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Influence of micro boron carbide particles on microstructure, mechanical properties, and dry sliding wear properties of an aluminium Al2214-B_4C metal matrix composite

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ABSTRACT

In this experimental research, an attempt is made to develop Al2214-B_4C composite materials with reinforcement of micro boron carbide (B_4C) (viz. 0, 1.5, 3, 4.5, and 6 wt.%) by using a novel liquid metallurgical stir casting technique with modified bottom pouring facilities and studying the microstructure, physical, mechanical, and dry sliding wear resistance responses. The microstructure of Al2214-B_4C composite samples with varied boron carbide weight percentages was examined under an electronic scanning microscope (SEM) equipped with an energy dispersive X-ray spectrometer (EDX) device. The physical characteristics like density and porosity, mechanical strength, such as micro and macro hardness, yield and ultimate tensile strength, and sliding wear response were examined under variable experimental conditions. The experimental results of the Al2214-B_4C composite revealed a decreased specific density with an increased weight percentage of boron carbide particles in the matrix and a homogeneous distribution of reinforced micro boron carbide particles in the Al2214 matrix. There was an appreciable improvement in mechanical properties and wear properties in composite materials as compared to an unreinforced aluminium alloy.

Keywords: Stir casting, metal matrix composites, wear, aluminium, boron carbide

Introduction

Lightweight metallic materials with high strength-to-weight ratios are in high demand in many fields of engineering. Thus, researchers are becoming more involved in exploring new materials and improving material properties to meet engineering demands. Among the various engineering materials, composites are the most promising materials prepared by the liquid metallurgical route.[1,2] Metal matrix composite materials (MMCs) find large applications in the automobile, aerospace, defense, and electronic packaging sectors owing to their elevated specific strength and tailorable properties being strength-to-weight ratio, mechanical properties, thermal properties, stiffness, and wear resistance strength as compared to conventional unreinforced alloys.[3–6]

Aluminium metal matrix composites (AlMMCs), owing to their light weight and enhanced mechanical, wear, and thermal properties, have gained greater attention in the past few decades.[7–10] However, AMMCs need further improvement of their properties conducive to extending their applications for subsequent engineering demands and challenges. AlMMCs are associated with several methods of processing and the addition of reinforcement materials to fabricate aluminium metal matrix composites (AlMMCs). This includes the different manufacturing techniques like solid–solid reaction, solid-liquid reaction, and liquid-liquid reaction. Among the various methods, the solid-liquid reaction process is widely used and has emerged as a potential route in terms of both technical, large-scale production, and economics. The liquid metallurgical casting method has been the most typical method as compared to other parallel metallurgical metal matrix composite production methods due to their simple casting arrangements, processing, and fabrication of intricate profiled shapes.[11–15] The various ceramic materials have been used to develop advanced aluminium metal matrix composites as a reinforcement material like carbides (B_4C, SiC), nitrides (BN), borides (TiB_2), and oxides (Al_2O_3) etc.[16,17] Wear is the most common phenomenon in metal matrix composite material interfaces, and it can be reduced by using hard ceramic particles as reinforcement, which provide resistance strength when combined with metal matrix material as a metallurgical reinforcement.[18] Boron carbide (B_4C) has been a prominent reinforcement material among the different ceramic particles due to its virtues of high melting temperature, high hardness, wear resistance, and low thermal expansion. Boron carbide (B_4C) was recorded as having good bonding strength and chemical

Table 1. Al2214 aluminium alloy chemical composition in weight percentage.

Element	Cu	Mg	Mn	Fe	Si	Zn	Ti	Cr	Al
Weight %	3.9-5	0.5-1.2	0.4-1.2	0.3	0.5-1.2	0.25	0.15	0.1	Reminder

