

Optimization and Characterization of B₄C Particle Reinforced AA 6063 Matrix Composites

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ABSTRACT

The aim of this study is to investigate the mechanical behavior and its relation with processing and microstructure of the B₄C reinforced aluminum matrix composite. Aluminum 6063 alloy is chosen as matrix alloy. Composites were processed by liquid casting technique. Aluminum has a combination of properties that makes it one of the most versatile of all engineering materials. It can be alloyed with other elements to get a customized set of mechanical properties. Aluminum alloy 6063 is one such combination which provides medium-to-high-strength, good formability and good corrosion resistance along with low density. Boron carbide is one of the hardest materials with a density of 2.54 g/cm³. The B₄C reinforced Aluminium metal matrix composite was prepared through liquid casting technique. Various Volume % of B₄C is added with AA 6063. There is a possibility of increasing the hardness and other mechanical properties of aluminum alloys without affecting the overall weight of the component by developing aluminum matrix composites. In the present study boron carbide particles were dispersed in AA6063 matrix forming a new aluminum matrix composite. For improving wettability, the K₂TiF₆ flux was added. The as cast composites were undergone T₆ heat treatment. The heat treated AA 6063- B₄C composites were undergone mechanical and wear tests. It shows that the wear rate is minimum at 5 vol% B₄C composites and hardness reaches maximum at 15 vol % B₄C composites.

INTRODUCTION COMPOSITE

Composite material is a material composed of two or more distinct phases (matrix phase and reinforcing phase) and having bulk properties significantly

different from those of any of the constituents. Many of common materials (metals, alloys, doped ceramics and polymers mixed with additives) also have a small amount of dispersed phases in their structures, however they are not considered as composite materials since their properties are similar to those of their base constituents (physical property of steel are similar to those of pure iron). Favorable properties of composites materials are high stiffness and high strength, low density, high temperature stability, high electrical and thermal conductivity, adjustable coefficient of thermal expansion, corrosion resistance, improved wear resistance etc.

(a) MATRIX PHASE

- The primary phase, having a continuous character,
- Usually more ductile and less hard phase,
- Holds the reinforcing phase and shares a load with it.

(b) REINFORCING PHASE

- Second phase (or phases) is imbedded in the matrix in a discontinuous form,
- Usually stronger than the matrix, therefore it is sometimes called reinforcing phase.

CLASSIFICATION OF COMPOSITES

Composite materials are classified

(a) On the basis of Matrix:

1. Metal Matrix Composites (MMC)
2. Ceramic Matrix Composites (CMC)
3. Polymer Matrix Composites (PMC)

(b) On the basis of Material Structure:

1. Particulate Composites
2. Fibrous Composites
3. Long-fiber reinforced composites.
4. Laminate Composites

RULE OF MIXTURES

Rule of Mixtures is a method of approach to approximate estimation of composite material properties, based on an assumption that a composite property is the volume weighed average of the phases (matrix and dispersed phase) properties. According to Rule of Mixtures properties of composite materials are estimated as follows:

$$\text{Density } d_c = d_m \cdot V_m + d_f \cdot V_f$$

Where,

d_c, d_m, d_f – densities of the composite, matrix and dispersed phase respectively;

V_m, V_f – volume fraction of the matrix and dispersed phase respectively.

Metal Matrix Composites (MMCs)

Metal Matrix Composites are composed of a metallic matrix (Al, Mg, Fe, Cu etc) and a dispersed ceramic (oxide, carbides) or metallic phase (Pb, Mo, W etc). Ceramic reinforcement may be silicon carbide, boron, alumina, silicon nitride, boron carbide, boron nitride etc. whereas Metallic Reinforcement may be tungsten, beryllium etc. MMCs are used for Space Shuttle, commercial airliners, electronic substrates, bicycles, automobiles, golf clubs and a variety of other applications. From a material point of view, when compared to polymer matrix composites, the advantages of MMCs lie in their retention of strength and stiffness at elevated temperature, good abrasion and creep resistance properties [19]. Most MMCs are still in the development stage or the early stages of production and are not so widely established as polymer matrix composites. The biggest disadvantages of MMCs are their high costs of fabrication, which has placed limitations on their actual applications [20]. There are also advantages in some of the physical attributes of MMCs such as no significant moisture absorption properties, non inflammability, low electrical and thermal conductivities and resistance to most radiations [21]. MMCs have existed for the past 30 years and a wide range of MMCs have been studied [19].

