Journal of Minerals and Materials Characterization and Engineering, 2017, 5, 274-287
http://www.scirp.org/journal/jmmce
ISSN Online: 2327-4085
ISSN Print: 2327-4077

Fatigue Behaviour of Silicon Carbide and Fly Ash Dispersion Strengthened High Performance Hybrid Al 5083 Metal Matrix Composites

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How to cite this paper: Santhosh, N., Kempaiah, U.N., Sajjan, G. and Gowda, A.C. (2017) Fatigue Behaviour of Silicon Carbide and Fly Ash Dispersion Strengthened High Performance Hybrid Al 5083 Metal Matrix Composites. *Journal of Minerals and Materials Characterization and Engineering*, **5**, 274-287.
https://doi.org/10.4236/jmmce.2017.55023

Received: June 30, 2017
Accepted: September 1, 2017
Published: September 4, 2017

Abstract

Fatigue is a major issue concerning the use of aluminium composites in structural applications. Fatigue leads to weakening of material majorly due to the strain bands formed in the material when it is subjected to repeated loading; the damage that occurs due to fatigue is a progressive and localized one. The fatigue may occur at a stress limit much lesser than the ultimate stress limit of the composite specimen. Henceforth in the current work, fatigue behaviour of silicon carbide and fly ash dispersion strengthened high performance hybrid Al 5083 metal matrix composites are evaluated. The main purpose of fatigue characterisation is to distinctly evaluate the life cycle of components that are fabricated from metal matrix composites and eventually develop a framework model for the significant study of fatigue strength of the structure with persistent striations all along the interstitials of aluminium-silicon carbide-fly ash interfaces. Fatigue is a stochastic process rather than a deterministic one that gives a considerable scatter, even among samples of similar composition with the tests carried out in some of the critically controlled environments. Hence there is a need for statistical validation of the results to authenticate the data collected. Thus in the current work, analysis of variance is carried out to establish the authenticity of the results and validate them. The results and plots are presented with suitable rationale and inferences.

Keywords

Fatigue, Aluminium, Silicon Carbide, Fly Ash, Statistical Validation

1. Introduction

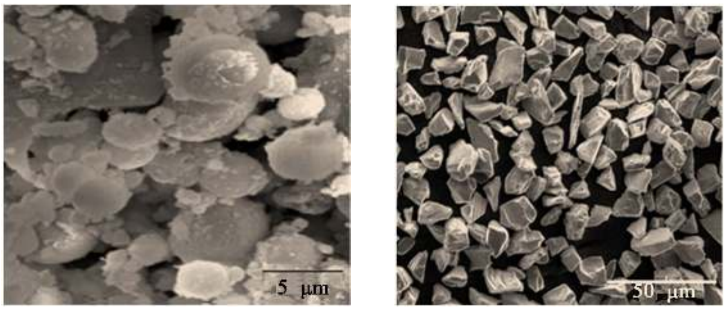
The utilization of silicon carbide (SiC) particulate-reinforced aluminum matrix composites as a substitute of solid aluminum combinations in auxiliary applications, particularly in the aviation and automobile industry, is ending up noticeably progressively alluring. This is a direct result of their predominant quality; however, the fatigue of the aluminium silicon carbide composites, at lower stress cycles is a matter of concern. The fatigue conduct of the above mentioned composites is commanded by the interface between the aluminum lattice and the SiC particles. While reinforcing of silicon carbide depends on the load transfer at the interface, durability is affected by the conduct of the split at the limit between the matrix and the reinforcement, henceforth, a lot of research is conducted to overcome this influence by the unwinding of pinnacle worries close to the interface in view of the plastic deformation at fracture [1] [2]. As a result, the non-versatile conduct of the composite is critically examined by researchers, *i.e.* the fatigue behavior, and furthermore the fractography is evaluated in view of the justification of the inferences made. These progressions comprise of isolation and precipitation caused by the heat treatment that is anticipated to radically influence the fatigue behaviour of the Al/SiC composites [3].

