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Indentation Fracture Toughness of Alumnum6061-Graphite Composites

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Abstract

The aim of this work is to study the behavior of Aluminum (6061) with graphite composite produced by the stir casting technique. For the study different composition of the particulate metal matrix composite used is aluminium 6061 with 0, 3, 6, 9% of graphite. The Vickers indentation method was used to determine hardness and indentation fracture toughness for different compositions of aluminium 6061-graphite particulate metal matrix composite. Fracture toughness test was performed on the samples obtained by the stir casting process. Scanning electron microscope is used to know the crack lengths. Vickers indentation experiment, fracture toughness K_{IC} *= 10.15 MPa m½ is obtained for Al-9%Gr. The results obtained by experimental and analytical methods agree with each other with a deviation of about 1.5–6.2%. There is a good correlation between analytical and experimental values of the fracture toughness.*

Keywords: aluminium-graphite composites, indentation fracture toughness, Vickers' hardness

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INTRODUCTION

Metal matrix composites (MMCs) which are used in applications requiring wear resistance, thermal management and mainly weight savings. MMCs are broadly classified into two categories as continuously and discontinuously reinforced MMCs. Both types of reinforced MMCs[1] are used in structural applications. Commonly used MMCs are based on aluminum alloys as matrix and reinforced with silicon carbide (SiC), alumina (Al_2O_3), carbon, or graphite.

Discontinuously reinforced MMCs are much less expensive to fabricate than continuously reinforced composites. The properties of discontinuously reinforced composites are nearly isotropic, whereas the properties of composites with continuous aligned reinforcements are highly anisotropic. Thus, in applications requiring isotropic properties, less expensive, discontinuously reinforced composites can outperform continuous fiber reinforced composites. Typically, ceramics and graphitic materials are used as reinforcement phases in discontinuously reinforced MMCs.

MMCs are broadly used in aerospace and automobile applications due to their less weight and superior mechanical, physical, thermal properties as compared to conventional metals. The objective involved in preparing MMCs is to unite the required properties of metals and ceramics. The exceptional mechanical properties of MMCs especially aluminium matrix composites materials make them a very attractive candidate for a range of applications.

Fracture toughness is a most important property of any material in design application defined as the capability of material having a crack to resist fracture. Fracture toughness is a property which expresses the capacity of a material having a crack to resist fracture.

Linear elastic fracture toughness (LEFM) of a material is calculated from the stress intensity factor (SIF) at which a thin crack in the material begins to grow. Fracture toughness is represented by K_{Ic}. Its unit in SI is MPa $m^{1/2}$. In K_{IC}, subscript IC represents first mode crack opening under tensile loading at right angles to the crack.

Main objective of this work is to investigate the effect of variation of the percentage composition of aluminium matrix graphite particulate reinforced composites to predict the fracture toughness using Vickers's indentation fracture testing method.

MATERIALS AND PROCESSING

Materials chosen for the study are discontinuously reinforced MMCs which have advantage that they are nearly isotropic. Typically, ceramics and graphitic materials are used as reinforcement phases in discontinuously reinforced MMCs.

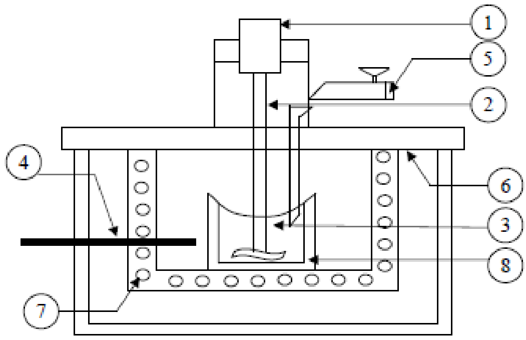
Table 1. *Chemical Composition of Aluminum 6061 Alloy.*

Contents								
Si	Fe	Cu	Mn	Mg	Zn	Cr	Ti	Al
0.70	0.21	0.28	0.027	0.81	0.019	0.14	0.32	Remaining

Aluminum matrix graphite particulate reinforced composite is characterized by an outstanding combination of thermal, physical, and mechanical properties and also a lower density than aluminum which leads to mass reductions in the areas of aerospace and automobiles. Aluminum 6061 with 0, 3, 6, 9% of graphite particulates were used for this study.

