Vol. 42, No. 2 (2020) 299-309, DOI: 10.24874/ti.777.10.19.04

Tribology in Industry

www.tribology.rs

RESEARCH

Determining the Significance of Cobalt Addition on the Wear Characteristics of Al-6.6Si-0.4Mg Hypoeutectic Alloy Using Design of Experiment

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Keywords:

Al alloys
A356
Wear behavior
Response surface methodology
Cobalt

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Received: 14 October 2019
Revised: 27 December 2019
Accepted: 18 April 2020

A B S T R A C T

Aluminium alloys have found application in many areas like aerospace industries and automobiles specifically in Machine tool parts, aircraft wheels, pump parts, marine hardware, valve bodies and automotive pistons, owed to their strength to low weight ratio. The present study deals with the growing demand for more durable aluminum alloys for the engine components with improved mechanical property/ tribological properties majorly focusing on the area of wear and tear in engine piston systems. In the present research, the simultaneous effect of cobalt (Co) addition and wear testing factors on the wear resistance of Al-6.6Si-0.4Mg hypoeutectic alloy is investigated through response surface methodology (RSM), a system employed in the design of experiments. Using Minitab software, the regression analysis was done and an equation was formulated to forecast the wear rate and also to investigate the significance of each experimental parameter on the subsequent wear rate. It was found from the current research that, with a surge in the cobalt content, the wear resistance of the alloy increased. It was also noted that, the wear rate was found to increase with an increase in the sliding velocity and load. Whereas, wear rate decreases with an increase in the sliding distance. In order to obtain the minimal wear rate, optimal values for each parameter were found out. FESEM investigation was conducted on the worn-out specimen to evaluate the worn-out surface of the regular and modified alloy for different wear testing conditions.

1. INTRODUCTION

Al-Si cast aluminium alloys possess an extensive variety of uses in several industries like automobile and aerospace to produce large components. Among the different grades in aluminium alloys, A356 alloy (Al-Si-Mg) plays a prominent role in the automotive component production sector due to its admirable properties which include excellent corrosion resistance, good castability, good weldability, and outstanding strength to low weight ratio.

Contrary to the above-mentioned properties, the low hardness exhibited by aluminium alloys makes them prone to wear. The high wear rates experienced by aluminium alloys tend to limit its use in various industries. As a result, consistent research works have been performed by several authors to enhance the hardness of the alloy and thereby reducing its wear behavior. This is achieved in many ways like - developing high strength aluminium alloys by the approach of adding alloying elements into the base alloy with transition metals or rear earth metals followed by surface modification techniques. Alloying the base metal/ alloy with transition metals and inducing corresponding heat treatments, that trigger precipitation hardening which ameliorates the mechanical attributes of the base metal/ alloy which in turn, has a greater effect on the wear rate as it is inversely proportional to the hardness. Alloying with rare earth metals is not encouraged widely on account of their high cost[1,2]. Hence most of the studies were concentrated upon alloying with transition elements in order to enhance the mechanical and tribological characteristics. Several studies have been accomplished on enhancing the properties of A356 alloys by different methods and research envisaged by different authors are listed below.