The reaction of the basic component to fatigue is very much important for some applications. On account of metal matrix composites (MMCs), the fatigue conduct varies from that of unreinforced metals in a few ways. On account of particle reinforced metals, various reviews have concentrated on understanding the impact of the strengthening molecule on the network microstructure and the relating impact on the fatigue conduct of the MMCs [4] [5] [6] [7] [8]. The size and weight percentage of the reinforcements are likewise influencing the fatigue life. Now and again, it has been observed that the fatigue behaviour may improve by the addition of fly ash as reinforcements [9] [10]. The association of various structures in view of the nearness of the reinforcements may prompt antagonistic consequences for the fatigue life. The fatigue quality of silicon carbide (SiC_P)-strengthened A359 aluminum matrix composites has been answered to be for the most part impacted by the thermo-mechanical synthesis of the composite. Late reviews have talked about the impact of heat treatment on the interfacial quality and the mechanical properties of silicon carbide (SiC_P)-strengthened A359 aluminum matrix composite [11]. The outcomes demonstrated the interrelation between the heat treatment, the matrix reinforcement interface quality and the characterization of static properties of the composite. Further to the static properties, the heat treatment is normal to be of huge significance for the dynamic conduct of these materials. The objective of this study involved the characteristic evaluation of fatigue properties of aluminium composites for varying percentages of silicon carbide and fly ash particulates and statistically validating the same for checking its authenticity.

2. Materials and Its Characteristics

Aluminium AA 5083 alloy with exceptional performance in extreme environments and highest strength among non heat treatable alloys is processed along with the class C Fly ash (Requirements matching ASTM C618 standards) and 35 micron to 50 micron size silicon carbide enroute stir casting. The properties of each of the materials chosen and process parameters selected for development of composite material are as given below in the following **Tables 1-4**.

The silicon carbide and fly ash particulates are observed and their micrographic images are obtained at a magnification of 500× and 7 kV acceleration voltage in an Hitachi make SU-3500 scanning electron microscope with a low vacuum premium SE detector setup. The SEM images clearly given an inference of the mesh size of each of the particulates taken, the size of silicon carbide particulates vary in the range of 30 microns to 50 microns, whereas the size of fly ash flakes vary in the range of 5 microns to 25 microns with some flakes having sizes more than 50 microns and extending up to 100 microns (**Figure 1**).



(a) (b)

Figure 1. (a) SEM image of Fly ash Particulates; (b) SEM image of Silicon Carbide particulates.

Table 1. Composition specification in weight percentage of elements.

Alloy	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Others	
									Each	**Total**
5083	0.45	0.45	0.15	0.80	4.5	0.15	0.25	0.15	0.10	0.20

Table 2. Properties table of Al AA 5083 alloy.

Alloy	Tensile Strength (MPa)	Yield Strength (MPa)	Elongation in (%)	Density in kg/m^3	Elastic Modulus (GPa)	Mean Coefficient of Thermal Expansion µm/m˚C	Thermal Conductivity (W/m.K)	Electrical Conductivity MS/m at 20˚C
5083	280	160	8-12	2660	71	23.8	117	51

Table 3. Composition table of Fly ash.

Composition	Requirements (ASTM C618), %
SiO_2, Al_2O_3, Fe_2O_3 (min)	45 to 55
SO_3, max	4 to 5
Moisture content, max	3 to 4
Loss on Ignition, max	5 to 7

Table 4. Property table of silicon carbide.

Formula	IUPAC ID	Melting Point	Density	Molar Mass
SiC	Silicon carbide	2725˚C	3.24 g/cm^3	40.11g/mol

3. Material Processing Methodology

Stir casting of aluminium-silicon carbide-Fly ash composites is achieved in a graphite crucible mounted in an oil fired furnace fitted with a zircon-graphite coated mild steel stirrer with impeller attachments.

Ingots of Aluminium 5083 alloys are initially cut into small pieces and weighed for a specified accuracy of the scale and are preheated at a temperature of 400˚C for a duration of 60 minutes to 90 minutes before melting and mixing the preheated and electro-less nickel coated silicon carbide and fly ash particulates, The temperature of the furnace is at the first, raised to about 750˚C + 100˚C to begin with the melting of the aluminium metal pieces and then brought down to the preset liquidus temperature of aluminium to facilitate the dispersion of silicon carbide and fly ash particulates in the molten metal, further the slurry is stirred using the refractory coated mild steel impeller coupled to a motor with a varying speed gear box attachment.

After initial stirring of the molten metal and the reinforcements, the furnace temperature is set to maintain at a parametric range selected in current work and stirred at a preset speed for definite time duration.

The process parameters selected for stir casting the aluminium composites based on extensive review of literature and thorough evaluation of the capabilities of the equipment, are listed below in Table 5.