Processing

The aluminum sheets cut into pieces were melted in the furnace as shown in Figure 1. After melting aluminum melt 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 suitable speed. The molten aluminum-graphite was poured into a split type permanent mold and it was allowed for solidification. The aluminum-graphite alloy bars were taken out from the mold. The specimens were prepared from as-cast alloys for determination of required properties.



1. Motor
2. Shaft
3. Molten aluminium
4. Thermocouple
5. Particle injection chamber
6. Insulation hard board
7. Furnace
8. Graphite crucible

Fig. 1. *Schematic View of Stirring Mechanism for the Fabrication of Composites.*[23]

Properties

Composite stiffness can be predicted using a micro-mechanics approach termed the rule of mixtures. Young's modulus of the aluminium graphite particulate metal matrix composite can be determined by the Eq. 1:

$$E_c = E_m V_m + E_f V_f \quad \text{Eq. (1)}$$

where $E_{c,f,m}$ is the Young's modulus of the composite, reinforcement, matrix material, respectively, $V_{f,m}$ the weight fraction of the reinforcement, matrix, respectively. Young's modulus for the various weight fraction of aluminum-graphite particulate MMC are calculated and listed in the Table 2.

Table 2. *Young's Modulus of the Aluminum-Graphite Particulate MMC.*

Sl. no	Composite	Young's modulus (GPa)		Young's modulus (GPa)
		Aluminum	Graphite	
1	Al-6061	68.9	15	68.9
2	Al-6061 + 3% Gr			67.2
3	Al-6061 + 6% Gr			65.6
4	Al-6061 + 9% Gr			64.05

EXPERIMENTATION

Vickers Hardness Test

Vickers hardness test[4] is simpler to use since the specified calculations are freelance of the dimensions of the indenter, and also the indenter is used for all materials regardless of hardness. The essential principle is to watch the material's ability to resist plastic deformation from a regular supply. The hardness number is set by the load over the extent of the indentation and not the area normal to the force, and is so not a pressure.

The unit of hardness given by the test is known as the Vickers Pyramid Number (HV) or Diamond Pyramid Hardness (DPH).

The HV number is then determined by the ratio *F/A*, where *F* is the force applied to the diamond in kilograms-force and *A* is the surface area of the resulting indentation in square millimeters. This can be approximated by evaluating the sine term to give (Figure 2).

$$A \approx \frac{a^2}{1.8544} \qquad \text{Eq. (2)}$$

where *a* is the average length of the diagonal left by the indenter in millimeters. Hence

$$HV = 1.8544F/a^2 \qquad \text{Eq. (3)}$$

where *F* is in kgf and *a* is in millimeters, VHV is in GPa.[6]

Hardness was measured by means of Vickers method using 30 kg loading and holding time was 10 s.

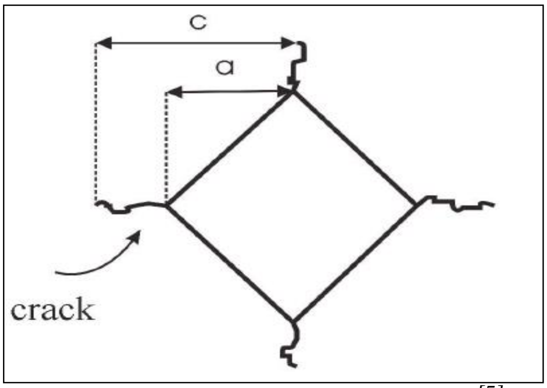
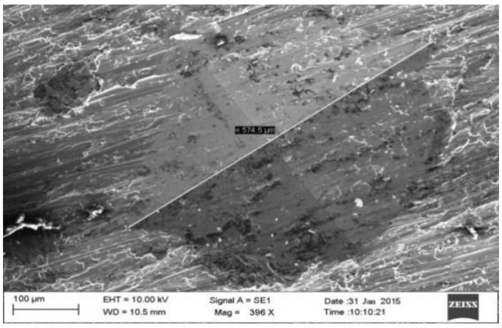


