Mechanical and tribological properties of Al7475-SiC_p composites by stir casting method and wear rate modeling using RSM

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Abstract. The microstructure, mechanical and wear properties of the Al 7475-SiC_p composites and to investigate the effects of SiC micro-particles reinforcement with alloy have been studied. Al 7475-SiC_p composites have been developed by a stir casting method. The SiC_p size in the range of 15–40 μm with weight.% of 0, 5, 10 and 15 were injected in molten Aluminum 7475 alloy in argon gas environment and stirrer using a mechanical method at 450 rpm to ensure uniform distribution of SiC particles. The mechanical properties such as hardness and compressive strength of the composites were found to be gradually improved with the addition of 5–15% SiC_p reinforcement. The ultimate tensile and impact strength increased with 10% of SiC_p reinforcement. For modeling the wear rate, the experiments were conducted in Pin-on Disc tribometer at room condition. A three-level central composite design with response surface methodology was used to reduce the experimental conditions and to predict the abrasive response of wear rate through the development of mathematical models. The model developed is efficiently predicted the rate of wear at 95% confidence level and the entire model validate with analysis of variance.

Keywords. Stir casting; Al 7475-SiC_p composites; RSM; analysis of variance.

1. Introduction

The enhancement of the mechanical and tribological properties of the alloy and composites by various strengthening mechanism such as dispersion strengthening, solid solution strengthening and grain boundary strengthening was done. The metal matrix composite is one of the strengthening mechanisms to improve the material properties. In Aluminum Matrix Composites (AMC) one of the aluminum alloys is termed as matrix phase. The other constituent embedded in this Aluminum alloys added as reinforcement commonly used ceramic reinforcement such as Al₂O₃ and SiC_p. The addition of SiC_p particle increases the material properties [1]. Advanced metal matrix composite like aluminium composite is widely in underwater, transportation, and aerospace transportation applications [2]. Metal Matrix Composites are the solution to this scenario, the development of MMCs Aluminum based matrix composites continue to be the most explored material. Aluminum composites reinforced with silicon carbide (SiC_p) particles are best suited for lower coefficient of thermal expansion, improved yield strength, higher wear resistance and more modulus of elasticity than the non-reinforced matrix alloy systems. Adequate interaction between reinforcement and matrix is necessary to achieve bonding, which is the Al₂O₃/Al-Li composites where bonding results from the reaction between Al₂O₃ and Li [3].

The sliding wear properties of the 7075/ SiC_p aluminum composite have shown significant improvement over the base alloy. The severe wear conditions have wear rate and higher wear volume loss. Comparing the wear rate between the different experimental conditions it was found that wear rate to be higher at high loads and less at higher speeds of rotation [4].

In general, with increase in sliding distance and load, the wear rate increases in 7075 aluminium alloy [5]. The formation of tribo-layer or mechanically mixed layer has been described to reduce the wear rate [6] and affected by load level, sliding speed and reinforcement content [7–9]. The effect may be adverse depending on the bonding of matrix [10] and wear behavior [11]. Under the condition of dry sliding wear the effect of sliding speed, load, and reinforcement, which influences the coefficient of friction. The size and type of the reinforcement segment were stated to have a negligible effect on the friction coefficient and wear rate [12]. Numerous developments in mathematical models can be employed to describe the preferred output variables and to specify the relationship between the output variables and input parameters at the least number of experiments [13]. Developing a suitable approximation method, Response Surface Methodology (RSM) will be effectively used to understand the relationship between the independent variables viz. the load, weight percentage of silicon carbide and sliding distance and the response

Table 1. Al7475 Chemical composition.

Elements	Zn	Cu	Mg	Mn	Fe	Si	Cr	Ti	Al
Al7475	5.2–6.2	1.2–1.9	1.9–2.6	0.06	0.12	0.10	0.18–0.25	0.06	Remainder

variables such as coefficient of friction and specific wear rate to characterize the composite nature [14]. RSM effectively demonstrated by several researchers [15, 16] for the development of an empirical methodology and to use the statistical design of the experiments.

