EVOLUTION OF TENSILE AND FRACTURE TOUGHNESS PROPERTIES OF ALUMINUM-7075 ALLOY REINFORCED WITH ZIRCONIUM SILICATE ($ZrSiO_4$) PARTICULATES

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Abstract – *The important parameters of structural materials are fracture toughness and fatigue crack growth behavior, to determine the life period, operation safety and service reliability in various conditions. In this research work, an effort has made to prepare Aluminum 7075 reinforced with various weight% (3%, 6%, 9%, 12%) of zirconium silicate fabricated through stir casting technique. Specimens were prepared as per ASTM standards. Tensile and Fracture Toughness tests have been conducted on prepared composite specimens of different compositions (3%, 6%, 9%, 12%) of zirconium silicate and compared with the Aluminum 7075 base alloy(as cast). The investigation shows that mechanical properties like ultimate tensile strength and fracture toughness have been improved due to the influence of reinforced 9% weight of zirconium silicate particles and there after properties decreases for 12% weight.*

Key Words**: mechanical properties, Fracture Toughness, Aluminum 7075, Zirconium silicate, fatigue crack growth, stir casting technique, etc.**

1. INTRODUCTION

Fracture toughness (KIc) refers in materials science to the ability of a material that contains a crack to resist fracture. In particular, fracture toughness testing characterizes fracture resistance in a neutral environment with a sharp crack and is one of any material's most important properties for virtually all design applications. The principle of plain strain fracture mechanics is used for measurement procedure of fracture toughness. The mechanism of fatigue failure is explained.

i. **Crack initiate-**This happens in regions of intensity of localized stress such as notch gaps, slots, main locations. Cracks, structural rotational symmetry and locations of current fractures and inclusions may also occur on the ground.
ii. **Gradual spread of crack-**Propagation of fatigue cracks at grain boundaries or along grain boundaries by a slow increase in crack size by increasing the stress levels further.
iii. **Final catastrophic failure-**The result of rapid fracture in buildings or device parts is that the region becomes too deficient to withstand the forces induced. Material is definitely unsuccessful at the final point of fatigue.

A material's tensile strength is the maximum limit of tensile stress, such as breaking or permanent deformation, that it can take before failure. To determine the tensile strength, a computerized universal testing machine is used. Properties immediately evaluated through the tensile experiment are ultimate tensile strength, peak elongation and yield strength.

2. LITERATURE REVIEW

[1] Mohan Kumar S et.al.[2014], finished examinations on an Al 7075-T6 and it's Electroless Nickel covering of 10 – 20 µm in thickness. Plane strain crack mechanics, confirmation was followed in this examination. Uncoated Al 7075-T6 composite exhibits a yield nature of 560 MPa, and again EN covering on mix of 10µm and the 20µm yield nature of amplifies to the 569 MPa and 603 MPa. The uncoated Aluminum essential load is 4.44 KN and K1c esteem is 22.28 mpa√m. Further for 10microns and 20microns secured aluminum compound has an essential load of 6.67 kN and 7.41 kN which separates to KIC estimations of 34.48 MPa√m and 37.67 MPa √m exclusively.

[2] Avinash Patil et.al. [2017] contemplated on break sturdiness and weariness development on aluminum compound A384. The Plain strain break durability of Al-compound A384 is resolved. Tests were completed on a widespread testing machine (Axial Fatigue Testing Machine). It is seen that the moderate crack strength esteem around 22.91 MPa is acquired for Al-combination A384. The weakness pre breaking burden is acquired for Al-amalgam A384 material is 1.97 KN which is required to create sharp split close to the break tip. The most extreme load (Pmax) acquired before complete break of the metal is around 2.67 KN. For Al-compound A384 the break load (PQ) is acquired is about 2.068 KN. The temporary crack durability of Al-compound A384 was seen around 18.53 MPa. Explanatory calculation like provisional fracture durability and fracture durability for Al-alloy A384, were calculated is 18.44 MPa and 23.78 MPa separately

[3] Tadeusz Szymczak, Zbigniew.L.Kowalewski[2013] Effctively created 4420 casting, aluminum combination reinforced with different wt% of the Saffil fibres, i.e. 10% , 15%, 20%.The basic results of stress concentration factor 44200 aluminum combination, come to the following levels: 12.201, 12.121, and 11.866 [MPam1/2], separately. The basic value of the stress concentrated factor of the composite was three times littler than that of the 40H steel accomplished. Impact of the Al_2O_3 saffil fibers

substance inside the run from 10% to 20% on the basic stress intensity factor was irrelevant little.

