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Effect of Thickness on Fracture Toughness of Al6061-Graphite

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ABSTRACT

This research work presents the study on fracture behavior of Al6061 with graphite particulate composite produced by the stir casting technique. The materials selected for the proposed work is Al6061 and graphite particles. Compact tension (CT) specimens were utilized to determine fracture toughness for different thickness of composite. In the present work, optimizing the parameters of the compact tension specimens is carried out using Taguchi method. Four parameters and two factors are considered to optimize the parameters. Factors considered are material composition and *a/W* ratio. From the Taguchi analysis, on compact tension specimens, Al6061-9%graphite is the optimized composition and fracture toughness is maximum for *a/W* ratio = 0.45. All the compact tension specimens of different thickness (B = 4, 5, 7, 10, 12, 15, 18 and 20*mm*) of *a/W*=0.45 were tested to find the fracture toughness. From the results, it was observed that the K_q reduces with increment in thickness to width (*B/W*) proportions and found to stay consistent for $B/W \geq 0.3$. This consistent estimation of K_q for $B/W \geq 0.3$ prevail the plane strain fracture toughness (K_{Ic}) of the composite.

Keywords: Al6061-graphite, MMC, Fracture toughness, CT Specimens, Taguchi analysis.

1 INTRODUCTION

FRACTURE toughness is typically utilized as a general phrase for measures of material imperviousness to crack propagation. Values of fracture toughness likewise may serve as a premise in performance evaluation, quality affirmation and material description for representative engineering structures, together with oil and gas pipelines, aircraft, ship and automotive structures, piping and pressure vessels, petrochemical tanks etc. In this manner, fracture toughness investigation and assessment have been a critical issue being developed of fracture mechanics technique and its engineering applications. The most important parameters [1] used in fracture mechanics are the elastic energy release rate G (or its equivalent accomplice – stress intensity factor K), the J-integral and the

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crack-tip opening displacement (CTOD). To measure these parameters many experimental techniques have been adopted to explain material's fracture toughness (K_{Ic}). Customary terminology relating to K_{Ic} testing and assessment has been defined in E399-90 [2] by the American Society for Testing and Materials (ASTM). All concepts and requisites relating to fracture tests utilized as a part of this work are characterized by ASTM E399.

Metal matrix composites (MMCs) have their applications where it requires weight savings, wear resistance and thermal management. Considerably the majority of commonly used metal matrix composites [3] has their base material as aluminum, magnesium, and titanium alloys reinforced with silicon carbide (SiC), alumina (Al_2O_3), carbon, or graphite.

ASTM fracture test standards prescribed many types of conventional fracture test specimens. These include single edge-notch bend (SENB) specimen, compact tension (CT) specimen, disk-shaped compact tension (DCT) specimen, arc-shaped bend (AB) specimen and arc-shaped tension (AT) specimen. Different specimen size requirements are prescribed for different fracture test standards so as to get valid fracture toughness, also to restrict the effects of crack-tip limitation on that fracture toughness parameter.

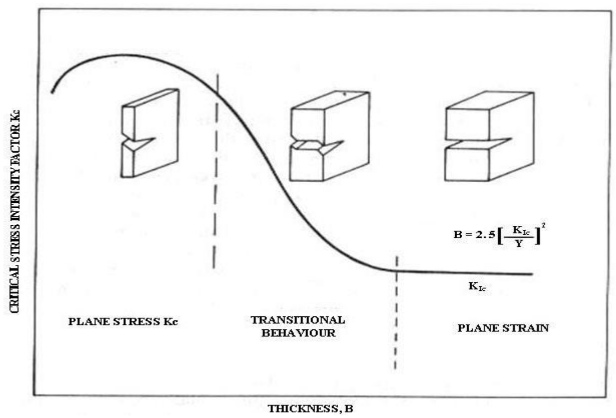


Fig.1
Fracture toughness with an increase in specimen thickness.

