Frictional Study of Al 6061 Red-Mud Composite under the Influence of Different Process Parameters

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ABSTRACT

Metal matrix composite having aluminium 6061 as matrix incorporating red mud reinforcement has been casted by employing stir casting. Scanning electron microscopy images has been taken to observe the uniformity of the red-mud reinforcement in the aluminium 6061 matrix. The inclusion of reinforcement inside the matrix of the fabricated composite has been confirmed by Energy dispersive spectroscopy. The results reveal that the coefficient of friction increases by larger sliding distance and decreases in response to higher sliding velocity. Also, coefficient of friction first increase up to second level with increase in applied load after that continuously reduced with further applying higher load. Study reveals that the coefficient of friction has been minimum at 125 micrometer particle size and has maximum value at 250 micrometer. Delta analysis shows percentage reinforcement has least effect on output i.e. coefficient of friction. Further, coefficient of friction decreases with higher aging time but again increases for 24 hour aging time. The ANOVA analysis concludes, the parameters i.e. aging time, sliding distance, sliding speed have found significant effect but the impact of particle size and load have been not comes out significant. The ANOVA revealed descending order of significance for the studied parameters has been: sliding speed, aging time, sliding distance, particle size and load.

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1. INTRODUCTION

Aluminum including its alloys when reinforced mostly by harder ceramic reinforcements has been known as aluminium matrix composites (AMC) [1-3]. Unreinforced aluminium alloys have been not able to meet the changing requirements of current era. AMCs have better properties than their monolithic parent alloy such as higher stiffness, improved

strength, better wear behaviour, more strength-to-weight ratio, higher tensile strength etc. this makes AMCs preferable over aluminum and their alloys [4-6]. Among Al-alloys, 6061Al-alloy is widely used. A number of materials such as SiC, Al₂O₃, B₄C, TiB₂, ZrO₂, SiO₂ and graphite are being used as reinforcements to improve the properties of 6061Al alloy [7-9]. Type of reinforcements and methods of fabrication influences the properties of aluminum

composites. AMC due to their superior properties comes out as important materials for aerospace, auto, defence, and other industrial applications [10-12]. Most often used reinforcements with aluminium has been SiC, TiB₂, B₄C, Al₂O₃, TiO₂, Gr, CNT, SiO₂, Fly-ash, bagasse-ash, rice husk-ash etc. Reinforcement included in a matrix may contain single, two or more materials [13-19]. Many fabrication techniques have been used for fabricating AMCs. These methods include powder metallurgy, diffusion bonding, squeeze casting, compo casting, stir casting physical vapour deposition etc. Stir casting has been proffered because of its simplicity and economy [20-25]. Design of experiment (DOE) has been employed to examine the influence of selected variables on output with reduced number of experiments. Taguchi methods have been applied mostly to study any product or process, influencing variables and their effect with minimum possible variation. The orthogonal array, signal-to-noise ratio and analysis of variance have been employed by researches to find optimum input variables in composite [26-30].

In this study friction behaviour of fabricated aluminium 6061 matrix based red mud composite has been studied and reported in detail. Coefficient of friction of composite has been measured on pin on disc type friction and wear monitor and the results has been reported. S/N ratio and mean values of results has been calculated using minitab software for further analysis. Delta and ANOVA analysis of mean and S/N ratio has been done to reveal the effect of input parameters upon wear and coefficient. Mathematical model for wear and coefficient of friction has been developed and the predicted results have been reported.

2. METHOD

2.1 Material preparation

Al6061 which has been available commercially, chosen as matrix. Material has been purchased from the market in the form of rods and angles. X-ray fluorescence (XRF) spectroscopy of purchased aluminum 6061 has been done at institute laboratory to find out composition of constituents. XRF results of purchased material have been shown in Table 1, gives the

composition of aluminum 6061. The Purchased rods and angles have been cut into small pieces before melting. Red Mud powder has been the reinforcement material and is procured from HINDALCO plant, situated at Renukut town, in Utter Pradesh state of India. The procured red-mud have been dried and crushed. Different particle size of red-mud has been separated by using standard sieves. Five different sizes of red mud have been separated.

