

## FATIGUE LIFE ESTIMATION OF HYBRID ALUMINIUM MATRIX COMPOSITES

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### Abstract

The fatigue and mechanical properties of composite consisting of AA 6061(LM 25) Aluminium alloy reinforced with silicon carbide and graphite particles were investigated with the primary objective of understanding the influence of the particulate reinforcement on the fatigue and mechanical behavior of the LM 25 Aluminium alloy. The combined silicon carbide and graphite content in the hybrid composite was 2.5wt %. The composite was fabricated by gravity die casting technique in which the reinforcement particles were dispersed in the vortex created in the molten matrix alloy. Statistical design of experiments was applied to carry out fatigue tests on rotating beam fatigue testing machine under stress controlled conditions. Three different stress levels at 0.9Su, 0.7Su and 0.5Su where Su=Ultimate Strength of the Composite were used. For the hybrid Al-SiC-Gr composite, improvements in Young's modulus, ultimate tensile strength (UTS), compressive strength, yield strength and hardness was observed but at the expense of ductility. Fatigue data exhibited large scatter. Monte Carlo Simulation model was developed. The Simulated fatigue data and the experimental data were compared and validated. The Simulated model helps designers to obtain accurate fatigue data without conducting large number of time consuming fatigue experiments.

**Key words:** Hybrid metal matrix composites, Monte Carlo Simulation, Fatigue

### I. INTRODUCTION

The presence of reinforcements, such as Silicon Carbide(SiC) in the Aluminium alloy matrix increases the mechanical properties and the load carrying capability[1]. T.J.A.Doel and P.Bowen[2] have reported the tensile behavior of SiC particulate reinforced Composite depends on particle size, and ageing conditions. Lin C.B, Chang R.J and Weng W.P[3] have reported the incorporation of the reinforcements in aluminium alloy matrix, such as graphite particles provide improved tribological properties. However, as the volume fraction of the graphite particles in the composite increases, its mechanical properties decrease[4]. The addition of graphite particles to aluminium alloys improves sliding wear and seizure resistance compared to non-reinforced aluminium alloys. Since graphite particles are lighter than matrix metallic alloys, aluminium graphite composites are used to reduce the weight of components[5]. Recent advances in the technology of automotive engines have generated the need to develop new materials for better antifriction and wear performance on specific components like piston, cylinder blocks or liners, connecting rods, various types of brakes, air diffusers and bushings. For bearing application, the aluminium-graphite composite save considerably in cost and weight and has the added benefit of being self-lubricating[6].

Cevdet Kaynak and Suha Boylu[7] investigated the effects of SiC particulates on the fatigue behaviour of Al alloy matrix composite. They found the improvement in

fatigue resistance with increasing content of SiC particulates upto 15wt%. Researchers T.S.Srivatsan et al. studied the fracture morphology of SiC particulate reinforcement phase in the 6061 aluminium alloy metal matrix. With the increase in SiC contents in the metal matrix, fractures of the composite were dominated by particulate cracking and decohesion at the particulate-matrix interface [8].

Little [9] discussed the methods of fatigue testing in design of fatigue experiments, planning of test program and common methods of fatigue data analysis. Lipson and Sheth[10] have given the procedure for selection of stress levels, sample size determination and determination of average fatigue life.

A combination of soft lubricant like graphite and hard reinforcements like SiC can improve the tribological properties of the composite and strength more than the properties of composites containing either SiC or graphite particles by themselves. Composites containing more than one type of reinforcements are called hybrid composites. Such composites by using two or more types of reinforcements extend the idea of tailor-making a composite material to meet specific property requirement. In addition, since graphite particles are lighter than the matrix metallic alloys, the hybrid composite can be used to reduce the weight more than the Al-SiC composite.

Recently there are attempts to use hybrid composites as bearing materials, which are prone to surface fatigue

wear. Reasonably good amount of data is available on

Mechanical and fatigue properties of Al-SiC and Al-Gr Composites. However, work related to fatigue characterization of Hybrid Al-SiC-Gr Composites is limited. . Thus, there is a need to establish fatigue properties of Aluminium matrix hybrid composites.

