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EFFECT OF IRON OXIDE ON TRIBOLOGICAL BEHAVIOUR OF AL- SI ALLOY – IRON OXIDE COMPOSITES - TAGUCHI APPROACH

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This study investigates the influence of factors such as weight percentage of iron oxide, applied load and sliding velocity on the wear loss and coefficient of friction of Al –Si alloy - Iron oxide composites using pin –on –disc wear testing rig. Composites were fabricated by two step stir casting method followed by squeeze casting method. Taguchi and Analysis of variance (ANOVA) were used to investigate the influence of factors on the wear loss and co efficient of friction of the composites. It was found that the applied load was the most dominant factor influencing the wear loss followed by sliding velocity and weight percentage of Iron oxide. On the other hand, iron oxide content was the most influencing factor followed by sliding velocity and applied load on the co- efficient of friction of composites.

Keywords: wear loss, coefficient of friction, Al –Si - Iron oxide composites, Taguchi, ANOVA, SEM

1. Introduction

Particulate reinforced metal matrix composites demonstrate superior tribological properties, high strength and stiffness by adding ceramic reinforcements into the metal matrix [1]. The prominent properties make these materials to be potential applications in automotive and aerospace industries [2-3]. Wear is material removal from one surface of the component to another during relative motion between them. Sannino and Rack [4] reviewed the dry sliding wear characteristics of aluminium alloy based composites with respect to reinforcement size, properties and volume fraction, sliding distance, applied load, sliding speed, hardness of the counter face on the wear behaviour. Cerit et al [5] have emphasized that tribological behaviour exhibited by composites are significantly influenced by the type, size, properties and weight percentage of reinforcement and distribution of reinforcing particles in the metal matrix.

Narayan et al [6] studied dry sliding wear of Al alloy 2024-Al_2O_3 particulate metal matrix composites. Srivastava and Mohan [7] investigated the mechanical and tribological behaviour of Al-Fe composite. They reported that

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wear rate decreases with increase in iron content for all combination of loads and sliding velocities. Khraisat and Jadayil [8] studied the effect of iron oxide powder in strengthening of aluminium to attain improved mechanical properties. They reported that the superior properties were observed in cast aluminium with iron oxide addition. Sasaki et al. [9] characterized consolidated nano crystalline Al-5 wt. % Fe alloy powders produced by mechanical alloying using spark plasma sintering. The sintered sample showed high strength with a large plastic strain of 15% at room temperature. Amro M. AI-Qutub et al. [10] emphasized the wear resistance of particulate metal matrix composites primarily depends on the type, size, and distribution of the reinforcing phase as well as the manufacturing technique. Alpas and Zhang [11] studied the effects of microstructure (namely, particulate volume fraction and particulate size) and the counterface materials on the dry-sliding wear resistance of 2014A1-SiC and 6061Al-Al_2O_3. They reported that with increasing the applied load, the wear rate of the composites increased and higher fraction of particulate in the composite leads to better wear resistance. Apasi et al [12] investigated the wear behaviour of Al-Si-Fe Alloy/Coconut shell ash particulate composites.

Limited work has been reported in studying the tribological behaviour of iron oxide reinforced aluminium matrix composites. The present work aims to investigate the tribological behaviour of Al- Si alloy - Iron oxide particulates composites fabricated by a two step stir casting method followed by squeeze casting method. Scanning Electronic Microscopy (SEM) was used to analyze the microstructure as well as worn surface morphology of the composites.

2. Experimentation

2.1. Specimen Preparation

Eutectic Al-Si alloy was used as the matrix material, iron oxide particles (120 microns) were used as reinforcement. Composition of Al-Si alloy is presented in Table 1.

Table 1

Composition of Al- Si alloy

Element	Fe	Si	Al
Wt.%	0.02	12.6	87.4

Squeeze casting method was employed to fabricate the Al- Si alloy- Iron oxide composites. Composite melt was prepared by employing two step stir casting method and poured into the preheated (350°C) mould cavity. 50 MPa squeeze pressure was applied on the composite melt for 50 seconds through the preheated punch till solidification was completed. Punch was removed and specimen was taken from the steel mould.