Specimens having standard extents yet different outright size produces diverse values for K_I. This outcome on the grounds that the stress states near the crack vary with the specimen thickness (B) until the thickness surpasses some critical extent. When the thickness surpasses the critical extent, the estimation of K_I turns out to be moderately steady (shown in Fig. 1) and the estimated value is known as the plane-strain fracture toughness (K_{Ic}).

The relationship between fracture toughness (K_{Ic}) and stress intensity (K_I) is same as the connection established between stress and tensile stress. The stress intensity corresponds to the intensity of "stress" at the crack tip whereas the fracture toughness is the maximum value of stress intensity that a material can withstand without fracture under plane-strain conditions. Unstable fracture occurs when the stress intensity factor reaches the K_{Ic} value.

Kulkarni D.M. et. al. [4] conducted experimental fracture toughness tests for generating results on the fracture behavior of extra deep drawn (EDD) (0.06%C) steel sheets. For the same utilized CT specimens and fracture criterion used is 'load-drop'. The basic CTOD was appeared to increases as specimen thickness increases and appeared to be moving toward a higher limiting value. Yi-Lan Kang et. al. [5] experimentally investigated the fracture toughness of copper foils with thicknesses (t) ranging from 0.02 to 1 *mm*. For the experiment utilized the double-edge cracked specimens to study the thickness effect on fracture toughness of metallic foil. The experimental outcomes appear that increment in thickness of specimen leads to increment in fracture toughness, then to reach a maximum for a thickness of around 0.3 *mm* and lastly to decrease at larger thicknesses.Toshiyuki Meshii et. al. [6, 7, 8] explains the investigations on CT specimens to find the fracture toughness of a material in the context of specimen thickness, in the transition temperature region. Also examined the effect of specimen thickness on 0.55% carbon steel S55C, expecting that T33-stress influenced the crack-tip triaxiality and along this constraint in the out-of-plane course. Marco Palombo et. al. [9] made an attempt to define correlation criterion between fracture toughness, CTOD, specimen thickness. For the same, they utilize SENB specimen of different size to perform CTOD tests on a carbon steel material. Through the experiment data, they found the correlation that allows evaluating fracture toughness and CTOD for specimens with a different thickness than the one characterizing tested specimens. Pandey A.B. et. al. [10] evaluated the fracture toughness of Al/SiC composite for different specimen thickness. The fracture toughness in the underaged condition increases considerably with a decrease in specimen thickness, even at thicknesses well underneath the value indicated by ASTM-E 813 for a valid fracture toughness test. The influence of thickness was significantly lower in the peak-aged (PA) condition. Raviraj M. S. et. al. [11]

studied fracture characteristics for Al6061-TiC particles. For the same, they utilize compact tension (CT) specimens of a/W = 0.5, and thickness to width (B/W) ratios of 0.2 to 0.7. Load versus CTOD data was plotted to estimate fracture toughness for various thickness of the specimen.

Taguchi method of optimization is one of the most effective techniques because of its simplicity to conduct the design of experiments. Main aim of the Taguchi technique is to evaluate the statistical data which is the input function for optimization. The technique developed for design of experiments to examine the different parameters and their effect on process mean and variance. Analysis of variance (ANOVA) on the data from the Taguchi design of experiments can be used to select new parameter values to optimize the performance behavior. Bharath K. N. et. al. [12] experimentally investigated fracture toughness of jute fabric reinforcement and epoxy resin for various notch sizes. To optimize the results Taguchi method was utilized. Each parameter was analyzed using Analysis of variance (ANOVA) and response surface analysis. From the analysis, it is obtained that load carrying capacity of the material decreases with a/W ratio increases and load bearing capacity increases with thickness of the specimen. Zamani P. et. al. [13] studied different parameters consecutively to obtain the highest safety of design and the use of gas pipelines in gas and petroleum industry. In their work, to study the effect of crack length, crack depth, crack position, internal pressure and thickness of pipe three dimensional finite element analyses has been utilized. To analyze the parameters Taguchi method was utilized. Result of the analysis shows the good agreement between numerical and experimental values. Assimina A. Pelegri et. al. [14] studied the cross ply graphite epoxy laminates for critical fracture toughness using Taguchi methods and design of experiments. The parameters considered were width, length, thickness. Also investigation has been conducted to analyze the effect of interfaces on delamination propagation.

