



## Experimental investigation on fracture toughness of Al6061–graphite by using Circumferential Notched Tensile Specimens

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**ABSTRACT.** This paper presents the experimental work carried out on the fracture behavior of aluminium 6061 (Al6061) and graphite particulate composites. The required specimens are prepared using stir casting method with graphite proportions ranging from 3 to 12 % by weight. The fracture behavior of Al6061-graphite particulate composites produced using stir casting method, was investigated by conducting experiments on Universal Testing Machine (UTM). Circumferential Notched Tensile (CNT) specimens were utilized to evaluate the fracture toughness of the composites. From the experiment the fracture toughness  $K_{IC} = 15.85 \text{MPa m}^{1/2}$  is obtained for Al6061-9% Graphite.

Further, the experimental results revealed that, except 12% graphite, the fracture toughness of Al6061-graphite was observed to increase with an increase in weight percentage of graphite. The experimental results reinforce that Al6061-graphite particulate MMCs are suitable for automotive and aerospace applications requiring high fracture toughness apart from good wear resistance.

**KEYWORDS.** Fracture Toughness; Circumferential Notched Tensile (CNT) Specimens; Aluminium Graphite Particulate Composites.



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### INTRODUCTION

**M**etal Matrix Composites (MMCs) are a widely varied group of materials that consist of a metallic alloy (aluminum, magnesium, and titanium alloys) as matrix and ceramic as reinforcement (alumina ( $\text{Al}_2\text{O}_3$ ), silicon carbide (SiC), carbon, or graphite) in the form of continuously aligned fibers, short fibers, whiskers, platelets



and particles. MMCs are used in automobile/aerospace applications, and also in applications requiring thermal management, wear resistance and weight reductions.

Aluminium alloys is widely used for construction of aircraft structures. There are different cracks being inspected in aircraft wings. Different types of cracks inspected are: (1) Hairline cracks in the inward wing structure, and (2) Cracks at the edges of the vertical web of the feet. If the elevated forces are applied to the fasteners during assembly which are not accounted, the stress arising from the interference fit will possibly lead to cracking [10]. The particular type of aluminium alloy used will also have an effect on the assembly where a balance has to be achieved between stiffness, strength and fracture toughness.

The literature survey presents a review of the published material available on the effect of various reinforcement types, their size and volume fraction, ageing behavior with Aluminium based MMCs are a combination of two phases, matrix and the reinforcement. Aluminium graphite composites for various compositions are prepared by using stir casting method [15], mechanical alloying (MI) and hot extrusion method [16] etc., and the specimens were tested for their hardness, tensile, wear and fracture properties etc. Mechanical characterization such as tensile strength and elongation experiments by using Universal Testing Machine (UTM) of Al/SiC has been reported [8] for varying mass fraction of SiCp with Aluminium. Hardness [2], Fracture toughness [3, 4], tensile fracture behavior on Circumferential Notched Tensile (CNT) Specimens [5,6] on Compact Tension (CT) test specimen [13, 14] of Al/SiC was studied by different researchers and most of them compared their results with the unreinforced aluminium alloy. In this research work, a new method of finding the fracture toughness, using Circumferential Notched Tensile (CNT) Specimens, is utilized which is a recent advance in fracture toughness testing method is adopted.

From the literature it is observed that relatively more work has been done on the tensile and fracture characteristics of aluminium silicon carbide particulate MMCs. However, a significant scope exists for research on the aluminium matrix composites reinforced with graphite particles, particularly in the area of fracture and fatigue in order to improve the strength and fracture characteristics of the material to avoid the cracking. In this backdrop, the current research work is proposed to study the fracture toughness of aluminium 6061 graphite particulate composite at varied weight fractions.

The specimen are prepared using stir casting method with graphite proportions of 3 to 12 % by weight. The specific objective of the research work is to study the fracture toughness of the aluminium graphite MMC at varied weight fractions of graphite (3%, 6%, 9%, and 12%) experimentally using Circumferential Notched Tensile (CNT) specimens. Also an attempt will be made to compare the results of Al6061-graphite composites with the Aluminium Silicon carbide particulate (Al-SiCp) composites.