Compared to monolithic metals, MMCs have:

- Higher strength-to-density ratios
- Higher stiffness-to-density ratios
- Better fatigue resistance
- Better elevated temperature properties
- Higher strength

- Lower creep rate
- Lower coefficients of thermal expansion
- Better wear resistance

The advantages of MMCs over polymer matrix composites are:

- Higher temperature capability
- Fire resistance
- Higher transverse stiffness and strength
- No moisture absorption
- Higher electrical and thermal conductivities
- Better radiation resistance
- No out gassing
- Fabric ability of whisker and particulate-reinforced MMCs with conventional metalworking equipment.

Some of the disadvantages of MMCs compared to monolithic metals and polymer matrix composites are:

- Higher cost of some material systems
- Relatively immature technology
- Complex fabrication methods for fiber-reinforced systems (except for casting)
- Limited service experience

The most important MMC systems are:

- Aluminum matrix
- Magnesium matrix
- Titanium matrix
- Copper matrix
- Superalloy matrices

STIR CASTING METHOD OF FABRICATION OF MMCs

Liquid state fabrication of Metal Matrix Composites involves incorporation of dispersed phase into a molten matrix metal, followed by its Solidification. In order to provide high level of mechanical properties of the composite, good interfacial bonding (wetting) between the dispersed phase and the liquid matrix should be obtained. Wetting improvement may be achieved by coating the dispersed phase particles (fibers). Proper coating not only reduces interfacial energy, but also prevents chemical interaction between the dispersed phase and the matrix. The simplest and

the most cost effective method of liquid state fabrication is Stir Casting.

Stir Casting

Stir Casting is a liquid state method of composite materials fabrication, in which a dispersed phase (ceramic particles, short fibers) is mixed with a molten matrix metal by means of mechanical stirring. The liquid composite material is then cast by conventional casting methods and may also be processed by conventional Metal forming technologies.

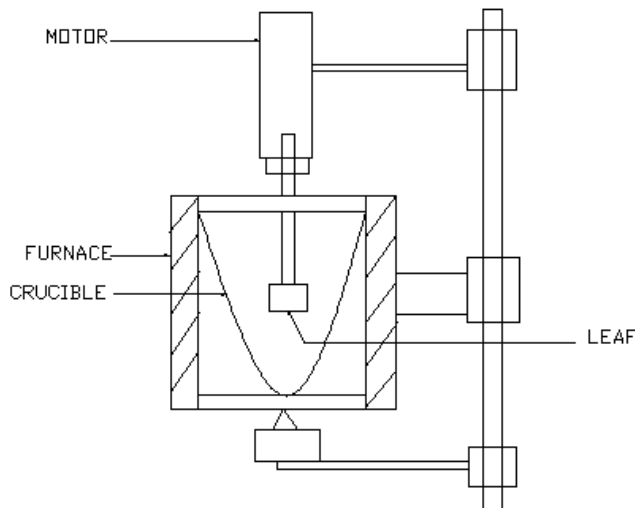


FIG 1.1 STIR CASTING



FIG 1.2 STIR CASTING

STRENGTHENING MECHANISM OF FIBRE REINFORCED COMPOSITE

In such type of composite the reinforcing phase carries the bulk of the load and the matrix transfers the load to the reinforcing phase by the mechanism of seam. The high strength of the reinforcing phase restrict the free elongation of the matrix especially in its vicinity, whereas later is free to elongate at some distance away from the former. This type of non uniform deformation of the matrix leads to a shear stress at the matrix reinforcement interface which results tensile stress at the reinforcing phase. Thus the stress is transferred to the reinforcing phase. The fibers either may be continuous or discontinuous in the matrix. In the former case the load is directly applied to the reinforcing phase and stress is constant over its entire length. In case of discontinuous fibers, the stress in the fibre increased from zero value at the end to a maximum value in the centre and thus average tensile strength developed is always less than those of continuous fibers. When the fracture of the reinforcing phase, therefore the strength of the discontinuous fibre reinforced composite increases with increasing the length of the fibre and artifacts that of the continuous fibre reinforced one. Also the strength of the fibre reinforced composite will be maximum when the fibres are aligned in the direction of the applied stress i.e in the isostrain condition. So the strength of this kind of composite depends on the volume fraction of the reinforcing element present in the composite, which can be determined by the simple rule of mixtures.