Different absolute size specimens with standard proportions will deliver diverse values for K_I. This outcome is on the grounds that the stress state surrounding the crack varies with the sample thickness (B) until the point when the thickness surpasses some significant dimension. When the thickness surpasses the significant dimension, stress intensity factor (K_I) value turns out to be moderately steady (shown in Fig. 1) and that value is actual material property which is known as the plane-strain fracture toughness (K_{Ic}). Thickness to width (B/W) ratio for the CT specimens can be considered [6] as 0.1 to 0.5.

It is identified from the literature that more research work has been done on fracture and fatigue behavior of aluminum matrix reinforced with silicon carbide particulate composites. Research has to be conducted in the area of fatigue and fracture, to avoid the cracking, on the aluminum-graphite particulate reinforced composites so as to enhance the material's fracture behavior. Objective of the present work is to study fracture toughness of the material at a different thickness of the specimen for optimized composition.

2 MATERIALS

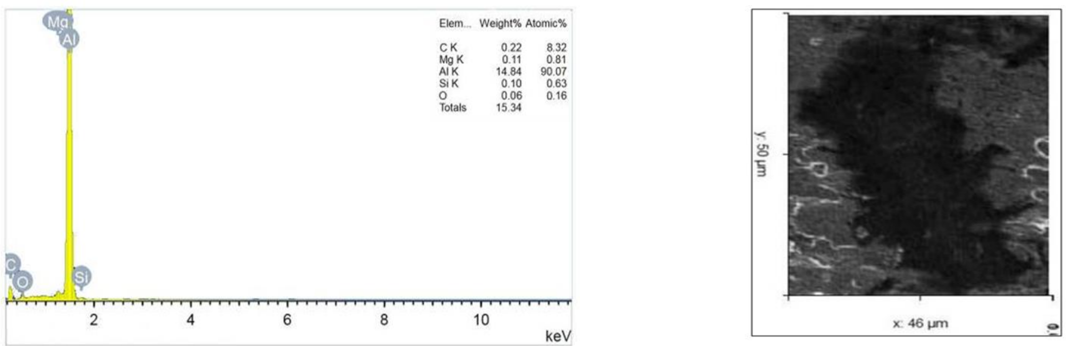
Precipitation-hardened aluminium alloy called Al6061 and its main alloying elements are silicon (0.70%) and magnesium (0.81%). Physical properties [15] of Al6061 are hardness 95 BHN, Elastic modulus 68.9 *GPa*, ultimate tensile strength 315 *MPa*, yield strength 275 *MPa*, extension 17%. Graphite is available in the shape of fibers and particles which has been identified as high strength material. Physical properties of graphite [16] are elastic modulus 15 *GPa*, yield strength 55 *MPa*, Thermal Expansion Coefficient is $8.2\text{x}10^{-6}$ °C. Out of many factors which influence the fracture properties, the particle size of graphite is most important microstructural variable. Al6061 and graphite particulate metal matrix composites produced by solidification techniques present greater tribological properties such as better machinability, low wear rate, high damping capacity, low coefficient of friction, and their outstanding antifriction properties used for a range of automobile applications [17]. Al6061 as a matrix and Graphite particles as reinforcement is utilized for the work. The reason to involve these materials is their density. The density of Al6061 is 2.65*g/cc* and of graphite is 2.26*g/cc*. The Al6061-graphite particulate composites exhibit isotropic properties [3] and also have outstanding combinations of physical, thermal, mechanical, structural properties.

