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ORIGINAL PAPER

Investigation of Mechanical Properties of Aluminium 6061-Silicon Carbide, Boron Carbide Metal Matrix Composite

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Abstract High demand on materials to increase the overall performance of automotive and aerospace components has forced the development of composite materials. Among the various composites, Aluminium Metal Matrix Composites (AMMC) are widely used to fulfill the emerging industrial needs. This paper deals with the investigation of mechanical properties of AMMC produced by the stir casting technique for various compositions of boron carbide and silicon carbide reinforced with aluminium alloy 6061. The tensile, flexural, hardness and impact tests were performed and it was found that the hybrid composites had better properties than pure aluminium. The microstructure of the hybrid composites was analysed using Scanning Electron Microscopy (SEM).

Keywords Aluminium · Silicon carbide · Boron carbide · Mechanical properties · Stir casting process

1 Introduction

Aluminium based metal matrix composites are of great interest due to their superior mechanical properties [1, 2]. Hybrid metal matrix composites are the materials in which two different types of metal particles are added as reinforcement in the matrix metal and they are used in advanced arms systems such as satellite bearings, laser reflectors and inertia navigation systems [3]. The silicon carbide reinforced metal matrix composites have very good hardness, stiffness, specific strength and thermal properties which are increasingly used for making cylinder heads, pistons, liners and brake motors [4, 5]. Ramnath et al. [6] reviewed the mechanical properties of AMMC with various reinforcements compared with the conventional engineering materials. Sun et al. [7] fabricated Aluminum Matrix Fly Ash (AMFA) Cenosphere composites using the stir casting technique and studied the effect of process parameters on composites. They also found that tensile strengths improved maximally by 50 % when the cenosphere content is 13 wt %. This type of composite is difficult to fabricate because of the abrasive nature of the alumina reinforcement. Garget et al. [8] discussed the major advantages of aluminium matrix composites over monolithic materials and other non-ferrous common metals. It was concluded that the machining process is one of the major problems, which resists the wider use of Al alloy in industrial applications.

The wear resistance of the Al 7075 reinforced with B_4C composite increases with the increasing amount of B_4C particles [9]. Madhavan et al. [10] performed rotating bending fatigue tests on smooth specimens of AA 6061-SiC composites with different solutionizing treatment and aging schedule. They found that the solutionizing time has more influence than the other two parameters, viz., aging temperature and aging time on the fatigue strength of the composite. Schneider et al. [11] investigated the deformation behaviour of an Al (6061)/Al_2O_3 metal matrix composite experimentally and numerically under low cycle fatigue. They found that the stress and strain concentrations in the microstructure are responsible for the formation of extrusions, intrusions and crack formation. Aluminium alloy with

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Table 1 Properties of the material

Material	Tensile strength (MPa)	Density (g/cm^3)	Thermal conductivity (W/m-K)	Modulus of elasticity (GPa)
6061 Aluminium alloy	300	2.70	167	68.9
Silicon carbide	137.9	3.1	120	450
Boron carbide	261	2.3	30 - 42	362

alumina-boron carbide metal matrix composites were fabricated and their mechanical properties were investigated. It was concluded that a high percentage of reinforcement increases the mechanical strength of AMMC [12]. It is recommended that the coated carbide cutting tool with high cutting speed and low feed rate produces a better surface finish [13]. Quan and Zhou [14] investigated the tool wear and its mechanism for cutting SiC particle-reinforced AMMC and found that the major damage mechanism is abrasive wear on the tool flank edge and the factor affecting tool life is volume fractions of SiC particles. Mahesh et al. [15] reported that the feed rate and cutting speed are the important parameters that affect the surface quality of the Al-SiC-B_4C composite using the Taguchi method. Prabu et al. [16] studied the distribution of particles in a metal matrix (aluminium alloy–silicon carbide) based on stirring speed and stirring time and observed that increase in stirring speed and stirring time results in homogenous distribution of the particles.

