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Elastic plastic fracture toughness of aluminium alloy AA6061 fly ash composites

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ABSTRACT

Aluminium fly ash metal matrix composites (MMCs) find important applications in aerospace and automobiles where specific stiffness is important. Low cost fly ash and silicon carbide reinforcement are widely used in aluminium metal and matrix composite due to its low density, high young modulus and strength apart from good mechanical and chemical compatibility & thermal stability. However the MMCs often suffer from low ductility, toughness and fatigue crack growth resistance relative to the matrix alloy. Linear elastic fracture mechanics (LEFM) has been used to characterize the plane strain fracture toughness using various specimen geometries and notches but very few studies using EPFM are reported in literature. In the present paper the influences of weight fraction of particulate reinforcement on tensile, fracture toughness have been evaluated. The tensile strength of aluminium fly ash composites increases with the addition of fly ash reinforcement. However the fracture toughness (K_{IC}) of the aluminium fly ash composite decreases that of base alloy. The fracture toughness K_Q of AA6061 ALFA composites varied between 13-14 MPa$\sqrt{m}$ as compared to 18 MPa$\sqrt{m}$ for the re-melted base alloy. Similarly the Elastic plastic fracture toughness J_Q for the base alloy AA6061 lies is the range of 20-23 kJ/m^2 and that of composites in the range 6-16 kJ/m^2. The fracture behavior and micro-mechanism of failure in base alloy and composites have been observed under SEM and optical microscopy. Copyright © 2014 VBRI press.

Keywords: Fracture toughness; aluminium fly ash composites; MMCs; damage mechanics.

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Introduction

Aluminium fly ash metal matrix composites (MMC) are low cost materials made by dispersion of fly ash particulate reinforcement in the aluminum matrix in order to improve the mechanical and physical properties of MMCs. Aluminium-fly ash composites due to their low density and high mechanical properties find many applications in automobile parts such as internal combustion engine, pistons and brake rotors. The strengthening of aluminium metal matrix composites with a dispersion of fine ceramic particulates has increased its wear resistance and frictional coefficient than base alloy. However the application of

MMCs is impeded in critical applications due to low ductility, toughness and fatigue crack growth resistance relative to the matrix alloy **[1-3]**. The fracture toughness of metal matrix composites depends on complex interaction between the matrix and reinforcement and its processing routes. The important properties which influence the fracture toughness of MMCs are type of reinforcement, size, shape, volume fraction, distribution in the matrix and the toughness of matrix **[4-6]**. The poor fracture toughness and fatigue crack growth rate of MMCs is due to low initiation energy for fracture due to high modulus and lower failure strain **[7]**. Linear elastic fracture mechanics (LEFM) has been used to characterize the plane strain fracture toughness using various specimen geometries and notches but very few studies using EPFM are reported in literature. In this paper, the fracture toughness of aluminum fly ash metal matrix composites AA6061 were evaluated by using EPFM principle. The aim of the present paper is to study the mechanical properties, fracture toughness properties (J_{IC} and K_{IC}) and micro-mechanisms of fracture.

Fig. 1. Experimental set for processing of AA6061/fly ash composites.

Experimental

Material

Aluminum alloy AA 6061 is used as base matrix with composition (weight percent) listed in **Table. 1**.

Table 1. Chemical composition of matrix alloy AA6061.

Grade	% Elements							
AA6061	Al	Cu	Mn	Mg	Zn	Fe	Cr	Si
	Base	**0.23**	**0.21**	**0.86**	**0.057**	**0.33**	**0.094**	**0.63**

The reinforcement used are silicon carbide and fly ash having particles of sizes 25-45 in 5% and 10% by weight and the chemical composition of fly ash reinforcement is as per **Table 2**.

Table 2. Chemical composition of fly ash reinforcement.