Table 1. Constituents of aluminum 6061 and red mud obtained by XRF analysis.

XRF Result for aluminium 6061		
Sr. no.	Element	Percentage
1	Al	97.6
2	Mg	0.79
3	Si	0.72
4	Mn	0.32
5	Cu	0.28
6	Fe	0.16
7	Cl	0.04
8	Ti	0.02
9	Cr	0.02
10	K	0.02
11	Ga	0.02
12	Zn	0.01
13	S	67PPM
14	N	66PPM
15	V	48PPM
XRF result for red mud		
Sr. no	Element	Percentage
1	Fe ₂ O ₃	35.26
2	Al ₂ O ₃	21.89
3	TiO ₂	15.11
4	SiO ₂	12.46
5	Na ₂ O	11.82
6	CaO	1.83
7	P ₂ O ₅	0.40
8	V ₂ O ₅	0.38
9	SO ₂	0.19
10	ZrO ₂	0.15
11	K ₂ O	0.13
12	MgO	0.12
13	Cr ₂ O ₃	0.11
14	Cl	0.04
15	MnO	0.04
16	CuO	0.02
17	Sc ₂ O ₃	0.01
18	Ga ₂ O ₃	0.01
19	Nb ₂ O ₅	0.01
20	ZnO	65PPM
21	Ag	56PPM
22	PbO	47PPM
23	As ₂ O ₃	45PPM
24	NiO	44PPM
25	SrO	43PPM
26	Y ₂ O ₃	22PPM

Table 2. Selected input Parameters with their respective levels for friction studies.

Sr. No.	Parameters/Level	1	2	3	4	5
1	Percentage Reinforcement(by wt)	4	8	12	16	20
2	Particle Size(μm)	250	177	149	125	74
3	Ageing Time(hr)	1/2hr	6	12	18	24
4	Load applied(kg)	1	2	3	4	5
5	Sliding Distance(m)	1000	1500	2000	2500	3000
6	Sliding Speed(m/s)	.2	.4	.6	.8	1

2.2 Selection of Parameters and Orthogonal array Friction behaviour

To study the friction behaviour six parameters have been chosen as follows: percentage reinforcement (PR), Particle size (PS) in microns, aging time (AT) in Hours, Load applied (L) in kg, sliding distance (SD) in meters, sliding speed (SS) in meter per second. The response of studied parameters has been taken as coefficient of friction (COF). To reveal the impact of chosen input parameters on wear, five levels of each parameter have been considered.

Table 3. L25 Orthogonal array with five levels values and six factors values.

Exp no.	Reinforcement (%wt)	Particle size (μm)	Aging time (Hr)	Load (kg)	SD (m)	Speed (m/s)
1	4	250	0.5	1	1000	0.2
2	4	177	6	2	1500	0.4
3	4	149	12	3	2000	0.6
4	4	74	18	4	2500	0.8
5	4	125	24	5	3000	1
6	8	250	6	3	2500	1
7	8	177	12	4	3000	0.2
8	8	149	18	5	1000	0.4
9	8	74	24	1	1500	0.6
10	8	125	0.5	2	2000	0.8
11	12	250	12	5	1500	0.8
12	12	177	18	1	2000	1
13	12	149	24	2	2500	0.2
14	12	74	0.5	3	3000	0.4
15	12	125	6	4	1000	0.6
16	16	250	18	2	3000	0.6
17	16	177	24	3	1000	0.8
18	16	149	0.5	4	1500	1
19	16	74	6	5	2000	0.2
20	16	125	12	1	2500	0.4
21	20	250	24	4	2000	0.4
22	20	177	0.5	5	2500	0.6
23	20	149	6	1	3000	0.8
24	20	74	12	2	1000	1
25	20	125	18	3	1500	0.2

L25 Orthogonal array (OA) has been chosen for conducting the experimentation. It has been a 5 level OA with maximum number of six factors. The maximum degree of freedom can be 24 for L25 orthogonal array. For friction behaviour six

factors has been considered for conducting the experiments. L25 OA for six factors and five levels has been shown in Table 3. The six factors have been taken from factor A to Factor-F. The five levels have been taken from Level-1 to Level-5. Reinforcement percentage by weight has been taken from 4 % to 20 % after reviewing literature [31-33].