Wu and Xi [17] employed the Back Pressure Equal Channel Angular Consolidation (BP-ECAC) technique in producing aluminium matrix composites with fine fly ash particles. BP-ECAC was proved advantageous over the conventional techniques because of its capability of incorporating very fine particles. Eizadjou et al. [18] investigated the mechanical properties of the Al/Cu composites which were produced by the Accumulative Roll Bonding (ARB) technique. It was found that after five cycles of the ARB process, the maximum yield and tensile strength were obtained. It was also noted that as the number of ARB cycles increased, the thickness of copper layers decreased. Akbari et al. [19] studied the fabrication of aluminium composites with nano-sized Al_2O_3 and observed that SiC nanoparticles have the tendency to float on the surface of the molten aluminium. After the experiments, SEM showed that the nanoparticles were uniformly distributed and the grain size of Al_2O_3 nanoparticles mixed composites showed better results than that of the pure alumina. Puneet and Lokesh [20] investigated the tool wear of alumina reinforced composites during turning operations and found an increase in tool wear with increasing reinforcement ratio. Siddique and Ramnath [21] reported that hybrid composites have better mechanical properties. In this present work, the composites with different weight fractions of reinforcements, namely silicon carbide and boron carbide, are fabricated using the stir casting technique. The mechanical properties of these composites were evaluated, and their internal structures were studied using a scanning electron microscope.

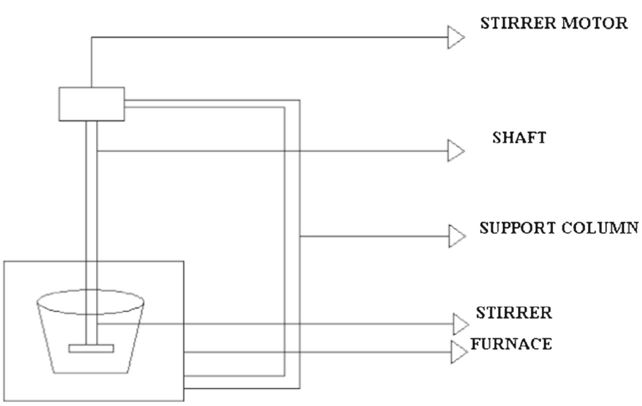


Fig. 1 Stir Casting Technique

2 Experimental Details

2.1 Materials

In this work, aluminium alloy 6061 is used as a matrix material. The reinforcements are silicon carbide and boron carbide. The properties of the matrix material and the reinforcements are given in Table 1.

2.1.1 6061 Aluminium Alloy

The 6061 aluminium alloy is normally used for aircraft and automotive applications due to its resistance to corrosion.

Table 2 Composition of matrix and reinforcement in %weight

Samples	6061Al (%)	SiC (%)	B_4C (%)
1	99	0.5	0.5
2	98	1	1
3	97	1.5	1.5
4	96	2	2

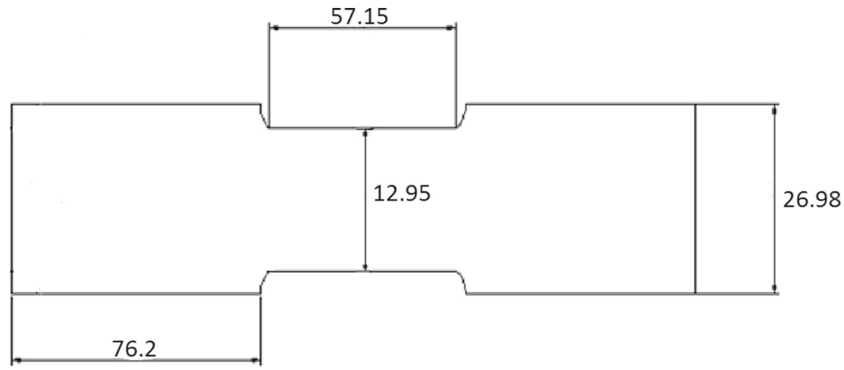


Fig. 2 Tensile Test Specimen

2.1.2 Silicon Carbide (SiC)

Silicon carbide is an excellent abrasive and is resistant to acids, alkalis and molten salts up to 800 °C. In the air, SiC forms a protective silicon oxide coating at 1200 °C, which remains up to 1600 °C. The high thermal conductivity along with low thermal expansion and high strength makes this material suitable for thermal shock resistant applications.

2.1.3 Boron Carbide (B_4C)

Boron carbide is one of the most important materials due to its properties like high strength, low density, high hardness, good chemical stability and neutron absorption capability. Due to its high hardness, B_4C could be an alternative to Al_2O_3 as reinforcement in AMC for applications where a good wear resistance is a major requirement.

