Effect of Carbon Nanotubes Addition on Fracture Toughness in Aluminium Silicon Carbide Composite

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Abstract— In this paper, an approach to find the effect of carbon nanotubes addition on fracture toughness in aluminium silicon carbide composite is been analyzed. Although properties like specific strength, specific stiffness, elevated temperature strength, wear and corrosion resistance increases has proven, property of fracture toughness is decreasing. In this paper aluminium silicon carbide in the proven composition 25% Silicon Carbide and 75% Aluminium has casted by using stir casting process as per standard dimensions (ASTM E399). With the same dimension aluminium silicon carbide composite with added carbon nanotubes were also casted in the ratio 0.2% multi walled Carbon Nanotube, 24.8% Silicon Carbide and 75% Aluminium. All the test pieces were tested by using universal testing machine and stress intensity factor K_{IC} was found out. Results showed that there is increase in fracture toughness of aluminium silicon carbide with added carbon nanotubes by 16% than the 25% Silicon Carbide and 75% Aluminium combination of composite

Keywords— composite; metal matrix composite; aluminium silicon carbide; carbon nanotube; stir casting; fracture toughness; stress intensity factor.

INTRODUCTION

Composite materials are important engineering materials due to their outstanding mechanical properties. Composites are materials in which the wanted properties of separate materials which are combined by mechanically or metallurgically binding them together. Each and every component retains its structure and characteristic, but the composite generally exhibits better properties than the component properties separately. Composite materials offer superior properties to conventional alloys for various applications as they have high stiffness, strength and wear resistance. Composite materials came from the continuous trying to improve various properties of engineering materials; they are composed of a combination of distinctly different two or more micro or macro constituents that differ in the form of composition and it is insoluble in each other. There are mainly two constituent in composites. One constituent is called the reinforcing phase and the one in which it is embedded is called the matrix. Matrix will larger in quantity as reinforcement is embedded into it. The reinforcing phase material may be in the form of fibers, particles, or flakes. In this work Aluminium is chosen as matrix and silicon carbide is chosen as reinforcement.

From the previous studies in the composite of aluminium silicon carbide, it is clear that adding silicon carbide in the aluminium matrix as reinforcement will increase the mechanical properties of the composite than pure aluminium. It increases properties such as hardness, strength, damping capacity, impact strength etc. However it has been studied by Lihe Quian et al, that adding of reinforcement particles can drastically degrade the ductility and fracture toughness of the composite materials. Fracture toughness is a property which describes the ability of a material containing a crack to resist fracture, and it is one of the most important properties of any material for virtually in all design applications or we can say that Fracture toughness is a quantitative way of expressing a material's resistance to brittle fracture when a crack is present in it. If a material has a large value of fracture toughness it will probably undergo ductile fracture. Materials with lower fracture toughness value will undergo brittle fracture. Technically, fracture toughness is an indication of the amount of stress required to propagate a pre existing flaw. As the fracture mechanics with a solid saying that there are no perfect materials without cracks, makes the topic more relevant. As composite materials are used in more crucial parts the need for fracture toughness is very essential property. Based on the problem of fracture toughness studies were made. However the high cost and difficulty of processing these composite is studied as a problem of making composite materials. Among the various methods, stir casting route is simple, less expensive, with no damage to the reinforcement particles and used for mass production.

Aluminium LM6 metal chosen as matrix and silicon carbide with grain size 20µm was chose as reinforcement. Reinforcement particle size 20µm was selected with reference to the best combination of aluminium silicon carbide metal matrix composites. Another factor for decreasing fracture toughness is the volume and size. Carbon nanotube is an allotrope of carbon with cylindrical structure. They have unusual mechanical and electrical properties, so that they find many applications as additives in various structural materials. According to the American Society for Testing and Materials, ASTM E399 is used for testing fracture toughness, i.e. it is the standard test method for linear-elastic plane-strain fracture toughness (K_{IC}) of metallic materials. In a study made by Prathap Chandran et al, proved that Carbon Nanotubes (CNT) has positive effect on increasing fracture toughness. But it's not yet tested in Aluminium Silicon Carbide composite. In this paper, an attempt to study the effect of carbon nanotubes in enhancing the fracture toughness is being studied in an experimental way. The driving force behind the fabrication of nano composites is to achieve high functional properties for high end applications. As Aluminium silicon carbide metal matrix composites are used in various fields and crucial parts like in aerospace, aircrafts, underwater, automobile, substrate in electronics, golf clubs, turbine blades, brake pads etc, it is very important that it should have good fracture toughness. Thus it can be used in places where fracture toughness is needed along with the normal properties of metal matrix composites.