Yang et al. [1] researched the significance of alloy addition on the hardness values of Al-Si-Cu-Ni-Mg piston alloy. It was inferred from the investigation that the value of hardness of the developed alloy improved when Ni, Mg, Cu and 3.83 wt.% of silicon were added into the Aluminium matrix. Prabhudev et al. [2] discussed the impact of Cu addition on the wear features in the dry condition of Al-Si-Mg (A356) alloy. The investigation exhibited enrichment in the wear resistance which is connected to the formation of intermediate phase that occurred due to alloy addition. The improvement in the wear resistance is attributed to the rise in the value of hardness of the modified alloy. Yi Meng et al. [3] conducted an experiment on the addition of Zr on the micrograph, wear and tensile behaviors of aluminum (Al) alloy developed by low-frequency electromagnetic casting. It was found from the study that, during solidification the grain size reduction in Al phase, promotes the formation of equiaxed grain structure which enhances the mechanical properties. In the research work conducted by Pramod et al. [4] the authors studied the influence of Scandium (Sc) adding and T6 aging characteristics on the secondary dendritic arm spacing (SDAS) which led to the modification of Si (silicon) morphology in eutectic condition. It was seen from the author's research that, by the addition 0.4 wt-% of Sc to Al-Mg-Si alloy, its mechanical properties like Vickers hardness , ultimate tensile strength , Yield strength and ductility enhanced by 20 %, 25 %, 20 % and 30 % respectively. Artificial aging treatment carried on the developed alloy resulted in the significant enhancement of tensile properties for Al-Mg-Si and Sc modified alloy. Prasada et al. [5] studied the morphological and wear characteristics of A356 / LM25 alloyed with Titanium (Ti), carbon (C) and Strontium (Sr) at 720 °C. Varying weight percentage (0.2, 0.5 and 1.0 wt.%) of each alloying elements were added into the Al base master alloy and the wear resistance was calculated for the amended alloys. It was found from the study that, the resistance to wear of the base alloy surged with the introduction of alloying material to the base alloy up till 0.5 wt.%. Torabian et al. [6] researched on the wear behavior of Al-Si alloys alloyed with 2–20 wt.% of Si with the help of pin-on-disc wear obtaining type device at room temperature. It has been inferred from the research that the wear rate is sturdily based on the alloy compound, sliding speed, and load. It can also be inferred from the researcher's work that the wear rate was observed to reduce and the alloy's load-bearing capacity was observed to increase with the rise in Si content. Alidokht et al. [7] conducted an investigation on A356 aluminium alloy in as-cast condition. The alloy in this investigation was obtained by friction stir technique at numerous rotation rates. Further, the as-cast alloys were imposed on morphological analysis and wear tests were conducted using dry sliding method. Friction stir processing led to microstructural modification and constant advancement in the wear manner of Al-Mg-Si as-cast alloy. The improvement in resistance to wear of these as-cast Al-Si-Mg alloys was associated with the significant variation in size, morphology, scattering of Si fragments, improvement in grains and increment in the hardness. Ikeda et al. [8] studied the impacts of minimal content of Sc and Zr on the engineering and microstructural characteristics of Al-0.4Mg-6.6Si/A356 aluminum alloy. The microstructure was found to be refined due to the addition of the alloying element. The Sc and Zr were found to be effective in the refinement of the microstructure. Riyadh [9] researched the significance load and speed on the tribological behavior of Al-Si cast alloy. It was found from the investigation that the wear rate of Al-Si alloy increased with an increment in the applied load and decreased with an increment in the sliding distance. The frictional force was greatly affected by the load and sliding speed. As the load increases, there was a significant increase in the wear rate of the as-cast alloy. Kori et al. [10] investigated the effect of copper (Cu) and (Mg) addition on the mechanical and morphological characteristics of Al-Mg-Si alloy. From the investigations the results indicated that minor feeding of Cu enhances the mechanical properties of the developed alloy. Vickers' hardness and strength of the developed alloy showed an improvement with the addition of magnesium (Mg). Structural property relationship between Al-Si-Mg (hypoeutectic) alloys alloyed with pure strontium (Sr) was studied by Closset et al. [11]. It was noted that the microstructure refinement took place with an addition of strontium into A356. Recent studies conducted by K.V. Shankar et al. [12] examined the variations between the mechanical and microstructural properties of A356 alloy that was cast in a permanent mold due to the addition of Co. Results from this study noted that there was an enhancement in the mechanical properties of the developed alloy with the addition of Co. The rise in the mechanical properties of the developed alloy was attributed to the precipitation hardening mechanism and formation of intermediate phase. Refinement in the microstructure was also observed by the addition of Co.

Numerous authors have done research about the wear behavior of various engineering materials using statistical techniques such as response surface method, Taguchi method, etc. Using statistical analysis, Y Sahin [13] studied the wear characteristics of Al alloy and its composites reiforced with SiC particles. The linear factorial design approach was utilized for the investigation. With the help of equations, it was established that the minimum wear rate was exhibited by the composite compared with the unreinforced Al matrix material. Recently, N. Radhika et al. [14] researched the wear characteristics of Al-Si12Cu in dry sliding conditions. The alloy was reinforced with TiB_2 to form a metal matrix composite (MMC). The parameters influencing the wear rate were analyzed using RSM method in design of experiment (DOE). A central composite design based on RSM was used to study the tribological behavior of the composite. This method enables in reducing the experiment duration by reducing the number of experiments and the software has several procedures, as forecasting the output for a different combination of the regression coefficients estimation, fitting of the experimental data, parameters, prediction of the result, and also checking the adequacy of the fitted model. N Radhika et al. [15] conducted research on the wear characteristics of aluminium 6061 coated using titanium nitride (TiN) by the process of DC magnetron sputtering. The wear characteristics of the surface-modified samples in the dry sliding state were explored with the help of a pin-on-disc tribometer by RSM.

It can be inferred from the above discussion that various studies were done on the improvement of wear behavior of A356 by the method of alloy addition. Zinc, nickel, and zirconium were the major elements used for the alloy addition. It can also be observed from the above discussions that the various statistical tools can also be used for wear analysis. To the best of the author's knowledge, the wear behavior of Al-Mg-Si alloy due to the effect of addition of Co has never been investigated before. The main purpose of this research is to examine the impact of Co addition on the wear behavior of Al-Mg-Si alloy. Response surface methodology was used for the same. The effect of experimental parameters like load, sliding distance and sliding velocity was also studied. Using response surface methodology, the statistical tool will be able to forecast the wear rate values within the given range of experimental parameter values. Also, it can be used to predict the optimal values of parameters so as to obtain a minimum wear rate.

2. MATERIALS AND METHODS

In this present research Al-6.6Si-0.4Mg, Al alloy ingot was employed. The composition of the purchased ingot was tested with the help of an arc spectroscopy Table 1 indicates the elemental composition of Al-6.6Si-0.4Mg base alloy.

Table 1. Composition of A356 alloy.