The present work aimed to study the combination of Al7475 with the addition of SiC_p reinforcement composites fabricated by a stir casting method. Wear rate modeling through Central Composite Design-Response Surface Methodology was adopted and regression analysis done by ANOVA to optimize and predict the wear rate in composite and minimize the number of experimental runs. Al7475 Universal application in aerospace industries and to reduce the weight of the components in high wear parts like stringers, frames, and structural overlapping areas. Adopting stir casting method for making a composite in aerospace grade aluminum alloy 7475 with the addition of SiC_p reinforcement to improve the mechanical and tribological properties. The addition of Silicon carbide reinforcement in the composite will enhance the tribological properties of aerospace grade aluminum alloy 7475.

2. Materials and experimental procedure

2.1 Raw materials

For the development of Al7475-SiC_p particulate composites, Al 7475 alloy 30 μm grain size of chemical composition presented in table 1 was used as the matrix, micro-SiC_p of size 15–40 μm.

2.1a Formation of the composite by a stir casting method:

The Composite samples were developed by stir casting process using mechanical stirrer mixing of the molten Al7475 alloy. The SiC_p powder pre-heated and injected into the melts inside the heating vessel inserted in the resistance heating furnace under argon gas atmosphere. The micro-SiC_p powder injected into the molten metal was chosen 0, 5, 10 and 15 wt.%. The furnace temperature chosen at 750°C, the stirring was continued for 15 minutes to produce the homogenous mixture of molten metal with a stirrer speed of 450 rpm. Then the bottom pouring valve opened the molten metal poured into mold and allowed to solidify and taking out the cast from the mold.

2.2 Experimental procedure

The microstructure of the surfaces prepared by grinding through 200 to 1000 grit papers and then by polishing with

1, 0.5 μm diamond paste. Microscopic investigation of the composites was carried out by the optical microscope. As per ASTM E82, the hardness values of the specimens measured using a ball with a diameter of 2.5 mm at a 100 kg load. To examine the mechanical behavior of the composites, the compression tests and tensile tests were conducted by universal testing machine as per ASTM E8. Izod method used to conduct Impact tests. Wear tests conducted on the specimen size 8 mm diameter and 30 mm length by Pin -on Disc Tribometer. SEM examination was conducted in SU6600-FESEM for reinforcement SiC_p powder and composites cast.

2.2a Modeling of wear rate by RSM: The parameters which influence coefficient of friction and specific wear rate [4] are the wt.% of SiC_p (A), load (B) and sliding distance (C). From the selected input parameters, the second order polynomial regression equation was used to represent the response surface 'Y' is given in Eqs. (2.1) and (2.2) (figure 1).

$$\text{Specific wear rate (SWR)} = f(A; B; C) \quad (2.1)$$

$$Y = b_0 + \sum b_i x_i + \sum b_{ii} x_i^2 + \sum b_{ij} x_i x_j + e_r \quad (2.2)$$

Figure 1. Flowchart shows the scheme of investigation of RSM.

Table 2. Input levels of process parameters.

S.No.	Parameter	Notation	Unit	Level		
				−1	0	1
1	Wt.% of Silicon carbide	A	%	0	5	10
2	Load	B	N	5	10	15
3	Sliding distance	C	m	400	800	1200

2.2b Experimental design: The wear rate depends on test conditions, such as sliding distance, load, matrix composition, and percentage of reinforcement. Due to the limitation of the number of samples, the key parameters of the process are assumed based on the observations [17]. The significant process parameters identified are weight percentage of the silicon carbide, the load applied, and the sliding distance. The statistical analysis done by the Design Expert[®] software and developed the model. The input parameter levels and the experimental design are shown in tables 2 and 3. Central composite design was used as response surface methodology.

2.2c Numerical design: The empirical model with desired good response, the tentative outcomes were examined and analyzed through RSM. The relationship between dependent response and the factors explained by linear, 2FI and quadratic models. The significant factors are determined, and the final model is formulated based on these factors. Table 4 shows the ANOVA results for wear rate.