3 PROCESSING

Stir casting method [17, 20] was utilized to prepare the Al6061-graphite particulate metal matrix composites at 9% weight fractions of graphite. The Al6061 blocks were allowed to melt in the stir casting furnace at a temperature about 720^0C. A degasifier has been added to the molten aluminum to remove the gases. The requisite quantity of graphite particles was added to the molten Al6061 while stirring with a stirrer at speed of 500*rpm*. In the split type graphite mold, molten Al6061-graphite was poured and it was allowed to solidify. From the bars are taken out from molds were utilized for determining required properties of Al6061-graphite alloy bars.

From the EDX analysis (Fig. 2(a)), it is found that Al6061-graphite MMCs are rich in both Si and Mg. The existence of $MgAl_2O_4$ at interfaces was confirmed in a detailed study on the interfaces in discontinuously reinforced metal-matrix composites. In all the compositions of Al6061-graphite, oxygen (O) content has been obtained. The content of O is due to the formation of Al_2O_3 on the top of the pits as the main compound on the surface.

Out of many factors which influence the fracture properties is the particle size of reinforcement. The particle size of reinforcement is most important microstructural variable. Fig. 2(b) indicates the average particle size of graphite in an Al6061 matrix. The average graphite particle size is 50 *μm*. Fine particle reinforced composites may have higher values of fracture toughness, fatigue crack growth rate, a lower rate of crack propagation etc than that of coarse particle reinforced composites.



(a) (b)

Fig.2
a) EDX profile analysis for 9% graphite and b) Particle size of 9% graphite.

4 OPTIMIZATION OF PARAMETERS

Doddamani et. al. [20] conducted fracture toughness of the Al6061-graphite particulate MMCs as per ASTM E399 standard testing procedures. Experimentation was conducted for different compositions i.e. 3, 6, 9 and 12% by weight fractions of reinforcement and for three different *a/W* ratio = 0.45, 0.47 and 0.50.

The objective of the present work is the find the effect of thickness of specimen on the fracture toughness of material. Technically, it is time consuming and a tedious work, to conduct fracture toughness test on all the composition and all the *a/W* ratios. Instead of conducting the fracture toughness experimentation for all the compositions and for all the *a/W* ratios, it is possible to analyze the K_{Ic} for a better composition and *a/W* ratio which affect the fracture behavior of the material. To optimize the better composition and *a/W* ratio statistical tools were used, among which design of experiments using Taguchi method is the widely used tool.

In the present work, optimizing the parameters of the compact tension (CT) specimens is carried out using Taguchi method. Four parameters and two factors are considered to optimize the parameters. Factors considered are material composition and *a/W* ratio. Levels considered are *a/W* = 0.45, 0.47 and 0.50, and material compositions considered are 3%, 6%, 9% and 12% of graphite reinforcement in the Al6061 matrix. The experimental data i.e load carrying capacity and fracture toughness are input functions for the Taguchi design. For the given input functions, Taguchi design has been analyzed. The results of the analysis are shown in Fig 3.

From the outcomes of the Taguchi design, it is observed that load carrying capacity of the composite decreases as *a/W* ratio increases. As composition increases load carrying capacity increases up to 9%of graphite and decreases for 12%graphite. From Fig. 3 (b) it is observed that fracture toughness of the composite decreases as *a/W* ratio increases. It is obvious that as the load carrying capacity decreases fracture toughness decreases. As composition increases fracture toughness increases up to 9%of graphite and decreases for 12%graphite.

The optimize composition is at 9%graphite based on load and fracture toughness of the Al6061-graphite composite. Also load carrying capacity is maximum for *a/W* = 0.45 and as there is not much difference in fracture toughness values for *a/W* ratio = 0.45 and 0.47. From the results of the CT specimens fracture toughness values increased as the increment in the graphite content by up to 9% of graphite [20]. From the Taguchi analysis, on CT specimens, Al6061-9%graphite is the optimized composition and fracture toughness is maximum for *a/W* ratio =

0.45. Hence Al6061-9% graphite will be considered as optimized composition. In further work, 9% of graphite particles will be considered to study the thickness effect on fracture toughness.

