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Influence of Particle Size on the Mechanical Properties of Al8011-SIC Composites-Taguchi Approach

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Abstract : Al 8011-SiC composites were produced with reinforcement of three different particle sizes of SiC(63,76,and 89ìm)and with different weight fractions (2, 4, and 6%) by the stir casting method. The mechanical properties of the Al8011-SiC composites due to the effect of particle size and different weight fraction of SiC is reported in this paper. Anova (Analysis of variance) and Taguchi method were used to find the optimum parameters for attaining the maximum mechanical properties such as hardness, tensile strength, elongation and toughness of the composites and the results were endorsed by confirmation test. From the result it is observed that with the decrease in particle size and increase in weight fraction of SiC the mechanical properties of the composites increased. Fine particles of SiC (63ìm) exhibit superior hardness, tensile strength, elongation and toughness than the intermediate (76ìm) and coarse particles (89ìm). Al 8011-6wt. %SiC exhibit superior hardness and tensile strength and Al8011-2wt.%SiC exhibit superior elongation and toughness of the composites. Particle size is the most prevailing factor followed by the amount of reinforcement inducing mechanical properties of the composites.

Keywords : mechanical, parameter, stir casting, Taguchi, Anova, optimum.

Introduction

Aluminium metal matrix composites are widely used in engineering and industrial applications because of their high specific strength, higher thermal conductivity, excellent wear resistance and lower coefficient of thermal expansion. Aluminium reinforced with ceramic materials like SiC possess higher mechanical properties and tribological properties than the unreinforced alloy. Shanmughasundaram et al analyzed the influence of different process parameters to obtain the maximum mechanical properties of Al-fly ash composites by Anova and taguchi method[1]**.** Mahendra et al investigated the mechanical properties of Al-4.5% Cu-fly ash composites fabricated by stir casting method. Different weight fractions of fly ash (5, 10, and 15%) were used as reinforcement. Their result reveals that the hardness, tensile strength, compression strength and impact strength increased with the increase in the amount of fly ash [2]. Hashim et al conducted experiment on the particle distribution in the metal matrix composites produced by casting. They reported that uniform distribution of reinforcement within the metal matrix was not easily achievable. Particle density, size, shape and volume fraction would have major effect on the settling rate of reinforcement [3]**.** Mahendra Boopathi et al analyzed the mechanical properties of Al2024-SiC-fly ash composites produced by stir casting method. They concluded that Al2024-SiC-fly ash composites exhibit higher hardness than the Al2024-SiC and Al2024-fly ash composites [4]. Senthilvelan et al conducted hardness test and tensile test on the Al7075-B4C, Al7075-SiC, and Al7075-Al2O3 composites. Three different types of aluminium metal matrix composites were produced by stir casting method, followed by hot rolling. Their result reveals that the Al7075-B4C composites exhibit superior mechanical properties than the other two composites because of the strong bonding between the Al7075 metal matrix and boron carbide particles [5]**.** Altinkok et al examined experiment on the microstructure and tensile behavior of Aluminium matrix composites reinforced with different particle size of Al2O3 /SiC produced by stir casting method. They concluded that tensile strength and porosity of the Al- Al2O3 -SiC composites decreased with the increase in particle size of SiC [6]**.** Shorowordi et al analyzed the microstructural behaviour of three different composites Al7075-B4C, Al7075-SiC, Al7075- Al2O3 composites fabricated by stir casting method. The composites were produced by maintaining stirring time before particle addition and after particle addition. Their result reveals that particle distribution was better in the Al7075-B4C composites than the Al7075-SiC, Al7075- Al2O3 composites [7]**.** Bhushan et al analyzed the mechanical properties of Al7075-SiC composites produced with different weight percentages of SiC (5, 10, and 15%) and for different stirring speeds (500, 650, 750 rpm) at constant time period of 10 minutes. They concluded that at stirring speed of 650 rpm and 10 minutes time period produced composites have uniform distribution of SiC particles. The increase in SiC weight percentage increased the mechanical properties of the composites [8]. Veereshkumar et al compared the mechanical properties of Al6061-SiC and Al7075- Al2O3 produced by stir casting method. They conclude that the mechanical properties of Al7075- Al2O3 composites were much higher than the Al6061-SiC composites [9]**.