LITERATURE SURVEY

Conventional monolithic materials have limitations in achieving good combination of stiffness, strength, density and toughness. To overcome these problems and to meet the ever increasing demand of modern day technology, most promising materials of present interest are composites. Composites are used in many applications in present days as they can be manufactured by tailoring the different properties without making many compromises in the required properties. For example: Fuselage and wings of an aircraft must be lightweight, strong, stiff and tough. Natural rubber alone is relatively weak, by adding carbon black strength can be improved.

Amol D. Sable et al; found that with increase in composition of SiC, there is an increase in hardness and impact strengths exist and best results has been obtained at 25% weight fraction of SiC particles. Homogenous dispersion of SiC particles in the Al matrix shows an increasing trend in the samples prepared by applying manual stirring process and with 2-Step method of stir casting technique respectively [1]. Brian G Falzon, et al; found that the addition of CNT in carbon fiber composite improved the average fracture toughness by 161% [3]. S. Balasivanandha Prabu, et al; found that Uniform distribution is in processing temperatures 750°C and 800°C.Ultimate strength of metal matrix composite decreases with increasing in holding time. The best result is got in 20 min holding time. Viscosity of Al matrix decreases with increase in processing temperatures. In the tension test ultimate strength increased gradually up to 800°C and starts to decrease gradually due to the improper distribution of SiC in the Al matrix. Holding time influences the viscosity & particles distribution. The hardness values increases with increasing of processing temperatures from 750°C to 800°C at 20 minutes holding time [4]. J Stein et al; found that 2% CNT dispersion in high performance aluminium alloy (Al, Mg, N atomized) showed 5% increase in Young's modulus, Yield strength by 9% and tensile strength by 15% with respect to pure aluminium in the same conditions. These increases are stated to CNT/ matrix load transfer and it is also attributed to the generation of additional dislocations [5]. Khalid Mahmood Ghauri, et al; found that SiC/Al composite which produced by reinforcing the various proportions of SiC (5, 10, 15, 25 and 30%) in aluminium matrix using stir casting technique that as the volume fraction of SiC in the composite is gradually increased, the hardness and toughness increase. Beyond a level of 25-30 percent SiC, the results are showing decreasing tendency and is not very consistent, and depends largely on the uniformity of distribution of SiC in the aluminium matrix [6].

Lihe Quian et al; found that adding silicon carbide in the aluminium matrix as reinforcement will increase the mechanical properties of the composite than pure aluminium. It increases mechanical properties, however adding of reinforcement particles can drastically degrade the ductility and fracture toughness of the composite materials [7]. B.R. Sridhar et al: found that there is reasonable increase in hardness and decrease of ductility with increasing silicon carbide content. This can be attributed with increase in volume fraction of silicon carbide in the alloy with increasing silicon carbide.SiC particles strongly attach with aluminum particles at last stage and also 5% addition of SiC increases hardness 15% and 10% addition of SiC increases hardness by 17% than pure aluminium. With increasing silicon carbide content the material failure is found in brittle mode [8]. Prathap Chandran, et al; studied on the common believe fact that the dispersion of carbon nanotubes in a composite has a profound effect on the properties of the composite. Ball milling was carried out using two different parameters to obtain distinctly different degrees of dispersion of carbon nanotubes (4 wt.%) in Al-9 wt.% Si powders. Composite disks, 80 mm in diameter, having good and bad dispersions of carbon nanotubes were obtained by hot pressing. Optical micrographs and Raman spectroscopy images showed the presence of larger carbon nanotube clusters in the bad dispersion sample. Transmission electron microscopy images confirmed the presence of large clusters in the bad dispersion sample, while the good dispersion sample showed individual carbon nanotubes in the Al matrix. authours found that Dispersion of Carbon NanoTubes in Al Si alloy composite has profound effect on the mechanical properties (41% increase in hardness, 27% increase in elastic to plastic work ratio, 185% increase in compression yield strength, 109% increase in fracture strength)[10] .Rohit Kumar et al: found that SiC particle of 20 µ with four volume fractions of 0, 5, 10 and 15% were incorporated into the alloy at the liquid state Stir casting followed by extrusion. By using optical and electron microscope microstructure analysis was carried out. It was found that tensile strength and yield strength of composites decreases with increasing the volume fraction of SiC particles, while hardness increases with increasing the volume fraction of the SiC particles in composites [11]. Rabindra Behera et al: found that Increasing in SiC percentage addition hardness increases, hardness is found highest in middle section compared to end sections, the forgeability of the composites decreases with increase in the wt% of SiC but the mechanical properties like hardness increased on increasing the wt% of SiC [12]. Sourav Kayal et al: found that SiC particles of 20 µ in Aluminium alloy, 2.5 to 15 wt% in steps of 2.5 wt% increments showed that cooling rate decreases with increasing SiC %, with increase in SiC particles hardness was found to increase. It is found that cooling rate decreases with the introduction of SiC with increasing SiC content [13].T.Lyashen Ko, et al; Experimented with a treated carbon nanotube-reinforced epoxy leaf is inserted at the midplane of the laminates and the fracture properties are measured by end-notched-flexure and 3-point bend tests. It is found that 85% improvement in mode II fracture toughness with addition of a small amount of that SP1 protein treated carbon nanotubes at the midplane of the carbon fabric (epoxy laminate) [14]. T. Laha et al: found that Presence of nanosized grains in the Al–Si alloy matrix and carbon nanotubes provides excellent interfacial bonding between Al alloy matrix and CNT was observed. The elastic modulus and hardness is found to be higher. Two thermal spraying techniques were used one is plasma spray forming and the next is high velocity oxy fluid spray technique. The High Velocity Oxy Fluid sprayed composite experience dense and more compact microstructure. Both the spray deposits contain nano sized grains in the Al–Si alloy matrix [15]. A A Cerit et al: found that Hardness of the AlSiC can be increased by raising the volume fraction of SiC when the particle size is constant and Hardness decreases by increasing particle size Best result got for SiC of 20μ and 40% volume. S.Das, D Chatterjee found that Stir Casting of Aluminium composite usually inherit porosity and degree of porosity depends on the processing parameters such as pouring temperature, volume fraction of reinforcement and type of matrix choosing.

