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Fatigue and Fracture Behavior of Al6061-B_4C Aluminium Matrix Composites

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***Abstract:** In the present day engineering design and development activities many Scientists, Researchers and Engineers are striving hard to develop new and better engineering materials, which accomplishes high strength, low weight and energy efficient materials since the problems of environment and energy are major threshold areas. The development of new materials is growing day by day to replace the conventional materials in aerospace, marine engineering, automobile engineering industries etc., Hence, composite materials are found to be an alternative. A variety of metals and their alloys such as Aluminum, Magnesium and Titanium are comprehensively used as matrix materials. Among these Aluminium alloys have been used extensively, because of their excellent strength, low density, corrosion resistance and toughness. Similarly, many researchers have attempted to develop aluminum based metal matrix composites using different reinforcements such as SiC, Al2O3, B4C, TiC, TiO2, B4C etc., are added to the matrix to get required MMC's. Among these reinforcements, B4C emerged as an exceptional reinforcement due to its high strength to density ratio, possesses high hardness and avoid the formation of interfacial reaction products with aluminum. Hence, in this paper attempts are made to fabricate Al 6061-3, 6, 9 and 12 wt.% B_4C metal matrix composites by stir casting process to study fatigue life and fracture toughness as per ASTM standards. It is evident that fatigue strength and fracture toughness of the composites were enhanced with the addition of the wt.% of the reinforcement.*

***Keywords:** Al6061-B4C MMC's, Fatigue life and Fracture toughness*

I. INTRODUCTION

In the present day engineering design and development activates many researchers are working towards the development of new materials to replace the conventional materials and found that composite materials are an alternative because to its high strength-to-weight ratio, higher stiffness, better fatigue, wear and corrosive resistance. Variety of aluminium alloys and different reinforcements such as SiC, B_4C, TiC, TiO_2, B4C etc. are comprehensively used to develop Aluminium Matrix Composites (AMC's) for aerospace, automobile marine and lightweight engineering applications.

AMC has alloy elements such as Si, Ni, Cu, Mg and Zn. Al-based MMCs have high specific strength, hardness, and attractive fatigue properties, particularly fracture toughness [3]. Inclusion of SiC, B4C, TiC, TiO2, B4C etc., reinforcements and soft lubricants into aluminum alloy to increase AMCs' fatigue life and fracture strength [3].

Hence, in this paper attempts are made to develop Al6061-B_4C AMC's by varying 3, 6, 9 and 12 wt.% B_4C to study the fatigue life and fracture strength as per ASTM standards.

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II. FABRICATION OF AL 6061-B_4C AMC'S

Several manufacturing techniques are used to synthesize metal matrix composites. The most commonly used techniques are liquid, solid and gaseous state [4], these processes includes Squeeze casting, Powder metallurgy, Spray forming, Diffusion bonding, Sinter-forging, Stir casting, In-Situ process. Among these manufacturing processes stir casting is generally accepted as a promising route to manufacture metal matrix composites in large volumes with minimum cost. Hence in this research work, stir casting technique is used to develop Al 6061-B_4C MMC's.

A. Stir Casting Process

Stir casting process is an extensively used method to fabricate AMC's in liquid state in which molten metal is mixed in the furnace by means of mechanical stirring [5]. It is noticed that almost all the composites were manufactured by this process using up to 30% volume fraction of reinforcement [6,7]. It is evident from the literature that use of stir casting process enables better mixing of matrix and reinforcement in the AMC's. Different components of stir casting process are as shown in Fig.1.

Fig. 1. Stir Casting Process Set-Up

Al 6061 rods and 3, 6, 9 and 12 wt.% of B4C are weighed as per the wt.% of the reinforcement and fed into the graphite crucible and heated using an electrical During stirring preheated B4C is gradually poured into the molten metal and stirring was continued about 10-12 minutes the melt was poured into a preheated cast iron molds. After solidification process castings were obtained as shown in Fig.2 and machining of different wt. % of B_4C was carried out as per different ASTM standards to estimate fatigue life and fracture strength of the composites developed.

