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Mechanical Characterization and Tribological Behaviour of Al-Gr-B_4c Metal Matrix Composite prepared by Stir Casting Technique

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ABSTRACT

In this work, using stir casting technique 99.85% pure aluminum matrix was reinforced with graphite particles and boron carbide particles to study the effect of graphite and boron carbide reinforcement using mechanical testing and wear behaviour. Different volume fractions of boron carbide viz. 2.5%, 5% and 7.5% are incorporated into the alloy, maintaining the volume fraction of graphite as 2% for all proportions. The distributions of reinforcement are made uniform by using a mechanical stirrer attachment and the various compositions of metal matrix composite are casted for testing. Microstructural characterization studies performed on the different compositions of composite prepared shows a uniform distribution of B_4C particles at microscopic scale with less porosity. Mechanical properties such as Micro-Vickers hardness test and compression strength are determined and tribological behaviour of the composite is studied using wear test. With 7.5% reinforcement of B_4C particles, the hardness and compression strength are higher and the results of wear test demonstrates an increase in wear resistance with increase in B_4C reinforcement.

Keywords - MMC, Boron carbide, micro-hardness, pin-on-disc, microstructural analysis.

1. INTRODUCTION

Nowadays composite materials reinforced with different ceramic particles having high strength and toughness is developed to suit the varying needs in aerospace and automotive applications. However, the performances of these metal matrix composites (MMCs) depends upon the matrix material, processing techniques, type of reinforcement and the processing parameters [1]. Aluminum based MMCs are widely used owing to their light weight, excellent mechanical properties and higher wear resistance. Particulate reinforced composite materials cost less and are isotropic in nature, which can be processed with conventional methods. The amount of plastic deformation in the Aluminum matrix is limited by the reinforcements used such as SiC, B_4C, TiC and Al_2O_3 which is examined through the wear behaviour of composite [2].

To understand the performance and behaviour of the cast composite, mechanical properties and wear behaviour are determined [3]. Stir casting techniques is the simplest and most economical method for fabricating the particulate MMCs but the problem remains with the uniform dispersion of the particulate reinforcement used into the liquid matrix, for which a mechanical type stir assembly setup should be used for uniform making the particulate to get dispersed uniformly. Mostly High-purity aluminum has been used as matrix to understand the reinforcement and matrix interface relationship, since the impurities that may be present in the base matrix material may influence the interface during the fabrication of composite [4]. For this purpose, 99.85% pure aluminum is chosen as the matrix material.

Self-lubricating composites are casted due to their low friction and wear, low thermal expansion and damping capacity by adding graphite as particulate reinforcement [5]. In order to improve the tribological behaviour of the cast MMC, volume fraction of graphite is maintained constant as 2%, to study the behaviour of ceramic particulate reinforced MMC. When comparing with other ceramic particles viz. SiC and Al_2O_3, boron carbide particles reinforced in pure aluminum matrix using stir casting technique have better distribution of particles and also exhibit better interfacial bonding. [6]. Aluminum-graphite composites developed through powder metallurgy route shows an increase in thermal conductivity and decrease in thermal expansion with increasing amount of graphite and the presence of pores in the composite lowers the thermal conductivity [7]. When B_4C particles are added to most of the aluminum alloys, it acts as an obstacle to retard the dislocation motion, resulting in high hardness, ultimate tensile, compression and flexural strength along with an increase in wear resistance [8].

Muthukumar et al. [9] conducted experiments on various fractions of SiC reinforced aluminum MMC using pin-on disc apparatus to examine the wear behaviour and found that abrasive wear resistance and corrosion resistance improved considerably with the addition of SiC particles and studied the worn surfaces using SEM examinations. Aluminum reinforced with graphite particulate MMCs can also be developed using other methods such as melt conditioned high-pressure die casting to improve the distribution of the reinforcement in the matrix [Barekar et al. 2009]. The mechanical behaviour of Al-Si-Cu/graphite composite fabricated using stir casting technique are studied at different strain rates in the ultimate tensile test and was found that the ultimate tensile strength was higher for all strain rate along with the hardness [11].

Arslan and Kalemtas [12] explored the possible processing routes that enable the infiltration of Al alloys into SiC and B_4C mixtures without the formation of Al_4C_3 and for this purpose, powder mixtures consisting of SiC and pre-treated B_4C were pressureless infiltrated with Al alloys at relatively low temperatures under an inert gas atmosphere which was achieved in the temperature range of 935–1420 °C. Alptekin et al. [13] investigated the production of A6063/SiC–B_4C hybrid composite using vacuum assisted block mould investment casting method porosity fraction of preforms was determined using Archimedes' test and are characterized using hardness tests, image analysis and SEM observations and EDX analysis. A reliable criterion for fabricating B_4C-Al particulate composites by rapidly heating to near 1200°C (to ensure wetting) and subsequently heat-treating below 1200°C (for microstructural development is employed to avoid lower densification temperatures and higher fracture toughness while adding a metal phase [14]

Not only pure aluminum but also aluminum alloys are also used as metal matrix for the reinforcement of ceramic particles viz. SiC, B_4C and Al_2O_3 by various techniques [15] and their mechanical characterization [16-17] are also studied.