ANOVA is a technique used for testing the developed model. Values of “P-value” less than 0.0500 indicates model terms are significant. The model terms A, C, AB, AC, BC, A², B² are very significant. Values 0.1000 greater than indicates the model terms are not significant. Many insignificant models (not counting those required to support hierarchy), the model reduction may improve our model. R² is the determination coefficient which is the indication of goodness of fit for the model. In the described model the determination coefficient R² is 0.9913, Adjusted R²: 0.9718 and Predicted R²: 0.9132 indicates that the model possesses with high significance. The Model 54.28 F-value implies that the model is significant. The 0.02% is only a chance that a “Model F-Value” is large and could occur due to noise.

The expression for the wear rate concerning A, B, and C variables, is given by:

$$\begin{aligned}
 \text{Wear rate} = & +18.51717 \quad * \text{ wt\% of SiC}_p \\
 & - 0.76365 \\
 & -1.25751 \quad * \text{ Load} \\
 & -0.012188 \quad * \text{ Sliding Distance} \\
 & +0.017975 \quad * \text{ wt\% of SiC}_p * \text{ Load} \\
 & +9.04938\text{E}-004 \quad * \text{ wt\% of SiC}_p * \text{ Sliding Distance} \\
 & +3.91063\text{E}-004 \quad * \text{ Load} * \text{ Sliding Distance} \\
 & -0.045363 \quad * \text{ wt\% of SiC}_p^2 \\
 & +0.042217 \quad * \text{ Load}^2
 \end{aligned}$$

Table 3. Experimental design and responses.

Standard	Run	A: wt.% of SiC _p (%)	B: Load (N)	C: Sliding distance (m)	Response: Wear rate x 10 ^{−4} (mm ³ /Nm)
4	1	10	15	400	0.745
8	2	10	15	1200	2.835
1	3	0	5	400	9.401
6	4	10	5	1200	0.465
14	5	5	10	1200	1.945
7	6	0	15	1200	1.730
9	7	0	10	800	2.832
13	8	5	10	400	4.649
5	9	0	5	1200	1.123
2	10	10	5	400	1.469
10	11	10	10	800	0.738
15	12	5	10	800	1.032
3	13	0	15	400	6.845
11	14	5	5	800	4.084
12	15	5	15	800	3.865

Table 4. ANOVA table for the wear rate (under Quadratic model).

Source	Sum of squares	DOF	Mean square	F value	P value
A: wt% of SiC _p	24.58	1	24.58	126.09	<0.0002
B: Load	0.027	1	0.027	0.14	0.7238
C: Sliding distance	22.53	1	22.53	115.58	0.0001
AB	1.62	1	1.62	8.29	0.346
AC	26.21	1	26.21	134.41	<0.0001
BC	4.89	1	4.89	25.10	0.0041
A ²	3.34	1	3.34	17.15	0.0090
B ²	2.90	1	2.90	14.86	0.0119
Model	84.66	8	10.58	F _{cal} = 54.28	0.0002
Residual	0.97	5	0.19	F _{table} = 6.00	

Standard deviation: 0.43, R²: 0.9913, Adjusted R²: 0.9718 and Predicted R²: 0.9132.

2.2d Checking the adequacy of the model: For checking the data and the adequacy of the model, there are three steps to be followed. They are checking the data normality, independency, and analysis of variance. Normal probability plot is the method of checking the normality of the data. The normal probability graphs of residuals are shown in figure 2.

From the normal probability plot, one can conclude that residuals are in a straight line, which indicate that the error normally distributed.

Testing of independency of data is done by plotting the residual and run-order graph. The presence of the trend in

Figure 2. Normal probability graph for wear rate.

Figure 3. Residual vs. run order graph of wear rate.

the residuals vs. run order graph indicates the dependency of the data. Figure 3 shows the residuals vs. run order graph for wear rate, as there is no predictable pattern, the independency of data is revealed.