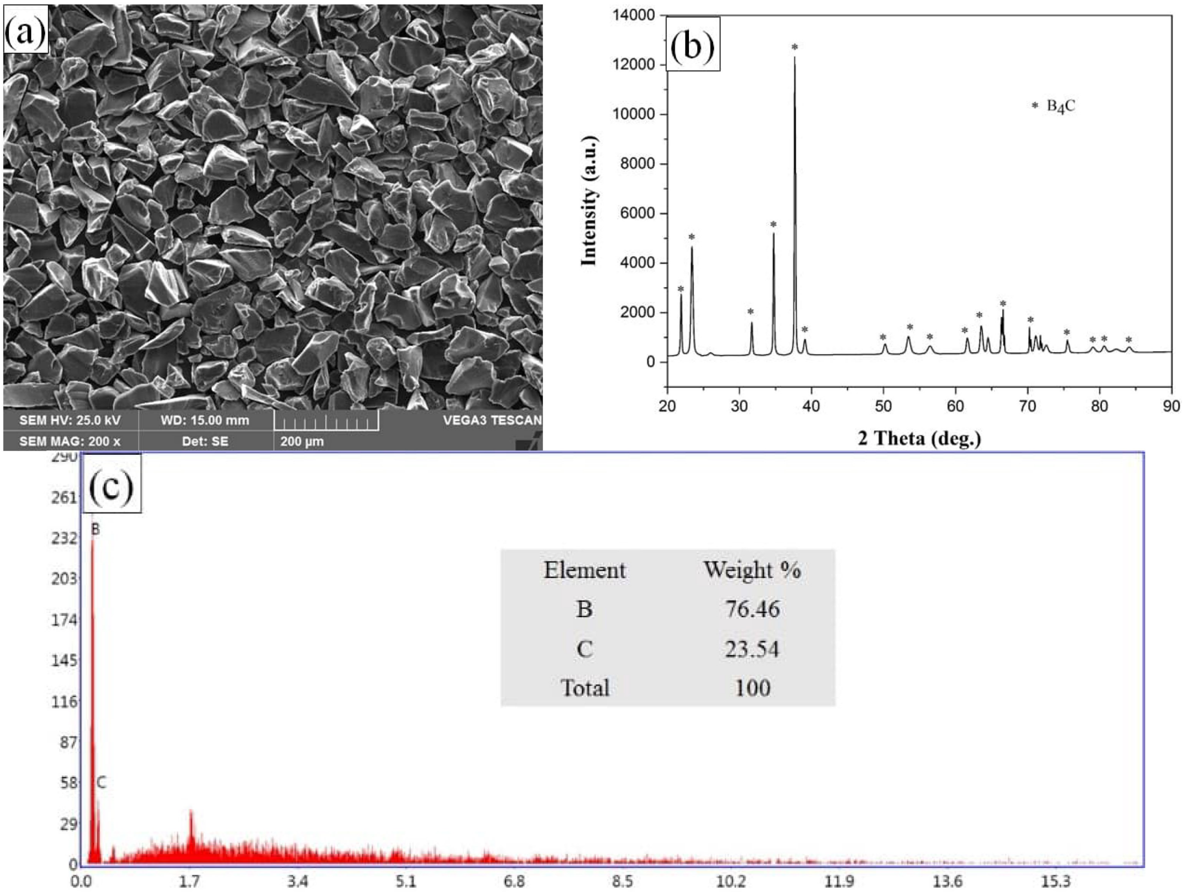

Figure 1. (a) SEM micrograph (b) XRD pattern (c) EDX spectrum of boron carbide (B_4C) particles as received

stability with aluminium alloy, a homogenous distribution of particles, and limited porosity by selecting appropriate process parameters such as uniform reinforcement particles feeding, molten metal temperature, stirring speed, and incorporation time.[19–22] In the present investigation, the material microstructure, physical, mechanical properties, and dry sliding wear properties of Al2214- B_4C composites were studied with different weight percentages of B_4C (viz. 0% to 6% in steps of 1.5% by weight).

Materials and Methods

Materials details

In the present studies, Al2214 aluminium alloy was a matrix material. The combination of chemical elements in the Al2214 alloy is given in Table 1. The boron carbide (B_4C) particles, with an average size of 60 µm are used as reinforcement material. Figure 1(a) shows a SEM micrograph of boron carbide (B_4C) particles, whereas Figure 1(b) shows boron carbide (B_4C) particle peaks were obtained from XRD spectra at different 2θ angles. The elements presence in boron carbide (B_4C) is presented in the EDX pattern in Figure 1(c).

After being thoroughly cleaned, the aluminium alloy ingots Al2214 matrix material in sizes of 20mmx30mmx50mm and weighing 1 kg were placed in a crucible of graphite to melt in an electrical furnace, and then boron carbide was added separately as reinforcement in each casting at different weight percentages (0% to 6% in steps of 1.5%). The melting temperature was maintained at a range of 750^0C to 850^0C. Meanwhile, the matrix and reinforcement wettability were enhanced further by the addition of 0.5% by weight of magnesium. At the same time, boron carbide was preheated to a 500^0C to 600^0C temperature range in an oven and poured into the molten matrix at a constant feed rate. The mixture was stirred rigorously to form a vortex with a mechanical stirrer connected to an electrical motor to achieve a homogenous mixture of boron carbide in an aluminium matrix. The stirring was continued during the addition of boron carbide and, after incorporation of a pre-measured weight percent of B_4C, the molten boron carbide reinforced aluminium composites were poured into a preheated split mould steel die through a bottom pouring facility provided in the casting arrangement. The molten composites Al2214-B_4C were allowed to solidify in a mould by natural cooling and were removed from it. The composite sample density of different weight percent of reinforcement was measured experimentally.

