MICROSTRUCTURE AND MECHANICAL BEHAVIOR OF 88 MICRON SIZED BORON CARBIDE PARTICLES REINFORCED AL7475 ALLOY METAL COMPOSITES

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ABSTRACT

In the present research aerospace aluminium alloy 7475 with 2, 4, 6, 8 and 10 weight percentages of varying B₄C particles reinforced composites were synthesized by adopting two step stir technique. The prepared composites were evaluated for microstructural studies using SEM and EDS. Further, mechanical properties like hardness, tensile strength, compression and creep behavior were evaluated as per ASTM testing methods. Scanning electron micrographs revealed the uniform distribution of particles in the Al7475 alloy matrix. The presence of 88 micron sized boron carbide particles improved the hardness, tensile strength, compression and creep behavior of Al7474 alloy composites. Failure analysis studies were carried out by observing SEM failure surfaces.

Keywords: Al7475 Alloy, B₄C Particles, Scanning Electron Microscope, Tensile Strength, Creep, Fractography

I. INTRODUCTION

Any composite material is a combination of two or more materials with non-identical chemical or physical properties, when fabricated produces entirely different product with distinct characteristic as compared with the individual material characteristics. The reinforcement of the material is usually fabricated at a macroscopic level. These materials are intermixed in such a ratio that its certain properties get enhanced. The ratios of two materials are optimized based on their applications. In the finished structure, individual material remains separate and distinct, but bonded together for better strength with lighter weight and cost effective with respect to the conventional material [1, 2]. The composite material so produced has tailored properties, which proves to be better than any of the constituent material [3-5]. These composites are usually preferred for their improvised mechanical properties, but also for thermal, electrical and environmental required properties. These materials are generally recommended for various applications like concretes, reinforced plastics such as fiber reinforced polymers (FRP), metal matrix composites (MMC), and ceramic matrix composites (CMC). Ceramic matrix composites and metal matrix composites are usually required for buildings, bridges and structure such as boat house, swimming pool structure, race car components, bath tubs, tanks, and also advanced materials in spacecraft’s, aircrafts building and etc., which are high in demand [6, 7].

The aluminium alloy matrix reinforced with SiC and B₄C particulate is of latest advanced materials [8, 9]. Generally hard materials are employed as reinforcements because of their potential enhancement in mechanical properties such as hardness and tensile strength, and they are the advantageous properties in tribological application. The improvements in mechanical properties are generally obtained by means of reinforcements with suitable particulates. Graphite fibers or particulates as reinforcing material have also been considered as a high strength, low density reinforcing material in MMC. Aluminium MMCs produced by solidification techniques with graphite particulate as reinforcing material, symbolizes a class of low-cost, tailor-made materials for a various engineering application such as brake pads, bushes and bearings in automotive industries [10, 11]. The aluminium metal matrix material with B₄C as reinforcement has a potential to produce a material with a better thermal conductivity, tremendous mechanical properties and good damping behaviour at elevated temperatures [12]. The recent research carried out so far on AMMC with ceramic reinforcement particulates reveals that increase in wear resistance and improvements in mechanical properties at elevated temperatures. The matrix deformation, load distribution and micro cracks that often develop along the friction direction could be effectively avoided due to presence of B₄C [13, 14].
The methodology of Al7475/B₄C composites production can be classified into three types: solid state method, semi solid-state method and liquid state method. Further solid-state method is classified into powder metallurgy, mechanical alloying and diffusion bonding methods [15, 16]. The most economical method among all the methods for metal matrix composite production is 'Liquid Metallurgy' technique, and further it is divided into four categories viz., pressure infiltration, stir casting, spray deposition and in-situ processing. Liquid metal stirring process has some important advantages over other methods like simple and inexpensive, better matrix/particle bonding, better control on matrix structure, wide selection of materials, flexibility and applicability to high production rates and excellent near net shaped components production [17, 18]. But, there are a few problems connected with stir casting of AMMCs like poor wettability and heterogeneous distribution of the reinforcement particles. Improvement in wettability to certain extent can be achieved by many methods such as addition of halide salts, stirring mechanically, reinforcement particulates preheating to eliminate the absorbed gases from the particle surface, addition of alloying elements like magnesium, zirconium and silicon nitride and surface coatings over reinforcement etc. [19, 20].

Investigating the mechanical behaviour of aluminium alloy and micro hard boron carbide reinforced composite is an interesting research area. Therefore, the present study aims to synthesize Al7475-B₄C MMC by stir casting method with B₄C particle size of 88-microns.

