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A Statistical Analysis of Optimization of Wear Behaviour of Al-Al_2O_3 Composites Using Taguchi Technique

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Abstract

This work deals with the effect of Al_2O_3 on wear properties of AA7075 metal matrix composite and the results were optimized by Taguchi technique. The composites were prepared by conventional liquid casting method with varying the Al_2O_3 content. The wear test was conducted with pin-on-disc apparatus with the controlling parameters were, applied load of 10, 20, 30, and 40N and sliding distance of 1200 m with regular interval of 200m at 0.6m/s sliding speed. The micro structural investigation on the worn surfaces was performed by Scanning Electron Microscope. A statistical analysis of wear test was conducted using Response Surface Methodology, and Taguchi technique under Design of Experiments with Regression Equation using MINITAB software. From these results, the optimum AA7075/ Al_2O_3 composite was evaluated and the optimum controlling parameters were examined on the basis of 'smaller the best'.

Keywords: Alloys; Al_2O_3; Wear; AA 7075; Response Surface Methodology (RSM); Taguchi technique

1. Main text

Metal matrix composites have many potential applications, because of the unique property combinations that can be achieved [1, 2]. Metal matrix composites have been developed to respond to the demand for materials with high specific strength, stiffness, and wear resistance [3]. Aluminum alloys are an important vital engineering material for tribological and mechanical applications due to its low density, high thermal conductivity and

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improved machinability for automobile, aerospace, marine and mineral processing industries. Due to its high wear loss nature it will not be applicable for many tribological applications. AMCs can be reinforced with SiC, Al_2O_3, B_4C, TiC, TiB_2, MgO, TiO_2 and BN. To avoid this drawback, aluminum alloy– Al_2O_3 particulate composites are being explored for the mechanical and the tribological applications. Therefore, the investigation of tribological and mechanical behavior of aluminum based materials is becoming increasingly important. The incorporation of a hard ceramic phase to a relatively soft matrix alloy, commonly aluminium, improves the strength, creep performance, and wear resistance of the alloy [4, 5].

Straffelini et al. [6] reported that the matrix hardness has a strong influence on the dry sliding wear behavior of Al 6061 –Al_2O_3 composites. Yu et al. [7] demonstrated the effects of applied load and temperature on the dry sliding wear behavior of the Al6061 –SiC composites, and concluded that the wear rate decreases with increased applied load. How and Baker [8] investigated the wear behavior of Al 6061-Saffil fiber, concluded that Saffil fibers are significant in improving wear resistance of composites. AA7075 pre-aging at various retrogression temperatures improves the hardness, tensile properties and electrical resistivity [9]. Kim et al. [10] concluded that the hardness of aged AA7075 alloy increases.

Many techniques were developed for producing particulate reinforced MMCs, such as powder metallurgy [11], in situ [12] and squeeze casting [13]. From all the above three methods, stir casting technique is the simplest and the most economical process for fabricating particulate reinforced MMCs [14]. This work aims to investigate wear behaviour of AA 7075 /$Al_2O_{3\,(p)}$ composites, with varying $Al_2O_{3\,(p)}$ content in the matrix.

Radhika et al. [15] found taguchi technique as a valuable technique to deal with responses influenced by multi-variables. It is formulated for process optimization and detection of optimal combination of the parameters for a given response. This method significantly reduces the number of trials that are required to model the response function compared with the full factorial design of experiments. The most important benefit of this technique is to find out the possible interaction between the factors.

The experiment is planned in such a way to estimate simultaneously two or more factors which possess their ability to affect the resultant average or variability of particular product or process characteristics. To accomplish this in a valuable and statistically proper method, levels of the factors are varied in a strategic manner. The results of the particular test combinations are observed and the complete set of results are analyzed to determine the preferred level of the various influencing factors whether increases or decreases of those levels will potentially lead to further enhancement [16].

Investigation of the experimental outcomes uses signal to noise ratio to support the determination of the finest process design. This method is effectively used to analysis of wear behaviour of composites materials [17]. In this work, the “smaller the best” quality characteristics were taken to finding the minimum wear rate under various applied load and sliding distance conditions.

