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Mechanical and wear behaviour of boron carbide fillers reinforced Lapox L-12 epoxy composites

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Abstract

To keep up with the growing demand for composites in fields like medicine, transportation, safety, and athletics, researchers constantly create new composites. These experiments examined the impact of boron carbide filler particles in epoxy by making composites out of Lapox L-12 epoxy with 5, 10, and 15 percent boron carbide fillers using the hand layup technique. The mechanical properties of the prepared composites were measured as per ASTM standards, including hardness, ultimate tensile strength, yield strength, elongation, and flexural strength. Further, wear behavior of prepared composites was evaluated as ASTM G99 standard with varying loads and speeds. Hardness, tensile and flexural strength were increased with a slight decrease in percentage elongation after boron carbide filler particles were added to epoxy Lapox L-12. Lapox L-12 with boron carbide fillers reinforced composites were shown an improvement of 56.4% in hardness, 52.5% in ultimate strength and 25.85% improvements in the flexural strength. The wear behaviour of epoxy and its composites were affected by applied load and speeds. However, Lapox L-12 with boron carbide fillers reinforced composites exhibits higher wear resistance with smooth worn surface morphologies. The improvement in the tensile and wear behavior of L-12 epoxy with B_4C composites can be utilized for several applications like air intake duct and air intake lip of an aircraft.

Keywords: B_4C Fillers, Epoxy L-12, Polymer composites, Tensile properties, Flexural strength, Wear

1. Introduction

The global automotive, aerospace, structural, and other high-tech industries have a growing demand for high-performance materials, and material scientists are increasingly called upon to meet that demand [1, 2]. As a result, advancements in composite materials that are both mechanically robust and tribologically superior have been made. Composites are favored because of their many uses, long lifespan, low cost, and ability to enhance the material's properties [3, 4]. Composites, which are made by combining or stacking multiple materials, have piqued the interest of scientists looking for alternatives to traditional metals. High specific strength, stiffness, fatigue behavior, and density [5, 6] make composites ideal for many applications, despite the product's weak matrix constituting polymers, which lead to low inter-laminar shear strength.

As the traditional lead caskets are found to be too cumbersome and chemically unstable to safely transport and store the spent nuclear fuel, there is a greater need for a better material to do so. Several academics have suggested epoxy for its superior performance in mechanical and structural applications [7, 8]. Epoxy composites are suited for mechanical uses for its high hardness, high fatigue resistance, and low contraction during curing. The epoxy's superior adhesion behavior to different reinforcements also makes it a great matrix material. Epoxy's excellent neutron stability and resilience behavior is another obvious reason for its use in many high-tech applications [9]. However, its resistance to wear and abrasion is subpar. Boron carbide (B_4C) is a ceramic material that has gained recent attention from the scientific community thanks to its remarkable mechanical, tribological, and structural qualities. Markandan and Lai [10] made a review on various fabrication methods, properties and industrial aspects of polymer composites with filler alignment. Nalaeram Sivaram et al. [11] studied the impact of sapodilla seed shell powder on the various properties of epoxy composites.

In addition, its hardness and density make it well-suited for some hard-wearing uses, such as abrasives, wear-resistant products, and even ballistics. Similarly, B_4C is used in nuclear industries for effective shielding of ionising radiations [12] due to its good neutron absorption cross section for catering the thermal neutrons and its 0.11A˚ -3 atomic number density. The improvement of mechanical and tribological properties has been studied, and research studies back the development of B_4C reinforced epoxy composites to achieve this goal. Reports also suggest that increasing the amount of particles added to B_4C composites can improve their wear resistance by helping the anchoring mechanism. While more of the same can be added to an epoxy environment, it has been found that doing so reduces the material's mechanical properties [13, 14].