Elements	wt.%
Al	balance
Si	6.629
Mg	0.417
Fe	0.169
Ti	0.093
Mn	0.054
Others	0.218

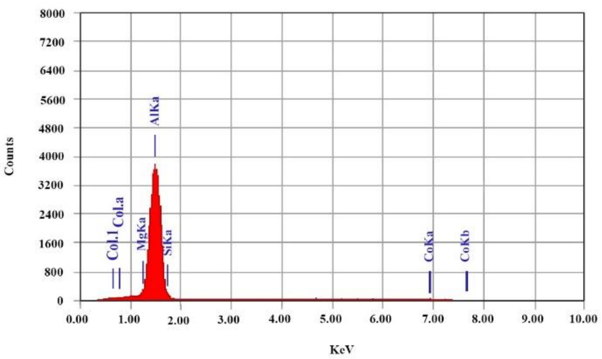


Fig. 1. EDS plot confirms the presence of Co in cast alloy.

The cast samples were prepared with 0 wt.% Co, 0.5 wt.% Co and 1 wt.% of Co in A356 alloy respectively. The melting of the alloy was conducted using an electrical arc furnace in a clay graphite crucible. Varying wt.% of Co was introduced into A356 alloy by adding the corresponding mass of pure Co into the crucible with Al ingot and was melted at a temperature of 754 ^{0}C. The melt was stirred using a stirrer at 150rpm for 8 minutes [24] in order to obtain homogenous mixing of the alloying element in to the LM 25 ingot. Subsequently, the melt was poured into a permanent mold die made of oil-hardened non shrinkage steel at a temperature of 675 ^{0}C and holding time was 30 seconds to obtain cylindrically shaped specimens with length 150 mm and diameter of 16 mm. The permanent mold was initially warmed to remove moisture content from the die. The preheating was counducted using a muffle furnace. The relative humidity at the foundry lab was 32 °C ±10 °C. Riser was incorporated in the mold design to counteract the effect of alloy shrinkage [16]. The samples were studied using Energy Dispersive X-ray Spectroscopy (EDS) to ensure the presence of elements in the cast alloy. The EDS plot shown in Fig. 1 confirms the presence of Co in A356 alloy. T6 heat treatment was carried out on the cast alloys as per the American society of materials handbook. Solutionizing was done at 540 ^{0}C for 12 hours [17] proceeded by quenching. Aging was done at 155 ^{0}C for 3 hours [12].

The Tribometer of Ducom make was used for testing the wear of heat-treated samples. Wear testing was done as per the ASTM G-99 standard on the pin–on–disk apparatus [18]. The cast samples were machined into the standard shape of a bullet with a diameter and length 10 mm, length 35 mm. Each specimen was weighed using an electric powered weighing instrument which has a least count (LC) of 0.1 mg. The heat-treated specimen was attached to a holder equipped with the machine and tightened evenly and the specimen was forced to rub against a rotating disc made of hardened steel EN 31 steel disc of hardness Rc 60 and surface roughness of *Ra* 0.15 µm. The counter disc was made to rotate at specific rotating velocity for a specific distance or time. The load was applied to the specimen so that the specimen always remains in contact with the disk. The above experiment was repeated for all three compositions. Initial and final weight readings of the heat-treated specimen, just after and prior to the test was noted and the wear rate for the corresponding specimens was calculated as per the equation (1) the wear rate for all the specimens had been calculated.

$$W = (M / \rho D) / Load \tag{1}$$

Where the wear rate (mm^3/Nm) is expressed in W, 'mass loss (g) is expressed in M' , density (g/mm^3) is expressed in 'ρ' and 'D' represents the sliding distance(m). As per the Archard's wear adhesion theory it is found that the wear rate is directly proportional to load and sliding distance. The wear coefficient (K) value for all the experiments conducted in this investigation are calculated using the equation (2):

$$W = K \times L \times D \tag{2}$$

Where, W is the sliding wear in (mm^3/Nm), K is the wear coefficient, L is the normal load in (N) and D is the sliding distance in (m)

3. DESIGN OF EXPERIMENTS

The design of Experiment technique was adapted for the analysis of wear. Four variables namely Co composition (Co wt.%), sliding distance (d), sliding velocity (v) and load (L) were identified and three levels of values were assigned for each variable as shown in Table 2 [14,15]. RSM was used to determine the experimental point and variable values for each factor. RSM is a statistical procedure that is utilized for the progress of a product or the progress of a process. This procedure is employed in conditions where different parameters affect the outcome. It helps in providing a clear correlation between the parameters and the response. RSM can also be effectively used to improve the parameters to obtain the desired results. Face centered Central Composite design (FCCD) of RSM was utilized in this work. The experimental data were analyzed using a response surface regression methodology to obtain a second-order polynomial equation of the form.

$$y = \beta_0 + \sum \beta_i x_i + \sum \beta_{ii} {x_i}^2 + \sum \beta_{ij} x_i x_j \quad (3)$$

From equation 3 it can be identified as y is the response, x_i and x_j are the coded independent variables. When normalized centered representations (coded levels) are used to represent factor levels, β_0, β_i, β_{ii} and β_{ij} are the mean values of responses, linear, quadratic and interaction constant coefficients respectively. Each coefficient (except that of interactions) allowed estimation of the change in the mean response per unit increase in x when all other factors are held constant (Bezerra et al. [19]. Results were formulated using Minitab software.

Table 2. Experimental parameters and their values used.