2.2 Micro Structural Analysis

Microstructure of the Al alloy – 5 wt. % Iron oxide composite (Figure 1) and Al alloy – 7.5 wt. % Iron oxide composite (Fig. 3) reveals that the distribution of iron oxide particles is uniformly distributed in the Al –Si alloy matrix. Moreover, iron particles are well bonded with Al –Si alloy and clustering of iron oxide particles was not seen in the composite.

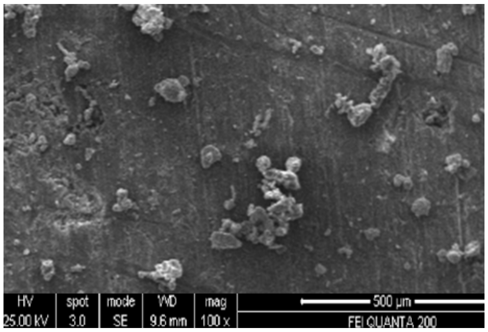
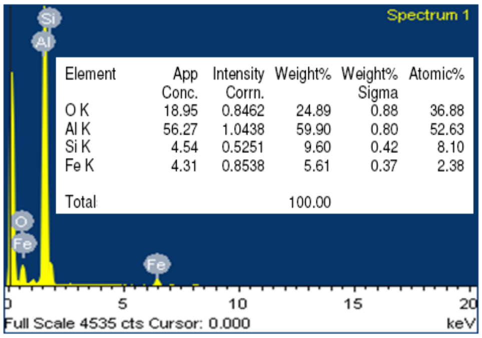


Fig.1. SEMmicrograph of the Al alloy–5wt% Iron oxide composite



Element	App Conc.	Intensity Corrn.	Weight%	Weight% Sigma	Atomic%
O K	18.95	0.8462	24.89	0.88	36.88
Al K	56.27	1.0438	59.90	0.80	52.63
Si K	4.54	0.5251	9.60	0.42	8.10
Fe K	4.31	0.8538	5.61	0.37	2.38
Total			100.00		

Fig. 2. EDS image of the Al alloy – 5 wt% Iron oxide composite

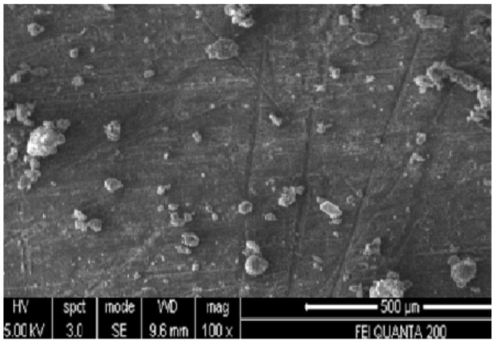
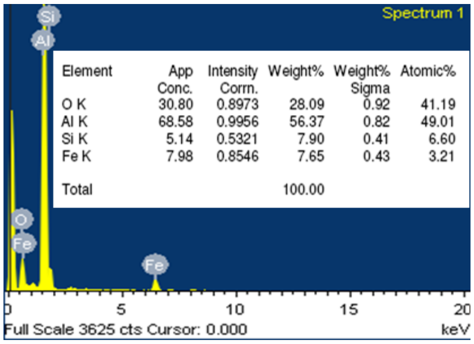


Fig. 3. SEM micrograph of the Al alloy– 7.5 wt% Iron oxide composite



Element	App Conc.	Intensity Corrn.	Weight%	Weight% Sigma	Atomic%
O K	30.80	0.8973	28.09	0.92	41.19
Al K	68.58	0.9956	56.37	0.82	49.01
Si K	5.14	0.5321	7.90	0.41	6.60
Fe K	7.98	0.8546	7.65	0.43	3.21
Total			100.00		

Fig. 4. EDS image of the Al alloy – 7.5 wt% Iron oxide composite

EDS image of the Al alloy –5 wt% Iron oxide composite and Al alloy –7.5 wt% Iron oxide composite are shown in Figure 2 and 4 respectively and it confirms the presence of Fe content in the Al alloy.

2.3. Hardness

Hardness was measured on the polished surfaces of the Al-Si alloy- iron oxide composite specimens using Brinell hardness tester. A 2.5 mm steel indenter with fixed indentation load of 187.5 kgf was used for all the tests. Five readings were taken for the samples of each composition and the average hardness was considered.

