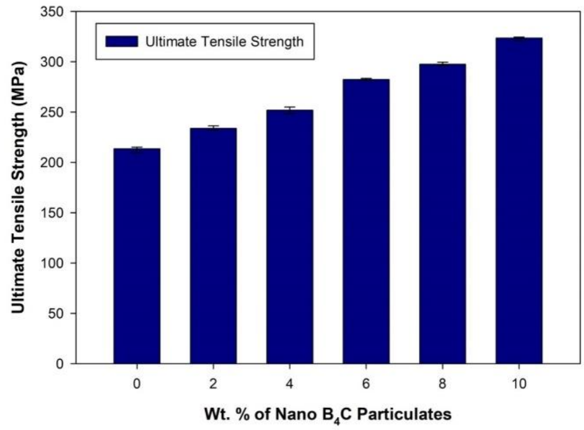


Fig. 6. UTS of Al7475 alloy and its nano B_4C composites at room temperature

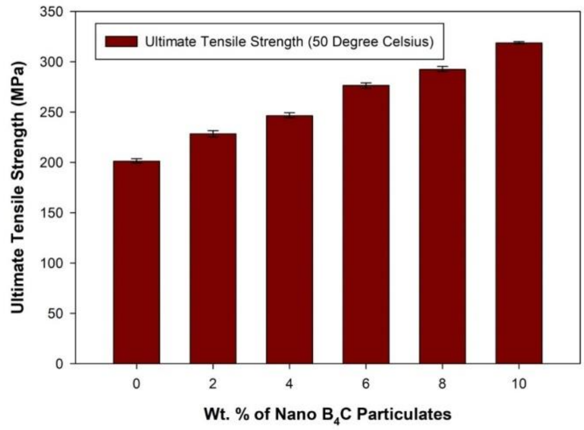


Fig. 7. UTS of Al7475 alloy and its nano B_4C composites at 50 °C

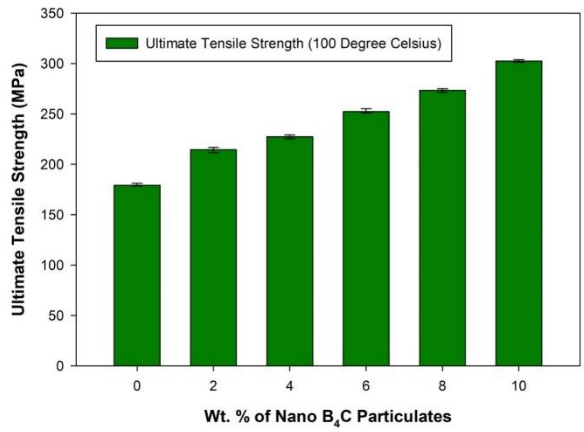


Fig. 8. UTS of Al7475 alloy and its nanoB_4C composites at 100 °C

Figure 6 displays the room-temperature ultimate tensile strength of Al7475 alloy and its nano B_4C reinforced composites, respectively. When Al7475 alloy is as cast, its maximal tensile strength is 212.43 MPa. Nano B_4C particles added at quantities between 2 and 10 % increased the UTS of Al7475 alloy. The following are the UTS values: The tensile strength of Al7475 alloy at 2% B_4C is 234.17 MPa, at 4 % B_4C it is 251.67 MPa, at 6 % B_4C it is 282.47 MPa, at 8 % B_4C it is 298.03 MPa, and at 10 % B_4C it is 322.53 MPa. The UTS of Al7475 alloy is enhanced by 52.8 % when nano B_4C is added at a concentration of 10 wt. %. Nanoparticle inclusion has resulted in increased ultimate strength, primarily as a result of reinforcing tougher particles in the soft matrix. During testing, strengthening particles work to prevent the matrix from undergoing plastic deformation because they are, by definition, stronger and more rigid than the matrix. However, the distribution of the boron carbide particles throughout the Al7475 alloy matrix is essential for preventing the matrix from deforming plastically [24,25].

Composites supplemented with 2–10 % nano boron carbide particles from Al7475 alloy exhibit higher ultimate tensile strength at 50 and 100 °C, as shown in Figs. 7 and 8. Increasing the percentage of reinforcement particles from 2 to 10 wt. % enhances the UTS of Al7475 alloy at both 50 and 100 °C, as shown by the graphs. The increased UTS of Al7475 alloy at high temperatures is extremely useful in a wide variety of applications. With UTS of

201.37 MPa at 50 °C and 179.80 MPa at 100 °C, Al7475 alloy possesses impressive properties as cast. After incorporating 10 wt. % nano boron carbide particles, the UTS increases to 318.87 MPa at 50 °C and 302.5 MPa at 100 °C. In both the 50 and 100 °C test conditions, the UTS of Al7475 alloy nano B_4C composites is greater than that of the base matrix. Nanoparticle-reinforced composites are advantageous mainly because to their resistance to plastic deformation. At 50 °C, the UTS of the Al7475 alloy rose by 58.26 %.

