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Experimental investigations on aluminum based metal matrix composites with B_4C, SiC and Mg

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This research study is framed with an objective to fabricate AlMMC reinforced with varying percentage of SiC, B_4C and Mg and evaluate their strength, quality and metallurgical integrity through destructive and non-destructive tests. The specimens indicate higher strength and bond integrity with increase in B_4C percentage. The outcome reveals that this AlMMC is an effective alternative to other materials owing to its cost effectiveness and mechanical strength and stability.

Keywords: AlMMC, SiC, B_4C, Mg, Matrix, Reinforcement

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1. Introduction: Ceramic materials are commonly used to reinforce aluminium are SiC, B_4C, TiC, ZrB_2, Al_2O_3 and SiO_2. Among these reinforced ceramic particles, SiC and B_4C is particularly focused owing to its excellent high young's modulus, low density, superior hardness, good thermal conductivity, high electrical conductivity, high elastic modulus and hardness, high melting point, superior wear resistance and good thermal stability. Combinations of these properties are not available in conventional materials. For these reasons, it is used in a large verity of applications such as aluminium melting crucibles, corrosion resistant applications and metal and ceramic composites. The wear resistance is an important factor for various engineering applications. The use of Aluminium metal matrix composites has been limited to specific applications such as aerospace and military weapons due to high processing cost. Recently, AlMMC have been used for the automobile products such as engine piston, cylinder liner, disc brake and drum brake etc., In addition to B_4C and SiC metal matrix composites has been observed to exponentially enhance stiffness, hardness and wear resistance. Much of the work in this field has been directed at Al based materials. Addition of Magnesium facilitates greater bonding between the matrix and reinforcement material and increase the wettability of the particulates.

M. N. Wahab et.al [1] investigated Al-Si matrix composites reinforced with AlN particles. It was observed that the hardness improved as the Al nitride distributes itself around Si phase. Lack of porosity exhibited in the microstructure of Al-Si matrix composite emphasises good particulate-matrix interface bonding. B. Ashok Kumar et. al.[2] fabricated AA6061–AlNp composites with different weight percentage of reinforcement viz., 0%, 5%, 10%, 15% and 20% by stir casting method. Greater bond integrity with AlNp reinforcement and the aluminium alloy matrix exited. It was reported that, hardness is proportionally increases with increase in % of AlNp while the % of elongation conversely reduces with increase in AlNp %.

B. Bhav Singha et.al [3] reported Aluminium alloy matrix composites with carbon fibre reinforcement they suggested that coating the carbon fibres with copper eluded interfacial reactions. Tensile strength and hardness appears to increase for higher % of fibre while % elongation decreases. F. Toptan et.al. [4] Al- B_4C composites were processed through a casting route with addition of K2TiF6 flux to form a reaction layer contains TiC and TiB_2 at the interface, in order to increase wettability and interface bonding. Due to the poor wetting of B_4C particles by liquid aluminium, an effective bonding could not be formed on the matrix/reinforcement interface in Al- B_4C composites produced at relatively lower temperatures like 850°C. K. Kalaiselvan et.al [5] attempted the extension study of reinforcing B_4C with Aluminium (6061-T6). This research supported the inference drawn from study that the importance in wetablity by the addition of K_2TiF_6 for similar composition of AlMMC reinforcement provided the confirmation regarding the proportional dependency of tensile strength of hardness with an increase in B_4C particulates.

Don-Hyun CHOI et al. [6] reported that the original microstructure of the BM underwent of alteration due to a fine re-crystallized grain structure, and SiC particles were homogeneously distributed in the Al matrix due to mechanical stirring. The hardness of the SZ is improved by reducing of grain size and dispersed SiC particles. Mohsen Ostad Shabani et.al**.** [7] Investigated A356 matrix reinforced with B_4C particulates. Besides a combination of artificial neural network (ANN) and finite element technique was implemented in order to model the mechanical properties including yield stress, UTS, hardness and elongation percentage. Microstructural characterization revealed that the B_4C particles were distributed between the dendrite branches. Microstructural observations revealed a reasonably uniform distribution of B_4C particles in the matrix. These particles decreased the coefficient of thermal expansion. Ege Anıl Diler et.al [8] presented some studies of Al-SiC composites. They observed that wear loss decreased as volume fraction increased; however, beyond volume fraction of 17.5%, it increased due to reinforcement particle clustering depending on volume fraction and matrix particle size to reinforcement particle size ratio. Reduction in of matrix particle size and increase in reinforcement particle size, decreases wear loss.

