Materials Today: Proceedings 21 (2020) 1441–1445

Contents lists available at ScienceDirect

Materials Today: Proceedings

journal homepage: www.elsevier.com/locate/matpr

Parametric optimization of fatigue behaviour of hybrid aluminium metal matrix composites

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ARTICLE INFO

Article history:
Received 22 July 2019
Received in revised form 13 September 2019
Accepted 1 October 2019
Available online 29 October 2019

Keywords:
Fatigue
Metal matrix composites
Stir casting
Reinforcements
Optimization
Analysis of variance

ABSTRACT

For various aerospace applications aluminium has emerged as most preferred material due to desirable attributes such as superior strength to density ratio, greater specific strength, better corrosion resistance, high toughness and cost effectiveness. The most desirable characteristics for aerospace materials are ability to withstand elevated temperature and sustain higher fatigue loadings. Current experimental investigation was carried out to explore and optimize fatigue characteristics of hybrid composites developed by infusing particulate reinforcements into aluminium alloy. Eggshell particles (wt% 0.5, 1 and 1.5, average particle size ≈ 60 μm), Silicon Carbide particles (wt% 1, 1.5 and 2, average particle size ≈ 65 μm) and Aluminium Oxide particles (wt% 1.5, 2 and 2.5, average particle size ≈ 90 μm) were reinforced into Al 7075-T6 metal matrix through electromagnetic stir casting route as per L9 orthogonal array of Taguchi's approach in order to synthesize hybrid aluminium metal matrix composites with enhanced fatigue resistance. Analysis of variance (ANOVA) was also conducted to observe the effect of different process parameters on fatigue life of developed composites. Nine hybrid composite specimens and one as-cast Al7075 -T6 specimen (in three replications) were prepared in accordance with ASTM E 468/606 and were evaluated for low cycle fatigue resistance at a constant load of 2 kg and constant speed of 500 rpms on rotating beam fatigue testing machine. It was observed that at 30 °C temperature, hybrid composite specimens exhibited significant enhancement in fatigue resistance in terms of reversible load cycles survived. The as-cast Al 7075-T6 specimen sustained only 94 load cycles while the highest number of load cycles i.e. 4560 were survived by hybrid composite specimen with Al 7075-T6 as base metal reinforced with 1.5 wt% of eggshell particles, 1.5 wt% of SiC particles and 1.5 wt% of Al_2O_3 particles (total reinforcement content only 4.5%) and mechanically stirred for 360 s.

Selection and peer-review under responsibility of the scientific committee of the International Conference on Mechanical and Energy Technologies.

1. Introduction

In recent years, metal matrix composites have emerged as insurgent engineering materials for aerospace and automobile applications. They are developed with an objective to have adjustable attributes by varying base metal, reinforcements and process parameters. Different metals such as magnesium, nickel and titanium etc are used for synthesis of metal matrix composites but aluminium is most preferred due to its light weight, high specific strength, better machinability and cost effectiveness [1,2]. The environmental regulations related to fuel consumption also support the usage of light weight aluminium metal matrix composites in avionic sector. Aluminium alloys infused with different particle reinforcements exhibit significantly enhanced mechanical properties such as strength, hardness, wear and fatigue resistance along with intrinsic homogeneity [3,4]. Fatigue behavior of aluminium composites is proven to be better due to low crack propagation rates as compared to their unreinforced counter parts. Aluminum mixed with SiC particles displayed increased fatigue resistance. Al 2024/SiC composites exhibited improved fatigue endurance at elevated temperatures [5]. However, aluminium matrix infused with single reinforcement may show enhancement in certain characteristics with simultaneous deterioration in other critical properties hence endorsing the synthesis of hybrid aluminium metal

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https://doi.org/10.1016/j.matpr.2019.10.002
2214-7853/
Selection and peer-review under responsibility of the scientific committee of the International Conference on Mechanical and Energy Technologies.

Table 1
Elemental composition of Al 7075-T6 [6].

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Others	Al
0.40	0.50	1.2–2.0	0.30	2.1–2.9	0.18–0.28	5.1–6.1	0.2	0.15	Remaining

Table 2
Experiment design.