[4] Ajit Bhandakkar et.al. [2014] fabricated aluminum 2024 and silicon carbide and fly ash as reinforcement material particle size of 25-45 μm in 5%, and 10% by weight. As the % of filler material increases, the ultimate stress, yield stress, and % of elongation also increases. The stress intensity KIC obtained for AA2024-fly ash composite is 18 MPa√m and 21 MPa√m for unreinforced and remolded base alloy. Homogeneous mixture of reinforcement alloy has been observed by thr micro structural analysis .

[22] Syed Ahamed et.al. [2014] successfully fabricated the Al-Si (LM-13) /kalonite/graphite carbon hybrid matrix material composites through liqud vortex method. Particle size of Kalonite/Graphite carbons is between 50-100μm.The different percentage of colonies are 3%, 6%, 9%, 12% and graphite carbon is kept constant to 2.5%. Nickel coating on graphite carbon particles through the electrolysis process was given. Different Chill thickness ranges from (10-25mm). The tensile, hardness, fracture toughness and microstructure tests were conducted. The increased hardness, ultimate tensile strength and fracture toughness are identified for 9% out of coolant in 25mm chill thickness IE.,82.8 BHN, 175.837Mpa(UTS) and 11.7mpa√m respectively. The microstructure of the models containing 9 weight% and 12 weight% dispersoids cast utilizing copper chill of 25 mm thick shows that kaolinite particles were delaminated from the matrix due to damage in a brittle manner as an effect of too much chilling, stress intensities and crack propagation.

3. EXPERIMENTAL PROCEDURE

3.1 Material selection

- Aluminium-7075
- Zirconium Silicate($ZrSiO_4$)

a) Aluminium-7075

It is one of the highest alloys accessible as a part of the 7000 series and is similar to many steel kinds. Aluminum 7075 is suitable for elevated stress / strain strength applications. Because of its strong resistance, it is often used in heavy pressure systems such as airplane seat spar and air defence machinery. Because of its elevated thermal conductivity, it has elevated heat dissipation ability and is appropriate for applications at elevated temperatures.
The supplier of Aluminium 7075 is FENFE METALLURGICALS, Harohalli, Bangalore.

Table 1: composition and properties of Al-7075

Element	Weight %
Zinc(Zn)	5.5
Magnesium (Mg)	2.8
Copper(Cu)	1.5
Iron (Fe)	0.5
Silicon (Si)	0.4
Manganese (Mn)	0.3
Titanium (Ti)	0.2
Chromium (Cr)	0.18
Aluminium (Al)	88.85

Density	2.81g/cm^3
Hardness (brinell)	150
Ultimate tensile strength	572mpa
Tensile yield strength	503mpa
Young's modulus	71.7gpa
Machinability	70%
Shear strength	331mpa
Melting point	635^{0}c

b) ZIRCONIUM SILICATE ($ZrSiO_4$)

Due to its simplest accessibility and elevated heat applicationss, Zirconium silicate (ZrSiO4) is chosen as the reinforcement particles. Zirconium silicate (ZrSiO4) has many appealing characteristics, such as small specific gravity, elevated hardness values, elevated elastic modulus quality, helping to make ZrSiO4 commonly used as armor components. Zirconium silicate is used to produce refractory products for apps where alkali metals require corrosion resistance. Corrosion resistance to crushed metals, wear resistance, high toughness of fracture and high hardness these characteristics produced excellent reinforcement ceramic for MMC manufacturing. The supplier of Zirconium silicate (ZrSiO4) is MINCO METSAL, Indira nagar, Bangalore.