Zhixiao Zhang et al [9] reported interesting fact of adding B_4C and SiC intergranular/intergranular nanocomposites with high hardness and high toughness through mechanochemical processing with B_4C, Si, and graphite powders and subsequent hot pressing without any sintering aid. The milled powders consist of stacking-disordered SiC and nano crystalline B_4C. Most nano/micron-sized SiC particles are homogeneously dispersed in B_4C matrix, and some nano-sized SiC and B_4C particles are embedded into B_4C grains to form an intergranular/intragranular structure. The disordered characteristic of the milled powders is the essential factor for the formation of the intragranular structure, sudden densification within the narrow temperature range (1700-1900 °C), and the preparation of dense samples under a relatively low temperature (1900 °C). It was noticed that the intergranular structure plays an important role in improving fracture toughness and hardness of the composites. Qiang Shen et.al [10] investigated Al-7075/ B_4C composites by plasma activated sintering (PAS), and heat treating the sintered product. Microstructures of the composites are characterized using field-emission scanning electron microscopy (FESEM) and transmission electron microscopy (TEM). Increasing the B_4C content increased the hardness, bending strength, and compressive yield strength of the composite. However, adding too much B_4C caused B_4C agglomerates decreasing the hardness and bending strength of the composite.

After sketching through the literatures, it has been observed that addition of various materials in the metal matrix would alter the properties and behaviour. Further, it has been clearly observed that B_4C and Mg have tendency to improve the material properties. However, there is no detailed information on aspects concern with micro structural aspects aiding the variation in mechanical strength. Hence, in this study and attempt is made to highlight the prominent features to establish its feasibility for industrial applications.

2. Experimental Procedure:

2.1 Fabrication process: The metal matrix composites of Al reinforced with SiC or B_4C are prepared in a crucible furnace. Degassing is done initially with hexachloroethane tablets followed by bubbling argon to remove the dross. The SiC and B_4C are pre oxidised at 650°C for 2 hours and poured into the liquid matrix stirred at a constant rate. Heat treatment is done in order to form a layer of B_4C on the SiC, which enhances the bonding between the molten metal. The melt is stirred at a constant rate of 670rpm for 10 minutes, after the addition of SiC and B_4C determined as optimum speed and time. After the continuous stirring, the melt is poured in to a permanent iron die mould to obtain composites of size 20mm diameter and 230mm length after that sprue pins are removed. No evidence of macro casting defects are seen. The matrix metal is also cast in the same process to standardize the casting process.

Magnesium is added to increase the wettability of the particulates. It improves the wettability of SiC and B4C with the aluminium melt lost from the melt by oxidation, during melting and stirring of the alloy. In order to compensate for this loss and maintain the wettability of the alloy, magnesium is added to the molten metal before the start of stirring.

2.2 Experimental set-up: The samples are prepared by stir casting unit setup. Furnace structure are outer shell size 600x600x600 mm, crucible volume size 200mm diameter x 300mm height with conical bottom of 50mm diameter, crucible material stainless steel AISI 310, furnace height 0.75m and high speed stirrer with various speed 300 to 500 rpm made with mild steel with zirconia coating (figure 1-3). The furnace operates at 3 phase /AC/230V, 6kW. The maximum temperature of the molten metal is 1000°C and the working temperature of the molten metal 990±0.1°C. The specification of the stir casting furnace is as follows:

Table (1): Process Parameters for Stir Casting

Parameters	Value	Unit
Spindle speed	300-500	Rpm
Stirring time	10	Min
Temperature of melt	900	°C
Preheated temperature of SiC particles	650	°C
Preheated temperature of B_4C particles	650	°C
Powder feed rate	0.75-1.0	g/s

Figure (1): Electrical Furnace

Figure (2): Stirrer

Figure (3): Stir casting setup

Table (2): Samples Specification

Samples No.	**Al wt.%**	**SiC wt.%**	**B_4C wt.%**	**Mg wt.%**
1	90	5	3	2
2	85	7	6	2
3	80	9	9	2
4	75	11	12	2

2.3 Experimental procedure: SiC and B_4C particles with an average particle size 40µm are used as reinforcement on Al 6061 subsequently matrix for this study. In order to enhance the wettability of B_4C powder, SiC powder and improve their incorporation behaviours into Al melts, hexachloroethane flux is used. The specifications in terms of these compositions are presented in table 2.