Composite specimen	Eggshell Particles weight fraction (wt%)	Silicon Carbide Particles weight fraction (wt%)	Aluminium Oxide Particles weight fraction (wt%)	Mechanical stirring time (s)
S1	0.5	1	1.5	120
S2	0.5	1.5	2	240
S3	0.5	2	2.5	360
S4	1	1	2	360
S5	1	1.5	2.5	120
S6	1	2	1.5	240
S7	1.5	1	2.5	240
S8	1.5	1.5	1.5	360
S9	1.5	2	2	120
S0	As-cast Al 7075-T6			

matrix composites with more than one filler [7]. In current experimental study hybrid aluminium composites were synthesized by infusing three particulate reinforcements (Eggshell powder, Silicon Carbide powder and Aluminum Oxide powder) into base metal with the help of stir casting. The most prevalent challenge in

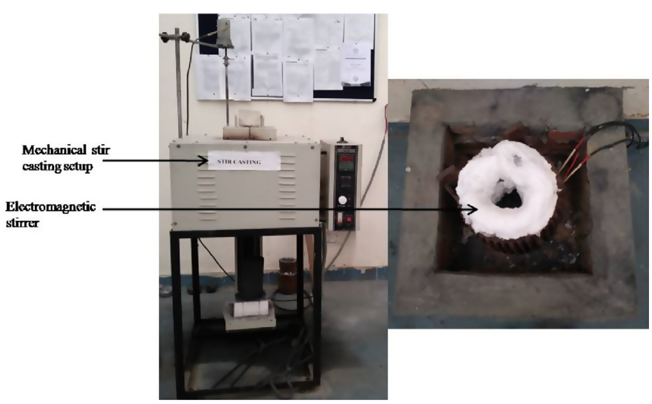

Fig. 1. Electromagnetic Stir casting setup.

Fig. 3. Castings.

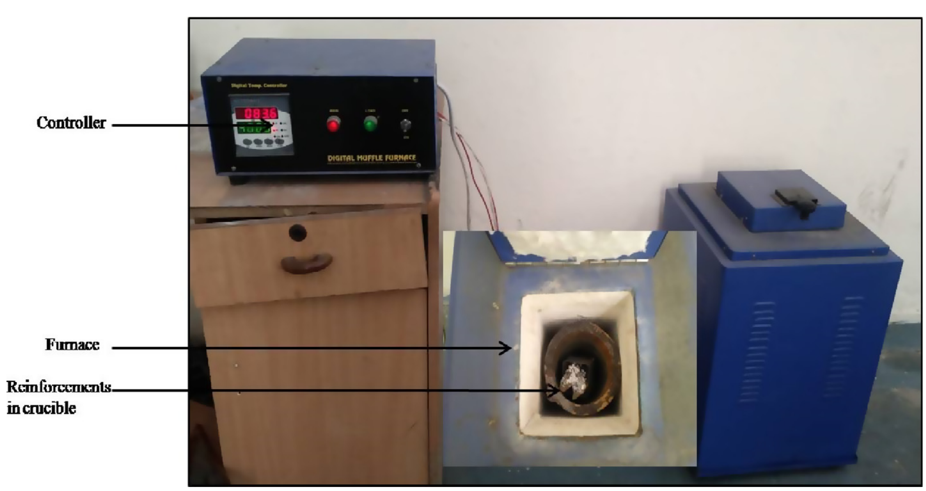

Fig. 2. Furnace for reinforcement preheating.

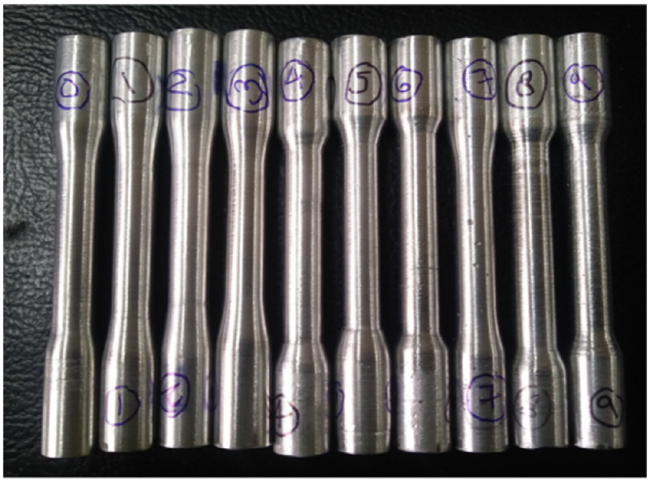

Fig. 4. Fatigue test specimens.

synthesis of particulate metal matrix composites is clustering of reinforcement particles resulting into their non-uniform dispersion in metal matrix and causing premature failure of fabricated mechanical components [8,9]. Sometimes it is also observed that under strain controlled cyclic loading conditions; composites demonstrated inferior low cyclic fatigue resistance which may be attributed to high dislocation densities near interfaces, stress concentrations close to reinforcement particles and restricted plastic flow of metal matrix [10,11]. Here an electromagnetic stirrer (3 phase, 10 hp electric motor) in conjunction with mechanical stir casting setup was used to provide uniform dispersion of reinforcement particles and homogeneous microstructure of synthesized composites resulting into enhanced mechanical properties.

