

Development of Al/Al₂O₃ and Al/LSP Composites: Mechanical and Tribological Perspective

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ABSTRACT

The present work focuses on the development of the aluminum composite with the addition of alumina (Al₂O₃) and industrial waste i.e. Limestone Slurry Particulate (LSP) in AA6082. The LSP is considered industrial waste and is available in abundance. The particle size used in the current work varies from 10µm to 60µm with an average size of 42 µm. The tribological characteristics were investigated for all the developed composites at different input parameters (like load, sliding distance and sliding velocity). The minimum and maximum value of wear rate (WR) for Al-alloy is 2.582mm³/m and 7.744 mm³/m; while for Al/Al₂O₃ composite is 4.345 mm³/m and 11.678 mm³/m & for Al/LSP composite is 2.303 mm³/m and 7.465 mm³/m. The minimum value of the coefficient of friction (CF) in the case of Al/LSP was 0.162. The morphological investigations of worn-out surfaces were made using scanning electron microscopy. It has been observed from morphological investigations that with the increase in reinforcement percentage in the aluminum composite, the grain boundaries thicken due to the segregation.

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INTRODUCTION

Cast composites have a lot of potential applications in India, especially in the energy, electromechanical machinery, and transportation sectors. The usage of composite not only helps in reducing economic expenses and energy consumption but also helps to minimize pollution in the environment. Stir casting and pressure infiltration have arisen as the two effective methods for the manufacture of composites. The fibers, whiskers, or particles are typically dispersed in a metallic alloy matrix in metal matrix composites. Due to these reinforcements, the composite gains importance nowadays, which would not be possible with monolithic alloys. Tribological properties of intermittently reinforced aluminum composites depend upon type, size, shape, orientation and quantity of reinforcement. Similarly, the tribological behavior of aluminum-based composites is mainly influenced by the counterpart material, effective load, sliding velocity, sliding distance, surroundings, and temperature (Sannino and Rack 1995).

In the past, researchers successfully developed α -Al₂O₃ (4 wt. %) reinforced Al-Si-Cu matrix by the mechanical stirring technique. It has been found that a considerably higher amount of alumina particles is retained in the castings when mechanical stirring is used as compared to manual stirring (Pai et al. 1976). During the mixing process, Al₂O₃ particles were broken into smaller pieces. The reason was that when the particles were led into the melt, the formation of MgO and thermal shock was observed. Aluminum matrix composite (AMC) is made with industrial residuals and agricultural wastes as reinforcements to curtail fabrication expenditure. However, a few technical complications come across in producing AMCs by stir casting process due to the following reasons: i) difference in densities ii) difference in liquefying state iii) immiscibility as well

as poor wettability, as described by researchers (Surappa 2003). Because an inhomogeneous distribution of second-phase particles in the matrix can result in premature failures in the matrix and reinforcement-rich areas, this is all because to particle-rich and particle-lean areas. Homogeneous distribution is essential for achieving a high-strengthening effect (Wessel 2004; Rosso 2006). Additionally, costly reinforced ceramic particles make the process costlier. To decrease the cost of the composite fabrication process, the selection of reinforcements should be in such a way that wettability must be retained at low-cost reinforcement (Lee et al. 2000; Bist, Saini & Sharma 2021; Totten and MacKenzie 2003). It was observed that the composite's density increased with the particle size reduction. The density of the AA2024-Al₂O₃ composites improved with a rising weight percentage. The rotational speed is one of the influencing parameters in stir casting. The increase in the stirrer's speed can create a vortex. The speed of stir casting as 500 rpm to 650 rpm was recommended (Kök and Özdin 2007). The present research utilizes Limestone Slurry Particulate (LSP) as a reinforcement, which is an industrial waste. The utilization of industrial waste as reinforcement material has gained attention in recent year. The aim of the present work is based on the development of composite using LSP as reinforcement (Demirel and Alyamaç 2018). Some studies based on limestone dust as reinforcement material for composite fabrication are discussed in the next paragraph.

Extensive research was carried out to study the physical, mechanical and tribological properties of AA6063 hybrid composites, which consist alumina and quarry dust (up to 10 wt. %). Incoherently, the composites' specific and tensile strength increased slightly with the percentage of quarry dust, while these characteristics were similar to those of a simple SiC-reinforced composite. The tribological characteristics of a ZA-27/CaO composite fabricated by the gravity-cast method were studied. The addition of quarry dust increases the composites' fracture and ductility stiffness significantly (Gangwar, Patnaik and Bhat 2018). In another research, it was reported that an increase in rice husk ash percentage was associated with an increase in the WR of aluminum hybrid composites and the wear mechanism of the composites also changed from abrasive to adhesive wear (Prasad, Shoba, and Ramanaiah 2014). Researchers found that the definitive rigidity and hardness were improved with the addition of silicon, graphite and fly ash in AA6063 (Loganathan et al. 2020).

