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Mechanical Properties in MMC of Aluminum Alloy (A356/LM25) Matrix and Boron Carbide (B_4C) Reinforcement

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Abstract- **In the recent trends Metal Matrix Composites (MMCs) are increasingly becoming a new class of material in aerospace, automobile applications. Since their properties can be tailored through the addition of selected reinforcements, superior strength to weight ratio, wear and high temperature resistance. In the present study Aluminum alloy (A356/LM25) and Boron Carbide (B_4C) were taken as matrix and reinforcement respectively. The Fabrication, mechanical and metallurgical investigation of Aluminum alloy (A356/LM25) and Boron Carbide (B_4C) composites containing the three different weight percentages 5%, 7.5% and 10% of B_4C by means of Two Step-Mixing method of Stir Casting Technique.**

Further it was found from the experimentation is that, the developed method is quite successful to obtain uniform dispersion of reinforcement in the matrix. The results indicated that the wear rate decreases and an increasing trend of hardness and tensile strength with increase in weight percentage of B_4C have been observed.

The internal structure of the composite is observed using Optical Metallurgical Microscope. It is observed that B_4C particles are dispersed uniformly in the aluminum matrix for all wt% and also Grain refinement was increased by increasing in percentage of Boron Carbide (B_4C) reinforcement in the Aluminum (LM25) Matrix.

Keywords: Metal Matrix Composites (MMC); Aluminum Alloy (A356/LM25); Boron Carbide (B_4C); Stir Castig Technique; Microsturture; Harndess; Tensile Strength;

I. INTRODUCTION:

The increasing demand for light weight, inexpensive, energy saving, stiff and strong material in aircraft, space, defence and automotive applications has stimulated a steadily growing effort to developed composite material. Nowadays, Metal Matrix Composites (MMCs) are under serious consideration to replace conventional materials for a large number of structural applications such as aeronautical / aerospace, transportation, defence and sports industries because of their superior properties. The excellent mechanical properties and comparatively low cost make them as an attractive option. In AMCs one of the constituent is aluminum alloy, is termed as matrix phase. The other constituent which is embedded in this aluminum alloy matrix is serves as reinforcement. The reinforcement is usually to be non-metallic and commonly ceramic. The aluminum matrix is getting strengthened when it is reinforced with the hard ceramic particles like SiC, Al_2O_3, and B_4C etc. Aluminum alloys are still the subjects of intense studies, as their low density gives additional advantages in several applications. These alloys have started to replace cast iron and bronze to manufacture wear resistance parts. MMCs reinforced with particles tend to offer enhancement of properties processed by conventional routes. A356/LM25 find applications in the food, chemical, marine, electrical, many other industries and in road transport vehicles where it is used for wheels, cylinder blocks and heads, and other engine and body castings.

Among different kinds of the recently developed composites, particle reinforced metal matrix composites and in particular aluminum base materials have already emerged as candidates for industrial applications. Boron Carbide particulate reinforced aluminum composites possess a unique combination of high specific strength, high elastic modulus, good wear resistance and good thermal stability than the corresponding non-reinforced matrix alloy system.

A limited research work has been reported on AMCs reinforced with B_4C due to higher raw material cost and poor wetting. B_4C is a robust material having excellent chemical and thermal stability, high hardness and low density (2.52 g/cm^3) and it is used for manufacturing bullet proof vests, armor tank etc. Hence, B_4C reinforced aluminum matrix composite has gained more attraction with low cost casting route.

To manufacture the MMC materials, large numbers of fabrication techniques are currently used based on the type of reinforcement. i.e., stir casting technique (or compo casting), liquid metal infiltration, squeeze casting and spray co-deposition. The microstructure is also a very important parameter which influences the properties of the composite.

II. SELECTION OF MATERIALS:

A. Aluminum:

Aluminum is the third most abundant element (after oxygen and silicon), and the most abundant metal, in the Earth's crust. Aluminum is remarkable for the metal's low density and for its ability to resist corrosion due to the phenomenon of passivation. Structural components made from aluminum and its alloys are vital role in aerospace industry, marine, transportation and structural materials. Commercially pure aluminum has a tensile strength of approximately 90 MPa and can be improved 180 MPa by cold working. The heat treatable grades can develop a tensile strength of around 570 MPa and even higher in some alloys. The coefficient of thermal expansion of aluminum alloys is affected by the nature of their constituents: example the presence of silicon and copper reduces expansion while magnesium increases it.