## II. EXPERIMENTS

The procedure to establish S-N Curve is as follows:

- Static tests to determine the ultimate tensile strength.
- Selecting the stress level.
- Determination of sample size.
- Conduct of tests.
- Analysis and presentation of data.

The Hybrid Al-SiC-Graphite composites specimens were cast by liquid metallurgy technique using aluminium alloy AA6061 (LM 25) as the matrix and containing 2.5% combined weight percentages of silicon carbide (SiC) particles of 10  $\mu$  size and Graphite of 74 $\mu$  size. The LM25 specimens were also cast without any reinforcements. Table 1 shows the chemical composition of matrix aluminium alloy. Tests were carried out to determine the mechanical properties of the LM25 and 2.5wt% hybrid Al-SiC-Gr composite. Fig. 1 shows the standard tensile test specimen details.

**Table 1. Chemical composition of the matrix alloy LM25**

Element	Si%	Mg%	Fe%	Cu%	Mn%	Ni%	Zn%	Cr%
Content	7.14	0.312	0.32	<0.012	0.281	0.010	0.002	0.004

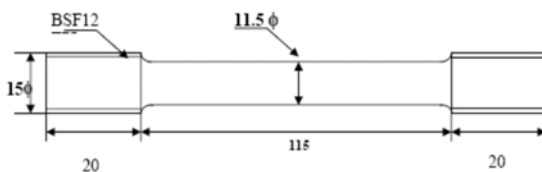


Fig. 1. Tensile Test Specimen

Table 2 and 3 shows the Mechanical Properties of LM25 alloy and 2.5wt% Hybrid Al-SiC-Gr Composite. For the 2.5wt% Hybrid Al-Si-Gr composite, the Ultimate tensile strength and the yield strength increases. The increase in UTS and Yield Strength can be attributed to the presence of hard SiC particles which impart strength to the LM 25 matrix, bestowing more resistance to the composite against the applied tensile stresses. This increase in UTS and yield strength is consistent with the results obtained by another investigator McDaneals[11] who tested SiC

particles reinforced MMCs with various alloy matrices.

**Table 2. Average values of Mechanical Properties of LM 25 pure alloy**

Ultimate Tensile Strength In MPa	Yield Strength in MPa	Modulus of Elasticity In GPa	Hardness (BHN)	Ductility (%Elongation)
135	48.92	89	67.02	3.04

**Table 3. Mechanical Properties for 2.5wt% Hybrid Al-SiC-Gr Composite.**

%SiC+%Gr	Ultimate Tensile Strength in MPa	Yield Strength in MPa	Modulus of Elasticity in GPa	Hardness in BHN	Ductility in %
2.5	140	52	68	71.66	1.5

### A. Microstructure characterization

Fracture surfaces of the tensile failed specimens were comprehensively examined in a CARL JOEL scanning electron microscope. The microstructure of the 2.5% Hybrid Al-SiC-Gr composite tensile fracture surface with tear ridges is shown in the Fig. 2. and with microscopic voids, crack and cracked particulates is shown in the Fig. 3. The discontinuous SiC and Gr particulate reinforcement phase in the 6061 aluminium alloy matrix, were of non-uniform size, irregularly shaped and dispersed randomly through the alloy matrix. At frequent intervals an agglomeration or clustering of the SiC and Gr reinforcements was observed resulting in particulate-rich and particulate-depleted regions. A non-uniform distribution of the reinforcing SiC and Gr particulates in the aluminium alloy matrix results in an anisotropic microstructure of the Hybrid composite. Observation of the tensile fracture specimen revealed the presence of microscopic voids in the matrix of the composite. Few of the microscopic voids were intermingled with tear ridges and isolated pockets of dimple.

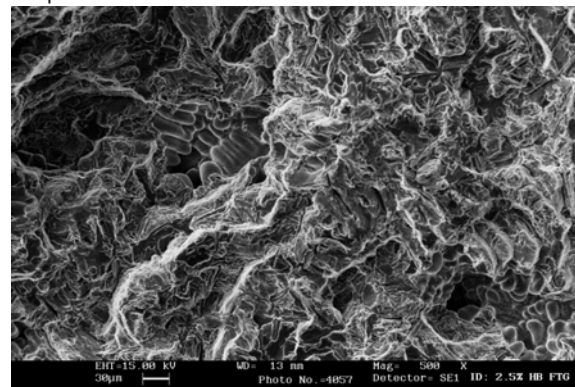


Fig. 2. Scanning electron micrograph of tensile fracture surface of 2.5% Hybrid Al-SiC-Gr composite showing tear ridges.