## MATERIALS

The material chosen for this research work is aluminium 6061 as matrix and graphite particles as reinforcement. The motivation to use these materials for this research work is the density of two materials involved, which are nearly same for aluminium (2.65g/cc) and graphite (2.2g/cc). The Al6061-graphite particulate composites have discontinuously reinforced composite properties which are nearly isotropic and also have outstanding combination of mechanical, structural, thermal and physical properties.

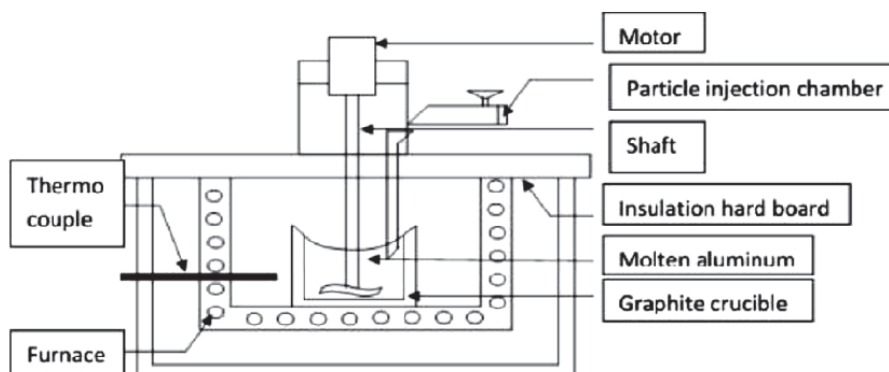


Figure 1: Schematic view of stirring mechanism used in the fabrication of MMC [15].



## PROCESSING

Aluminium 6061-graphite specimens are prepared at varied weight fractions of graphite (3%, 6%, 9%, and 12%) using stir casting method. The aluminium blocks were melted in the furnace as shown in Fig. 1. After melting, molten aluminium was super-heated to desired temperature (about 750° C). The required amounts of graphite particles were added to the aluminium melts while stirring with stirrer at speed of 550 rpm. The molten aluminium-graphite was poured into a split type permanent mould and it was allowed to solidify. The aluminium-graphite alloy bars were taken out from the mould. The specimens were prepared from as-cast alloys for determination of required properties.

## EXPERIMENTATION

To investigate the fracture toughness, there are different methods. Basically American Society for Testing and Materials (ASTM) standards and recent advances in fracture toughness testing methods are used for testing of aluminium alloys and some of aluminium matrix particulate reinforced composites. ASTM standard testing methods include Fracture toughness testing by Single Edge Notch Bend (SENB) Specimen and Compact Tension (CT) Specimen. Other testing methods which are getting popular for their ease include Fracture toughness by Circumferential Notched Tensile (CNT) specimens, Round Bar, and Indentation techniques.

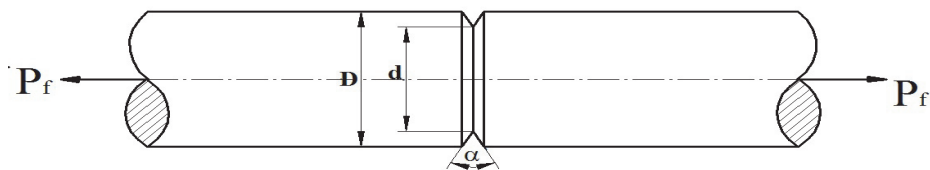


Figure 2: Schematic representation of the CNT specimen [13].