Aluminum is almost always alloyed, which markedly improves its mechanical properties, especially when tempered. The main alloying agents are copper, zinc, magnesium, manganese, and silicon and the levels of these other metals are in the range of a few percent by weight.

B. Boron Carbide:

Boron carbide (B_4C) is an extremely hard boron–carbon ceramic and ionic material, used in tank armor, bulletproof vests, engine sabotage powders, as well as numerous industrial applications. It is one of the hardest known materials, behind cubic boron nitride and diamond.

Boron Carbide particulate reinforced aluminum composites possess a unique combination of high specific strength, high elastic modulus, good wear resistance and good thermal stability than the corresponding non-reinforced matrix alloy system. A limited research work has been reported on AMCs reinforced with B_4C due to higher raw material cost and poor wetting. B_4C is a robust material having excellent chemical and thermal stability, high hardness and low density (2.52 g/cm^3) also it is used for manufacturing bullet proof vests, armor tank, etc. Hence, B_4C reinforced aluminum matrix composite has gained more attraction with low cost casting route.

III. METHODOLOGY:

A. Composition for Fabrication:

The fabrication is done with the composition of B_4C and Al. Here the Aluminum alloy (A356/LM25) is chosen as a parent material and B_4C as a host material. In the present study B_4C is reinforced with LM25 with different wt% compositions of 5, 7.5 and 10.

According to BS 1490:1988, the chemical composition of A356/LM25 alloy is as below:

Table 1: Chemical Composition of A356/LM25 alloy by Wt%

Cu	Mg	Si	Fe	Mn	Ni	Zn	Pb	Sn	Ti	Al
0.1	0.6	7.5	0.5	0.3	0.1	0.1	0.1	0.05	0.2	Balance

Table 2: Physical Properties of A356/LM25 alloy

Coefficient of Thermal Expansion (per°C at 20-100°C)	0.000022
Thermal Conductivity (cal/cm 2 /cm/°C at 25°C)	0.36
Electrical Conductivity (% copper standard at 20°C)	39
Density (g/cm^3)	2.68
Freezing Range (°C) approx	615-550

B. Reinforcement:

In the present study boron carbide (B_4C) is acted as a reinforcement agent with different Wt %.(5, 7.5 and 10%). Boron carbide has low wettability property, hence it cannot be readily mix with Aluminum melt. In order to improve the wettability and remove moisture content it is preheated to 480°C for 2 hour in a muffle furnace.

Table 3: Properties of Boron Carbide (B_4C)

Molecular formula	B_4C
Molar mass	55.255 g/mol
Density	2.52 g/cm^3, solid.
Melting point	2,763 °C (5,005 °F; 3,036 K)
Boiling point	3,500 °C (6,330 °F; 3,770 K)
Acidity (pK_a)	6–7 (20 °C)
Appearance	Dark Gray or Black Powder, odorless
Solubility in water	Insoluble

C. Preparation of Composition by Stir Casting Method:

Stir casting is the best and economical method for producing the aluminum metal matrix composite and mixing of ceramic materials effectively.

i. Construction of Stir Casting Furnace:

Here Al-B_4C Composite is fabricated by using Stir casting technique. For that, we require a stir casting furnace with 3 blade graphite stirrer. Since stir casting is not a conventional casting method, we have to design a suitable one. Even though some stir casting furnaces are readily available in the market, a custom made conventional stir casting furnace is cheaper and it is best suited for the present work to various process parameters according the requirements.

A conventional stir casting furnace consists of the following basic components.

a. Furnace
b. Crucible
c. Temperature Controller
d. Stirring Setup

ii. Preparation of Furnace:

A furnace is prepared by using a cylindrical thick sheet metal drum. The inner wall of furnace is lined with refractory ceramic material to prevent heat losses and it is sealed with glass wool material which is prepared from glass. Total furnace was made with kanthaal wire. It is applicable to produce heat up to 1350^{0}C. It is protected by 15mm thickness of ceramic material integrated with 10% of iron.

iii. Preparation of Stirrer:

A 1200 rpm high torque reversible motor is taken and connected to a potentiometer for varying speeds as per the requirement. The motor shaft is coupled to one end of a stainless steel stirrer rod and the other end is connected to a graphite three-blade impeller and is tested by stirring water in the crucible and grinded to the desired angle for producing vortex.