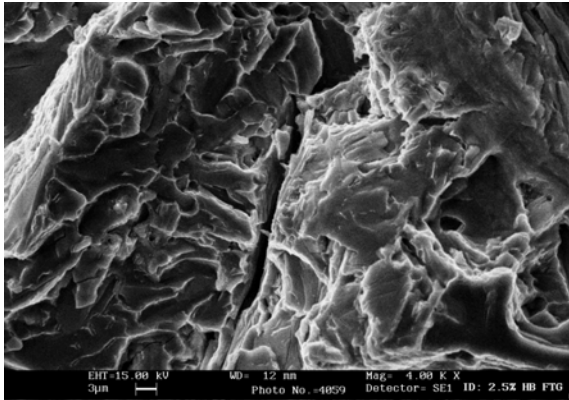


Fig. 3. Scanning electron micrograph of tensile fracture surface of the of 2.5% Hybrid Al-SiC-Gr composite showing microscopic voids, crack and cracked particulates.

**B. Sample size determination**

Statistical design of experiments was carried out to determine the correct sample size.

The relationship between specimen allocated, percent error that can be tolerated, confidence level and the expected variation in the fatigue life can be determined by the following methodology.

Percent error is defined as the error made when the sample average  $x_i$  is accepted to be the population log mean  $\mu_i$ .

Percent Error is given by =

$$\pm \left[ \frac{s_1 t_{\alpha/2; v}}{\bar{x}_i \sqrt{n}} \right] \tag{1}$$

$x_i$  is the sample log average life, equal to

$$\left[ \sum_{i=1}^n \frac{(x_i)^i}{n} \right] \tag{2}$$

$n$  = sample size

$v$  = degree of freedom ( $n-1$ )

$\alpha/2$  = degree of confidence, where confidence is equal to  $(1-\alpha)$

$S_1$  = sample log standard deviation of life is given by;

$$S_1 = \left[ \frac{\sum_{i=1}^n \frac{(x_i - \bar{x}_i)^2}{n-1} \right]^{1/2} \tag{3}$$

$t_{2,v}$  = value of t statistics, available in standard tables.

Fig. 4 shows the standard fatigue test specimen details. The ratio of percent error to coefficient of variation when plotted against sample size at different confidence levels, a plot as shown in Fig 5 can be obtained from which sample size at different stress levels can be determined. Since fatigue testing is time consuming it is generally recommended to conduct tests at 3 or 5 levels [12, 13, and 14]. In this investigation it was chosen to use three-stress level fatigue test program. The tests were conducted at Level I ( $0.9 S_u$ ), Level II ( $0.7 S_u$ ), Level III ( $0.5 S_u$ ) (where  $S_u$  is the Ultimate Tensile Strength).[9]

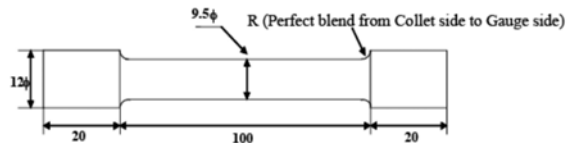


Fig. 4. Fatigue Testing Specimen

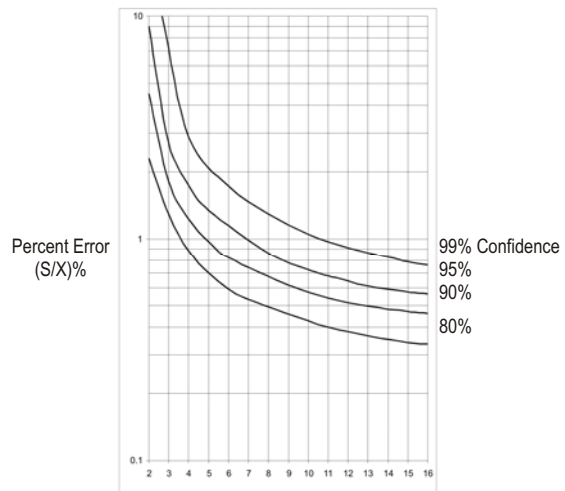


Fig. 5. Sample size determination for estimating average fatigue life [10]

The sample size at each stress level was determined at confidence level of 90% based on the following assumptions.