2.3 Sample fabrication

The composite under this study has been manufactured by using stir casting process. Total number of fifty castings has been done according to L25 orthogonal array with a repetition of two. In accordance with the design of experiments quantity of matrix material and reinforcement has been taken for castings. Aluminium 6061 has been melted at 800 °C in a crucible made from graphite using electric muffle furnace shown in Fig. 1.

Fig. 1. Stir casting setup.

For melting aluminium 6061 pieces in the form of rod and angles has cut and placed inside the crucible. Weight of the Aluminium 6061 and red mud reinforcement has been done at institute laboratory before melting. Mechanical stirrer has been inserted in molten alloy for creating vortex. Red mud reinforcement particles preheated at 400 °C in a separate furnace has been injected to vortex [34]. Vortex has been created for obtaining uniform spreading of red mud in the aluminium matrix. Magnesium in a small quantity (1 %) has been incorporated in the mixture for getting improved wettability of red-mud particles with molten matrix material. The molten mixture has been poured inside preheated cylindrical mild steel moulds. The obtained castings have been machined further to prepare the samples for conducting different experiments and tests.

2.4 Heat treatment

Heat treatment of the fabricated samples has been done to improve properties and more accurate results. Homogenizing of prepared aluminium composite has been performed to achieve uniformity in material structure and better properties. In homogenizing samples has been heated to a temperature of 525°C for eight hours inside electric furnace[35]. Quenching of heated composite has been done by water. After those samples has been dried and used for further operation. Aging heat treatment of the composite has been performed in electric furnace. Aging has been done at a temperature of 175 ±5°C. Aging time duration has been 0.5, 6, 12, 18 and 24 hrs. Aging duration of the composite samples has been taken from the L25 orthogonal array prepared for current study. After ageing sample has been allowed to cool down in the furnace.

2.5 SEM analysis

SEM images of fabricated samples have been shown in figures below. SEM images have been taken at a zoom of 1000X, 1200X, 2000X, 15000X and 45000X. Whitish colour particles visible in the images have been red mud. The dark gray area visible in the images has been aluminium 6061. It can be seen inside the images (Fig. 2) that reinforcement red-mud have been uniform in aluminium matrix. Some particle clustering has been seen in image of 16 % and 20 % reinforcement.

(a) 4 % red-mud

(b) 8 % red-mud

(c) 12 % red-mud

(d) 16 % red-mud

(e) 20 % red-mud

Fig. 2. SEM photographs of casted aluminum 6061 matrix red-mud reinforcement composite.

2.6 EDS analysis

The red-mud reinforcement constituents has been shown in Energy dispersive spectroscopy (EDS) spectrum of studied aluminum red-mud samples. The EDS Spectrum of sample has been shown in Fig. 3. EDS results reveals the presence of Calcium (Ca), Oxygen (O), Iron (Fe), Sodium (Na), Zinc (Zn), vanadium (W), silicon (Si), Titanium (Ti), potassium (k) etc. inside the matrix. Selected area for EDS spectrum has been shown at right side of each image. Obtained EDS spectrums showing different elements have been shown at left side of each image.

(a) Spectrum area

(b) EDS spectrum

Fig. 3. EDS analysis of aluminum matrix red-mud reinforcement composite.

2.7 FRICTION TEST

Friction test has been performed using pin-on-disk wear tester (Model: TR-20LE-PHM-CHM400 from DUCOM Bangalore) displayed in Fig. 4. ASTM G99 test standard has been used to perform the test.

Fig. 4. Pin on disk type wear and friction monitor.

(a) Sample 1

(b) Sample 2

Fig. 5. Coefficient of friction with respect to time for experiment no-1.