Table 2. Reinforcement % in casted composites samples.

Samples	Reinforcement (B_4C)
A0	0%
B1	1.5%
B2	3%
B3	4.5%
B4	6%

Samples were prepared as per ASTM standards from prepared cast composites in order to conduct various metallurgical, mechanical, and wear characterizations and analyses. The specimens prepared were subjected to microstructure studies, the specimens were cut to a 12 mm diameter and a 5 mm thickness from received die-cast composites by a precision, low damage cutting machine. To evaluate the tensile behavior of the boron carbide reinforced Al2214 composites, the specimens are machined in accordance with ASTM standard E8. The overall length of specimen is 104, with gauge length of 45 mm, and 9 mm in gauge diameter. and the wear resistance strength of composites at various conditions, i.e., wt. % of reinforcement, load, speed, and sliding distance, were measured with pin-on-disc apparatus.

Results and Discussion

Microstructural analysis of cast specimens

Metallographic studies are a dominant analytical and quality control tool. The reinforced particle size, grain structures, and distribution were observed using a TESCAN Vega 3 scanning electron microscope (SEM). The microstructure analysis samples were prepared by surface grinding with different grit sizes, from coarse (40 mesh) to fine (600 mesh). Subsequently using 3 µm diamond paste suspended in distilled water by a mechanical polishing machining. Finally, the specimen's surfaces are etched by Keller's reagent. The microstructure of composites at various weight percentages of boron carbide reinforcement is shown in Figure 2.

The SEM images evidently reveal the presence of boron carbide particles (B_4C), their scattering in an aluminium matrix phase, free from voids, and also a dendritic structure formed within the Al2214-B_4C composites. The