Figure 1: Zirconium silicate (ZrSiO4)

Table 2: composition and properties of $ZrSiO_4$

Element	Weight %
Zircon Di oxide (ZrO_2)	64.80
Silicon Di oxide (SiO_2)	32.50
Ferric oxide (Fe_2O_3)	0.70
Titanium Di oxide (TiO_2)	0.15
Alumina (Al_2O_3)	1.20

Melting point	2550 °C
Density	3.9 g/cm^3
Tensile strength	290 Mpa
Grain size	Fine powder

Table 3: weight of Al-7075/ ZrSiO4 for different composition

No of composition	Aluminium-7075	Zirconium silicate($ZrSiO_4$)
1	100% - 350gm	0% - 0gm
2	97% - 340gm	3% - 10gm
3	94% - 330gm	6% - 20gm
4	91% - 320gm	9% - 30gm
5	88% - 310gm	12% - 40gm

3.2 STIR CASTING PROCESS

Base alloy Aluminum 7075 and Reinforcement particle zirconium silicate ($ZrSiO_4$) was successfully fabricated by using liquid vortex method. Crucible and mould box is kept for preheating to remove moisture and other particles from the inner surface. The various volume fraction of reinforcement particles are 3%, 6%, 9% and 12% of $ZrSiO_4$. The different weight % of $ZrSiO_4$ are taken separately in small crucibles and kept for preheat in a muffle furnace. The preheat temperature was held at 750˚C. 340 grams of Aluminium pieces is fed into the crucible which starts melting as the temperature of open hearth go to around 720˚C. As the temperature of furnace reaches to 700˚C, Aluminium pieces in the crucible will melt down. Hexachloroethane (C_2Cl_6) Degasifier is added to semi-solid phase Aluminium, to remove the hydrogen content from molten Aluminum. Slag formed in the crucible is removed and preheated (750˚C) $ZrSiO_4$ powder is poured slowly into the crucible containing Liquid stage Aluminium. Stirring action has performed with a mechanical stirrer continuously for 5 minutes. The Cover flux (45%NaCl+45%KCl+10%NaF) is added to the liquid molten metal. Forms a protective layer over the liquid metal which reduces oxidation. Then liquid Aluminium poured in to the mould box and specimen is obtained. The casted specimens are sent for machining to perform various tests as per ASTM standards.

Figure 2: Stir casting set up

3.3 Mechanical Properties
a) Tensile test

One of the most significant and commonly analyzed characteristics of materials used in composite materials is the ability to with stand cracking under tensile stress. To determine the tensile strength, a computerized universal testing machine is used. Tensile specimen is prepared using lathe machine in accordance with the ASTM E8 M standard.

Figure 3: Computerized Universal Testing Machine

Diameter of width section – 12mm
Gauge diameter - 9mm
overall length – 104mm
Gauge length – 52mm

Figure 4: Tensile Specimens before and after test

In a tensile test, a model is fixed to end of the grippers which is connected to upper plate and lower plate of the UTM. A specimen is elongated using the controlled system connected to the UTM up to its breaking point to define the ultimate tensile strength of the material. Throughout the experiment, the quantity of force (F) applied and the sample elongation (ΔL) are analyzed. Material characteristics are frequently described in words of stress (force per unit area, σ) and strain (change in length, Δ). The results are received as a load v / s displacement graph straight on the XY chart.

b) Fracture toughness Test
Fracture toughness specimen (SENB)

The specimen used for evaluate fracture toughness (K1c) was Single edge notch bending (SENB). It is the most convenient mode of specimen because, it consumes less material. This specimen is prepared as per ASTM standard E399.

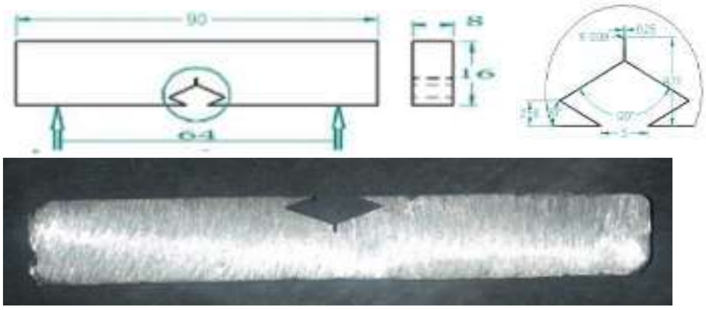

Figure 5: SENB specimen dimensions as per ASTM E399

CNC wire cut (EDM) Electronic Discharge Machine is used to prepare the Notch on the SENB specimen. Molybdenum is used as wire material and wire diameter is 0.18mm.