3. Metal testing and metallurgical characterization: The fabricated specimens are evaluated from the insight of mechanical and metallurgical responses to various loading conditions. The objectives of this examination are to determine the strength, quality and distribution of particles governing the bond integrity. Figure 4 shows the samples prepared for various destructive (Mechanical) tests. Subsequently, the results of those tests are illustrated in figure 5.

Figure (4): Before Testing the Samples

Figure (5): Tensile and Compression Tested Specimens

3.1 Tension test: Tensile test is conducted using universal testing machine with a capacity of 40 tonnes at temperature ranging between from room temperature to 900°C. ASTM standard for metal E8 sub size group is used. The results for each of these samples are provided in Table (3)

It may be observed that from Table (3) that the ultimate tensile stress is higher in case of the first sample where the composite composition has lesser B_4C content as compared to other samples. Presence of higher percentage of Al tends to increase the tensile strength. This increase in the tensile strength is owing to the fact of uniformly distributed fine Al.SiC particles. It may be observed that more number of

Al-SiC particles are precipitated from the super solid solution of Al during homogenization which resulted in higher strength.

Table (3): Tensile test report

Sample No	Area (mm^2)	Diameter (mm)	Gauge Length (mm)	Final Gauge Length (mm)	Ultra Break Load (N)	Yield Load (kN)	Ultra Stress (Mpa)	Yield Stress (Mpa)	Elongation %
1	28.475	6.02	30	26.62	4920	4.06	172.786	142.58	6.48
2	27.91	5.96	30	26.7	3940	3.24	141.169	116.08	6.8
3	28.097	5.98	30	26.54	4600	3.5	163.716	124.56	6.16
4	28.38	6.01	30	26.02	4460	3.82	157.153	134.6	4.08

3.2 Compression test: Compression test is conducted in universal testing machine with a capacity of 40 tonnes at temperature range from room temperature to 900°C. ASTM standard for metal E9 standard is used. The results and the corresponding plots are presented in table 4.

Table (4): Compression Test Results

Sample No	Diameter in mm	Gauge Length in mm	Ultra Break Load in N	Area in mm^2	Ultra Stress MPa
1	20	30	89740	314.286	285.536
2	20	30	85020	314.286	270.518
3	20	30	105240	314.286	334.855
4	20	30	91160	314.286	290.055

Sample 3 appears higher in terms of its ultra stress. 9% of B_4C and SiC increased the strain with increase in temperature due to softening of the matrix. Further, the flow stress of the sample also increases considerably. The composites demonstrates higher loads than the aluminium-silicon composition and this increase is greater for higher the amount of boron carbide. This signifies that the addition of boron carbide leads to enhancement in the compressive strength by introducing the B4C particles owing to the homogeneous distribution of the B4C particles in aluminium alloy matrix. These particles prevent the movement of dislocations in pure Al alloy matrix through dispersion strengthening mechanism. Besides, increasing the amount of B4C particles leads to a decrease in the distance between them which cause an increase in the required stress for dislocations movement between the B_4C particles. It eventually increases the material strength and causes decrease in the ductility.

3.3 Impact test: Charpy and izod impact test is employed as another destructive testing with v-notch at room temperature. ASTM standard E23 group is used.