Boron Carbide

Boron Carbide is one of the hardest materials known, ranking third behind diamond and cubic boron nitride. It is the hardest material produced in tonnage quantities. Originally discovered in mid 19th century as a by-product in the production of metal borides, boron carbide was only studied in detail since 1930.

Boron carbide powder is mainly produced by reacting carbon with B₂O₃ in an electric arc furnace, through carbo thermal reduction or by gas phase reactions. For commercial use B₄C powders usually need to be milled and purified to remove metallic impurities.

In common with other non-oxide materials boron carbide is difficult to sinter to full density, with hot pressing or sinter HIP being required to achieve greater than 95% of theoretical density. Even using these techniques, in order to achieve sintering at realistic temperatures (e.g. 1900 - 2200°C), small quantities of dopants such as fine carbon, or silicon carbide are usually required. As an alternative, B4C can be formed as a coating on a suitable substrate by vapour phase reaction techniques e.g. using boron halides or di-borane with methane or another chemical carbon source. Its Vickers hardness (38 GPa) and fracture toughness (3.5 MPa•m^{1/2}) approach the corresponding values for diamond (115 GPa and 5.3 MPa•m^{1/2}).

Boron carbide (B4C) is the third hardest material after diamond and cubic boron nitride, which possesses low density (2.52g /cm³), high degree of chemical inertness, high temperature stability, and excellent thermoelectric properties. The atomic structure of boron carbide is rather unique. This unusual structure and bonding is responsible for the excellent thermo mechanical properties of boron carbide, thus making it a good substitute for many applications. The widely accepted structure of boron carbide is rhombohedral with boron icosahedra. It can be used in the form of powder, sintered product, as well as thin films for various applications such as, coated cutting tools, armor uses in manual and vehicle protection, and protective coating for electronic instruments.¹ Another important characteristic of boron carbide is its high neutron absorption capacity which makes it attractive for neutron-shielding applications. Boron has a naturally occurring isotope, B10, which is an efficient absorber of neutrons² and has a neutron capture cross-section of approximately 4000 barns (1 barn=10⁻²⁴ cm²). Typically, B10 constitutes approximately 20% of boron, with the remainder being B11. Therefore, boron carbide compounds with a boron-rich stoichiometry are suitable for neutron-absorbing reactions. Although, boron carbide can be compacted into fully dense bodies, structures made entirely of boron carbide generally have low fracture toughness and poor thermal shock resistance. Therefore, in order to take advantage of its neutron absorption properties,

structures containing boron carbide have been fabricated in different forms, namely, (1) boron carbide particles has been encased in stainless steel tubes for use as control rods in nuclear reactor cores, (2) boron carbide pellets have been clad with zirconium–aluminum alloys for use as a burnable poison in nuclear reactors, and (3) low strength boron carbide–aluminum sheets have been clad with thin aluminum alloy sheets and used to line steel canisters for housing spent nuclear fuel. For structural nuclear-shielding applications such as nuclear waste containers or shielding elements for nuclear submarines, the material should also be manufacturable into a desired shape, should possess high strength and toughness, and should not be prone to brittle fracture. One of the solutions is going for boron carbide-reinforced metal matrix composites (MMC), which are uniquely suited as a structural neutron-shielding material, where tailorable properties of neutron absorption as well as enhanced mechanical properties such as high strength, stiffness, and hardness can be obtained.

Criteria which are important in considering the interface that exists in a MMC material:

- a. Adsorption and Wetting
- b. Inter-diffusion
- c. Chemical bonding
- d. Mechanical adhesion

Adsorption and Wetting

Good wettability is needed to generate a strong interface that will allow transfer and distribution of load from the matrix to the dispersed phase, without premature thermodynamically reversible work needed to separate interface into its component parts:

$$W_a = Y_s + Y_L - Y_{SL} \dots\dots\dots (1)$$

Y_S = Surface energy of solid

Y_L = Surface energy of liquid

Y_{SL} = Interfacial energy of solid-liquid phase

Young – Dupre’s equation:

$$Y_S = Y_{SL} + Y_L \cos\theta \dots\dots\dots (2)$$

θ = contact angle

Combining (1) and (2)

$$W_a = Y_L (1 + \cos\theta)$$

Thus from a knowledge of θ and Y_L, the work of adhesion can be found out.