It can be concluded from the above literature that the mixing of hard ceramic particles with aluminum alloy enhances the characteristics of the base metal/alloy (Abbas et al. 2023). Most of the work was

focused on improving the mechanical behaviour of the fabricated composites (Purohit et al. 2024; Dash et al. 2024). Despite the fact in the literature that many studies have been done on the superior wear resistance of metal matrix composites (MMCs) over base metal, very few investigations have been reported on the tribological properties of the composites, which discuss diverse parameters affecting the wear loss and the importance of the reinforcement phases. Therefore, in the present work, three different composites have been developed using the stir-casting route. Out of them, one is developed using industrial waste, namely LSP. The tribological characteristics (i.e. WR and CF) are investigated at different settings of load, sliding speed and sliding distance. The morphology of worn-out surfaces is recorded by SEM micrographs.

MATERIALS AND METHODS

Matrix Material

The chemical composition of matrix material is provided in Table 1. The matrix material used for the development of the composite is AA6082, having a significant amount of Si and Mg; thus, also known as Al-Si-Mg alloys.

Table 1. Chemical composition of AA-6082.

Mn	Fe	Zn	Cu	Mg	Si	Al
0.60%	0.08%	0.1%	0.1%	0.85%	0.95%	Balance

Preparation of Reinforcement (i.e. LSP)

Since the scale of production in the stone processing industry is significantly increasing, industrial waste is also increasing daily. Recycling is an important sector for sustainable development; thus, the adverse effects on the environment would be minimized. The LSP has been collected from a nearby industry, Siva Sai Granites, Tekkali. It is dried for 15 days to remove the moisture content, followed by preheating for 3 hours (upto 300°C).

Fabrication of Al-LSP Composites

A step-wise procedure to obtain the Al-LSP composite is presented in Figure 1. The reinforcements used in the current work are Al₂O₃ and LSP, and the particle size for both is varied from 10 µm to 60 µm with an average size of 42 µm. In the first step, the reinforcements and matrix material are placed in the muffle furnace at a temperature of 300 °C to remove any moisture content (if present). In the second step, the AA6082 material (in the form of ingots after measuring weight), along with reinforcements, was placed in a vertical furnace, and the temperature of the furnace was set at 750°C. The crucible and the stirrer are made of graphite. The rotational speed of the stirrer

and stirring time were set at 300 rpm and 20 minutes for the homogeneous mixing of the material. After that molten mixture is placed in a die to give it a proper shape. The splitting of cope and drag will take place to extract the cast composite.

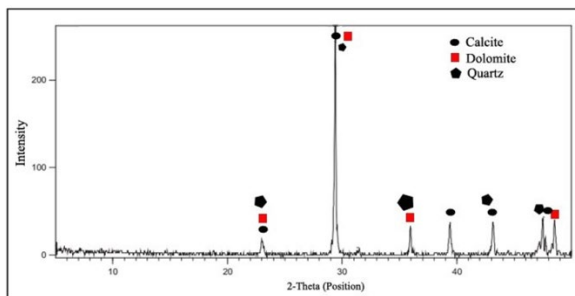
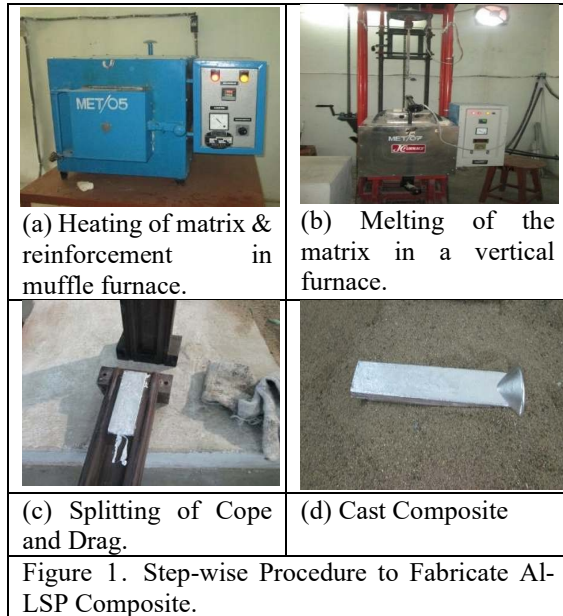
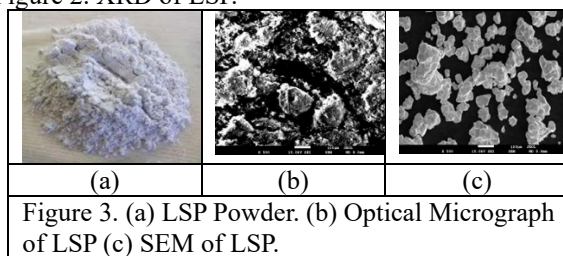


Figure 2. XRD of LSP.