Table (5): Impact Test Results

Sample No	1	2	3	4
Energy (J)	4	4	2	2

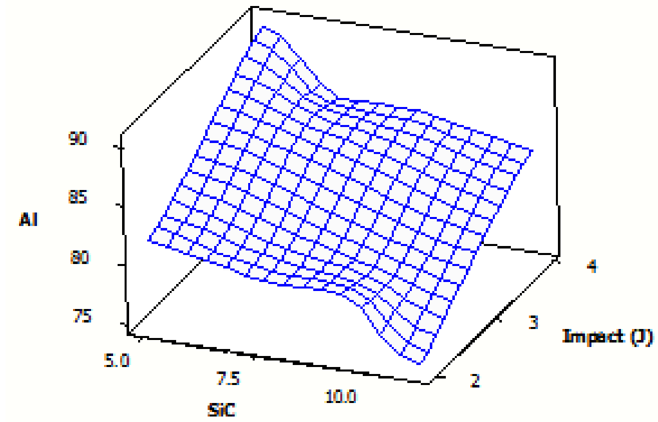

Figure (6): Graphical representation of tensile test results

Figure (6) reveals that by varying the % of B4C, Impact strength of Al- SiC-B4C composites gets altered. Test results illustrate that, while increasing B4C percentage with aluminium, the brittleness of the material increases. Owing to higher brittleness the impact strength of the material decreased. However, for small change in percentage of B4C has negligible effect on the impact strength as seen from figure 6.

3.4 Hardness test:

Table (6): Hardness Test Results

Sample No	1	2	3	4
5mm Ball / 250 kg Load HBW	61.2	59	64.9	64.9
	60.1	58.4	64.2	65.5
	61.2	60.1	64.9	64.9

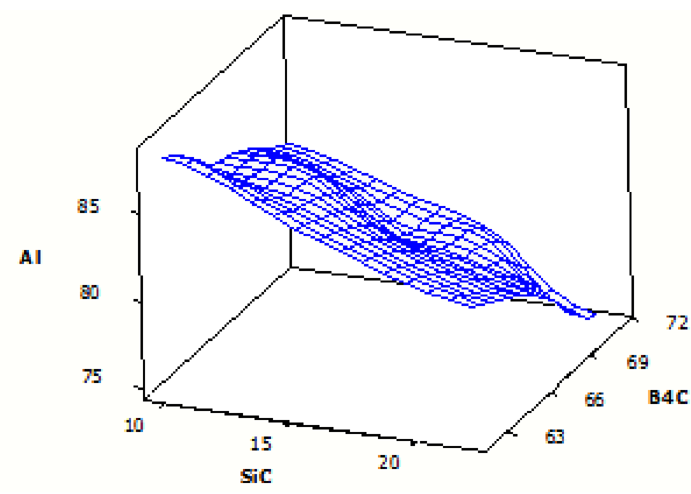

Figure (7): Graphical Representation of Hardness Results

Figure (7) and table clearly depict that there is considerable increase in the hardness as B_4C and SiC % is increased. This is turn enhances the mechanical properties in terms of their strength. However, it must be ensure that if it increases to more than 20%, the possibility of increase in brittleness is more which is undesirable for industrial applications.

3.5 Wear analysis: Friction wear properties SiC reinforced MMC's are investigated. Coefficient of friction was estimated and is discussed for the various SiC compositions. The wear rate and coefficient of friction for various aluminium compositions are shown in Fig.8. As the SiC content is increased to 15 %, the frictional force increases and when the load is increased from 10 N to 30 N (by keeping the velocity constant at 191 RPM), shows an increased behavior of coefficient of friction.

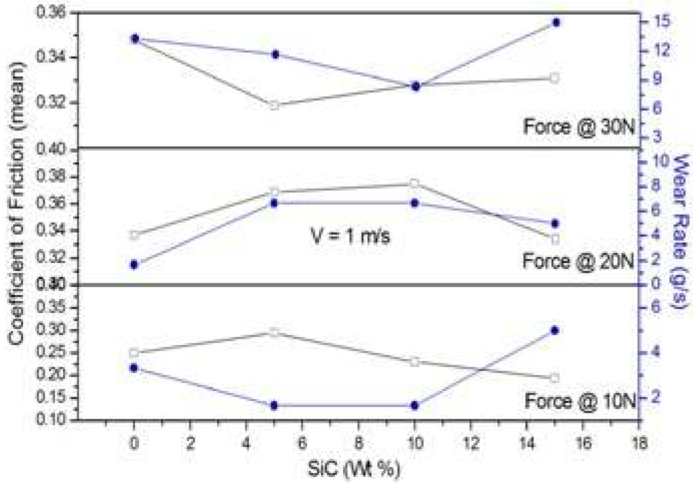

Figure (8): Coefficient of friction, Wear rate Vs SiC content at different loads (by keeping the velocity constant at 1 m/s)

From the Figure (8), it can be seen that as the load increases the coefficient of friction increases due to which there will be loss of the materials from the surface. The loss of material on the surface was probed by SEM analysis. When the velocity is increased, the coefficient of friction increases.