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Wear properties of any engineering materials mainly contingent on load, speed, material hardness and existence of cross link material, also operating temperature and condition [15, 16]. The load and sliding velocity during pin-on-disc testing method are the main parameters which effect the wear rate of composites, and the aluminium composites shows low wear rate compared to the composite with low weight percentage of the B_4C particle reinforcement [17, 18]. Polymer based composite have widespread application in the agricultural feld and industries. In these places abrasive wear contributes to principal mode of failure in various applications such as conveyors, gears, bearings, bushes, seals etc. are some [19, 20]. Low cost and easily available fillers should improve the mechanical characteristics of the composites. Because hard particle fillers are well dispersed in polymer matrix composites, they enhance mechanical, thermal, and tribological properties; however, it is more optimal to add a smaller amount of nano and micro fillers to the matrix in order to maximize the properties of the composites [21, 22]. Composites reinforced with epoxy LY-556 and nano Al_2O_3 fillers were tribologically characterized by Dilip Kumar et al. [23]. Epoxy composites reinforced with nano fillers exhibited increased resistance to wear when tested with a range of sliding speeds and weights. Rice husk fillers reinforced polyethylene composites were developed by Arjmandi et al. [24], studied wear behavior of 0 to 6 wt. % of rice husk fillers reinforced epoxy composites. Rice husk filled polyethylene epoxy composites were more wear resistance against load and sliding speeds.

Based on the literature, tremendous research has been carried out on fillers reinforced composites. In the present investigation low micron sized B_4C fillers have been used to improve the properties of the L-12 epoxy. Also, in the present research an attempt has made to use upto 15 wt. % of carbide particles in the epoxy, beyond 15 wt. % of the particles in the epoxy decreases the elongation and makes the material brittle and leading to the catastrophic failure of the component.

The purpose of the experiments presented here was to characterize the mechanical and wear properties of epoxy composites that had been reinforced with boron carbide fillers. The goal of this research was to determine how increasing the B_4C filler content from 5 to 15 wt.% would affect the polymer composites' hardness, ultimate strength, yield strength, elongation, flexural strength and wear behaviour under varying loads and speeds.

2. Experimental details

2.1 Materials

For a long time, epoxy has been the go-to material for polymer matrix composites in aerospace and automotive applications due to its low cost, high strength-to-weight ratio, and high processing ease. The epoxy matrix material used in this investigation was made at room temperature by combining epoxy L-12 and hardener K-6 in a 10:1 ratio. The main reason to choose L-12 is due to its high performance applications. The L-12 epoxy can be cured to increase the strength in static and dynamic loading conditions. Epoxy polymer composites were filled with boron carbide particles. The B_4C particles used in the present studies were purchased from Speedfam Ltd., Chennai, and had a size distribution (Figure 1) typical of particles in the 10-15 microns in size range. Epoxy and hardener ratio is specified by the supplier in the ratio of 10:1, same has been adopted for the development of composites. The major reason choose the 10 to 15 micron sized particles is mainly to enhance the wear resistance of the composites. If particle size is too bigger, deboning will happen, and smaller particles leads to agglomeration in the composites. The primary characteristics of epoxy L-12 and boron carbide particles are shown in Tables 1 and 2, respectively.

Table 1 Mechanical properties of epoxy Lapox L-12

Density g/cc	Strength MPa	Young's Modulus GPa
1.2-1.3	50-125	2.5-40

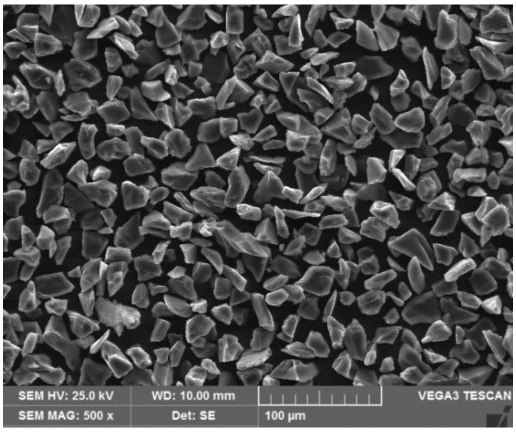


Figure 1 Scanning electron micrograph of B_4C particles used in the study

Table 2 Typical properties of B_4C

Properties	Born Carbide
Melting Point	2450°C
Hardness	3250 kg/mm^2
Density	2.52 g/cm^3
Co-efficient of Thermal Expansion	5 x 10^{-6}°C
Fracture Toughness	3.7 MPa m$^{1/2}$
Poisson's Ratio	0.21