2. SELECTION OF MATRIX AND REINFORCEMENT MATERIAL

Aluminum and its alloys are the most economical and attractive, whose variety of uses are appearance, light weight, fabricability, physical properties, mechanical properties, and corrosion resistance [18]. The important advantages of aluminum and its alloys are their high strength-to-weight ratios, high thermal and electrical conductivities, nontoxicity, reflectivity, appearance, and ease of formability and machinability and nonmagnetic. The principal uses of aluminum and its alloys are in containers and packaging architectural and structural applications, transportation, electrical applications, consumer durables and portable tools [19]. Apart from using aluminum as a matrix material, aluminum powders can also be used as reinforcement in other matrixes such as epoxy resin, to improve the mechanical properties which are commonly used in rapid tooling applications [20]

Boron carbide (B_4C) is the black solid with metallic luster and the hardest ceramic material known in nature after diamond and cubic boron nitride [21] and has rhombohedra crystal lattice structure. It has high chemical stability in hostile environment and high resistance to wear by sufficiently higher mechanical strength. It is used in high temperature applications because of high refractoriness property achieved due to the high melting point of 2450 °C. It has very low thermal conductivity and high compressive strength and hardness.

Graphite is a crystalline form of carbon having a layered structure with basal planes or sheets of close-packed carbon atoms. Consequently, graphite is weak when sheared along the layers. This characteristic, in turn, gives graphite its low frictional properties as a solid lubricant. However, its frictional properties are low only in an environment of air or moisture; in a vacuum, graphite is abrasive and a poor lubricant. Unlike in other materials, strength and stiffness of graphite increase with temperature. Also, its low absorption cross section and high scattering cross section for thermal neutrons make graphite suitable for nuclear applications [19].

3. METHODOLOGIES USED

The methodologies that are adopted to determine the mechanical properties [22] and tribological behaviour of the Aluminum-Graphite-B_4C metal matrix composite is shown in Fig. 1.

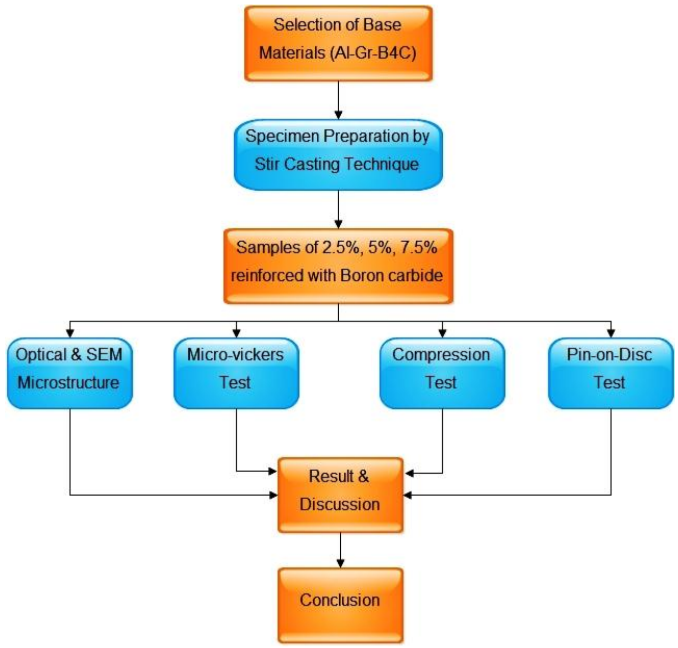

Fig. 1 Methodology used in this work

Initially the base material chosen are taken according to the volume fraction and melted in a stir casting setup [23-24] attached with a motorized stirrer attachment as shown in Fig. 2. Specimens are casted for various compositions of B_4C such as 2.5%, 5% and 7.5% that are reinforced into the matrix of aluminum which is also reinforced with graphite to visualize the distribution of the reinforced particulates in the metal matrix and to determine the mechanical properties such as hardness and compression strength and tribological behaviour viz. frictional force, coefficient of friction and wear rate.

The specification of equipment used for measuring the hardness (micro-Vickers) have a testing load range between 10 grams to 1 kg, Wilson Wolpert–Germany make with a Vernier caliper least count of 0.01 mm and the available Hardness testing scales are HV, HRA, HRC, 15N, 30N etc. Compression strength (tensile testing machine) is measured with equipment having specifications of load range of maximum 5 Ton with digital encoder having a gear rotation speed (for gradual loading) of 1.25, 1.5 and 2.5 mm/min with relevant software. The frictional force, coefficient of friction and wear rate is measured using pin-on-disc apparatus having a standard disc of diameter 55 mm, pin diameter 8 mm and length of the pin 6 to 8 mm, which are shown in Fig. 3.