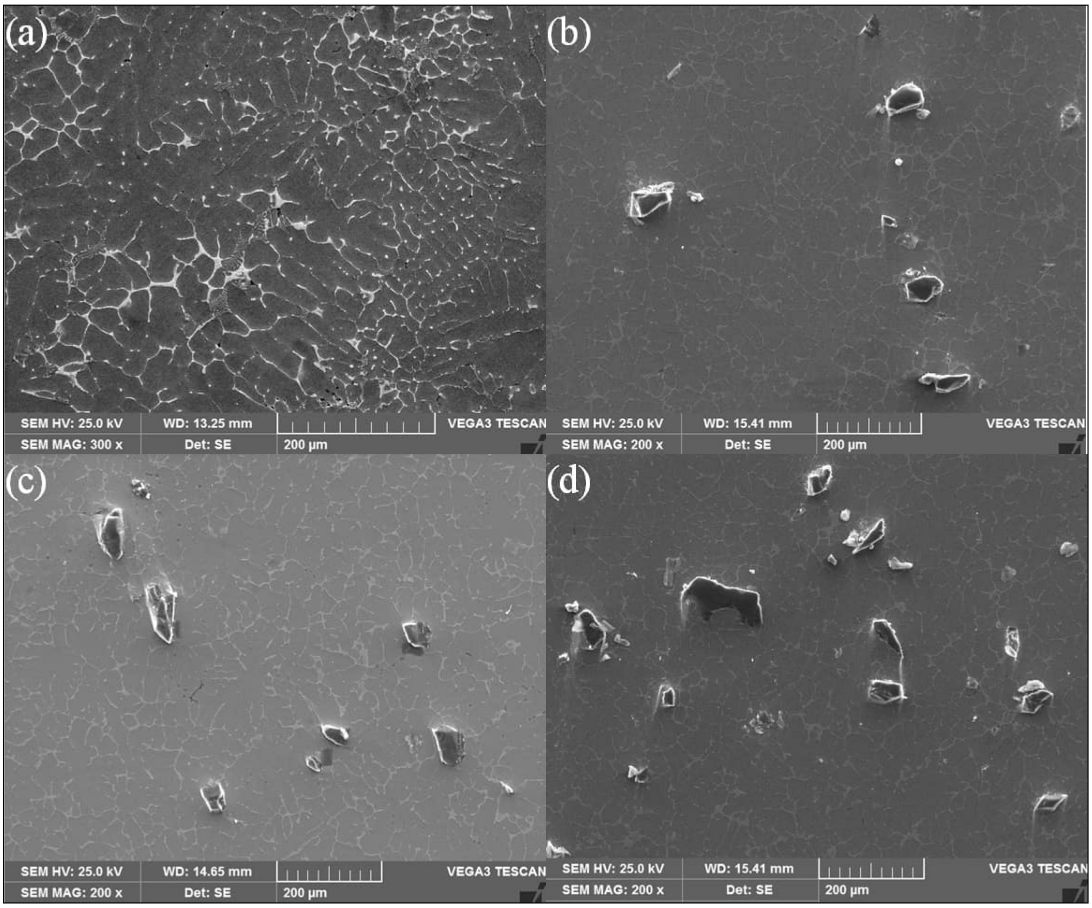

Figure 2. SEM images of Al2214 - B_4C composites (a) 0% wt. B_4C (b) 3% wt. B_4C (c) 4.5% wt. B_4C (d) 6% wt. B_4C

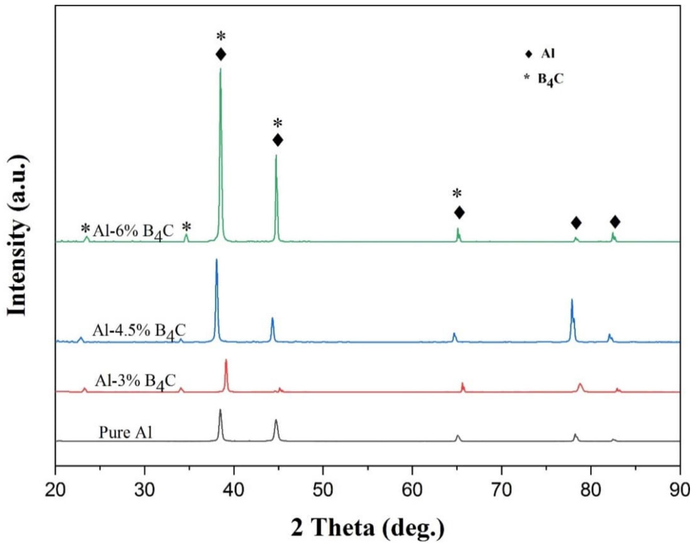

Figure 3. XRD Pattern of Al2214-B_4C composites (a) Al2214-0% wt. B_4C (b) Al2214-3% wt. B_4C (c) Al2214-4.5% wt. B_4C (d) Al2214-6% wt. B_4C

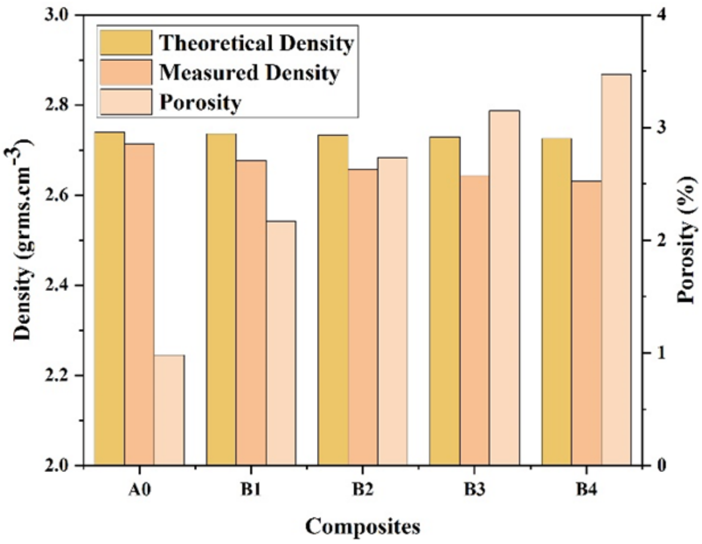

Figure 4. Specific density and porosity variation with different wt. % of reinforcement.

results of SEM images support the analysis of material properties. The XRD pattern in Figure 3 reveals peaks of matrix (Al) and reinforcement (B_4C) constituents of the MMC.

XRD analysis was carried out on Al2214- boron carbide with different weight % of reinforcement (viz., 0, 1.5, 3, 4.5, and 6 wt.%) by an X-ray diffractometer. The XRD image pattern of aluminium and its composites represented aluminium and boron carbide particle phases at various peaks with different weight percent of reinforcement. The aluminium peaks were observed at 39^0, 45^0, 65^0 72^0 and 82^0 2θ values with different intensities. Similarly, boron carbide particle phases were identified at 28^0, 37^0, 39^0, 45^0, and 65^0 angles, respectively.