For the preparation of the epoxy with B_4C fillers reinforced composites, a hand layup process was used. At first, a mixture of L-12 epoxy and K-6 hardener was made at a ratio of 10:1. In addition, a manually operated mechanical stirrer did a great job of dispersing fillers of boron carbide (at a concentration of 5 wt. %). The investing epoxy composites were fabricated using open moulding technology. A mould of 300 mm x 300 mm x 3 mm was coated with mould releasing agent were used for B_4C fillers filled epoxy composites. The final composites were prepared in a 300 mm x 300 mm, 3 mm thick mould (Figure 2). In addition, the same method was used to obtain 10 wt.% and 15 wt.% B_4C fillers reinforced polymer composites. At the end of 6 hours of curing, the composites plate shown in Figure 3 (300 mm x 300 mm x 3 mm) had obtained. Afterwards, the composites plates were dried out by being heat treated for 2 hours at 75 degrees Celsius in an electric oven. The fabricated composites plate of 3 mm thickness was cut into required size as per ASTM standards to conduct hardness, tensile, flexural and wear tests.

Figure 2 Mould used for the preparation of epoxy with boron carbide composites

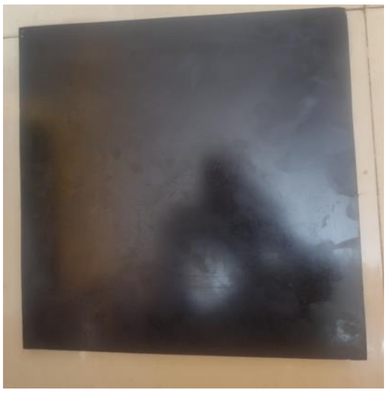


Figure 3 Epoxy with boron carbide fillers reinforced polymer composites

Machining these prepped composites to ASTM D638 specifications (Figure 4) allowed researchers to examine their diverse mechanical properties. Tensile tests were performed on 165 mm x 19 mm x 3 mm composites made from epoxy L-12 reinforced with 5, 10, and 15 wt.% of boron carbide fillers [25]. The tensile properties, like tensile strength and elongation, were discovered through experimentation. The mean of three samples was reported for each composition.

Flexural properties of epoxy composites were studied in relation to the addition of B_4C filler particles as per ASTM D790 (Figure 5). Flexural tests were performed on 127 mm x 12.7 mm x 3 mm composites made from epoxy L-12 reinforced with 5, 10, and 15 wt.% of boron carbide fillers [26]. Three samples of each composition were analyzed, and the average value was reported.

Figure 4 Tensile test specimen

Figure 5 Flexural test specimen

Dry sliding wear tests on L-12 epoxy with 5, 10 and 15 wt. % of B_4C fillers composites are conducted using a computerized pin-on-disc wear testing apparatus (Make: DUCOM Instruments Pvt. Ltd., Model: TR20LE) in compliance with the ASTM G99 standard [27]. En-32 steel discs with a hardness of HRC65 can accommodate track diameters up to 160 mm in diameter. Circular specimens of 3 mm in thickness and 25 mm in height are used to carry out the experiments. The wear loss of the pin in microns and weight loss in grammes are recorded in every test using a 1.0 µm least count LVDT. We then examine the associated volumetric wear loss.

3. Results and discussion

3.1 Tensile properties

Ultimate tensile strength is compared in Table 3 for epoxy L-12 and epoxy L-12 reinforced with 5–15 wt.% of micro B_4C filler particles.

Table 3 Ultimate tensile strength of epoxy L-12 with boron carbide filler composites

Sl. No.	Weight % of Epoxy L-12	Weight % of B_4C	Average Ultimate Tensile Strength (MPa)
1	100	--	47.10
2	95	5	57.47
3	90	10	65.30
4	85	15	71.87

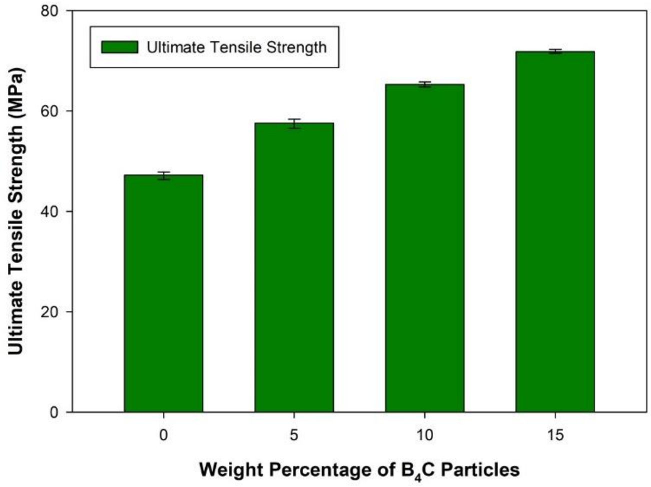


Figure 6 Ultimate tensile strength of epoxy with boron carbide fillers reinforced composites