3. Results and discussions

3.1 Microstructure study

The optical micrographs of fabricated composites are shown in figure 4. More or less uniform distribution of particles reinforced has been observed. The reinforced particles inhibit the dendritic growth, which results in better mechanical properties. The obtained optical micrographs of all casted composites possess a interface indicates better bonding of SiC_p particles and Al matrix. The variation of the matrix structure of the each composite fabricated is due to the presence of particulates of different percentages of SiC_p particles in the aluminum alloy matrix. The homogeneous allocation of particles preferred for attaining improved wear performance and mechanical properties. The stirring the slurry results in high strain rate and hence the homogeneous distribution of the reinforcement particles in melt alloy matrix. Observed from the micrographs that, as the weight fraction of reinforcement microparticles increases, the decrease in the grain size of the matrix occurs. The performance is due to a higher occurrence of grain boundary pinning that avoids grain growth. The reinforcement SiC_p particles uniformly distributed with Al7475 in stir casting route, the homogenous micro structure produced by stir casting method. The good dense and cast defectless microstructure always produce excellent mechanical and tribological properties.

Figure 4. The optical microscopic images at 100 μm of Al7475 alloy and composites: (a) 0 wt.% of SiC_p , (b) 5 wt.% of SiC_p , (c) 10 wt.% of SiC_p and (d) 15 wt.% of SiC_p .

3.2 SEM analysis

Commercially available black silicon carbide particles possess polyhedral and hexagonal crystal structure morphologies. Figure 5 shows the images of SiC_p particles in Scanning Electron Microscope provides the SiC_p particles size. The ASTM E112-12 test procedure for Al7475 base alloy and composites measured using intercept method in microstructure at $100\times$ Magnification. The reinforcement grain size was measured in the range of 15–40 μm and this reinforcement added with 30 μm grain size of Al7475 ingot, the average grain size of composite was approximately 28 μm . As per Hume-Rothery rules, the reinforcement grain size lesser or equal to base material will improve the material properties. The uniform dispersion of SiC reinforcement particle in Al7475 base alloy is clearly seen in microstructure.

Figure 5. SEM images of SiC_p .

Figure 6. Hardness variation of composites with different wt.% of SiC_p .

3.3 Hardness test

The Rockwell hardness test was conducted with 100 kg load for three specimens of Al7475- SiC_p composites. The results were obtained for Al7475 alloy and its composites at different weight percentages of SiC_p . In figure 6 the influence of micro-silicon carbide particle content on the hardness of the casted composites is depicted. Hardness of the composite with higher wt.% of SiC_p shows the 10% of highest hardness value when compared to base alloy, due to the reinforcement particle uniformly distributed in the molten metal during stirring action. The reinforcement and matrix bonding are better due to the pre-heating of reinforcement.

3.4 Tension test

As per ASTM E8, test was conducted for three specimens of Al7475- SiC_p composites and the average tensile strength was plotted in graph. Figure 7 shows the variation of the ultimate tensile strength of composites with different micro- SiC_p weight fractions. The composites offer high strength than the Aluminum alloy in as-cast condition because of uniform distribution of particles. The strength enhancement effected by the bearing of high load and strengthening by reinforcement of SiC_p micro particles. As increasing weight

Figure 7. The variation of ultimate tensile strength of the composites.

Table 5. Ultimate tensile and ductility value of composites.

Sample	UTS value in Mpa	Ductility value in % of elongation
Al7475+0% SiC_p	488.92	3.93
Al7475+5% SiC_p	498.032	5.39
Al7475+10% SiC_p	521.518	6.71
Al7475+15% SiC_p	513.37	5.94

percentage or volume fraction of the reinforcement, the majority of the load falls on the reinforcement that also results in higher yield strength. However, with volume fraction of SiC_p increasing above 10%, a reduction in tensile strength can be seen. Due to increase in volume fraction of hard particles (SiC_p) in Al-matrix composite tends to become brittle. Also increasing the volume fraction of SiC_p can result in agglomerates of reinforcement, leading to high structural heterogeneity and reduction in load capacity. Table 5 shows the ultimate tensile strength and ductility values of Al 7475 alloy and composites.