Factors	Levels		
Co Composition (wt.%)	0	0.5	1
Sliding Distance (m)	500	750	1000
Velocity (m/s)	1	2	3
Load (N)	10	20	30

4. RESULTS AND DISCUSSIONS

4.1 Analysis using Response surface methodology (RSM)

The ideal combination of wear parameters for the experiments was determined using FCC design under RSM. One of the advantages of using FCCD design with 4 factors and 3 levels was that the number of experiments was reduced from 81 experiments in one factor at a time approach to 28. RSM also helps in simultaneous evaluation of the influence of each factor as well as an interaction effect of the factors on the response (wear rate). The parameters for each experiment along with the corresponding wear rate was calculated from the mass loss and the results are shown in Table 3. Table 4 shows the wear coefficient value (K) for all the wear experiments conducted. The K value was calculated using the equation (2).

Table 3. Experimental conditions and results.

Exp. No	Co wt.%	Sliding Distance (m)	Velocity (m/s)	Load (N)	Wear Rate ($10^{-5}mm^3/Nm$)
1	1	1000	3	10	4.81
2	0.5	750	2	20	5.185
3	0.5	750	2	30	6.506667
4	0.5	750	3	20	9.875
5	0	750	2	20	46.42
6	0	500	3	10	10.37
7	0.5	1000	2	20	23.705
8	1	750	2	20	8.64
9	0.5	750	2	20	6.585
10	0	1000	3	30	8.643333
11	1	1000	1	10	15.19
12	0.5	750	2	20	17.775
13	1	500	3	10	12.96
14	1	1000	3	30	3.826667
15	0.5	750	2	20	14.075
16	0	500	1	30	5.166667
17	0	1000	1	10	11.48
18	1	500	1	30	31.11
19	0.5	750	2	10	16.29
20	1	500	1	10	15.55
21	0	1000	3	10	51.85
22	0	500	3	30	65.43
23	0	1000	1	30	9.256667
24	0.5	750	1	20	11.605
25	1	1000	1	30	7.406667
26	0	500	1	10	10.37
27	0.5	500	2	20	6.17
28	1	500	3	30	6.583333

Table 4. Wear coefficient values.

Exp No.	Wear Rate ($10^{-5}mm^3/Nm$)	Wear Coefficient (K)(10^{-4})
1	4.81	4.810
2	5.185	3.457
3	6.506667	2.892
4	9.875	6.583
5	46.42	30.947
6	10.37	20.740
7	23.705	11.853
8	8.64	5.760
9	6.585	4.390
10	8.643333	2.881
11	15.19	15.190
12	17.775	11.850
13	12.96	25.920
14	3.826667	1.276
15	14.075	9.383
16	5.166667	3.444
17	11.48	11.480
18	31.11	20.740
19	16.29	21.720
20	15.55	31.100
21	51.85	51.850
22	65.43	43.620
23	9.256667	3.086
24	11.605	7.737
25	7.406667	2.469
26	10.37	20.740
27	6.17	6.170
28	6.583333	4.389

Minitab 17 software was utilized for the regression analysis. The factors possessing positive coefficients contribute towards an increment in the wear rate whereas those with the negative coefficients cause a decrease in the same. Table 5 depicts the response surface regression analysis for the wear rate of Al-6.6Si-0.4Mg alloy modified with wt.% of Co. The p-value counts the importance of all parameters in the regression model. If the p-value of the coefficient is below the significance level of 0.10, the relation between the response and the parameter is statistically significant. It is evident that interaction terms also have contributed towards the determination of rate in addition to linear terms. Hence the analysis should be done based on the interaction of the parameters. It is to be seen that the coefficient values in Table 5 are given in the coded units. The experimental data are analyzed using a second-order polynomial equation. Here it is considered only those factors that were significantly based on a statistical significance of 0.1. All the other factors which were not significant are ignored.

Table 5. Regression analysis for wear.

Terms	Coefficient	T value	P-value
Constant	3.145	5.32	0.000
Co wt.%	-1.277	-1.73	0.098
Sliding Distance	-0.935	-1.27	0.219
Velocity	0.659	0.89	0.382
Load	1.572	2.13	0.045
Co wt.% x velocity	-1.979	-2.53	0.019
Sliding distance x Load	-1.697	-2.17	0.042

The regression equation for the wear rate, in terms of actual units, with respect to the wear parameters that is Co wt.%, sliding distance, sliding velocity, and load are obtained as:

$$W.R = 11.27 + 5.36\ Co\ wt\% + 0.00984\ d + 2.64\ v + 0.666\ L - 3.96\ Co\ wt\% \times v - 0.000679\ d \times L \quad (4)$$

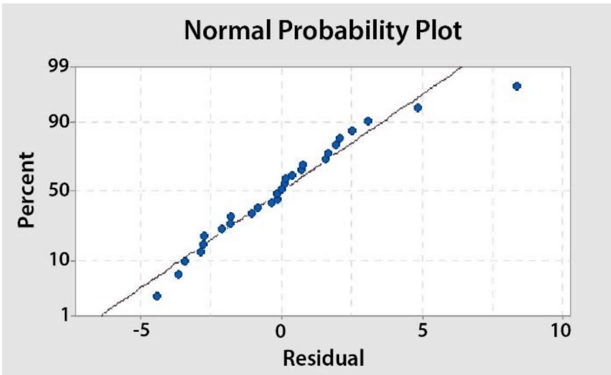
Here 'W.R' stands for wear rate expressed in 'x 10^{-3} mm^3/m', 'd' represents the sliding distance in 'm', 'v' represents the sliding velocity in 'ms^{-1}' and 'L' is the load in 'N'.