- 1) Scatter in fatigue lives is not uniform at all stress levels,
- 2) Percent error of 10 % is tolerable and
- 3) Coefficient of variation (C.O.V) of fatigue lives at level I = 4%, level II = 5% and at level III = 7%. The assumption 3 is only tentative. In the event that variation of fatigue life is more than the assumed at a given stress level, additional specimens can be tested in order to maintain the same percent error and confidence at all three stress levels. Table 4 shows the required sample size for 10%error and 90% Confidence for 2.5% Hybrid Al-SiC-Gr Composite.

**Table 4. Required Sample Size for 10% error and 90% Confidence for 2.5% Hybrid Composites**

Stress(MPa)	Assumed C.O.V.(%)	% Error / Assumed C.O.V (%)	Required sample size
126 (0.9Su)	4	2.5	3
98 (0.7Su)	5	2	3
70(0.5Su)	7	1.43	4

**C. Determination of average fatigue life**

Experiments were conducted at three different stress levels. The number of test specimens to be tested at each stress level was determined using Fig. 5. The number of cycles of rotation corresponding to the specimen failure is noted down and is considered as the fatigue life of the specimen. The average speed of rotation was around 2000 rpm. The tests were conducted in a random order to minimize the effect of uncontrollable variables.

**D. Analysis of fatigue results**

Table 5 shows the analysis of Test Results to determine Average Fatigue Life within 10% Error and 90% confidence according to initial estimate for 2.5% Hybrid composite. Table 6 shows the revised Test Plan for 2.5% Hybrid Composites. The actual COV is less than the assumed value. From the Graph of fig 5, It is clear that 3 samples are sufficient, however 11 more samples were tested, so that totally 14 specimens were tested in all the three stress levels to determine the scatter accurately.

**Table 5. Analysis of Test Results to determine Average Fatigue Life within 10% Error and 90% confidence according to initial estimate for 2.5% Hybrid composite.**

Sample Number	Stress Level I 126 MPa		Stress Level II 98 MPa		Stress Level III 70 MPa	
	Life (Cycles)	Log (Life)	Life (Cycles)	Log (Life)	Life (Cycles)	Log (Life)
1	182362	5.2609	1037655	6.0160	1338256	6.1265
2	375654	5.5747	380876	5.5807	811226	5.9091
3	204517	5.3107	610073	5.7853	667849	5.8246
4					728114	5.8621
Average	254178	5.3821	676201	5.794	886361	5.9306
Standard Deviation	0.1686		0.218		0.1351	
% C. O. V	3.13		3.76		2.28	

**Table 6. Revised Test Plan for 2.5% Hybrid Composite**

Stress(MPa)	Actual C.O.V. (%)	% Error / Actual C.O.V (%)	Actual sample size
126	3.13	3.194	14
98	3.76	2.659	14
70	2.28	4.385	14

Large number of specimens is required to be tested at each level to determine the wide scatter. Reference 10 gives the guidelines for the sample size requirement based on minimum percentage replication as given in table 7.

**Table 7. Guidelines for Replication and sample size in stress life testing[10]**

Type of test	Minimum Replication	Percentage	Minimum number of Specimens
Preliminary and Exploratory	17-33		6-12
Research and Development Testing	33-50		6-12
Design Allowances Data	50-75		12-24
Reliability Data	75-88		12-24

Percentage replication is the portion of total number of specimens that may be used for obtaining an estimate of variability of replicate tests. The percentage replication was calculated as:

$$\text{Percentage Replication} = 100 [1 - (TL/TN)]$$

Where

TL = Total number of different stress levels used in testing = 3

TN = Total number of specimens tested = 3 stress levels x 14 specimens = 48

$$\text{Replication percentage} = [1 - (3/48)] * 100$$

= 94% which agrees with the values given in Table 7.

