Estimation of Wear Behavioural Response of Al-Limestone Slurry Composite Using Taguchi Orthogonal Array

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ABSTRACT

Limestone slurry powder (LSP) is one of the solid wastes generated from stone processing industry, used as reinforcing agent replaced conventional ceramic compounds in Aluminum Metal Matrix composites (AMCs) to increase mechanical and tribological properties. In this work aluminum (Al)-magnesium (Mg)-silicon (Si) alloy is strengthened with addition of LSP to determining the tribological performance of Al-LSP composites are composed with 4, 8, 12 and 16 % weight ratio, and prepared via double stir casting. The tribological tests were conducted on Pin-on-disc Tester, and used to evaluate sliding wear rate (WR) and coefficient of friction (CF). The results indicate that, the wear rate increased with increase of applied load and sliding velocity, but decreased with increasing LSP. Wear mechanism is observed with increase of applied load and changing from abrasion wear to delamination wear. The dispersoids phase in sub-surfaces, worn-out surface and distribution of LSP in base material are examined by Scanning Electron Microscope (SEM) and optical microscope. Taguchi Orthogonal Array (L25) is considered to estimate an optimal response. Analysis of variance (ANOVA) revealed that the most influencing parameters are sliding distance and working load on WR and CF respectively.

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1. INTRODUCTION

AMCs are trading in structural, transportation, precision tooling, constructional and automotive sectors owing to their excellent structural and thermal properties. A pertinent research is available on monolithic materials. In recent decades designers / researchers and manufacturers are emphasizing on utilization of

wastage obtained from either industrial or agriculture[1–3].

This study is focused on utilization of industrial wastage i.e. stone cutting dust. Stone enterprise is a crucial contributor to the world economy. A large quantity of residue is produced in ornamental stone enterprise. It is observed that, there may be a diversification in waste

generation i.e., waste obtained from quarries and off-cut/waste coming out from processing plant. Moreover, there are two forms of mining stone processing waste: stable and semi-liquid or slurry. In reality in the course of the marble slicing technique via gang saws, water is used as a coolant and the powder flows alongside it as waste stone slurry [4–7].

Numerous research work have been reported on AMCs, with most conventional ceramic particulate such as SiC, Al₂O₃, TiC, B₄C, Si₃N₄ and AlN, but those are expensive. Hence, continuous attempts being made with natural resource by-products such as flyash, coconut shell, silica sand, stone dust and red mud particulate [3, 8-10]. The properties of composites such as physical, mechanical and wear resistance increased with increasing volume of reinforcement.

Sudarshan and Surappa, [8] reported as the dry sliding wear resistance of Al-fly ash reinforced 12 % of volume. The wear behaviour of composites is tested under a constant speed of 1m/s with various loads. The fly ash composite is exhibited almost similar to that of Al₂O₃ and SiC reinforced Al-alloy. Kumar et al., [11] fabricated a hybrid Al 6061 composite reinforced with Magnesium (4 %), graphite (4 %) and various composition of fly ash (10,15 and 20 %), they reported as an addition of fly ash, hardness increases that material becomes brittle, which improves specific wear rate and coefficient of friction. The fly ash composite has been prepared using treated (TFA) and untreated fly ash (UFA) particles. Al- Treated fly ash composite have superior physical, mechanical and tribological properties than untreated fly ash composites. Wear resistance of Al-TFA composites exhibited better than Al-UFA composite [12,13].

Atuanya et al., [14] prepared Al-Si-Fe / breadfruit hull seed ash composite using stir casting process. The increase in strength and hardness of composite due to increases in the amount of the hard breadfruit hull ash phase in the ductile metal phase which lead to the increase in dislocation density at the matrix-particle inter phase.

Kanayo et al. [15] Investigated on physical, mechanical and tribological performance of Al6063 hybrid composites consisting alumina and quarry dust varied in weight ratio up to 10 %. It was revealed that hardness and tensile

strength increases with increasing alumina up to 7.5 %, then decreased. The composite with 5 % Al₂O₃ and 5 % quarry dust, has exhibited better wear resistance.

The mechanical and wear behaviour of the Al-Mg-Si - quarry dust (QD) and SiC composites are investigated by Alaneme and Bamiye [16]. They observed density, hardness, and wear resistance of composites (i.e., 5 and 9 %) decreased, and fracture toughness increased with increase in QD.

Kumar et al. [17] studied the effect of Marble Dust (MD) on mechanical and Microstructural properties of Al-Cu-Ni / MD composites. The tensile and hardness values of Al-Cu-Ni / MD composites increased up to 9 wt.%, then decreased (12 wt.%) due to due to the agglomeration of MD particles. There is a reduction in Impact Energy and percentage of elongation with an increase in MD particles.

