Studies on Tensile Response of Aluminium Alloy/Soda lime Glass Composites at Elevated Temperature through Taguchi's Orthogonal Array Approach

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Abstract

Al-Si eutectic based metal matrix composites with soda lime glass powder as reinforcement were produced using stir casting technique. Glass particles of average size 75, 125 and 210 micron, at three different levels (1.5, 3.0 and 4.5 wt.%) formed the reinforcement. Taguchi's orthogonal array approach was used to design the experiments. Ultimate tensile strength (UTS) was evaluated at elevated temperatures for these composites and the significant factors that influence the UTS were identified. A regression analysis was employed to analyze the variation of UTS.

Keywords: Ultimate tensile strength, Composite materials, glass particles, Al-Si alloy, Taguchi's orthogonal array.

1. Introduction

Aluminium and its alloys have wide use in engineering applications, especially in the aerospace and automobile fields. Aluminium alloys inherently have high strength-to-weight ratio but suffer from inadequate yield strength, low wear resistance and poor thermal properties. As alloy development has almost reached saturation, the enhanced demands have to be met by newer class of materials such as metal matrix composites (MMCs). Tailoring of specific properties is achieved in MMCs by incorporating a controlled amount of ceramic particles or fibers in a base metal matrix. A number of material combinations have been attempted and documented in the literature. Applications of MMCs range from structural components to electronic packaging.

Substantial development work has been carried out on aluminium based MMCs with ceramics (silicon carbide, alumina, zirconia, silica and graphite) as the reinforcement [1]. However, the use of non-refractory materials such as glass powder as reinforcement in MMCs has not been attempted extensively [2]. Compared to the other reinforcing materials in use, glass offers several advantages, in particular on the fronts of availability and cost. Likewise, several aluminium alloys have been investigated by previous workers as the matrix, but the most versatile cast alloy viz., Al-Si eutectic (LM6 alloy) has not been exploited so much. Therefore, there seems to be scope and immediate need to undertake an experimental investigation to produce LM6 based, glass powder reinforced MMCs and to characterize the MMCs thus produced for physical, mechanical thermal and other properties and micro-structural features.

2. Experimental details

2.1 Preparations of composites

LM6 aluminum alloy (eutectic alloy) is the most widely used aluminum cast alloy. Hence, this alloy was chosen for the present work as matrix and soda lime glass powder as the reinforcement material. Soda lime glass powder of required fineness was obtained after crushing and sieving commercially available soda lime glass sheets. The compositions of the base alloy LM6 and soda lime glass are shown in Table 1 and 2 respectively.

Table 1. Chemical composition of LM6 alloy

Element	Wt. %
Si	11.24
Cu	0.08
Mg	0.1
Fe	0.46
Mn	0.14
Ti	0.16
Ni	0.01
Zn	0.01
Lead	0.01
Al	Balance

Table 2. Chemical composition of commercial soda lime glass

Constituent	Wt. %
SiO_2	71-73
Na_2O_2	14-15
CaO	8-10
MgO	1.5-3.5
Al_2O_3	0.5-1.5

Pre-treatment of reinforcement particles consists of cleaning the particles with alcohol and drying them before pre-heating. Pre-treatment and pre-heating of reinforcement improve the wetting and dispersion of particles in the matrix. In addition, a small amount of magnesium (0.50%) was added to the melt to promote wetting of glass powder by the liquid alloy. Optimization of the process parameters and procedure was required to produce composite materials with homogeneous distribution of reinforcement particles and to get composites with minimum level of micro-structural defects. Earlier trials showed that the temperature of the matrix alloy before the introduction of glass powder is one of the important parameter [4]. Furthermore, the rate of introduction of the particles, pre-treatment of reinforcement and stirring parameters are also important to achieve good quality composites.
LM6 alloy ingots were charged into a graphite crucible and melted in a resistance heated furnace. When the melt reached 720^oC, which is well above the melting temperature of LM6 alloy, about 10 gm of magnesium was added in order to improve wetting. This was followed by degassing with hexa-chloro-ethane.
Melt was positioned under the stirrer and stirred at a fixed stirring speed of 400 RPM to form a sufficiently large vortex. Pre-heated soda lime glass powder was added at the rate of 20 gm per min. to the vortex point. After adding the particles, impeller was driven for some more time till the temperature of the melt lowered to 640^oC. Soon after, the melt mixture was poured into the metallic die pre-heated to 200^oC.
LM6 alloy /soda lime glass particles composites with 1.5%, 3.0% and 4.5 % (weight fraction), and 75, 125 and 210 micron (average particle size) at different pre-heated temperatures (260^oC, 380^oC and 500^oC) of soda lime glass powder were produced using above procedure.