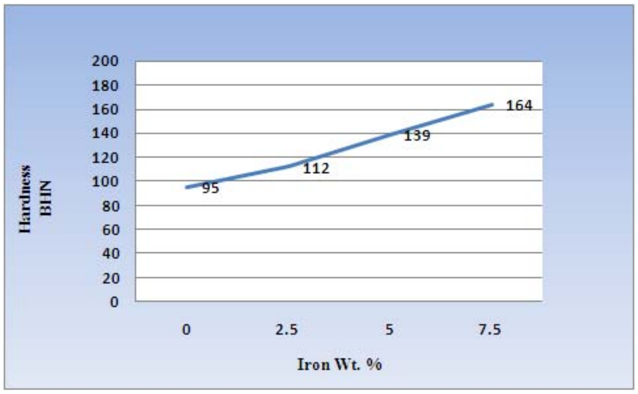


Fig. 5 Hardness of specimens

Hardness of Al-Si alloy- iron oxide composites increases with increase in weight % of iron oxide particles. The values which are presented in the Figure 5 are average of the five readings for each composition of the composite and the scatter of the hardness values were about the 3% of the average hardness values for the composite. The hardness value of Al- Si alloy increased by 73% when the iron oxide content was incorporated up to 7.5 wt. %.

2.4. Dry Sliding Wear Test

Dry sliding wear tests were conducted using pin-on-disc wear testing rig which is shown in Figure 6. The wear loss and co efficient of friction of the composite specimens were recorded with accuracy 1.0 µm. A cylindrical pin of size 10mm diameter and 15mm height, composite specimens were prepared and loaded in a computer interfaced pin- on - disc wear testing rig **.** Prior to testing, the surface of the specimens was polished by using 1000 grit paper. The rotating disc was made of EN 32 steel and hardness of 65 HRC. Wear tests were carried out at 27°C room temperature and 60% relative humidity for 30 minutes.

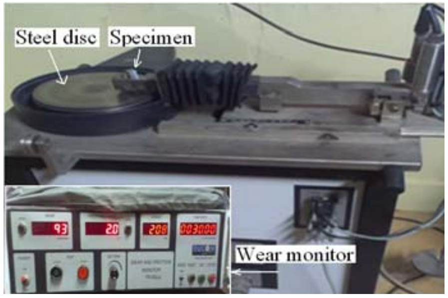


Fig. 6 Wear test rig

3. Taguchi and ANOVA methods

Taguchi's parameter design can be employed for determining the optimum levels of the factors which have an influence on the process and performance. Since a smaller wear loss and co-efficient of friction were desirable, "smaller is better" S/N ratio was used to predict the optimum levels of the factors. Mathematical equation of the S/N ratio for "smaller is better" is given in the equation (i).

$$\frac{S}{N} = -10\text{Log}\left(\frac{1}{n}\sum_i \frac{1}{y_i^2}\right) \tag{1}$$

where, *y* is the observed data and *n* is the number of observations.

In the present investigation, wear tests were conducted in the composite material as per the L27 orthogonal array. Accordingly, 27 experiments were carried out and each experiment was repeated twice in order to minimize the experimental errors. The factors and the corresponding levels are given in Table 2 .In addition, the experimental results were analyzed using analysis of variance (ANOVA) to study the influence of the factors on wear loss and co efficient of friction.

Table 2.

Factors and the corresponding levels

Level	Factors		
	Iron oxide (wt. %) (A)	load(N) (B)	Sliding Velocity (m/s) (C)
1	2.5	5	1.00
2	5.0	15	1.75
3	7.5	25	2.50

Table 3.

Measured values and S/N ratios for wear loss and co efficient of friction of composites

Exp .No	Factors			Measured Value		Signal / Noise Ratio	
	Iron oxide (wt. %) (A)	load(N) (B)	Sliding Velocity (m/s) (C)	Wear loss (μm)	Coefficient of friction (μ)	Wear loss	Coefficient of friction
1	2.5	5	1.00	101.31	0.62	-40.113	4.152166
2	2.5	5	1.75	132.50	0.65	-42.4443	3.741733