Grade	% Elements							
Fly ash	Al_2O_{3+}	SiO_{2+}	Fe_2O_3	CaO	MgO	Na_2O	K_2O	SO_3
	92.49			**-**	**2.13**	**0.73**	**-**	**1.06**

Processing of aluminum fly ash composites

Fig. 1 and **2** shows the experimental setup for fabrication of aluminum metal matrix composite through liquid metallurgy route. About 1 kilograms of the AA 6061 alloy was cleaned and loaded in the silicon carbide crucible and heated to above its liquidus temperature. The temperature was recorded using chromel-alumel thermocouple. To maintain the solid fraction of about 0.4, the temperature of the melt was lowered before stirring. The specially designed mechanical graphite stirrer is introduced into the melt and stirred at ~ 400 rpm.

Fig. 2. Experimental set up for fabrication of aluminum metal matrix composite.

The depth to which the impeller was immersed is approx 1/3rd the heights of the molten melt from the bottom of the crucible. The preheated (800^{0}C) fly ash particulates (25-45μm) were and 900 ^{0}C for silicon carbide (1500 grit) added through a preheated pipe by manual tapping into the slurry, while it was being stirred. **Table 3** gives the stir casting process details. A post-addition stirring time of 30 min was allowed to enhance the wetting of particulates by the metal. The temperature of the slurry was sufficiently raised above the melting range of the matrix alloy before pouring the composite melt into preheated permanent mould.

Table 3. Stir casting process details for fabrication of aluminum fly ash composites.

Material	Initial Diameter (mm)	Final Diameter (mm)	% Reduction
AA6061 base alloy	49.5	17.74	64.16
AA6061 -5%FA	49.5	17.74	64.16
AA6061 -10%FA	49.5	17.74	64.16

Secondary processing

The as-cast composite billets were extruded/hot rolled at 450ºC (Soaking for 4 hrs) in order to get rid of the porosities induced during primary processing. It also improves the distribution of the reinforcement in the aluminium matrix. Secondary processing improves distribution of fly ash reinforcement in the matrix, imparts directional properties, whereby mechanical properties are improved. The hot extrusion/rolling details of Metal Matrix Composite are shown in **Table 4**.

Table 4. Extrusion ratio used for secondary processing of AA6061/fly ash composites.

Composite System	Reinforcement Size (μm)	Preheat Temp. of reinforcement	Total Stirring time	Pouring Temp. (^{0}C)
AA6061 5%FA	25-45	800^{0}C	30min	750
AA606110% FA	25-45	800^{0}C	30min	800

Specimen preparation

The tensile specimens were fabricated from the extruded rods of the base metal and composite extrusions as shown in **Fig. 3** as per ASTM E8 were used for tensile testing. The SENB specimens for K_{IC} and J_{IC} tests are prepared in LT direction with notch and intended direction perpendicular to the extrusion direction as per ASTM E-1820 and ASTM E-647 standards as shown in **Fig. 4** and **Fig. 5**.

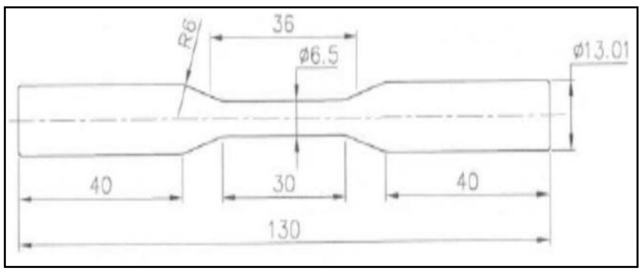

Fig. 3. Tensile test specimen as per ASTM E-8.

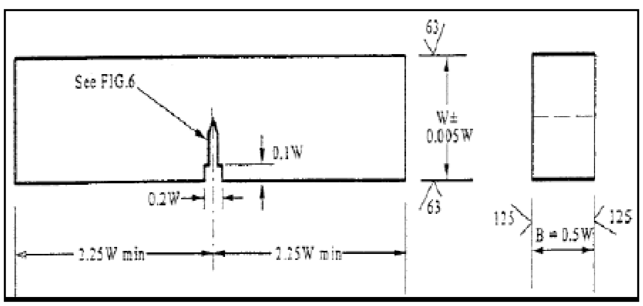

Fig. 4. Fracture toughness test specimens SENB.