Density Measurements

Figure 4 shows specific densities of Al2214-B_4C composites with various weight percentages of boron carbide reinforcement (viz., 0, 1.5, 3, 4.5, and 6 wt.%). Theoretical specific densities of composites were obtained by a rule of mixture given by an Eq. (1), and experimental specific densities were calculated by the Archimedes principle given by an Eq. (2), and the porosity of the samples was calculated by an Eq. (3). The results reveal that with an increased addition in weight percent of boron carbide reinforcement, the specific density of the Al2214-B_4C composite material decreases owing to the low specific density of reinforcement of boron carbide (B_4C) micro particles in the aluminium Al2214 matrix.

$$\rho_{th} = \left(\frac{W_m}{\rho_m} + \frac{W_r}{\rho_r}\right)^{-1} \quad (1)$$

Here, ρ_{th}: Theoretical specific density in (grms.cm^{-3}); W_m: Matrix material weight fraction, ρ_m: Matrix material mass density (grms/cm^{-3}), W_r: Reinforcement material weight fraction, ρ_r: reinforcement material mass density (grms/cm^{-3}).

$$\rho_{ex} = \frac{m}{V} \quad (2)$$

Here, ρ_{ex}; Experimental density of the sample in (grms.cm^{-3}); m: Mass of the sample (grms); V: Volume of water displaced (cm^3)

The porosity level (%) of samples were measured by an Eq.3

$$\text{Porosity}(\%) = \left(1 - \frac{\rho_{ex}}{\rho_{th}}\right) \times 100 \quad (3)$$

Further, experimental specific density results of composites are shown to be slightly lower than theoretical values due to the formation of voids/porosity during casting and the level of porosity (%) with different reinforcements, which is obtained from theoretical and experimental values shown in Figure 4, and the results reveal the porosity (%) variations with increased addition of weight percent of reinforcement in the matrix.

Hardness

Figure 5 shows the measured average (5- trail) mechanical hardness value of aluminium composites with various reinforcement weight percentages of boron carbide. The micro hardness has been measured by Vickers hardness number (VHN) at 10 N applied load at a 15 second dwell period. and macro hardness by Brinell hardness number (BHN) according to an ASTM (ASTM E10) standard with steel ball 10 mm diameter, applied load 10 N at 20 second dwell period. With an increased addition of wt.% of reinforcements, both approaches resulted in a discernible increase in hardness of the composites. The enhancement of the hardness value in the composite is revealed by the homogenous reinforcement particles

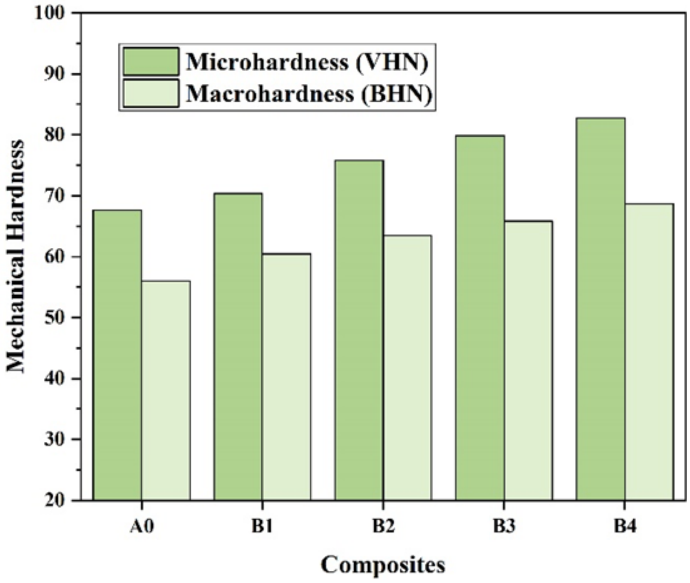

Figure 5. Mechanical hardness variation with wt. % of reinforcement.

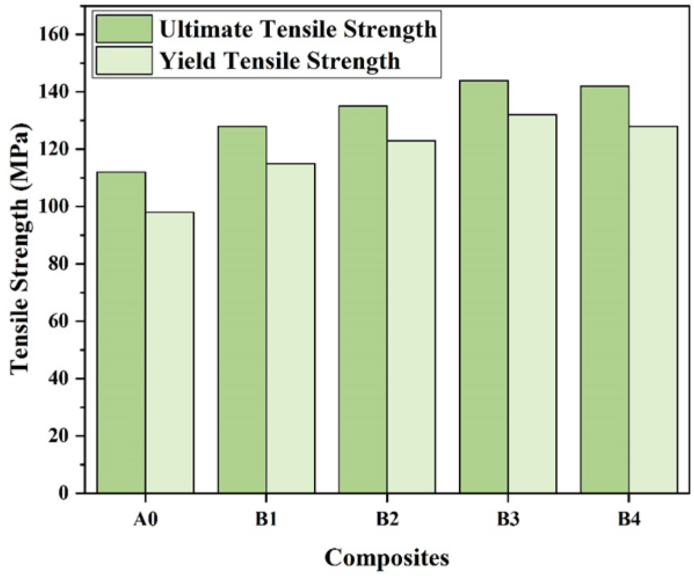

Figure 6. Tensile strength variation with wt. % of reinforcement.