2.2 Fabrication Procedure

The stir casting technique is one of the important methods used in the metallurgical process. This method is used for melting metals such as copper, aluminium, magnesium, etc. It is one of the economical and prominent methods for developing and processing metal matrix composites. The schematic diagram of stir casting is shown in Fig. 1. In this work, aluminium metal matrix composites are prepared by the stir casting technique that is simple and cost effective. It is a process of producing composite by stirring the molten base metal continuously. Reinforcements are added after the stirring is done. The mixture is then poured into the die for solidification. Vigorous stirring at high temperature is useful for dissolving the agglomerates.

In this work, 6061 aluminium alloy was melted at 800 °C in a furnace. The silicon carbide and boron carbide reinforcements were first preheated to 450 °C and added to the molten aluminium metal and then vigorous stirring was done. This procedure was repeated varying the composition of other samples. The compositions of four samples prepared are given in Table 2.

2.3 Morphological Analysis:

Morphological analysis was carried out on tested specimens to find the internal surface defects like blow holes, hot spots and accumulation of reinforcements using a Scanning Electron Microscope (SEM). In SEM, the bombardment of electrons that are reflected are formed as an image. Scanning electron microscopy is used to analyse the microstructure of 6061 Aluminum alloy composite fabricated by stir casting process with different weight fractions of silicon carbide and boron carbide.

3 Testing of Composite

The following tests were conducted to determine the mechanical properties of the aluminium alloy composites made by the stir casting technique on four different samples.

3.1 Tensile Test

The tensile test was performed to determine the ability of the material (composite) to withstand the static load in tension or compression. The tensile test was carried out in a Universal Testing Machine (UTM). The specimen was prepared as per ASTM B: 557M standard as shown in Fig. 2.

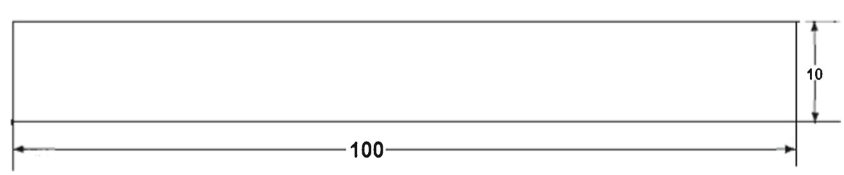


Fig. 3 Flexural test specimen

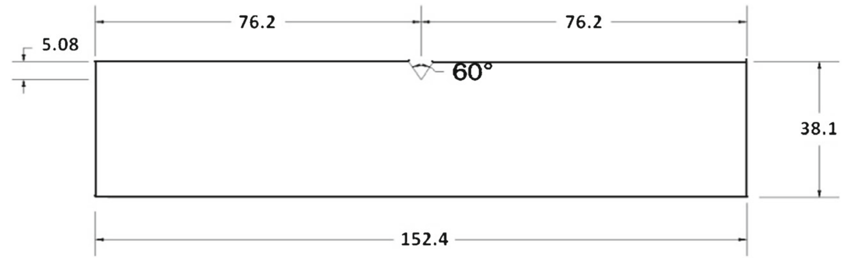


Fig. 4 Impact test specimen

3.2 Flexural Test

The behavior of material subjected to simple bending load was measured by the flexural test. The specimen was prepared as per ASTM A: 370 standards as shown in Fig. 3.

3.3 Impact Test

The amount of energy absorbed by the specimen when subjected to sudden dynamic load was measured using an impact test. The specimen was prepared as per IS: 1757 standards as shown in Fig. 4. In this work, the Charpy impact test was used.

3.4 Hardness Test

The resistance of a material to indentation under a static load was measured using a hardness test. The Brinell hardness test was carried out to find the hardness of the composites.

4 Results and Discussion

4.1 Tensile Test

Table 3 shows the result of tensile tests for the four samples. It was found that the breaking load and tensile strength of sample 4 are higher than for other samples but the elongation is lower than for sample 1. This is due to the presence of high amounts of ceramic reinforcements, namely silicon carbide and boron carbide. Since the content of reinforcements decreased from sample 4 to sample 1, it is also observed that the tensile strength decreases from sample 4 to sample 1. Figure 5 shows the force versus stroke graph for tensile tests. Since sample 1 contains a higher percentage of aluminium as compared to the other samples, it undergoes maximum displacement. Here, the strain was calculated using the formula, Strain = (change in length/original length).