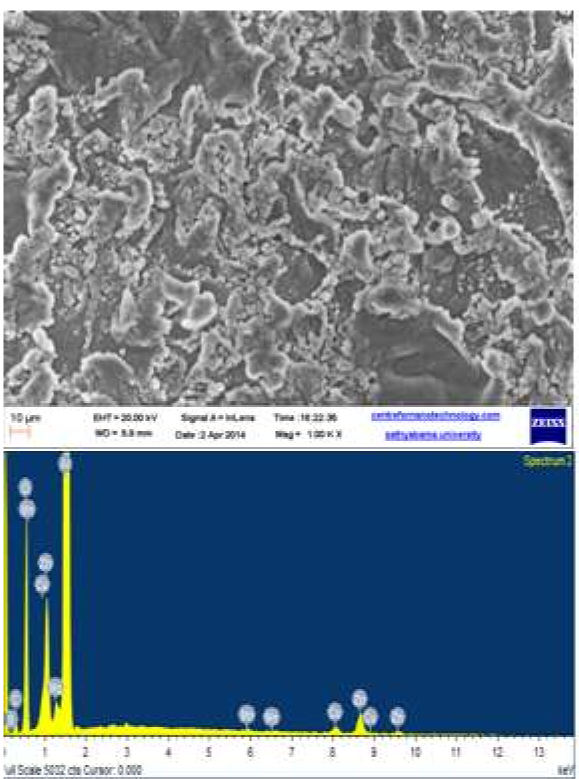

Figure (9a): SEM and EDAX for sample 1

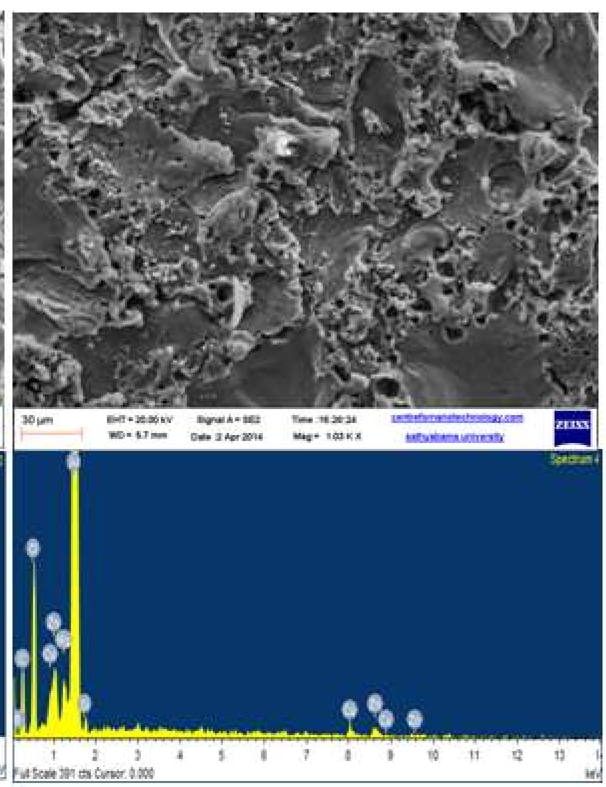

Figure (9b): SEM and EDAX for sample 2

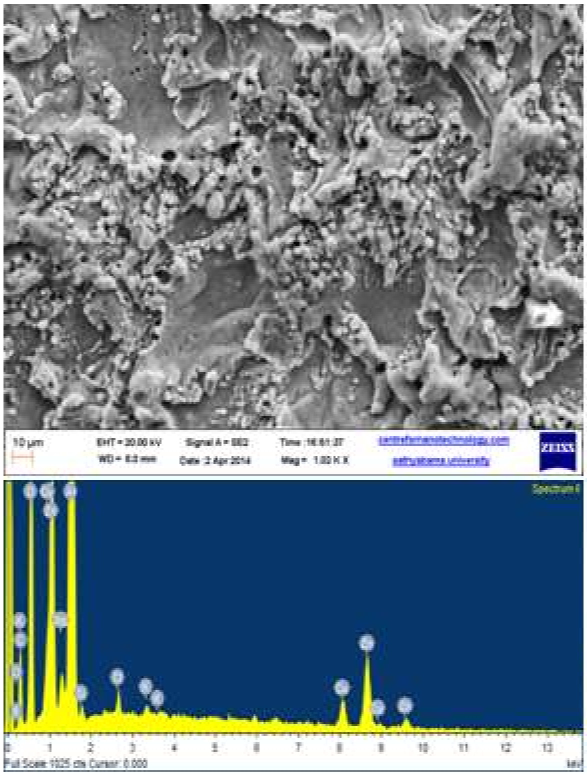

Figure (9c): SEM and EDAX for sample

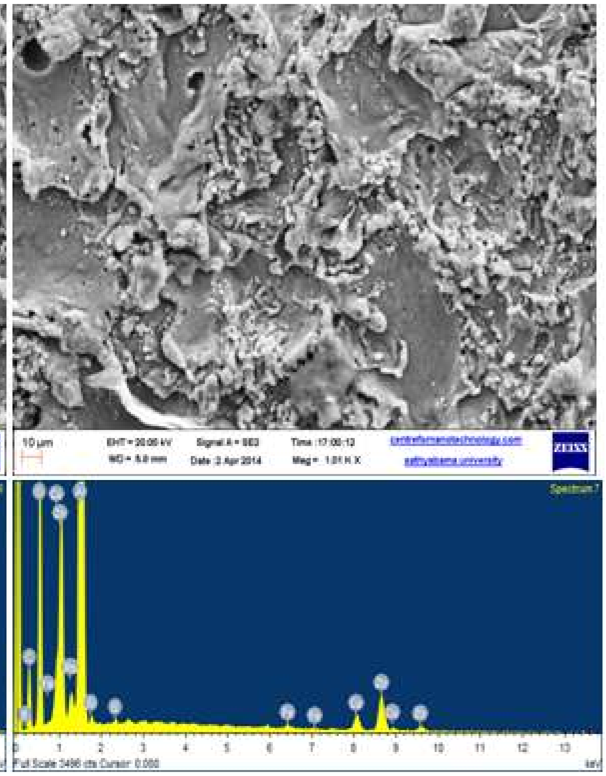

Figure (9d): SEM and EDAX for sample 4

3.5 Metallurgical characterization: Evaluation of the Al, SiC and B_4C composites are carried out by cutting the composites into small cylindrical pellet. The distributions of crystalline phases are investigated by elemental maps for Al, Si and B of the compositions are displayed in figure 9. The SEM/EDEX analysis of the composites is performed with the objective of determining the segregation of the metallic infiltrate in the channel of the ceramic matrix in the composite cools to the detective point. Small grains of Al and Si phases are distributed in narrow spaces between B_4C particles. The Al phase place a key role in defining of the B_4C, SiC and Al composites as the solid solubility of Al in the SiC pellets is very low.

However the distribution of Al Si and B are uniform throughout the sample protrusion of the hard Si particle of the alloy and of Si and B_4C particle of the composites may silhouette the Al phase once the electron beam intersects the high angle pitted samples. Al and Si phases have phase centred cubic crystalline lattices. The metallic matrix of Al is largely constituted by fine domains with sizes ranging from 0.25 to 2µm. This attributes to higher bond integrity and greater hardness exhibited by the materials.

4. Conclusions: The aluminium alloy composites containing different percentages of Silicon Carbide and boron carbide particles are produced. Uniform distribution of the boron carbide particles in the matrix phase is obtained. The prominent points from raised from this study emphasizes that with an increase in percentage of boron carbide addition to Al, there is a transition from Al–B–C formation to formation of boron rich Al–B at grain boundaries. This transition along with retention as discussed derivative of boron carbide resulted in a decrease in interfacial strength. Consequently, there is reduction in strength of aluminum based boron carbide composite with increasing B4C reinforcement. The result illustrates that the modulus of the composite relies on the weight percentage of reinforcement rather than the interfacial wetting. A judicious heat treatment in solid state may ensure wetting and thus will reduce the embrittlement of the MMC. Even in presence of embrittlement, drastic improvement in hardness

(50–550 Hv5) with increase of reinforcement from 0 wt.% to 25 wt.%, rise in modulus of the composite from 22 GPa at 0 wt.% to 183GPa at 25 wt.% reinforcement, retention of electrical conductivity (11% IACS at 25 wt.% addition) and the boron content encourages the use of the composite in high technology areas such as Atomic power generation and forging industries.

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