Visual
Abstract

Fracture analysis of AA6061-graphite composite for the application of helicopter rotor blade

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ABSTRACT. The main objective of the work is to study the fracture behavior of AA6061-graphite material using both experimental technique and finite element simulation by considering helicopter rotor blade as a case study. From the case study, it has been observed that the helicopter rotor blade, made of AA6061, has been failed at the threaded portion of the hole. Experimental fracture toughness is carried out using the compact tension specimens as per ASTM standard testing procedure. Modeling of compact tension specimens and the threaded portion of the bolt hole was utilized to analyze the fracture toughness using a simulation tool. From the results and the comparison, it is recommended to use AA6061-9wt% graphite material as a replacement of AA6061 in the application of main rotor blades of the helicopter.

KEYWORDS. Metal matrix composite; Al-graphite composite; Simulations; Fracture toughness; Rotor blade.

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INTRODUCTION

The property of material through which it is capable of resisting the propagation of crack [1] is known as fracture toughness. Many experimental measurement methods and standardized fracture toughness testing techniques were utilized to cherecterize the material, performance evalutionand also quality assurance of various engineering structures. Thus the fracture toughness determination and testing plays the vital role in the development of fracture mechanics and their applications. The American society for testing and materials (ASTM) provides the standard method for fracture toughness testing and evaluation and also its terminology. One of those methods were ASTM E1823 [2]. The first fracture toughness testing for metallic materials was ASTM E399 [2] which is developed to determine the plain strain fracture toughness K_{Ic}.

The ASTM E399 can also be applied to the disconitusly reinforced or particulate reinforced metal matrix composites (MMCs). These composites nearly exhibits the isotropic properties [3] whereas the fiber aligned MMCs are highly anisotropic. Some of the particulate reinforcements used were ceramic particles such as silicon carbide, alumina, graphite, boron carbide, titanium carbide etc.

Many experimentation techniques have been conducted [4] on the fracture toughness of the Al6061-graphite particulate composites. Also the comparison of the fracture toughness values of Al-SiC and Al-graphite composites has been carried out. From the results it is observed that the Al-graphite particulate composites exhibits the better fracture toughness, light weight, wear resistant, higher coefficient of friction and ductility than the other metal matrix composites. Thus the Al-graphite composites can be utilized for the many automobile and aerospace composites. The Al6061 T6 is used in the many applications like bycycle frames and components, wings and fuselages of aircrafts, helicopter rotor blade, etc.

Many authours [5-9] ware studied the failure of helicopter. Literature shows that failure of helicopter occurred is at the threaded hole region of rotor blade. Many helicopter rotor blades are failed due to the fatigue loading, corrosion of threaded holes [5-6]. Litreatures also shows that many helicopter failures occurred in air i.ein the operational conditions [5-7]. Crack developed and propagated, in the rotor blade fittings i.e bolt hole [6,8], edge spar [7] without giving any prior indication. Many researchers reported that main rotor blades are made of aluminum 6061-T6 alloy [5-9].

Mikael Amura et al [5] investigated rescue military helicopter crash in Italy in the oprating conditions. Their investigation revealed that the crash was caused by the fatigue failure of the spar of a main rotor blade. Among five rotor blades, four blades are found in the crash site whereas fifth blade found at a distance of about 900m from the crash site. From the investigation it was found that failure of blade happened while helicopter is in the air. Main rotor blade was made of 6061-T6 aluminum alloy. Dr Arjen Romeyn [6] also reported that failure of one of the rotor blades of Robinson R22 helicopter. Failure of the blade occurred at the section of root fitting. Material of the rotor blade is aluminum alloy. Surise helicopters inc [7] investigated the failure of main rotor blade of Bell 206L helicopter, Canada. Material used in the rotor blade is aluminum alloy. The blade fracture was intiated at on the inner surface of the spar, at the location of the void in the adhesive used to bond the lead weight to the spar at station.

Rolf Kieselbach et al [8] studied the failure of a helicopter rotor. Experiments have been conducted to find the material properties. From the result, it is suggested a proposal to detect the cracks before they reach to a critical size. SylwesterKlysz et al [9] also reported the faulire of main rotor blade of the Mi-8 helicopter. Blades of the Mi-8 helicopter are made of 6061-T6 aluminum alloy. Also conducted the strength and fatigue tests of the material of the helicopter blades. Experiments have been carried out to find the strength and fracture characteristics of the material from the main rotor blades of Mi-8 helicopter. Specimens used are disk-shaped compact specimen (DCT) per ASTM standards Fatigue crack growth experiments have been carried out and found that threshold fracture toughness ΔK_{Ic}as 1.34 to 2.81 MPa$\sqrt{m}$.