Experimental procedure
Fatigue Pre-cracking

The main aim of fatigue pre-crack is to obtain a sharp crack. It is important in the test specimen to stimulate a straight propagation of crack. The fatigue pre-cracking is made on BISS Servo Hydraulic Axial Testing Machine. The specimen is fixed in the state of 3 point bending fixture in the machine and an Extensometer is fixed to the notch. Extensometer is used to measure the (CTOD) Crack tip opening displacement. Now the dimensions of the specimen like width (W), thickness (t), crack length (a), span length(S) and properties like yield strength (σys), Poisson's ratio (ρ), pre-cracking load (Pf) and other parameters like frequency, R-value, test control should be input to the computer. Next step is to start the cycle. Now the calculated precracking load is applied on specimen with number of cycles, after it reaches the required a/W crack length, the specimen is eligible for K1c test.

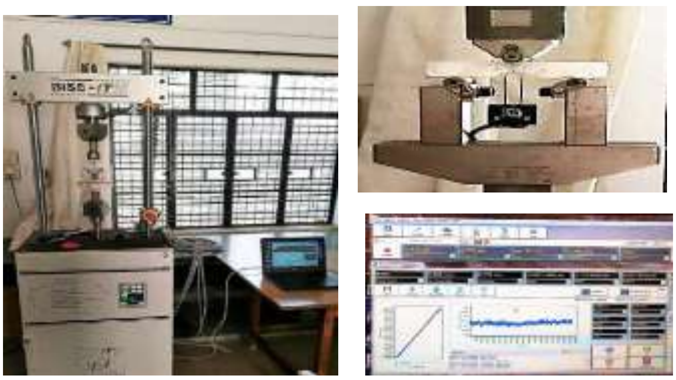

Figure 6: The cyclic load acting on the specimen, Axial Testing Machine

Fracture toughness (K1c) Test

The K1c test is conducted on the same Axial testing machine. After the pre-cracking of the specimen, a load is applied on middle of the specimen as the 3 point bending load, the extensometer connected will measure the (COD) crack opening displacement, by increasing the load levels further, propagation of fatigue cracks takes place until it reaches the catastrophic failure. The values of K1c load in KN and COD in mm will plot in a graph. Maximum load (Pmax), fracture loads (PQ), maximum COD will be noted and fracture toughness KQ obtained is experimental result and it should be compared with theoretical results. The test is valid only when KQ is equal to K1c and following conditions should be satisfied.

Crack length (a) > 2.5× $(K1c/\sigma ys)^2$
Specimen thickness (B) > 2.5× $(K1c/\sigma ys)^2$
Specimen width (W) > 5× $(K1c/\sigma ys)^2$

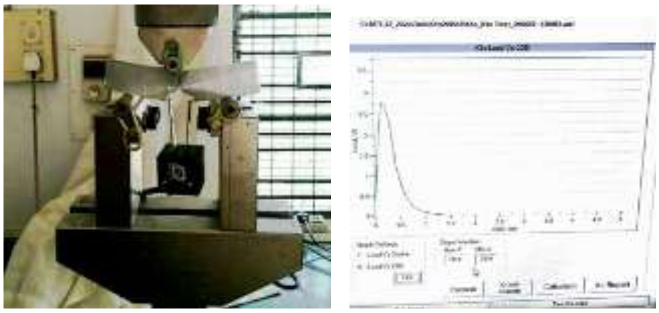

Figure 7: Load v/s COD curve and Specimen at Catastrophic failure

4. RESULT AND DISCUSSION
Tensile Strength

Tensile tests were conducted to evaluate the tensile characteristics of Aluminium7075-ZrSiO4. Total 10 test specimens has prepared as per ASTM standard. 2 specimens were chosen from each composition and best result obtained is listed in the table. The properties like yield strength, Ultimate tensile strength and percentage elongation were evaluated for various composition of ZrSiO4.