4. Experiments and Validation

The fatigue test is carried out on an Instron make Rotating beam fatigue testing machine, wherein the specimen is taken to be a beam loaded symmetrically at either ends such that the specimen is subjected to a cycle of tension and compression and thereby the flexural stresses above and below the neutral fibre becomes maximum and minimum during one course of loading [12]-[17]. The test is carried out for all the specimens in accordance with the ASTM F1160, ISO 1143 specifications and the values noted for further tabulation and statistical validations. The maximum load applied on specimen is 75 kg (735 N, Approximately 0.75 kN).

The specimen is a straight shank one, prepared as per the drawings given by Instron, the gauge diameter of the specimen is taken as 8 mm with the gauge length considered as 49.212 mm; the overall length of the specimen is considered at 87.31 mm (Figure 2).

The trials are carried out as per the design of experiments comprehensively including L16 orthogonal array using Taguchi method for characteristic evaluation.

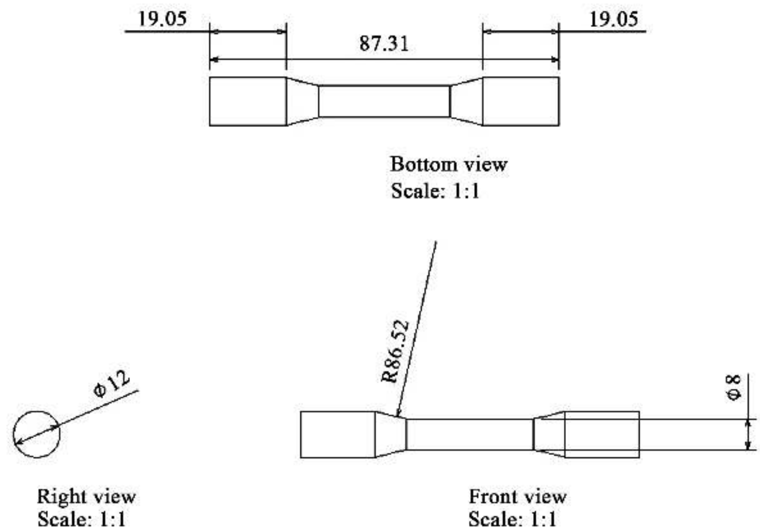


Figure 2. Specimen dimensions for Fatigue test (Source: Instron RRM Equipment Manual).

Table 5. Process parameters selected for stir casting.

Melt Temperature	Rotation Speed	Stirring Duration	Wt% of SiCp	Wt% of Fly ash
650	50	15	3	2
670	100	20	5	3
690	150	25	7	4
710	200	30	9	5

The Taguchi method is majorly used, especially in situations where the settings of many factors are necessary. The Taguchi method is extensively of help in processing of a composite and evaluation of the properties of the material developed. Henceforth it is very important to choose appropriate orthogonal arrays especially in case of multiple factors as in current work. An extensive of available literature has been carried out and appropriately a L_{16} orthogonal array is constituted for experimentations.

The L_{16} orthogonal array is constituted considering five factors namely, Melt temperature, Rotation speed, Stirring duration, Wt % of SiCp, Wt % of Fly ash, The table gives a matrix of 16 experiments that is carried out in particular relation to the factors and the response (which is the fatigue strength of the specimens) is noted for each and every trial. Further upon the analysis of variance is carried out to effectively determine the variation of means of the results obtained at the end of each trial.

The results of fatigue tests for different trials designed as per L_{16} orthogonal array are tabulated and further analyzed for optimized parameters, rank and delta values for each of the factors considered.

The specimens are evaluated for fatigue life and fracture behaviour and the data obtained are validated for authenticity.

In order to carry out the fatigue test, the specimen is held tightly by the collets and supported by the clamp using a press down type locking arrangement; the load to be applied on the specimen is decided upon the bending moment to be imposed. Better loading capabilities is ensured by making use of a pin support, otherwise the specimen will rotate without the application of load; once the specimen is loaded, the motor is started and thus the alternate cycles of load is imposed on either side of the neutral axis and there by flexural tensile stress and flexural compressive stress are imparted on the opposite sides of mid-plane [18] [19] [20] [21] [22] (**Figure 3**).