** Charles et al analyzed the microstructure and mechanical properties of Aluminium–SiC-fly ash composites fabricated by stir casting method and powder metallurgy technique. Three different volume fractions of SiC (10, 15, and 20%) and 10% volume of fly ash were used as reinforcement. They conclude that composite produced by stir casting method have higher mechanical properties due to close interfacial bonding when compared to powder metallurgy method [10] **.** David Raja et al conducted experiment on the Al6061-fly ash-SiC composites prepared with two different weight fractions of SiC (7.5, 10) and constant weight fraction of fly ash (7.5) by the stir casting method. They concluded that hardness and tensile strength of the composites improved with the increase in amount of SiC with the fly ash content [11]**.** Unlu analyzed the tribological and mechanical properties of Al2O3–SiC reinforced Al composites produced by stir casting method and powder metallurgy technique. Their result reveals that hardness of the composites was higher than the unreinforced alloy because of the reinforcement of alumina and SiC particle in the Aluminium matrix [12]. Pugalenthi et al analyzed the mechanical properties of Al7075-SiC- Al2O3 composites produced by stir casting method. They concluded that hardness and tensile strength of the composites were increased due to the increase in amount of SiC and alumina [13]**.** Pathak et al conducted experiment on the mechanical properties of Al-Si-SiC composites fabricated by liquid metallurgy technique. Their result reveals that mechanical properties of the composites were increased with the increase in amount of silicon carbide powder; however the elongation of the composites decreases [14]**.** Khairel Rafezi Ahmad et al investigated the effect of particle sizes of alumina (0.3, 1, 3, 12.5, 25ìm) on the hardness of Al-Al2O3 composites produced by powder metallurgy route. They conclude that the fine alumina particles have the highest hardness, because the fine particles have large number of barriers per unit volume against dislocation than the intermediate and coarse alumina particles [15] **.** Mahadavi et al examined the effect of particle size on the hardness and dry sliding wear behaviour of Al6061-SiC and Al6061-SiC-Graphite composites. Three different particle sizes of SiC (19, 93, 146ìm) with 10 vol. % and 5vol. % of graphite by in-situ powder metallurgy technique. They concluded that fine SiC exhibit superior hardness than the coarse and intermediate SiC particles [16]**.** Kok et al analyzed the effect of particle size and amount of alumina on the mechanical properties of Al2024- Al2O3 composites fabricated by vortex method and applied pressure. They concluded that the mechanical property of the composites increased with the decrease in particle size and increased in weight fraction of alumina [17]**.** Rahimian et al conducted experiment on the effect of weight fractions (5, 10, and 15) and particle sizes of alumina (3, 12, and 48ìm) on the mechanical properties of Al-alumina composites. Their result shows that mechanical properties like hardness, yield strength, compressive strength and elongation increases for the reinforcement of smaller particles of alumina [18]**.** Sudarshan et al conducted experiment on the mechanical properties of Al356-fly ash composites by stir casting method .They used two different particles narrow size (53-106ìm) and wide size (0.5-400ìm) of fly ash as reinforcement. They concluded that narrow size fly ash particles exhibit higher hardness, tensile strength and compressive strength than the wide size fly ash particles [19]**.** Anilkumar et al analyzed the effect of particle size of fly ash on the mechanical properties of Al 6061 composites produced by stir casting method. Three different particle sizes of fly ash (4-25, 45-50, 75-100ìm) were used as reinforcement. Their result shows that small particle sizes (4-25ìm) have higher mechanical properties than the other two particles [20]**.**

From the above results, it was noted that the particle size and weight fraction of the reinforcement plays a major role on the mechanical properties of the composites. The previous researchers stated that mechanical properties of the composites were increased with the decrease in particle size and increase in weight fraction of particles. Hence, a systematic study has to be carried out to analyze the effect of particle size on the mechanical properties of the composites. In this research work, Taguchi L9 orthogonal array with 2 factors and 3 levels and Anova techniques were used to explore the effect of particle size and weight fraction of SiC on the mechanical properties of the Al8011-SiC composites produced by the stir casting method. The experimented values of hardness, tensile strength, elongation, toughness of the Al8011-SiC composites were compared with the calculated values by the Taguchi and Anova method.