METHODOLOGY

A EXPERIMENTAL METHOD

As the aim of this study was to find the effect of carbon nanotubes in aluminium silicon carbide composite on improving fracture toughness of the composite, the preferred method is by testing experimentally.

The main step followed in the method was

- Casting of aluminium silicon carbide composite samples and testing of its fracture toughness.
- Casting of aluminium silicon carbide composite samples by adding carbon nanotubes and testing of its fracture toughness.
- Comparing both results

B SELECTION OF COMPONENTS

Usually there are several matrixes and reinforcements. From a number of matrices Aluminium was selected due to its easiness in availability. It is light weight, i.e. Aluminium weighs less by volume than most other metals. Actually, it is about one-third the weight of, steel, iron, brass or copper. Aluminium profiles can be made as strong as needed for most applications. In cold weather applications aluminium is particularly well served because, as temperatures falls, aluminium actually becomes stronger. We can say also that it is less expensive also. From a number of reinforcements Silicon Carbide was selected due to availability, Increases strength to weight ratio by 3 times more than mild steel, Improves wear resistance, Thermal stability etc. Carbon nanotubes which is having high strength to weigh ratio is proved in enhancing the mechanical properties and fracture toughness in a magnesium alloy composite but is not yet tested in aluminium metal matrix composite. Carbon nanotubes have main properties such as high tensile strength, it posses high thermal and electrical conductivity, it has low thermal expansion coefficient and high aspect ratio which make carbon nanotubes very useful in many sectors. In a belief that carbon nanotube will enhance the fracture toughness, it is also added in composite making. From several casting techniques such as squeeze casting, powder metallurgy etc. Stir Casting is decided to be used for casting process because stir casting the best cost effective method which produces high strength materials. It can be also called as fabricating method for high strength low cost materials. It can offer wide range of shapes and larger sizes up to 500 Kg. In this method there won’t be any damage to reinforcement.

EXPERIMENT AND TESTING

Stir casting involves incorporation of reinforcement particulate into liquid aluminium melt and allowing the mixture to solidify at normal conditions. Here, the crucial thing is to create good wetting between the particulate reinforcement and the liquid aluminium melt. The simplest and most commercially used technique is known as vortex technique or stir-casting technique.