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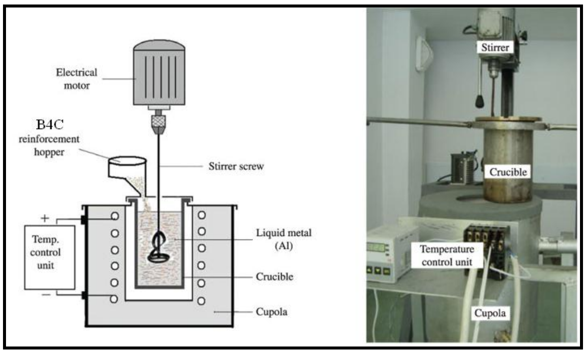

Figure 1: Schematic diagram of Stir Casting Technique

iv. Temperature controller:

A temperature controller is used to control the temperature of the furnace with the help of heat sensor.

v. Consumables and Miscellaneous Materials:

A 15 litre silicon carbide crucible is bought and it is preheated to red hot condition (650^{0}C) to relieve internal stress. A stand is prepared for mounting of stirrer assembly above the furnace. To avoid vibrations in the stirrer, motor is mounted on springs which damp the vibrations. A ceramic cap is used to prevent motor from exposing to direct heat from the furnace. The stand is prepared as such that some small adjustments can be made to centre the stirrer to the crucible.

vi. Procurement of Raw Materials:

The present work is carried out with the help of SIBAR Automotive Parts Pvt. Ltd, Chennai. Aluminium alloy (LM25) was given from the company's inventory. Boron carbide powder & Graphite blade were purchased from the Matrix Powder Metallurgy, Vizag and also it is designed for desired particle size and shape.

Figure 2: Three-Blade Graphite Impeller

Figure 3: Stainless Steel Stirrer Rod

Figure 4: Potentiometer

vii. Sample Preparation

A standard test bar is prepared by using sand casting, which will produce Inch diameter cylindrical rod which has a length of 280 mm with conical shape in upper part to avoid shrinkage (which causes to decrease in sizes). It was tested that the test cavity consumes 580 to 600grams of molten metal.

Stir casting method was used in preparing composite samples, which could distribute boron carbide particles homogenously in the aluminium matrix by forming vortex in molten metallic. It could pull boron carbide particles through molten metallic and distributed them homogenously. Stir casting improves mechanical and physical properties of the aluminium matrix.

Metal is melted in a furnace which is maintained at 710^{o}C temperature. The stirrer is mounted on the top of the furnace. The molten metal is transferred to the cavity by using M.S ladle which carries 400 grams of molten aluminium.

At first raw aluminium of weight 3 kg is taken in to the stir casting furnace and it is melted to 665^{0}C. Take a sample with 0% of B_4C. After that Boron carbide of 5% by weight is measured separately and simultaneously preheated in LPG burner with the help of stainless steel ladle. When the temperature in the furnace were settled nearly above 700^{o}C, metal treatment is carried out by adding overall to the molten metal which removes oxides and other impurities in the metal.

Later, stirrer is inserted and allowed to rotate and create vortex in the crucible. The speed of the stirrer is controlled using potentiometer to get desired vortex. The desired speed is maintained in the crucible and reinforce-ements were added slowly to the vortex. After the complete addition of reinforcements, the stirrer is further allowed to rotate for ten more minutes for uniform distribution of particulates in the matrix.

Figure 5: Fabricated LM25 and Boron Carbide Composite

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After stirring, molten metal from the crucible is poured slowly into the mould cavity and allowed to cool for about two minutes, mould part removed from the cavity. The remaining molten metal in the crucible is also used for the test samples of 7.5% and 10% of Boron carbide. All the samples were grouped and marked based on the composition of reinforcements and is sent to heat treatment process.

All the samples were fully heat treated which includes solution heat treatment for 12 hours at 520-530ºC and quenched in hot water followed by precipitation treatment of 8 hours at 170ºC.

IV. EXPERIMENTAL SET UP:

After heat treatment of samples the following operations were performed.

1. Specimens were analysed for variation in density as per Archimedes principle.
2. Specimens were freed from risers and turned to required dimensions on a lathe machine and polished.
3. Tensile test was conducted on turned samples with the help of Universal Testing Machine and the average values of each composition were noted.
4. Hardness test was conducted on the riser sections.