Yasmin et al [10], S Doddamani et al [11] worked on aluminum matrix reinforced with graphite particles has been studied for the mechanical and fracture characteristics of the composite respectively. ASTM has prescribed compact tension specimen for the fracture toughness testing [12]. S Doddamani et al [13] uses compact tension specimen to study the fracture toughness of Al6061-graphite MMC at varied weight fractions. K.K. Alaneme et al [14] studied the fracture toughness of Al6063-SiC particulate MMC. It is observed from the results of the fracture toughness testing of Al6061-graphite [15] and Al6063-SiC [16] that Al6061-graphite composite has more fracture toughness values. Different authors [15-21] studied the different methods of the finite element techniques to determine the mechanical/fracture behavior of the materials.

Experimental techniques on prototype provide information concerning the structure in the pattern of the experiment only. Whereas predicting the dynamic behavior of the structure, under different boundary conditions & loading, can be done by finite element models, but the reliability of the finite element model (FEM) is often not guaranteed. To verification and optimization of these FEM analysis results can be accomplished by the experimental data. The outcome of a model updating examination is a FEM technique that is more reliable for further prediction. FEM software, like

ANSYS, solves the issues related to structural and mechanical. Structural and mechanical issues incorporate static/dynamic, heat transfer & fluid problems, linear & nonlinear structural analysis, and additionally electromagnetic and acoustic issues.

Many two dimensional, three dimensional tutorials ware also available to evaluate the fracture toughness [22-24] using finite element methods, most of them ware used ANSYS tool for the same. While simulating the fracture related issues, it requires the use of PLANE182, which will fit the crack tip section. PLANE182, as shown in Fig 1, is a higher order form of the 2-D, eight-node component. It gives more exact outcomes to blended (quadrilateral-triangular) automatic meshes and can hold up under sporadic shapes without as much loss of accuracy. The 8-node components have ideal displacement shapes and are appropriate to model curved boundaries.
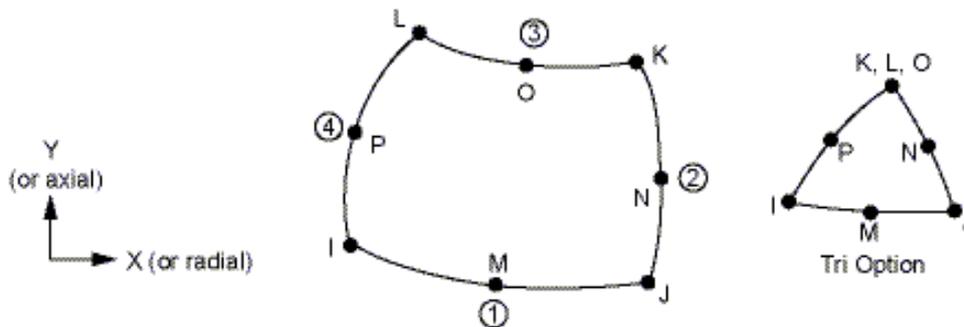
Figure 1:PLANE182 Geometry.

The 8- node component is characterized by eight nodes having two degrees of freedom at every node: interpretations in the nodal x and y directions. The component might be utilized as a plane component or as an axis-symmetric component. The component has stress stiffening, large deflection, plasticity, creep, swelling, and extensive strain abilities. The stress intensity factors at a crack for a linear elastic fracture mechanics analysis may be computed. The analysis uses a fit of the nodal displacements in the vicinity of the crack.

From the literature it is identified the helicopter rotor blade, made of AA6061, was failed at the threaded portion of the rotor blade. The main objective of the work is to study the fracture behavior of AA6061-graphite material using both experimentation and finite element simulation method by considering helicopter rotor blade as a case study. The finite element model is built for the AA6061 and AA6061-graphite composite. Through this work an attempt has been made to compare the existing use of material with the composite material to prepare the helicopter rotor blade so as to enhance its fatigue crack resistance property.