The equipment can be used for a wide range of loads up to 200 N and speed from 200 to 2000 rpm. The apparatus can be used to evaluate the friction and wear behaviour of a specimen under sliding contact for different test variations. The sliding contact happens to be between a stationary pin of composite samples under study and a moving hard material disc. The applied load that is normal to disk, rpm and track diameter on disk can be varied for a sample. Tangential force and wear have been observed using electronic sensors and recorded with computer. Studied parameters have been plotted as functions of load and speed. The disc is made up of EN-31 having a diameter of 100 mm and 8 mm thickness and a hardness value of 60 HRc (ground to surface roughness of 1.6 Ra). The specimens used are in the shape of cylindrical pin and have a diameter of 10 mm with 30 mm length. The mean coefficient of friction has been calculated by the computer software shown by Fig. 5.

3. RESULTS OF COEFFICIENT OF FRICTION

To evaluate the impact of selected input parameters on coefficient of friction, five levels have been considered. L_{25} Taguchi OA has been chosen for performing the experiments. Fifty number of experiments have been performed i.e. twice of each type shown in Taguchi OA. The calculated results for coefficient of friction have been reported in Table 4.

Table 4. Results of coefficient of friction for aluminum 6061 red-mud composite.

Sr. No	PR (by wt)	PS (μm)	AT (hr)	L (kg)	SD (m)	SS (m/s)	COF ₁	COF ₂
1	4	250	0.5	1	1000	0.2	0.52	0.509
2	4	177	6	2	1500	0.4	0.457	0.437
3	4	149	12	3	2000	0.6	0.416	0.392
4	4	74	18	4	2500	0.8	0.364	0.335
5	4	125	24	5	3000	1	0.404	0.359
6	8	250	6	3	2500	1	0.342	0.342
7	8	177	12	4	3000	0.2	0.486	0.486
8	8	149	18	5	1000	0.4	0.369	0.369
9	8	74	24	1	1500	0.6	0.366	0.392
10	8	125	0.5	2	2000	0.8	0.349	0.352
11	12	250	12	5	1500	0.8	0.371	0.33
12	12	177	18	1	2000	1	0.218	0.218
13	12	149	24	2	2500	0.2	0.577	0.577
14	12	74	0.5	3	3000	0.4	0.566	0.562
15	12	125	6	4	1000	0.6	0.372	0.389
16	16	250	18	2	3000	0.6	0.488	0.459
17	16	177	24	3	1000	0.8	0.369	0.354

18	16	149	0.5	4	1500	1	0.361	0.31
19	16	74	6	5	2000	0.2	0.518	0.425
20	16	125	12	1	2500	0.4	0.268	0.38
21	20	250	24	4	2000	0.4	0.508	0.528
22	20	177	0.5	5	2500	0.6	0.372	0.366
23	20	149	6	1	3000	0.8	0.41	0.37
24	20	74	12	2	1000	1	0.294	0.294
25	20	125	18	3	1500	0.2	0.422	0.422

In the table, values are given for percentage reinforcement (PR), Particle size (PS) in microns, aging time (AT) in Hours, Load applied (L) in kg, Sliding distance (SD) in meters, sliding speed (SS) in meter per second, coefficient of friction (COF) and Signal to noise ratio (S/N). Smaller is better criteria has been chosen for coefficient of friction study because smaller the friction more has been the utility of composite.

Table 5. Mean value of coefficient of friction and respective S/N ratio.

Sr. No	PR (by wt)	PS (μm)	AT (hr)	L (kg)	SD (m)	SS (m/s)	Mean	S/N
1	4	250	0.5	1	1000	0.2	0.5145	5.7718
2	4	177	6	2	1500	0.4	0.4470	6.9917
3	4	149	12	3	2000	0.6	0.4040	7.8685
4	4	74	18	4	2500	0.8	0.3495	9.1236
5	4	125	24	5	3000	1	0.3815	8.3550
6	8	250	6	3	2500	1	0.3420	9.3195
7	8	177	12	4	3000	0.2	0.4860	6.2673
8	8	149	18	5	1000	0.4	0.3690	8.6595
9	8	74	24	1	1500	0.6	0.3790	8.4221
10	8	125	0	2	2000	0.8	0.3505	9.1062
11	12	250	12	5	1500	0.8	0.3505	9.0914
12	12	177	18	1	2000	1	0.2180	13.2309
13	12	149	24	2	2500	0.2	0.5770	4.7765
14	12	74	0	3	3000	0.4	0.5640	4.9744
15	12	125	6	4	1000	0.6	0.3805	8.3907
16	16	250	18	2	3000	0.6	0.4735	6.4895
17	16	177	24	3	1000	0.8	0.3615	8.8360
18	16	149	0	4	1500	1	0.3355	9.4611
19	16	74	6	5	2000	0.2	0.4715	6.4883
20	16	125	12	1	2500	0.4	0.3240	9.6613
21	20	250	24	4	2000	0.4	0.5180	5.7118
22	20	177	0	5	2500	0.6	0.3690	8.6592
23	20	149	6	1	3000	0.8	0.3900	8.1673
24	20	74	12	2	1000	1	0.2940	10.633
25	20	125	18	3	1500	0.2	0.4220	7.4938