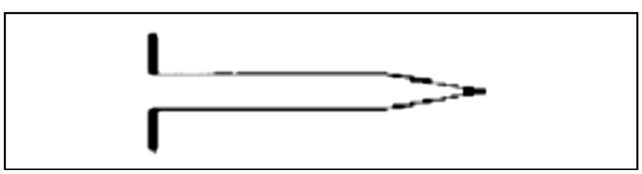

Fig. 5. Fatigue crack starter notch configuration.

Three Point bend Test specimen with a 4.5 mm thickness were machined from round bars of 12.5 mm in diameter **Fig. 4** shows the specimen dimensions. Fatigue precracks were grown by keeping the BISS servo hydraulic machine under displacement control, with frequencies between 10 to 15 Hz by maintaining a/w ratio between 0.55-0.70. Straight notches were used in the specimen in order to enhance the initiation of the fatigue crack. The tests were made in the BISS machine as shown in **Fig. 6** using displacement control with a load point displacement rate of 0.1 mm/min Load vs. mouth opening displacement (P vs. V) plots were obtained. The values of J_{IC} and J-R were obtained following the ASTM E-1820 standards. From the obtained J_{IC}, the equivalent K_{IC}, were calculated by Eqn 1.

Results and discussion

Tensile properties

The mechanical properties such as ultimate tensile strength, 0.2% yield strength and percentage elongation have been evaluated for AA 6061 base alloy and fly ash composites and are listed in **Table 5** and shown in **Fig. 7**.

Table 5. Tensile test results of AA6061 base alloy and AA6061/fly ash composites.

Condition (Rolled)	0.2% Y.S (MPa)	UTS (MPa)	% Elongation
AA6061 + 0% wt. fly ash	122	184	10
AA 6061 + 5% wt.fly ash	136	222	3.45
AA 6061 + 10% wt. fly ash	184	249	3.20

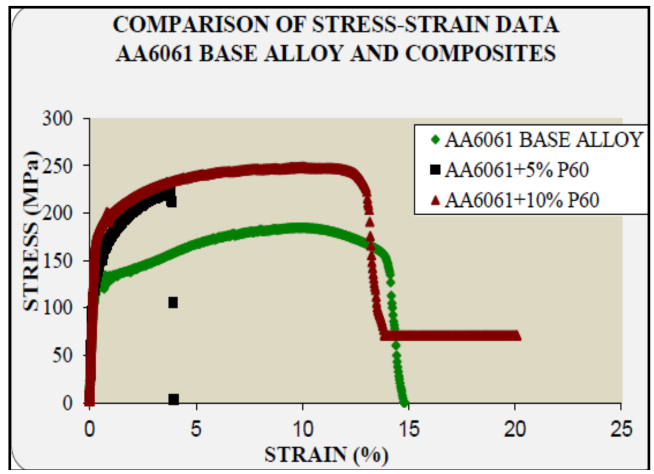

Fig. 7. True Stress True Strain plot of AA6061 base alloy and composites

Table 6. Hardness of AA6061 base alloy and fly ash composites.

Grade	Hardness (VPN)
AA6061 base alloy	48
AA 6061 + 5% Fly ash	52
AA 6061 + 10% Fly ash	61
AA6061 + 20% Fly ash	70

Hardness of AA6061 fly ash composites

The hardness have been evaluated for AA6061/fly ash composites with Leco Vickers Micro hardness tester and the hardness values of the base alloy and composites are listed in **Table. 6**. The hardness of the aluminum fly ash composites increase with the fly ash reinforcement. The increase in the micro hardness is due to strain fields created around fly ash particles because of the difference in the thermal expansion coefficients of aluminum base alloy and fly ash particles. The strain field's piles up dislocations and the interaction between dislocations and fly ash particles offer resistance to the propagation of cracks. The grain refinement provided by the fly ash particles during solidification is also responsible for increase in the micro hardness.