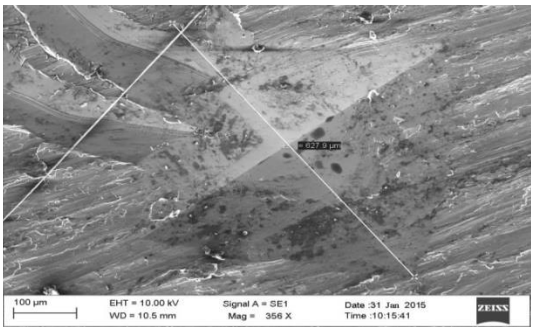
Fig. 2. *Vickers Indentation Mark.[5]*

SEM Analysis

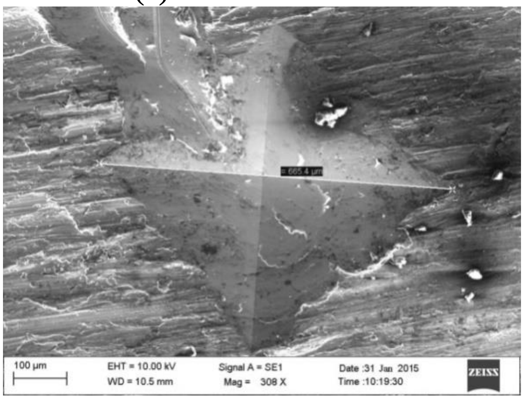
The Vicker's indented test specimens are inspected in the scanning electron microscope (SEM) for the measurement of crack length. The typical Vickers indent and typical cracks on the surface of an experimental material are illustrated in Figure 3.



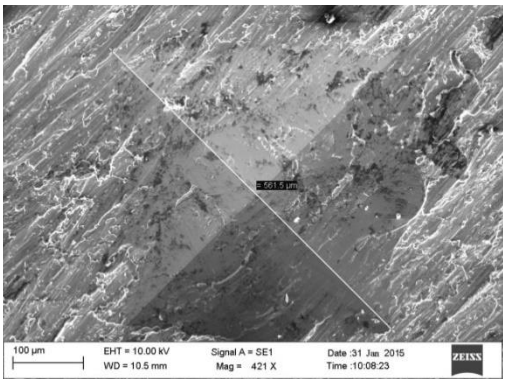
(a) SEM of Al-6061



(d) SEM of Al-3%Gr



(c) SEM of Al-6%Gr



(d) SEM of Al-9%Gr

Fig. 3. *Scanning Electron Micrographs (SEM) Showing Indent Subsurface.*

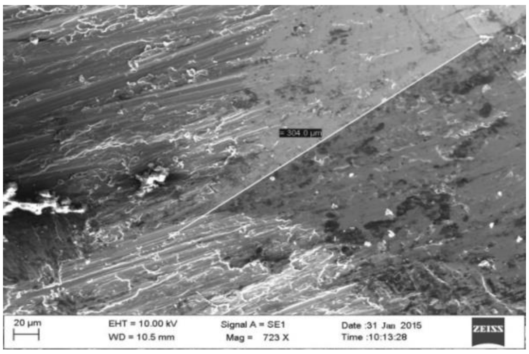
Vicker's hardness for the various weight fraction of aluminum graphite particulate MMC are calculated and listed in the Table 3.