Circumferential Notch Tensile (CNT) specimen shown in Fig. 2 was fabricated for estimation of fracture toughness, in a manner confirming with Alaneme and Aluko [3]. The CNT samples were machined for the following dimensions: sample diameter  $D=12.5\text{mm}$ , notch diameter  $d=11.24\text{mm}$ , gauge length  $L=62.5\text{mm}$ , and notch angle  $\alpha=60^\circ$ . The test samples were subjected to tensile test on UTM for the determination of fracture toughness. The load at fracture ( $P_f$ ) acquired from the CNT specimens load-expansion plots (Fig. 3) were utilized to assess the fracture toughness [3] by applying observational relations by Dieter:

$$K_{IC} = \frac{P_f}{D^{3/2} \left[ 1.72 \left[ \frac{D}{d} \right] - 1.27 \right]} \quad (1)$$

where,

$P_f$  = load at fracture, in N

$D$  = specimen diameter, in mm and

$d$  = notch diameter, in mm.

In accordance with Nath and Das [11], the reliability of the CNT testing method and the achievement of the plane strain condition were evaluated using the relations:

$$D \geq \left[ \frac{K_{IC}}{\sigma_y} \right]^2 \quad (2)$$



where,

$\sigma_y$  is the yield strength, in N/mm<sup>2</sup>

$K_{IC}$  is fracture toughness, MPa m<sup>1/2</sup>

Also, the length of the specimen is taken here for the testing was 4 times the specimen diameter which was the requirement taken into consideration while preparing the CNT specimens.

Tension test was performed at room temperature on the CNT specimens for the Al6061-Graphite particulate metal matrix composites of 3%, 6%, 9% and 12% graphite using a UTM following standard test procedures in agreement with the ASTM:E8M – 91 standards [14].

The CNT specimens are allowed for tensile test. The load at fracture ( $P_f$ ) is noted for each specimen of above said weight fractions. The load at fracture ( $P_f$ ) obtained are taken in consideration to calculate the fracture toughness ( $K_{IC}$ ) using the empirical relation (1).

Evaluation of fracture toughness was investigated for Al6061-graphite MMC using CNT specimen testing. From the outcomes it was observed that the crack durability results assessed from the CNT test were justifiable (in plain strain condition) even though the samples were not fatigue pre-cracked.

## RESULT AND DISCUSSIONS

Fracture toughness for the various weight fractions of Al6061-Graphite particulate MMC are evaluated experimentally and results are shown in Tab. 1. Fracture toughness of the A6061-Graphite composite for 3, 6, 9, 12% Graphite is determined using CNT specimens on UTM. The plane strain fracture toughness condition was met with the CNT sample diameter of  $D=12.5$  mm using Eq. (2) which validates the fracture toughness values obtained from experimentation.

Sl. No	Composite	Fracture load ( $P_f$ ) kN	Fracture Toughness ( $K_{IC}$ ) MPa m <sup>1/2</sup>
1	Al6061-3%Gr	12.51	13.92
2	Al6061-6%Gr	13.70	15.25
3	Al6061-9%Gr	14.24	15.85
4	Al6061-12%Gr	14.10	15.69

Table 1: Experimental fracture toughness of Al6061-Graphite MMC.

From the outcomes it is observed that the fracture toughness results assessed from the CNT test were substantial (in plain strain condition) even though the samples were not fatigue pre-cracked.

Fracture toughness of the A6061-Graphite composite for 3, 6, 9, 12% Graphite is determined using CNT specimens on UTM. For each composition three specimens are prepared and tested for fracture toughness. Load – elongation curve for Al-graphite for different weight fractions of graphite is shown in the Fig. 3. It is observed that the elongation increases with increase in load. For all specimens there is small difference in change in elongation. Fracture load and the maximum elongation of Al-3% graphite is  $P_f = 12.51$ kN and 4.21mm respectively. Fracture load and the maximum elongation of Al-6% graphite is  $P_f = 13.70$ kN and 4.31mm respectively. Fracture load and the maximum elongation of Al-9% graphite is  $P_f = 14.24$ kN and 4.58mm respectively. Fracture load and the maximum elongation of Al-12% graphite is  $P_f = 14.10$ kN and 4.55mm respectively.

The increase in elongation is because of the existence of the hard and higher modulus graphite particles embedded in the Al6061 matrix, which act as a barricade to oppose plastic flow when the MMC is subjected to an applied load. Also, the decreased interparticle spacing, due to the increased weight percent of graphite reinforcement, creates increased resistance to dislocation motion, which gives the improved strength to MMCs.