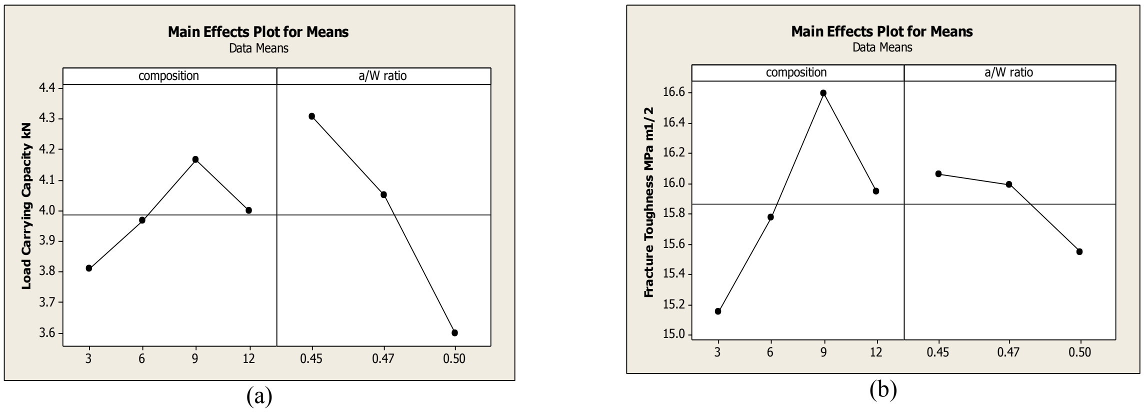


Fig.3
a) Load carrying capacity *vs* Composition and *a/W* ratio. b) Fracture Toughness K_{Ic} *vs* Composition and *a/W* ratio.

Analysis of variance in short called ANOVA is a statistical tool used to evaluate the level of the individual involvement of the process parameter on the responses such as fracture toughness and load carrying capacity, and furthermore give precisely the arrangement of the process parameters. Individual optimal values for the process parameters and their predefined performance attributes can be found. Table 1., shows the results of ANOVA for Load carrying capacity, and Fracture toughness.

Table 1
ANOVA for Load carrying capacity.

Source	DF	Seq SS	Adj MS	F-Value	P-Value	confidence level %
Composition	3	0.26687	0.08896	18.61	0.161	15.22
a/W ratio	2	1.43927	0.71963	150.23	0.134	82.06
Error	2	0.04781	0.00478			02.72
Total	7	1.75394				100

ANOVA for Fracture Toughness.

Source	DF	Seq SS	Adj MS	F-Value	P-Value	confidence level %
Composition	3	5.0904	1.6968	22.23	0.136	76.12
a/W ratio	2	0.8337	0.4168	5.46	0.257	12.47
Error	2	0.7635	0.0763			11.41
Total	7	6.6875				100

DF=Degrees of freedom, SS=sum of squares, MS=Mean Square, F=Variance & P= test statics.

From the ANOVA outcomes it is observed that, the factors affecting the load carrying capacity are the composition (15.22%) and *a/W* ratio (82.06%). The ANOVA analysis demonstrates that load carrying capacity of the material mainly influenced by *a/W* ratio then the composition of the material. It is obvious that as crack length (*a*) increases load carrying capacity decreases. Also, the factors affecting the fracture toughness are the composition (76.12%) and *a/W* ratio (12.47%). The ANOVA analysis demonstrates that fracture toughness of the material mainly influenced by composition of the material and also by the *a/W* ratio. It is obvious that as crack length (*a*) increases load carrying capacity decreases in turn reduces the fracture toughness.