Ultimate tensile strength $= \frac{Maximum\ Force}{Area} = \frac{Fmax}{A}$ N/mm²

Percentage elongation $= \frac{\text{Change in length}}{\text{original length}} \times 100 = \frac{\Delta L}{L} \times 100$

Table 4 - Tensile test results

Sl no.	composition	Maximum force F_{max} (KN)	Maximum displacement (mm)	Ultimate tensile strength (mpa)	Yield strength (mpa)	Percentage elongation %
1	Al7075	8.7	2.5	137	129	4.62
2	Al7075-3%$ZrSiO_4$	12.22	2.310	192	168	4.27
3	Al7075-6%$ZrSiO_4$	13.12	2.14	204	179	3.96
4	Al7075-9%$ZrSiO_4$	14.64	1.8	230	194	3.33
5	Al7075-12%$ZrSiO_4$	14.32	3.140	225	186	5.8

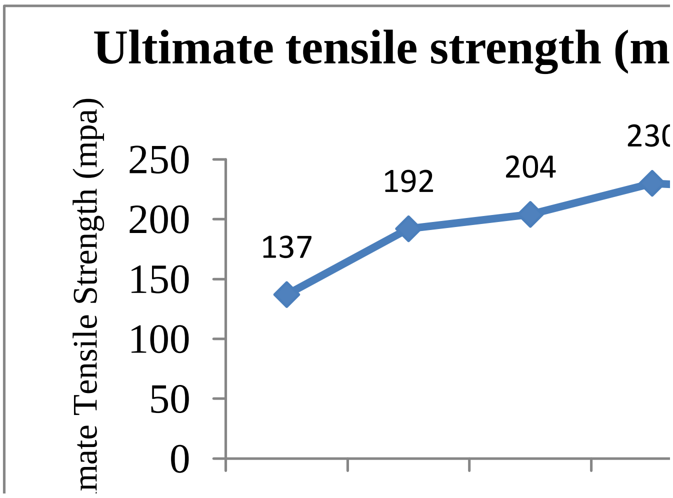

Figure 8: Ultimate tensile strength V/s weight % of $ZrSiO_4$

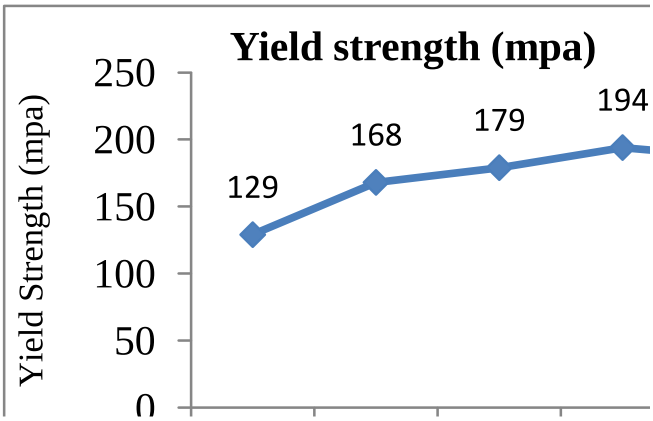

Figure 9: strength V/s weight % of $ZrSiO_4$

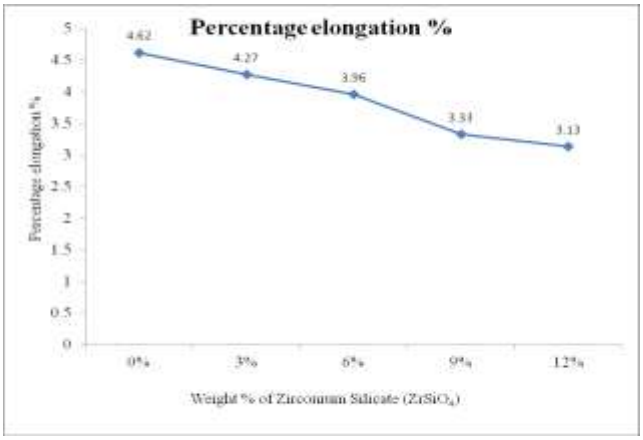

Figure 10: Percentage ElongationV/s weight % of $ZrSiO_4$

The above graph shows the variation of Ultimate Tensile strength, yield strength and percentage elongation with respect to different composition of Aluminium 7075 and zirconium silicate metal matrix composite. It is observed that ultimate tensile, yield strength, increases with increases in weight % of $ZrSiO_4$ particles till 9% weight of $ZrSiO_4$, after it shows decline in UTS, yield strength and for 12% weight of $ZrSiO_4$. Percentage elongation increases with increase in weight % of $ZrSiO_4$.