distribution throughout the matrix. The results clearly demonstrate that hardness values improved with an increase in boron carbide particles, and the highest hardness was obtained in Al2214-B_4C composites with 6 wt. % of B_4C reinforcement.

Tensile Strength

Figure 6 shows the influence of B_4C particle reinforcement in wt.% on the composite yield tensile and ultimate tensile strengths of the Al2214-B_4C composite. The ultimate tensile strength and yield strength values of composites were significantly improved with an increased wt.% of boron carbide particles reinforcement in an aluminium matrix. The improvement in yield tensile and ultimate tensile strength values was attributed to the presence of boron carbide with uniform distribution, a

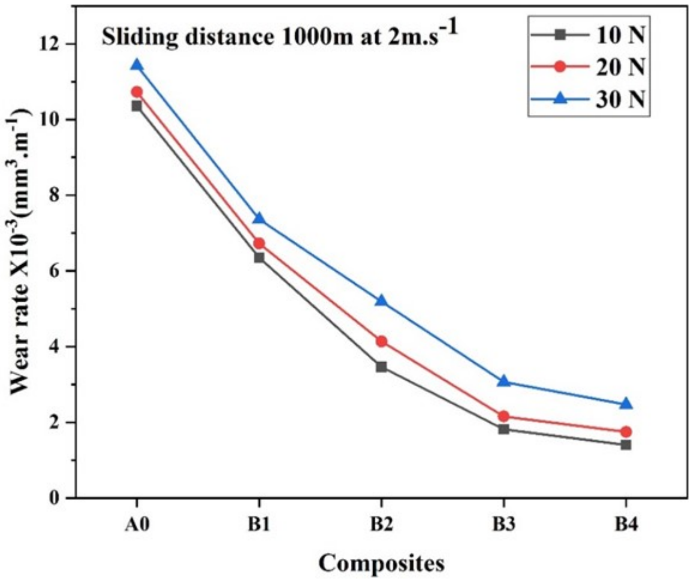

Figure 7. Wear rate variation at constant speed and distance at different reinforcement

refined dendritic microstructure, and a lower degree of porosity (%) in an Al2214-B_4C aluminium composite.

Wear resistance strength

A wear test was conducted on Al2214-B_4C composites with various wt.% of boron carbide (B_4C) reinforcement (viz., 0, 1.5, 3, 4.5, and 6 wt.%) in accordance with ASTM standard G99-05. The composite samples were machined to a cylindrical shape with a size of (16 mm in radius x 30 mm in height) from castings and, by using a wear testing machine (pin-on-disc apparatus), wear test experiments were conducted at dry sliding conditions. The wear behaviors were discussed under applied load conditions.

Reinforcement

Figure 7 shows the Al2214-B_4C composites wear resistance variation rate (mm^3/m) at different wt.% of reinforcement. The wear rate results of different wt.% reinforced Al2214- boron carbide composites under different loads of 10N, 20N, and 30N were calculated. At different loads, the wear loss in composites decreased with an increased addition of wt.% of reinforcement. The outcome results of the wear test show the wear resistance value of composites was strongly dependent on boron carbide micro particles wt.% of in the matrix. The rate of wear loss is gradually decreasing with the increased reinforcement particles addition. The wear resistance strength of composites was maximum at 6% of wt. of reinforcement due to the higher wear resistance strength of ceramic reinforcement particles.

Load

Figure 8 shows the dry sliding wear rate (mm^3/m) response of Al2214- boron carbide composites with different wt. % reinforcement under varying loads of 10N, 20N, and 30N. The wear resistance strength gradually decreases with an increase in the applied load at a constant