The endurance strength for the given specimen are generally calculated using either Soderberg, Goodman or Gerber equations, out of which Soderberg equation is the most conservative one, Thus Soderberg equation is considered as the governing equation for establishing the relationship for endurance strength of the specimens (**Figure 4**).

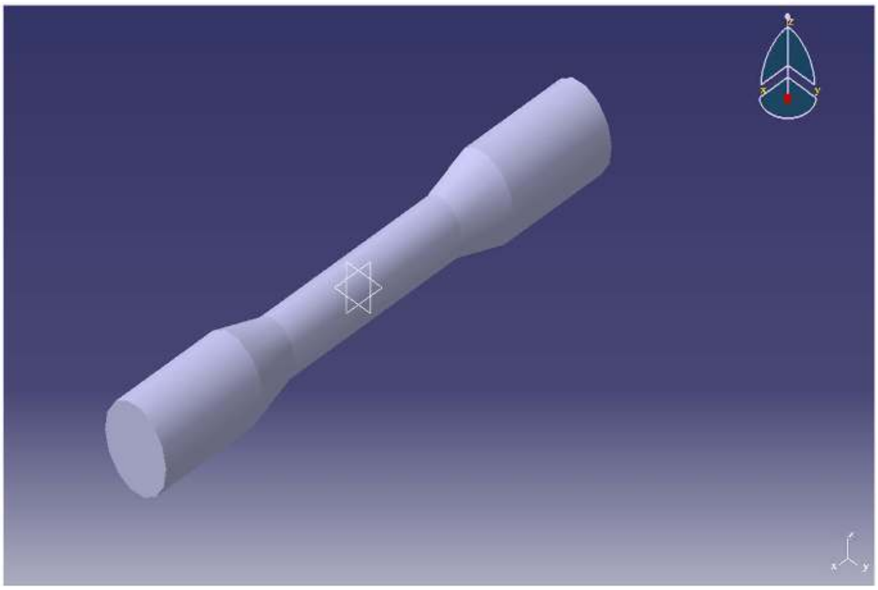


Figure 3. Catia part model of the fatigue specimen.

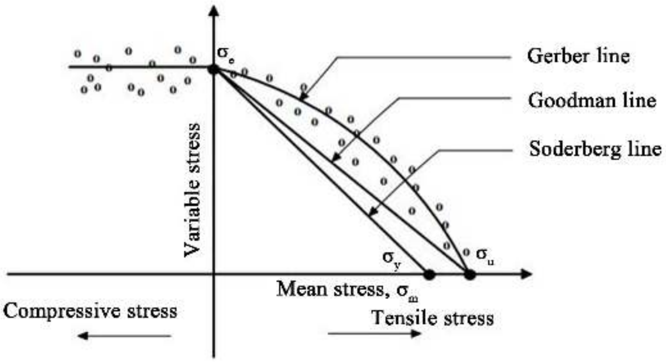


Figure 4. A typical schematic showing Gerber, Goodman and Soderberg lines and relation between the variable stress and the mean stress in an ideal fatigue test (Image Source: NPTEL Courseware) [23].

$$\frac{\sigma_a}{\sigma_e} + \frac{\sigma_m}{\sigma_o} = 1 \quad (1)$$

where σ_a is the stress amplitude, σ_e is the endurance limit, σ_m is the mean stress value and σ_o is the yield stress limit of the specimen.

The stress caused in specimen due to fatigue is determined from the experimentation using the equation

$$\sigma = \frac{M}{Z} \quad (2)$$

where M is the bending moment given by the equation

$$M = \frac{F * L}{4} \quad (3)$$

Z is the section modulus given by the equation

$$Z = \frac{\pi * d^3}{32} \quad (4)$$

5. Results and Discussion

5.1. Experimental Values

The results of the experiments carried out as per the L_{16} orthogonal array is presented as in the table below, and critical inferences are drawn based upon the results obtained.

The results of the fatigue test for different composition and parameters as obtained from L_{16} orthogonal array of Taguchi Genichi method are as tabulated in Table 6, it can be noticed from the table that the fatigue strength of the specimens ranges from a minimum of 138.65 MPa to a maximum of 218.52 MPa and the number of cycles to failure varies from a minimum of 8.29×10^3 cycles to a maximum of 4.37×10^7 cycles, *i.e.* the number of cycles to failure varies in the range of 10^3 cycles to 10^5 cycles for specimens with lesser endurance limit, (considered as fatigue strength in present work) whereas it ranges up to 10^9 cycles for specimens with higher endurance limit. The SN curve clearly indicates that the endurance limit is a major factor to exhibit fatigue behaviour by any material (Figure 5).