Table 8 shows the results of Revised Sample Size=14, for 2.5% Hybrid Composite.

**Table 8. Results of fatigue failure of Revised Sample Size = 14, for 2.5% Hybrid Composites**

Sample Number	Stress level-I(126MPa)		Stress level-II(98MPa)		Stress level-III(70MPa)	
	Life(Cycles)	Log (Life)	Life (Cycles)	Log (Life)	Life (Cycles)	Log (Life)
1	182362	5.2609	1037655	6.0160	1338256	6.1265
2	375654	5.5747	380876	5.5807	811226	5.9091
3	204517	5.3107	610073	5.7853	667849	5.8246
4	8694	3.9392	154549	5.1890	728114	5.8621
5	194833	5.2896	886413	5.9476	24475	4.3887
6	644217	5.8090	745384	5.8723	554713	5.7440
7	13085	4.1167	19864	4.2980	1025416	6.0109
8	381152	5.5810	1285218	6.1089	65434	4.8158
9	385473	5.5859	276480	5.4416	345477	5.5384
10	676394	5.8301	433129	5.6366	476543	5.6781
11	495815	5.6953	547718	6.7385	934994	5.9708
12	70334	4.8471	752667	5.8766	1167883	6.0673
13	112422	5.0508	47369	4.6754	872913	5.9409
14	191176	5.2814	457961	5.6608	1096695	6.0400
Average	281152	5.4489	545384	5.7367	722142	5.8586

Fig. 6 shows S-N curve comparison of 2.5wt% Hybrid Al-SiC-Gr Composite and base Alloy LM25. The fatigue resistance of Hybrid Al-SiC-Gr composite is superior to that of the matrix alloy.

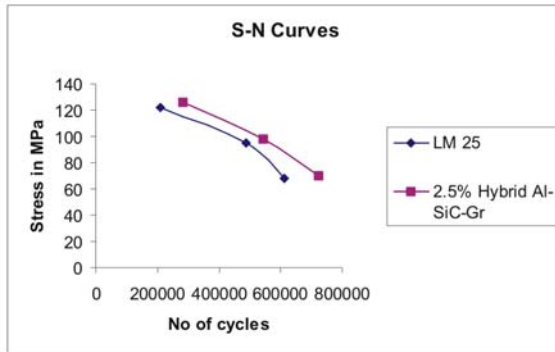


Fig. 6. Comparison of Fatigue Behavior of 2.5wt%Hybrid Al-SiC-Gr Composite with base Alloy LM25.

### III. MONTE CARLO SIMULATION

Monte Carlo method is a computational algorithm that relies on repeated random sampling to compute results. Monte Carlo methods are often used when simulating physical and mathematical systems. Because of their reliance on repeated computation and random or pseudo-random numbers, Monte Carlo methods are most suited to calculation by a computer. Monte Carlo methods tend to be used when it is infeasible or impossible to compute an exact result with a deterministic algorithm.

The term Monte Carlo was coined in the 1940s by physicists working on nuclear weapon projects in the Los Alamos National Laboratory. Essentially, the Monte Carlo method is a sophisticated means of randomly selecting a sample from one distribution and comparing it with a sample taken from a different distribution.

N. Metropolis and S. Ulam[15] have given the fundamentals of Monte Carlo method. Fishman, G.S.[16] have discussed the detailed Concepts, Algorithms, and Applications of Monte Carlo methods. D. Kahneman and A. Tversky [17] have given the detailed procedure to apply Monte Carlo method during situations of uncertainty. R. E. Caflisch [18] analyzed the correct procedure for the application of Monte Carlo methods.

There are many situations where the probability of occurrence of a random variable is not constant, as in the case of fatigue data which generally follow log normal distribution or weibull distribution. The fatigue data exhibit large scatter. Work related to development of a simulation model for Hybrid composites is limited.

The laborious problem of carrying out a large number of fatigue experiments to determine the scatter can be

avoided by this fatigue simulation model.