The obtained results have been analyzed using Minitab software. From the obtained results mean value and S/N ratio has been evaluated by Minitab software. The respective mean values and S/N ratio has been given in following Table 5.

4. DISCUSSION

4.1 Delta Analysis for coefficient of Friction

Delta analysis of the results has been done using Minitab software. Here, mean value of each parameter at each level has been calculated. Then the difference in maximum value of mean and minimum value of mean has been calculated. More has been the gap between the maximum mean and minimum mean of parameter more has been the influence of the parameter on output.

Table 6. Response Table for S/N Ratios for coefficient of friction.

Level	Reinforcement (%by wt)	Particle Size (μm)	Aging Time (hr)	Load (kg)	Sliding Distance (m)	Speed (m/s)
1	7.622	7.928	7.595	9.051	8.458	6.160
2	8.355	8.601	7.872	7.599	8.292	7.200
3	8.093	7.787	8.704	7.698	8.481	7.966
4	8.187	8.797	8.999	7.791	8.308	8.865
5	8.133	7.277	7.220	8.251	6.851	10.20
Delta	0.733	1.520	1.779	1.451	1.630	4.040
Rank	6	4	2	5	3	1

Table 7. Response Table for Means of coefficient of friction.

Level	Reinforcement (% by wt)	Particle Size (μm)	Aging Time (hr)	Load (kg)	Sliding Distance (m)	Speed (m/s)
1	0.4193	0.4116	0.4267	0.3651	0.3839	0.4942
2	0.3853	0.3717	0.4062	0.4284	0.3868	0.4444
3	0.4180	0.4151	0.3717	0.4187	0.3924	0.4012
4	0.3932	0.3763	0.3664	0.4139	0.3923	0.3604
5	0.3986	0.4397	0.4434	0.3883	0.4590	0.3142
Delta	0.0340	0.0680	0.0770	0.0633	0.0751	0.1800
Rank	6	4	2	5	3	1

The above Tables 6 and 7 displays the means of signal to noise ratios and mean values for coefficient of friction of the studied aluminum red-mud composite at respective level. The above analysis concludes the sliding speed has highest influences on the coefficient (rank 1) while percentage reinforcement has least effect (rank 6). Since the percentage reinforcement has least effect on output hence it is neglected for further analysis. Similar results have been reported by authors et al. [33].

4.2 ANOVA Analysis for Coefficient of Friction

The ANOVA analysis found out that the parameter aging time, sliding distance, sliding speed have been significant but the impact of particle size and load are not significant enough. The significance order of the parameters has been Sliding speed, aging time, sliding distance, particle size and load.

Table 8. ANOVA table for coefficient of friction.

Source	Degree of Freedom	Sum of Squares	Mean Squares	F Ratio	P value	Contribution (%)
Particle size	4	7.701	1.9252	5.14	0.071	9.047
Aging Time	4	11.267	2.8167	7.52	0.038	13.237
Load	4	7.157	1.7894	4.78	0.08	8.408
Sliding Distance	4	9.560	2.3901	6.38	0.050	11.231
Speed	4	47.931	11.9827	31.99	0.003	56.313
Residual Error	4	1.498	.3746			1.759
Total	24	85.115				

4.3 Estimation of optimum Coefficient of Friction

In this section optimum value of coefficient of friction and confidence interval of coefficient of friction have been predicted analytically by employing Taguchi's technique. By recognising the effect of factors optimum value of coefficient of friction has been calculated.