3	2.5	5	2.50	157.76	0.68	-43.9599	3.349822
4	2.5	15	1.00	121.31	0.6	-41.6779	4.436975
5	2.5	15	1.75	156.01	0.63	-43.863	4.013189
6	2.5	15	2.50	180.32	0.65	-45.1209	3.741733
7	2.5	25	1.00	178.92	0.56	-45.0532	5.036239
8	2.5	25	1.75	231.43	0.59	-47.2884	4.58296
9	2.5	25	2.50	288.90	0.62	-49.215	4.152166
10	5.0	5	1.00	92.46	0.67	-39.3191	3.478504
11	5.0	5	1.75	103.45	0.72	-40.2946	2.85335
12	5.0	5	2.50	115.23	0.73	-41.2313	2.733543
13	5.0	15	1.00	103.31	0.66	-40.2828	3.609121
14	5.0	15	1.75	125.33	0.71	-41.9611	2.974833
15	5.0	15	2.50	147.360	0.74	-43.3676	2.615366
16	5.0	25	1.00	137.630	0.64	-42.7743	3.876401
17	5.0	25	1.75	194.560	0.69	-45.7811	3.223018
18	5.0	25	2.50	243.450	0.7	-47.7282	3.098039
19	7.5	5	1.00	61.820	0.72	-35.8226	2.85335
20	7.5	5	1.75	65.960	0.75	-36.3856	2.498775
21	7.5	5	2.50	69.770	0.77	-36.8734	2.270185
22	7.5	15	1.00	93.740	0.71	-39.4385	2.974833
23	7.5	15	1.75	136.440	0.74	-42.6988	2.615366
24	7.5	15	2.50	179.120	0.76	-45.0629	2.383728

25	7.5	25	1.00	93.090	0.69	-39.3781	3.223018
26	7.5	25	1.75	148.605	0.73	-43.4407	2.733543
27	7.5	25	2.50	198.120	0.76	-45.9386	2.383728

Table 4

Response table for Signal to Noise Ratios - Smaller is better (wear loss)

Level	A-Iron oxide content (wt. %)	B-Applied load (N)	C-Sliding velocity (m/s)
1	-44.30	-39.60	-40.43
2	-42.53	-42.61	-42.68
3	-40.56	-45.18	-44.28
Delta	3.74	5.57	3.85
Rank	3	1	2

Table 5

Response table for Signal to Noise Ratios - Smaller is better (Coefficient of friction)

Level	Iron oxide content (wt. %)	B-Applied load (N)	C-Sliding velocity (m/s)
1	4.134	3.103	3.738
2	3.162	3.263	3.249
3	2.660	3.590	2.970
Delta	1.474	0.486	0.768
Rank	1	3	2

Table 6.

ANOVA analysis for Wear loss

Factor	DoF	SS	F-Value	P value	Pc
Iron oxide content (wt.%) – (A)	2	14078.4	65.32	0.000	17.32
Applied load (N) –(B)	2	37159.7	172.41	0.000	45.71
Sliding Velocity (m/s) -(C)	2	19774.9	91.75	0.000	24.33
Interaction term ‘AxB’	4	4606.1	10.69	0.003	5.67
Interaction term ‘AxC’	4	233.2	0.54	0.711	0.29
Interaction term ‘BxC’	4	4577.4	10.62	0.003	5.63
Error	8	862.1			1.06
Total	26	81291.8			100.00

Table 7.

ANOVA analysis for Co efficient of friction

Factor	DoF	SS	F-Value	P value	Pc
Iron oxide content (wt.%) – (A)	2	0.0604963	759.72	0.000	70.78
Applied load (N) –(B)	2	0.0062741	78.79	0.000	7.34
Sliding Velocity (m/s) -(C)	2	0.0165630	208.00	0.000	19.38
Interaction term 'AxB'	4	0.0014370	9.02	0.005	1.68
Interaction term 'AxC'	4	0.0003481	2.19	0.161	0.41
Interaction term 'BxC'	4	0.0000370	0.23	0.912	0.04
Error	8	0.0003185			0.37
Total	26	0.0854741			100.00

DoF- Degrees of Freedom; Seq.SS- Sequential sums of squares; Adj.MS- Adjusted sums of squares Pc-Percentage of contribution

4. Results and discussion

4.1 Results of S/N Ratio

The Signal to Noise ratio for each factor level can be computed by averaging the S/N ratio at the corresponding level. Process factors with the highest S/N ratio will give an optimum quality with minimum variance. Measured values and S/N ratios for wear loss and co efficient of friction of composites are given in the table.3.The influence of factors such as weight percentage of iron oxide content, applied load and sliding velocity on wear loss and coefficient of friction have been analyzed. Ranking of factors is presented in table 4 and table 5 for wear loss and co efficient of friction of composites respectively. It was observed that the applied load is a dominant factor on the wear loss followed by sliding velocity and iron content in case of wear of composites. On the other hand, the weight percentage of Iron oxide content is a dominant factor on the co efficient of friction followed by sliding velocity and finally applied load. From the response diagram of S/N ratio (Fig. 7), it was found that the optimum factors were wt. % Iron oxide (7.5 wt. %), load (5N) and sliding velocity (1m/s) in minimizing the wear of the composites.