2. Experimental procedure

Al 7075-T6 alloy was used as metal matrix for this experimental investigation. The elemental composition of base metal is given in Table 1.

Eggshell particles (average particle size ≈ 60 μm, wt% 0.5, 1 and 1.5), Silicon Carbide particles (average particle size ≈ 65 μm, wt% 1, 1.5 and 2) and Aluminium Oxide particles (average particle size ≈ 90 μm wt% 1.5, 2 and 2.5) were reinforced into Al 7075-T6 metal matrix as per Taguchi's orthogonal array L9 given in Table 2 to prepare nine hybrid composite specimens using experimental setup as shown in Fig. 1. Cleaned aluminium ingots were kept into graphite crucible in an electric furnace and heated upto 900 °C. In parallel, calculated and weighed reinforcements content was preheated in a muffle furnace (Fig. 2) for one hour at 500 °C to remove moisture and enhance wettability for uniform infusion of reinforcements into metal matrix [2].

Fig. 5. Rotating beam fatigue testing machine and broken test specimen.

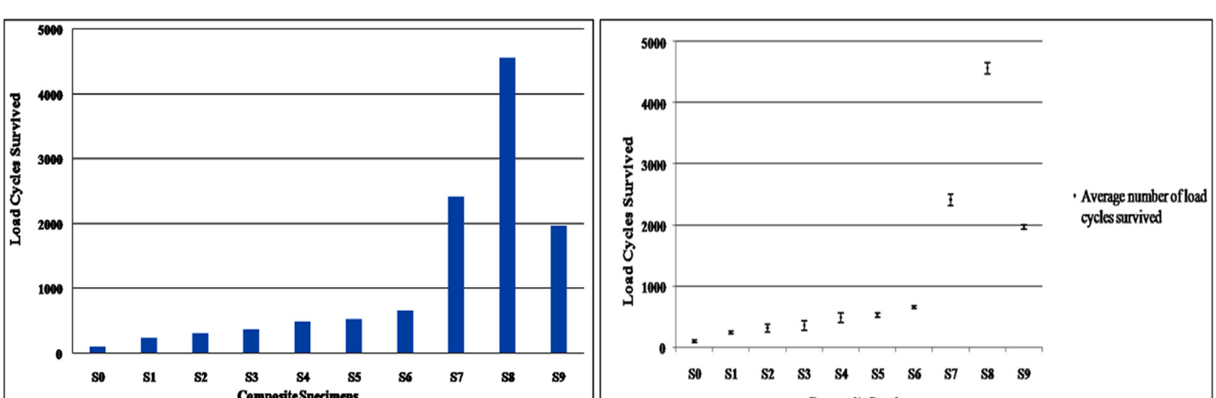

Fig. 6. Fatigue resistance of test specimens.

Preheated reinforcements were added to molten metal and stirred mechanically for specified period of time, as given in Table 2. The crucible with molten metal and reinforcement's mixture was further put into electromagnetic stirrer for additional 30 s to conceive better mixing and uniform dispersion of perform into metal matrix. After 30 s of electromagnetic stirring, hybrid composite and Al 7075-T6 castings (Fig. 3) were allowed to solidify and standard fatigue test specimens (Fig. 4) were prepared as per ASTM E 468/606 (in three replications) for rotating beam fatigue test (Fig. 5) with a fixed load of 2 kg and constant speed of 500 rpms to evaluate them for low cycle fatigue resistance.

3. Result and discussions

As-cast Al 7075-T6 standard fatigue specimen along with nine hybrid aluminium composite standard specimens, in three replications were investigated for fatigue resistance on rotating beam fatigue testing machine. The comparative low cycle fatigue resistance of various specimens is shown in Fig. 6.

For parametric optimization, Taguchi approach depending upon certain instructions provides guidance to conduct least number of experiments to obtain information about various control factors in terms of S/N ration and mean response [12]. Analysis of variance

Table 3
Various process parameters with levels.