Figure 6 and Table 3 display the results of room-temperature tensile tests conducted on epoxy L-12 composites with varying percentages of micro B_4C fillers. As can be seen in Figure 5, when fillers are included in the L-12 epoxy, the average UTS values improve. The L-12 epoxy's micro B_4C particle shields the more delicate matrix. L-12 epoxy has UTS of 47.10 MPa. In addition, the UTS of epoxy L-12 mixed with 5, 10, or 15 wt.% of micro B_4C composites is 57.47 MPa, 65.30 MPa, or 71.87 MPa.

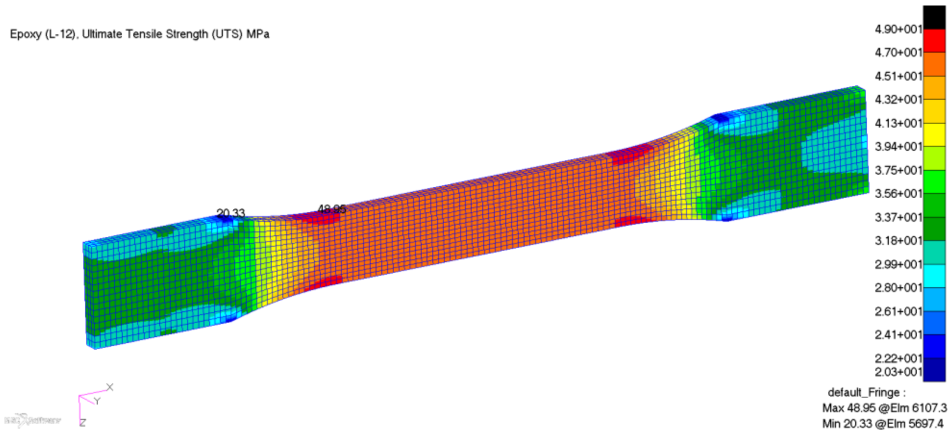


Figure 7 FEM analysis of L-12

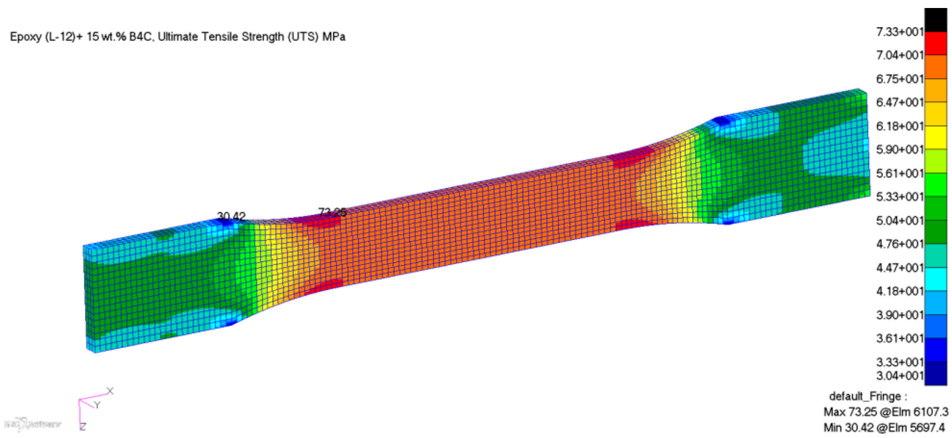


Figure 8 FEM analysis of L-12 epoxy with 15 wt.% of B_4C composites

Figure 7 and Figure 8 are representing the ultimate tensile strength of epoxy L-12 and epoxy with 15 wt.% of B_4C fillers reinforced composites. This FEM simulation has been carried out using MSC Patran and Nastran software. The tensile strength of epoxy L-12 with FEM analysis is 48.95 MPa, further the ultimate strength obtained form the experimental is 47.10 MPa. Similarly, simulations have been carried out for the epoxy with 15 wt. % of B_4C fillers reinforced composites. The FEM analysis results are conventional testing results of the composites are almost in line.