Table 3. *Vickers's Hardness Number.*

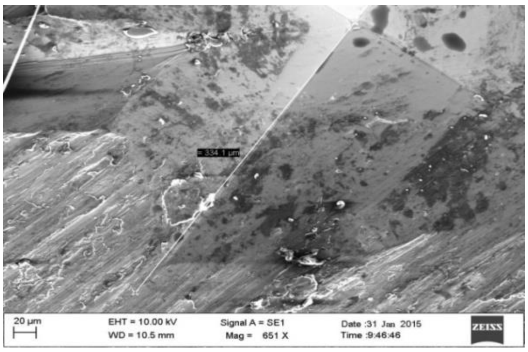
Sl. no	Composite	Load applied (F) (kgf)	Diagonal length (2a) (mm)	Half diagonal length (a) (mm)	Vickers's hardness (GPa)
1	Al-6061	30	0.5745	0.2872	6.61
2	Al-6061 + 3% Gr	30	0.6279	0.3139	5.53
3	Al-6061 + 6% Gr	30	0.6654	0.3327	4.93
4	Al-6061 + 9% Gr	30	0.5615	0.2807	6.92

Finding the Crack Length

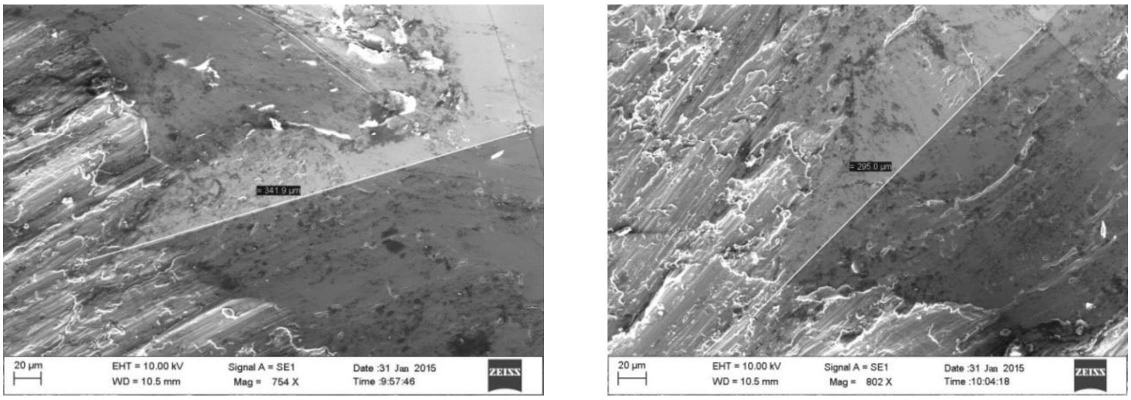
Fracture toughness was measured using indentation method from crack lengths. The 2-3 indents for each specimen were performed. The length of cracks was measured by Scanning electron microscope. The cracks are straight without clear deviation of the crack path shown in Figure 4.



(a) SEM of Al-6061



(b) SEM of Al-3%Gr



(c) SEM of Al-6%Gr (d) SEM of Al-9%Gr

Fig. 4. *Scanning Electron Micrographs Showing Indent With Subsurface Crack Profile.*

From the length of the indentation cracks fracture toughness was calculated by applying the Anstis' Eq. 4[6–8]:

$$K_{IC} = \eta\ (E/HV)^{0.5}\ (F/c^{1.5}) \qquad \text{Eq. (4)}$$

where K_{IC} is the fracture toughness (MPa m½), η the shape factor (0.016 ± 0.04), E the Young's modulus (GPa), VHN the hardness (GPa), F the indentation load (N), and c is the crack length (μm).

Table 4 shows the results of the SEM study and Fracture Toughness for the various volume fraction of Al-Gr particulate MMC are calculated using Anstis' Eq. 4.

Table 4. *Experimental Fracture Toughness.*

Composite	Indentation load (F)(kg)	Crack length (c)(μm)	Hardness (VHN)(GPa)	Young's modulus (E)(GPa)	K_{IC}(MPa m½)
Al-6061	30	304.0	6.61	68.9	10.03
Al-6061 + 3% Gr	30	334.1	5.53	67.2	09.40
Al-6061 + 6% Gr	30	341.9	4.93	65.6	09.51
Al-6061 + 9% Gr	30	295.0	6.92	64.05	10.15