MATERIALS

A luminum alloy (AA) 6061 and its main alloying elements are silicon (0.70%) and magnesium (0.81%). Physical properties [25] of AA6061 were hardness 95 BHN, elastic modulus 68.9 GPa, ultimate tensile strength 315 MPa, yield strength 275 MPa, extension 17%. Graphite is available in the shape of fibers and particles which has been identified as high strength material. Physical properties of graphite [26] are elastic modulus 15 GPa, yield strength 119 MPa, Thermal Expansion Coefficient is $8.2\times10^{-6}°C$. Out of many factors which influence the fracture properties, the particle size of graphite is most important microstructural variable. AA6061 and graphite particulate metal matrix composites produced by solidification techniques presents better mechanical properties which can be potential materials for aerospace and automobile applications [27-30].The mechanical properties of the AA6061-graphite composites used for this study are listed in the Tab. 1.

Sl.No	Specimens	Yield strength (MPa)	Ultimate tensile strength (MPa)	Percentage Elongation	Elastic Modulus (GPa)
1	AA6061	85.6	102.4	16.8	68.9
2	AA6061-6wt%SiC	93.3	114.1	14.1	65.6
3	AA6061-9wt%SiC	99.1	117.3	14.3	64.2
4	AA6061-12wt%SiC	98.9	115.8	13.7	64.4

Table 1:Mechanical properties of AA6061-graphite composites

METHODS

Experimentation

The compact tension (CT) specimen is used to test the fracture toughness as per the ASTM E399 standard testing procedures. The geometry of the specimen is as shown in the Fig 2(a). The crack length to width (a/W) ratio considered is 0.45, width of the specimen considered is 40mm and thickness of the specimen is 12mm which confirms the conditions [12-13, 28] of plane strain fracture toughness. The experimentation has been carried out using servo hydraulic testing machine by maintaining the frequency of 5 Hz and displacement rate 1mm/min.
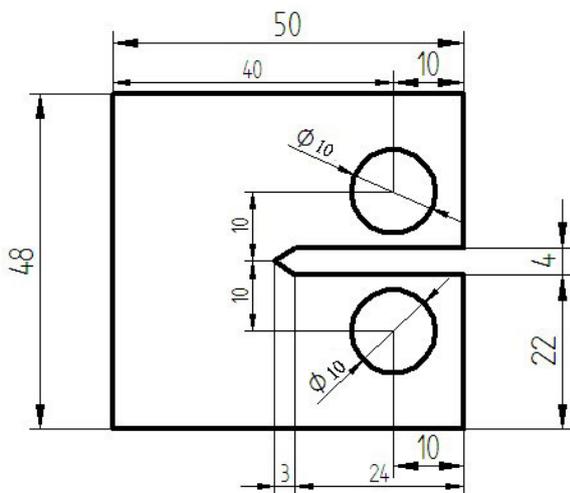
Figure 2(a): Geometry of the CT specimens.
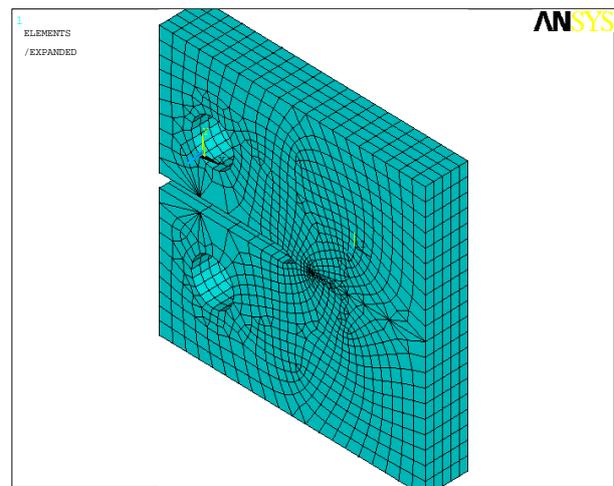
Figure 2(b): Finite Element Model
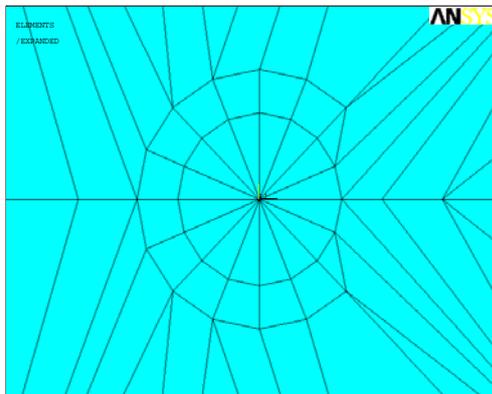
(a)Full Crack Model
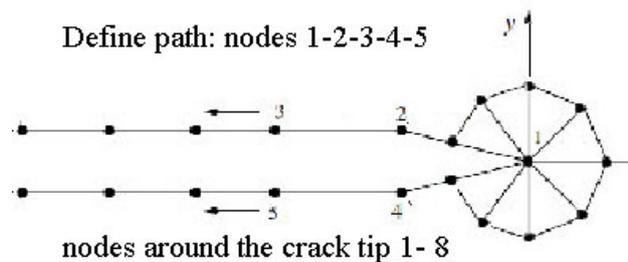
(b) Nodes around the crack tip