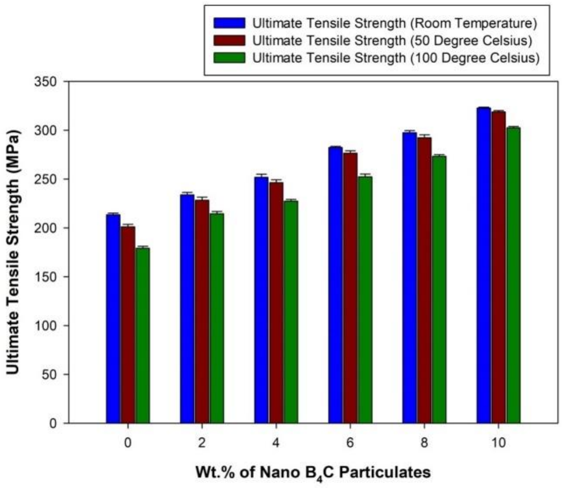


Fig. 9. Comparison of UTS of Al7475 alloy and its nano B_4C composites at room temperature and elevated temperatures

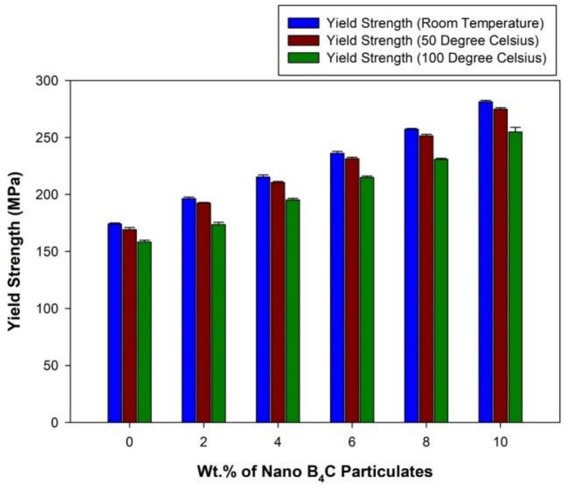


Fig. 10. Comparison of YS of Al7475 alloy and its nano B_4C composites at room temperature and elevated temperatures

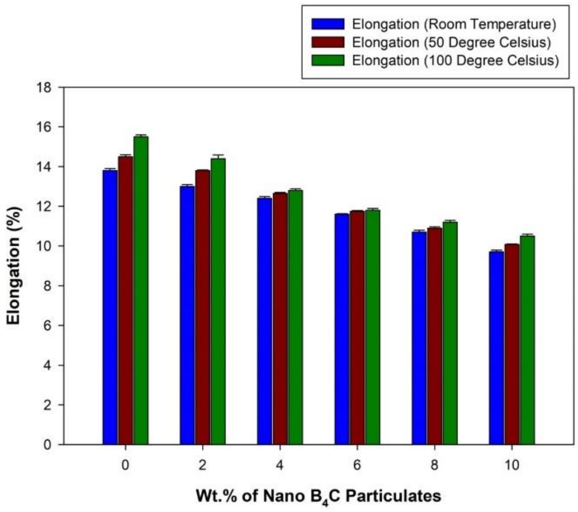


Fig. 11. Comparison of elongation of Al7475 alloy and its nano B_4C composites at room temperature and elevated temperatures

Ultimate tensile strength comparisons at room temperature and increased temperatures (50 and 100 °C) for Al7475 alloy and various wt. % of B_4C reinforced composites are shown in Fig. 9. As cast alloy has a UTS of 212.43 MPa at room temperature; at 50 and 100 °C, the UTS is 201.37 MPa (50 °C) and 179.80 MPa (100 °C), respectively. The as cast Al7475 alloy's UTS decreases from ambient temperature to higher temperatures. More plastic deformation of alloy occurs at higher temperatures, which is the primary cause of this decrease in UTS.