Table 3 Tensile properties of composites

Sample	Break load (kN)	Maximum displacement (mm)	Tensile strength (MPa)	Elongation (%)
Sample 1	6.89	12.98	107.64	9.20
Sample 2	6.99	12.40	117.16	8.80
Sample 3	7.38	11.40	117.70	7.89
Sample 4	8.29	9.70	128.24	7.53

4.2 Flexural Test

The flexural properties of the composites are given in Table 4. It was found that the breaking load and flexural strength of sample 4 are greater than for other samples due to the presence of a high percentage of SiC-B_4C, but its deflection is lower than for other samples. Figure 6 shows the force versus stroke graphs for flexural tests. Sample 1 has maximum deflection, followed by sample 2 and sample 3; this is due to the presence of aluminium in the dispersed condition in the matrix.

4.3 Impact Test

The Charpy impact test was performed, and the energies absorbed by the composites are given in Table 5. It was found that the sample 1 absorbs more energy than other samples, since it contain least amount of SiC that makes it ductile for absorbing more energy.

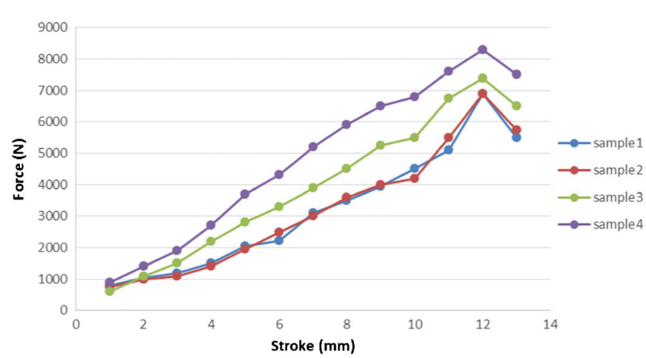


Fig. 5 Force vs stroke graph for tensile test

Table 4 Flexural properties of composites

Sample	Flexural break Load (kN)	Maximum deflection (mm)	Flexural strength (MPa)
Sample 1	1.77	10.6	111.08
Sample 2	2.47	7.48	157.50
Sample 3	2.52	7.39	169.62
Sample 4	3.68	5.6	214.12

Table 5 Impact properties of composites

Sample	Energy absorbed (J)
Sample 1	8.24
Sample 2	6.41
Sample 3	6.1
Sample 4	4.32

4.4 Hardness Test

The Brinell hardness test was carried out, and the results are shown in Table 6. The hardness of sample 4 is higher than for other samples due to the presence of the high amount of silicon carbide and boron carbide.

The following inferences are made after conducting various tests:

i The tensile and flexural strength of sample 4 (96 % 6061Al, 2 % SiC and 2 % B_4C) are higher than for the other samples due to the presence of the high content of carbides as reinforcement.

ii The impact test results show that the sample 1 (99 % 6061 Al, 0.5 % SiC and 0.5 % B_4C) absorbs more energy due to the presence of the high amount of aluminum.

iii The Brinell hardness of sample 4 (96 % 6061 Al, 2 % SiC and 2 % B_4C) is higher than for other samples.

5 Microstructure Analysis of Samples

Figure 7a shows the microstructure for the fractured surface of the tensile tested specimen of sample 1 at 250x magnification. It shows the accumulation of the aluminum matrix due to improper stirring. Figure 7b shows the microstructure for sample 2 at 250x magnification. The distribution of aluminium molecules and reinforcements are visible in this image. It was observed that the patches of boron carbide in the sample have the possibility to initiate a crack and also to propagate in the sample. This is due to the improper mixing of boron carbide in the molten aluminium matrix and also the temperature of reinforcement before mixing. The darker zones are boron carbide, and the lighter zones are aluminium. Figure 7c shows the microstructure for the surface of the flexural tested specimen of sample 1 at 250x magnification. Here, traces of silicon carbide are found. Figure 7d shows the microstructure for sample 2 in which solid boron carbide grains are found.