From the model, it can be clearly understood that the weight percentage of Co in the alloy and the interaction terms are significant for wear rate. An R^2 value of 57.99 % is obtained which indicates that 57.99 % of the variation in the response can be explained by the combination of settings of the four parameters. This may be due to the influence of uncontrollable factors such as heat production during the course of wear tests. Higher the R^2 values, the better the polynomial is for describing the behavior of the system. The model is valid only within the range of parameters discussed in this investigation.

Since the interaction effect observed between the parameters is significant, the individual study of each parameter may not be effective. Interaction parameter sliding distance x load significantly implies that how the wear rate is influenced by sliding distance is dependent on how much is the load. Hence, it may be unfair to study the plots of wear rate versus each parameter. So the contour plots that allow simultaneous evaluation of the impact of two factors on the wear rate at a time were investigated.

4.2 Uncertinity Analysis

In experimenting and analysing data using design of experiments, the uncertainty analysis is done with p values, R2 values and residual plots. The response surface regression analysis of experimental data for significance of the factors considered on wear rate is presented in Table 6.



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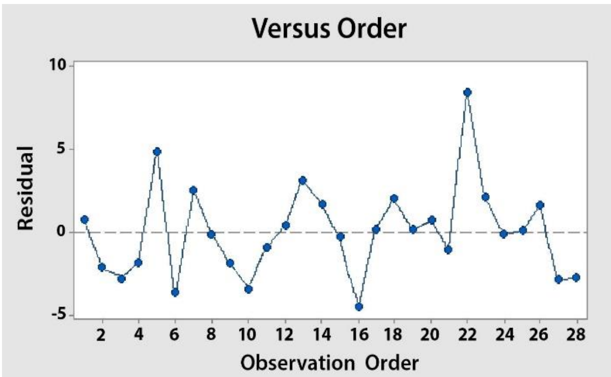

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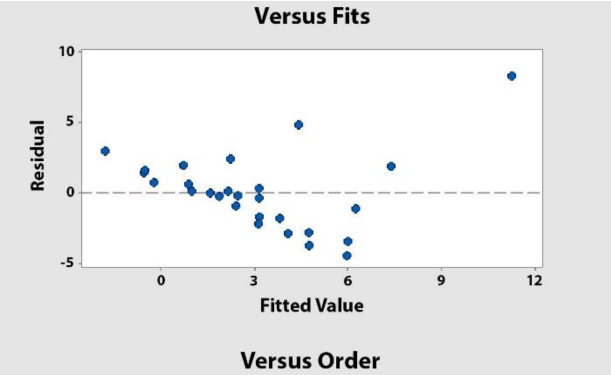

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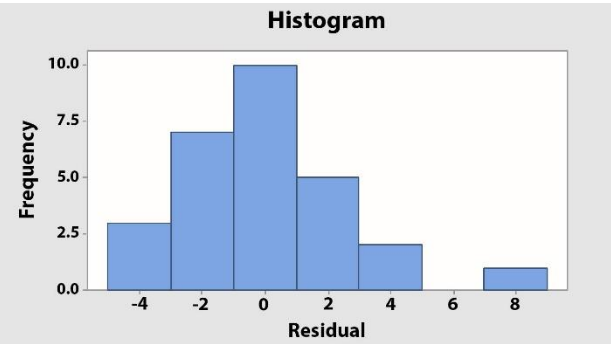


(d)

Fig. 2. Residual plots for wear rate.

Table 6. Uncertanity analysis.

Source	DF	Adj SS	Adj MS	F value	P value
Model	14	238.705	17.0503	1.28	0.330
Linear	4	97.369	24.3422	1.83	0.183
Co wt%	1	29.345	29.3451	2.21	0.161
Sliding distance	1	15.740	15.7402	1.18	0.296
Velocity	1	7.811	7.81133	0.59	0.457
Load	1	44.472	44.4722	3.34	0.091
Square	4	20.227	5.0566	0.38	0.819
Co wt.%* Co wt.%	1	17.506	17.5059	1.32	0.272
Sliding distance* Sliding distance	1	0.019	0.0193	0.00	0.970
Velocity*Velocity	1	1.462	1.4622	0.11	0.746
Load*Load	1	3.180	3.1802	0.24	0.633
2-way interaction	6	121.110	20.1849	1.52	0.248
Co wt.%*sliding distance	1	0.476	0.4764	0.04	0.853
Co wt.%*velocity	1	62.650	62.6503	4.71	0.049
Co wt.%*load	1	4.320	4.3204	0.32	0.578
Sliding distance*velocity	1	4.753	4.7531	0.36	0.560
Sliding distance*load	1	46.085	46.0850	3.46	0.085
Velocity*load	1	2.824	2.8244	0.21	0.653
Error	13	172.951	13.3040		
Lack-of-Fit	10	168.606	16.8606	11.64	0.034
Pure error	3	4.345	1.4484		
Total	27	411.656			