A. *Tensile Test:*

ASTM (American standards for testing of Materials) specification gives the drawing of the specimen to be prepared for conducting the test with tolerances. The prepared tensile specimen were inspected after machining and loaded in the tensile testing machine or universal testing machine and the tensile force is given. A tensile specimen is a standardized sample cross-section. It has two shoulders and a gauge (section) in between. The shoulders are large so they can be readily gripped, whereas the gauge section has a smaller cross-section so that the deformation and failure can occur in this area.

The specifications for tensile testing are as shown.

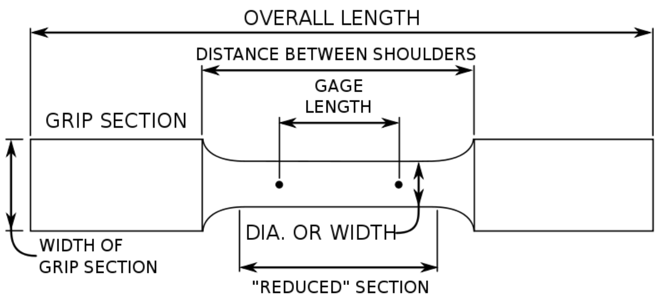

Figure 6: Drawing of Specimen as per ASTM Specification for Tensile Test

The test process involves placing the test specimen in the testing machine and applying tension on it until it fractures. During the application of tension, the elongation of the gauge section is recorded against the applied force. The data is manipulated so that it is not specific to the geometry of the test sample. The elongation measurement is used to calculate the engineering strain, ε.

Table 4: Specifications of Tensile Test Specimens

Specification	Dimensions (mm)
Diameter	6
Distance between shoulders	50
Overall length	80
Diameter of grip section	20
Length of the grip section	15

Figure 7: Tensile Test on various Al-B_4C Compositions

B. *Hardness Test:*

The hardness of the Al alloy (LM25) and Al-B_4C composites was evaluated using Brinell hardness testing machine with 500 kg load and 10 mm diameter steel ball indenter. The indentation time for hardness measurement was 15 seconds. An average of five readings was taken for each hardness value. The final BHN value calculated from the following equation.

$$\mathrm{BHN} = \frac{2P}{\pi D\left(D - \sqrt{D^2 - d^2}\right)}$$

Where: P is the applied load in kilograms
D is the diameter of indenter in mm
d is the diameter of indentation in mm

The average hardness of the Al alloy and Al-B_4C composites is shown in Graph 2.

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Figure 8: Brinell Hardness Test on various Al-B_4C Compositions

C. *Density measurement:*

The density of the alloy and composites was measured by Archimedes drainage method by using the following equation. ρMMC = m / ((m-m1) X ρ_{H2O}) Where ρMMC is the density of the Al-B_4C composite, 'm' is the mass of the composite sample in air, 'm1' is the mass of the same composite in distilled water and 'ρ_{H2O}' is the density of distilled water(at 293K) is 998 kg/m^3. Graph 1 shows the density of the Al alloy and Al- B_4C composites in cast condition.

V. RESULTS AND DISCUSSIONS:

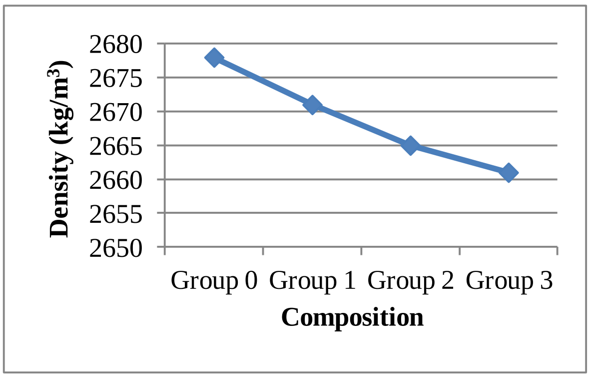
After heat treatment of all the samples, each sample was separately tested for the density, hardness and tensile strength and the average values were analyzed by comparing with the zero sample. The results in various tests were discussed below.