Control parameters	Factors nomination	Level 1	Level 2	Level 3
Eggshell particles weight fraction (wt%)	A	0.5	1	1.5
Silicon carbide particles weight fraction (wt%)	B	1	1.5	2
Aluminium oxide particles weight fraction (wt%)	C	1.5	2	2.5
Mechanical Stirring time (s)	D	120	240	360

Table 4
Observations for reversible load cycles survived and S/N ratio.

Load cycles survived					
Load cycles survived by as-cast Al7075-T6 Specimen S0: 94					
Composite Specimen	Observation 1	Observation 2	Observation 3	Mean	S/N ratio (dB)
S1	234	230	233	232	45.56
S2	307	300	314	307	47.98
S3	361	355	345	354	49.21
S4	480	470	485	478	51.83
S5	521	520	515	519	52.54
S6	650	652	648	650	54.5
S7	2410	2396	2415	2407	65.87
S8	4560	4555	4572	4562	71.42
S9	1970	1965	1972	1969	64.12

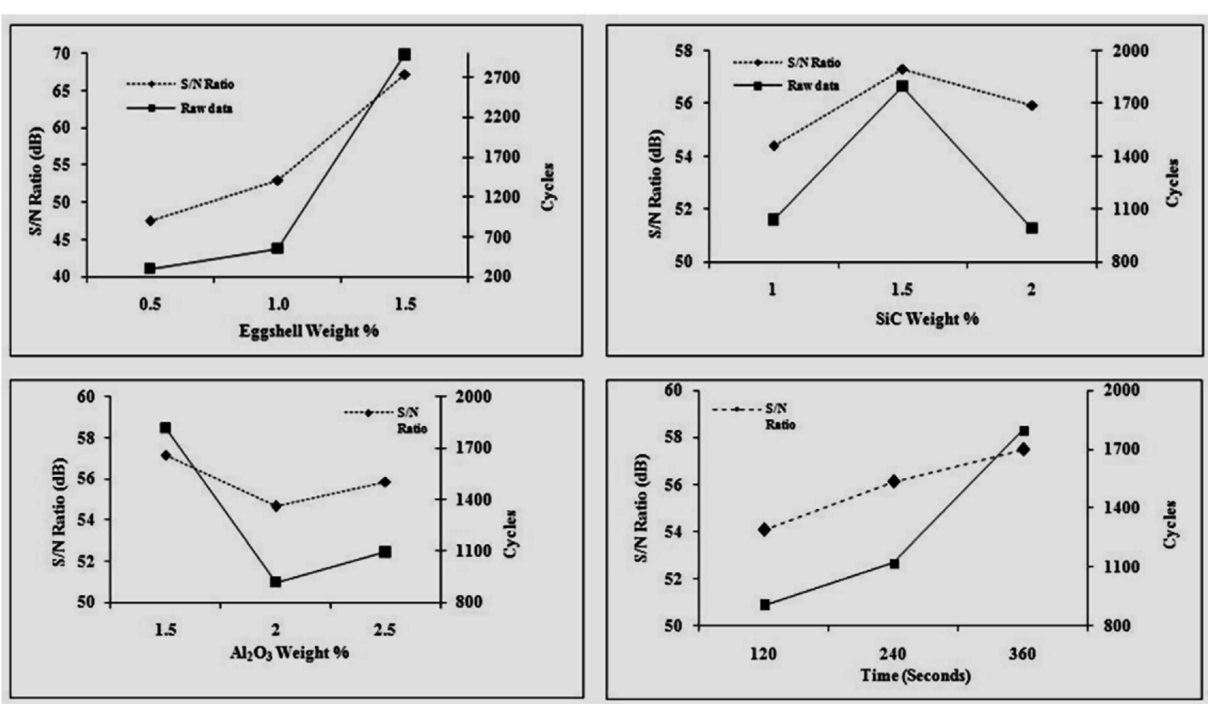

Fig. 7. Control factor effects on fatigue resistance and S/N ratio.

Table 5
Analysis of variance (ANOVA) for fatigue resistance.

Factor	Sum of squares (SS)	Degrees of freedom	Variance (V)	Percentage contribution (P)	F-Ratio
Eggshell particles weight fraction (wt%)	394864.1	2	197432.05	25.33	4704.93
Silicon carbide particles weight fraction (wt%)	366975.85	2	183487.93	23.54	4372.64
Aluminium oxide particles weight fraction (wt%)	406739.63	2	203369.82	26.09	4846.43
Mechanical Stirring time (s)	389634.41	2	194817.21	24.99	4642.62
Others/errors	755.33	18	41.96	0.05	–
Total	1558969.32	26	–	100	–

Table 6
Confirmation experiment for fatigue resistances.