Fig. 2. Casted Specimen

III. EXPERIMENTAL PROCEDURE FOR FATIGUE AND FRACTURE TEST

Fatigue is an important property of materials which respond to cyclic loads. It is noticed that 90% of failures of metallic structures and rotating machine parts are subjected to fatigue failure on a macroscopic-scale. Fatigue life depends on stress level, state of stress, mode of cycle and environmental conditions. Due to these reasons different design tools have been developed to analyze the fatigue failure. Commonly used tool to estimate the fatigue life of the components is S-N curve.

A. Specimen Preparation

Specimens were prepared as per **ASTM E606** standard shown in Fig.3 with specified tolerances to conduct fatigue test using rotating bending machine.

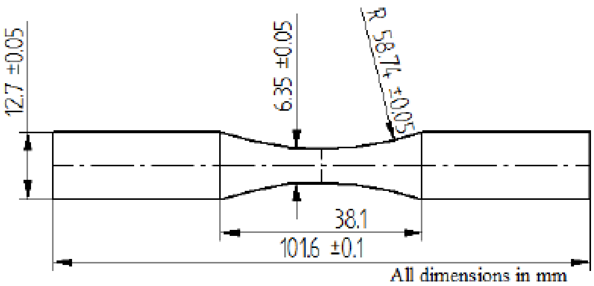

Fig. 3. ASTM Standard Fatigue Test Specimen

B. Test Procedure

Fatigue test for Al 6061- B_4C composites were conducted using rotating bending machine as shown in Fig 4. Specimen is rotated about the longitudinal axis, the upper and the lower parts of the specimen is subjected to cyclic stress and varies sinusoidal at any point on the specimen surface until failure takes place.

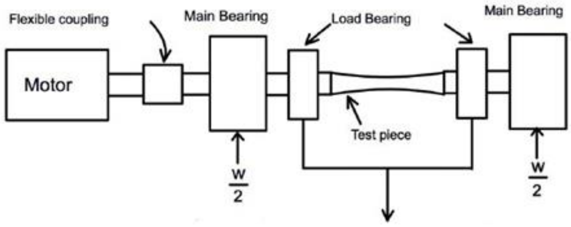

Fig.4. Rotating bending machine

C. Fracture Test

Destruction or separation of a solid body under the action of stress is known as fracture. It occurs over a short period under different loading conditions.

D. Fracture Toughness *(KIC)*

Mechanical components produced by various manufacturing techniques have common defects like cracks, voids, inclusions and other design discontinuities which is not completely avoidable hence the study of these defects is essential in the design of mechanical components.

Fracture toughness indicates the amount of stress required to propagate a pre-existing flaw. Stress-intensity factor (K) is used to estimate the fracture toughness of most of the materials which is dependent on Loading condition, crack size and geometry.

E. Specimen Preparation

As per **ASTM E399** standard fracture test specimen shown in Fig.5. was fabricated using milling and wire cut EDM process to evaluate fracture toughness using universal fracture testing machine (TUE 600C)

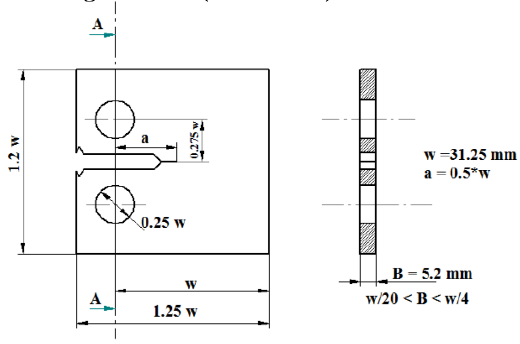

Fig.5 ASTM E-399 Fracture test specimen

A pre-cracked specimen was held between the fixtures during the test, the load and displacement for different wt.% of B_4C specimens were recorded. In the present work fracture tests were carried with a cross-head speed of 5mm/min which is commonly chosen for technical convenience in fracture toughness-test.