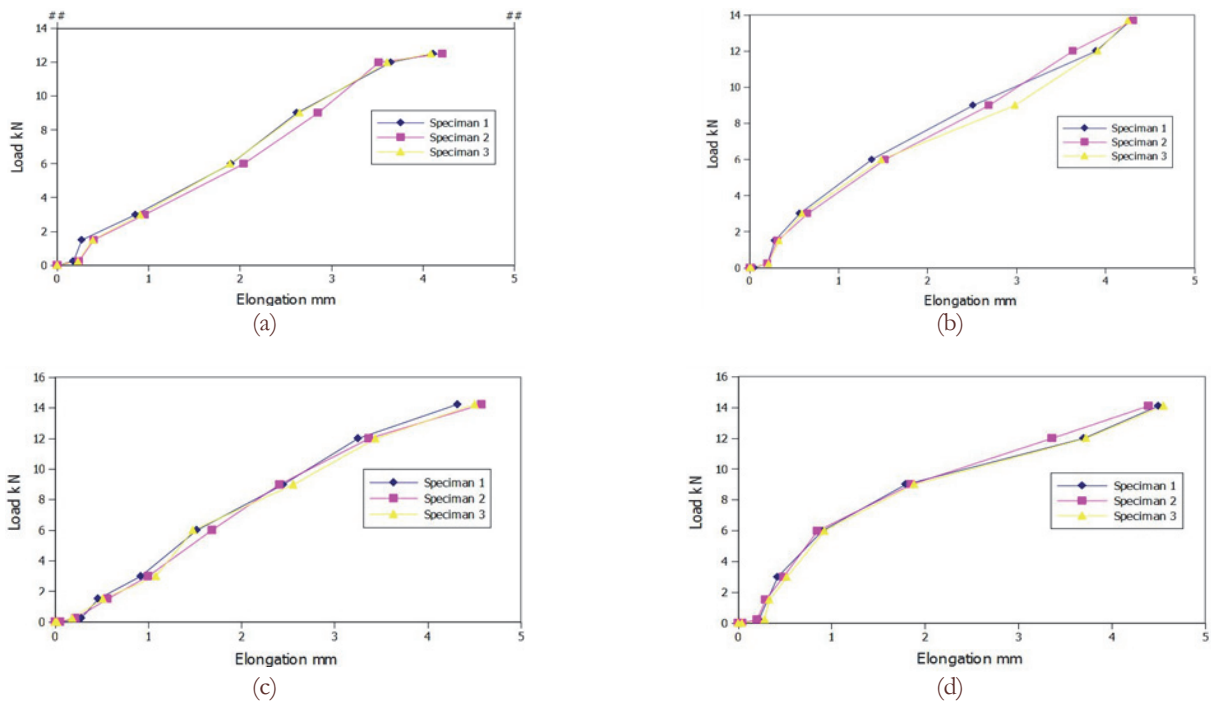


Figure 3: Load-Elongation curve for (a) Al-3% graphite (b) Al-6% graphite (c) Al-9% graphite (d) Al-12% graphite.