A APPARATUS AND PROCEDURE FOR STIR CASTING

The apparatus used for stir casting method is shown below. It has the following parts

- Motor - For stirring of blade (Stirrer)
- Dimmer - Controls the speed of the motor
- Shaft - Connects stirrer and motor
- Graphite crucible - Molten Aluminium is kept in this
- Furnace - For the purpose of heating and Melting
- Thermo couple - For the temperature measurements

The aluminium scraps and silicon carbide powder is carried out in the graphite crucible in to the electric furnace. First the scraps of aluminium were preheated for 3 to 4 hours at 450°C and silicon carbide powder also heated with 900°C and both the preheated mixtures is then mechanically mixed with each other below their melting points. Then this metal-matrix AlSiC is poured into the graphite crucible and then it is put in to the electric furnace at 760°C temperature. After completing the experiment the slurry has been taken into the sand mould within thirty seconds allow it to solidify.

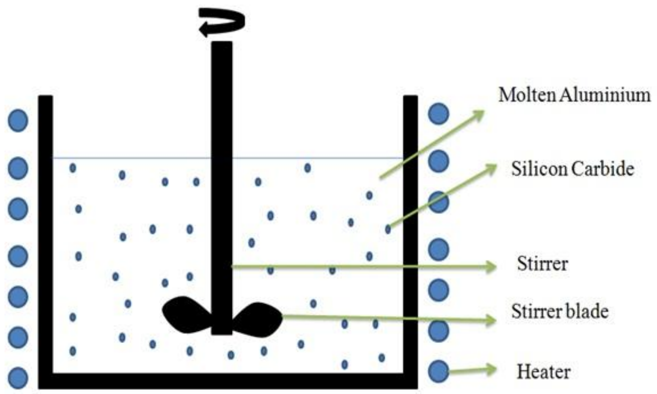

Figure 1 Apparatus for Stir Casting

B CASTING OF ALUMINIUM SILICON CARBIDE

Composites are being an investigative subject from the past and its still improving its level. In the present study as subject to find the effect of carbon nanotube in addition. Raw material aluminium collected by crushing the bike pistons which is made up of aluminium. Silicon carbide was given by Carborundum Universal, Naalukettu. Carbon nanotubes were given by Amrita University. Stir casting machine were made available from the Karunya University Coimbatore.

Stir casting process starts with placing empty crucible in the muffle. At first heater temperature is set to 500°C and then it is gradually increased up to 900°C. High temperature of the muffle helps to melt aluminium quickly, reduces oxidation level, enhance the wetability of the reinforcement particles in the matrix metal. Required quantity of aluminium alloy is taken cleaned to remove dust and poured into the crucible. Silicon carbide will be preheated to remove moisture and it will be added continuously into the molten aluminium as reinforcement. Reinforcements are heated for half hour and at temperature of 500°C. When matrix was in fully molten condition stirring is started. The speed of stirrer is gradually increased from 0 to 300 RPM with the help of speed controller. Silicon carbide is then allowed to fall into the molten aluminium in a uniform rate. Temperature of the heater is set to 630°C which is below the melting temperature of the matrix. A uniform semisolid stage of the molten matrix was achieved by stirring it at 630°C.Pouring of preheated reinforcements at the semisolid stage of the matrix enhance the wetability of the reinforcement and it reduces the particle settling at the bottom of the crucible. Dispersion time was taken as 5 minutes. After stirring 5 minutes at semisolid stage slurry was reheated and hold at a temperature 900°C to make sure slurry was fully liquid. Stirrer RPM was then gradually lowered to the zero. The stir casting apparatus is manually kept side and then molten composite slurry is poured in the

Figure 2 Casting of Metal matrix composite casting

metallic mould. Mould is preheated at temperature 500°C before pouring of the molten slurry in the mould. This makes sure that slurry is in molten condition throughout the pouring. While pouring the slurry in the mould the flow of the slurry is kept uniform to avoid trapping of gas. Then it is quick quenched with the help of air to reduce the settling time of the particles in the matrix.

C CASTING OF ALUMINIUM SILICON CARBIDE WITH CARBON NANOTUBES

The procedure is same for the casting of aluminium silicon carbide with carbon nanotubes except in preheating stage. Carbon nanotubes are having a very high melting point which is equal to almost 3500°C which is higher than silicon carbide. While pre heating both silicon carbide and 0.2 weight percentages of carbon nanotubes will be mechanically mixed thoroughly for continuously 20 minutes, then it is transferred to graphite crucible for preheating the same half an hour is employed for silicon carbide carbon nanotube mix at 500°C. The mould is preheated to a temperature of 500°C. When matrix was in the fully molten condition stirring is started. The speed of the stirrer is gradually increased from 0 to 300 RPM with the help of speed controller. Silicon carbide carbon nanotube mix is then allowed to fall into the molten aluminium in a uniform rate. Temperature of the heater is set to 630°C which is below the melting temperature of the matrix. Dispersion time was taken as 5 minutes. After stirring 5 minutes at semisolid stage slurry was reheated and hold at a temperature 900°C to make sure slurry was fully liquid. Stirrer RPM was then gradually lowered to the zero. The stir casting apparatus is manually kept side and then molten composite slurry is poured in the metallic mould. Thus the test pieces for Aluminium silicon carbide with added nanotubes were made.