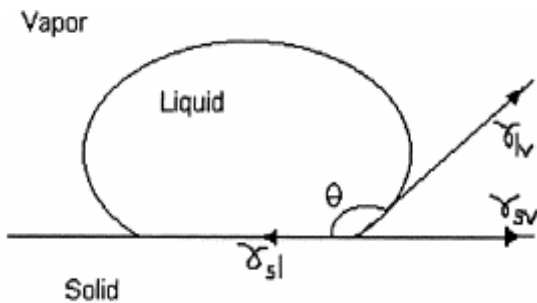


Fig 1.3 liquid drop on the solid surface

- For $\theta=180$, the drop is spherical with only point contact with the solid and no wetting takes place
- For $\theta=0$, the wetting is perfect.
- For $0 < \theta < 180$, the degree of wetting increases as θ decreases.

Adsorption

It is a surface reaction which is dependent on concentration, temperature, and diffusivity. The greater the adsorption, the more the solute tends to lower the surface energy.

Inter-diffusion

Inter-diffusion plays only a minor role at low temperatures, but at elevated temperatures approaching the mp of the matrix, inter-diffusion and chemical reaction can result in the formation of brittle intermetallics which are detrimental to the mechanical properties of MMCs.

Chemical bonding

For strong chemical bonding between the reinforcement and matrix a controlled amount of chemical reaction at the interface is always desirable. However, too thick an interfacial zones adversely the mechanical properties of the composites and leads to premature failure.

EXPERIMENTAL WORK

MATRIX METAL

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Others	Al
0.2-0.6	0-0.35	0-0.10	0-0.10	0.45-0.9	0-0.10	0-0.10	0-0.10	0-0.10	Balance

Table3.1 COMPOSITION OF AA6063

EXPERIMENTAL PROCEDURE

First of all, 1000 gm of commercially pure aluminium was melted in a resistance heated muffle furnace and casted in a graphite crucible. For this the melt temperature was raised to 800°C and it was degassed by purging hexachloro ethane tablets. Then the aluminium-B₄C composite was prepared by stir casting route. For this we took 1000 gm of commercially pure aluminium and 5,10,15,20 Vol % of B₄C. The B₄C particles were preheated to 373°C for two hours to remove the moisture. Commercially pure aluminium was melted by raising its temperature to 800°C and it was degassed by purging hexachloro ethane tablets. Then the melt was stirred using a mild steel stirrer. B₄C particles were added to the melt at the time of formation of vortex in the melt due to stirring. The melt temperature was maintained at 800- 850 °C during the addition of the particles. Then the melt was casted in a steel mold as shown in fig.1.