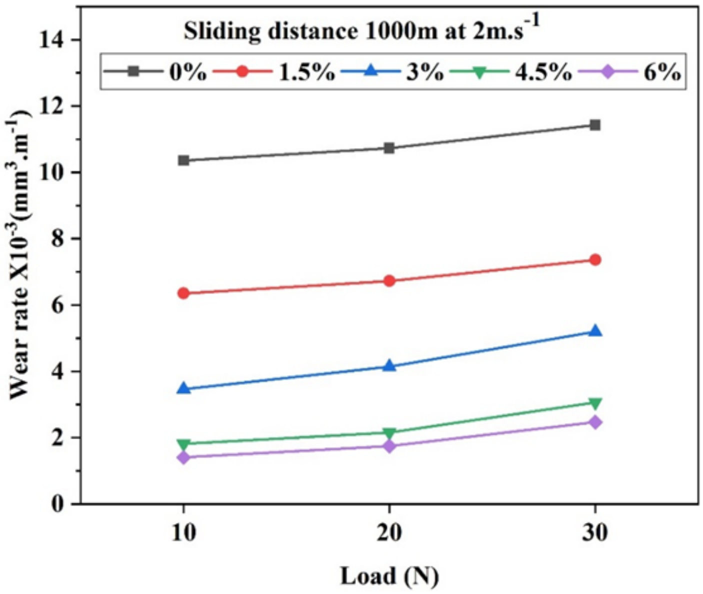

Figure 8. Wear loss variation at constant speed and distance at different loads.

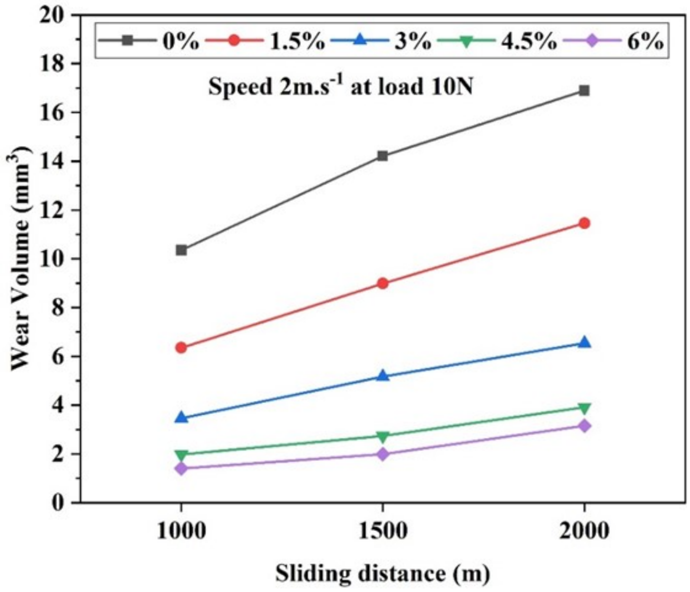

Figure 9. Wear loss variation at constant speed and load at different sliding distance.

reinforcement weight percent of boron carbide micro particles in an aluminium Al2214- boron carbide composite. The wear rate results of experiments conducted on Al2214-B_4C composites with different wt.% reinforcement show the loss of wear rate of composites is mainly dependent on the applied load and wear loss was maximum at higher applied load.

Sliding distance

Figure 9 shows the experimental wear rate results obtained from the composites of Al2214-B_4C at various wt.% of reinforcement against different dry sliding travelled distances.

The results clearly indicate the rate of wear loss is proportional to the steadily travelled sliding distance at different load intensities, and the wear rate is gradually increasing at enhanced load intensities. At the same time, the wear resistance strength increases with the addition of boron carbide reinforcement in the matrix as compared to an unreinforced aluminium alloy. The wear rate decreases with increasing reinforcement particle weight percentage, sliding speed, and sliding distance. The increased wear resistance of the composites may be due to the incorporation of hard particles, which act as a harder phase in the matrix. Because the strong interface bond plays a critical role in transferring loads from the Al matrix to the hard reinforcement particles, when the hard particles become strongly bonded with the matrix, they protect the surface from the counter face's severe destructive action. [23,24]

Worn surface morphology

The worn surface images are shown in Figure 10, obtained by an electronic scanning microscope (SEM) of an unreinforced aluminium alloy and an Al2214- boron carbide particles metal matrix with a different wt.% of reinforced samples. The surface morphology reveals the adhesions in an aluminum alloy without reinforcement. The Al2214 alloy, being ductile, tends to adhere to a sliding disc while wear testing. There was no adhesion observed in composites of boron carbide reinforced Al2214- boron carbide composite. These results show boron carbide reinforced Al2214 composites with varying weight percentages. They have better wear resistance strength compared with pure Al2214.

Conclusion

In the present investigation, Al2214- boron carbide particles metal matrix composites at different wt. % of micro boron carbide reinforcement produced by a novel modified stir casting method have been studied.

Microstructure studies of composites by SEM results show reduced porosity and a fairly homogeneous distribution of reinforced micro boron carbide particles in the matrix. The reinforced boron carbide particles phases in the matrix were confirmed by an X-RD examination.