II. EXPERIMENTAL DETAILS

Materials Used

The 7XXX series (Al-Zn-Mg-Cu) aluminium alloys are extensively used in aircraft industry due to their superior strength, ductility fracture toughness and fatigue life of about 500 MPa in heat treated condition. This Al7475 aluminium alloy is chosen as matrix material based on its high demand in aircraft and other industries due to its high strength. In this series alloys, significant alloying elements are zinc and magnesium, but sometimes for better strength and unique mechanical properties some amount of copper will also be added. During fracture test of this alloy, large sizes of dimples are seen telling that intermetallic particles are coarser. The intermetallic particles are mainly precipitated in the grain boundary region; there are precipitation free zones in the alloy microstructure. Hence in 77475 series aluminium alloys, energy required for crack propagation is greater than crack formation. The Table 4.1 below confirms the chemical composition of Al7475 alloy.

<table>
<thead>
<tr>
<th>Elements</th>
<th>Symbol</th>
<th>Weight %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zinc</td>
<td>Zn</td>
<td>6.0</td>
</tr>
<tr>
<td>Magnesium</td>
<td>Mg</td>
<td>2.40</td>
</tr>
<tr>
<td>Silicon</td>
<td>Si</td>
<td>0.10</td>
</tr>
<tr>
<td>Iron</td>
<td>Fe</td>
<td>0.12</td>
</tr>
<tr>
<td>Copper</td>
<td>Cu</td>
<td>1.80</td>
</tr>
<tr>
<td>Titanium</td>
<td>Ti</td>
<td>0.06</td>
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<tr>
<td>Manganese</td>
<td>Mn</td>
<td>0.06</td>
</tr>
<tr>
<td>Chromium</td>
<td>Cr</td>
<td>0.25</td>
</tr>
<tr>
<td>Aluminium</td>
<td>Al</td>
<td>Balance</td>
</tr>
</tbody>
</table>

Preparation of Composites

There are many methods to produce metal matrix composites, among these methods basic stir casting method is adopted due to its cost effective and simple process for manufacturing of Al7475/ B₄C composites. The detailed step by step procedure is given below about the method of composite manufacturing, apparatus, equipments and machines used for the experimental work.

1. Predetermined weight of Al7475 alloy blocks are charged in to the crucible and is kept in the furnace for alloy to melt till liquid state up to a temperature of 750°C
ii. Predetermined weight of B$_4$C reinforce particulates, stirrer and cast iron moulds are preheated up to a temperature of 300°C to separate out all the moisture and gases from the surfaces.

iii. While heating alloy to molten metal stage, gases will be released due to chemical reaction between base metal and alloying elements. This entrapped gas to be removed by method of sprinkling the degassing agent (2-3 grams hexachloroethane C$_2$Cl$_6$) on the molten metal surface and stirring the molten metal manually.

iv. A layer of slag will be formed above the molten metal surface, which has to be skimmed out by using the shovel kind of skimmer.

v. Molten metal to be stirred to form a vortex by immersing the stirrer vertically down to a depth of 55 to 65% of the molten metal height in the crucible and rotating it up to a speed of 300 rpm. A stirrer is a fan type made of steel coated with zirconia.

vi. The preheated B$_4$C reinforce particulates are poured slowly into the vortex in two-phases with the stirrer speed maintaining at 300 rpm.

vii. Intermittent stirring of the molten metal to be continued for about 5 minutes after addition of reinforce particulates on to molten metal vortex. It is to be noted that the temperature of the melt to be maintained at 730°C throughout.

viii. Molten metal so prepared as stated in previous point is ready for pouring into the preheated mould. It may be noted that the moulds are also required to be heated to 300°C before pouring the molten metal mixture to prevent surface cracks due to sudden cooling & uneven flowing in the moulds. Mould surfaces were painted using graphite to get the good surface finish of the specimens.

ix. The aluminium alloy metal matrix composites castings of 15 mm dia. & 120 mm length dimensions were produced by opening the cast iron mould after solidification and reaching to room temperature cooling. The prepared composites were evaluated for microstructural studies and various mechanical properties as per ASTM standards.

Fig 1: Creep test specimen dimensions

### III. RESULTS AND DISCUSSION

**Microstructural Studies**

The quantity of reinforcing element of B$_4$C particles of 88 µm size used in the composites development of varying reinforcement i.e. 2, 4, 6, 8 and 10% by weight. The metallographic specimens of all the composites and base material are prepared by machining into cylindrical form, and then the different samples are ground sequentially with 220, 400, 600, 800 and 1000 grit size papers. The mechanical polishing, lapping, further with Keller’s chemical solution etching which is generally suggested for Al alloys and its composites, are done to obtain better contrast. The 88 µm size B$_4$C particulate distribution in the Al7475 alloy matrix of different composite fabrication conditions are examined through scanning electron microscope (SEM).
Fig. 2: Scanning electron micrographs of (a) as cast Al7475 alloy (b) Al7475-2 wt. % 88 μm B₄C (c) Al7475-4 wt. % 88 μm B₄C (d) Al7475-6 wt. % 88 μm B₄C (e) Al7475-8 wt. % 88 μm B₄C (f) Al7475-10 wt. % 88 μm B₄C particles