From the Table 6, it is observed that the p-value of the linear terms, square terms and interaction terms are 0.183, 0.819 and 0.248 respectively. The p-value associated with the t-statistic quantifies how significant each term is in the polynomial model, It is the probability that the observed results could occur when the null hypothesis (there is no relationship between the factor considered and the response) is true. If the p-value of a coefficient is less than the chosen α-level, such as 0.1, the relationship between the predictor and the response is statistically significant. Further analysis was carried out after removing the terms that have p-value significantly higher than α from the model. The R2 value of regression is 57.99 % which means that 57.99 % of the variation in wear rate can be explained by the model. The residual plots for wear rate is presented in Figs. 2a–2d.

It can be inferred from Fig. 2 that the normal probability plot of the residuals of wear rate shows that the residuals fall on the straight line. It means that the errors are normally distributed. The histogram of the residuals also show the same trend and it can be concluded that the assumption of normal distribution of residuals in DoE is not violated. The residual vs. fitted value plot is also random without any trend. Hence the constant variance assumption is not violated. The residual vs. order shows random pattern. Hence it can be concluded that the residuals are uncorrelated with each other.

4.3 Analysis of response surface plots

Figure 3 depicts the contour plot that shows the relation between Co wt.% and sliding distance and its combined effect on the wear rate

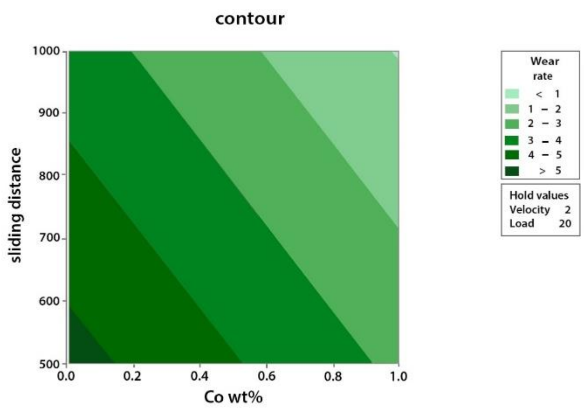


Fig. 3. Contour plot of wear rate w.r.t Co wt.% and sliding distance.

It can be inferred from the contour plots that, the wear rate decrease as the composition of wt.% of Co in A356 increases. Also, the wear rate reduces as the sliding distance increases. The decrease in wear rate for an increment in Co concentration accounts for the development of intermetallic phase formation due to the addition of Co [12]. The homogeneous distribution of the intermetallic phase between Al and Co improves the properties of alloys by eliminating the dendritic structure of A356 alloy. This hence improves the mechanical behaviors of A356 alloys which are reflected in the wear rate. As the composition of Co increases the intermetallic phase formation becomes more intense. As a result, the material experiences enhanced wear resistance as compared with pure A356 alloy [12] The increment in sliding distance causes a constant reduction in wear rate for every composition of Co. This may be due to the development of a slim oxide layer, called mechanically mixed layer (MML). In this case, the pin surface interacts with the disk for a greater period of time. As a result, the reaction might take place between aluminium, air, and steel which triggers the development of the oxide layer which avoids the direct interaction between the pin and the disk. This formation of MML also acts as solid lubrication, which further contributes to a reduction in wear [19,20].

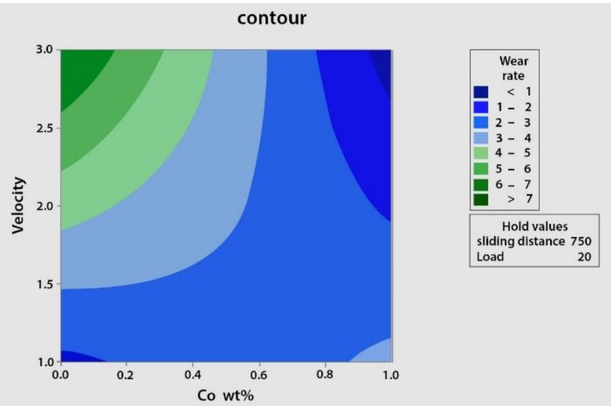


Fig. 4. Contour plot of wear rate w.r.t to velocity and Co wt.%

Figure 4 shows the contour plots for the interaction between Co wt% and sliding velocity and their effect on the wear rate In Fig. 5, the sliding distance and load were held constant at 750 m and 20 N respectively. As discussed from Fig. 4, the general trend is that the wear resistance was found to improve with the increment in the Co content irrespective of the velocity. This can be ascribed to the development of intermetallic phase formation between the Al and Co particles. This improves the microstructure and hence improves the wear behavior. The increment in the sliding velocity contributes to the increment in the wear rate. Higher velocity imparts a high temperature on the sliding surface. As a result, it leads to the softening of the region. This, in turn, contributes to the increment in the wear rate which is reflected in the contour plots [21].