Figure 3: Crack tip region.

Model Generation

Using ANSYS, the geometric model was created. A finite element model was constructed utilizing PLANE182 and SOLID185 components shown in Fig 2(b). The nodes around the crack tip appear in Fig 3. Von Neumann's method is used, which is the most widely used approach, to study the stability of numerical schemes. It is not necessary to refine the mesh of the entire model. From the Saint-Venant's Principle, the model can be refined at the regions of interest. Thus the coarse element sizes are refined at the crack tip to the fine mesh. The mesh refinement at the crack tip leads to reduction

of errors significantly. From the mesh refinement, the convergence of solutions can be increased without an increment in the problem size it can be solved.

The singularity, in fracture mechanics, is essential. At the crack tip, there is the small localized plastic zone will be formed due to the higher stresses at that region. Crack tip is the sharp corner which causes the worst conceivable geometrical singularity. In the singularity region the stresses become infinite. It is difficult to compute the stress field in finite element simulations because of the singularity. However it is not necessary to investigate the details of crack tip. There are direct approaches to determine the fracture toughness of the material. Since these approaches determine the global quantities far from crack, the singularity can be ignored.

The finite element model was built using PLANE182 element [31], for the crack analysis of the aluminum-graphite alloy. The crack analysis was carried out and the resulting analysis is shown in Tab. 1.

FAILURE OF A HELICOPTER MAIN ROTOR BLADE

A rescue military helicopter crashed in the middle of a ferry flight towards an air terminal where an activity was planned. All team individuals endured fatal injuries [5-7]. The rescue military helicopter suddenly changed direction, and lost control due to the detachment of one of the rotor blades. The increase of fatigue crack growth reduces the strength of the blade to an extent that allowed the fracture to occur under normal flight loads. In view of the direction of failure of the helicopter, the Safety Investigation Board found part of the failed blade separated around 900 m before the disaster area. The failure analysis of the fractured blade was conducted and it was determined that part of the blade detached in the air due to which helicopter become uncontrollable. The main rotor blade is about 9 m long. The structural part of the blade is made of 6061-T6 aluminum alloy [5-8] and were 4.5 mm thick on average.

The observations demonstrated various initiation points along an cut on the external and internal surface. Blade fracture happened because of the initiation of a fatigue crack in the bolt hole in the blade spar to root fitting joint. Fig 4 shows the root fitting of the blade, an aluminum alloy that accommodates the blade spindle and bearings, had fractured at the innermost bolt hole of the root fitting to blade spar joint.

Figure 4(a) recovered main rotor head assembly [6]

Figure 4 (b) fractured main rotor blade [6]

Figure 5(a) Fitting side, or inboard side, of the fracture [6]

Figure 5(b) The blade side, or outboard side, of the fracture [6]