5.2. Taguchi Method

Taguchi genichi method mainly aims at optimizing the loss function. In this approach, basically the deviation of a value from its characteristic nominal value is optimized. It basically gives an overview of the uncontrollable factors termed as noise in this approach and its responsible parameters for deviation of the results in experiments. Thus it gives an array of different runs (trials) for conducting the experiments such that the design of experiments developed is robust to give optimal solutions. In Taguchi method the process and product parameters are set such that the variability is minimized and the results optimized, that is the design experiments is majorly aimed at designing experiments such the signal to

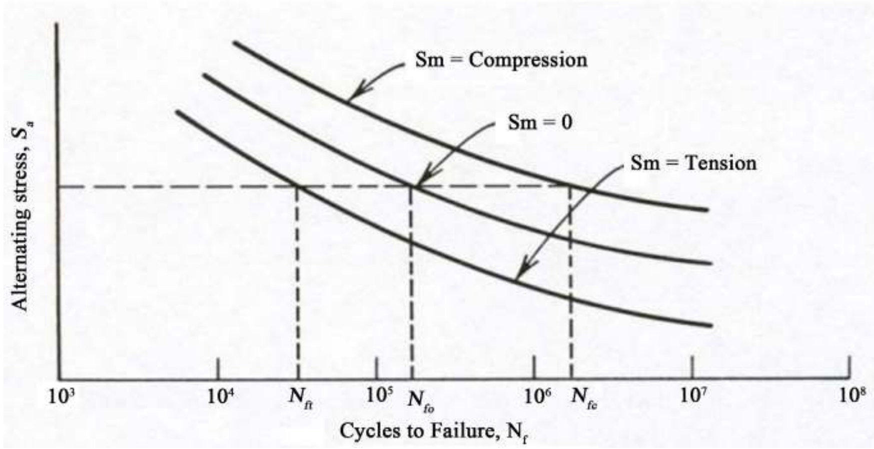


Figure 5. A Typical SN Curve for estimating the fatigue life (Image Source: Metal Fatigue in Engineering, 2nd Edn, Ralph I. Stephens, Ali Fatemi, Robert R. Stephens, Henry O. Fuchs) [24].

Table 6. Results of fatigue test carried out in the run order of L_{16} Orthogonal array.

Expt No. (as per L16 Orthogognal array)	Stress Range in MPa	Maximum Flexural Stress in MPa	Minimum Stress in MPa	Mean Stress in MPa	Stress Amplitude in MPa	Number of Cycles to failure, Range
1	286.58	143.29	−143.29	0	143.29	3.76e3, 5.25e5
2	340.22	170.11	−170.11	0	170.11	8.79e4, 7.46e6
3	369.34	184.67	−184.67	0	184.67	5.14e5, 8.64e7
4	384.76	192.38	−192.38	0	192.38	6.83e5, 9.17e7
5	420.88	210.44	−210.44	0	210.44	8.76e5, 1.11e9
6	437.04	218.52	−218.52	0	218.52	9.29e5, 2.64e9
7	288.4	144.20	−144.20	0	144.20	4.22e3, 6.12e5
8	312.66	156.33	−156.33	0	156.33	7.34e3, 8.10e5
9	363.18	181.59	−181.59	0	181.59	4.63e5, 7.19e7
10	335.12	167.56	−167.56	0	167.56	3.06e4, 5.22e6
11	389.48	194.74	−194.74	0	194.74	7.47e5, 9.33e7
12	277.3	138.65	−138.65	0	138.65	2.15e3, 5.01e5
13	377.84	188.92	−188.92	0	188.92	5.37e5, 9.13e7
14	330.98	165.49	−165.49	0	165.49	2.32e4, 4.21e6
15	343.36	171.68	−171.68	0	171.68	8.92e4, 7.81e6
16	379.64	189.82	−189.82	0	189.82	5.54e5, 9.56e7

noise ratios are determined to optimize the factors considered for design of the experiments. The signals to noise (SN) ratios are basically derived based on the loss functions as suggested by Taguchi. In current work, the condition of "Larger is Better", is considered for determining the SN ratio to evaluate the effect of design factors on fatigue behavior of the specimens. The response considered for evaluation is fatigue strength (Endurance limit) in MPa, with factors considered for the same being Melt temperature in degree Celsius, stirring speed in rpm, stirring duration in minutes, weight percentage of SiCp, weight percentage of fly ash. The plots obtained after Taguchi analysis is mean of means versus temperature and mean of SN ratios versus temperature. The critical elements of results of the Taguchi analysis are as tabulated (**Table 7**).