Figure3.1 Steel Die

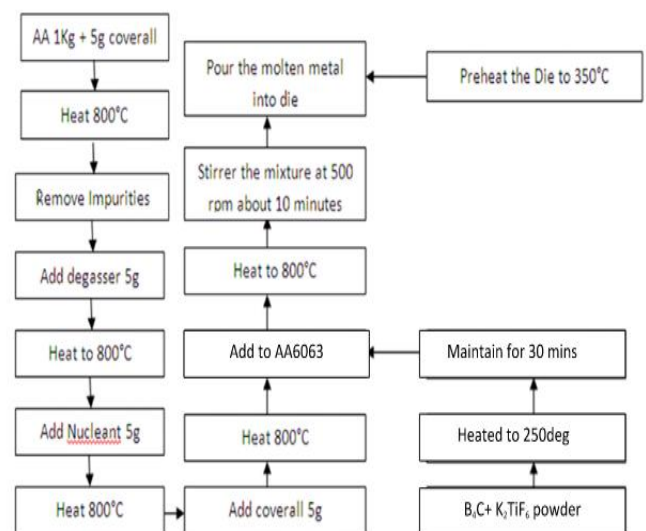


Figure3.2 Experimental Procedure



Figure3.3 Aluminum rods to be cast

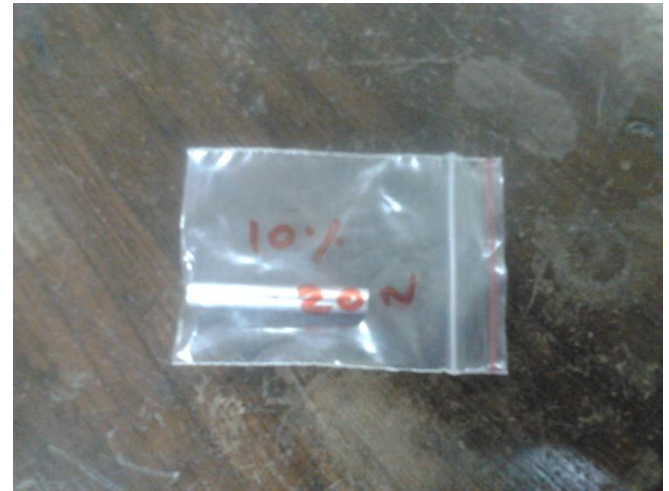


Figure3.6 Pin prepared from AArod



Figure3.4 Molten AAmatrix being casted



Figure3.5 Casted Aluminum rods

Heat Treatment

All of the specimens were heat treated according to ASM T6 heat treatment procedures. The heat treated samples were solution treated at 480 °C for 55 to 65 minutes. Then they were quenched into water. Finally precipitation heat treatment was carried out for 24 hours at 120 °C.

The hardness testing and density measurement will be carried out for both commercially pure Al and Al-B4C composite. The hardness of the samples will be determined by Brinell hardness testing machine with 500 kg load and 10 mm diameter steel ball indenter.

After preparing the samples in accordance with the standard metallographic procedure, the microstructural characterization of the investigated alloys was analyzed using a Jeol 6060 scanning electron microscope (SEM) (Karuna University, Coimbatore) equipped with an energy-dispersive X-ray spectroscope (EDS).

RESULTS AND DISCUSSION

Hardness Test Results

Hardness tests were carried out to observe the effects of heat treatment and effects of vol% addition of boron carbide on aluminum alloy matrix (AA 6063) since hardness is an indicator of a materials resistance to plastic deformation. Figure 4.1. shows the variation of hardness values with vol % boron carbide. Hardness test results are listed in Table 4.1

Measurement No.	1	2	3	4	5	Average
AA 6063	86	92	90	85	85	89
AA 6063 / 5 vol%	113	107	106	108	116	110
AA 6063 / 10 vol %	132	134	138	133	138	135
AA 6063 / 15 vol%	145	154	159	149	155	152

Table 4.1 Hardness test values (BHN)

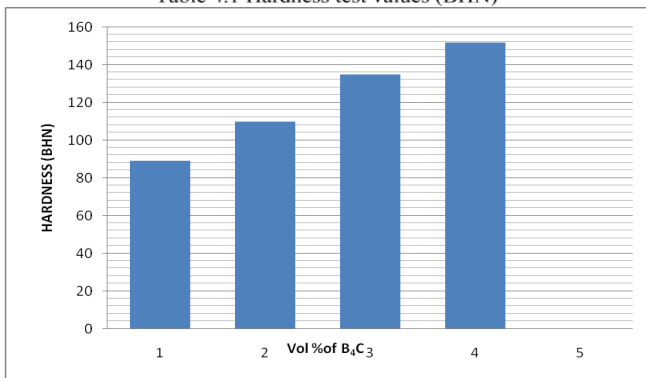


Figure 4.1 variation of Hardness with varying vol% of B₄C

From the above fig it shows that the hardness value of the B₄C reinforced composites greater than that of Al 6063 alloy and the hardness value of the composites 22 % greater than that of base alloy. The hardness value increases with increase the content of boron carbide.

Wear Test

The wear test was conducted at room temperature by using pin on disc. The wear rate for AA6063- Boron carbide composite was decreasing with increasing wt % of B₄C. From the fig.4.2 it shows that 5 Vol % of B₄C was the optimum. The wear resistance of the composite was increased as compared to base matrix.