Figure 6: Sites of fatigue crack initiation (arrowed) [6].
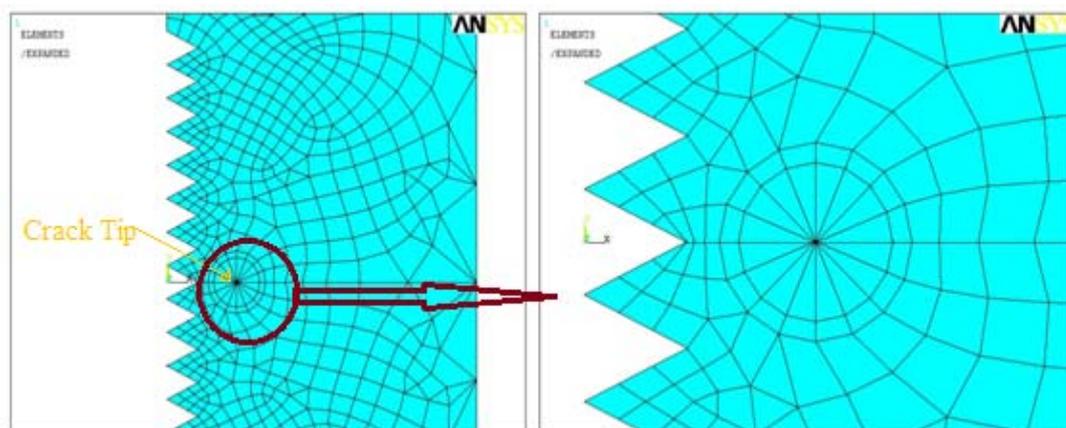
Figure 7(a) FEA Model   Figure 7(b) FEA nodes around the crack tip

From the Fig 5(a), (b) it is observed from the fracture surface features that fracture take place as a result of the progressive crack growth from the inboard bolt hole. The fatigue crack growth mechanism was used, i.e., crack initiation and crack propagation in response to the development of repeated alternating stresses throughout the operation.

Due to the failure of the adhesive bond (disbonding) at the bolt hole, failure of the main rotor blade occurs. The disbonding take place at spar end, and the root fitting of upper and lower blade skins as shown in Fig 5.

From Fig 6, it is clear that moisture reacted with the crack surfaces. Followed by localized corrosion occurred in the counterbore (Fig 6 (b,c)). The nature of crack propagation marks signifies that fatigue crack initiation occurred at (a) the lower side of the bolt hole, (b) the thread on the upper side of the bolt hole and (c) the counterbore on the upper side of the bolt hole. From Fig 6 it is evident that the failure of the rotor blade occurred at the bolt hole and threaded portion of the bolt hole.

The FEM model to find the fracture toughness is created using ANSYS. A structural model was created using an 8-node PLANE182 element with no real constants values. For the element PLANE182, the area has been created with a concentrated key point at the crack tip. The model was meshed, gave symmetric boundary conditions and loads applied before solving the problem. The finite element model is built using PLANE182 elements, crack tip and nodes around the crack tip are shown in Fig 7.

ANSYS, there is no possibility of voids, clustering of reinforcements, particle and matrix interfaces; material will not have any other crack in its structure. Since the fracture toughness depends on the material properties (Tab. 1), crack length and the load at fracture (Pf), nearly better results will be obtained as compared to experimental results.

RESULTS AND DISCUSSIONS

The fracture toughness of the AA6061 and AA6061-graphite composites has been carried out, both experimental and 3D simulations, using CT specimens and threaded portion of the AA6061 and AA6061-graphite composites using finite element simulations. The result of the analysis has been given in the Tab. 2.

Sl No	Composite	Fracture Toughness (K_{Ic}) MPa $\sqrt{m}$		
		Experimental	Simulation of CT specimen	Simulation of Threaded portion
1	AA6061	15.45	15.34	15.94
2	AA6061-6%graphite	16.22	16.42	17.21
3	AA6061-9% graphite	16.74	18.73	18.28
4	AA6061-12% graphite	15.70	17.64	17.98

Table 2: Fracture Toughness results of AA6061 & AA6061-graphite composites.