Specific density of the composites was decreased with boron carbide reinforcement. The micro and macro hardness have improved in the composites with the addition of boron carbide (B_4C) reinforcement and found the maximum at 6 wt.%.

The yield tensile and ultimate tensile strengths improved with the addition of boron carbide (B_4C) reinforcement in an alloy.

The wear resistance of Al2214 alloy at different loads and sliding distances was examined by the ASTM standards, and the result shows the wear resistance strength of Al2214 alloy increases a substantial amount with an increased addition of wt.% of boron carbide particles in the matrix.

The experimental results are reported as the micro boron carbide particles are potential reinforcement

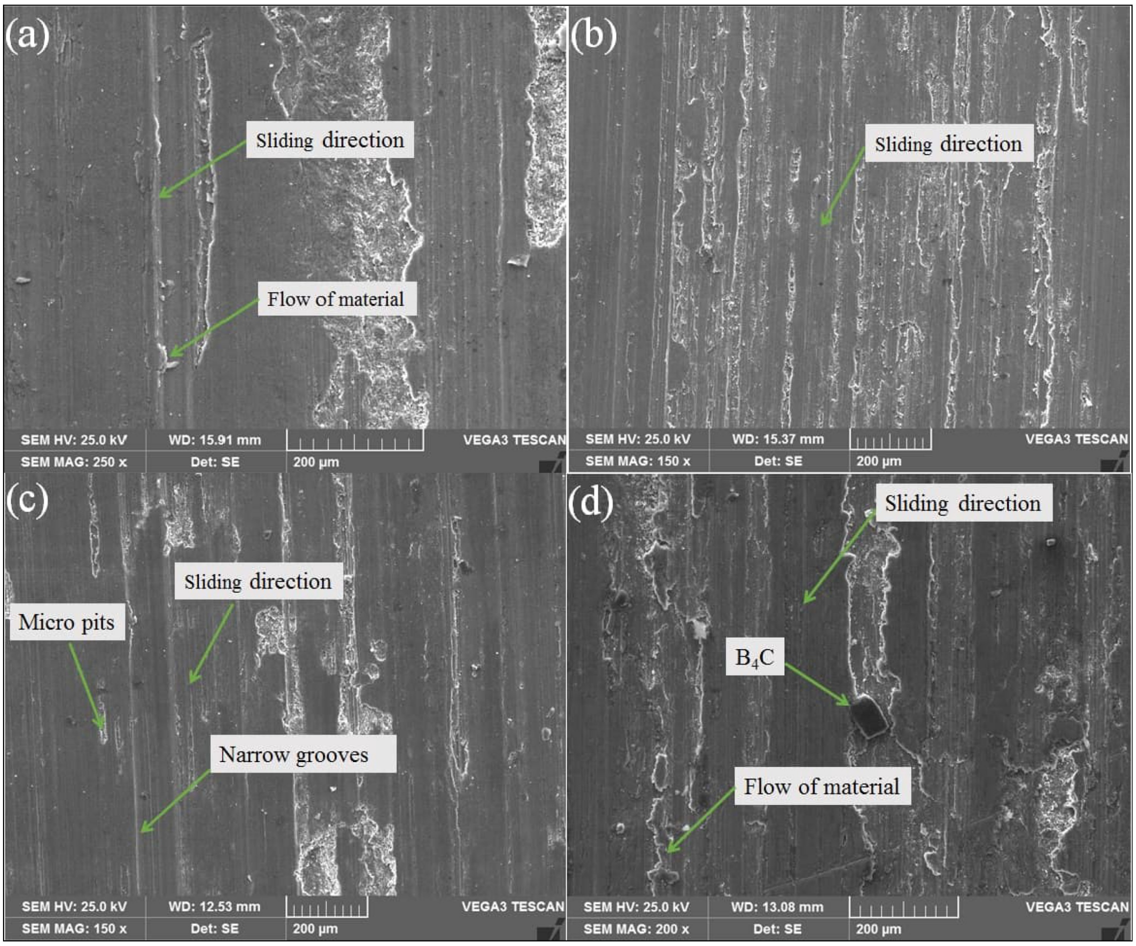

Figure 10. SEM micrographs of worn surface (a) Al2214-0% wt. B_4C at 10 N (b) Al2214-3% wt. B_4C at 10 N (c) Al2214-4.5% wt. B_4C at 20 N (d) Al2214-6 % wt. B_4C at 20 N

material in the Al2214-B_4C metal matrix material to increase the mechanical properties and sliding wear properties.

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