Fig. 2 Stir casting machine setup

(a) Micro-Vickers (b) Compression Test (c) Pin-on-Disc

Fig. 3 Testing equipment's used for measurement

3.1 Microstructure Analysis

Metallography, also known as materialography is the scientific discipline of examining and determining the constitution and spatial relationships between and the structure of the constituents in metals, alloys and materials. Optical characterization of the microstructures of metals and alloys basically involves identification and measurement of phases, precipitates, and constituents, and determination of the size and shape of the grains, characteristics of grain boundaries and other defects that can be observed [25]. To study the microstructure of a given material, the optical microscope is the most important tool, which uses optical light for illumination even though the evolution of sophisticated electron metallographic instruments is possible. Both Scanning electron microscopy and transmission electron microscopy should be used in conjunction with optical microscope, rather than as a substitute. Macro-examination of aluminum alloys is accomplished using techniques that are similar to those used for other metals. Macro-examination of cast specimen is used to reveal the degree of refinement of the grain structure; grain size, grain boundary, evidence of abnormally coarse constituents, oxide inclusions, porosity within the composite and in many cases the type of failure that normally occurs due to blow holes etc. From the sectioned, machined and macro-etched specimens, grain size, grain flow and fabricating/casting defects can be observed. The Scanning Electron Microscope (SEM) is one of the most versatile instruments for investigating the microstructure of materials. Under electron bombardment, a variety of different signals is generated (including secondary electrons, backscattered electrons, characteristic x-rays, and long-wave radiation in the ultraviolet and visible region of the spectrum) that can be used for materials characterization. Using secondary electrons, scanning electron microscopy (SEM) expands the resolution range to a few nanometers (under favorable conditions), thus bridging the gap between optical (light) microscopy and transmission electron microscopy [18]

3.2 Micro-Vickers Hardness

The characteristic of a material is evaluated by its hardness, which is a measure of resistance to indentation, and can be determined by measuring the permanent depth of the indentation. A fixed load is given to the indenter and depending upon the hardness the indention will be smaller (Harder material) or bigger (Soft material). The Vickers hardness test method, which is also referred as a micro-hardness test method, uses a square base pyramid shaped diamond for testing in the Vickers scale with load typically ranging from a few grams to one or several kilograms. The micro-hardness methods are used to test on metals, ceramics, and composites for almost any type of material. Because of th very small indention in the Vickers test it is broadly used in applications such as testing very thin materials like foils or measuring the surface of a part, small parts or small areas and measuring the depth of case hardening. Due to this the Vickers method are more commonly used.

3.3 Compression Strength

According to ASM Handbook, Axial compression testing is a useful procedure for measuring the plastic flow behavior and ductile fracture limits of a material. The behaviour of materials under the influence of crushing load is characterized by means of compression test, which records the various loads during material deformation.

Elastic limit, proportional limit, yield point, yield strength and compressive strength are calculated by this test and graphs are also plotted between load vs. displacement, stress vs. displacement, stress vs. strain and bending moment diagram. Axial compression testing is also useful for measuring the elastic and compressive fracture properties of low ductile material / brittle materials and in some cases, the use of large L/D ratio specimens should be avoided to prevent buckling and shearing modes of deformation. The machine used for compression test and extensometers are those used for tension tests in universal testing machine. The problem that generally occurs during compression test is the possibility that load chain may buckle prior to material failure or the sample may get fractured, which is prevented by keeping the specimens short and stubby.

3.4 Wear Test

From literature, it is observed that the wear and friction behaviour of MMCs having aluminum as matrix strongly depends on the particles used for reinforcement, its size and volume fraction of particles. The coefficients of friction of the metal matrix composites are high if the rate of reinforcement particle in MMC is low and besides this, the wear resistance increases with increasing volume fraction of reinforcing particulates [26-30]. If the particulates used for reinforcement bonded well to the matrix, the wear resistance of the composite increases continuously with increase in the volume fraction of ceramics particles and the critical volume fraction mostly depends on the load applied during the wear test [2].

A tribometer is an instrument that measures the tribological quantities such as coefficient of friction, friction force, and wears volume, between two surfaces in contact. The simplest of the tribometer is pin-on-disc tribometer, consisting of a stationary pin that is spherical in shape, which will be in contact with the rotating disc for a given load. Coefficient of friction is determined by the ratio of the frictional force to the load applied on the pin. Wear rate is calculated by the formulae given in Equ. 1.

$$Wear\ rate = \frac{\Delta w}{2\pi rNt}\ gm./cm \tag{1}$$

where Δw – is the difference in weight before and after wear test $w_1 - w_2$ (gm.), $2\pi rNt$ – is the sliding distance (cm), N – is the rotational speed of the disc (800 rpm), t – is the time period of wear test (10 min).