Nomenclature

Δm	Average Mass Loss (g)
AA	Aluminium Alloy
Al_2O_3	Aluminium Oxide
AMCs	Aluminium Matrix Composites
B_4C	Boron Carbide
BN	Boron Nitrate
COF	Coefficient of Friction
D	Sliding Distance (m)
DOE	Design of Experiments
K_0	Specific Wear Rate ($N^{-1}m^2$)
L	Applied Load (N)
MgO	Magnesium Oxide
MMCs	Metal Matrix Composites
p	Particles

RSM	Response Surface Methodology
SD	Standard Deviation
SEM	Scanning Electron Microscope
SiC	Silicon Carbide
TiB_2	Titanium Boride
TiC	Titanium Carbide
TiO_2	Titanium Oxide
X_1	Independent Process Parameters
X_2	Independent Process Parameters
Y	Response
β_0	Constant
β_1	Linear Coefficients
β_{11}	Quadratic Coefficients
β_{12}	Interaction Coefficients
β_2	Linear Coefficients
ρ	Density of the Materials (g/m^3)

2. Materials And Experimental Details

2.1. Materials

The AA7075 was stir casted with Al_2O_3 to fabricate AA7075/ Al_2O_3 composites. The temperature of the furnace is to be precisely measured and accurately controlled (±1ºC). Two thermocouples and one PID controller are used for this purpose. A 1HP motor was used to rotate the stirrer at different speeds. A screw operated lifting mechanism was used to bring the stirrer in contact with composite material. As shown in Fig. 1, 1 Kg of AA7075 was taken in a graphite crucible and heated to about 850ºC in an electric furnace and the chemical composition of the AA 7075 [10] is shown in table 1.

Table 1. Chemical composition of AA7075.

Elements	Zn	Cu	Mn	Mg	Fe	Cr	Si	Al
Weight %	5.4	1.42	0.12	2.42	0.42	0.21	0.13	Remaining

Simultaneously, in another furnace according to Wt % of Al_2O_3 particles were measured by using digital electronic weighing machine and are kept in a furnace. The temperature was raised about 480ºC. Degasser and nucleant chemicals were added for removing the impurities. AA 7075 molten metal is taken out from the furnace and the preheated Al_2O_3 particles were added. The AA 7075 / Al_2O_3 composite are again kept in a furnace and are heated to about 800 ºC. The melt was subsequently stirred at 450 rpm using a graphite impeller attached to a variable speed motor. The temperature of the furnace was kept constant at 850°C for 10 minutes. Now, the molten metal was poured into the mould and 7075 aluminium alloy was obtained. The same procedure was repeated for fabricating the other compositions. The casted AA7075/ Al_2O_3 composite were machined to specimen for conducting various tests.