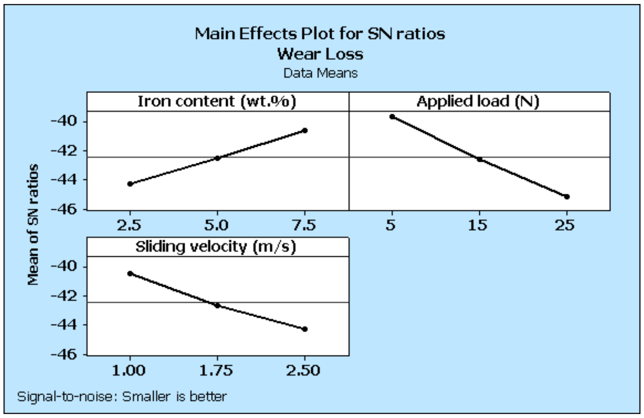


Fig.. 7 Response diagram of S/N ratio for wear loss of Al alloy –Iron oxide Composites

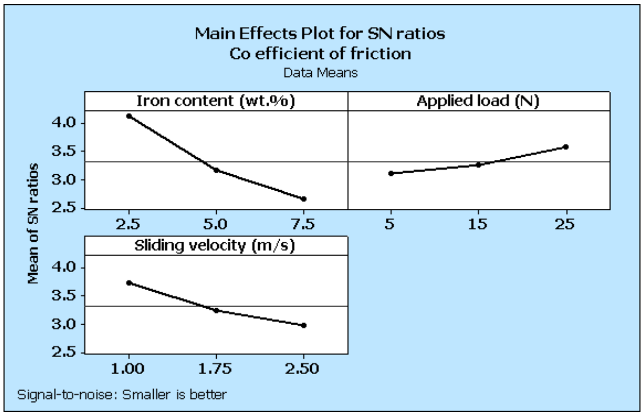


Fig. 8 Response diagram of S/N ratio for co-efficient of friction of Al alloy –Iron oxide Composites

It can be inferred from the response diagram of S/N ratio (Fig. 8), it was found that the optimum factors were wt. % Iron oxide (2.5 wt. %), load (25N) and sliding velocity (1m/s) in minimizing the co- efficient of friction of the composites.

4.2 Results of ANOVA

ANOVA was carried out using MINITAB16 software for a level of significance of 5% to study the contribution of the factors. In the ANOVA table, the p value is used to test the significance of factor and interaction between the factors. When the P-value is less than 0.05, then the factor is considered as statistically highly significant. It was observed from the table 6 that wt. % Iron oxide, applied load , sliding velocity and interaction effect between iron oxide content and applied load, applied load and sliding velocity have less than 0.05, which means that they are highly significant at 95% confidence level. Table 7 infers that P- Value for the iron oxide content , applied load and interaction effect between iron oxide content and applied load on the co efficient of friction of the composites have less than 0.05 and these terms are significantly influencing the co efficient of friction of composites.

4.3 Multiple Linear Regression Model

Multiple linear regression equations were developed to establish the correlation among the significant factors on the response. The value of regression coefficient, R^2 (0.9894) is in good agreement with the adjusted R^2 (0.9655) for wear loss of the Al- Si alloy – iron oxide composites. The value of regression coefficient, R^2 (0.9963) is in good agreement with the adjusted R^2 (0.9879) for co-efficient of friction of the Al- Si alloy – iron oxide composites. Since both the values are reasonably close to unity, models provide reasonably good explanation of the relationship between the independent factors and the response.