The silicon carbide traces observed in both Fig. 7c and d enable the crack to initiate and also to propagate. To eliminate this problem, the pouring temperature of reinforcement should be maintained constant before mixing with the matrix. This can be achieved by maintaining the furnace temperature to the exact requirement and also using highly insulated crucibles for holding the matrix. Accumulations of SiC and B_4C are observed in Fig. 7e and f which can be eliminated by preheating the reinforcements to maximum temperature and maintaining it at constant temperature

Fig. 6 Force vs stroke graph for flexural test

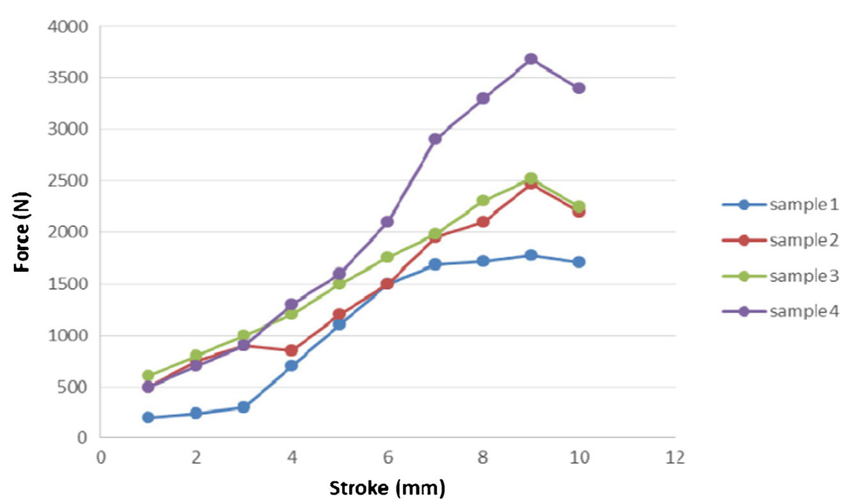
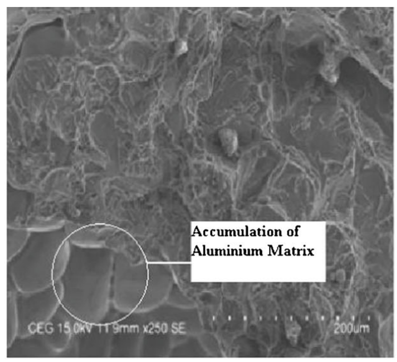


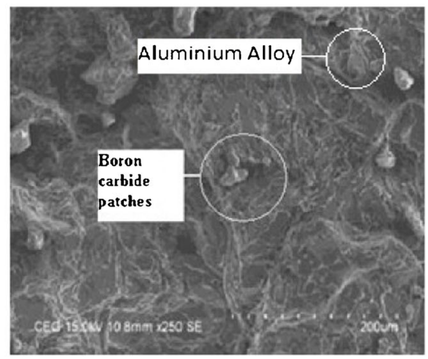
Table 6 Hardness of Composites

Sample	Trial 1 (BHN)	Trial 2 (BHN)	Trial 3 (BHN)	Average Hardness(BHN)
Sample 1	30.6	30.5	30.2	30.43
Sample 2	31.2	31.4	31.1	31.23
Sample 3	32.9	32.1	32.9	32.63
Sample 4	45.9	45.6	45.9	45.8

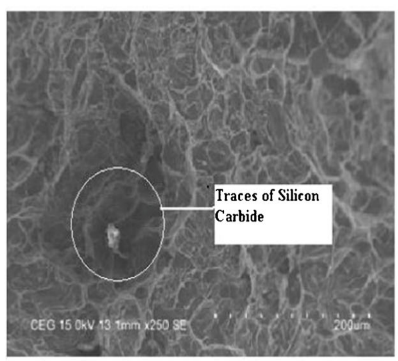
before mixing with the matrix. Also, a small blow hole is observed which can be solved by selecting the proper stirring speed. In Fig. 7g an aluminium inclusion is found along with a silicon carbide particle. Also, deep blow holes that are observed from Fig. 7h are formed due to improper cooling of castings.