The main effect plot for SN ratios gives a clear inference that the weight percentage of silicon carbide is the major factor in deciding the fatigue strength followed by weight percentage of fly ash, stirring duration, stirring speed and melt temperature. The SN ratio is optimized for larger is better condition and tabulated (**Figure 6**).

From critical evaluation of the response **Table 8** for signal to noise ratios, it can be clearly seen that the weight percentage of silicon carbide is the major factor that improves the fatigue strength ranked first among all the other contributing factors, followed by weight percentage of fly ash, stirring duration, stirring speed and melt temperature. The combination of weight of about 9% of silicon carbide, weight of about 5% of fly ash, stirring duration of 15 minutes, stirring speed of 50 rpm, and melt temperature of 670˚C is the optimized set of parameters that will yield the best result, *i.e.* the maximum fatigue strength possible (**Figure 7**).

Table 7. L_{16} orthogonal array for design of experiments using Taguchi Genichi statistical validation methods.

Trial No.	Melt Temperature in ˚C	Stirring Speed in rpm	Stirring Duration in minutes	Wt% of SiCp	Wt% of Fly ash	Response in terms of Fatigue Strength (Endurance Limit) in MPa
1	650	50	15	3	2	143.29
2	650	100	20	5	3	170.11
3	650	150	25	7	4	184.67
4	650	200	30	9	5	192.38
5	670	50	20	7	5	210.44
6	670	100	15	9	4	218.52
7	670	150	30	3	3	144.20
8	670	200	25	5	2	156.33
9	690	50	25	9	3	181.59
10	690	100	30	7	2	167.56
11	690	150	15	5	5	194.74
12	690	200	20	3	4	138.65
13	710	50	30	5	4	188.92
14	710	100	25	3	5	165.49
15	710	150	20	9	2	171.68
16	710	200	15	7	3	189.82

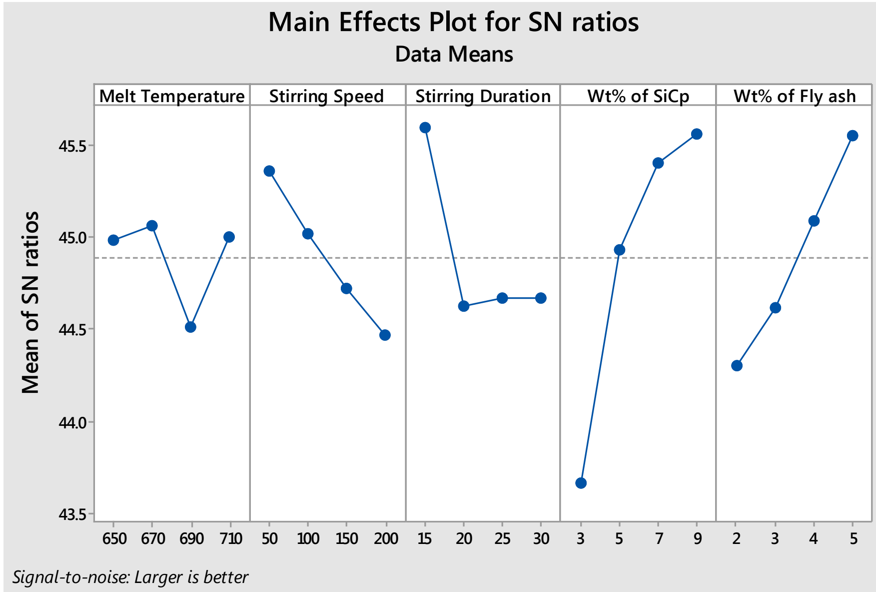


Figure 6. Main Effects Plot for SN ratios.