5 EXPERIMENTATION

Fracture behavior of Al6061 alloy matrix, reinforced with graphite particles by 9*wt*% is studied experimentally. As per ASTM E399 specifications, the CT specimens are prepared to estimate the fracture toughness of said composite. The compact tension specimens are prepared for a crack to width (*a/W*) ratio of 0.45 and thickness to the width *B/W* ratio of 0.1 to 0.5. Different thickness (B) of the specimen considered as 4, 5, 7, 10, 12, 15, 18, 20 *mm* as shown in Fig. 4. From the Al6061-graphite block prepared using stir casting methods are machined to the required width and thickness to fulfill the plain strain condition. As per the ASTM standard, the notch is prepared by using wire-cut EDM at an accuracy of 0.2 *mm*. Notch size is 4 *mm* × 17*mm* for all the specimens.

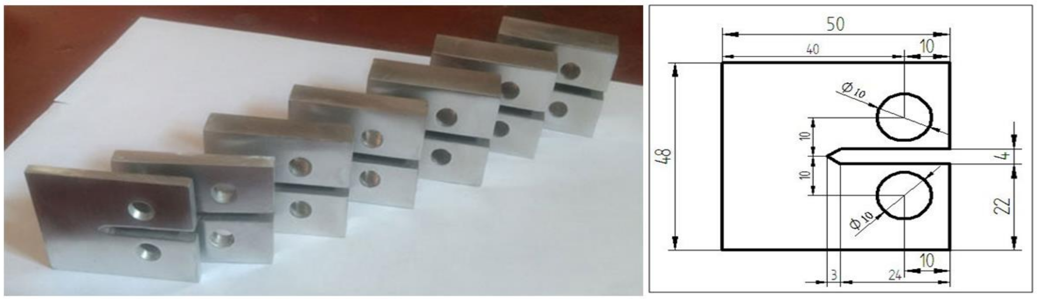


Fig.4
CT specimens with different thicknesses and geometry.

The fatigue pre-cracking of the compact tension specimens is done. For the same, servo-hydraulic testing machine is utilized with tensile cyclic loading. CT specimens are successfully pre-cracked in this manner with the cyclic loading of 0.3 times the yield load of the material by maintaining the frequency of 5 *Hz*. When crack self-arrest occurred the loads were changed to complete the pre-cracking process. A pre-crack of 0.5 *mm* was eventually measured after 40,000 cycles. Different load ranges were used depending on the specimen thickness. Once the crack initiates and propagates by 2.0 *mm* the fatigue loading would stop by the machine control. Diverse load ranges were utilized relying upon the specimen thickness.

All the CT specimens of 4, 5, 7, 10, 12, 15, 18, 20 *mm* thickness (B) are tested to find the fracture toughness. Fracture toughness and fracture characteristics of the aluminum-graphite particulate metal matrix composite will be determined using a universal testing machine (UTM) as per ASTM standard testing procedure. The fracture toughness tests were conducted by maintaining the displacement rate 1mm/min. For each test, the P_Q value and crack opening displacement is measured and provisional fracture toughness K_q is determined using the empirical Eq.(1).

$$K = \frac{P_Q}{B\sqrt{W}} f\left(\frac{a}{W}\right) \tag{1}$$

where, $$f\left(\frac{a}{W}\right) = \frac{\left(2+\frac{a}{W}\right)}{\left(1-\frac{a}{W}\right)^{3/2}}\left(0.886+4.64\left(\frac{a}{W}\right)-13.32\left(\frac{a}{W}\right)^2+14.72\left(\frac{a}{W}\right)^3-5.6\left(\frac{a}{W}\right)^4\right)$$

Fracture load and the calculated value of fracture toughness of the Al6061-9%graphite MMCs for different specimen thickness has been listed in Table 2.

Table 2
K_{Ic} of Al6061-9%graphite for different specimen thickness.