FRACTURE TOUGHNESS TEST

The linear strain fracture toughness (K1c) of metal were investigated using pre-cracked fatigue specimens. The maximum Cyclic load (P_f) required to form pre-crack on the SENB specimen is given by

$$P_f = \frac{\sigma ys \times B(W-a)^2}{2S}$$

Table 5: maximum cyclic load for pre-cracking the specimen

Sl no	Composition	Yield strength	maximum Cyclic load (P_f) N	$\frac{\text{Crack length}(a)}{width(W)}$
1	Al7075	129	752	0.4523
2	Al7075-3%$ZrSiO_4$	168	979	0.4889
3	Al7075-6%$ZrSiO_4$	179	1043	0.4608
4	Al7075-9%$ZrSiO_4$	194	1131	0.4785
5	Al7075-12%$ZrSiO_4$	186	1084	0.4541

Table : Experimental results critical Fracture toughness (Kq) and maximum fracture toughness (Kmax)

Table : Theoritical results critical Fracture toughness

Sl no	Composition	a/w	f(a/w)	Pmax (kN)	Pq (kN)	Kmax mpa√m	Kq mpa√m
1	Al7075	0.4523	2.3	2.14	1.739	16.58	14.43
2	Al7075-3%$ZrSiO_4$	0.4889	2.32	2.276	2.135	17.68	16.58
3	Al7075-6%$ZrSiO_4$	0.4608	2.35	2.378	2.073	18.21	16.68
4	Al7075-9%$ZrSiO_4$	0.4785	2.48	2.76	2.713	23.63	22.67
5	Al7075-12%$ZrSiO_4$	0.4541	2.56	2.645	2.433	21.42	19.32

(Kq) and maximum fracture toughness (Kmax)

Sl no	Composition	a/w	f(a/w)	Pmax (kN)	Pq (kN)	Kmax mpa√m	Kq mpa√m
1	Al7075	0.4523	2.3	2.14	1.739	16.30	14.77
2	Al7075-3%$ZrSiO_4$	0.4889	2.32	2.276	2.135	17.49	16.40
3	Al7075-6%$ZrSiO_4$	0.4608	2.35	2.378	2.073	18.51	16.52
4	Al7075-9%$ZrSiO_4$	0.4785	2.56	2.76	2.433	23.40	22.15
5	Al7075-12%$ZrSiO_4$	0.4541	2.48	2.645	2.713	21.72	19.98