4. RESULTS AND DISCUSSION

After casting the specimens with various volume fractions of B_4C particulate reinforcement, the distribution of B_4C particulates and graphite particles in the aluminum matrix are studied using optical microscope and scanning electron microscope (SEM). The etchant used is HF solution and a magnification of 250X is used for the optical image. For a reinforcement of 2.5% B_4C given in Fig. 4, the matrix shows the distribution of the particulates in aluminium metal matrix, having fine eutectic particles of Al- B_4C particles. The composite particles are agglomerated at certain locations of the metal matrix. The graphite particles are more grouped together.

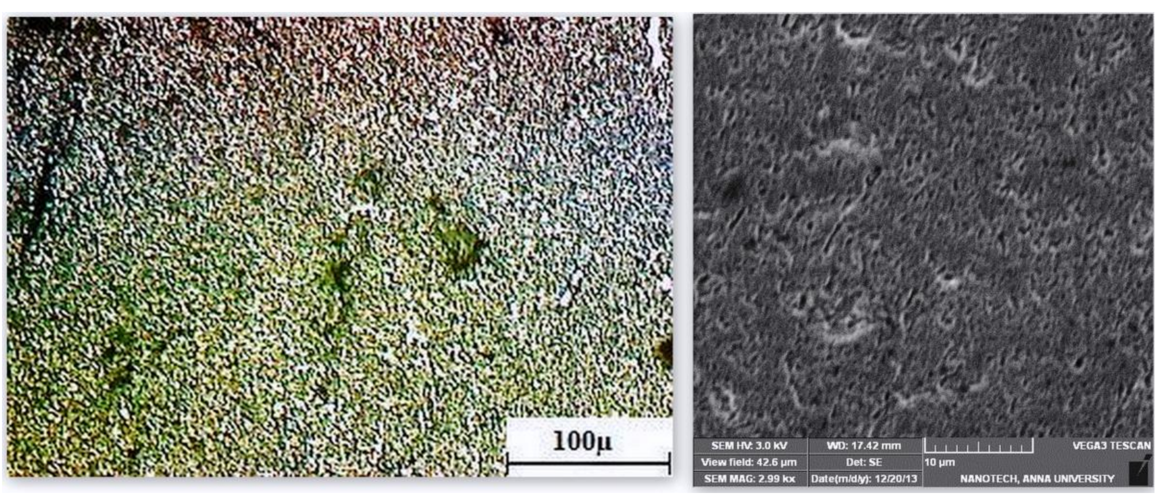

Fig. 4 Optical & SEM image of 2.5% B_4C reinforced Al MMC

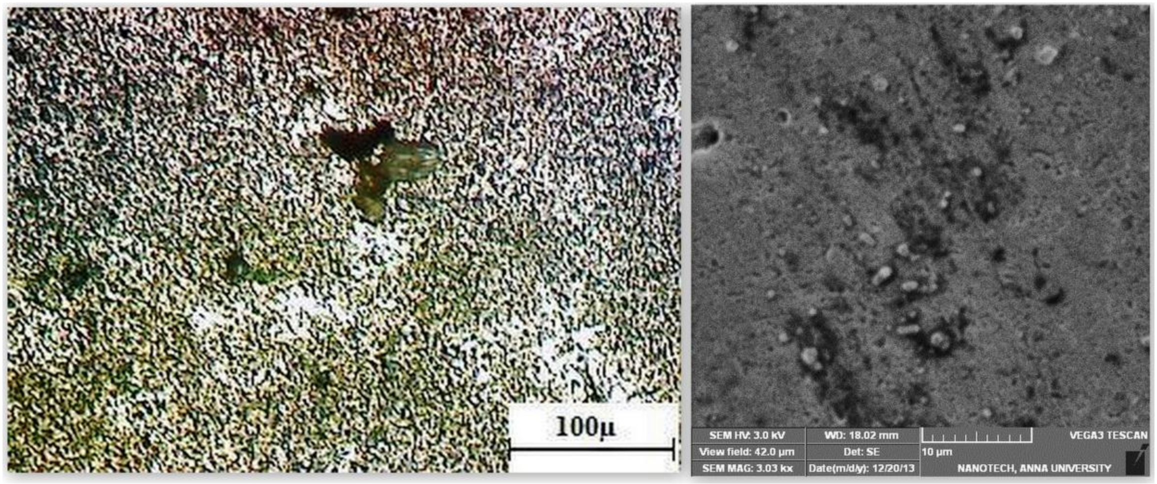

Fig. 5 Optical & SEM image of 5% B_4C reinforced Al MMC

The microstructure of the aluminium matrix having a reinforcement of 5% B_4C shown in Fig. 5, has fine eutectic particles of Al- B_4C particles. The composite particles are agglomerated at certain locations of the metal matrix. The graphite particles and the boron carbides are grouped together. More particles of boron carbide are observed and the distribution is even.