B/W ratio	Thickness (B)mm	Width (W)mm	Fracture Load (P_Q) K_N	$f(a/w)$	K_{Ic} $MPa\sqrt{m}$
0.10	04	40	2.13	8.34	22.21
0.13	05	40	2.65	8.34	22.10
0.18	07	40	3.34	8.34	19.90
0.25	10	40	4.26	8.34	17.76
0.30	12	40	4.74	8.34	16.47
0.38	15	40	5.92	8.34	16.46
0.45	18	40	7.11	8.34	16.47
0.50	20	40	7.88	8.34	16.43

6 RESULTS AND DISCUSSIONS

All the compact tension (CT) specimens of different thickness are tested to find the fracture toughness. Fracture toughness and fracture characteristics of the aluminum-graphite particulate metal matrix composite will be determined using a universal testing machine (UTM) as per ASTM standard testing procedure. Results of the experiment were plotted in Fig. 5. The increase in the crack length from 18 *mm* to 20.3 *mm* is measured during fatigue pre-cracking of tested specimens concerning the number of cycles for a load range (R) of 0.1. Fig. 5 displays the plot of a number of cycles and crack length for CT specimens for different B/W ratios for Al6061-graphite with 9 *wt*% graphite particles. The nature of variation of crack length and a number of cycles is similar to the earlier works [4, 5, 8, 11]. It is evidently observed from Fig. 5 that as the thickness of the specimen increases the number of cycles (N) decreases for the given weight percentage of graphite in the composites. This is due to the increased flaws in the specimens of higher B/W ratios. Also, higher B/W ratios lead to the brittleness of the specimens.

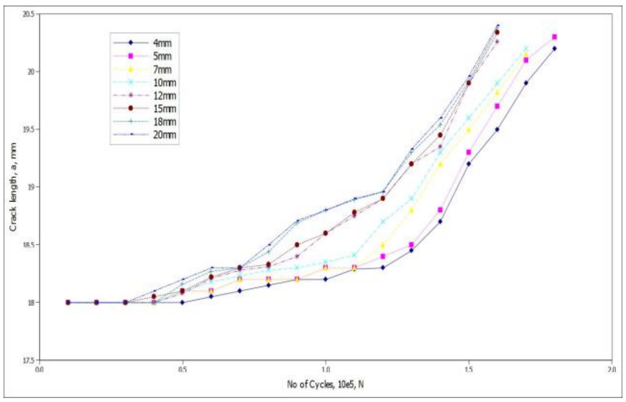


Fig.5
Crack length *vs*. Number of cycles for different B/W ratios.

The variations of load versus crack opening displacement for Al6061-9%grahite composites for various thicknesses (B) are shown in the Fig.6. It is found that the maximum load increases with increase in thickness of the specimen. The specimens with thickness (B) less than 10 *mm* (i.e B/W<0.25) experience plane stress fracture because of high plasticity and less stress triaxiality contrasted to the specimens with thickness more than 10 *mm* (i.e $B/W \geq 0.25$). The nature of the variation of the plot shows the brittle fracture for the higher B/W ratios [3].

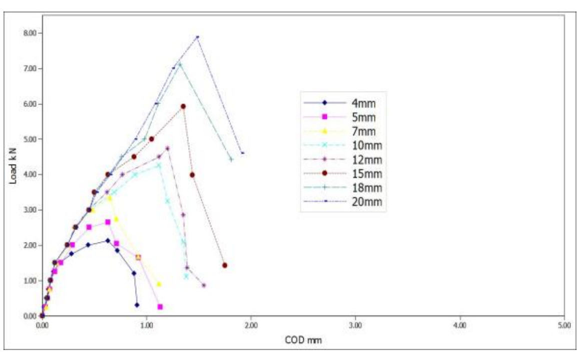


Fig.6
Load-crack opening displacement (COD) curves for various B/W ratios.