The X-Ray diffraction (XRD) of the powder was performed to analyze the elements present in it. The XRD was performed on a Panalytical make X'Pert Pro with Cu as a source of X-rays. The XRD plot (Figure 2) reveals that calcite (CaCO₃) is a major quantity, followed by the presence of a few compounds such as dolomite (Mg(CaCO₃)₂) and quartz (SiO₂) in LSP. The tap density of LSP is found to be 2.46 g/cm³. The dolomite and calcite consist of calcium oxide (CaO), acting in response with alumina (Al₂O₃) and silica (SiO₂), which appear as aluminates and calcium silicates. LSP used as reinforcement for making the

composite is shown in Figure 3a. From Figures 3(b) and 3(c), it is found that the major quantity of LSP particles is in the shape of spheres.

Wear Test

Wear tests are performed to observe the influence of the parameters on the response variable during the dry sliding conditions. The control variables in the current research are load, sliding speed and sliding velocity; however, the output variables are wear rate (WR) and Coefficient of friction (CF), which are computed as per ASTM standards. The pin-on-disc machine (Ducom make, TR-20) is used for performing tribological investigations. The specimen dimensions in the present work are 6 mm in diameter and 27 mm in length (ASTM G-99-95). All the specimens were polished with different mesh-size abrasive paper before the wear test. During the wear test, the counter surface was made of EN-31 hardened steel with having 63 HRC value. For the measurement of WR, the weight of the pin is recorded before and after the wear test using a weighing balance. After every test, the disc is cleaned with acetone to remove any dust/debris. The WR is computed using Eq. 1, and the units of the obtained WR are mm³/m.

$$WR = \frac{\Delta m / \rho}{v.t} \quad (1)$$

where, WR-Wear rate in (mm³/m), Δm- mass loss in (g), ρ-density (g/cm³), V- sliding velocity (m/s), t-test duration (s).

Hardness Test

The Brinell test was performed on RASNB model at Fuel Instruments & Engineers Pvt Ltd. to measure the hardness of the developed composites. Before the test all the surfaces were cleaned with the help of acetone. The samples were prepared according to ASTM-384 standard, and an average of three was selected for analysis purposes. These three readings are also useful to confirm the repeatability.

Tensile Test

A computerized universal testing machine (UTM) is utilized to investigate tensile strength. The specimens are prepared according to ASTM-E8 standards. The load is applied gradually by releasing the pressure valve. The tensile test was performed on Heico make UTM (capacity: 25 kN) with a standard loading rate of 10⁻² N/s.

RESULTS AND DISCUSSION

The experimental responses were observed for all developed materials, and the values are presented in Table 2, corresponding to different input parameter settings. The effect of process parameters on the responses (WR and CF) is investigated and discussed in this section.

Table 2. L₉ Experimental layout with the corresponding results.

Run	Input Parameters			Al-alloy	CF	Al-12%Al ₂ O ₃	CF	Al-12%LSP	CF
	L(N)	D (m)	V (m/s)	WR (mm ³ /m)		WR (mm ³ /m)		WR (mm ³ /m)	
1	10	1000	0.875	4.936	0.279	4.495	0.412	4.657	0.174
2	10	1500	1.250	3.759	0.273	4.795	0.213	3.480	0.168
3	10	2000	1.625	2.582	0.267	4.345	0.210	2.303	0.162
4	30	1000	1.250	6.340	0.394	7.791	0.210	6.061	0.288
5	30	1500	1.625	5.163	0.387	9.390	0.207	4.884	0.282
6	30	2000	0.875	3.242	0.422	5.094	0.106	2.963	0.317
7	50	1000	1.625	7.744	0.508	11.687	0.412	7.465	0.403
8	50	1500	0.875	5.823	0.543	8.391	0.311	5.544	0.438
9	50	2000	1.250	4.646	0.537	5.244	0.112	4.367	0.432

Analysis of Variance (ANOVA) of WR and CF

Table 3 shows the ANOVA for WR in terms of control parameters (L, D and V). The significance of the input control variables is depicted in Table 2. A parameter is significant if its P-value is less than 0.05. In Table 3, the 'D' has the maximum contribution (59.7%), followed by load (38.6%). The values of R² and Adj-R² are found within the limit, which clarifies that the present model can predict future outcomes. The 98.8% variability of WR in Al-alloy is only due to significant factors. The addition of Al₂O₃ as reinforcement is used to develop a new composite. It has been found that L has the maximum influence (50.9%) followed by D (31%) and V (16.8%). The P-values of L and D are less than 0.05, representing

these parameters' significance on the WR. The values of R² and Adj-R² are in close agreement. The ANOVA of Al/LSP shows that D has a maximum (59.7%) contribution, followed by L (38.5%). Out of all the experiments (in Table 3), Experiment No. 3 (L = 10, D = 2000, V = 1.625) shows minimum value of WR. Using linear regression, the models for WR have been developed for Al-alloys, Al/ Al₂O₃ and Al/LSP in terms of L, D and V, and are given in Eqs. 2, 3 and 4.