3.5 Compression test

According to ASTM E9-89, the three compression test specimens were prepared, and the tests were conducted. The Compression strength values are plotted in figure 8. From the results obtained from the experiments, it was concluded that the compression strength of the composite was increasing as the percentage of silicon carbide reinforcement increased. From figure 8, the compressive strength of Al7475 alloy is, 358.09 MPa and that of Al7475/ 15% SiC_p is 373.09 MPa. The literature studies indicate that if the silicon carbide reinforcement increases beyond 17 percentages, the compressive strength decreases. Meanwhile silicon carbide reinforcement increases beyond the certain limits, the ductility of the alloy matrix decreases, and thus lowering the compressive strength.

Figure 8. The variation of ultimate compressive strength of the composites.

Figure 9. The variation of Impact strength of the composites.

Figure 10. Wear rate perturbation plot.

3.6 Impact test

The Izod impact test was conducted as per ASTM E23 standard. The three test specimens were prepared and impact strength values were plotted in figure 9. The Izod impact test is the high strain rate test in which the toughness value can measure the amount of energy stored by the

material during fracture. The impact strength of the composites increased in 16% at addition of 10% SiC_p reinforcement, due to moderate quantity of reinforcement and uniform distribution of SiC_p. The impact strength of the composites beyond 10% the volume fraction of SiC_p decreasing the strength by the clustering effect and material changing into brittle nature. The matrix and reinforcement bonding failure at higher concentration of reinforcement in the Izod impact test was noticed.

3.7 Wear rate model analysis

3.7a Perturbation plot: The effect of all significant factors can be shown on a single plot, and is called perturbation plot. The response plotted by changing one factor over its range while holding of the constant factors. The Design Expert sets the reference point at the (coded 0) midpoint of all factors. A curvature or steep slope in a factor shows that the response is sensitive to that factor. A flat line shows insensitivity to change in that particular factor. If there are more than two factors, the plot could be used to find those factors that most affect the response. The perturbation plot with parameters at its center point on wear rate shown in figure 10.

As depicted in figure 10, the increase in silicon carbide percentage (A), the wear rate is decreasing. The load (B) shows the negative effect on wear rate, i.e., as the load increases the wear rate also increases, after the particular range. After absolute limit, the load may be sufficient to deplete the oxide layer formed and causing the wear of the surface. The wear rate is inversely proportional to the sliding distance, due to that the formation of the oxide layer in the interface was seen.

3.7b Interaction effect on wear rate: An interaction occurs when the response is different depending on the settings of two factors. Plots make it easy to interpret two-factor interactions. Figure 11 shows the 3D (three dimensional) plot of interactions of two parameters on wear rate.

Figure 11(a) gives the effect of weight % of SiC_p and load upon the wear rate. However, the wear rate is decreasing with increase in weight % of SiC_p and load from 5 to 15 N. It can be the result of oxide layer formation at the contacting faces of pin and disc. The interaction graph of weight % of SiC_p and the sliding distance are given in figure 11(b). There is double curvature on the graph. As the sliding distance increases, the wear rate is less because of oxidative layer formation, and increased SiC_p weight % is also contributed to lower the wear rate. The small increment in the wear rate may be due to delamination. Figure 11(c) represents the interaction effect of sliding distance and load on wear rate. From the graph, it can be ascertained that wear rate is less with moderate load and high sliding distance. At high loads wear rate is high because of delamination and oxidative layer depletion.

Figure 11. (a), (b), (c) Interaction graphs of wear rate.

4. Conclusion

In the present investigation, the microstructure and mechanical properties of stir cast Al7475-SiC_p composites (with 0,5,10 and 15 weight % reinforcement) were studied and modeling of wear rate was carried out using RSM method and checked for the adequacy. The following conclusions are made.

- The Al7475 alloy and composites were successfully fabricated by stir casting method.
- The reinforcement SiC_p was uniformly distributed with Al7475 alloy in stir casting route. The good dense and cast defectless microstructure produced excellent mechanical and tribological properties.
- The mechanical properties such as hardness and compressive strength of the composites were found to be improved in 15% of SiC_p reinforcement.
- The ultimate tensile and impact strength increased with 10% of SiC_p reinforcement.
- The central composite design with response surface methodology was used to reduce the experimental conditions and to predict the abrasive response of wear rate.

- The model developed is efficiently predicted the rate of wear at 95% confidence level and the entire model is validated with analysis of variance.

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