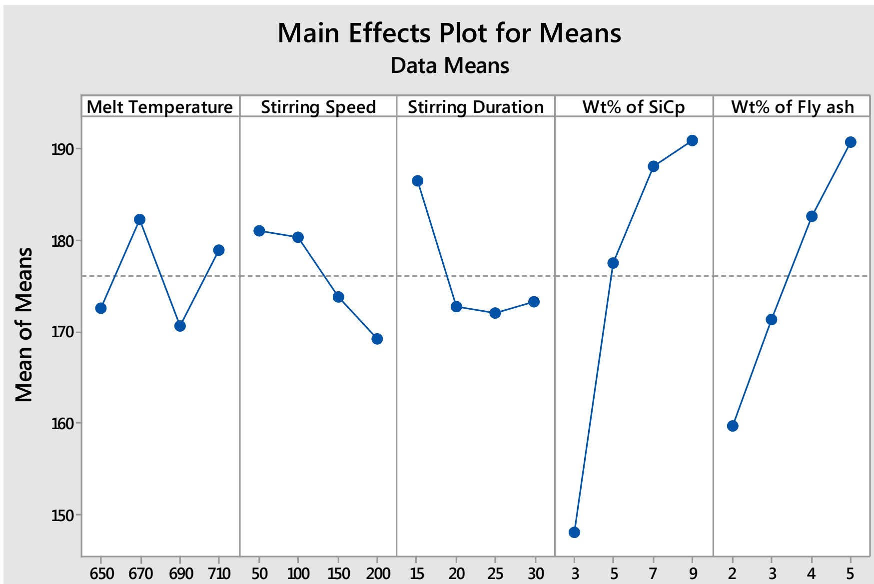


Figure 7. Mean of Means plot for different factors.

Table 8. Response matrix for signal to noise ratios (Larger is better).

Level	Melt Temperature	Stirring Speed	Stirring Duration	Wt% of SiCp	Wt% of Flyash
1	44.69	45.07	45.32	43.38	44.05
2	45.08	45.07	44.65	44.95	44.64
3	44.57	44.75	44.69	45.46	45.12
4	45.04	44.59	44.72	45.59	45.58
Delta	0.50	0.58	0.67	2.21	1.53
Rank	5	4	3	1	2

The main effect plot for mean of means gives a clear inference that the weight % of silicon carbide is the major factor which can enhance the fatigue strength of the specimens, followed by the weight % of fly ash, stirring duration, stirring speed and melt temperature.

From critical evaluation of response Table 9 for mean of means, it can be clearly seen that the mean of means of fatigue strength is maximum for a weight of 9% of silicon carbide, followed by a weight of 5% of fly ash, stirring duration of 15 minutes, stirring speed of 50 rpm and melt temperature of 670˚C.

Thus the Taguchi method gives an optimized set of values which yield maximum fracture strength among all the composites developed. These results can be used to further enhance the characteristics of composite materials developed by adopting process parameters provided by statistical validations as optimum from rigorous analysis.

5.3. Fractography

Fractography of the specimen is taken to visualize the fatigue zone, in which the stress is fully reversed; the irregular striations with random and crack front locations are identically seen in fractograph captured using SEM. The typical fractograph for the composite developed with 3% Silicon carbide and 2% Fly ash at a melt temperature of 650˚C, stirring speed of 50 rpm and stirring duration of 15 minutes is given in Figure 8.