D SHAPING TEST PIECES FOR FRACTURE TOUGHNESS TESTING

As the material for testing is aluminium and fracture toughness is to be tested, American Society for Testing Material standard was made. ASTM E399 standard was chosen. Standard size for the test piece is calculated and mould is prepared. Mould is clamped in between bench vice after preheating the mould at 500°C for 30 minutes. After the composite is made by stir casting and is at right temperature for pouring, the slurry is then poured into the mould which is preheated so that the chance for trapping gas in between the casting is reduced. The casted test piece is then allowed to cool normally at room temperature. After the required test pieces are made, as per required dimensions for fracture toughness two holes are to be drilled and a ‘v’ grove is to be made. Drill hole centers were calculated and marked. Drilling operation is followed then. After the hole making, the next step is to make the ‘v’ grove. Grove dimension are calculated and marked for cutting operation. Cutting followed after the marking and the standard dimension with grove is made by filing operation using flat file and triangular file.

E TEST FOR FRACTURE TOUGHNESS

After shaping the standard test pieces for fracture toughness testing, the next step is to test for the fracture toughness. As fracture toughness cannot be found directly as a value, we need to find the maximum load that the test pieces can afford to resist the crack propagation. Grove will act as a crack. As per the definition for fracture toughness is the ability of a material which is having a crack to resist the propagation of the crack. In the test piece prepared there is crack and we need to find how much load it can resist the crack propagation. For that Universal Testing Machine can be used. The jaws for clamping the required test piece are prepared and test piece is clamped properly. After setting the test piece properly the load is given gradually. No sudden loading is given because the

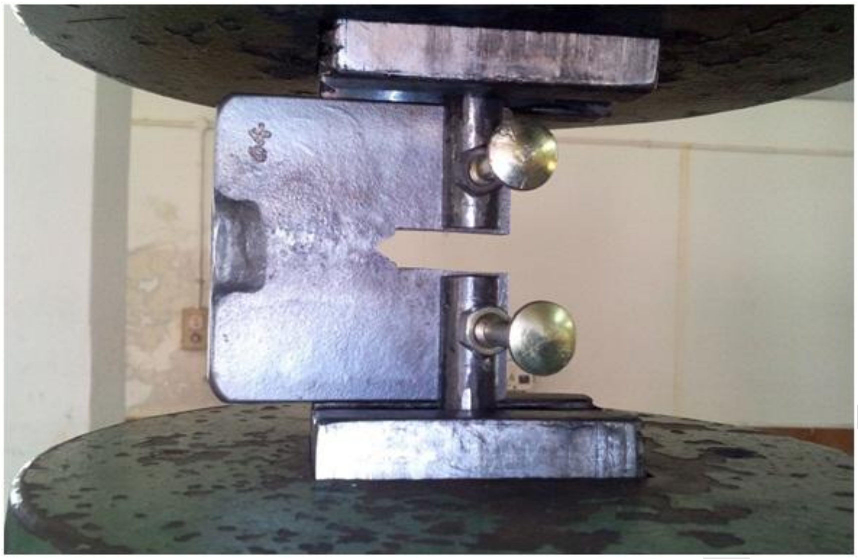

Figure 3 Test Plate with Fixture

correct energy at which the material fails to resist crack is to be find out. By gradual loading the load at which test piece fails to resist crack is found out and recorded. The same procedure is followed for every test piece. Test pieces were fixed in jaw and gradual loading will be given till the material with crack fail to withstand load. Load at which each test piece fail is found out and recorded these recorded data is used for finding the stress intensity factor of the composite which is also known as the fracture toughness of the composite.

Figure 4 Test Plate after reaching maximum load

F COMPARING RESULTS

As per the standard test pieces were casted and cooled. Drill holes and grove were made as per measurements. Fracture toughness testing was done in universal testing machine by fixing a suitable fixture for holding the standard test piece. Maximum load for each standard test piece will be taken in the formula for finding stress concentration factor (K_{IC}). For the piece which is having highest (K_{IC}) will be having increased fracture toughness.