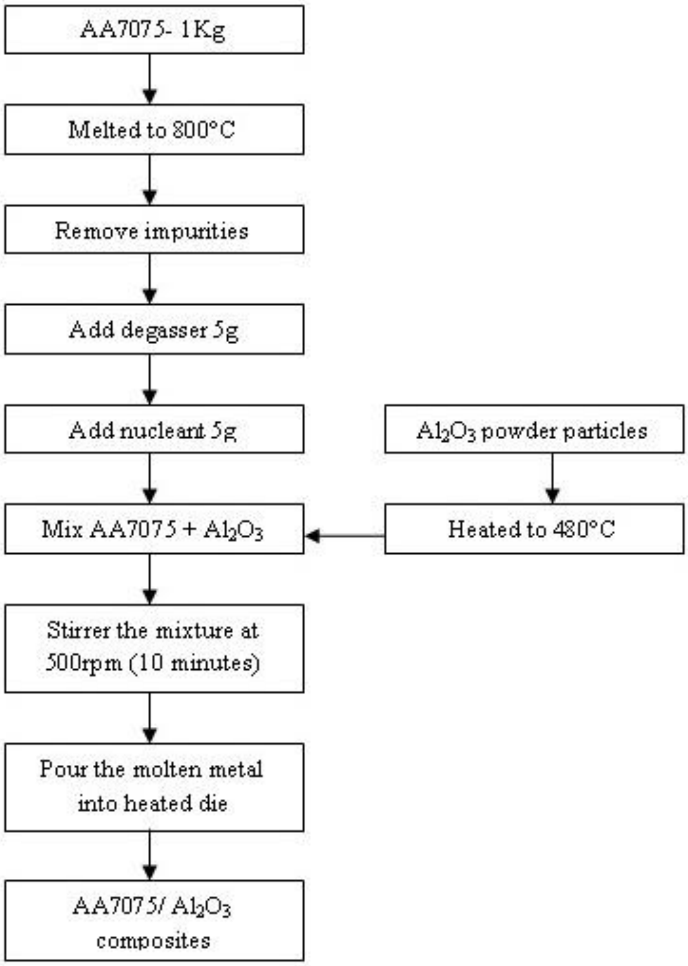

Fig. 1. Steps involved in stir casting process.

2.2. Wear Analysis

The wear behavior of the samples was investigated using a pin-on-disc wear test machine according to ASTM G99-95 standards. The OHNS steel with a hardness of 62 HRc was used as the disc. Samples of 6mm diameter and 15mm height pins were prepared from the composites, and then polished metallographically for the wear test. The tests were conducted at room temperature (30°C) and humidity 60-65%, at a sliding speed of 0.6m/s under 10, 20, 30 and 40N applied load, sliding distance of 1200m with an interval of 200m and unlubricated conditions, with a wear track diameter of 30mm. On completion of the running through the required sliding distance the specimens were cleaned with acetone, dried and their weights were determined for ascertaining the weight loss by using an electronic weighting machine with a resolution of ±0.1mg. The average mass loss was used to calculate the specific wear rate (K_0) shown in equation (1).

$$K_0 = \Delta m / DL\rho \quad (N^{-1}m^2) \tag{1}$$

Where, Δm is the average mass loss (g), D the sliding distance (m), L the applied load (N), and ρ the density of the materials (g/m^3). After the wear test the worn surfaces were analyzed with HITACHI–S3400 scanning electron microscope.The friction coefficient was continuously recorded along with the sliding distance.

2.3. Statistical Analysis

The optimization process involves the studying the response based on the combinations, estimating the coefficients, fitting the experimental data, predicting the response and checking the adequacy of the fitted model. Applied load and sliding distance were chosen as the independent variables and wear rate was selected as response variable for the composites. The first independent variable (Applied load) was varied over the low and high levels 10 and 40N with the centre point of 30N. While the second independent variable (Sliding distance) was varied over the low and high levels of 200 and 1200m with the centre point of 600m as shown in Table 2.

Table 2. Independent variables and the levels in Taguchi design.

Parameters	-1	0	+1
Applied Load (N)	10	30	40
Sliding distance (m)	200	600	1200

In order to the combined effects of the independent variables on the responses, a face centred central composite response surface design with 20 sets of experiment with five repetitions were carried out. The observed responses were fitted to a second order polynomial model shown in equation (2).

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_{11} X_1^2 + \beta_{12} X_1 X_2 \quad (2)$$

Where, Y is the observed response; X_1 and X_2 are the independent process parameters; β_0 is the constant; β_1 and β_2 are the linear coefficients; β_{11} is the quadratic coefficients; β_{12}, is the interaction coefficients.

From this the regression equation was derived for the composites and the taguchi technique was applied to evaluate the optimum composite and condition. The taguchi technique evaluate these composites using S/N curve, SD method and mean by the “smaller the best” quality characteristics to finding the minimum wear rate under various applied load and sliding distance conditions.

The investigational results and calculated values were obtained based on the plan of experiment and then the results were analyzed with the help of commercial software MINITAB 14 as specially utilized for the Design of Experiment and statistical analysis of experiment applications.

3. Results and Discussion

3.1. Wear Behavior

The wear rate for AA7075/Al_2O_3 composite was lower with compared to base alloy. From the figure 2(a), it shows that 6 Wt % of Al_2O_3 was the lowest wear rate at various load conditions for 1200m sliding distance. The wear resistance of the composite was increased as compared to base matrix. The unreinforced aluminium alloy was softer than the Al_2O_3 reinforced composites and due to this the base alloy undergoes heavy plastic deformation on the surface which causes the high wear rate of base alloy, as shown in figure 2(b).