FRACTURE TOUGHNESS USING ANSYS

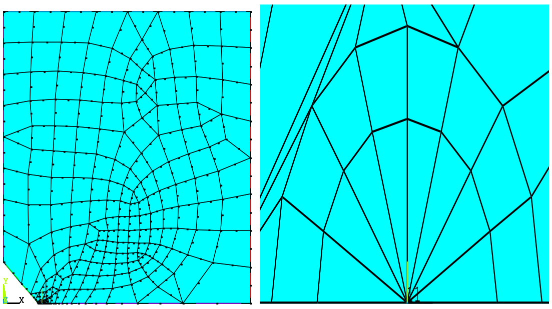
ANSYS Assumptions and Approach

- Linear elastic fracture mechanics (LEFM).
- Plane strain problem.
- Since the LEFM assumption is used, the SIFs at a crack tip may be computed using the ANSYS's **KCALC** command. The analysis used a fit of the nodal displacements in the vicinity of the crack tip.
- Due to the symmetry of the problem, only a quarter models are analyzed.
- The crack-tip region is meshed using quarter-point (singular) 8-node quadrilateral elements (PLANE82).

PLANE82 is eight nodded higher order 2D element. It gives additional correct results for quadrilateral and triangular meshes and might tolerate irregular shapes while not the maximum amount loss of accuracy.

Model Generation

The geometric model is created in ANSYS.[9] The finite element model is built using PLANE82 elements as shown in Figure 5.



(a) Finite element model (b) crack tip
Fig. 5. *Finite Element Models.*

Fracture Toughness Analysis Results by ANSYS

The finite element model is built using PLANE82 element with symmetric boundary conditions. For the crack analysis of the aluminium-graphite metal matrix composite, the material properties used are given in the Table 4. Crack analysis was carried out and result of the analysis is listed in Table 5.

Table 5. *Analytical Fracture Toughness Results of Al-Gr Alloy.*

Sl. no	Composite	K_{IC} (MPa) $\sqrt{m}$
1	Al-6061	10.34
2	Al-6061 + 3% Gr	10.26
3	Al-6061 + 6% Gr	10.27
4	Al-6061 + 9% Gr	10.82

From the fracture toughness analysis using ANSYS software, it is clear that fracture toughness decreases with increase of graphite content. However for Al-9%Gr there is a slight increase in the value of the fracture toughness to 10.82 MPa $\sqrt{m}$ was observed.

Comparison of Experimental and ANSYS Results

The data collected from both experimental and ANSYS analysis is shown in Table 6.

Table 6. *Comparison of ANSYS and Experimental Results of Aluminum-Graphite.*

Composite	Experimental K_{IC} (MPa m½)	ANSYS K_{IC} (MPa m½)	% Deviation
Al-6061	10.03	10.34	3.0
Al-6061 + 3% Gr	09.40	09.26	1.5
Al-6061 + 6% Gr	09.51	09.27	2.5
Al-6061 + 9% Gr	10.15	10.82	6.2

The results obtained by experimental and analytical methods agree with each other with a deviation of about 1.5–6.2%. There is a good correlation between analytical and experimental values of the fracture toughness.

Fracture toughness of Al/Gr_p was observed to increase with an increase in weight percent of graphite particles. This increment was due to same size of particles, good bonding between the particle/matrix interfaces which act as a barricade for crack nucleation. Addition of graphite particles to aluminium matrix it was observed to be increase in the fracture toughness of the composite. At 9% of graphite, the fracture toughness of composite was found to be 10.15 MPa m½.

CONCLUSIONS

Based on an experimental and analytical study using the crack-opening displacements from Vickers indentation cracks to determine the fracture toughness of aluminum graphite MMCs' the following conclusions are made.

- Vickers hardness for the various volume fraction of aluminium-graphite particulate MMCs' are calculated. Results shows the maximum Vickers's hardness of 6.92 GPa was found to the Al-9%Gr.
- Using the Vickers indentation experiment, fracture toughness K_{IC} = 10.15 MPa m½ is obtained for Al-9%Gr.
- Fracture analysis of Al-Gr alloy done by using ANSYS and the maximum value of fracture toughness can be observed at Al-9%Gr of 10.82 MPa m½.

- The results obtained by both the methods agree with each other with a deviation of about 1.5–6.2%. There is a good correlation between analytical and experimental values of the modal analysis.

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