In addition, when compared to epoxy L-12, the tensile strength of B_4C fillers reinforced epoxy L-12 composites was significantly higher. When the system combination makes proper contact with the supporting elements, the strength significantly increases. Improved strong unbending nature is credited to the hard B_4C fillers, which offer an incentive to the system combination along this path. Difference in coefficient of produced between elastic network and particles [28] may have given rise to significant persistent compressive uneasiness made alongside solidifying as a result of the growth of these hard-miniature particles. This increase in UTS are obtained in epoxy after reinforcing with hard ceramic B_4C particles. This enhancement is observed because of increasing the addition level of boron particulates in the epoxy L-12.

Table 4 Yield strength of epoxy L-12 with boron carbide filler composites

Sl. No.	Weight % of Epoxy L-12	Weight % of B_4C	Average Yield Strength (MPa)
1	100	--	43.50
2	95	5	53.80
3	90	10	63.17
4	85	15	69.30

Table 4 shows the comparison between yield strength of epoxy L-12 and epoxy L-12 with 5 to 15 weight percentages of micro B_4C filler particles reinforced composites.

As can be seen in Figure 9, when fillers are added to L-12 epoxy, the average yield values improve. Epoxy L-12 has a Young's modulus of 43.50 MPa. In addition, the Yield Strengths (YS) of epoxy L-12 with 5, 10, and 15 wt.% of micro B_4C composites are 53.80 MPa, 63.17 MPa, and 69.30 MPa, respectively.

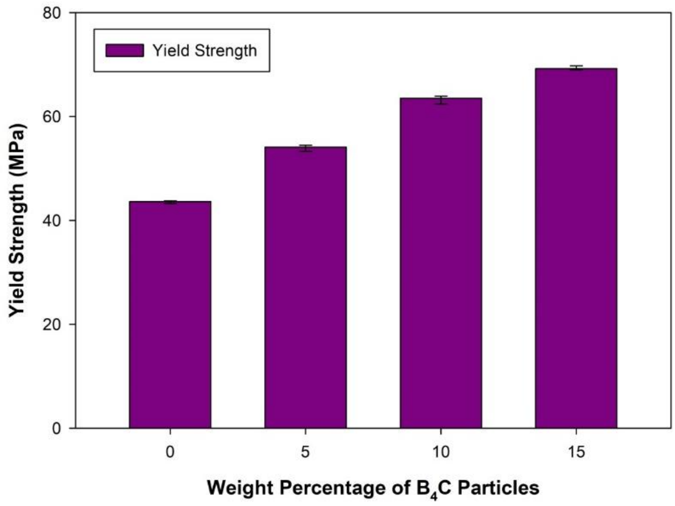


Figure 9 Yield strength of epoxy with boron carbide fillers reinforced composites

Figure 9 shows that compared to epoxy without filler, tensile values for the composite with filler are nearly twice as high, suggesting that the filler does not degrade the composite's tensile strength. Figure 6 depicts the tensile strength for loading in an L-12 epoxy with boron carbide filler composite, revealing an increase in tensile strength from 5 wt.% fillers to 15 wt.% fillers. The tensile strength of a composite material can be improved by increasing the filler weight fraction and the filler [29, 30]. Multiple tests showed that a composite containing 15 wt.% of B_4C fillers exhibited exceptional tensile strength.

Figure 10 and Table 5 show the percentage elongation of B_4C fillers reinforced composites. The ductility of L-12 epoxy is 1.63%, epoxy with 5% B_4C fillers is 1.46%, epoxy with 10% B_4C fillers is 1.36%, and epoxy with 15% B_4C fillers is 1.25%. Epoxy composites had their ductility reduced when B_4C fillers were added to them. Furthermore, as seen in plot 7, the elongation decreases as the B_4C filler content is raised from 5% to 15%. The addition of 15 wt.% B_4C fillers to epoxy L-12 decreased the material's ductility to 1.25 percent.