For convenience of presentation and plotting, from here onwards pure LM25 samples were referred as **Group 0**, LM25 with 5% Boron Carbide samples were referred as **Group 1** , LM 25 with 7.5% Boron Carbide samples were referred as **Group 2** and LM 25 With 10% Boron Carbide Samples Were referred as **Group 3.**

a) *Density:*

Density of each sample was measured based on Archimedes principle in a calibrated glass jar. From the Graph 1 it is notice that the density of Group1 is less compared to the Group 0 because the density of Boron Carbide powder is less compared to aluminium. Further, the density of Group 2 is decreases because of the increase of boron carbide in the composite and also Group 3 too decreases continuously as again boron carbide is increases in the composite.

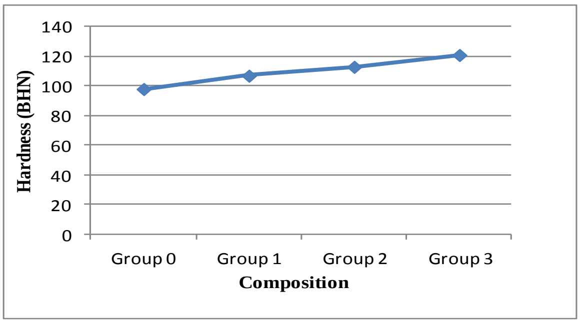
Graph 1: Density Vs Composition



b) *Hardness:*

Hardness is the main property for various applications. Since the boron carbide is superior to aluminium, in general we can expect the dominance of boron carbide in increase of hardness of the composite. The practical observations revealed that the hardness of the composite increased considerably. It was noticed that the increase of hardness from Group 0 to Group 1 is form 98 BHN to 107 BHN has a difference of 9 BHN, the increase from Group 1 to Group 2 is from 107 BHN to 113 BHN has a difference of only 6 BHN and the increase from Group 2 to Group 3 is from 113 BHN to 121BHN has difference of 8 BHN.

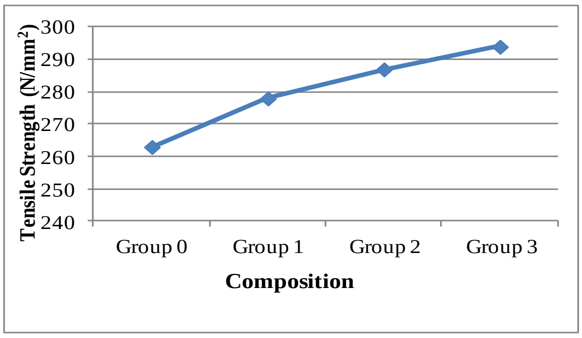
Graph 2: Hardness Vs Composition



c) *Tensile Strength:*

As it was the maximum stress that a material can withstand while being stretched, interfacial bonds may affect greatly on the tensile strength of the composite. From the Graph 3, we can see that the tensile strength was increased in the Al-B_4C composites but doesn't have comparable variation. Weak interfacial bonds may result in decrease in tensile strength of the composite, but here the increase of tensile strength shows that there was good interfacial strength. Since the reinforcements were preheated before mixing with aluminium matrix there might be uniform distribution and smooth interface while mixing. From this result we can expect good interfacial strength when we heat the reinforcements at higher temperatures which will facilitate uniform distribution of more amount of composite without losing the strength.

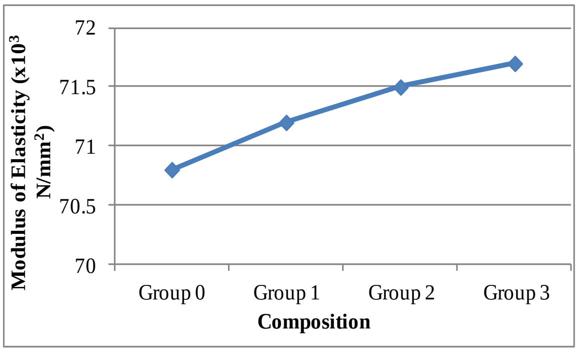
Graph 3: *Tensile Strength* Vs Composition



d) Modulus of Elasticity:

Modulus of elasticity shows linear relation with tensile strength as same as conventional materials. From the Graph 4, we can observe that the modulus of elasticity was increased but not greatly as same as tensile strength. The elongation of material is similar to the base alloy, almost negligible amount of elongation for all the groups. Since all the samples are fully heat treated, the samples will gain brittleness and hardness losing ductility which might be resulted in tendency of brittle failure.