2.2 Design of experiments

Taguchi's orthogonal array (OA) for three factors (each at three levels) was used in planning the experimentation. Based on the degrees of freedom on levels of factors, $L_9(3^4)$ OA was selected. LM6 alloy/soda lime glass particulate composites in this work were prepared with the three control variables viz., weight fraction, particle size and pre-heat temperature of reinforcement, each at three levels listed in Table 3.

The L_9 array of Taguchi for the test is shown in Table 4. The influence of reinforcement parameters was evaluated using Signal-to-Noise ratio (SN ratio) analysis.
SN ratio for '*larger is the better*' quality characteristic = $-10 \log_{10} (1/n) \sum (1/y_i^2)$
('n' is the number of observations and 'y_i' is the observed data).

Table 3.Levels of the reinforcement parameters

Control factor	Level		
	1	2	3
A: Weight Percent	1.5	3.0	4.5
B: particle size (micron)	75	125	210
C: Pre-heat temperature (^oC)	260	380	500

Table 4.Taguchi orthogonal array $L_9(3^4)$

Test Run	A: Weight percent	B: Particle size (micron)	C: Pre-heat temperature (^oC)
1	1.5	75	260
2	1.5	125	380
3	1.5	210	500
4	3.0	75	380
5	3.0	125	500
6	3.0	210	260
7	4.5	75	500
8	4.5	125	260
9	4.5	210	380

2.3 Assessment of UTS

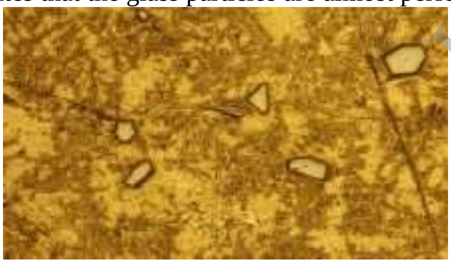
INSTRON tensile testing machine was used to determine the UTS of the test specimens (prepared as per ASTM standard Designation: **E 8/E 8M – 08**) at elevated temperatures. The specimen was enclosed in the heating furnace and tested at the selected elevated temperature maintained by the furnace. Thermocouples and regulators control the temperature in the furnace. The machine is interfaced with computer having suitable software.

Figure 1. INSTRON Tensile test equipment

3. Results and Discussions

3.1 Microstructures

Micro-structural examination of the composite was conducted to confirm uniform distribution and interface bonding of reinforced glass particles in the LM6 alloy matrix. Typical microstructures are shown in the Figures 2(a) and 2(b). It may be inferred that glass particles are uniformly distributed in the LM6 alloy matrix. The cast microstructure of the LM6 alloy is not significantly affected by the presence of the reinforcing glass phase. In particular, no casting defect such as porosity was found at the interface between the glass particle and the matrix. This indicates that the glass particles are almost perfectly



(a) 1.5%glass reinforcement (400X)

(b) 4.5% glass reinforcement (100X)

Figure 2.Microstructure of LM6 alloy/ glass composite

embedded inside the LM6 alloy matrix without any interface de-bonding. This is due to adequate wettability between glass particles and LM6 alloy matrix.

3.2 Tensile Behavior

Nine samples of LM6 alloy/soda lime glass particles composites were produced as per the design parameter combinations as per the L_9 (3^4) orthogonal array. The experimental runs were done each with three replications. UTS values were assessed and SN ratio was calculated for every run. Tensile tests were carried out at three different test temperature conditions viz., 30°C, 100°C and 200°C respectively. The results were analyzed using the commercial software MINITAB14, specifically meant for design of experiment applications. The influence of reinforcement parameters on UTS was then evaluated using SN ratio response table. The ranking of the process parameters using SN ratios obtained for different parameter levels for UTS are shown in Tables 8, 9 and 10 respectively corresponding to test temperatures of 30°C, 100°C and 200°C.

3.2 Main Effect Plot

Figures 4, 5 and 6 show the main effects plots (data means) for SN ratio corresponding to the three test temperatures viz., 30°C, 100°C and 200°C. It may be seen that among all the factors, weight percent of glass powder is the most significant, followed by particle size. Pre-heat temperature of the glass particle has the least or almost no significant influence on UTS. The UTS corresponding to factor A (weight percent) is maximum at level 1 compared to levels 2 and 3. For factor B (particle size), at level 1, UTS is maximum. The analysis of the responses based on SN ratio leads to the conclusion that factor combination A1:B1 results in the maximum UTS. The optimum combination of reinforcement parameters levels were selected for the higher SN ratio values and the results are tabulated in Table 11. Results distinctly reveal that soda lime glass particle reinforcements do reduce the UTS significantly. It is also observed UTS of the MMCs decrease steadily at elevated temperatures.