Table 5 Percentage elongation of epoxy L-12 with boron carbide filler composites

Sl. No.	Weight % of Epoxy L-12	Weight % of B_4C	Average Elongation (%)
1	100	--	1.63
2	95	5	1.46
3	90	10	1.36
4	85	15	1.25

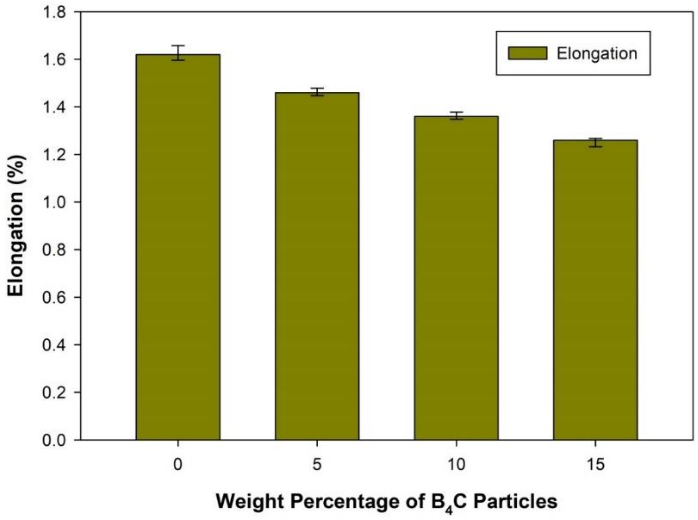


Figure 10 Elongation of epoxy with boron carbide fillers reinforced composites

3.2 Flexural strength

Table 6 shows the comparison between the flexural strength of epoxy L-12 and epoxy L-12 with 5 to 15 weight percentages of micro B_4C filler particles reinforced composites.

From the Figure 11 it is observed that the average flexural strength values are enhanced with the addition of fillers in the L-12 epoxy. The flexural strength of epoxy L-12 is 146.37 MPa. Further, the flexural strength of epoxy L-12 with 5, 10 and 15 wt. % of micro B_4C composites are 161.53 MPa, 176.77 MPa and 184.33 MPa respectively. Figure 8 depicts that as the wt. % of boron carbide particles increases from 5 wt. % to 15 wt. %, there is an increase in the flexural strength of epoxy. This increase in strength is mainly due to the presence of filler particles in the L-12 epoxy, acts as a barrier for the deformation during loading [31].

Table 6 Flexural strength of epoxy L-12 with boron carbide filler composites

Sl. No.	Weight % of Epoxy L-12	Weight % of B_4C	Average Flexural Strength (MPa)
1	100	--	146.37
2	95	5	161.53
3	90	10	176.77
4	85	15	184.33

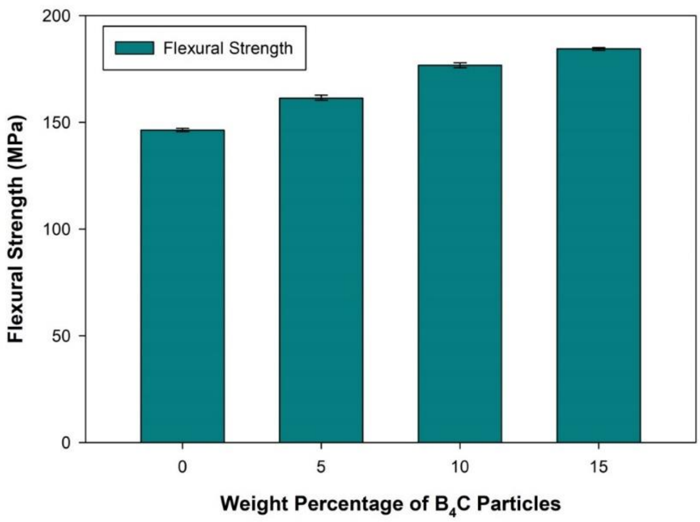


Figure 11 Flexural strength of epoxy with boron carbide fillers reinforced composites

3.3 Wear properties

The impact of load on the wear loss of epoxy L-12 and L-12 with 5, 10 and 15 wt. % of boron carbide fillers composites while sliding at a constant 400 rpm over a distance of 2500 meters under 10 N, 20 N and 30 N is illustrated in Figure 12.