#### A. Procedure for Monte Carlo Simulation of Fatigue Data Using EXCEL

- Determine the experimental fatigue values.
- Determine the Average and Std. Deviation of the experimental fatigue values.
- If  $P(x)$  is the probability of failure at a particular lifecycle, then random number denotes its occurrence.
- Formulate a mathematical relationship to simulate values to the left and right of the mean value as shown in Fig. 7.
- For the values to the left of the mean, the relationship is  $LF1 = Avg - (Std.Dev * Random\ number)$
- For the values to the right of the mean, the relationship is  $LF2 = Avg + (Std.Dev * Random\ number)$
- Use the above relationship and generate random fatigue lives using Excel.
- Verify the best distribution of the simulated values i.e., Lognormal or Weibull distribution by determining Anderson Darling Coefficient and Correlation Coefficient.

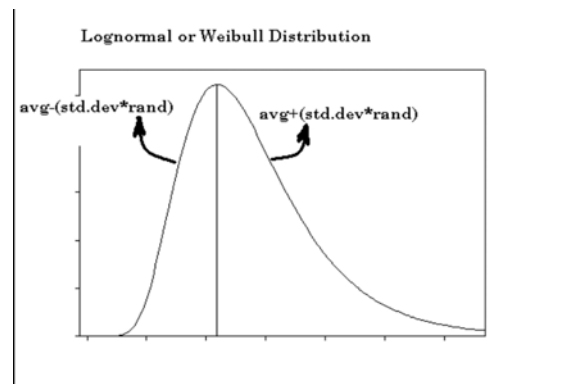


Fig. 7. Mathematical relationship for the simulated values for Monte Carlo Simulation of Fatigue Data Using EXCEL.

#### B. Procedure for Monte Carlo Simulation of Fatigue Data Using MATLAB

A suitable software is developed to simulate fatigue lives using MATLAB. Using the software developed the fatigue lives are simulated at different stress levels and these values are compared with the experimental values.

#### C. Analysis of Monte Carlo Simulation results

Comparison of experimental fatigue values with Monte Carlo simulated values for 2.5% Hybrid composite

at stress level-1 is given in Table 9. The average experimental fatigue values and the Monte Carlo simulated fatigue values are same. The probability distribution plot to determine goodness of fit for 2.5% Hybrid composite at stress level-1 for experimental fatigue values is given in Fig. 8. Monte Carlo simulated fatigue lives using EXCEL is given in Fig. 9 and Monte Carlo simulated fatigue lives using MATLAB is given in Fig. 10. The comparison of probability distribution parameters for 2.5% Hybrid Composite at stress level-1 for Experimental fatigue lives, Monte Carlo Simulated fatigue lives using EXCEL and Monte Carlo simulated fatigue lives using MATLAB is given in Table 10.

**Table 9. Comparison of Experimental Fatigue values with Monte Carlo Simulated Values for 2.5% Hybrid Composite at Stress Level - I**

Sample Number	Experimental Values	Monte-Carlo Simulated - EXCEL	Monte-Carlo Simulated - MATLAB
1	8694	52140	6012
2	13085	117615	8062
3	70334	162789	11054
4	112422	166903	15699
5	182362	173985	22485
6	191176	200410	22623
7	194833	233456	33950
8	204517	328847	53164
9	375654	361893	87123
10	381152	395400	153350
11	385473	388318	293100
12	495815	399514	639608
13	644217	444688	961226
14	676394	510163	1628672
Average	281152	281152	281152

**Table 10. Comparison of Probability Distribution Parameters for 2.5% Hybrid Composite at Stress Level-I**

	Anderson-Darling		Correlation-Coefficient		Mean Time To Failure	
	Coefficient				(MTTF-Cycles)	
	Weibull	Lognormal	Weibull	Lognormal	Weibull	Lognormal
Experimental	1.227	1.654	0.964	0.920	325827	401816
Monte Carlo(EXCEL)	1.163	1.348	0.980	0.947	286189	296548
Monte Carlo(MATLAB)	1.891	1.142	0.933	0.976	194892	420237