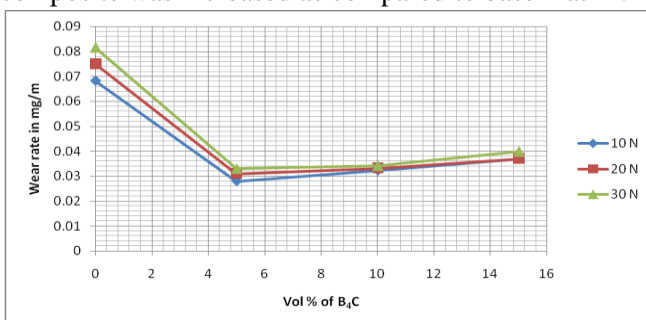


Figure 4.2 Variation of wear rate with varying vol % of B₄C

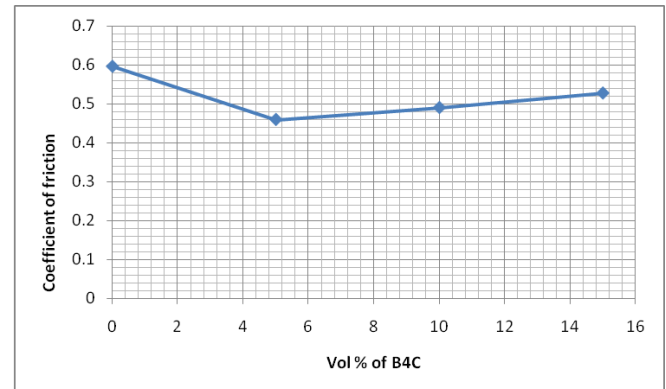


Figure 4.3 Co efficient of friction with varying vol % of B₄C

The co efficient of friction decreases with increasing vol % of Boron carbide as compared to base alloy and it reaches its minimum value at 5 vol % of B₄C.

SEM photo graphs

An examination of the morphologies of the worn surfaces indicates the existence of abrasion and delamination wear mechanisms in these composites. The result also indicates that increasing the concentration of B₄C beyond 5 % in the composite increases the wear. The hard B₄C particles create deep marks on the surface of the steel counterface. Higher concentration of B₄C increases the number of scars on the steel counterface which inturn increase the wear rate of the composite. The hard B₄C particles support the normal pressure on the surface leading to higher wear resistance.

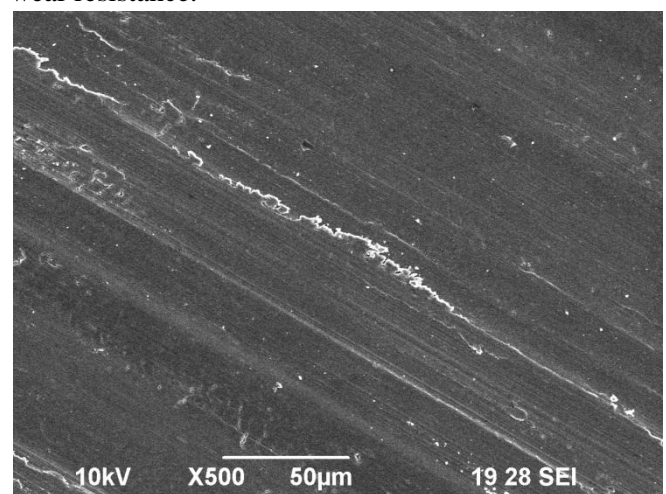


Figure 4.4 SEM Morphology of worn surfaces of AA6063 (10 N)

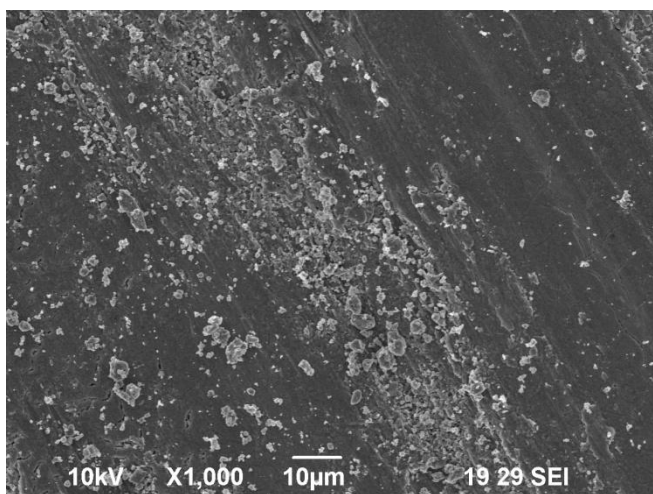


Figure 4.5 SEM Morphology of worn surfaces of AA6063 -5 vol % of B₄C (10N)