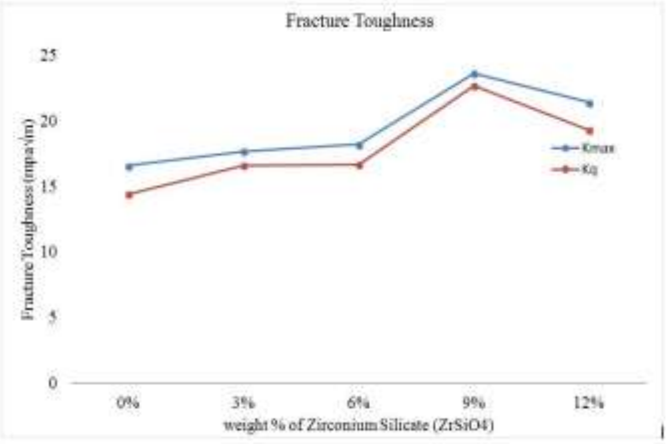

Figure 10: Experimental results of fracture toughness

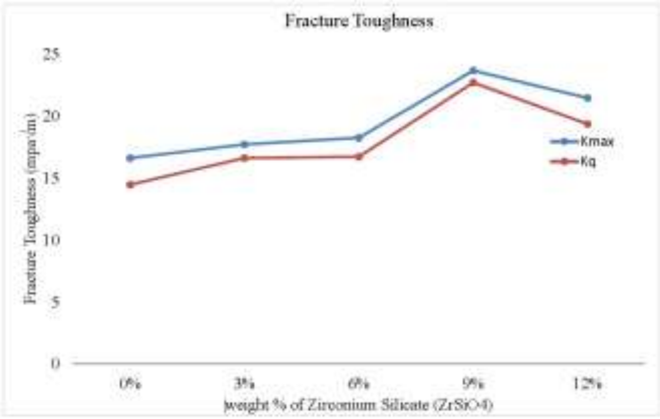

Figure 11: Theoretical results of fracture toughness

The graphs shown in figure 10 and 11 are K1c Load V/s COD curves for all 5 composition of Aluminium 7075 and Zirconium silicate composite. 5% secant linear line is drawn to the P-COD curve and at intersection we can find out the fracture load (Pq). The fracture load (Pq) obtained for base alloy is 1.739 KN and maximum fracture load (Pmax) is 2.14 KN and Fracture load (Pq) obtained for Al7075-9% $ZrSiO_4$ is 2.713 KN and maximum Fracture load (Pq) is 2.73 Experimental analysis of Maximum fracture toughness (Kmax) is 23.63 mpa√m and critical fracture toughness (K1c) is 22.67 mpa√m has obtained for 9% weight of $ZrSiO_4$, whereas the Maximum fracture toughness (Kmax) and critical fracture toughness (K1c) obtained for base metal Aluminium-7075 are 16.58 mpa√m and 14.43 mpa√m respectively. Analytical results shows Maximum fracture toughness (Kmax) is 23.40 mpa√m and critical fracture toughness (K1c) is 22.15 mpa√m has obtained for 9% weight of $ZrSiO_4$. Critical Fracture toughness (K1c) of the Aluminium-7075 increased by 57% after adding 9% weight of $ZrSiO_4$ and for 12% weight of $ZrSiO_4$ the fracture toughness decreases. The result clearly shows that fracture toughness increases with maximizing weight % of $ZrSiO_4$. From the results it is understood that the brittle ness of the material increases with increase in weight % of $ZrSiO_4$ [7]. The hard, brittle $ZrSiO_4$ particles in soft Al-alloy metal matrix resists the plastic flow of matrix during cyclic loading, reason for brittle fracture on account of increase in ZrSiO4 particles is the matrix becomes dense, stronger and accommodates the dispersoids rigidly[8]. The sudden fracture occurs for the Al-7075 with 12% of $ZrSiO_4$. Fracture toughness can also be determined by Analytical method. Table 5.4 shows the analytical fracture toughness results. Experimental results are very similar to the analytical results.

5. CONCLUSION

The experimental study has been carried out for the investigation of mechanical and tribological properties of Aluminium 7075 reinforced with various weight % (3, 6, 9, 12) $ZrSiO_4$. The specimens has been fabricated as per ASTM standards through Stir casting technique. Various tests like tensile test, fracture toughness test has been carried out for determination of mechanical and tribological properties. The following remarks has been made after obtaining all the test results.

1 Ultimate tensile strength increased by 67%, yield strength increased by 50.12, Fracture toughness(K1c) increased by 57% and hardness increased by 40% after adding 9% $ZrSiO_4$ to al-7075 alloy
2 Ultimate tensile strength is 230 mpa and yield strength is 194 mpa obtained for Al-7075 reinforced with 9% $ZrSiO_4$, whereas Al-7075 base metal has Ultimate tensile strength 137 mpa and yield strength 129 mpa.
3 Fracture toughness (K1c) of Al-7075 base metal improves with maximizing the weight % of $ZrSiO_4$. Test specimens of all 5 composition shows valid results by satisfying all the required condition.
4 Experimental analysis of Maximum fracture toughness (Kmax) is 23.63 and critical fracture toughness (K1c) is 22.67 has obtained for 9% weight of $ZrSiO_4$.
5 Analytical results shows Maximum fracture toughness (Kmax) is 23.40 and critical fracture toughness (K1c) is 22.15 has obtained for 9% weight of $ZrSiO_4$.
6 Experimental results and analytical results shows similar results for all test specimens.

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