Further, load at the failure of the specimens were recorded to determine the fracture toughness using Equation 1.

$$K_{IC} = P_{max} / BW\sqrt{\pi a} \quad (1)$$

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IV. RESULTS AND DISCUSSIONS

A. Fatigue Behavior of Al6061-B4C AMC's

A series of fatigue tests were conducted on Al 6061 and different wt. of % B4C composites as per **ASTM E606** standard to determine fatigue strength and number of cycles of failure. For each weight fraction three tests were conducted on a rotating bending machine and average number of cycles of failure were recorded and tabulated in the Table.1

Table:1. Average No. of cycles failure for Al 6061-B4C composites

Wt. % of Reinforcement	Average No. of failure cycles
0	5,24,717
3	1,75,339
6	1,56,832
9	53,441
12	31,526

It is clear from the results that with an increase in wt.% of the reinforcement there is decrease in the service life or number of cycles. During the test, presence of B_4C particle in the matrix forms micro cracks at the interfaces which intern forms weak interphase between the matrix and the reinforcement particulates result in formation of voids leads to the propagation of cracks at faster rate, hence number of cycles before failure decreases. Further, it is evident from the literature that addition of the hard B_4C particles leads to a growth in the brittle nature intern reduces the fatigue life and faster failure of the composite material.

Further, it is evident from the fractured fatigue test specimens that shiny appearance of the failure surface of the composites indicate the brittle fracture. Hence it represents the formation of voids around which cracks initiate and fail faster and hence the fatigue life of the composites decreases with the addition of the reinforcement.

Fatigue strength of the composites developed are calculated based on the number failure cycles (Table-1) using the Equation 2. The value of 'S' in the equation is treated as stress based on the assumption of elastic behaviour. However, it does not represent a real stress when the elastic range is exceeded. Values of 'S' (Table:1) for different wt.% of a composite were calculated to draw the S-N curve.

$$S = (14{,}479/\sqrt{N}) + 96.5\,MPa \qquad (2)$$

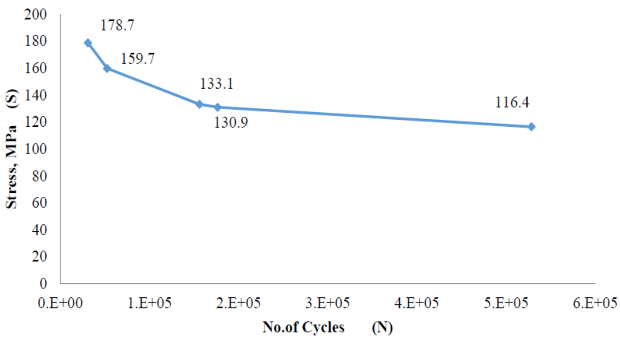


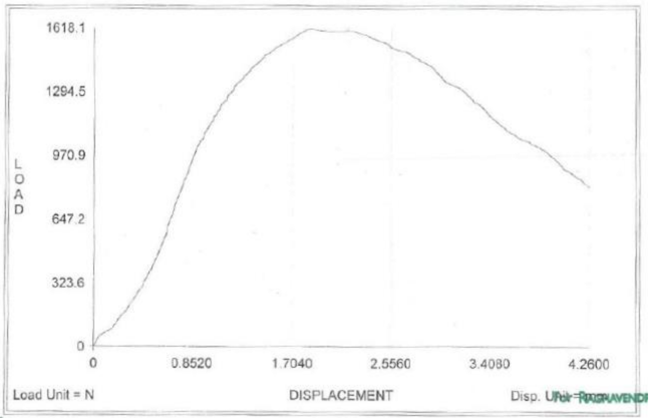
Fig: 6. S-N curve for different wt.% of TiB_4C

It is observed from the Fig.6 that fatigue strength of Al 6061 with different wt.% of B_4C composites are enhanced with addition of hard particles of B_4C. Further it evident that fatigue life or number of cycles of failure of the composites decreases with the addition of the reinforcement.

It is evident from the literature that enhancement in the fatigue strength is due to the addition of fine size B_4C particles during stir casting process, development of brittle phase, good thermal bonding, uniform and homogeneous dispersion of reinforcement in Al 6061 matrix are the major factors. Hence with the addition of B_4C fatigue strength of the composites developed can be enriched.

B. Fracture Characteristics of Al6061-B4C AMC's

For each wt.% of the reinforcement load-displacement plots as shown in Fig.7 were obtained using computerized fracture testing machine and the maximum load were recorded and tabulated in the Table 2 to determine fracture toughness and stress intensity factor.



The results reveals that addition of the reinforcement enhances the energy required to open the crack and crack propagation. Hence, fracture toughness of B_4C reinforced composites increases.