For 7.5% B_4C reinforced in the matrix of aluminum shown in Fig. 6, the microstructure shows the fine eutectic particles of Al- B_4C particles. The composite particles are agglomerated at certain locations of the metal matrix. The graphite particles occupied the grain boundaries of the aluminium phase grains in the matrix. The boron carbides are in the metal matrix and the grain boundaries are clearly visible.

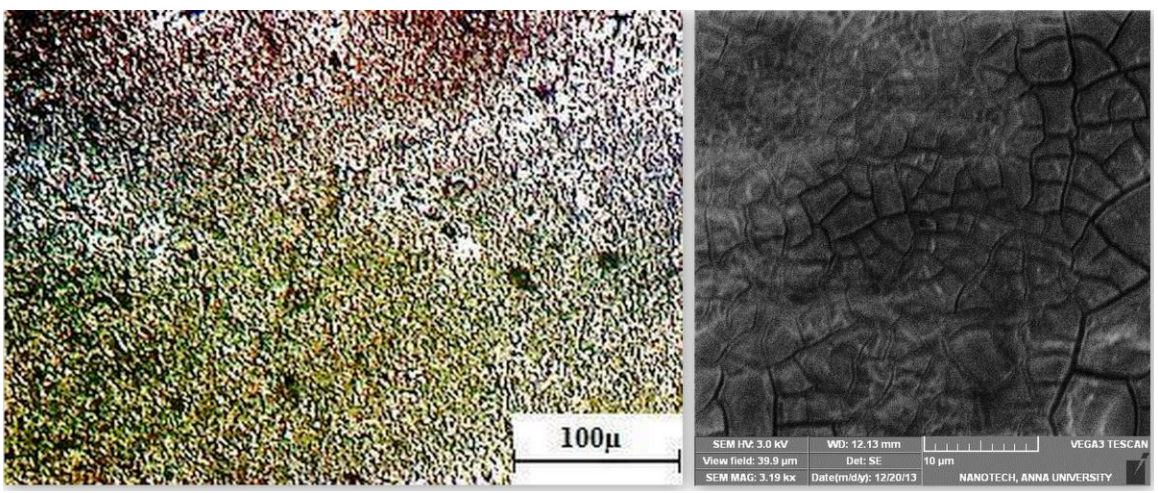

Fig. 6 Optical & SEM image of 7.5% B_4C reinforced Al MMC

The hardness of the casted specimens was evaluated using Micro-Vickers hardness test with a load of 0.5 kg and the results are shown in Table 1. From the obtained hardness values, it is observed that as the reinforcement of B_4C particulates increases in the MMC, the hardness increases proportionally. When the B_4C volume fraction is increased from 2.5% to 5%, the hardness value increases by 48% and when it is increased from 5% to 7.5%, 11.83% increase in hardness value is observed, which shows that initially the hardness value increases drastically and with further reinforcement, the increase in hardness value is lower.

With the help of compression test performed over the cast MMC on a universal testing machine, the parameters viz., ultimate stress, breaking load, displacement at FMax and max displacement are determined, which are shown in Fig. 8. It is observed that when the reinforcement of B_4C is increased in the aluminum matrix from 2.5% to 5%, ultimate stress increases by 56.16%, breaking load increases by 56.54%, displacement at FMax increases by 72.41% and maximum displacement increases by 27.08%. But with further increases in reinforcement of B_4C particulates from 5% to 7.5%, a reduction in ultimate stress by 0.88%, breaking load by 0.97%, displacement at FMax by 54% and maximum displacement by 44.26% is noticed. This is because of the decrease in ductility of the aluminum matrix and limitation in plastic deformation of the MMC due to the addition of more amount of B_4C particulates. This result can be well understood and correlated with the hardness values obtained.

Table 1 Micro-Vickers hardness value for various composition of MMC

Sl. No	Cast MMC	Hardness Values (Micro-Vickers)				Average (HV)
1	Al-Gr-2.5 % B_4C	29.5	30.6	22.3	30.1	28.125
2	Al-Gr-5 % B_4C	41.8	39.7	43.8	41.2	41.625
3	Al-Gr-7.5 % B_4C	47.1	46.0	46.1	47.0	46.550