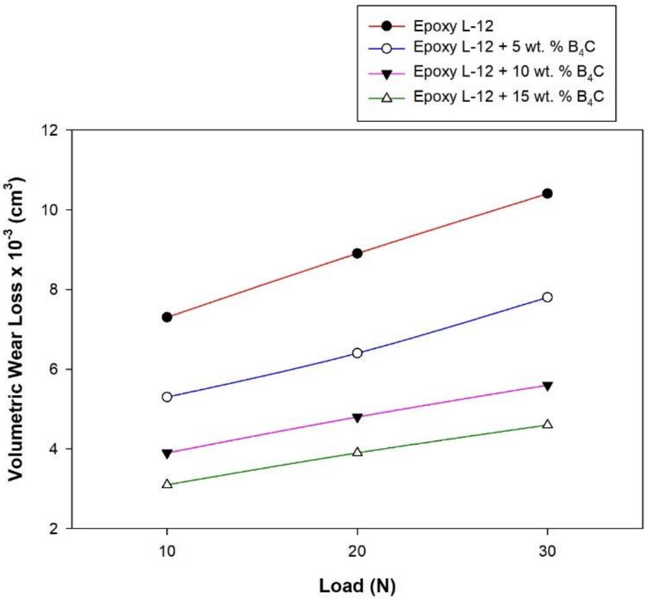


Figure 12 Volumetric wear loss of L-12 epoxy with B_4C fillers at varying loads

Volumetric wear loss exhibits an upward trend as the load escalates from 10 N to 30 N, particularly in the event of base epoxy L-12 matrix and composites that comprise 5 to 15 wt.% of B_4C fillers. The volumetric loss of B_4C fillers reinforced polymer composites is diminished in comparison to L-12 epoxy. Additionally, composites composed of L-12 with 15% B_4C exhibited the least amount of volumetric wear loss. As the load increases by 30 N, both the epoxy and the composites experience a consistent escalation in wear degradation. Volumetric loss increased for every sample of L-12 base epoxy matrix and composite as the load was increased.

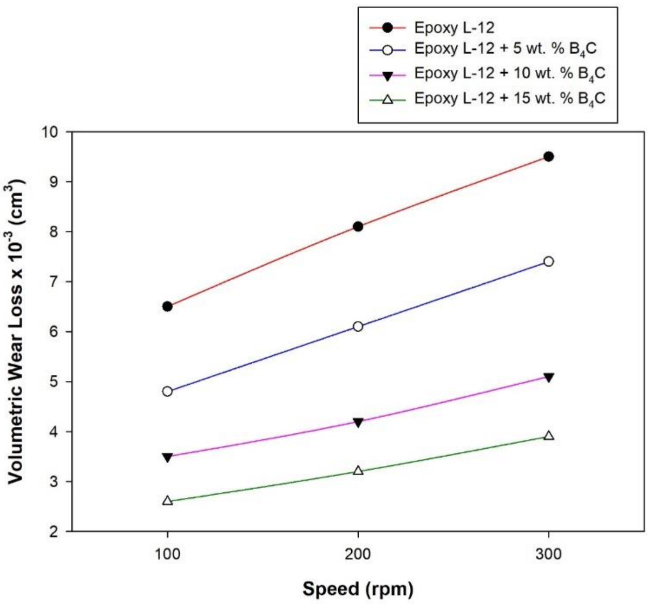
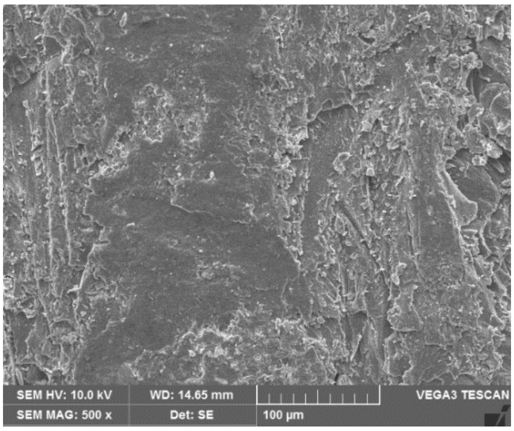