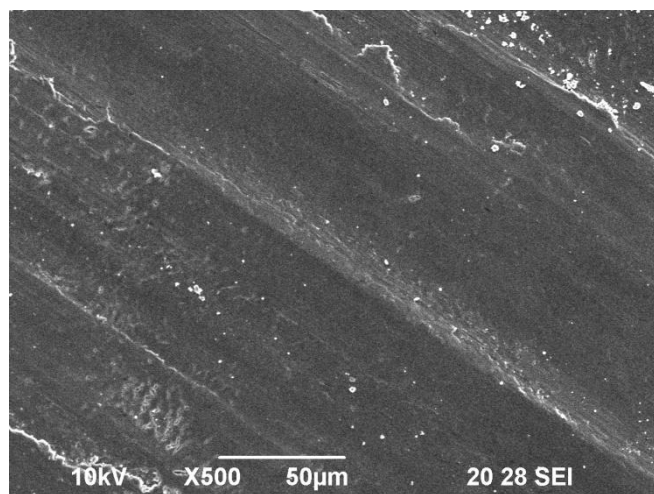


Figure 4.8 SEM Morphology of worn surfaces of AA6063 (30 N)

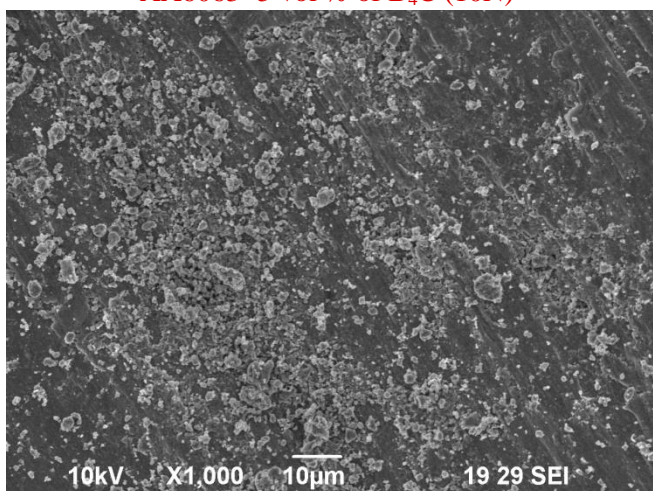


Figure 4.6 SEM Morphology of worn surfaces of AA6063 -10 vol % of B₄C (10N)

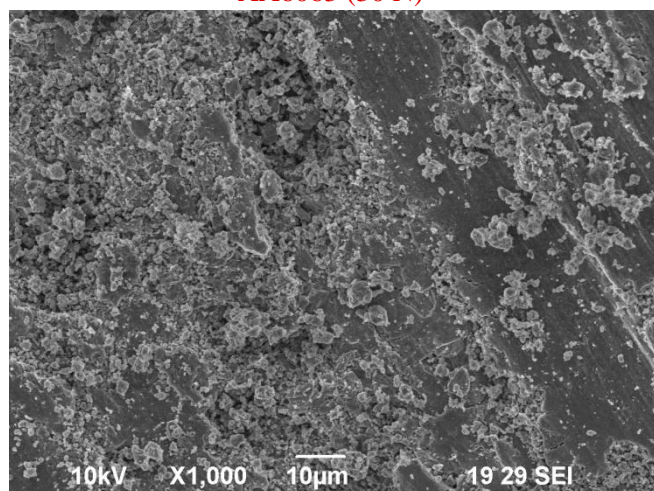


Figure 4.9 SEM Morphology of worn surfaces of AA6063 -5 vol % of B₄C (30N)