Experimental

Preparation of samples

In this study Al8011-SiC composites were produced with three different particle size of SiC, fine(63ìm),intermediate(76ìm), and coarse (89ìm) and three different weight fractions (2,4,and 6%) by employing stir casting method.

SiC particles were preheated in a separate muffle furnace for 60 minutes to remove the moisture content. Al8011 scraps were made to melt completely by adding in to the graphite crucible when the furnace temperature was maintained at 780˚ C .By reducing the melt temperature to 720˚ C, semi-solid state was obtained, then the Mg and preheated SiC particles were added and stirred at the speed of 300 rpm. Mg was added to the molten slurry to increase the wetting action between the Al8011 matrix and SiC particles. Finally, the molten temperature was raised to liquidus temperature and poured into steel mould to solidify.

Figure (1): Stir casting setup.

Mechanical Properties

Figure (2): Experimented samples of Al8011-SiC composites.

The hardness test was carried out by Rockwell hardness machine MSM model with ASTM E18:2014 standard with 1/16” inch ball indenter with a load of 100kgf.The loading time was 15 seconds. Tensile test was conducted using UTM machine M30 model as per ASTM standard E8:2015 standard for the Al8011 and Al8011-SiC Composites. Toughness was determined by charpy impact test machine (AIT-300-EN) model. The test was performed using ISO-148-1:2009 standard. Three specimens were tested and the average of three readings was considered.

Results and discussion

Design of Experiments (DOE):

Taguchi method avoids the usage of repeated experiments and saves time, material and cost. It provides a systematic approach and efficient methodology for finding optimum parameters that influence the process and performance. With the analysis of factors on the results, the combination of optimum parameters to obtain the desired mechanical properties can be achieved. In this method the desirable value (mean) was expressed by the term 'signal' and undesirable value (standard deviation) was expressed by the term 'noise' for the output quality characteristics. In this study, "Larger is better" S/N ratio was used to calculate the optimum parameters which will provide the maximum mechanical properties of the composites.L9 orthogonal array was used and the hardness, tensile strength, elongation, toughness tests of the composites were conducted according to the array.9 tests were conducted and each test was repeated three times and the average of the three readings were taken and noted.

Results of Anova

The optimum parameters to obtain the maximum mechanical properties of the Al8011-SiC composites from the table and response diagram of S/N ratio (Fig.3, Fig.4, Fig.5, Fig.6), was particle size of SiC-63ìm for (hardness, tensile strength, elongation, toughness), material-6wt.% for (hardness and tensile strength) and material-2wt% for(elongation and toughness). ANOVA method gives more accurately the process parameters through inspecting the reasonable importance among the parameters. ANOVA method was performed with the help of MINITAB15 software. From the ANOVA table significance of each parameter is identified by the p-value. When the value of p-value is less than 0.05, which indicates the parameter can be considered to be highly significant. It is observed that the p-values of factors (particle size and material) were less than 0.05, so that they are highly significant at 95% confidence level. The last column of the table shows the percentage contribution of controlling each parameter on the mechanical properties of the composites. It was observed that the particle size (63ìm) was the most dominant contributing factor followed by material (6wt. % SiC) enhancing the hardness and tensile strength of the Al8011-SiC composites, similarly for elongation and toughness of the composites with material (2wt. %SiC). The conclusion of S/N ratio and ANOVA shows that the results were very close to each other. The percentage contribution was material (65%), particle size (32%) for hardness, similarly material (86%), and particle size (13%) for tensile strength. It was also observed that the percentage contribution for elongation was particle size (67%), material (29%) and for toughness particle size (25%), material (74%).

Multiple Linear Regression Models:

Multiple linear regression equation was used to find the correlation regarding the factors and response. The values of regression coefficient, R^2 (97.69) is in good agreement with the adjusted R^2 (95.39) for hardness and R^2 (99.12) is in good agreement with the adjusted R^2 (98.24) for tensile strength and similarly R^2 (96.04) is in good agreement with the adjusted R^2 (92.08) for elongation and for the toughness regression coefficient, R^2 (98.65) is in good agreement with the adjusted R^2 (97.30).