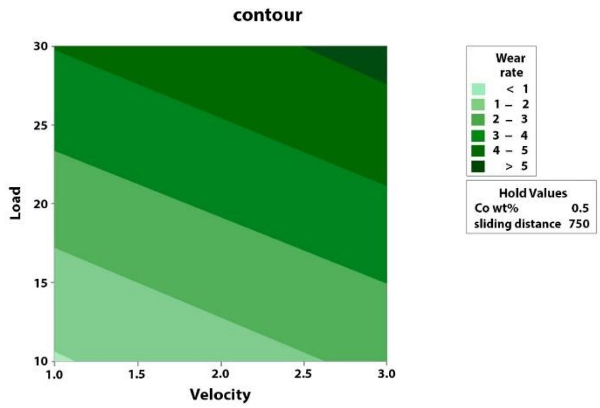


Fig. 5. Contour plot of wear rate w.r.t to velocity and load.

Figure 5 depicts the contour plot for the interaction of load and velocity in determining the wear rate respectively. It is clear that the increment in both load and velocity contributes to an increment in the wear rate. As in the previous case, heat formation due to the high velocity may soften the interacting surface. This leads to an increment in wear rate. Increment in the load imparts higher contact stress through the pin. The load makes sure that the pin always remains in contact with the disc. A higher load causes higher contact stresses. This creates a greater frictional force at the interacting surface. This triggers more material removal which in turn is reflected as an increase in wear rate. The present study was found in accordance with the studies of previous literature [19,20].

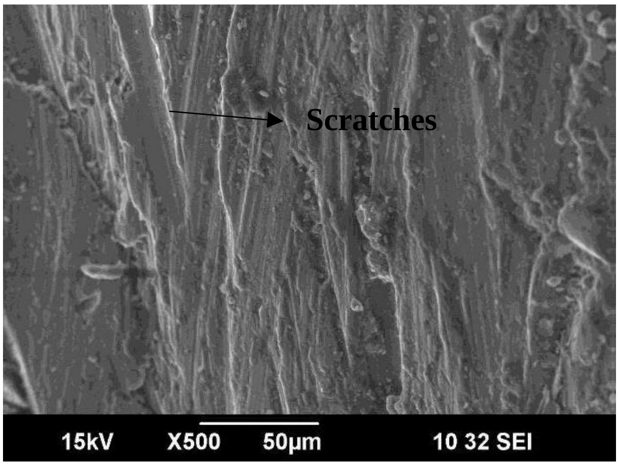
4.4 Optimization of wear

Optimization of the experimental parameters using response surface methodology which would result in a lower wear rate by determining the association between the parameters were wt.% Co composition, sliding distance, velocity, and load. The target wear rate and the upper bound limits were given as the inputs in the optimization process. It is inferred that the global solution for acquiring the target wear rate of 0.000481 mm^3/m is a Co composition of 1 wt.%, a sliding distance of 500 m, the velocity of 3 m/s and a load of 10 N.

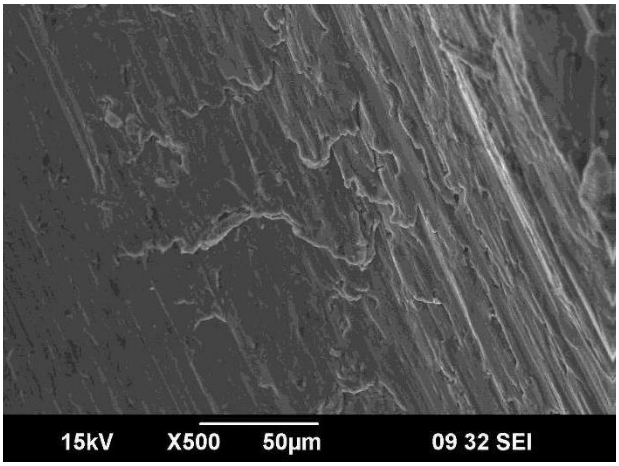
4.5 SEM analysis of worn out surface

Figure 6a-6c indicates the specimens subjected to wear test with varying wt.% of Co composition and the rest of the parameters were kept constant, which is a sliding distance of 750 m, the velocity of 2 m/s and a load of 20 N. Figure 6a depicts the SEM image of the worn-out surface of the sample with 0 wt.% of Co, Fig. 6b indicates the worn-out surface wherein the Co composition is 0.5 wt.% and Fig. 6c shows the SEM image of worn-out surface of sample with 1 wt.% Co.