The SEM micrographs bring out the distribution of 88-micron size B₄C reinforcement particles with different percentage of weight, which is almost uniform throughout the Al 7475 matrix, and it is evident from the Fig. 52 (b-f) above. Fig. 2 (a) is the SEM image of as cast Al7475 alloy, which is free from particles. Further, Fig. 2(b-f) is showing the SEM micrographs of Al7475 alloy with 2, 4, 6, 8 and 10 wt. % of B₄C reinforced composites. The presence of particles is less in the lower wt. % of reinforcement, further as the weight % of B₄C particles increases from 2 to 10 wt. % as in Fig. 2 (f), there is more number of particles in the Al7475 alloy matrix. Also, it can be observed from the Fig. 2 (b-f) that the strong bonding exists between the matrix and reinforcement.

For determining elements and its relative proportion presence EDS is one of the powerful and useful techniques. In chemical analysis one can find out the elements present in the sample, but quantifying proportion of presence is not so accurate therefore EDS is used. EDS technique is adopted for elemental analysis of Al7475-2 wt. % 88 μm B₄C, Al7475-4 wt. % 88 μm B₄C, Al7475-6 wt. % 88 μm B₄C, Al7475-8 wt. % 88 μm B₄C and Al7475-10 wt. % 88 μm B₄C reinforced composites, the compositions of above said composites are tabulated and shown in the Table 2.

<table>
<thead>
<tr>
<th>Elements</th>
<th>Al 7475</th>
<th>Al 7475 + wt. % B₄C 88 micron size</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2 wt. % B₄C</td>
</tr>
<tr>
<td>Zn</td>
<td>6.00</td>
<td>5.44</td>
</tr>
<tr>
<td>Mg</td>
<td>2.40</td>
<td>1.95</td>
</tr>
<tr>
<td>Si</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td>Fe</td>
<td>0.12</td>
<td>0.10</td>
</tr>
</tbody>
</table>
Fig 3: Energy dispersive spectrograph of as cast Al7475 Aluminium alloy

Fig. 3 is the EDS spectrograph of as cast Al7475 aluminium alloy. The spectrum confirms the presence of aluminium as the highest element followed by zinc along with magnesium, silicon, iron, copper, titanium, manganese & chromium alloys as other alloying elements.

Fig 4: Energy dispersive spectrograph of Al7475 - 10 wt.% 88 μm B₄C composite

In the Fig. 4 shows the EDS spectrograph of Al7475 - 10 wt.% 88 μm B₄C composite, from the graph it is noticed that the presence of boron (B) and carbon (C) along with the elements of Al 7475 aluminium alloy. Besides in the scanned image the dark patches observed which are scattered very densely with respect to 8 wt. % 88 μm B₄C nothing but B₄C particulates and it confirms the presence of B₄C in Al7475 alloy.

Hardness Measurements

The material hardness is the measure of resistance exhibited by that material to the permanent plastic deformation. The hardness of cast Al7475 and Al7475-88 μm B₄C composites containing (2, 4, 6, 8 and 10 wt. %)
%) are evaluated Brinell hardness testing machine using 5mm ball indenter, with 250 kgf load application and dwell time 30 seconds for all the specimen at several locations. It may be observed in the Fig. 5 that the composites hardness values are higher than the cast matrix material of the composite; from Fig 5, it is evident that the hardness increases with the increasing wt. % of -88 µm B₄C in composites. The trend hardness increase is due to hardness of the B₄C particles, which is to be dispersed uniformly, will add to the hardness of the composite because they behave as barriers to the progress of displacements within the matrix [22, 23].

![Chart of Hardness vs. Wt. % of 88 micron sized B₄C particulates](chart1.png)

**Fig 5:** Hardness of Al7475 alloy and its 88-micron size B₄C reinforced composites

### Evaluation of Tensile Properties

The tensile strength improved in composites can be due to the reality that the reinforcement B₄C owns higher strength, because of the better bonding and dispersion of B₄C particulates uniformly in base matrix. In the current case, the increase in UTS and yield strength of the composites specimen is clearly due to the presence of B₄C particles, which improves the matrix alloy strength, imparting additional resistance in the composite opposite to the applied tensile stresses. Further, this strong bonding improved the tensile properties. Likewise, different strengthening mechanisms have been projected to clarify the enhancement in quality on account of intermittently strengthened Al MMGs. These incorporate the usual composite strengthening through the load exchange between the soft material and the hard and brittle reinforcement [24, 25].