The regression equation developed for hardness is
Hardness = 106 + 3.83 A -Material - 0.205 B-Particle Size (1)
The regression equation developed for tensile strength is
Tensile strength = 85.5 + 13.2 A -Material - 0.397 B-Particle Size (2)
The regression equation developed for elongation is
Elongation = 10.2 - 0.233 A -Material - 0.0269 B-Particle Size (3)
The regression equation developed for toughness is
Toughness = 25.2 - 1.50 A -Material - 0.0769 B-Particle Size (4)

It was noted form the Eqn. (1), Eqn. (2), Eq. (3), Eq. (4) that the particle size (63ìm) plays a major role on hardness, tensile strength, elongation, toughness of the composites followed by the material.

Confirmation test

The confirmation test was carried out based on the factors shown in the Table.6 and the results were displayed in the Table.7 and Table.8 .The experimental values of the different mechanical properties (hardness, tensile strength, elongation, and toughness) were shown in Table.2 and Table.3. Experimented values and calculated values of the mechanical properties of the composites obtained from the regression equation are nearly same and close to each other with least error (± 4 %).So it can be observed that the mechanical properties of Al8011-SiC composites can be predicted from the resulting equations.

Table 1: Factors and level

Level	Material	Particle size
I	Al-2wt.%SiC	89μm
II	Al-4wt.%SiC	76μm
III	Al-6wt.%SiC	63μm

Table 2: S/N ratios and measured values for hardness, tensile strength of composites

Exp No	Material	Particle Size	Measured values		Signal/Noise Ratio	
			Hardness (HRB)	Tensile strength (MPa)	Hardness (HRB)	Tensile strength (MPa)
1	Al-2wt.%SiC	89μm	92	73	39.2758	37.2665
2	Al-2wt.%SiC	76μm	94	78	39.4626	37.8419
3	Al-2wt.%SiC	63μm	96	84	39.6454	38.4856
4	Al-4wt.%SiC	89μm	95	88	39.5545	38.8897
5	Al-4wt. %SiC	76μm	99	93	39.9127	39.3697
6	Al-4wt. %SiC	63μm	100	95	40.0000	39.5545
7	Al-6wt. %SiC	89μm	98	98	39.8245	39.8245
8	Al-6wt. %SiC	76μm	102	105	40.1720	40.4238
9	Al-6wt. %SiC	63μm	105	111	40.4238	40.9065