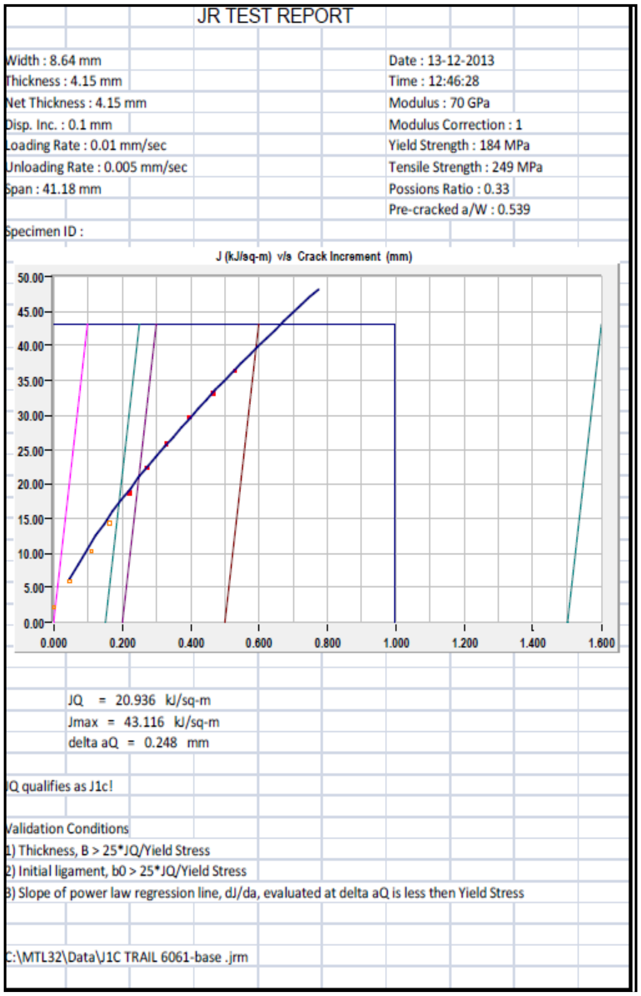

Fig. 8. J- Δa curve of base alloy 6061 + 0%FA.

Tensile test results as listed in **Table. 9** and **Fig. 7** of aluminum fly ash composites at room temperature indicates that with the increase in the fly ash reinforcement from 0% to 10% , the yield strength increases from 122 MPa to 184 MPa and the tensile strength increases from 184 MPa to 249 MPa . This increase in the yield strength and tensile strength of aluminum fly ash composites attributed due to the presence of high dislocation densities at the particle/matrix interface and due to the difference in coefficient of thermal expansion between aluminium alloy matrix and fly ash particles.

Elastic plastic fracture toughness testing

Elastic plastic fracture toughness J_{IC} tests and fatigue crack growth rate (FCGR) were conducted on BiSS 50 KN servo hydraulic Universal Testing Machine by using SENB as per ASTM E-1820 **[8]** and as shown in **Fig. 5**. The conditional fracture toughness was calculated using following Eqn.1 and the values of fracture toughness of base alloy and composites are listed in **Table 7** and **8**.

$$K_Q = \frac{P_Q}{B.W^{\frac{1}{2}}} x L x f\left(\frac{a}{w}\right) \quad (1)$$

K_Q = Conditional Fracture Toughness
P_Q = Load value obtained by 95% secant line.
L = Span length
A = Crack length
W = Width of the specimen

Table 7. Fracture toughness K_{IC} of AA6061/fly ash composites.

Composite grade	a/W (intial)	a/W (final)	f (a/W)	Pmax	K (Mpam$^{1/2}$)
AA6061 Base	0.40	0.55	3.07	515	18.21
AA6061-5%FA	0.40	0.60	3.81	390	13.77
AA6061 -10%FA	0.40	0.55	3.20	366	14.27

Table 8. Elastic plastic fracture toughness J_{IC} of .AA6061 fly ash composites.