The significant process parameters for weight loss due to wear have been SS_1 , SD_1 and AT_1 . The mean value of calculated coefficient of friction [37]:

$$W_{\mu} = SS_1 + SD_5 + AT_4 - 2T_{\mu} \quad (1)$$

where, T_{μ} is Average of all values of Coefficient of Friction: 0.40288; SS_5 Average value of Coefficient of Friction at fifth level of sliding speed: 0.3142; SD_1 Average value of Coefficient of Friction at first level of sliding distance= 0.3839; AT_4 Average value of Coefficient of Friction at first level of Aging Time= 0.3664; W_{μ} = 0.25874 Confidence interval has been calculated by Eq. (2) using following values: Predicted confidence interval has been evaluated using equation-2 [37]

$$CI = \sqrt{F_{\alpha}(1, f_e) V_e \left[\frac{1}{n_{eff}} + \frac{1}{R} \right]} \quad (2)$$

Here, the term CI= has been Confidence interval; $F_{\alpha}(1, f_e)$ is the F-ratio having confidence level of $(1-\alpha)$ at DOF=1 and at error degree of freedom (f_e); V_e has been the Variance of error; R is the sample size taken for confirmation experiment; N_{eff} has been effective number of repetition= $N/[1+\text{total degree of freedom for the estimation of mean}]$; N is the total number of results i.e. 50. Using the values: V_e = 0.001149; Total DOF for estimation of mean are 12; n_{eff} is equal to 3.8461; $F_{0.05}(1, 12)$ has value of 4.75.

The confidence interval comes out = 0.004.

The CI of estimated coefficient of friction at 95 % confidence Interval has been $=0.259 \pm 0.004$ (0.263-0.255).

The optimum level of input parameters for the best value of coefficient of friction using smaller the better criteria has been written as follows: Reinforcement level: 8 %, Particle size: 125-micron, Aging time: 18 Hr, Load: 1kg, Sliding Distance: 1000 m, Sliding Speed: 1.0m/s.

4.4 Confirmation experiments for coefficient of friction

The optimized results have been verified with conformation experiments at optimum level of input parameters. The mean coefficient of friction of confirmation experiments has been given in Table 9. The coefficient of friction result of confirmation experiments has been comes out near to the estimated results and lies between the limits of confidence interval predicted which is ± 0.004 .

Table 9. Confirmation experiments result for coefficient of friction.

Response Characteristics	Optimum parameters and respective level	Predicted Optimum Value of coefficient of friction	Confidence Interval at 95%	Experimental Value
Coefficient of Friction	A ₅ , B ₅ , C ₅	0.259	± 0.004	0.261
Coefficient of Friction (Base Aluminum 6061)				0.351

4.5 Effect of Selected parameters on Coefficient of Friction

Impact of chosen parameters such as reinforcement, particle size, aging time, load, sliding distance, sliding speed on coefficient of friction has been discussed below.

4.5.1 Effect of percentage reinforcement on coefficient of friction

The value of coefficient of friction with respective percentage reinforcement has been displayed in Fig. 6 Coefficient of friction has been shown on y-axis and percentage reinforcement has been shown on x-axis. There has been arbitrary trend shown by percentage reinforcement on coefficient of friction. This may be due to dominance of different behaviour of

percentage reinforcement such as improvement in hardness with higher reinforcement percentage, clustering of particles with increase in percentage, formation of grooves, three body effect for reduction in friction.

Fig. 6. Mean values of COF at each level of percentage reinforcement.

Delta analysis shows percentage reinforcement (rank=6) has least effect on coefficient of friction. Similar trends have been reported by authors et al. [36].

4.5.2 Effect of particle size on coefficient of friction

Graphical representation of coefficient of friction with respective particle size has been shown in Fig. 7. Y-axis represents coefficient of friction and x-axis denotes particle size. Particle size shows arbitrary trend for coefficient of friction. This variation again may be due to dominance of different behaviour at different levels such as three body effect of particles, hardness effect of particles with decrease in size, formation of grooves due to particles and clustering of particles.