Ramesh et al. [18] fabricated A356- Quarry dust composite with 10 % weight by stir casting route. They revealed that porosity and thermal conductivity increased with increase of Quarry dust, decrease in density.

Rajak et al. [5] developed C93200 composites reinforced with marble dust (1.5-6 %) varying weight of 1.5 % via stir casting in vacuum condition. They studied cumulative properties of composites using multi-criteria decision making (MCDM) and revealed composite with 4.5%wt. provided best combination in bearing application. Gangwar et al. [19] Investigated on tribological performance of ZA-27/ CaO composite fabricated via gravity casting technique. DMA and TMA analysis has been performed at 850 °C and revealed tribosurface behaviour characterized using surface profile and EDSA. Storage modulus and wear rate of composite increased with increasing of wt. % CaO.

This study details on tribological performance of Al-LSP composites developed with various weight fractions using stir casting route. The influencing parameters on Al-LSP composites are applied load, % of LSP, sliding velocity and linear distance of disc; whereas, responses were wear rate and coefficient of friction. L25 orthogonal array is used to design the experiments, and ANOVA revealed response characteristic on influencing factors.

2. FABRICATION AND TESTING OF AL-LSP COMPOSITES

The reinforcement (LSP) has collected in wet form from a stone cutting industry (Siva Sai Granites, Tekkali, and Andhra Pradesh). The wet slurry is dried for 15 days; then, preheated to 300 °C for 3 hr to remove moisture. A ball mill has used to make finer particulates followed by screening to 90 BSS mesh ($\leq 60 \mu\text{m}$). The finer LSP particulates were used as reinforcement to make AMCs. Before preparing AMCs, the base matrix and LSP particulates were preheated at different temperatures. The base matrix (Al-Mg-Si) has been cut into small pieces and collected in graphite crucible kept in bottom pouring furnace maintained at 425 °C. Simultaneously, the LSP particulates are preheated in a muffle furnace (Model: ENV120T, Naskar) at 1230 °C for 2 hr, to attain wettability. The composites are fabricated using double stir casting. The casting process explained elsewhere [20,21]. Several tests are conducted on Al-LSP composites and exposed to different conditions to know their behavioural properties. The specimens were made from the middle portion of cast Al-LSP composites.

Tensile strength and Hardness value of Al-LSP are determined by Universal Testing Machine (Model: TUE-C-100) and Brinell hardness tester (Model: RASN-B) respectively.

Metallographic examination has been followed a standard technique (ASTM E-7-17). Tribological properties of LSP composites are tested using Pin-on-Disc tester (Model: TE-165-LE, Magnum Engineers, and Bangalore). The counter pin has a dimension of 6 mm in diameter and 27 mm in length. The wear rate (WR) has been measured using weight loss method. The WR has been specified in mm^3/Nm . Based on friction forces, coefficient of friction is determined. The worn-out and metallography samples were examined using SEM (Model: JEOL JSM-5600LV) and Optical microscope (Model: METZ-797) respectively.

2.1 Orthogonal Experimental Design Analysis

In order to develop a correlation between responses (wear rate (WR) & coefficient of friction (CF)) and controlled parameters such as applied load(L), % of LSP (R), sliding velocity (V) and sliding distance (D), Taguchi Orthogonal

array (L25) is used. Controlled variables with their levels are listed in Table 1. The experimental results are analyzed based on regression and ANOVA [22].

Table 1. Control variables with levels.

Parameters	Units	Level 1	Level 2	Level 3	Level 4	Level 5
Applied load (L)	N/ mm^2	10	20	30	40	50
% of LSP (R)	%wt.	0	4	8	12	16
Sliding distance (D)	mm	500	1000	1500	2000	2500
Sliding velocity (V)	m/s	0.5	0.875	1.25	1.625	2

3. RESULTS AND DISCUSSION

The LSP particles are shown in Fig. 1a. The particles are seen to be spherical and few are oblated in shape having average size of $58\mu\text{m}$. The XRD plot (Fig. 1b) revealed that, the compounds such as Calcite (CaCO_3), dolomite ($\text{Mg}(\text{CaCO}_3)_2$) and quartz (SiO_2) are presented in LSP. Calcite is an alkaline compound and act as binder. Similarly, Quartz is a hard phase compound, which enhanced properties of composite.

Fig. 1. (a) LSP Particles, and (b) XRD of LSP.

The density of LSP is 2.46 g/cm^3 . Figure 2 (a-e) shows micrographs of Al-LSP composites and observed that uniform dispersion of the LSP in Al-Mg-Si with hardly visible gathering of particle clusters and enhancing quality of cast is good. The weight ratio of LSP increases the grain size decreased in Al-LSP composites; also, thickened boundaries due to heterogeneous nucleation. It is also observed that bright area indicates matrix and dark area indicates LSP.