The experimental fracture toughness of the AA6061-graphite composites has been carried out for the different weight fractions of the graphite. For each composition, three CT specimens were prepared and tested. The mean value of the fracture toughness has been listed in the Tab.2. The fracture toughness with increment in the graphite percentage has been plotted as shown in the Fig 8. Specimens of unreinforced Al6061 exhibits the lesser deviations for the samples tested. However, the samples AA6061-6wt% and 9wt%graphite shows the similar deviation whereas the AA6061-12wt%graphite have the increased deviation than others. This larger deviation is may be due to the difference in the fracture toughness values among the specimens tested. Also as the graphite composition increases the fracture toughness increases up to 9wt% of graphite and later decreases at 12wt% of graphite. This decrement is due the increase of reinforcement decreases the ductility, thus decreases the fracture toughness of the said composite.
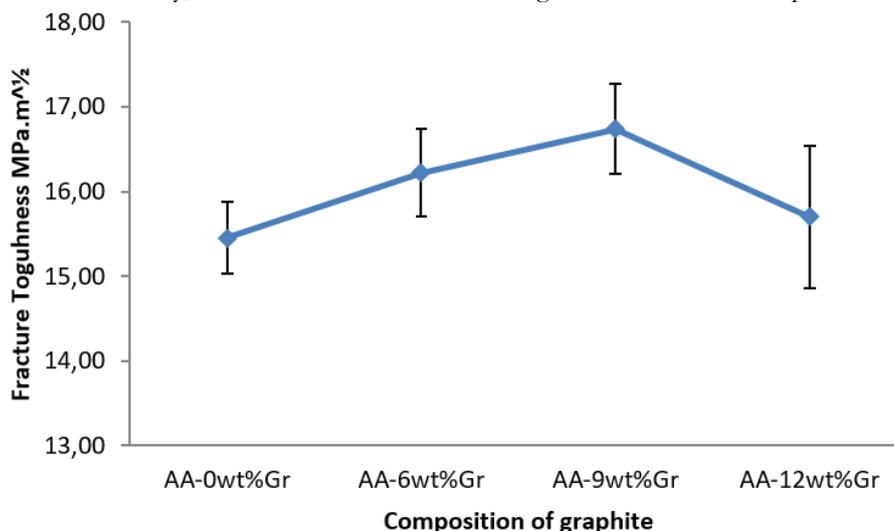
Figure 8: Fracture toughness of the AA6061-graphite composites.

From the Tab. 2 it is observed that the fracture toughness values are almost near to each other. However the FE simulation results are higher than the experimental results. This is due to the fact that only one crack has been introduced in the simulation model whereas in the experimental specimen there may be many voids, dislocations and micro-cracks were available leads to the reduction in the fracture toughness.
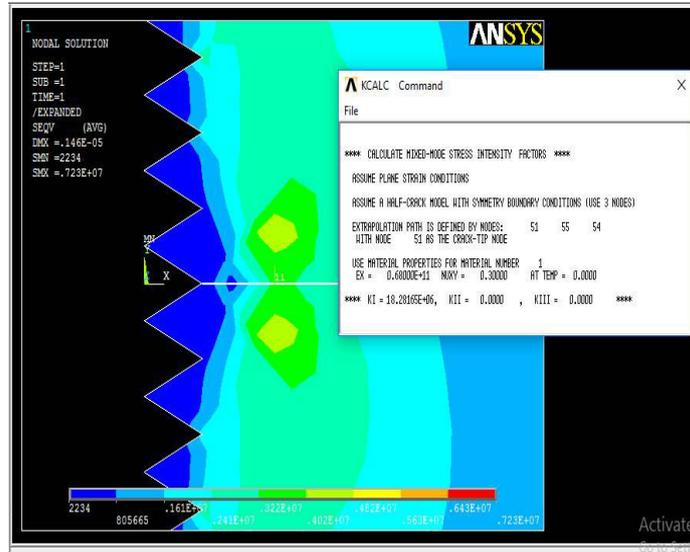
Figure9:Stress concentration factor K1 of AA6061-9%graphite for rotor blade.