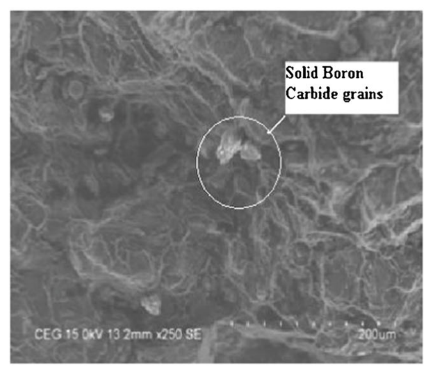
(a) Sample 1 of Tensile Test



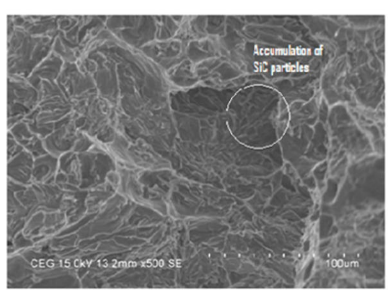
(b) Sample 2 of Tensile Test



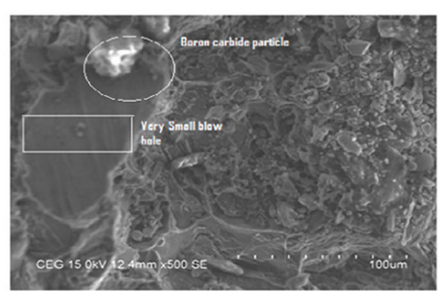
(c) Sample 1 of Flexural test



(d) Sample 2 of Flexural test



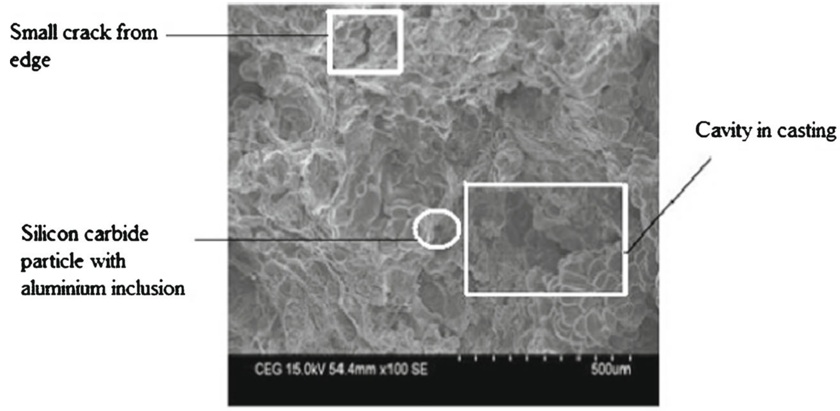
(e) Sample 3 of Tensile test



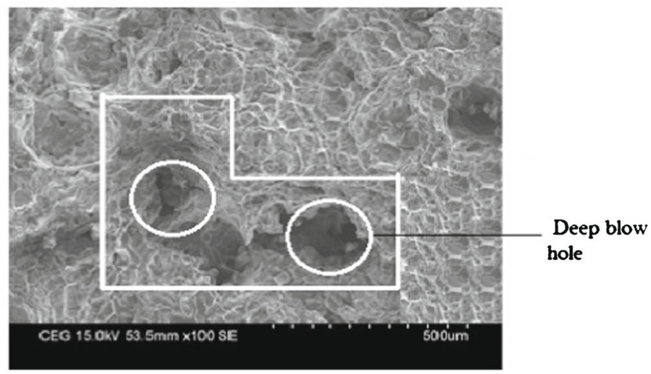
(f) Sample 4 of Flexural test

Fig. 7 SEM images of various test specimens. **a** Sample 1 of Tensile test, **b** Sample 2 of Tensile test, **c** Sample 1 of Flexural test, **d** Sample 2 of Flexural test, **e** Sample 3 of Tensile test, **f** Sample 4 of Flexural test, **g** Sample 3 of Flexural test, **h** Sample 4 of Tensile test

Fig. 7 (continued)



(g) *Sample 3 of Flexural test*



(h) *Sample 4 of Tensile Test*

6 Conclusions

In this work, the stir casting technique is used for fabrication of aluminium metal matrix composites with different compositions of silicon carbide and boron carbide. Of the different samples tested, sample 4 (96 % 6061 Al, 2 % SiC and 2 % B_4C) has higher tensile, flexural strength and hardness due to the presence of the high quantity of carbides in the composite. In addition, sample 4 which contains a high amount of aluminium, absorbs more energy. This work can be further extended by fabricating the composites with different casting methods and comparing their effect on the mechanical properties of composites.

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