Furthermore, Fig. 9 shows that the UTS is enhanced both at room temperature and at elevated temperatures as the weight percentage of B_4C particles is increased from 2 to 10 wt. %. UTS values for composites of Al7475 – 2 wt. % of B_4C reinforcement at room temperature (RT), 50˚C, and 100˚C, respectively, are 234.17, 228.4, and 214.13 MPa. As cast alloy has a UTS of 212.43 MPa at room temperature. The UTS of Al7475 alloy is enhanced by the addition of 2 wt. % of nanoparticles in all situations at ambient temperature as well as at increased temperatures. Furthermore, the ultimate strength of as cast Al7475 alloy and its composites decreases from room temperature to 100 °C. The softening of the material caused by exposure to high temperatures is responsible for most of the drop in UTS. The ultimate strength of the Al7475 alloy without any particles is 212.43 MPa at room temperature, this ultimate strength has been improved to 322.53 MPa with 10 wt. % of B_4C particles in the Al7475 alloy. Al7475 – 10 wt. % of B_4C composites exhibited an improvement of 51.82 % in the ultimate tensile strength at room temperature.

Yield strength comparisons at room temperature and increased temperatures (50 and 100 °C) between Al7475 alloy and various wt. % of B_4C reinforced composites are shown in Fig. 10. As cast alloy has YS of 173.83 MPa at room temperature; similarly, it has YS of 169.57 MPa (at 50 °C) and 157.73 MPa (at 100 °C) in test settings. As cast Al7475 alloy has a lower YS at high temperatures than at ambient temperature. When heated, alloy undergoes increased plastic deformation, leading to a drop in YS.

Furthermore, as shown in Fig. 10, increasing the proportion of B_4C particles from 2 to 10 wt. % improves YS at both room temperature and higher temperatures. The YS values of composites made from Al7475 alloy and 2 wt. % of B_4C reinforcement were 196.4 MPa at RT, 192.2 MPa at 50 °C, and 173.47 MPa at 100 °C. The addition of 2 wt. % of nano particles improves the YS of Al7475 alloy under all conditions, including at room temperature and higher temperatures. The yield strength of as cast Al7475 alloy and its composites diminishes from 0 to 100 °C. This decrease in YS can be traced back to the material softening as a result of prolonged contact to high temperatures [26,27].

Figure 11 displays the elongation as a percentage of the initial length at room temperature and high temperature for Al7475 alloy and nano boron carbide reinforced composites, respectively. As can be seen in Fig. 11 the ductility of Al7475 alloy is diminished when hard boron carbide particles are added to it. Experiments conducted at room temperature reveal a 13.83 % stretch in as cast Al7475 alloy. In addition, nano B_4C reinforced composites at 10 wt. % for Al7475 alloy have a value of 9.73 %. From the plot it is observed that as the testing temperature increases from RT to 100 °C, there is increase in the elongation due to the higher temperature.

Figure 12 represents SEM images of tensile fractured surfaces of Al7475 alloy and Al7475 with 10 wt. % of B_4C reinforced composites at room temperature and at 100 °C temperatures tensile test specimens. Figure 12(a) is the tensile fractured surface of Al7475 alloy at room temperature test conducted specimen. This shows grains and void dimples. Further, the fracture surface of Al7475 alloy at 100 °C testing environment exhibited the elongated grains, which is mainly due to improved ductility at higher temperature. Figure 12(c–d) are representing the tensile fractured surfaces of Al7475 alloy with 10 wt. % of B_4C composites. These samples surfaces are showing combined brittle and ductile mode of fracture due to presence of hard particles [28].