Quality characteristic	Replications			Mean
Fatigue resistance of composites in terms of load cycles survived	Replication 1 4569	Replication 2 4597	Replication 3 4539	4568

(ANOVA) was carried out to study the effect of process parameters on quality characteristics i.e. low cycle fatigue resistance. The process parameters for present study with their levels are given in Table 3.

Fatigue test observations corresponding to three replications of developed hybrid composite specimens with respective S/N ratio for "larger the better" type of quality characteristic are given in Table 4.

Graphs in Fig. 7 exhibit the influence of different control factors on signal to noise ratio and fatigue resistance of synthesized hybrid composites. For maximum fatigue resistance (in terms of reversible load cycles survived) and S/N ratio, optimum control factor levels are A_3, B_2, C_1 and D_3.

ANOVA results in terms of F-ratio and percentage contribution of different process parameters, computed at a confidence level of 95% are given in Table 5. It can be interpreted from Table 5 that all the four process parameters Eggshell wt%, Silicon Carbide wt%, Aluminium Oxide wt% and mechanical stirring time have significant influence on low cycle fatigue resistance of synthesized hybrid composites.

S/N ratio and mean response characteristics analysis was carried out using optimum levels of significant factors as A_3, B_2, C_1 and D_3 for prediction of load cycles survived (Z_{mp}). Following components were evaluated using experimental data from Table 4.

$\overline{G} = 1275.37$, $\overline{A_3} = 2979.44$, $\overline{B_2} = 1796$, $\overline{C_1} = 1814.89$ and $\overline{D_3} = 1798.11$

$$Z_{mp} = \overline{G} + \left(\overline{A_3} - \overline{G}\right) + \left(\overline{B_2} - \overline{G}\right) + \left(\overline{C_1} - \overline{G}\right) + \left(\overline{D_3} - \overline{G}\right) \quad (1)$$

Predicted mean optimum value of low cycle fatigue resistance in terms of number of load cycles survived by composites $Z_{mp} = 4562$ was obtained using Eq. (1). From Table 5, error variance = 41.96 and DOF for error = 18 were observed. At 95% confidence interval, F-ratio value was determined from standard statistical table and the confidence interval (CI) calculated was ± 11. Confidence interval for predicted optimum load cycles survived with respect to 95% confidence level was 4562 ± 11, i.e. 4551 < load cycles survived (LCS) < 4573. Further a confirmation experiment was conducted by running three additional replications for fatigue resistance in synthesized composites at optimal levels of control factors. Confirmation experiment observations are given in Table 6 and it was recorded that mean number of load cycles survived by composite were 4568 falling within the confidence interval i.e. 4551 < FCS < 4573, hence being in good agreement with Taguchi optimization technique.

In present investigation, the enhancement in fatigue resistance of developed hybrid composites may be attributed to the load bearing performance of hard filler particles, restricting the dislocation movement and strain localization initiated at reinforcement-base metal interface [13–14].

4. Conclusion

In present experimental study, Al 7075-T6/Eggshell/SiC/Al_2O_3 hybrid composites were synthesized through electromagnetic stir casting route. Developed hybrid composites were investigated for low cycle fatigue resistance and it was observed that on infusing a very nominal amount of reinforcements (total reinforcements wt% = 4.5 only) into metal matrix, number of load cycles survived increased upto many folds in comparison to their unreinforced counterparts. The as-cast Al 7075-T6 specimen S0 survived only 94 reversible load cycles whereas the highest number of load cycles i.e. 4562 was survived by composite specimen S8 with optimum levels of control factors A_3 (Eggshell wt% 1.5), B_2 (Silicon carbide wt% 1.5), C_1 (Aluminium oxide wt% 1.5) and D_3 (mechanical stirring time 360 s). At 95% confidence interval, the forecasted optimum value of load cycles survived was 4551 < load cycles survived (LCS) < 4573 followed by a confirmation experiment with 4568 mean load cycles survived. The confirmation experiment observations fell within the forecasted confidence interval thus supporting Taguchi's approach for experiment design and parametric optimization, hence posing the synthesized composites suitable for light weight fatigue resistant applications.

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