The regression equation developed for wear loss of the Al- Si alloy – iron oxide composite is

$$W= 53.5 - 11.2\,(A) + 4.52\,(B) + 44.2\,(C) \tag{2}$$

The regression equation developed for co-efficient of friction of the Al-Si alloy – iron oxide composite is

$$F= 0.528 +0.0229\,(A) - 0.00183(B) + 0.04\,(C) \tag{3}$$

where *W*= Dry sliding wear loss, *F*= Co-efficient of friction, *A*- Iron oxide content, wt. %, *B*-Applied load, N, *C*-Sliding velocity, m/s.

It can be observed from the Eq.2 that the coefficient associated with Iron oxide content (A) is negative. It indicates that the wear loss of the composite decreases with increasing Iron oxide content. Conversely, the wear loss of the composite increases with increasing applied load and sliding velocity since the co efficients associated with them are positive. Eq.3 infers that the coefficients associated with iron oxide content (A) and sliding velocity (C) are positive. It shows that the co efficient of friction of the composite increases with increasing iron oxide content and sliding velocity. On the other hand, co efficient of friction decreases with increasing applied load (B).

The last column of the table 6 shows the percentage contribution (Pc %) of each variable in the total variation indicating their degree of influence on the wear loss of the composites. It can be observed that the load (45.71%) was the major contributing factor followed by sliding velocity (24.33%) and wt.% of Iron oxide (17.32%) influencing the wear loss of the Al- Iron oxide composites. On contrary, table 7 infers that the wt. % of Iron oxide (70.78%) was the major contributing factor followed by sliding velocity (19.38%) and finally load (7.34%) influencing the co-efficient of friction of the Al- Iron oxide composites. It can be inferred that the friction co efficient is insensitive to applied load which has lowest contribution compared to wt. % of Iron oxide and sliding velocity.

It can also be noted that increasing the fraction of iron oxide content resulted in higher friction coefficient. It could be due to the more adhesion between the asperities of reinforcing material and the counter disc. Though particulate metal matrix composites provided higher friction coefficient compared to unreinforced alloy, they offered higher wear resistance. The increase in friction coefficient does not have a tendency to increase in higher wear rate. The results are consistent with the reported by Aigbodion et al [13].

4.4 Confirmation Test

A confirmation experiment is the final stage in the design of experiment process. The confirmation experiments were conducted and results are presented in the table.8. Typical curves of wear of Al-Iron oxide composite are shown in Figures 9 and 10. The experimental values for the wear loss and co efficient of friction of the composites and calculated values from the regression equation are nearly same with least error (± 3 %). The resulting equations are capable of predicting the wear loss and co efficient of friction to the acceptable level of accuracy.

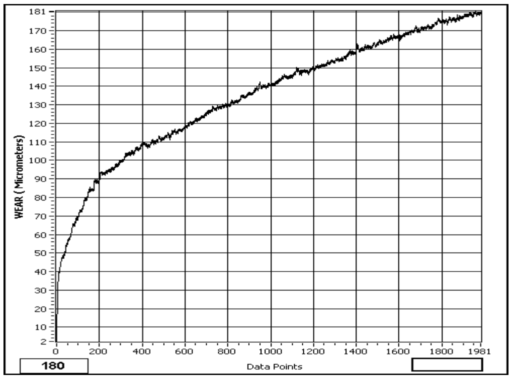


Fig. 9 Typical curve of wear of Al-7 wt. % Iron oxide composite against steel as a function of sliding velocity at 20 N,2.5 m/s.

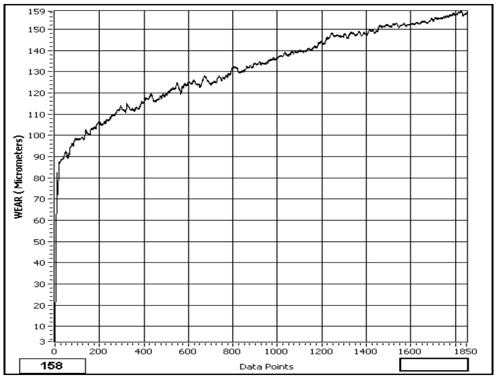


Fig. 10 Typical curve of wear of Al-5 wt. % Iron oxide composite against steel as a function of sliding velocity at 15 N ,2 m/s .