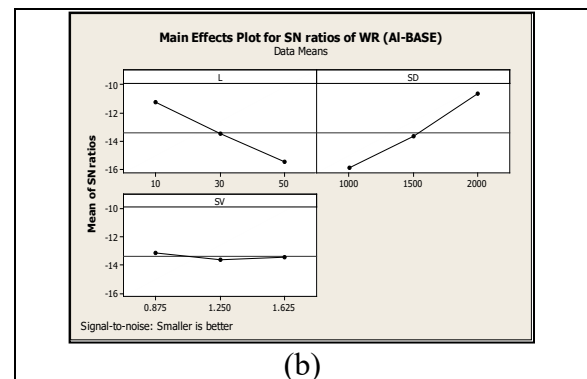
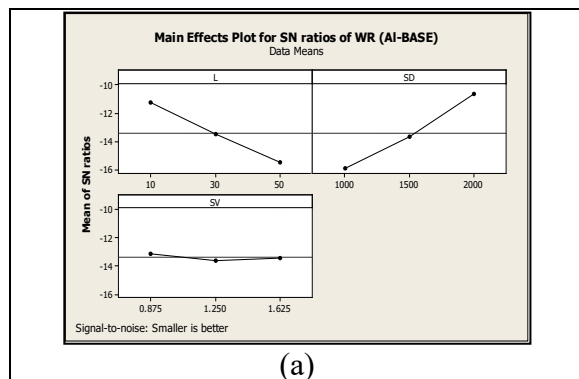
$$WR_{Al} = 6.629 + 0.0578L - 0.00285D + 0.6613V \tag{2}$$

$$WR_{Al-Al_2O_3} = 4.39 + 0.0974L - 0.00310D + 3.31V \tag{3}$$

$$WR_{Al-LSP} = 6.35 + 0.0578L - 0.00285D + 0.6613V \tag{4}$$

Table 3. ANOVA of WR.

Source	DF	Al-Alloy			Al/Al ₂ O ₃			Al/LSP		
		F	P	%Cont.	F	P	%Cont.	F	P	%Cont.
L	2	33.20	0.029	38.6%	38.68	0.025	50.9%	29.38	0.033	38.5%
D	2	51.41	0.019	59.7%	23.53	0.041	31.0%	45.54	0.021	59.7%
V	2	0.46	0.686	0.5%	12.74	0.073	16.8%	0.41	0.711	0.5%
Error	2									
Total	8	R-Sq(adj)=95.4%; R-Sq =98.8%			R-Sq(adj)=94.7%; R-Sq =98.7%			R-Sq(adj)=94.8%; R-Sq =98.7%		



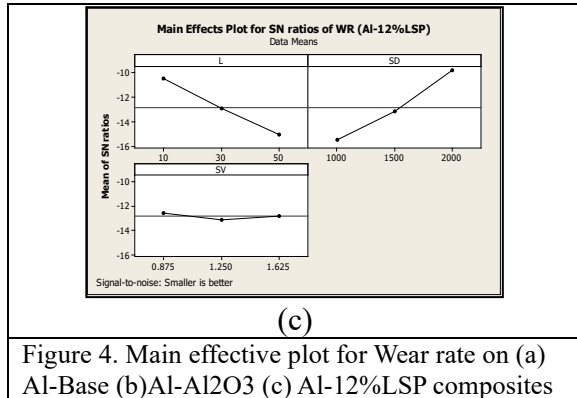


Figure 4 based on the mean values of the response graph developed for each parameter level, describes the effect of each parameter. The graph is constructed by determining the mean value in S/N ratios. See Figure 4(a) for an illustration of the ideal conduction of Al-base materials on wear rate: L1D3V1. Figure 4(b) shows that the wear rate for an Al-12%Al₂O₃ composite is L1D3V1. Same way to get the lowest possible wear rate using Al-12% LSP, the ideal combination of parameters is L1D3V1, shown in Figure 4(c).

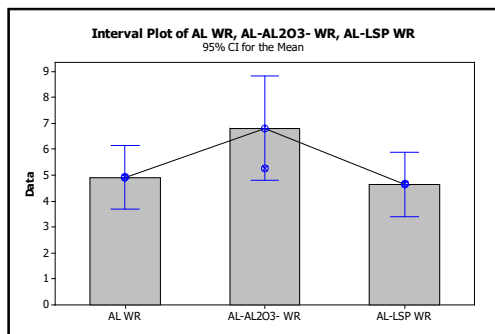


Figure 5. Mean interval plot for wear rate of all composites.

Minitab displays the group means as well as a range of possible population show the sample mean and a range of possible population mean values using interval graphs. Measurements of wear rate across various

intervals are shown in Figure 5. The means may seem to be different, but the overlap between the interval bars suggests that the difference is likely not statistically significant. The 95% confidence interval (CI) for the mean wear rate of Al-Pure ranges from 3.682 to 6.147, with a median value of 4.396. Additionally, for Al-Al₂O₃, the median is 6.803, and the 95% CI is from 4.792 to 8.815. The median for Al-LSP is 4.636, with a 95% CI ranging from 3.403 to 5.868.