(a)

(b)

(c)

(d)

(e)

Fig. 2. Microstructures of composites (a) Al-Mg-Si, (b) Al-4 % LSP, (c) Al-8 % LSP, (d) Al-12 % LSP, and (e) Al-16 % LSP.

SEM surface of 8 % LSP composite is shown in Fig. 3a, and Energy dispersive X-ray spectroscopy (EDS) has revealed that the list of elements such as Al, Fe, Ca, Si, Mg, and Na are presence in LSP composites, shown in Fig. 3b.

(a)

(b)

Fig. 3. (a) Microstructure of 8 % LSP, and (b) EDAX of Composite.

(a)

(b)

Fig. 4. Mechanical properties of developed composites (a) BHN and density (b) tensile strength and elongation.

Physical and Mechanical properties of Al-LSP composites are presented in Fig. 4 (a and b). The test results reported that 12 % LSP composite has exhibited better as compared to other LSP composites as well virgin alloy. The hardness (Fig. 4a) and tensile strength (Fig. 4b) of Al-LSP composites are increased with

increase in LSP content, owing to presence of hard compounds like quartz and dolomite. The presence of calcite enhanced greater bonding with matrix and LSP particulates. While, resulted in reduction of composite density and elongation with increasing LSP content.

3.1 Wear behaviour of Al-LSP composites

Abrasive wear rate of Al-LSP composites are shown in Figs. 5 and 6. All the LSP composites are tested at a pressure of 0.6 N/mm², and sliding velocity of 1.25 m/s. From Fig. 5, it is observed that wear rate decreased with increase in sliding distance due to reduction of friction between pin and disc by formation of lubricated layer is observed and explained by Archard [23].

Fig. 5. Effect of wear rate on sliding distance.

Fig. 6. Effect of wear rate on applied pressure.

Similarly, Fig. 6 reveals that with increasing pressure on composite, wear rate increased. This attributes to rapid crack propagation / fracture of hard phase compounds in LSP. It is concluded that from Fig. 5 and 6, 12 % LSP composite exhibited

better wear resistance than other composites. At higher pressure, coefficient of friction is exhibited maximum in all materials as shown in Fig. 7. This attributes to shattered debris laid between tribo surfaces as well as cracking of protection layer. It is identified that softer phase (Al-Mg-Si) exhibited maximum friction and 12 % LSP composite exhibited least friction at all pressures, the filler material (LSP) acts as load barrier and forms self protective layer.

Fig. 7. Effect of coefficient of friction on applied pressure.

Fig. 8. Effect of coefficient of friction on Sliding Distance.

Figure 8 represents increase of sliding distance with increase in coefficient of friction due to tearing/ cracking of protective layer.

3.2 Analysis of Variance (ANOVA) on Wear Responses

Taguchi approach (L25) is used for design of experiments (DOE) and depicted in Table 2. Signal to Noise (SN) ratio of responses are computed by MINITAB-16. The SN ratio value is found least as -20.191 and 5.297 for WR and CF respectively.

The order of significant effective factors on WR as $D > L > V > R$ is observed from Table 3 and $L > R > V > D$ for CF (Table 4). Sliding distance is most influencing factor on WR, and applied load is significance parameter on CF.

Table 2. Design matrix and responses with S/N values.

Run	L	R	D	V	WR	CF	SNRA WR	SNRA CF
1	1	1	1	1	5.725	0.311	-15.155	10.149
2	1	2	2	2	4.482	0.230	-13.029	12.759
3	1	3	3	3	3.324	0.182	-10.433	14.776
4	1	4	4	4	2.252	0.168	-7.051	15.505
5	1	5	5	5	3.265	0.186	-2.042	14.606
6	2	1	2	3	5.480	0.363	-14.776	8.801
7	2	2	3	4	3.947	0.267	-11.926	11.458
8	2	3	4	5	2.500	0.205	-7.959	13.779
9	2	4	5	1	1.687	0.259	-4.541	11.736
10	2	5	1	2	7.901	0.200	-17.954	13.961
11	3	1	3	5	4.586	0.412	-13.228	7.694
12	3	2	4	1	2.403	0.397	-7.613	8.014
13	3	3	5	2	2.576	0.294	-8.218	10.643
14	3	4	1	3	8.660	0.229	-18.750	12.807
15	3	5	2	4	5.846	0.267	-15.338	11.462
16	4	1	4	2	3.682	0.540	-11.321	5.347
17	4	2	5	3	3.480	0.389	-10.831	8.212
18	4	3	1	4	9.434	0.317	-19.494	9.966
19	4	4	2	5	6.245	0.308	-15.910	10.234
20	4	5	3	1	3.720	0.398	-11.411	8.013
21	5	1	5	4	4.399	0.543	-12.867	5.297
22	5	2	1	5	10.222	0.466	-20.191	6.629
23	5	3	2	1	6.328	0.487	-16.025	6.255
24	5	4	3	2	4.760	0.436	-13.552	7.211
25	5	5	4	3	5.277	0.418	-10.309	7.572

Table 3. ANOVA of wear rate.