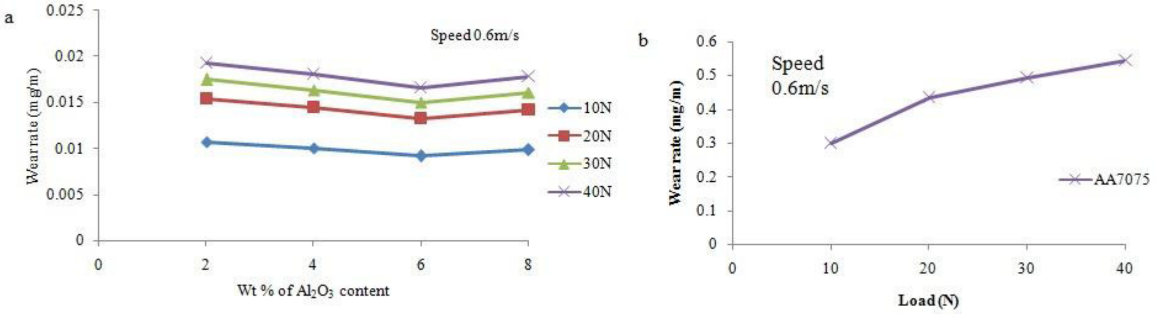

Fig. 2. Variation of Wear rate under various load Conditions (a) AA7075/ Al_2O_3 (b) AA7075 composites.

The high wear mass loss is observed in base alloy and minimum wear mass loss is noticed at 6 wt. % of Al_2O_3 composites. The wear rate increases with increasing applied load due to increasing temperature at higher loads and MML is no longer formed. At a larger load conditions produces large uncertainties which prevented the formation of a protective MML. The wear rate increases on increasing the applied load in all load conditions, and it was the minimum at 6 wt. % of Al_2O_3 composites. During abrasive wear, the Al_2O_3 particles strengthen the aluminium matrix and also protect the softer matrix. From figures 7, it is seen that the wear mass loss increases on increasing the sliding distance and effect of applied load.

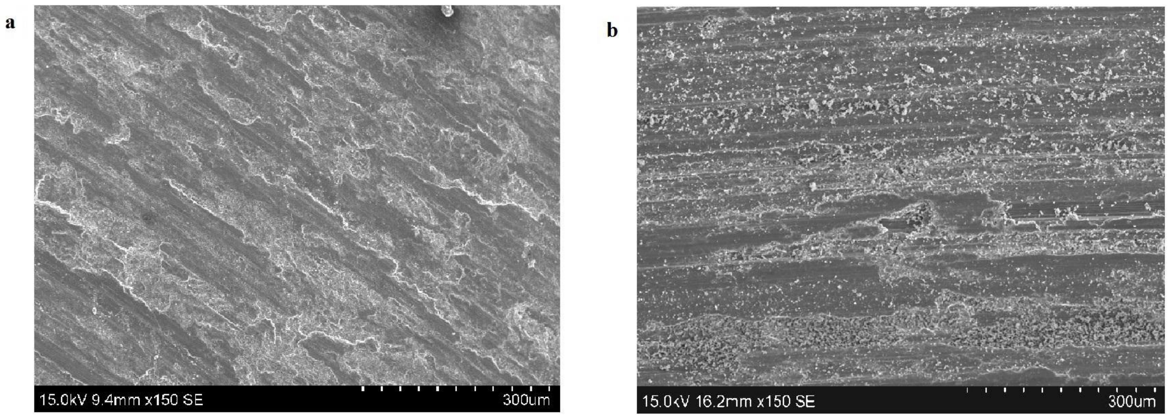

Fig. 3. Worn surface morphology of (a) AA 7075 (b) AA 7075 / 6 Wt % of Al_2O_3 composites at 0.6 m/s and 1200 meters sliding distance.

SEM micrographs in fig. 3, the worn surfaces of the composites show a combined wear pattern, narrow grooves and heavy flow of material along the sliding direction, indicating a greater degree of wear and localized adhesion between the specimen pin surface and the counter body. The worn surfaces were somewhat similar to that of the unreinforced material alloy, and mainly characterized by plastic deformation with some ploughing and cutting effects. The dominant abrasive wear mechanism is ploughing, and it is indicated by the worn surface of the topographies of the composites. The morphologies of the worn surfaces indicate the existence of abrasion and delaminating wear mechanisms in composites.