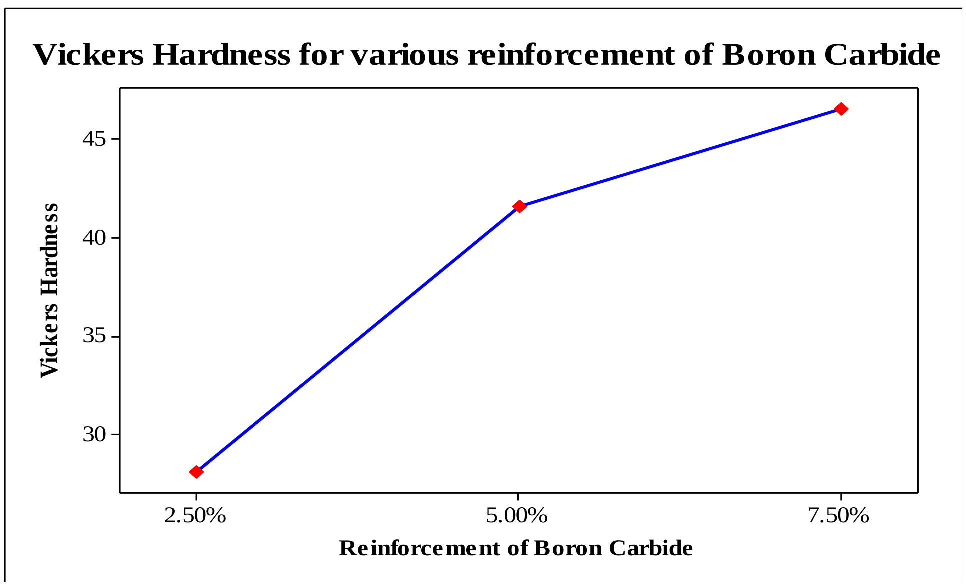

Fig. 7 Micro-hardness for various B_4C reinforced MMC

The compression strength of various compositions of cast MMCs is shown in Fig. 9. The maximum load that can be withstand by 2.5% reinforcement of B_4C composite is 6.915 kN, by 5% B_4C reinforcement is 10.825 kN and by 7.5% B_4C reinforcement is 10.72 kN. It is observed that the load bearing capacity of the composite is increased by 56.54% when the reinforcement of B_4C particulates is increased from 2.5% to 5% whereas the load bearing capacity of the MMC decreases by 0.97% when the reinforcement of B_4C particulates is increased from 5% to 7.5%. This is also due to the lost of ductile porperty and limitation in the plastic deformation of the aluminum metal matrix by adding more amount of B_4C particles. From the graph it is obvious that the composition of Al-Gr-5%B_4C MMC bears a higher load along with a larger displacement.

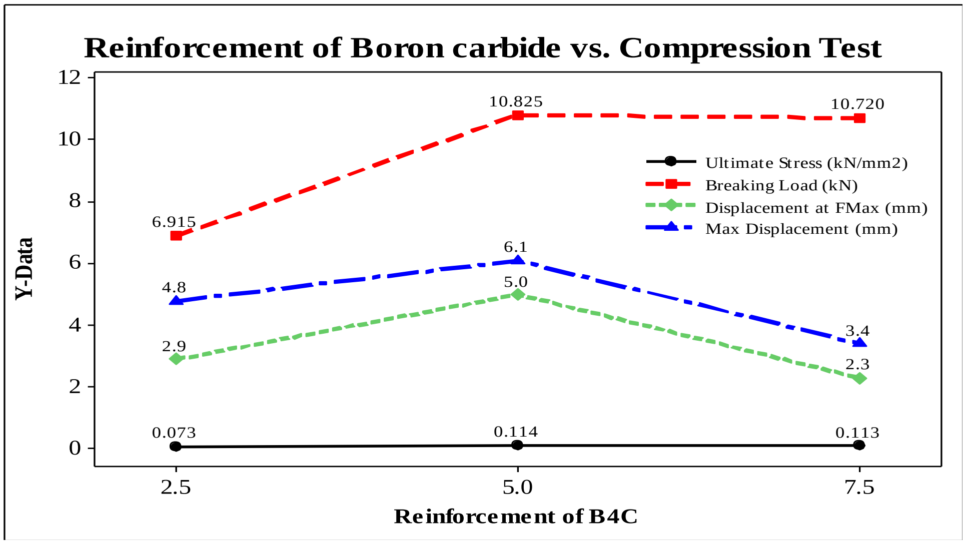

Fig. 8 Variation of compression test result for various reinforcement of B_4C

During performing the pin-on-disc (wear test) experiment, the variation of frictional force during the test for various reinforcement of B_4C is shown in Fig. 10. From the graph, it is observed that frictional force is low for 5% reinforcement of B_4C particulate rather than 2.5% and 7.5% reinforcement. When the reinforcement is increased from 2.5% to 5% the frictional forces are reduced by 10.08% and with further increase in reinforcement from 5% to 7.5%, the frictional forces increases by 6.54%.

The variation of coefficient of friction observed during performing the wear test for various reinforcement of B_4C is shown in Fig. 11. It is observed that the coefficient of friction is low for 5% reinforcement of B_4C particulate than that of 2.5% and 7.5% reinforcements. When the reinforcement is increased from 2.5% to 5% the coefficient of friction is reduced by 10.13% and with further increase in reinforcement from 5% to 7.5%, the coefficient of friction increases by 7.04%.