Source	DF	SS	ADJ SS	Adj MS	F	% Cont.
L	4	61.44	61.44	15.361	17.05	16
R	4	12.18	12.18	3.044	3.38	3
D	4	286.79	286.79	71.696	79.6	73
V	4	26.38	26.38	6.595	7.32	7
Error	8	7.21	7.21	7.206	0.9	2
Total	24	393.99				

DF: degree of freedom; SS: sequential sum of square; Adj SS: adjacent sum of square; Adj MS: adjacent sum of mean square; F: variance; P: test (% cont.: percentage of contribution).

Table 4. ANOVA of coefficient of friction.

Source	DF	SS	ADJ SS	Adj MS	F	% Cont.
L	4	153.62	153.62	38.40	104.8	67
R	4	57.11	57.11	14.28	38.94	25
D	4	2.38	2.38	0.60	1.63	1
V	4	11.86	11.86	2.97	8.09	5
Error	8	2.93	2.93	0.37		1
Total	24	227.90

(a)

(b)

Fig. 9. Effect of control variables on (a) wear rate, (b) coefficient of friction of Al-LSP composites.

The optimal condition for wear rate is $L_1R_4D_5V_1$ and $L_1R_4D_1V_4$ for coefficient of friction, is shown in Figs. 9a and 9b. The optimal values are 6.577 and 0.175 for WR and CF respectively. The predicted values are obtained using regression Equations (1) and (2) for wear rate and coefficient of friction. The regression value of R^2 and R^2_{adj} is 98.1 % and 94.2 % for WR. Similarly for CF show R^2 and R^2_{adj} is 98.7 % and 96.1 % respectively.

$$WR = 6.63 + 0.0578 * L - 0.0233 * R - 0.00285 * D + 0.661 * V \quad (1)$$

$$CF = 0.232 + 0.00641 * L - 0.00876 * R + 0.000015 * D - 0.0366 * V \quad (2)$$

Table 5. Confirmation Test Parameters and Responses.

Load	D	CF (Cal.)	CF (Act.)	WR (Cal.)	WR (Act.)
15	700	0.187	0.182	6.048	6.265
25	1400	0.248	0.258	4.631	5.08
35	2100	0.336	0.366	3.214	3.169

Confirmation tests (Table 5) are conducted at a constant sliding velocity of 1.25 m/s and LSP of 12 %. The results obtained from regression model are satisfied. Table 5 shows calculated (Cal.) and experimental (Act.) values of wear responses, with an error of ± 5 %.

3.3 Worn-out surface analysis

Figure 10 studies on morphological examination of worn-out surface for base alloy, 8 % of LSP and optimal condition of wear rate. Figure 10a and Fig. 10b examined under a steady state condition of applied load of 30 N (0.6 N/mm²), sliding distance of 1500 m and sliding velocity of 1.25 m/s. Figure 10c has studied at optimal condition of WR i.e., $L_1R_4D_5V_1$. Severe deformation/delamination are observed on worn-out surface, shown in Fig. 10a. This attributes to, shear forces causing enhancement of heat generation at tribo interface; then, debris formation and increase in surface roughness leads to ploughing of softer phase, which results increased wear rate. Similarly, Fig. 10b shows decrease in ploughing effect causing reduction in wear rate.

(a)

(b)

(c)

Fig. 10. Worn-out surfaces of (a) Al-Mg-Si, (b) Al-8 % LSP, and (c) Optimal condition ($L_1R_5D_5V_1$).

The micrograph (Fig. 10c) at optimal condition shows two kinds of wear mechanisms i.e. abrasive and abrasion. The morphology surface is smoother as compared to other, which correlates findings (Fig. 5) at high sliding distances.

4. CONCLUSIONS

The present work emphasized on indigenous devolvement of Al-LSP composites using stir casting. XRD of LSP revealed that calcite (CaCO_3) is in rich form followed by dolomite ($\text{Mg}(\text{CaCO}_3)_2$) and quartz (SiO_2). Mechanical

and tribological performances of Al-LSP composites are studied. It is revealed that properties of composites increased with increasing addition of LSP. Subsurface examination are conducted, and results are corroborates with findings. ANOVA has been performed, identified significant effective factors on WR as $D>L>V>R$ and $L>R>V>D$ for CF. Hence, sliding distance is more influencing factor on WR and Load is significant parameter on CF. The optimal condition for wear rate is $L_1R_4D_5V_1$ and $L_1R_4D_1V_4$ for coefficient of friction is obtained. Examination of worn-out surfaces explained the change in wear mechanism from abrasive to abrasion.

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