In the case of the slope of the load-displacement record of Al6061-graphite, the curve obtained was Type III curve [20] as shown in Fig. 6. The maximum value of the load itself will be the critical load (P_q). This corresponds to about 2% ductile crack expansion; this may be an effective crack expansion linked to plastic zone development. K_{Ic} values were determined from the P_q values as prescribed in ASTM E399 Standard [19].

The fracture toughness (K_{Ic}) of the Al6061-9%graphite is measured according to ASTM-E399 standard using the Eq. (1) [2, 19] and results of the calculations were listed in Table 2. Fracture toughness data were plotted in a graph (Fig.7) for various thicknesses (B) of compact tension (CT) specimen of Al6061-9%graphite MMCs. Specimens having standard extents yet various sizes create distinctive values for K_I. This outcome on the grounds that the stress states around the flaw vary with the thickness of the specimen (B) until the point that the thickness surpasses some critical dimension. Once the thickness surpasses the critical dimension, the value of K_I turns out to be moderately steady (shown in Fig. 7) and that value is a true material property which is known as the plane-strain fracture toughness (K_{Ic}). The experimentally computed K_q is drawn with respect to the different thickness (*B/W* ratios) for Al6061-9%graphite composites. Fig. 7 demonstrates the variation of K_q versus *B/W* ratios for different Al6061-graphite composites. It is seen that the K_q reduces with increment in *B/W* proportions and found to stay consistent for $B/W \geq 0.3$. This consistent estimation of K_q for $B/W \geq 0.3$ prevail the plane strain fracture toughness (K_{Ic}) of the composite.

The stress state at the crack tip is addressed as stress intensity (K_I) whereas the highest estimation of K_I that a material can withstand without fracture below certain conditions represents the fracture toughness (K_{Ic}). As the crack advances to some critical level under loading, stress intensity (K_I) factor reaches the K_{Ic} value, unstable fracture occurs. All the CT specimens of different thickness are tested to find the critical fracture toughness K_{Ic} for Al6061-9%graphite MMCs. The calculated value of fracture toughness of the Al-graphite MMCs for different specimen thickness has been listed in Table 1. The maximum value is 16.47 $MPa\sqrt{m}$ found at a thickness (B) = 12 *mm*.

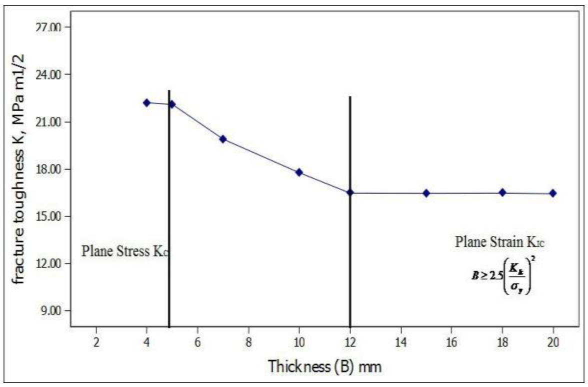


Fig.7
Effect of specimen thickness on fracture toughness.

7 CONCLUSIONS

To optimize composition of composite, Taguchi design of experiments is used. Load carrying capacity is maximum for *a/W* = 0.45. From the Taguchi analysis, on CT specimens, Al6061-9%graphite is the optimized composition and fracture toughness is maximum for *a/W* ratio = 0.45. The ANOVA analysis demonstrates that load carrying capacity of the material mainly influenced by *a/W* ratio then the composition of the material and fracture toughness of the material mainly influenced by composition of the material and also by the *a/W* ratio. All the CT specimens of different thickness (B = 4, 5, 7, 10, 12, 15, 18 and 20 *mm*) of *a/W*=0.45 were tested to find the fracture toughness for Al6061-9%graphite. From the results, it is observed that the K_q reduces with increment in *B/W* proportions and found to stay consistent for $B/W \geq 0.3$ (i.e. B is greater than 12 *mm*). This consistent estimation of K_q for $B/W \geq 0.3$ prevails the plane strain fracture toughness (K_{Ic}) of the composite.

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