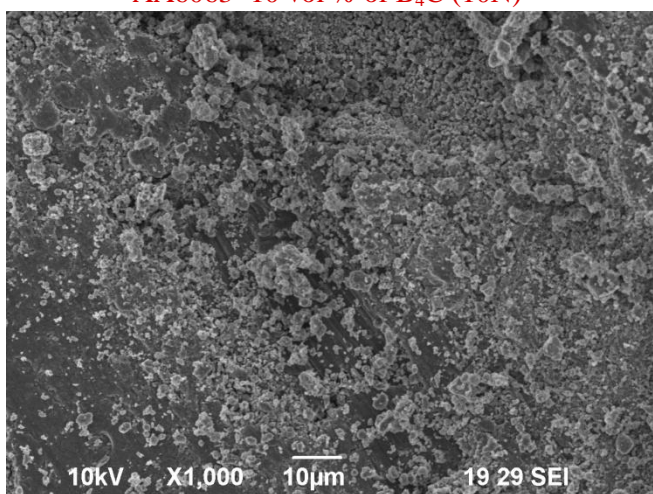


Figure 4.7 SEM Morphology of worn surfaces of AA6063 -15 vol % of B₄C (10N)

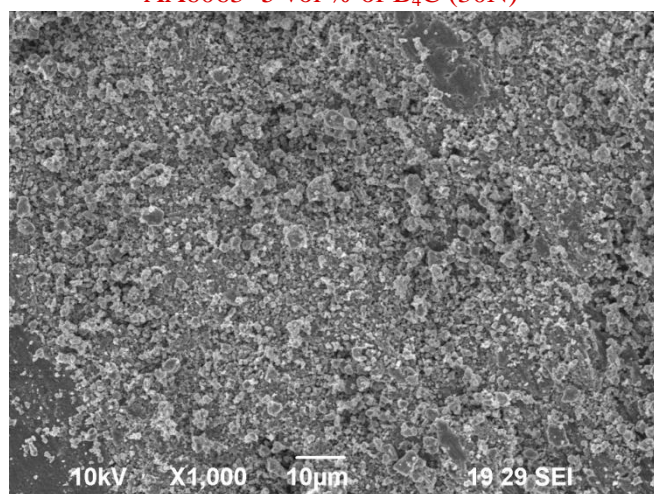


Figure 4.10 SEM Morphology of worn surfaces of AA6063 -10 vol % of B₄C (30N)

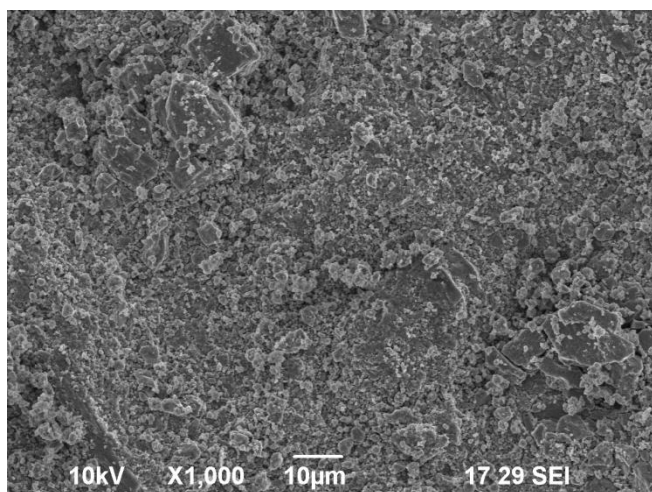


Figure 4.11 SEM Morphology of worn surfaces of AA6063 -15 vol % of B₄C (30N)

CONCLUSION

The objective of this study is to investigate the mechanical and tribological behavior of boron carbide reinforced aluminum matrix composite. Hardness tests, compression tests, wear test and SEM analysis were performed.

The following results were obtained:

(i) Al 6063 – B₄C composites were fabricated successfully by using liquid casting technique by adding K₂TiF₆ flux.

(ii) Hardness values increased with the increase of B₄C addition in both as-cast and heat treated composites. The maximum hardness value was obtained at 20 Vol % of B₄C.

(iii) The hardness values were obtained after T6 heat treatment procedure. Composites were solution heat treated at 480 °C for 55-65 minutes. Peak hardness values are about 20-25% higher than as-cast hardness values.

(iv) The compression strength increased with increasing reinforcement content up to 15 vol% B₄C in both as-cast and heat treated composites. 15 vol% B₄C composites showed enough internal ductility to attain full strength.

(v) The wear resistance of composites are greater than that of AA 6063 and it will be optimum at 5 vol % of B₄C.

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