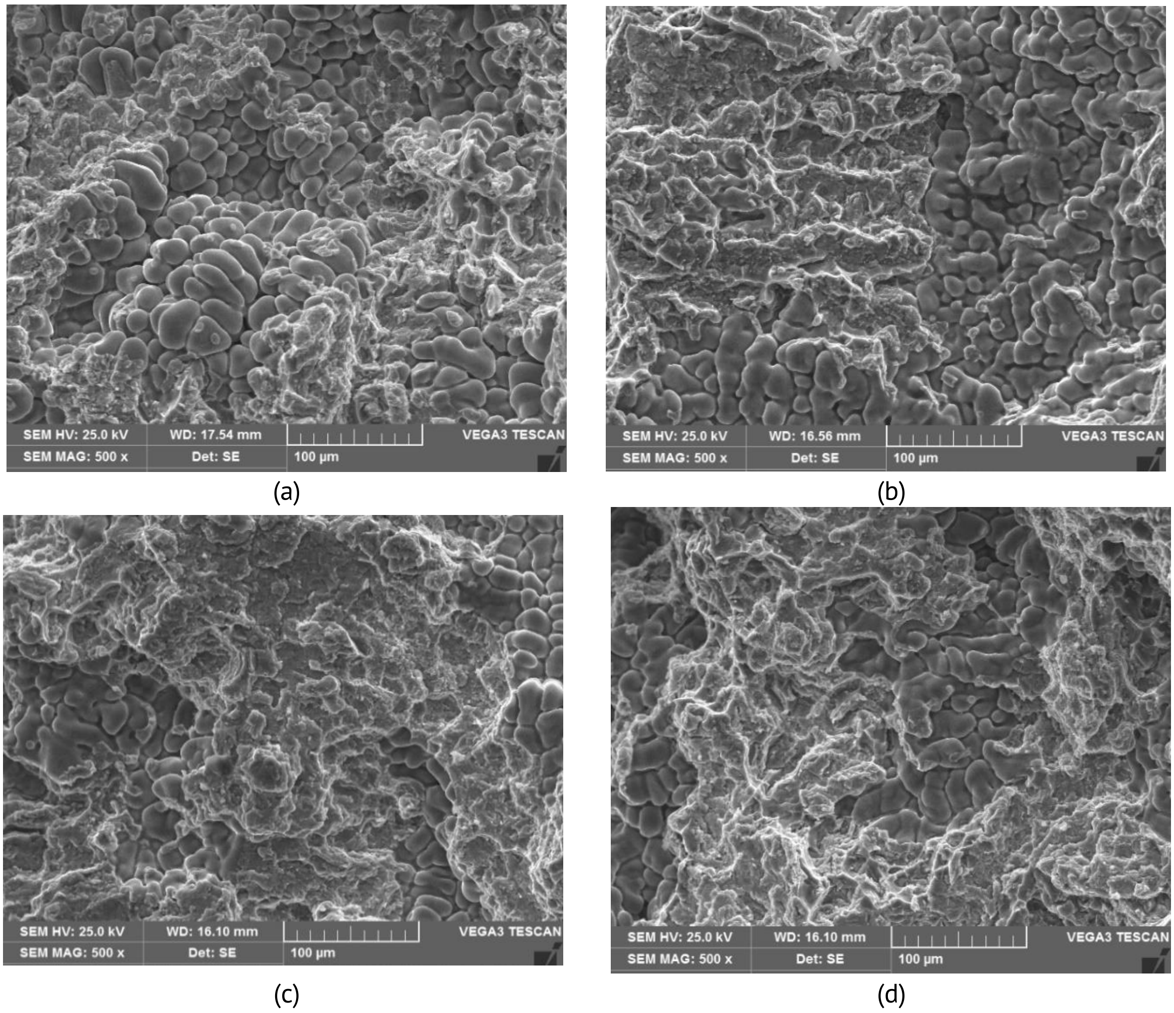


Fig. 12. Tensile fractured SEM of (a) Al7475 alloy at room temperature, (b) Al7475 alloy at 100 °C, (c) Al7475 – 10 wt. % of B_4C composites at room temperature, (d) Al7475 – 10 wt. % of B_4C composites at 100 °C

Conclusions

The stir cast method is suitable for producing Al7475 alloy with B_4C particles of nano in size and MMCs of 2 to 10 wt. %. Scanning electron microscopy images show that B_4C particles are evenly dispersed across the Al7475 alloy. This study analyzed the EDS patterns of composites made from Al7475 alloy and B_4C particles at 2 to 10 wt. %. The presence of boron and carbon elements in Al7475 alloy with B_4C composites are confirmed by EDS spectrums. The incorporation of B_4C particles reduced the density of Al7475 alloy composites. Further, theoretical and experimental densities are very nearer to each other, which indicate the proper casting method of Al7475 alloy and B_4C composites. The hardness of Al7475 alloy has increased with the incorporation of B_4C particles. The highest hardness is observed in the case of Al7475 alloy with 10 wt. % of B_4C composites. The ultimate strength of the Al7475 alloy without any particles is 212.43 MPa at room temperature, this ultimate strength has been improved to 322.53 MPa with 10 wt. % of B_4C particles in the Al7475 alloy. Ultimate and yield strengths of Al7475 alloy have enhanced with the 2 to 10 wt. % of boron carbide particles reinforced addition. Improvements in the UTS and YS with 10 wt. % of B_4C particles in Al7475 alloy is 51.8 and 61.6 % respectively. Further, UTS and YS values of as cast Al7475 alloy and its 2 to 10 wt. % of boron carbide composites decreased at elevated 50 and 100 °C. The ductility of Al7475 alloy has been slightly reduced with the incorporation of boron carbide particles in the Al7475 alloy matrix. The ductility has been improved in the case of elevated temperatures as compared to the room temperature experimental values. Tensile fractured surfaces at elevated temperatures exhibited larger and elongated grains. Metal composites with B_4C shown combined brittle and ductile mode of fracture behavior.

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