CF of Developed Composites

Table 4 demonstrates the ANOVA of the developed composites. The load (L) has the maximum (98.9%) contribution in the investigation of CF, followed by V (1%). The 'D' has no influential contribution to CF due to a P-value greater than 0.05. The percentage contribution is computed by dividing the parameter SS value by the total SS value. The high F-value corresponds to the larger contribution of the control variable. The value of R² shows that 100% process variability can be predicted from the current model due to significant and non-significant process parameters. However, 99.9% variability (Adj-R²) can be investigated due to significant parameters only. The ANOVA of Al/Al₂O₃ shows that D has a maximum (63.5%) influence, followed by L (19.1%) and V (15.7%). The values of R² and Adj-R² of Al/Al₂O₃ have a close agreement.

The ANOVA of Al/LSP shows that L has a maximum contribution on CF followed by V and D. In this analysis, D has no significance due to a P-value greater than 0.05. The regression analysis for all three developed composites was done, and empirical models were developed for CF, which are given in Eqs. 5, 6 and 7.

$$CF_{Al} = 0.2319 + 0.00641L + 0.000015D - 0.03644V \quad (5)$$

$$CF_{Al-Al_2O_3} = 0.547 - 0.000202D \quad (6)$$

$$CF_{Al-LSP} = 0.1263 + 0.006408L + 0.000015D - 0.03644V \quad (7)$$

Table 4. ANOVA for CF.

Source	DF	Al-Alloy			Al/Al ₂ O ₃			Al/LSP		
		F	P	% Cont.	F	P	% Cont.	F	P	% Cont.
L	2	6644.1	0.000	98.9%	11.60	0.079	19.1%	3018.95	0.000	98.9%
D	2	11.13	0.082	0.2%	38.59	0.025	63.5%	3.60	0.217	0.1%
V	2	64.98	0.015	1.0%	9.54	0.095	15.7%	28.45	0.034	0.9%
Error	2									
Total	8	R-Sq(adj)=99.9%; R-Sq=100.0%			R-Sq(adj)=93.4%; R-Sq=98.4%			R-Sq(adj)=99.9%; R-Sq=100.0%		

The graph is then shown in Figure 6 based on these mean values. As shown in Figure 6(a), the ideal conduction for Al-base materials on CF is L1D1V3.

Figure 6(b) similarly shows the L2D3V2 for the Al-12% Al₂O₃ composite on CF. As seen in Figure

6(c), the load (L) is the most important parameter, with

sliding velocity coming in second. For minimal CF, L1D1V3 is the best combination of parameters.

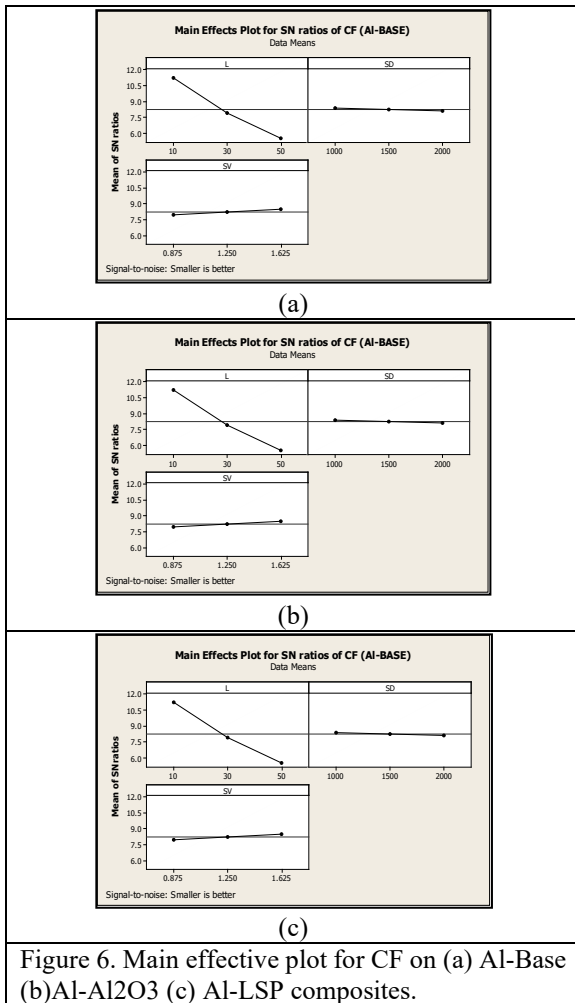


Figure 6. Main effective plot for CF on (a) Al-Base (b)Al-Al₂O₃ (c) Al-LSP composites.

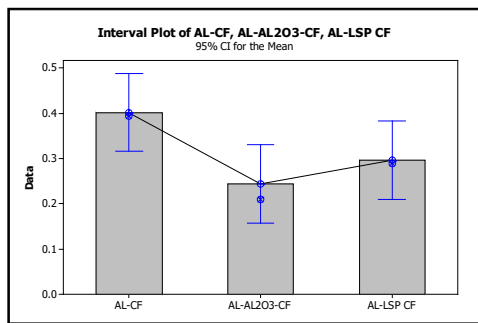


Figure 7. Mean interval plot for CF of all composites.