The wear rate calculated using Equ. 1 for various reinforcement of B_4C particulate is given in Table 2. It is observed that, as the percentage of B_4C reinforcement increases in the aluminum-graphite metal matrix, the wear rate decreases due to the increased resistance offered by the particulate material.

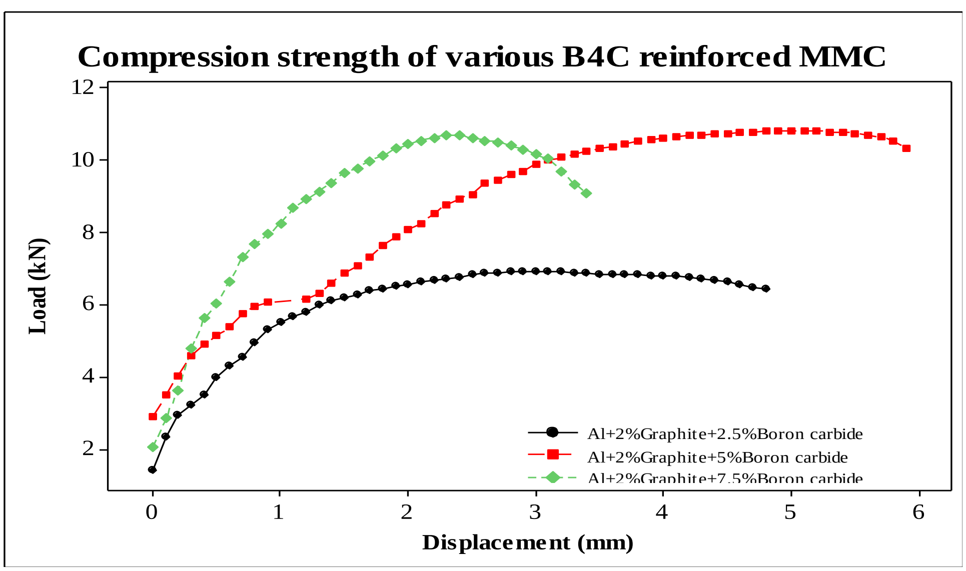

Fig. 9 Compression strength of various B_4C reinforced MMC

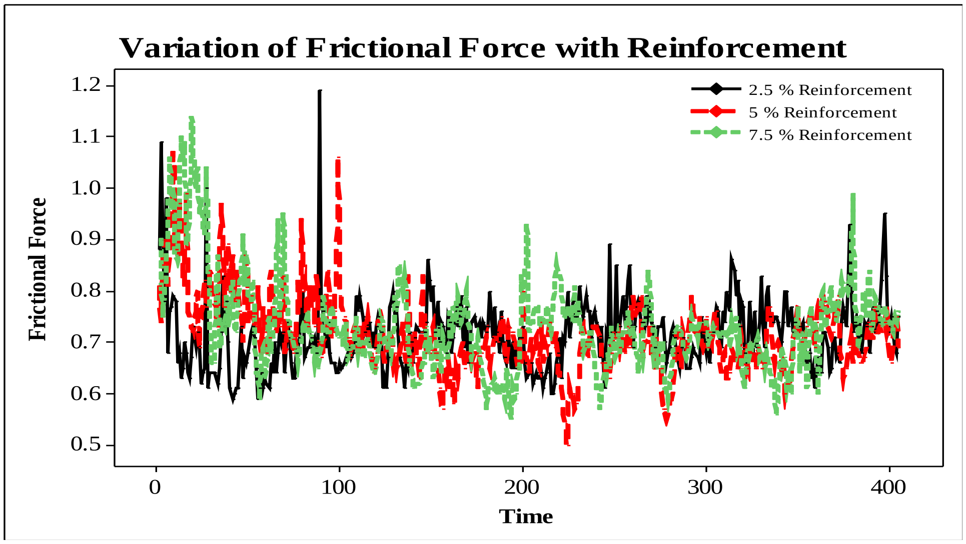

Fig. 10 Frictional force required for various B_4C reinforced MMC

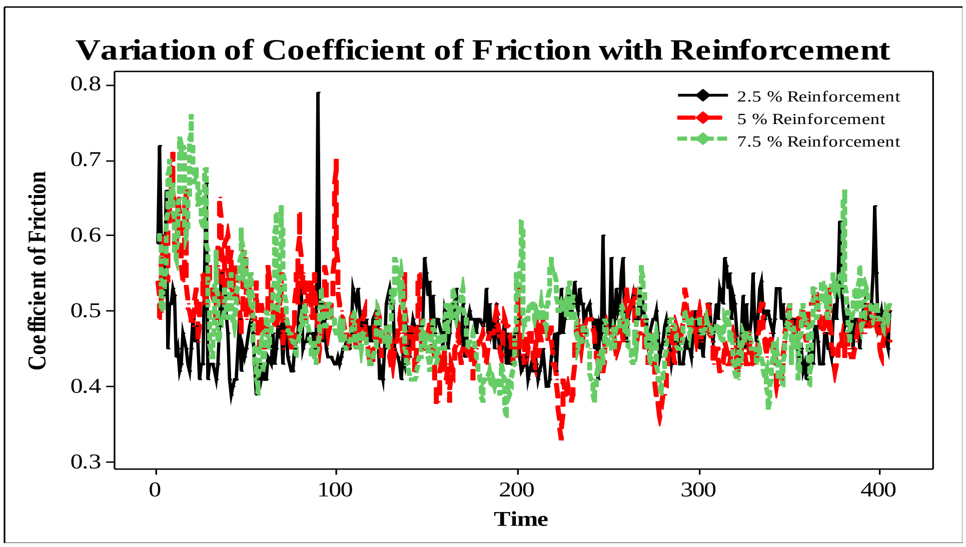

Fig. 11 Coefficient of friction for various B_4C reinforced MMC

The variation of wear rate for various composition of MMC is shown in Fig. 12. From the graph, it is observed that when the reinforcement of B_4C particulates is increased from 2.5% to 5% the wear rate is reduced by 39.98% and with further increase in B_4C reinforcement from 5% to 7.5%, the wear rate is further reduced by 33.40% due to the change of material behaviour from soft to hard.

Table 2 Wear rate for various compositions of MMCs

Sl. No	Cast MMC	Wear rate (gm./cm)
1	Al-Gr-2.5 % B_4C	0.893×10^{-7}
2	Al-Gr-5 % B_4C	0.536×10^{-7}
3	Al-Gr-7.5 % B_4C	0.357×10^{-7}

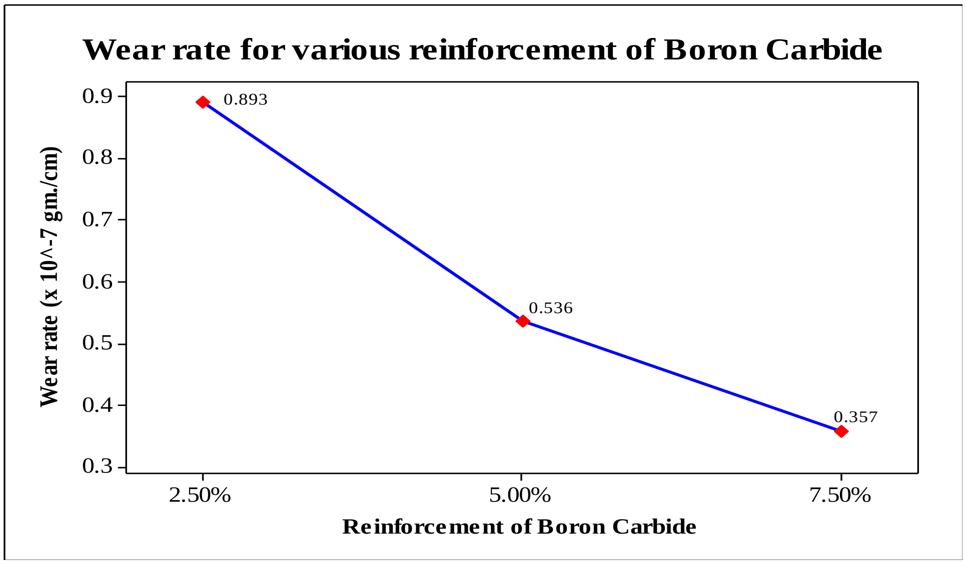

Fig. 12 Wear rate of various B_4C reinforced MMCs

5. CONCLUSIONS

From the study on mechanical characterization and tribological behaviour of Al-Gr-B_4C reinforced metal matrix composite, the following conclusions are drawn.

1. With the stir casting technique setup attached with mechanical stirrer assembly, it is possible to develop MMC with uniform distribution of reinforced particulates on aluminum matrix.
2. Depending on the amount of B_4C reinforcement, hardness values obtained by micro-Vickers shows an increasing trend with volume fractions of B_4C reinforcement, which is because of the limitation of plastic deformation of aluminum matrix.
3. From the compression test results, it is observed that the ultimate stress, breaking load, max displacement increases up to 5% reinforcement of B_4C particulates in aluminum matrix and after that it reduces.
4. Compression strength is higher for 5% B_4C reinforced MMC having a maximum load carrying capacity of 10.825 kN.
5. Pin-on-disc wear test shows a reduction in frictional force and coefficient of friction values for 5% B_4C reinforcement. The wear rate reduces with increases in B_4C reinforcement in aluminum matrix.
6. From the results obtained, it is observed that 5% B_4C reinforced MMC is better applicable than the other B_4C reinforced MMC due to their superior characterization.

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