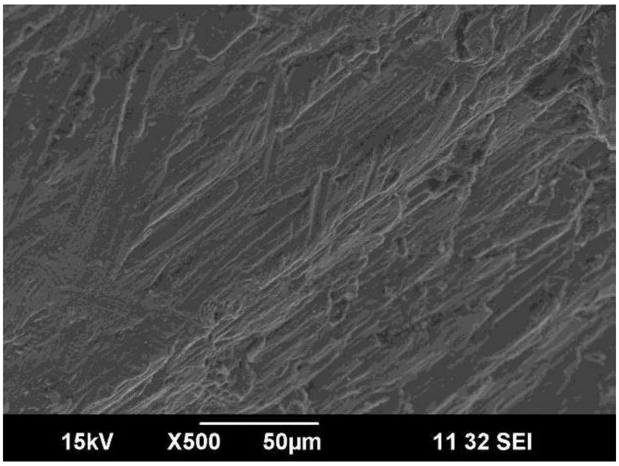
It is evident from Fig. 6a that the specimen had undergone more wear compared with the other two specimens which are attributed to the more number of scratches indicating more material removal. Since there is no presence of Co, there is no intermetallic phase formation involving Al and Co as in the other two but the phase formation between Mg and Si is favored. The intermediate phase present in the 0 wt.% Co could be Mg_2Si which will be of low hardness. Hence the material removal will be more compared with the other two. In Fig. 6b, the number and depth of the scratches are much lesser than those in Fig. 6a. This indicates that material removal is much less as compared with the previous Fig. 6a. It clearly suggests that the wear rate has improved with the introduction of Co. This is due to the precipitation hardening mechanism and intermetallic phase formation between Al and Co that improves the mechanical properties of the alloy. On further addition of Co, it is clearly evident that the number of scratches has reduced substantially, indicating a better wear resistance compared with previous ones, and thus exhibiting enhanced wear behavior.



(a)



(b)



(c)

Fig. 6. SEM images of samples with experimental parameters as d=750 m, v=2 ms^{-1}, l=20 N, (a) Sample with 0 wt.% Co (b) Sample with 0.5 wt.% Co (c) Sample with 1 wt.% Co.

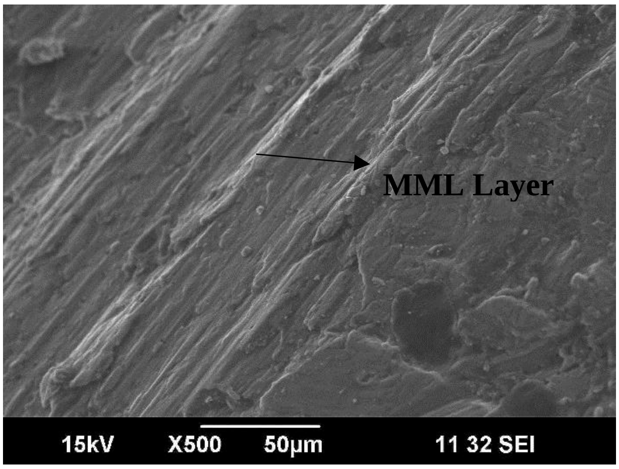


Fig. 7. SEM image of MML formation.

The same scenario is observed while predicting the wear behavior using the surface response model. In both cases, it is observed that the wear resistance of the alloy is improved with the increase in Co wt.%. The alloy with 0 wt.% of Co experience lesser wear resistance than other modified alloys. The alloy with 1 wt.% of Co experienced the least wear rate among the three. Hence it can be inferred that the addition of Co into A356 master alloy improves the wear properties of the A356 alloy.

The same has been studied in the previous literature and has obtained a similar microstructure as in Fig. 7 for the formation of MML in Al alloys [22-23]. This oxide layer formation is due to the interaction of aluminium and steel with oxygen. Figure 8 shows the EDS analysis which confirms the presence of oxide layer in 1 wt.% of Co added Al-6.6Si-0.4Mg alloy. The same oxide layer is visible in 0.5wt.% Co.

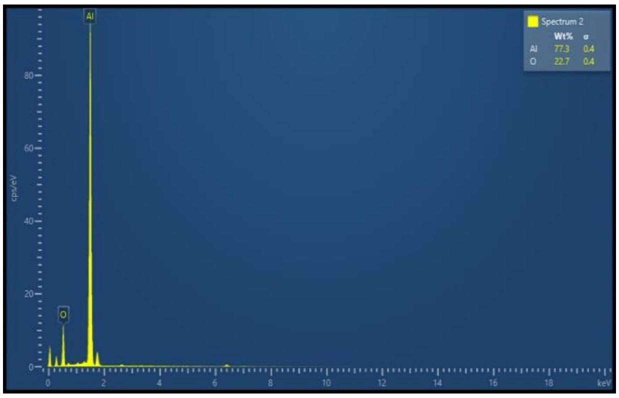


Fig. 8. Oxide layer in 1 wt.% of Co.

This MML formation prevents the direct contact between the pin and disk resulting in a lower wear rate. This also acts as a solid lubricant that prevents wear. Hence the material exhibits lower wear rates at a higher sliding distance.

5. CONCLUSIONS

A research was conducted to identify the effect of Co content on the wear behavior of Al-Si-Mg alloy using the design of experiments and the following conclusions were made.

- The wear behavior of A356 alloy modified with Co was studied using the RSM technique. The addition of Co improves the wear properties of A356 alloy.
- Owing to the formation of MML between Al, O and steel the wear rate of A356 modified with Co was found to reduce with an increment in the sliding distance.
- As the wt.% of Co content increases the wear rate was found to reduce with an increment in the sliding velocity.
- A surge in wear rate was observed for A356 modified with Co with an increment in the load applied.
- The optimum values of wear parameters to obtain a minimum wear rate were obtained using the RSM model. The wear mechanism was studied with the support of FESEM images of the worn-out surface.
- The formation of MML at a higher sliding distance was investigated using the FESEM image.

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