3.2. Statistical Analysis on Wear

The regression equations (3-7) are found using MINITAB 14 software. They are listed below for the various composites at 0.6m/s with controlling parameters is load (L) and sliding distance (D). The table 2 shows the results of effect of load and sliding distance on the AA7075/ Al_2O_3composites. And the table 3 shows the S, (R-Sq) and (R-Sq (adj)) values to prove the optimum composite.

Table 3. Analysis of Wear behaviour using for S/N ratio, Means and SD results.

Response	S/N Ratio		Means		Standard Deviations	
Level	Load (N)	Sliding Distance (m)	Load (N)	Sliding Distance (m)	Load (N)	Sliding Distance (m)
1	-39.50	-37.40	54.77	39.08	104.64	74.67
2	-45.96	-45.96	100.35	100.35	175.01	175.01
3	-44.65	-46.75	99.07	99.07	189.27	219.24
Delta	6.46	9.35	45.58	75.68	84.63	144.58
Rank	2	1	2	1	2	1

Table 4. Analysis of Wear behaviour of AA7075/ Al_2O_3 Compositions using Regression Equation.

Composites	S	R-Sq	R-Sq(adj)
AA7075	34.4073	94.5%	94.0%
AA7075/2 wt. % Al_2O_3	1.22022	94.5%	94.0%
AA7075/4 wt. % Al_2O_3	1.14412	94.5%	94.0%
AA7075/6 wt. % Al_2O_3	1.04872	94.5%	94.0%
AA7075/8 wt. % Al_2O_3	2.42590	82.0%	75.9%

$$Y_{AA7075} = -70.3 + 7.03L + 0.376D \quad (3)$$

$$Y_{2\%} = -2.49 + 0.249L + 0.0133D \quad (4)$$

$$Y_{4\%} = -2.34 + 0.234L + 0.0125D \quad (5)$$

$$Y_{6\%} = -2.14 + 0.214L + 0.0115D \quad (6)$$

$$Y_{8\%} = 0.003 + 0.213L + 0.0109D \quad (7)$$

The quadratic equations (8-12) from RSM for various composites at 0.6m/s with controlling parameters are Load (X_1) and sliding distance (X_2). The factors of wear are examined and shown in table 4.

$$Y_{AA7075} = -128.827 + 25.0247X_1 + 0.1736X_2 + -0.46X_1^2 + 0.00642667X_1X_2 \quad (8)$$

$$Y_{2\%} = -4.56978 + 0.887289X_1 + 0.00616X_2 + -0.016311X_1^2 + 0.000228X_1X_2 \quad (9)$$

$$Y_{4\%} = -4.28467 + 0.832267X_1 + 0.00577333X_2 + -0.0153X_1^2 + 0.000213667X_1X_2 \quad (10)$$

$$Y_{6\%} = -3.92311 + 0.762422X_1 + 0.00529333X_2 + -0.0140111X_1^2 + 0.000195667X_1X_2 \quad (11)$$

$$Y_{8\%} = -4.20822 + 0.817444X_1 + 0.00568X_2 + -0.0150222X_1^2 + 0.00021X_1X_2 \quad (12)$$

Table 5. Analysis of Wear behaviour of AA7075/ Al_2O_3 Compositions using RSM.