Graph 4: Modulus of Elasticity Vs Composition



VI. MICROSTRUCTURE STUDY:

The study of microstructure is very useful for the analysis of properties and proportion of mixing in the aluminum matrix. In that the microstructure reveals the strength of materials. A carefully prepared specimen and magnification are needed for microscopic examination. Proper preparation of the specimen and the material's surface requires that a rigid step-by-step process be followed.

Figure 9: Emery papers and Optical Metallurgical Microscope

The first step is carefully selecting a small sample of the material to undergo microstructure analysis with consideration given to location and orientation. This step is followed by sectioning, mounting, grinding, polishing and etching to reveal accurate microstructure and content. The following figure shows the microstructure of the three different compositions.

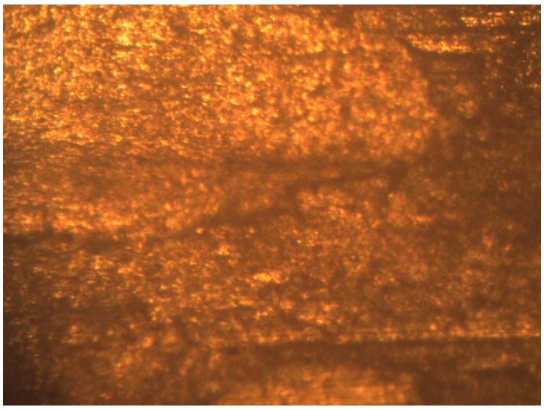


Figure 10: Optical microstructure of metal mould casted MMC Containing 5.0 wt% of reinforcement at 100X Magnification

Figure 11: Optical microstructure of metal mould casted MMC Containing 7.5 wt% of reinforcement at 100X Magnification

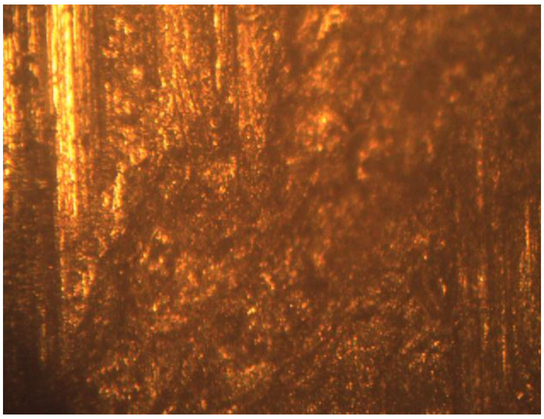


Figure 12: Optical microstructure of metal mould casted MMC Containing 10wt% of reinforcement at 100X Magnification

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From the microstructures it is observed that B_4C particles are dispersed uniformly in the aluminum matrix for all particle sizes and for all wt%. This can be attributed to the effective stirring action and the use of appropriate process parameters.

- In the 5% Boron Carbide reinforcement the grain size is large.
- In the 7.5% Boron Carbide reinforcement the grain size is fine.
- In the 10% Boron Carbide reinforcement the grain size is very fine.

✓ Grain refinement was increased by increasing in percentage of Boron Carbide reinforcement in Aluminium Matrix.

✓ As per the Metallurgical aspect the grain refinement improves the mechanical properties.

i.e., Boron Carbide is a grain refiner in al matrix. It may be the cause to improve the mechanical properties.

VII. CONCLUSION:

The A356/LM25 - B_4C composites produced by stir cast method with different weight percentages (viz 5, 7.5 and 10) of reinforcement and the corresponding microstructure, mechanical properties were evaluated. The conclusions of the study are as follows:

1. Addition of Boron-Carbide reinforcement to the Al matrix increases the mechanical properties of the composite.
2. Hardness of the composite increases with increase of boron-carbide.
3. Tensile strength of the Al-B_4C Composite has been increased with the increase in the percentage of boron carbide reinforcement in aluminum matrix.
4. It was observed that the modulus of elasticity of Al-B_4C Composite is increased with increase in the percentage of boron carbide reinforcement in aluminum matrix.
5. The mechanical properties improvements are mainly due to the highly hardness boron carbide particles.
6. From the Microstructure it was observed that Grain refinement was increased by increase in percentage of Boron Carbide reinforcement in Aluminum Matrix.
7. As per the Metallurgical aspect the grain refinement improves the mechanical properties.
   i.e., Boron Carbide is a grain refiner in Al matrix. It may be the cause to improve the mechanical properties.

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