Measurements of the coefficient of friction across various intervals are shown in Figure 7. The 95% confidence interval (CI) for the mean wear rate of Al-Pure ranges from 0.315 to 0.487, with a median value of 0.401. Additionally, for Al-Al₂O₃, the median is 0.244, and the 95% CI is from 0.156 to 0.331. The median for Al-LSP is 0.296, with a 95% CI ranging from 0.210 to 0.381.

Variation of Process Parameters

The variations of the response variables (WR and CF) along with the input parameters (L, D and V) for all three developed composites are depicted in Figure 8. It is clear from Figure 8a that with the increase in load value (from 10 N to 50 N), the WR increases for all developed composites. In the case of Al-alloy, the WR increases up to 6.071 mm³/m. However, after the addition of LSP as reinforcement, the WR value was found to be decreased and became equal to 5.792 mm³/m. As evident from Figure 8(a), the variation of WR for the Al/LSP composite is lowest among the other two composites. However, in each case, with the increase in load value, the WR was found to increase. The main reason for this is the increase in the contact pressure, which may increase the mechanical damage at the interface. Thus, an increase in WR was observed for each developed composite. Figure 8(b) represents the variation of WR with respect to the sliding distance (D) for developed composites. It is clear from Figure 8b that with the increase in D value from 1000 m to 2000 m, the WR decreases from 6.34 mm³/m to 3.49 mm³/m, 7.991 mm³/m to 4.894 mm³/m, 6.061 mm³/m to 3.211 mm³/m for Al-alloy, Al/Al₂O₃ and Al/LSP composite respectively. The probable reason behind this decrement may be the metal matrix layer, which was developed during the stir-casting route. Another factor for the decrease in the WR may be the transition from grooving abrasion to rolling abrasion, which results in the reduction of WR.

At the start of experiments, the upper layer of the developed composite comes in contact with the counter surface, which removes any irregularities from the surface. Therefore, a large amount of material removal takes place with a higher WR value. Once all the irregularities are settled, the WR is decreased. The minimum value of WR was observed for Al/LSP and was equal to 3.211 mm³/m. The variation of WR with respect to V is shown in Figure 8(c), and it is clear from Figure 8c that with the increase in V values, the WR values increase. The main fact behind this is the softening of the material at a higher sliding speed, which reduces the shear strength and increases the WR. The minimum value of WR is 4.388 mm³/m for Al/LSP composite at 0.875 m/s. The main reason is the presence of calcite and dolomite in the Al/LSP composite. The hardness of the reinforced particles is much higher than the matrix materials and therefore increases the overall strength of the composite. The variation of CF with respect to L is provided in Figure 8d. It is evident from Figure 8(d) that with the increase in L value from 10N to 50N, the CF increased from 0.273 to 0.5293, 0.168 to 0.4243 for Al-alloys and Al/LSP, respectively. As CF is lower, the better type quality characteristic; therefore, minimum CF is suggested. The minimum value of CF is 0.168, corresponding to a 10 N load for Al/LSP. As the value of L increases from 10 N to 50 N, the pressure on the

pin increases, which increases the CF. Figure 8(e) suggests that an increase in D value increases the CF slightly. Also, in the case of Al/Al₂O₃, the CF decreases with the increase in D. The main fact behind this is the steady state of the pin. Once it comes in contact with the counter surface, the pin experiences certain CF, but with the increase in D, it may obtain steady state and a decrement in CF is observed. However, minimum CF is observed for a minimum value of D (i.e. 1000 m) for Al/LSP. Figure 8(f) depicts the variation of CF with the V. It has been observed from Figure 8(f) that with the increase in V value from 0.875m/s to 1.625m/s, the value of CF was found to decrease. Therefore, a minimum V is suggested for low CF. In the case of Al/Al₂O₃, the minimum CF (i.e. 0.1783) is observed at 1.25 m/s. After this, when the value of V is increased from 1.25 m/s to 1.625 m/s, the CF value is found to be increased up to 0.2763 m/s. The reason behind the initial decrement of the CF is the presence of a metal matrix layer (MML); once V is increased, the MML breaks and enhances the CF.

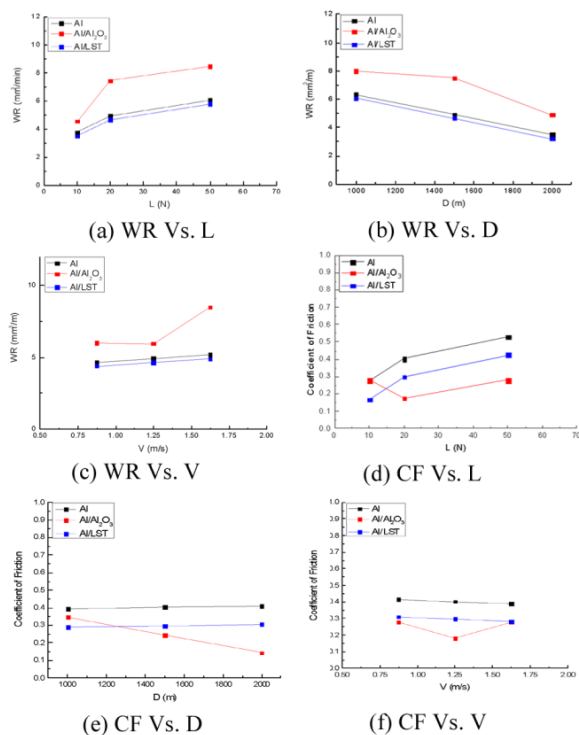


Figure 8. Variation of WR and CF with respect to input parameters.