Load (N)	Distance (m)	AA7075	2%	4%	6%	8%	SNRA1	LSTD1	STDE1	MEAN1	CV1
10	400	169	5.994	5.619	5.151	5.526	-37.59	4.29	73.09	38.26	1.91
10	600	243.1	8.622	8.083	7.41	7.948	-40.74	4.66	105.13	55.03	1.91
10	800	283.1	10.041	9.413	8.629	9.256	-42.07	4.81	122.43	64.09	1.91
10	1000	345.9	12.268	11.501	10.543	11.31	-43.81	5.01	149.59	78.30	1.91
10	1200	360.9	12.8	12	11	11.8	-44.18	5.05	156.08	81.70	1.91
20	400	239.7	8.501	7.97	7.306	7.837	-40.62	4.64	103.66	54.26	1.91
20	600	340.7	12.084	11.328	10.384	11.14	-43.68	4.99	147.34	77.13	1.91
20	800	400	14.187	13.3	12.192	13.078	-45.07	5.15	172.99	90.55	1.91
20	1000	489.5	17.361	16.276	14.92	16.005	-46.82	5.36	211.69	110.81	1.91
20	1200	520.6	18.464	17.31	15.868	17.022	-47.36	5.42	225.14	117.85	1.91
30	400	260.4	9.236	8.658	7.937	8.514	-41.34	4.72	112.62	58.95	1.91
30	600	395.1	14.013	13.137	12.042	12.918	-44.96	5.14	170.87	89.44	1.91
30	800	443.3	15.722	14.74	13.511	14.494	-45.96	5.26	191.71	100.35	1.91
30	1000	555.6	19.705	18.474	16.934	18.166	-47.92	5.48	240.28	125.78	1.91
30	1200	590.9	20.957	19.648	18.01	19.32	-48.46	5.54	255.55	133.77	1.91
40	400	310.9	11.027	10.337	9.476	10.165	-42.88	4.84	126.77	70.38	1.80
40	600	434	15.393	14.431	13.228	14.19	-45.78	5.18	176.96	98.25	1.80
40	800	505.3	17.921	16.801	15.401	16.521	-47.10	5.33	206.03	114.39	1.80
40	1000	620.9	22.021	20.645	18.925	20.301	-48.89	5.53	253.16	140.56	1.80
40	1200	653	23.16	21.712	19.903	21.351	-49.33	5.58	266.25	147.83	1.80

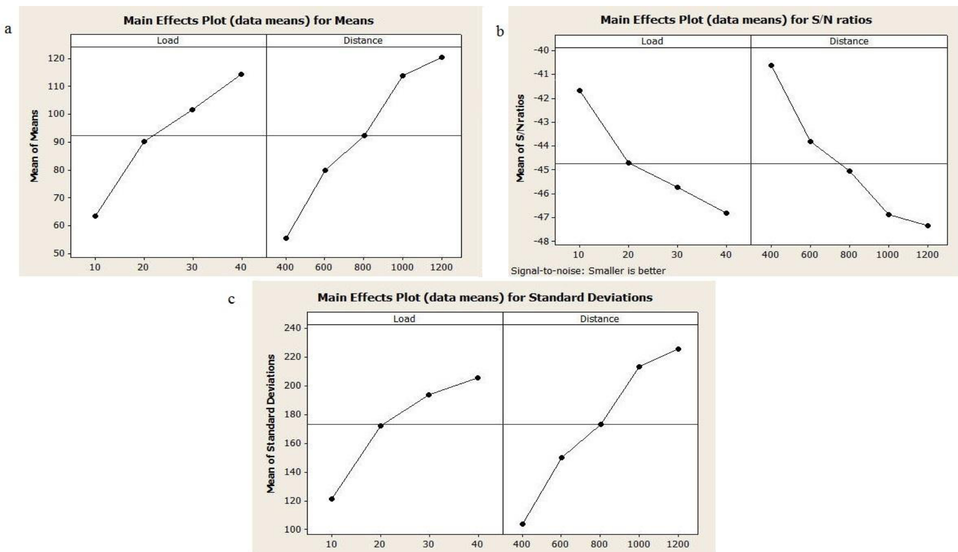

Fig. 4. Analysis of Wear behaviour of AA7075/ Al_2O_3 Compositions using Taguchi method.