Grade	a/w (intial)	a/w After Pre cracking	P (KN)	Kmax	Jmax	JQ
AA6061 base alloy	0.40	0.53	0.483	18.78	43.11	20.9
AA6061-5%FA	0.40	0.60	0.330	15.28	38.52	16.5
AA6061-10%FA	0.40	0.57	0.369	21.20	23.50	10.9

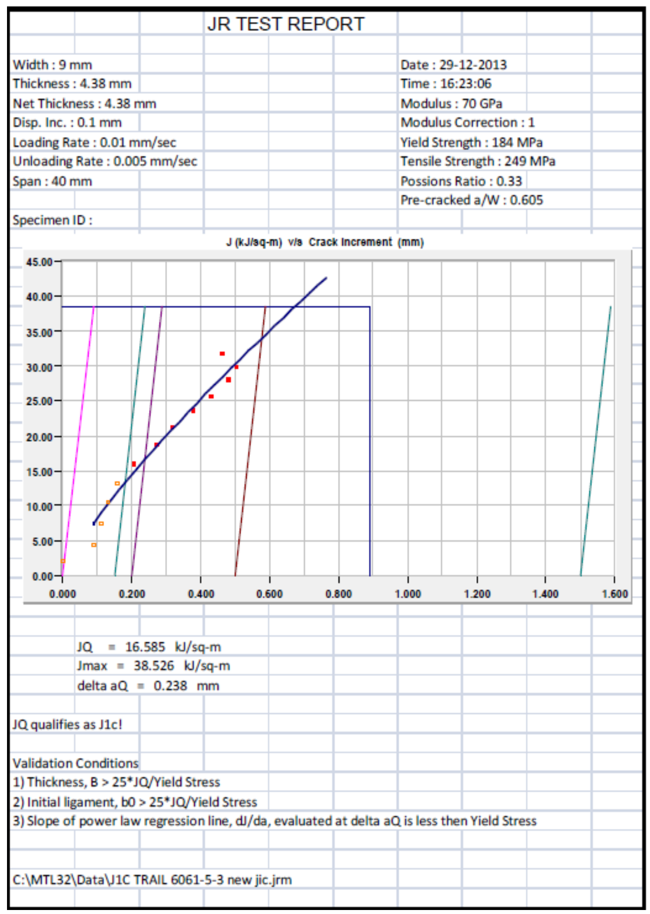

Fig. 9. J- Δa curve of base alloy AA6061-5%FA.

The fracture toughness of AA6061 fly ash composites varied between 13-14 MPa√m as compared to 18 MPa√m for the re melted base alloy AA6061 as listed in **Table 7**, which is consistent with the reported data. The Elastic plastic fracture toughness J_Q for the base alloy AA6061 is 20.93 kJ/m^2 and for AA6061-5% FA is 16.52 kJ/m^2 and AA6061-10% FA 10.90 kJ/m^2.

It may be noted from the **Fig. 8** to **Fig. 11** J V/s Δa curve and load V/s COD for AA6061 composites and the base alloy. The load and COD plot shows a typical observation i.e. hysteresis loop in loading and unloading compliance curve. This is indicative of crack closure. The reason for crack closure may be surface roughness resulting from fly ash particles in the composites.

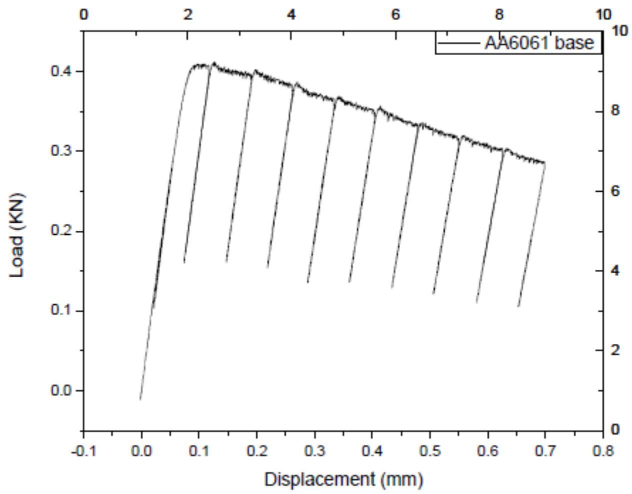

Fig.10. Load vs COD plot for AA6061 base alloy.