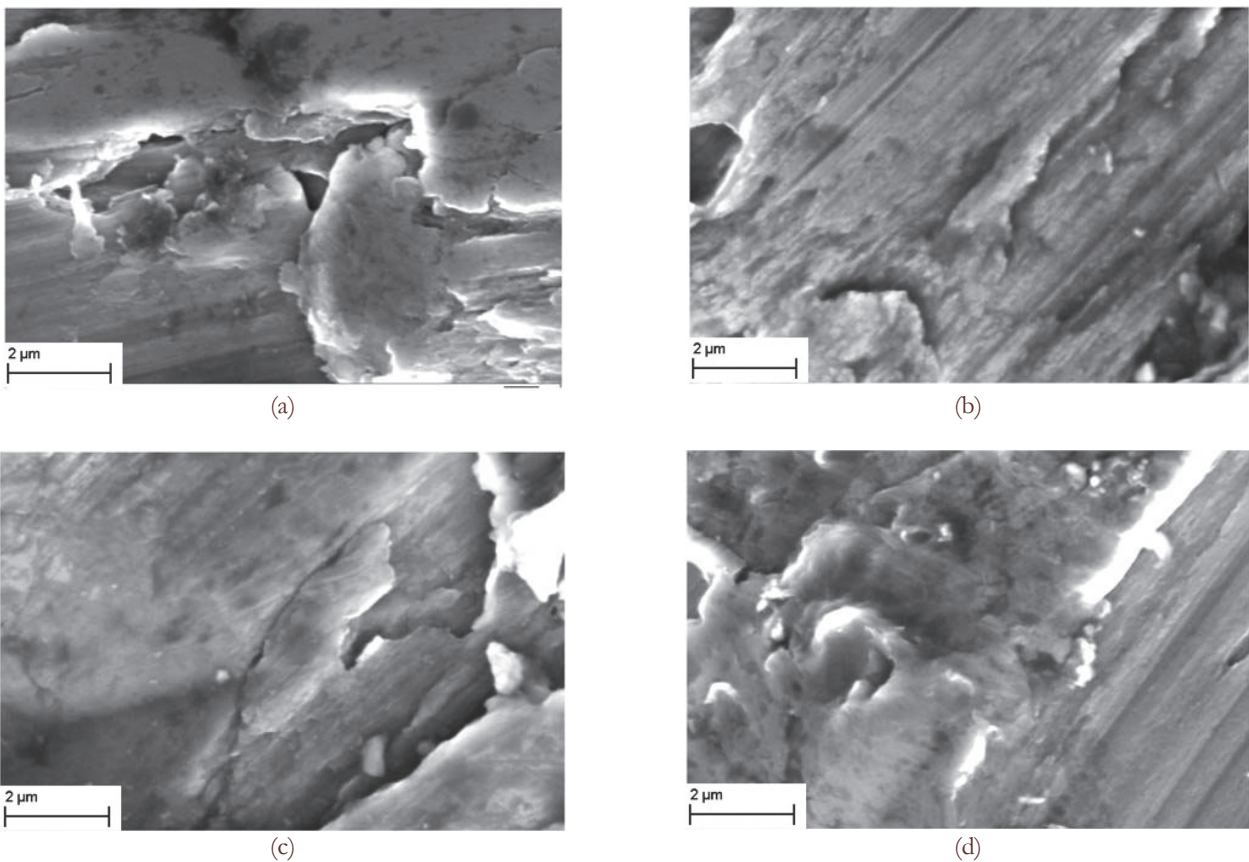


Figure 4: SEM micrographs of fracture surface of (a) Al-3% graphite (b) Al-6% graphite (c) Al-9% graphite (d) Al-12% graphite.



For studying the nature of crack and bonding of matrix and reinforcement it is essential to examine the fractured surfaces of all the specimens. Scanning electron microscope (SEM) is used to examine the fractured specimens of Al-graphite for the nature of fractured surface either ductile or brittle failure.

Fractographic inspection was made on the fractured surface of CNT specimens for various Al-graphite composites. Fig. 4(a-d) show the fractographs of the fractured CNT specimens for various Al-graphite composites. From Fig. 4 (a-d) the failure of Al-graphite composites show dimples which grown through the matrix and are formed by void nucleation. Void nucleation cause particle rupture and debonding at the matrix-reinforcement interfaces which in turn cause the crack initiation. These micro cracks propagate from the vicinity of crack tip and passes through the matrix unstructured matrix.

From experimental results it was observed that, except 12% graphite, the fracture toughness of Al6061-graphite was observed to increase with an increase in weight percent of graphite. This increase in fracture toughness is the effect of graphite particulates which act as barricade to internal cracks in the microstructure.

However for 12% graphite there is decrease in the fracture toughness was observed. This decrement may be due to increased particles which causes particle clustering and the surrounding matrix. The maximum fracture toughness was found for Al6061-9%Gr and the value is  $15.85 \text{ MPa m}^{1/2}$ .