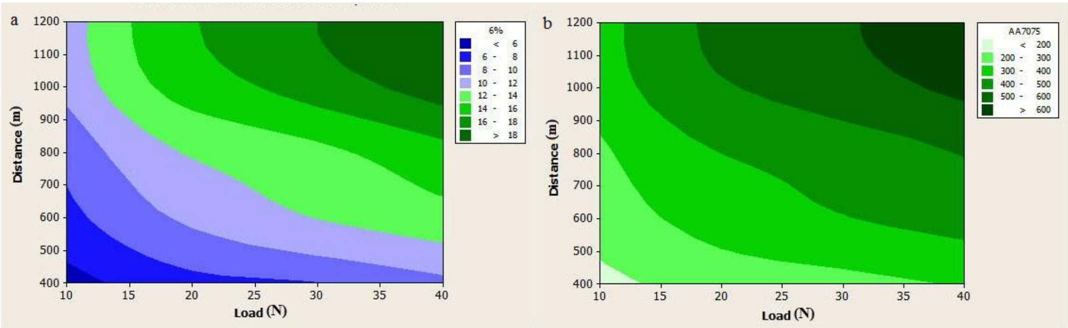

Fig. 5. Contour plot of variation in wear mass loss (a) 6 Wt % of Al_2O_3 (b) AA7075 composites.

The taguchi analyzer is used to evaluate the high wear resistive composite. The above results of fig. 5 and table 5, proves the wear properties of AA7075/ Al_2O_3, that 6 wt. % of Al_2O_3provides a wear mass loss at various conditions compared to other composites and base alloy. The wear mass loss at 10N applied load at 400m sliding distance is observed as optimum combination for optimum result.

The wear mass loss of AA7075/ Al_2O_3composites is graphically explained in fig. 4 by MINITAB software. From these results, the darker region shows low wear mass loss and the lighter region shows high wear mass loss. This helps to identify low wear mass loss is minimum at 6 wt. % of Al_2O_3 as compared to other composites and base alloy.

3.3. Coefficient of Friction

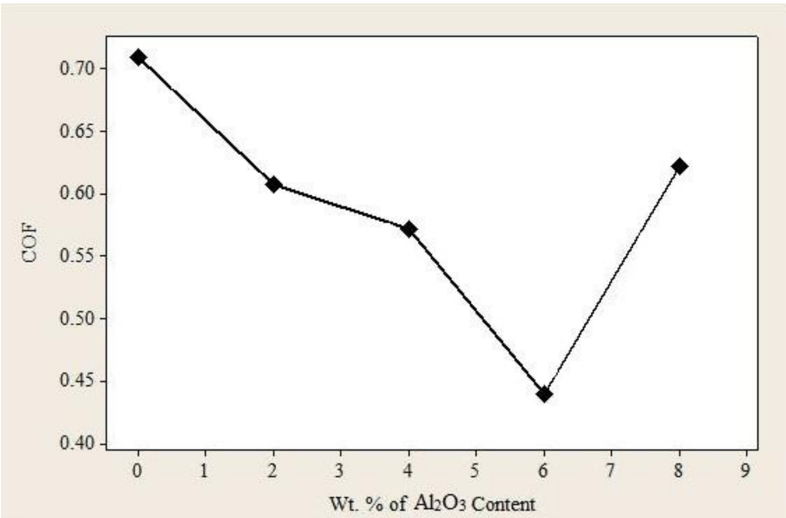

Fig. 6. Variation of COF with increasing Wt % of Al_2O_3.

Fig. 6 shows the variation of the coefficient of friction of these samples for varying wt. % Al_2O_3. The coefficient of friction decreases on increasing the wt % of Al_2O_3 and reaches a minimum at 6 wt. % Al_2O_3.The Al_2O_3 particles is used for forming the load on the composite surface and also the sliding surface of the material. This is the reason for the lower COF between the disc and the pin material of composites which are lower than that of base alloy.

4. Conclusions

- The AA7075/ Al_2O_3 composites have been successfully produced by the stir casting route for study on the mechanical and tribological properties.
- The wear resistance of the composites increased with addition of the Al_2O_3 particle content. The wear rate is significantly less for the composites compared to pure matrix material. The wear rate at 6 wt. % Al_2O_3 is only $1/10^{th}$ of the wear rate for the pure matrix material. The MML formed on the worn surface of the composite is the key role player in controlling the wear properties of the composites.
- The graphical and analytical results of taguchi shows the optimum combination of applied load as 10N and sliding distance of 400m for minimum wear mass loss at 6 wt. % of Al_2O_3 as compared to other composites and base alloy.
- The coefficient of friction decreases with addition the Al_2O_3 content, and reaches a minimum of 0.44 at 6 wt. % of Al_2O_3 composite.
- From these results, the tribological applications are achieved by AA7075/ 6 wt. % of Al_2O_3 composite.

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