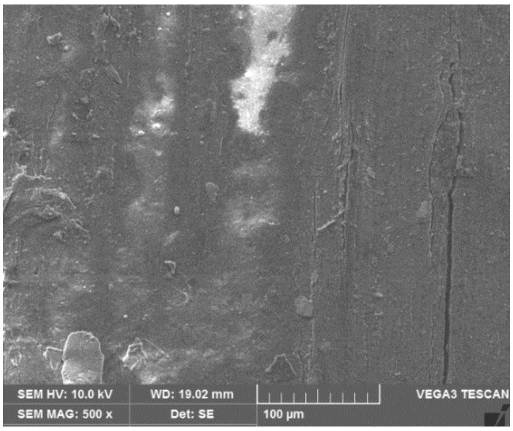
Figure 13 Volumetric wear loss of L-12 epoxy with B_4C fillers at varying speeds

In Figure 13, the impact of speed on the wear loss of L-12 epoxy and fillers reinforced composites supplemented with 5 to 15 wt. % of B_4C is illustrated. The experimental conditions involved a constant 30 N load, a distance of approximately 2500 metres, and sliding velocities of 100, 200 and 300 revolutions per minute. When subjected to sliding velocities ranging from 100 to 300 revolutions per minute, base epoxy and composites containing 5 to 15 weight percent of B_4C experienced the most significant volumetric loss. In contrast to the epoxy matrix, B_4C fillers reinforced composites exhibit a diminished volumetric wear loss. Additionally, composites composed of epoxy L-12 with 15% B_4C fillers exhibited the least amount of volumetric wear loss.

As the sliding velocity increases, the wear measurements for both the epoxy combination and composites reveal a consistent escalation in wear loss, spanning from 100 rpm to 300 rpm. This is not surprising given that a greater distance can be traversed in an equivalent length of time when travelling at a higher speed. At higher velocities, the discernible indications of deterioration, including rough spots and an unappealing surface, become more conspicuous. Pramanik [31] and colleagues discovered that surface materials become gentler when heated and subjected to increased strength, but harden when metal oxides are formed. Notwithstanding the solid state and elevated dissolving temperature of the metal oxide interface in comparison to pure metal, the oxide layer is subjected to more rapid sliding velocities when sheared by its constituent materials.



(a)



(b)

Figure 14 SEM images of worn surfaces at 500 X (a) epoxy L-12 (b) L-12 with 15 wt. % of B_4C filler composites

Figure 14 (a-b) shows scanning electron microscopy images of the worn surfaces of the epoxy L-12 and composite with a 15 wt.% of B_4C fillers, obtained under conditions of a 30N load and a sliding speed of 300 rpm. When looking closely at the worn epoxy surface, large grooved areas become apparent. The plastic deformation of unreinforced epoxy material causes deeper grooves, surface fractures, and scratches. There are some damaged spots and continuous wear grooves, as seen in Figure 14 (a).

Figure 14 (b) shows that compared to unreinforced epoxy, the wear surface of L-12 with a 15 wt.% of B_4C composite is smooth, as shown by the reduction in volumetric wear loss. There are still smooth wear tracks evident on the worn surface of micro B_4C composites, which indicates that the wear mechanism is abrasion. No debonding or pulling out of the reinforcing phase is visible on the worn surfaces.

4. Conclusions

According to the findings of this investigation, the tensile strength of the filler material composite improved. Epoxy composites with 15 wt. % of boron carbide fillers exhibited superior ultimate and yield strength. Further, elongation of B_4C filler reinforced epoxy composites decreased as weight percentage of fillers increased to 15 wt.%. Epoxy with 15 wt. % of boron carbide filler composites shown more flexural strength. Lapox L-12 with boron carbide fillers reinforced composites were shown an improvement of 56.4% in hardness, 52.5% in ultimate strength and 25.85% improvements in the flexural strength. The tensile strength of the L-12 and its composites were validated by FEM analysis. Volumetric wear loss of epoxy L-12 and B_4C fillers reinforced composites affected by the applied load and speeds. As load increased from 10 N to 30 N and speed increased from 100 rpm to 300 rpm. The volumetric wear loss increased in all prepared specimens. However, boron carbide fillers reinforced epoxy L-12 composites exhibited superior wear resistance. The improvement in the tensile and wear behavior of L-12 epoxy with B_4C composites can be utilized for several applications like air intake duct and air intake lip of an aircraft.

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