The ultimate tensile strength and yield strength were increased with increasing B₄C percentage. The B₄C particulates in the matrix alloy provide enhanced protection to the softer matrix. Al7475 alloy with 88-micron size B₄C composites show more UTS and YS values as compared to 88-micron size composites. This increase in strength for smaller particulate reinforcement is mainly due to good bonding, as particle size decreases. Fig. 6 and 7 are indicating the yield strength and ultimate tensile strength of prepared composites.

![Chart of Yield Strength vs. Weight % of B₄C Particulates](chart2.png)

**Fig 6:** YS of Al7475 - 88-micron size B₄C particles
In the current investigation, the yield strength increase is chiefly by the increased dislocation density rising from a thermal disparity between the reinforcement and matrix. Metal matrix composites are characterized with great difference in the coefficient thermal expansion of the matrix and reinforcement. With the infinitesimal temperature changes produce thermal stresses in the matrix Al7475 alloy. So produced thermal stresses can be partly diffused by dislocation generation at the vicinity of the matrix and particulate interface.

![Fig 7: UTS of Al7475 - 88-micron size B₄C particles](image)

When the specimen subjected in its axial direction load the material have a tendency to elongate. In tensile testing the ratio of increase in test specimens gauge length after it fractures to its original gauge length gives us the elongation of that specimen. Generally, elongation of a specimen parameter is expressed in percentage, higher the percent elongation higher is the ductility of the material. Fig. 8 denotes the percent elongation of as cast Al7475, Al7475-2 wt. % 88 µm B₄C, Al7475-4 wt. % 88 µm B₄C, Al7475-6 wt. % 88 µm B₄C, Al7475-8 wt. % 88 µm B₄C and Al7475-10 wt. % 88µm B₄C particulates composites resulted in tensile testing. The loss of ductility or decrease in percent elongation when compared with as cast Al7475 alloy is due to B₄C particulates of hard ceramic are added.

![Fig 8: Percentage elongation of Al7475 alloy with Al7475-B₄C reinforced composites](image)
Compression Strength

![Compression Strength Graph](image)

**Fig 9:** Compression strength of Al7475 alloy - 88-micron size B₄C reinforced composites

Compression strength of material is significant for those materials which are intended to carry compressive loads in service. The Fig 9 indicates that the increase in wt. % of 88-micron B₄C particulates in Al7475 Alloy - wt. % B₄C composite increases the compression strength. Always particles strength is expressed in terms of compression strength, due to brittle in nature. These boron carbide particles are very hard nature and having high compression strength. Due to incorporation of these hard particles compression of Al7475 alloy has increased.

Creep Behavior

![Creep Behavior Graph](image)

**Fig 10:** Creep behavior of Al7475 alloy and 88 micron size B₄C composites

Fig. 10 is showing the creep of Al7475 alloy and its 88 micron sized B₄C reinforced composites. The change in length is more in the case of as cast Al7475 alloy, as the weight % of 88 micron B₄C particles increases, there is decrease in the change in length. The addition of hard particles makes the soft Al matrix as brittle and reduces the ductility. This reduced ductility has impacted the creep behavior of Al7475 alloy with B₄C composites, which improved the creep resistance.
Tensile Fractography

Fig 11: (a-f): SEM tensile fractured surfaces micrographs

Fig. 11 a-f are the SEM examination of as cast Al7475alloy shows the dimpled fracture surface, leading to the evidence of ductile fracture whereas SEM examination for the reinforced Al7475-2, 4, 6, 8 &10 wt. % 88 µm B₄C material shows nonuniform spreading of big dimples connected by pieces of smaller dimples representing a pattern resulting from ductile void growth coalescence, but higher percentage of B₄C particulates reinforced composites show brittle fracture failure with bigger dimples. Hence, it is likely that the B₄C particulates properties have important impact on composite mechanical properties.

IV. CONCLUSION

In the current work Al7475- B₄C composites were successfully synthesized with 2 to 10 wt. % of 88 microns sized particles reinforced composites by the utilization of stir casting technology. ASTM criteria refer to the micro-structural study and significant mechanical performance such as hardness, UTS and YS, percentage elongation, compression strength, creep and fractography behavior. As cast-alloy and equally distributed micro B₄C composite, the matrix is practically pores-free, as can be seen from SEM micrographs. The EDS analysis indicates that the Al7475 alloy matrix includes B₄C particles. The improved hardness, tensile, creep and compression strengths were found with the addition of 88 micron sized boron carbide particles addition.

V. REFERENCES