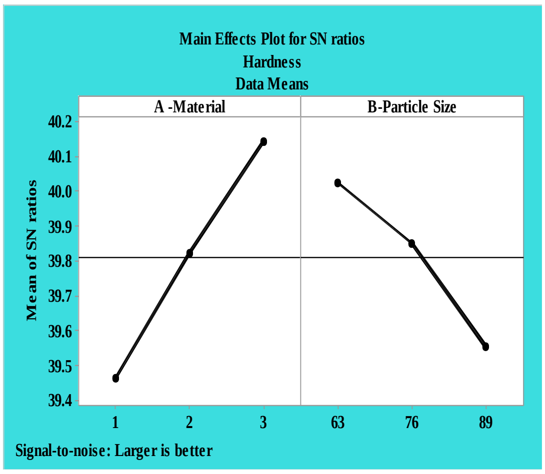

Figure (3): Main Effects plot for SN ratios-Hardness

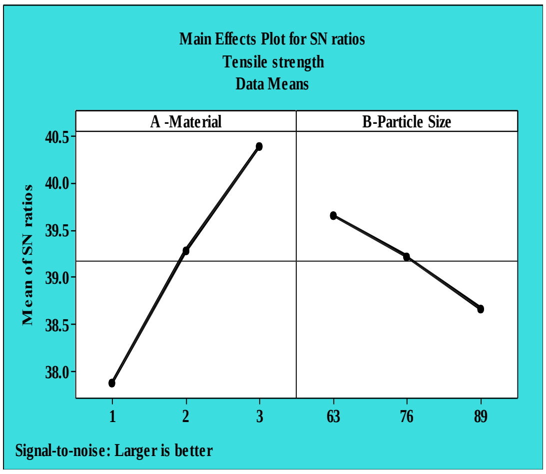

Figure (4): Main Effects plot for SN ratios-Tensile strength

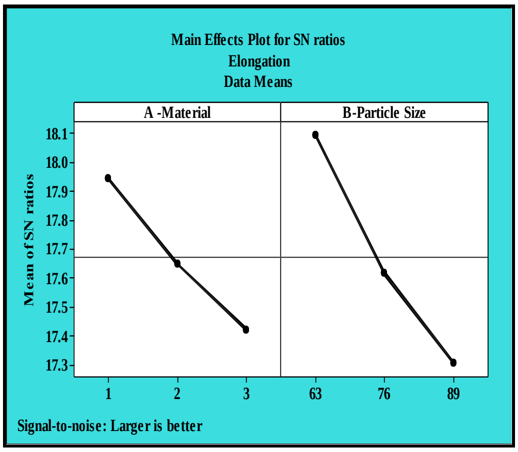

Figure 5: Main Effects plot for SN ratios-Elongation

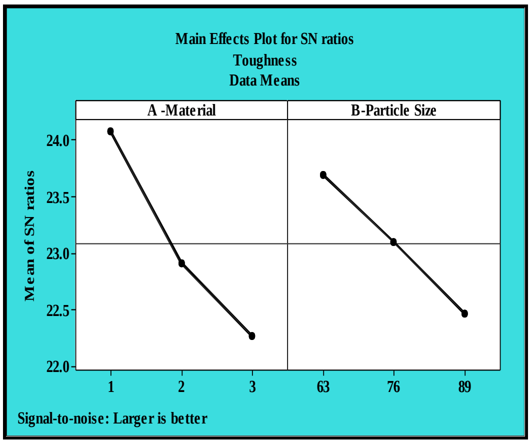

Figure 6: Main Effects plot for SN ratios - Toughness

Table 3: S/N ratios and measured values for elongation, toughness of composites

Exp No	Material	Particle Size	Measured values		Signal/Noise Ratio	
			Elongation (%)	Toughness (Joules)	Elongation (%)	Toughness (Joules)
1	Al-2wt.%SiC	89μm	7.5	15	17.5012	23.5218
2	Al-2wt.%SiC	76μm	7.8	16	17.8419	24.0824
3	Al-2wt.%SiC	63μm	8.4	17	18.4856	24.6090
4	Al-4wt.%SiC	89μm	7.3	13	17.2665	22.2789
5	Al-4wt. %SiC	76μm	7.6	14	17.6163	22.9226
6	Al-4wt. %SiC	63μm	8	16	18.0618	23.5218
7	Al-6wt. %SiC	89μm	7.2	11	17.1466	21.5836
8	Al-6wt. %SiC	76μm	7.4	12	17.3846	22.2789
9	Al-6wt. %SiC	63μm	7.7	13	17.7298	22.9226

Table 4: Anova analysis for hardness, tensile strength of composites

Factors	DoF	Hardness				Tensile strength			
		SS	F	P value	Pc%	SS	F	P value	Pc%
Material	2	88.22	56.71	0.001	65.40	1040.67	195.13	0.000	85.86
Particle size	2	43.55	28.00	0.004	32.28	160.67	30.13	0.004	13.25
Error	4	3.111			2.306	10.67			0.0088
Total	8	134.88			100	1212.00			100

Table 5: Anova analysis for elongation, toughness of composites

Factors	DoF	Elongation				Toughness			
		SS	F	P value	Pc%	SS	F	P value	Pc%
Material	2	0.3288	14.80	0.014	29.29	24.22	109.00	0.000	73.66
Particle size	2	0.7488	33.70	0.003	66.72	8.222	37.00	0.003	25.00
Error	4	0.0444			3.956	0.444			1.35
Total	8	1.1222			100	32.88			100

Table.6: Parameters used in the confirmation test

Level	Particle size (A)	Material (B)
I	76μm	Al-3wt.%SiC
II	89μm	Al-3wt.%SiC
III	89μm	Al-3wt.%SiC
IV	63μm	Al-3wt.%SiC