Fig. 7. Mean value of COF at each level of particle size.

Value of coefficient of friction has been minimum at 125 micrometer particle size and coefficient of friction has maximum value at 250

micrometer. The ANOVA analysis of the variables reports that the impact of particle size ($P=0.071>0.05$) on coefficient of friction has been not found significant. Analysis also found that sliding speed (56.31 %), aging time (13.23 %), sliding distance (11.23 %) has been more effective than particle size and load (8.4 %) has been less effective.

4.5.3 Effect of aging time on coefficient of friction

The Figure 8 shows values of friction coefficient at different levels of aging time. COF has been shown on vertical axis and aging time has been shown on horizontal axis. Coefficient of friction reduced by increase in aging time but again increases for 24-hour aging time. Reduction in COF may be due to increase in hardness of the contact surface.

Fig. 8. Mean values of coefficient of friction at each level of aging time.

At 24-hour aging time, coefficient of friction increases and this may be because of formation of hard grooves on the mating surface and which in turn increases friction force. ANOVA analysis of the input parameters on coefficient of friction concluded that aging time ($P=0.038\leq 0.05$) has been a significant parameter affecting coefficient of friction. The analysis also reveals that aging time (13.23 %) has been second most effective parameter out of selected input parameters, affecting coefficient of friction after sliding speed.

4.5.4 Effect of load on coefficient of friction

The relation between coefficient of friction and applied load has been given in Fig. 9. Coefficient of friction has been represented on y-axis and load has been represented on x-axis. The friction coefficient first increases by increasing applied load after that continuously decreased when

further load increased. First increase in coefficient of friction may be due to increase in contact pressure and hence increase in friction force. But more increase in load reduces coefficient of friction that may be due to removal of reinforcement particles cause's three body phenomena and reduces friction between the contact surfaces.

Fig. 9. Mean values of COF at each level of load.

The effect of load ($P=0.08>0.05$) on coefficient of friction has not been reported significant by ANOVA analysis. Load (8.4%) has been found least effective parameter on coefficient of friction after percentage reinforcement by the above analysis.

4.5.5 Effect of sliding distance on coefficient of friction

The variation of coefficient of friction at each level of sliding distance has been shown in Fig. 10. The figure shows coefficient of friction on ordinate axis and sliding distance on abscissa.

Fig. 10. Mean values of COF at each level of sliding distance.

From the Fig. 10, it can be seen that the coefficient of friction increases by increasing

sliding distance. This effect may be due with more sliding distance surface become rougher by formation of cavities in the contact surface due to removal of material and reinforcement particles. The ANOVA analysis of the input parameters on the coefficient of friction reports that the impact of sliding distance ($P=0.05 \leq 0.05$) has been found significant. The analysis further reports that the sliding distance (11.23 %) has been more influential than the percentage reinforcement (rank=6), particle size (9.04 %) and load (8.4 %) but less influential than the sliding speed (56.31 %) and aging time (13.23 %).

4.5.6 Effect of sliding speed on coefficient of friction

It can be observed from the Fig. 11 coefficient of friction decreases with increase in sliding speed. The may be due to increase in sliding speed, friction between pin and disk surface reduces hence coefficient of friction decreases.

Fig. 11. Mean values of coefficient of friction at each level of sliding speed.

ANOVA analysis of the input variables on the coefficient of friction reported that the effect of sliding speed ($P=0.003 \leq 0.05$) has been found significant. The analysis also reveals that the sliding speed (56.31 %) has been most significant factor among all selected factors.

4.6 Mathematical model for Coefficient of Friction

By considering the Six parameters, namely percentage reinforcement as PR, Particle size as PS, Aging time as AT, Load as L, Sliding Distance as SD and Sliding speed as SS and using MINITAB software mathematical model has been developed for predicting the value of Coefficient of Friction. The regression equation for Coefficient of Friction has been as follows:

$$\begin{aligned} \text{Coefficient of Friction} = & - 8.509 + 0.1880 \text{ PR} - 0.009481 \text{ PS} - 0.1975 \text{ AT} - 0.1557 \text{ L} + 0.01533 \text{ SD} - 20.38 \text{ SS} - 0.000199 \text{ PR} \cdot \text{PS} - 0.01719 \text{ PR} \cdot \text{AT} + 0.3470 \text{ PR} \cdot \text{L} - 0.000735 \text{ PR} \cdot \text{SD} + 0.6116 \text{ PR} \cdot \text{SS} - 0.000858 \text{ PS} \cdot \text{AT} + 0.005394 \text{ PS} \cdot \text{L} + 0.000009 \text{ PS} \cdot \text{SD} - 0.02517 \text{ PS} \cdot \text{SS} + 0.06564 \text{ AT} \cdot \text{L} + 0.000010 \text{ AT} \cdot \text{SD} + 0.4430 \text{ AT} \cdot \text{SS} - 0.003049 \text{ L} \cdot \text{SD} - 0.1205 \text{ L} \cdot \text{SS} + 0.004882 \text{ SD} \cdot \text{SS} + 0.004073 \text{ PR} \cdot \text{PR} + 0.000010 \text{ PS} \cdot \text{PS} + 0.002787 \text{ AT} \cdot \text{AT} \end{aligned} \quad (3)$$

Where PR is percentage reinforcement, in weight %, PS is particle size in micrometers (μm), AT is aging time in hours (Hr), L is load in kg, SD is sliding distance in meters, SS is sliding speed in m/s.

Table 9. Predicted Results of Coefficient of Friction.

PR (by wt)	PS (μm)	AT (hr)	L (kg)	SD (m)	SS (m/s)	Mean COF	Predicted COF
4	250	0.5	1	1000	0.2	0.5145	0.4888
4	177	6	2	1500	0.4	0.447	0.4210
4	149	12	3	2000	0.6	0.404	0.3816
4	74	18	4	2500	0.8	0.3495	0.3568
4	125	24	5	3000	1	0.3815	0.3741
8	250	6	3	2500	1	0.342	0.2795
8	177	12	4	3000	0.2	0.486	0.4560
8	149	18	5	1000	0.4	0.369	0.3953
8	74	24	1	1500	0.6	0.379	0.3854
8	125	0.5	2	2000	0.8	0.3505	0.3293
12	250	12	5	1500	0.8	0.3505	0.3647
12	177	18	1	2000	1	0.218	0.1923
12	149	24	2	2500	0.2	0.577	0.5732
12	74	0.5	3	3000	0.4	0.564	0.5733
12	125	6	4	1000	0.6	0.3805	0.4106
16	250	18	2	3000	0.6	0.4735	0.4194
16	177	24	3	1000	0.8	0.3615	0.3936
16	149	0.5	4	1500	1	0.3355	0.3638
16	74	6	5	2000	0.2	0.4715	0.5364
16	125	12	1	2500	0.4	0.324	0.3102
20	250	24	4	2000	0.4	0.518	0.5481
20	177	0.5	5	2500	0.6	0.369	0.4043
20	149	6	1	3000	0.8	0.39	0.3560
20	74	12	2	1000	1	0.294	0.3254
20	125	18	3	1500	0.2	0.422	0.4674

The predicted results of Coefficient of Friction by this mathematical model have been reported in Table 9. As it can be observed from the Table 9 that the predicted results show good agreement with the experimentally obtained results.

5. CONCLUSIONS

The coefficient of friction increased by increasing sliding distance. Coefficient of friction decreased when there has been an increase in sliding velocity. Coefficient of friction first increase up to second level with increase in applied load after that continuously decreased when further hike in load. The coefficient of friction has been minimum at 125 micrometer

particle size and coefficient of friction has maximum value at 250 micrometer. There has been arbitrary trend shown by percentage reinforcement on coefficient of friction. Delta analysis shows percentage reinforcement has least effect on coefficient on coefficient of friction. Coefficient of friction decreases with increase in aging time but again increases for 24-hour aging time. By ANOVA, the parameters i.e. aging time, sliding distance, sliding speed have found significant while the impact of particle size and load have been not found significant. The order of significance of the factors has been Sliding speed (56.3 %), aging time (13.26 %), sliding distance (11.23 %), particle size (9.04 %) and load (8.4 %).

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