Confirmation Tests

The confirmatory experiments are carried out to validate the regression equations. Pin-on-disc tests are run on three additional experimental points (Table 5), which are not in the Taguchi L₉ orthogonal array. The experimentally measured WR and CF values are compared to the values predicted from the regression equation, and the error is computed. Error % less than 10% indicates that regression equations are reasonably

accurate.

Table 5. Confirmation Tests Results.

Response	L	D	V	Pred.	Exp.	Error
WR-Alalloy	15	1200	1.2	4.870	4.725	3.1%
WR-Al-Al ₂ O ₃	15	1200	1.2	6.106	5.623	8.6%
WR-Al-LSP	15	1200	1.2	4.591	4.900	-6.3%
WR-Alalloy	20	1500	1	4.172	4.482	-6.9%
WR-Al-Al ₂ O ₃	20	1500	1	5.003	5.287	-5.4%
WR-Al-LSP	20	1500	1	3.893	3.687	5.6%
WR-Alalloy	30	1000	1.5	6.605	6.324	4.4%
WR-Al-Al ₂ O ₃	30	1000	1.5	9.179	8.601	6.7%
WR-Al-LSP	30	1000	1.5	6.226	5.901	5.5%
CF-Alalloy	15	1200	1.2	0.302	0.311	-2.8%
CF-Al-Al ₂ O ₃	15	1200	1.2	0.304	0.312	-2.5%
CF-Al-LSP	15	1200	1.2	0.197	0.205	-3.9%
CF-Alalloy	20	1500	1	0.346	0.330	4.9%
CF-Al-Al ₂ O ₃	20	1500	1	0.244	0.285	-14.3%
CF-Al-LSP	20	1500	1	0.241	0.252	-4.4%
CF-Alalloy	30	1000	1.5	0.385	0.382	0.7%
CF-Al-Al ₂ O ₃	30	1000	1.5	0.345	0.334	3.2%
CF-Al-LSP	30	1000	1.5	0.279	0.266	5.0%

Hardness

It can be observed that from the three developed composites, Al-12% Al₂O₃ is the hardest, Al-12% LSP is of intermediate hardness, and Al-Alloy is the softest material. The main reason for the highest hardness of Al-12% Al₂O₃ is the high hardness of the reinforcement (Al₂O₃) over the LSP. Table 6 and Figure 9 shows the hardness of three composites.

Table 6. Hardness of three Composites.

Material	Hardness (HB)	% Change
Al-Alloy	47.3±1.7	---
Al-12%Al ₂ O ₃	53.0±2.3	12.1%
Al-12%LSP	51.3±2.1	8.5%

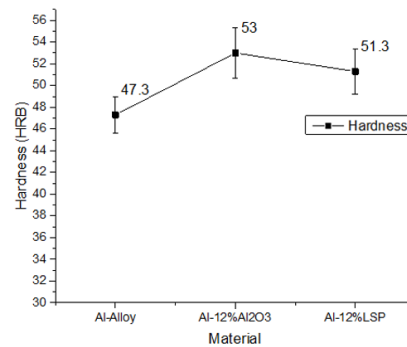


Figure 9. Hardness of three Composites.

Tensile strength

Figure 10 depicts that the ultimate tensile strength increases with the increase in percentage increase in LSP. A decrease in elongation is observed with an increase in LSP particles, thereby making the composite more brittle (less ductile). The presence of quartz (SiC) in the LSP increases the tensile strength and decreases ductility. The tensile strength is enhanced with the addition of LSP reinforcement. The reason behind the increment in the strength is the existence of MML, which was developed between the matrix material and the particulate.

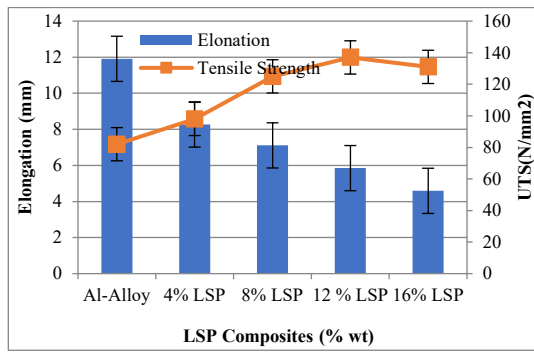


Figure 10. Tensile Properties of Al-LSP Composites.