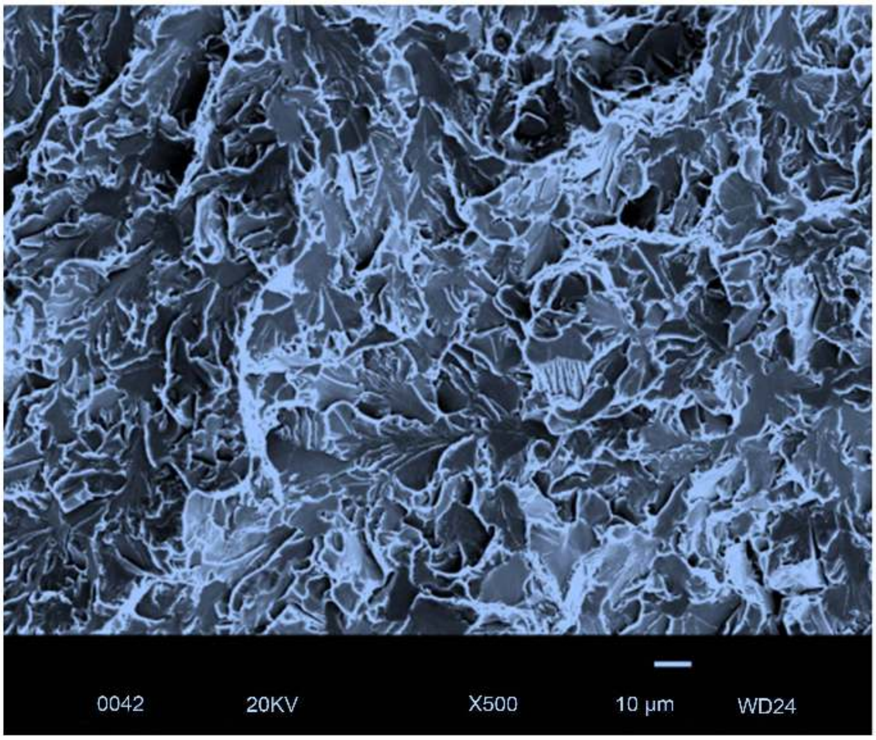


Figure 8. SEM Fractograph of Aluminium—3% SiC and 2% Fly ash composite specimen cast at a melt temperature of 650˚C, Stirring speed of 50 rpm and Stirring duration of 15 minutes.

Table 9. Response matrix for mean of means.

Level	Melt Temperature	Stirring Speed	Stirring Duration	Wt% of SiCp	Wt% of Flyash
1	172.6	181.1	186.6	147.9	159.7
2	182.4	180.4	172.7	177.5	171.4
3	170.6	173.8	172.0	188.1	182.7
4	179.0	169.3	173.3	191.0	190.8
Delta	11.7	11.8	14.6	43.1	31.0
Rank	5	4	3	1	2

From the fractograph, clear inferences can be drawn with regard to the mode of fracture which is essentially a ductile one, signified by the dimple structures and cavities interlaced with irregular striations. The cavities generally aggravate due to inclusions of precipitates that are enlarged further upon by repeated loading. The monotonic zone observed in the fractograph is an indication of the severe plastic deformation developed at the juncture of intermediate loading in the fatigue band of the specimen.

The fractograph of a fatigue specimen serves as the basis for analyzing the fracture mechanism in the component. The inferences drawn clearly give an overview of the failure of the specimen in the very context that the coarse slip bands formed provide the crack path that tends to be localized with varying stress intensity.

6. Conclusions

The analysis of the results obtained has yielded us with enough inferences to the very fact that the fatigue strength of the aluminium increases with the addition of particulate reinforcements, *i.e.* silicon carbide and interfacial lubricating particles in the form of fly ash particles. Furthermore, the conclusions drawn from the results of current work are:

1) The fatigue strength of specimens varies from a minimum of 138.65 MPa for the composite specimen developed with 3 weight percentage of SiCp, 4 weight percentage of fly ash at a melt temperature of 690˚C, stirring speed of 200 rpm and stirring time of 20 minutes to a maximum of 218.52 MPa for the composite specimen developed with 9 weight percentage of SiCp, 4 weight percentage of fly ash at a melt temperature of 670˚C, stirring speed of 100 rpm and stirring duration of 15 minutes.
2) The fatigue life cycle of the specimens varies from 10^3 cycles to 10^9 cycles with varying composition and process parameters. The fatigue life for the specimen with minimum fatigue strength of 138.65 MPa ranges from 2.15e3 to 5.01e5 cycles, while the fatigue life cycle for the specimen with maximum fatigue strength of 218.52 MPa ranges from 9.29e5 to 2.64e9 cycles.
3) The Taguchi method constituted using L_{16} orthogonal array has given a range of optimum parameters for the factors considered in the experimentation. The

SN ratio is considered to be optimum for "Larger is the best condition" and henceforth the ranking based on the delta value is the highest for silicon carbide and least for the melt temperature. *i.e.*, the effect of the weight percentage of silicon carbide as a factor on the fatigue strength is ranked first, followed by weight percentage of fly ash, stirring duration, stirring speed, and melt temperature.

4) The optimized set of values of 9 weight percentage of SiC, 5 weight percentage of Fly ash, stirring duration of 15 minutes, stirring speed of 50 rpm and melt temperature of 670˚C will yield the maximum fatigue strength based on the signal to noise ratio and mean values obtained from Taguchi analysis.
5) The fractographs clearly indicate the presence of irregular striations with random and crack front locations interlaced with dimple structures and cavities that are a distinctive feature of fatigue failure.

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