Table 2. Crack Opening Displacement (COD)

wt.% of B_4C	Maximum Load, N	COD, mm
0	3599	10.344
3	1539.6	5.423
6	1618.1	4.26
9	1814.2	3.657
12	1392.5	2.308

Increase in the fracture toughness attributed to the uniform distribution, formation of fine particles during casting process, strong interfacial mechanism developed between matrix and the reinforcement, interaction of B_4C particles with a crack tip forms residual thermal stress which block the initiation of internal cracks in the composites due to these reasons COD decreases with increase in wt.% of B_4C reinforcement. Further, it is evident from the previous works that load bearing capacity of the composites decreases due to the clustering of B_4C particles in the surrounding matrix and addition of hard B_4C leads to the formation of brittle phase.
Further, it is evident from the fractured specimens that crack propagation in all the specimens appears to be perpendicular to the direction of the load this is realistic for all conventional materials.

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Hence, the Al 6061- B_4C composites developed by stir casting process are seeming to be free from casting defects.

C. Stress Intensity Factor (KIC)

Stress intensity factor is one of the important parameter in the fracture mechanics to predict the state of stress near the crack tip when flaws exist and propagate in any structure. In the present research work stress intensity factor of Al 6061 and different Wt.% of B_4C were theoretically calculated using maximum load (Table 2) obtained from the fracture tests as per **ASTM E399** and Equation 3.

$$KIC = P_{max}/B\, W \sqrt{\pi a} \qquad (3)$$

Where,

P_{max} = Maximum peak load in N
B = Thickness of the specimen (**6.42 mm)**
W= Width of the specimen (**30.59 mm)**
a = length of notch (**5mm**)

Table: 3. Stress intensity factor for different weight fractions of B4C

Wt. % of Reinforcement	Peak Load, N	KIC, MPa.$m^{1/2}$
0	3599	72.33
3	1539.6	30.94
6	1618.1	32.52
9	1814.2	36.46
12	1392.5	27.98

Table 3 shows that stress intensity factors for Al 6061 and 3, 6, 9 and 12 wt.% of B_4C. It is noticed that with increase in the addition of the reinforcement stress intensity factor decreases. Hence, stresses developed in the composites due to the application of the load decreases drastically. It is observed that Al 6061 base alloy has K**IC** value as 72.33 whereas 12 wt. % B_4C reinforced composite material has KIC value 27.98 for same test conditions. It indicates that stress concentration near the vicinity of the crack tip decrease around 62 % with the addition of the reinforcement hence the stress level in the components decreases with reduction in stress intensity factor.

Reduction in the stress intensity factor may be due to uniform distribution of B_4C particles, increase in rigidity, interaction of B_4C particles with a crack tip starts dominating the toughening process and cause a continuous increase in the fracture toughness of the composite with reduction in KIC.

V. CONCLUSIONS

Fatigue strength and number of cycles to failure of Al 6061-B4C composites were estimated using rotating bending machine as per ASTM E606 standard. It is noticed from the results that service life of the composites decreases with increase in wt.% of the B_4C intern enhances the fatigue strength. Presence of B_4C particle forms micro cracks and voids at the interfaces leads to weak bonding between the matrix and the reinforcement result in the propagation of cracks at faster rate, hence number of cycles before failure decreases with the addition of B_4C reinforcement.

Fatigue strength of Al and - 3, 6, 9 and 12 wt.% of B_4C composites were calculated using average number of cycles to failure obtained from the experiments using theoretical Equation. It is observed from the results that fatigue strength of the composites developed were enhanced from 116.4 MPa to 178.7 MPa with addition of B_4C particles.

Fracture toughness, Crack Opening Displacement (COD) and stress intensity factor of Al 6061- B4C composites were estimated per ASTM E399 standard. It is observed from experimental results that COD decreases from 10.344 mm to 2.308 mm this is the fact that addition of the reinforcement enhances the energy required to open the crack and its propagation, interaction of B4C particles with a crack tip forms residual thermal stress which block the initiation of internal cracks in the composites due to these reasons COD decreases with increase in wt.% of B4C reinforcement. Hence, fracture toughness of B4C reinforced composites increases.

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