CALCULATION AND RESULTS

A ANALYSIS

As per the ASTM E399 standard for finding the stress intensity factor, aluminium silicon carbide composite test pieces with and without adding carbon nanotubes. This experiment is based on the previous studies in another composite, adding of carbon nanotubes will increase the fracture toughness. With the same basement an attempt was made in aluminium silicon carbide composite also. The standard test piece which is shaped according to the standard was clamped into the universal testing machine using a fixture which was made by cutting and drilling operation on a mild steel. The pieces were fixed in universal testing machine properly. Load of 100 KN was given for the testing. The unit markings needed for breaking each test piece is the load at which test piece fails to withstand the crack.

The load at which each test pieces failed to with stand the load was recorded. The details are given below.

Table 1 Load at which each test piece failed

SL NO	Aluminium % in Composite	Silicon Carbide % in Composite	Carbon Nanotube % in Composite	Maximum Load at Test Piece Failed
1	75	25	-	8 KN
2	75	25	-	7.5 KN
3	75	25	-	7.75 KN
4	75	24.8	0.2	9 KN
5	75	24.8	0.2	8.5 KN
6	75	24.8	0.2	9.5 KN

B CALCULTION

- Average load at which breaking occurs for the 25% Silicon Carbide 75% Aluminium composite is = 7.75 KN
- Average load at which breaking occurs for the 24.8% Silicon Carbide 75% Aluminium composite with 0.2% carbon nanotubes is = 9 KN
- Formula for finding Stress Intensity Factor (K_{IC}) = $\frac{P}{B\sqrt{W}} * f\left(\frac{a}{w}\right) * 10^{-6}\ MPa\sqrt{m}$

Where P = Maximum load in Newton

B = Thickness in mm

W = Width in mm

a = Vertical distance between centre of circle to crack in mm

For a = 32 mm w = 84 mm f(a/w) = 6.9 [16]

Table 2 Calculation for Stress Intensity Factor

	Thickness of Test plate (B) in mm	Width of Test plate (W) in mm	Average load of breaking occurs in Newton	Stress Intensity Factor (K_{IC}) in MPa√m
25% SiC 75% Al composite	0.01	0.084	7750	18.450
24.8% SiC 75% Al composite with 0.2% CNT	0.01	0.084	9000	21.426

C RESULTS

All the test pieces casted were tested using universal testing machine under a load of 100 KN. Higher value of stress intensity factor indicates higher fracture toughness. By comparing the results we can confirm that the fracture toughness of the test piece which is enforced with carbon nanotubes has enhanced fracture toughness than the best combination of aluminium silicon carbide mix. It showed that by adding carbon nanotubes (24.8% SiC 0.2% CNT & 75% Al) fracture toughness could be improved. It is found that test piece with carbon nanotube addition has positive effect on improving the fracture toughness in aluminium silicon carbide composite and it showed that by adding carbon nanotubes (24.8% SiC 0.2% CNT & 75% Al) there is 16 % increase in fracture toughness than the best combination of 25% SiC and 75% Al

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CONCLUSION

In this study, the subject was to find the effect of carbon nanotube addition in aluminium silicon carbide composite. Literature survey about the specified topic made clear that although there is many advantage for metal matrix composites in advancing the properties than the pure metal which is being used in metal matrix composite, fracture toughness property is decreasing with increase in the reinforcement. As the fracture mechanics is starting with a solid saying that there are no perfect materials without cracks, makes the topic more relevant. As composite materials could be used in more crucial parts, the need for fracture toughness is very essential. Aluminium silicon carbide with carbon nanotube and without carbon nanotube matrix was casted and shaped into standard test pieces. Test pieces were shaped according to the ASTM e399, which is a standard used for fracture toughness testing. Standard piece will look like a square plate with two drill holes and a 'v' grove which is a pre crack. All the test pieces were tested and by using the 100 KN load in universal testing machine and the stress intensity factor was found out. Higher value of stress intensity factor indicates higher fracture toughness. It is found that test piece with carbon nanotube addition has positive effect on improving the fracture toughness in aluminium silicon carbide composite and it showed that by adding carbon nanotubes(24.8% SiC 0.2% CNT & 75% Al) there is 16 % increase in fracture toughness than the best combination of 25% SiC and 75% Al.

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