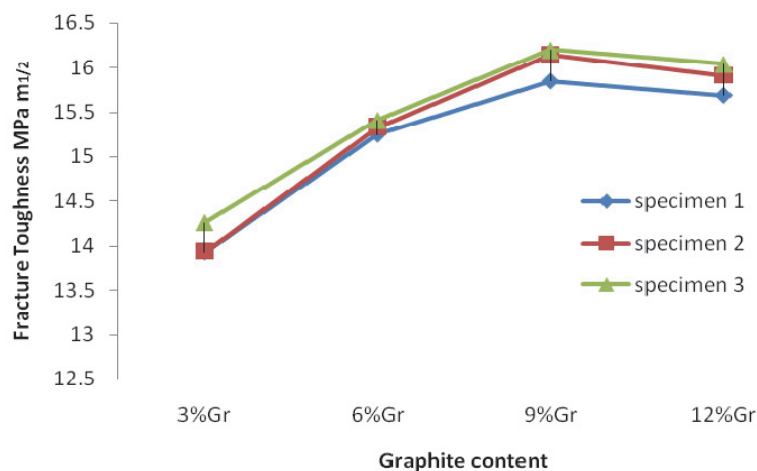


Figure 5: Fracture toughness of Al-Gr MMC.

Fig. 5 shows comparison of fracture toughness of Al-Gr for all three specimens. From the outcomes it is observed that the fracture toughness results assessed from the CNT specimens were significant. From experimental results it was observed that, except 12% graphite, the fracture toughness of Al6061-graphite was observed to increase with an increase in weight percent of graphite. The for specimen 1 maximum fracture toughness was found for Al6061-9%Gr and the value is  $15.85 \text{ MPa m}^{1/2}$ .

## COMPARISON OF ALUMINIUM SILICON CARBIDE WITH ALUMINIUM GRAPHITE

Alaneme and Aluko [3] utilized the Tensile and CNT specimens for tension testing to evaluate, respectively, the tensile properties and fracture toughness of the composite Al-SiC for 3, 6, 9, and 12 volume percent of SiC. From the experimental results obtained for both the tests it concluded that significant improvement in the strength of the Al matrix composites is achieved when 9 and 12 vol% of SiC is used as reinforcement; and the ductility of the composites is not adversely affected at these compositions in comparison with the monolithic alloy.

Tab. 2 shows the comparison of fracture toughness of aluminium silicon carbide with aluminium graphite.

From the comparison, it is found that the fracture toughness of the aluminium graphite is more compared to aluminium silicon carbide. Therefore, aluminium graphite can be considered as a promising material for aerospace and automobile applications where high crack arrest abilities and high strength with reduced weight is required. Further, it will contribute to crash worthy design of aircraft/automobile structures.



Sl.No	Weight percentage	Fracture Toughness ( $K_{IC}$ ) MPa m <sup>1/2</sup>	
		Al-SiC	Al-Graphite
1	3%	6.61	13.92
2	6%	6.59	15.25
3	9%	5.63	15.85
4	12%	6.71	15.69

Table 2: Comparison of fracture toughness of Al-SiC [3] and Al-Gr.

## CONCLUSIONS

Based on the experimental study of Al6061-graphite MMCs the following conclusions are made. The experimental study of the fracture toughness of the Al6061-graphite was conducted in this work. From experimental results it was observed that, except 12% graphite, the fracture toughness of Al6061-graphite was observed to increase with an increase in weight percent of graphite. This increase in fracture toughness is the effect of percentage increment of graphite particulates which act as barricade to internal cracks in the microstructure. From the comparison it is found that the fracture toughness of the aluminium graphite is more compared to aluminium silicon carbide.

Based on the conclusions made here, one can consider the Al6061-graphite particulate MMC for automobile applications such as: Bearing surfaces, cylinder liners, pistons, cam shafts, brake components, etc., and aerospace applications such as internal aerospace engine components, exhaust systems, wing and fuselage (main body) of aircraft structure.

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