(a) Unreinforced Al6061 alloy

(b) Al6061-6wt% of SiC

(c) Al6061-9wt% of SiC

(d) Al6061-12wt% of SiC
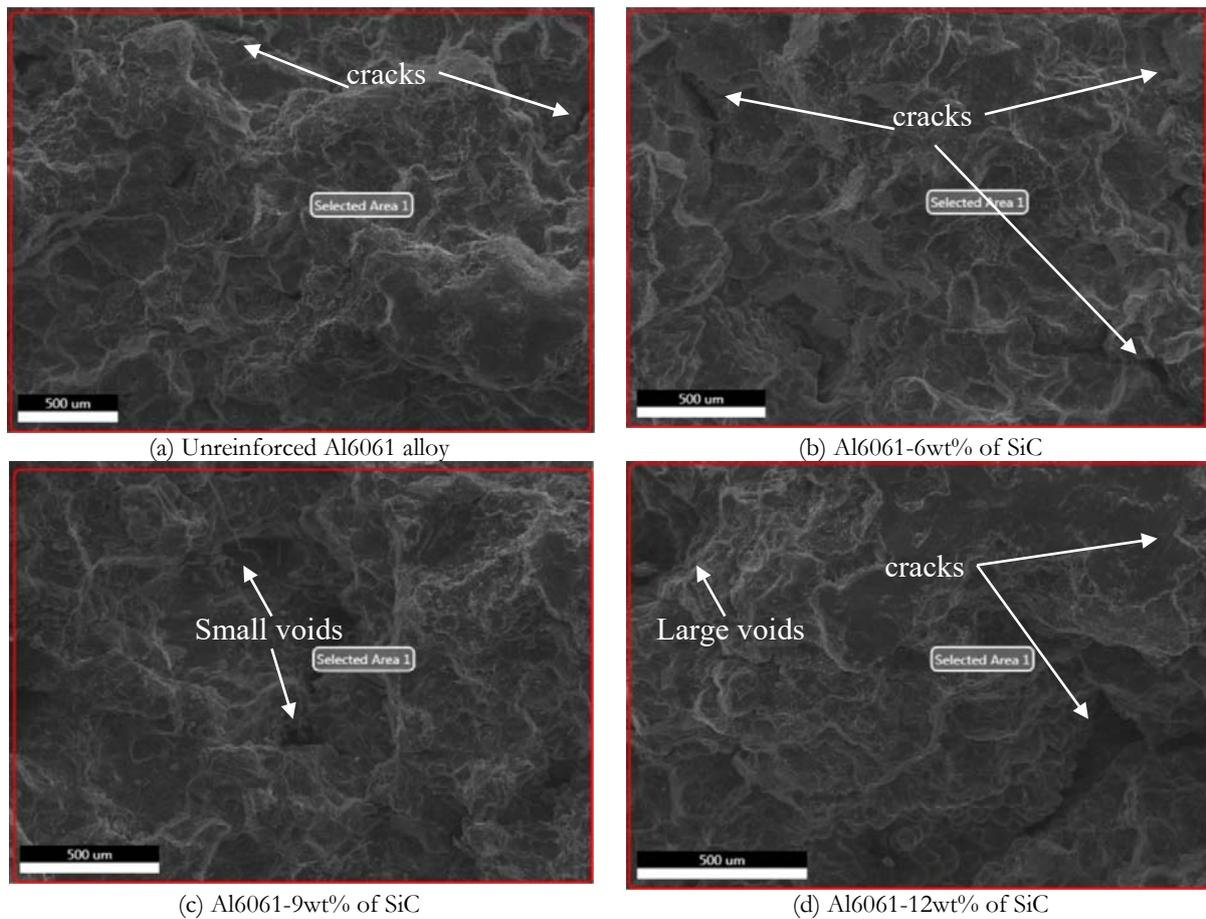
Figure 10. SEM Fractographic images

Fig 9 shows the fracture toughness value of the AA6061 with 9wt% graphite particles and also shows the shape of the plastic zone. The shape of the plastic zone obtained indicates the plane strain fracture toughness [1]. The fracture toughness of the AA6061 with 9wt% graphite composite exhibits the higher values. Thus it is considered to be the better composition of the composite among tested. From the above results it is recommended that AA6061-9%graphite material can be considered as a potential rotor blade material as a replacement of AA6061 in the application of main rotor blades of the helicopter.

Fig10 shows the fractographic images of the Al6061-graphite composites obtained through the SEM. Fractographic images shows the formation of cracks at the unreinforced aluminum alloy and at 6wt% of graphite whereas at the 9wt% of graphite have the smaller voids which transforms into the cracks on loading. Thus the increased fracture toughness has been observed. The decrement in the fracture toughness after the 9wt%graphite, is due to increased hardness and increased crack initiation sites and reduced ductility.From the Fig. 9 it is also observed that, all the Al-graphite composites exhibits the dull and fibrus surface. Which means that the said composites have the ductile fracture. Thus the increased fracture toughness of the Al-graphite composite is the addition of graphite reinforcement. However the increment in other reinforcements such as SiC [14] in the aluminum composites exhibits the lesser ductility and fracture toughness values.

CONCLUSIONS

The failure of the helicopter rotor blade occurred at the threaded portion of the bolt hole. The finite element model of the bolt hole and the compact tension specimen was successfully modeled using the ANSYS. The fracture toughness values obtained from the FE simulation are in close agreement with data obtained from standard K_{Ic} testing. From the comparison of experimental and the FE simulation results, it is recommended that AA6061-9%graphite material can be considered as a potential rotor blade material as a replacement of AA6061 in the application of main rotor blades of the helicopter.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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