The presence of hard particles resists the material against abrasion and adhesion. This may be due to the strong interfacial bonding between the matrix and the reinforcement. At reinforcement levels beyond 12% LSP, a slight reduction in tensile strength was observed. This decline is primarily attributed to particle agglomeration, which leads to the formation of microstructural defects, such as voids and weak interfacial zones. These defects act as stress concentrators under tensile loading, promoting early crack initiation and propagation. Similar trends have been reported in earlier studies, where the addition of ceramic or mineral reinforcements beyond an optimal level resulted in reduced mechanical performance due to poor dispersion and interfacial bonding (Radhika, Subramanian, and Prasat 2011; Kumar, Saravanan and Sellamuthu 2018). Thus, while moderate additions of LSP improve strength, excessive loading undermines these benefits due to non-uniform distribution and weakened matrix-reinforcement interactions. The sharp decline in elongation observed with increasing LSP percentage—from 9.08 mm for base Al-alloy to 4.59 mm for 16% LSP—indicates a clear reduction in ductility. This is attributed to the presence of hard, brittle particles such as calcite and quartz within the matrix, which hinder dislocation movement and limit plastic deformation. While this leads to improved hardness and tensile strength up to an optimal reinforcement level, it also introduces brittleness in the material.

From an application standpoint, this trade-off suggests that Al-LSP composites with higher reinforcement levels may be more suitable for structural and tribological applications where wear resistance and strength are critical, such as automotive components (e.g., brake drums), pump housings, or wear plates. However, their limited ductility may render them less effective for load-bearing components subject to impact, or for parts requiring plastic forming processes, like stamping or extrusion. Therefore, the reinforcement content must be optimized based on the intended application to balance strength and ductility.

Microstructural examination

The study's design of an Al-base matrix microstructure is illustrated in Figure 11 (a). Grain sizes range from 10 to 50 micrometres in this typical single-phase structure. Images of reinforced AMC microstructures may be seen in Figures 11b and 11c. Metallographic pictures show dendritic structures and reinforcing particles in dark regions at the grain boundary, while the matrix itself appears brilliant. The grain line thickens because the particles within it are dispersed and do not have uniform distributions; as a result, the grain is fine-grained. Composites with fine grains have higher tensile strengths and harder surfaces. Figure 12 also shows the volume fraction, which is determined using an analyser. When compared to the predicted mass balance quantities, the observed values check out.

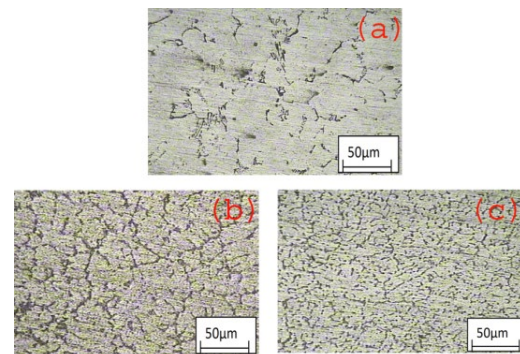


Figure 11. Microstructure of composites (a) Al-base (b) Al-12%LSP (c) Al-12%Al₂O₃.

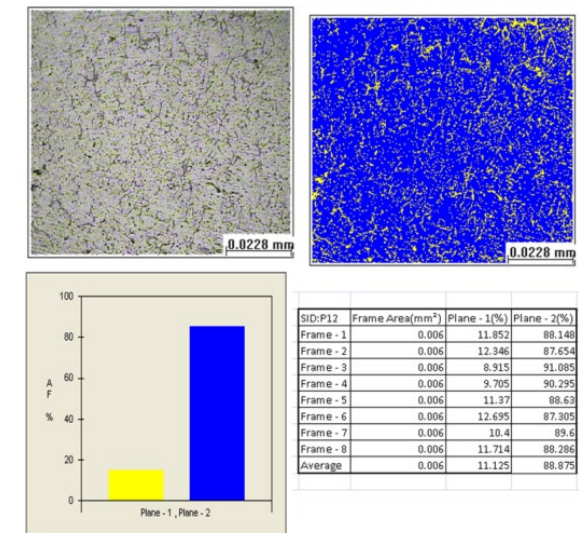


Figure 12. Distribution of reinforcement in Al-12%Al₂O₃ composite and establish volume fraction.

Tribo-Surface Examination

The worn-out surfaces at the optimal condition of WR and CF are examined for Al-Alloy, Al-12% Al₂O₃, Al-12% LSP composite. Figure 13(a), (b), and

Agglomeration at higher LSP content slightly lowered strength.

- SEM analysis confirmed that reinforcement type strongly influenced wear mechanisms: Al₂O₃ led to abrasive wear, while LSP contributed to the formation of protective tribo-layers and delamination wear resistance.

The use of industrial waste such as LSP as a reinforcement offers a cost-effective, sustainable route to develop wear-resistant aluminum composites. These materials are potentially suitable for automotive, construction, and mechanical applications where moderate strength and high wear resistance are required. Further research can be directed toward:

- Optimizing particle distribution and interfacial bonding to prevent agglomeration at higher wt.%,
- Evaluating long-term corrosion resistance in harsh environments,
- Exploring hybrid reinforcements combining LSP with other agro-industrial waste,
- Investigating thermal stability and fatigue performance under cyclic loading.

Conflict of interest

The authors declare that they have no conflicts of interest.

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