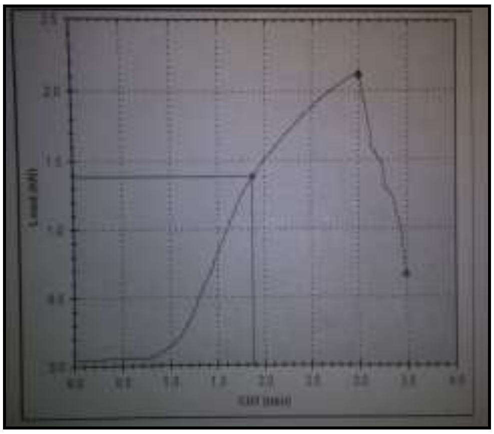

Figure 7: Load vs. Cross Head Travel for tensile test of Al8011-3wt. %SiC composite.

Table.7: Results of confirmation tests for hardness and tensile strength

Test 1			Test 2		
Hardness			**Tensile strength**		
Model equation	**Expt.**	**Error,%**	**Model equation**	**Expt.**	**Error,%**
101.91	98	3.83	89.76	86	4.1

Table.8: Results of confirmation tests for elongation and toughness

Test 3			Test 4		
Elongation			**Toughness**		
Model equation	**Expt.**	**Error,%**	**Model equation**	**Expt.**	**Error,%**
7.10	7.2	-1.40	15.85	16	-0.94

Discussions

The hardness of the composites increases with the decrease in particle size of SiC .The maximum hardness was observed to be 105 HRB for the Al8011-6wt.%SiC(63ìm),16% higher than the unreinforced alloy(90 HRB).Hardness of SiC particles were higher than the aluminium and hard SiC particles acts as the resistance against the load [21] .Bulk hardness of the unreinforced aluminium can be improved with the addition of hard ceramic particles [22].The hardness of fine particle reinforcement of SiC for 2wt. % was 96 HRB ,higher than the intermediate particle SiC(94 HRB)and coarse particle SiC(92 HRB).Similar condition was observed for the 4wt.% and 6wt.%.These results are in line with the declaration by Kok [17].When the amount of reinforcement of SiC increases the hardness increases. Fine particles have higher hardness because it exhibits lesser defects than the coarse particles and larger interfacial area was observed to be between the soft and hard phases [18] .Similarly it was noted that tensile strength of the composites decreases with the increase in particle size. Tensile strength of Al8011-2wt. %SiC-63ìm was 84 MPa which was13% higher than Al8011-2wt. %SiC-89ìm (73 MPa).This improvement in tensile strength was because of the increase in dislocation density due to the thermal mismatch caused by the SiC particles [23].The addition of fine SiC particles reduces the distance between the reinforcement particles, which leads to higher strength of the composites than the coarse SiC particles. At smaller particle size, high grain boundaries were formed that resist the movement of dislocation caused by plastic deformation. The dislocation density was inversely proportional to particle size and directly proportional to flow stress which increase the strength of the composites [24]. Elongation decreases as the reinforcement of SiC increases. Fine particles exhibit higher elongation than the coarse particles, because the distance between the hard phases was reduced and dislocation density increased due to the large amount of SiC .Toughness of the composites like elongation also decreases with increase in amount of reinforcement. The Toughness of the Al8011-SiC composites was higher than the pure aluminium 8011 alloy because of the presence of hard SiC

Conclusion

From the results of S/N ratio and Anova it can be observed that the particle size of SiC was the most important parameter followed by material. It was found that the optimum parameters were particle size of SiC (63ìm), material (Al-6wt. %SiC) for the hardness and tensile strength, similarly particle size (63ìm), material (Al-2wt. %SiC) for elongation and toughness of the composites. The optimum parameters were tested by conducting verification experiments. The highest results of mechanical properties like hardness (105 HRB), tensile strength (111 MPa) was observed for fine particle size (63ìm) with 6wt. % reinforcement of SiC , and elongation (8.4%), toughness (17 Joules) was observed for fine particle size (63ìm) with 2wt. % reinforcement of SiC.

The values of the calculated S/N ratio by taguchi analysis and experimental values were very close to each other which indicate taguchi experimental technique can be used successfully for both optimization and prediction. From the results it was clear that the uniform dispersion of SiC particles in the Al matrix and maximum mechanical properties was obtained successfully by the developed method.

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