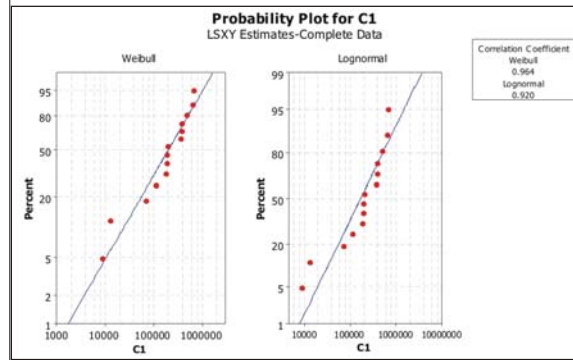


Fig. 8. Probability Distribution Plot for 2.5% Hybrid Composite Stress Level-I(Experimental)

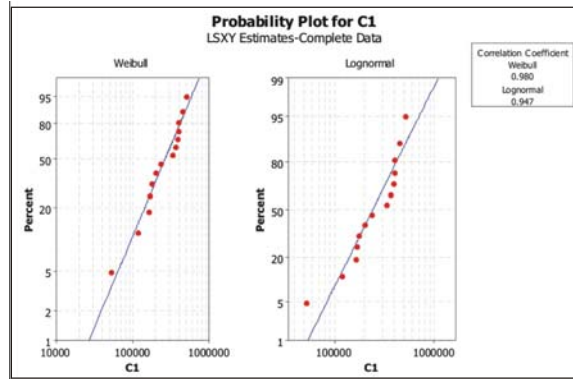


Fig. 9. Probability Distribution Plot for 2.5% Hybrid Composite at Stress Level-I(Monte Carlo Simulated-EXCEL)

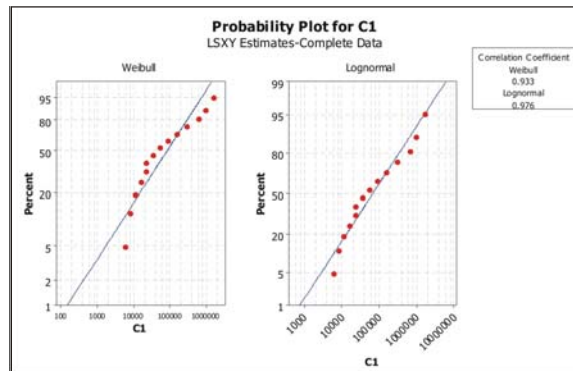


Fig. 10. Probability Distribution Plot for 2.5% Hybrid Composite Stress Level-I(Monte Carlo Simulated-MATLAB)

Anderson-Darling Coefficient is a measure of how far the plot points fall from the fitted line in a probability plot. A smaller Anderson-Darling Coefficient indicates that the distribution fits the data better [19] whereas a higher Correlation Coefficient indicates that the distribution fits the data better. It is clear from the Table 10 that for experimental fatigue values, the Anderson Darling Coefficient is lower for weibull distribution and Correlation Coefficient is higher. For Monte Carlo simulated fatigue

lives using EXCEL also weibull distribution is the best fit. However for Monte Carlo simulated fatigue lives using MATLAB, lognormal distribution is the best fit.

The comparison of Mean Time to Failure (MTTF) for the experimental fatigue lives and the Monte Carlo simulated fatigue lives using EXCEL and MATLAB is also given in Table 10. MTTF between Monte Carlo (EXCEL) and Experimental values for weibull distribution exhibited less deviation. However, MTTF between Monte Carlo (MATLAB) and Experimental values for lognormal distribution, exhibited less deviation. Therefore, for weibull distribution, Monte Carlo (EXCEL) is more suitable and for log normal distribution, Monte Carlo (MATLAB) is preferable.

#### IV. CONCLUSION

Fatigue lives for 2.5wt% Hybrid Al-SiC-Gr composite is determined experimentally at different stress levels and compared with the base alloy LM 25. Hybrid composite showed an improvement in the fatigue resistance compared to base alloy LM 25. The fatigue data exhibited large scatter. A large number of experiments need to be conducted to determine the scatter. Monte Carlo simulation fatigue life estimation model was developed to simulate fatigue lives. The Comparison of experimentally determined and Monte Carlo simulated average fatigue lives showed they are the same. The Comparison of probability distribution parameters using Anderson-Darling Coefficient and Correlation Coefficient helped in selecting the best fit. The tedious job of conducting large number of experiments can be avoided by using this simulation model.

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