Table 5. Experimental data with mean UTS and SN ratio (test temperature: 30°C)

Test Run	A	B	C	Observed values of UTS (MPa)			Mean UTS (MPa)	SN ratio (dB)
1	1.5	75	260	195.30	159.10	172.30	175.567	44.7970
2	1.5	125	380	180.36	158.74	165.80	168.300	44.4854
3	1.5	210	500	167.91	151.19	168.34	162.480	44.1830
4	3.0	75	380	142.40	159.60	143.21	148.403	43.3935
5	3.0	125	500	150.01	135.12	142.21	142.447	43.0493
6	3.0	210	260	139.83	127.38	136.80	134.670	42.5646
7	4.5	75	500	108.77	132.92	120.85	120.847	41.5574
8	4.5	125	260	119.23	100.64	98.89	106.253	40.4362
9	4.5	210	380	97.87	80.90	91.87	90.213	39.0231

Table 6. Experimental data with mean UTS and SN ratio (test temperature: 100°C)

Test Run	A	B	C	Observed values of UTS (MPa)			Mean UTS (MPa)	SN ratio (dB)
1	1.5	75	260	149.24	148.33	150.10	149.223	43.4764
2	1.5	125	380	150.13	141.20	149.32	146.883	43.3294
3	1.5	210	500	149.86	142.56	137.67	143.363	43.1130
4	3.0	75	380	138.23	141.10	140.72	140.017	42.9225
5	3.0	125	500	152.55	120.46	142.16	138.390	42.6930
6	3.0	210	260	135.94	142.45	130.81	136.400	42.6805
7	4.5	75	500	132.23	127.78	127.13	129.047	42.2110
8	4.5	125	260	122.1	121.29	116.92	120.103	41.5863
9	4.5	210	380	118.10	116.42	114.51	116.343	41.3128

Table7. Experimental data with mean UTS and SN ratio (test temperature: 200°C)

Test Run	A	B	C	Observed values of UTS (MPa)			Mean UTS (MPa)	SN ratio (dB)
1	1.5	75	260	143.9	146.12	143.47	144.50	43.1963
2	1.5	125	380	138.16	139.53	138.19	138.63	42.8367
3	1.5	210	500	120.10	126.78	124.44	123.77	41.8460
4	3.0	75	380	126.12	124.94	125.10	125.39	41.9648
5	3.0	125	500	122.34	122.10	121.73	122.06	41.7312
6	3.0	210	260	125.28	122.54	114.35	120.72	41.6160
7	4.5	75	500	98.87	103.56	98.74	100.39	40.0274
8	4.5	125	260	88.76	102.45	91.56	94.26	39.4374
9	4.5	210	380	92.30	84.38	81.72	86.13	38.6692

Table 8. Response table –SN ratios for UTS (Test temperature: 30°C)

Level	A	B	C
1	44.49	43.25	42.60
2	43.00	42.66	42.30
3	40.34	41.92	42.93
Delta	4.15	1.33	0.63
Rank	**1**	**2**	**3**

Table 9. Response table –SN ratios for UTS (Test temperature: 100°C)

Level	A	B	C
1	43.31	42.87	42.58
2	42.77	42.54	42.52
3	41.70	42.37	42.67
Delta	1.60	0.50	0.15
Rank	**1**	**2**	**3**

Table 10. Response table –SN ratios for UTS (Test temperature: 200^{o}C)

Level	A	B	C
1	42.63	41.73	41.42
2	41.77	41.34	41.16
3	39.38	40.71	41.20
Delta	3.25	1.02	0.26
Rank	**1**	**2**	**3**

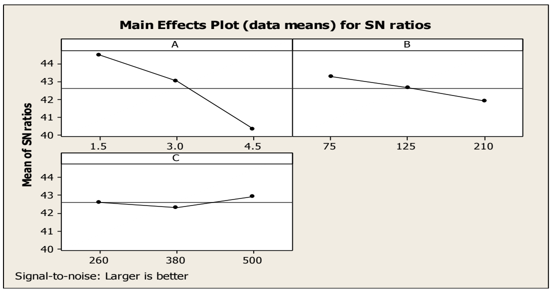


Figure 3.Main effects plot (data mean) for SN ratios (Test temperature- 30^{o}C)