Table 8

Result of confirmation experiments and their comparison with regression model

Exp No	Iron oxide content (wt. %) (A)	Applied load(N) (B)	Sliding velocity (m/s) (C)	Model Eqn. (2) Wear (μm)	Exp. wear (μ m)	% error	Model Eqn.(3) COF (μ)	Exp. COF (μ)	% error
1	7	20	2.5	176.0	175	0.57	0.7517	0.76	1.10
2	5	15	2.0	153.7	158	2.79	0.6950	0.71	2.16

The lower wear obtained at a load of 5N and a sliding velocity of 1m/s. The enhanced wear resistance of composite is due to good bonding between Al-Si alloy and iron oxide particles. Since the Al alloy- 7.5 wt. % iron oxide composites exhibit the maximum hardness, they have load bearing capability.

During relative movement between the composite pin and steel counter face, the release of iron oxide particles onto the interface caused formation of a thin film which prevents the direct contact between them and increases the resistance to wear. SEM micrograph of the worn surface of the Al-Si alloy 7.5 wt. % iron oxide composite at 5N with 2.5 m/s sliding velocity is shown in Figure 11. It can be observed that raised peaks or deep valleys were not seen on the worn surface of the composite. The iron oxide particles support the low loads, resulting in decreased wear considerably.

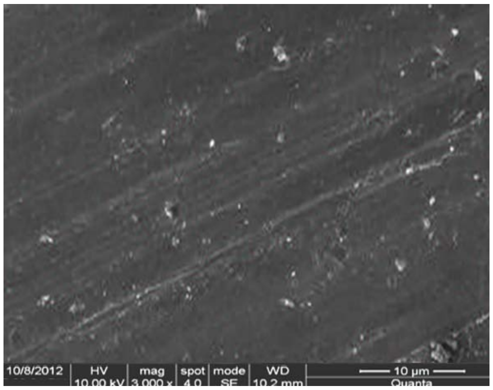


Fig. 11 SEM micrograph of the worn surface of the Al-Si alloy 7.5 wt. % iron oxide composite at a normal load of 5N with 2.5 m/s sliding velocity

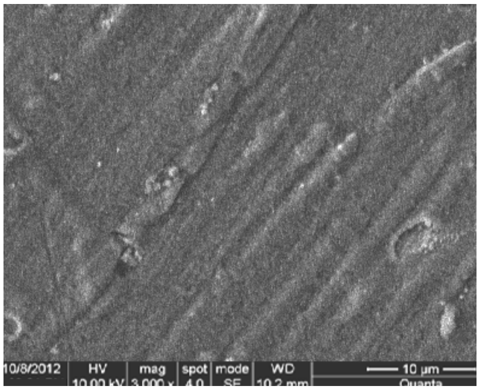


Fig. 12 SEM micrograph of the worn surface of the Al- Si alloy- 7.5 wt. % composite at a normal load of 25 N with 2.5m/s sliding velocity

The wear loss increased when the composite was subjected to the higher load (25N) with higher sliding velocity (2.5m/s). Moreover, interfacial temperature between Al-Si alloy and iron oxide particles increases, resulting in wear grooves spreads in the sub surface as shown in Figure 12.

The morphology of the worn surfaces changes from small grooves to deep grooves when the load was increased to 25N at a sliding velocity of 2.5 m/s. The transfer of material between the pin and counter material leads a rapid rate of material removal and wear mechanism changes from mild wear to severe wear, with increasing load.

6. Conclusions

This paper has presented an application of L27 orthogonal array of Taguchi method and analysis of variance for investigating the influences of wt. % of Iron oxide particles, applied load and sliding velocity on the wear loss and co - efficient of friction of composites. Based on this study, the following conclusions have been summarized. The results revealed that applied load (45.71%) was the most significant factor followed by sliding velocity (24.33%) and wt. % of iron oxide particles (17.32%)on the wear loss. It was found that the optimum factors for minimum wear loss were wt. % of Iron oxide (7.5wt. %), load (5N) and sliding velocity (1m/s).

Iron oxide particle content (70.78%) was the dominant factor on the co-efficient of friction of the composites followed by sliding velocity (19.38%) and applied load (7.34%). It was found that the optimum factors for minimum co-efficient of friction were wt. % of Iron oxide (2.5wt. %), load (25N) and sliding velocity (1m/s).

It was found that mild wear occurs at low applied load and sliding velocity while severe wear occurs at higher applied load and sliding velocity. Analysis of worn surfaces revealed that at lower load, abrasion was the dominant wear mechanism whereas at higher load, delamination and adhesion were found to be dominant for the Al alloy- Iron oxide composites.

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