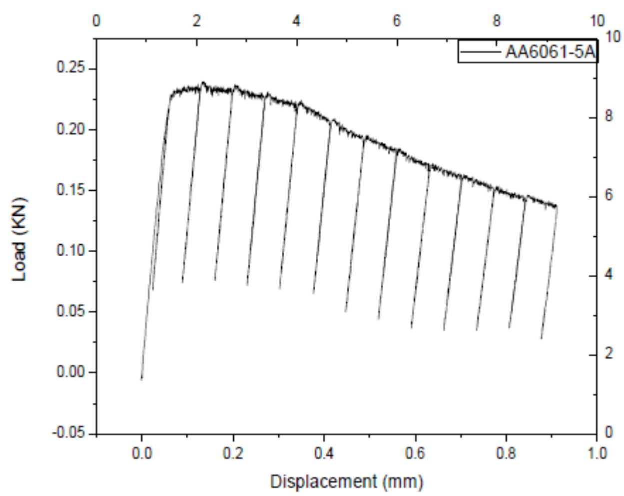

Fig. 11. Load vs COD plot for AA6061 base alloy.

This decrease in the fracture toughness of the composites is due to weak interface between the fly ash reinforcement and aluminum alloy matrix which acts as small micro cracks as shown in SEM micrograph **Fig. 12**. Also during stir casting lot of casting defects such as void, porosity generates during stirring of fly ash reinforcement. Ashby tried to design composites based on fracture toughness J_{IC} and K_{IC} as a design property for Aluminium alloys are linked to SiC particulate. The J_{IC} values obtained for studied composites lie near the lower limit i.e. close to the values reported by Ashby et.al **[9]** and Prasad et.al **[10]**.

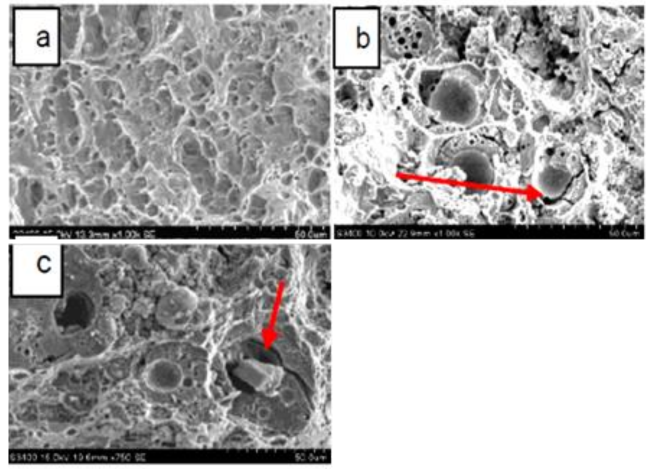

Fig. 12. Fracure surface of (a) AA6061 base alloy, (b) AA6061-5%FA and (c) AA6061-10%FA.

Conclusion

1. Uniform distribution of fly ash and silicon carbide particles in the aluminium matrix was obtained by liquid metallurgy route of stir casting followed by hot extrusion.

2. The yield strength, tensile strength of AA6061 fly ash metal matrix composites increases with the increase in reinforcement, however % elongation decreases with the increase in reinforcement.

3. The fracture toughness of AA6061 fly ash composite the fracture toughness of the composite is 13-14 MPa$\sqrt{m}$ as compared to 18 MPa$\sqrt{m}$ for unreinforced and re melted base alloy.

4. The Elastic plastic fracture toughness J_Q for the base alloy AA6061 is 20.93 KJ/m^2 and for AA6061-5%FA is 16.52 KJ/m^2 and AA6061-10%FA 10.90 KJ/m^2

5. The load and COD plot of the composite shows a hysteresis loop in loading and unloading compliance curve. This is indicative of crack closure. The reason for crack closure may be surface roughness resulting from silicon carbide particles in the composites.

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