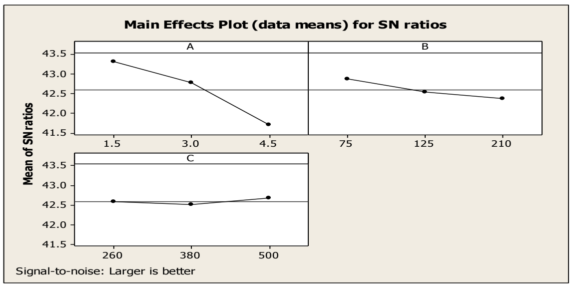


Figure 4.Main effects plot (data mean) for SN ratios (Test temperature- 100^{o}C)

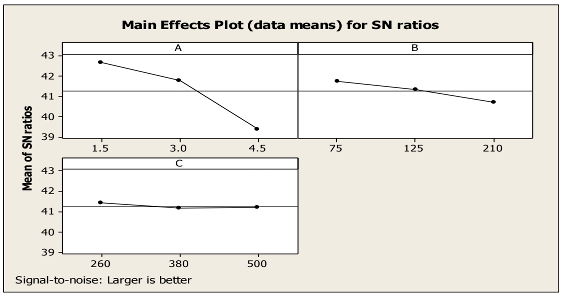


Figure 5.Main effects plot (data mean) for SN ratios (Test temperature- 200^{o}C)

3.3 Regression Analysis

The weight percent, particle size and temperature of the glass particles were considered in the development of mathematical models for UTS. The correlation between factors and UTS on LM6 alloy/soda lime glass composite was obtained through multiple linear regressions. The standard commercial statistical software package MINITAB14 was used in the model. Following are the regression equations thus developed.

Regression equation (Test temperature- 30^{o}C):
UTS(MPa) = 216 - 21.0 A - 0.139 B + 0.0129 C
[R^2 = 97.9%]

Regression equation (Test temperature- 100^{o}C):
UTS(MPa) = 165 - 8.22 A - 0.0528 B + 0.0070 C
[R^2 = 94.3%]

Regression equation (Test temperature- 200^{o}C):
UTS(MPa) = 180 -14.0 A – 0.0976 B – 0.0184 C
[R^2 = 94.3%]

In the multiple regression analysis, R^2, the regression coefficient has values > 0.94 in all the models. This indicates that the fit of the experimental data is highly satisfactory. From the regression equations, it is observed that the weight percent of the glass particles plays prominent role in controlling UTS, followed by glass particle size. The negative value of the coefficient corresponding to the weight percent of the glass particles indicates that decrease in weight percent of the glass particles increases the UTS.

3.4 Confirmation Experiment

The experimental confirmation test is the final step in verifying the results drawn based on Taguchi's design approach. Accordingly, a conformation experiment was conducted on LM6 alloy/soda lime glass composite prepared with optimal levels of the reinforce parameters (viz., A1:B1) obtained from the analysis. Tensile test was carried out at test temperatures of 30^{o}C, 100^{o}C and 200^{o}C. Table 12 shows the results obtained from regression equation and the experimentation. The experimental value of the UTS compares well with the UTS calculated using the regression equation (percentage variation is only less than 1.38%).

Table 11. Optimum level of reinforcement parameters for maximum UTS

Sl. No.	Test Temperature (^oC)	A: Weight percent	B: Particle size (micron)	C: Particle temperature (^oC)
1	30	1.5	75	500
2	100	1.5	75	500
3	200	1.5	75	260

Table 12. Comparison of confirmation experiment and regression equation

Sl. No.	Test Temperature (^oC)	Experimental UTS (MPa)				Regression model UTS (MPa)	% Error
		Observed values			Mean		
1	30	180.45	172.34	173.56	175.75	177.57	-1.03
2	100	151.57	150.89	150.40	150.95	152.21	-0.83
3	200	145.67	143.23	145.78	144.89	146.89	-1.38

4. Conclusions

- Mechanical mixing of the glass particles reinforcement into the LM6 alloy matrix is possible by stir casting techniques to produce MMCs.
- Taguchi's SN ratio approach adopted to analyze the effect of the reinforcement parameters, has lead to reliable results on UTS of the MMCs.
- Soda lime glass particle reinforcement reduces UTS of the base alloy.
- UTS of the LM6 alloy/glass composite reduces at the elevated test temperature compared to the values at room temperature.
- Confirmation tests carried out to validate the accuracy of the analysis to justify the outcome of the investigation.
- Regression equations developed in this work predict the UTS of the MMCs corresponding to varying reinforcement parameters with very reasonable accuracy.

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