Dry Sliding Wear Behaviour of Al-Si-Ti Alloys Using Taguchi Method

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Abstract: ***The present study deals with investigation relating to the influence of wear parameters like sliding speed, applied load and sliding distance on the dry sliding wear of aluminium silicon titanium alloys. The design of experiment approach was employed to acquire data in controlled way using Taguchi method. A pin-on-disc apparatus was used to conduct the dry sliding wear test. An orthogonal array, signal-to-noise ratio and analysis of variance were employed to investigate the wear behavior of aluminium and it's alloys. The mathematical model was obtained to determine the wear rate of the aluminium and it's alloys. Addition of titanium in aluminium silicon alloys modifies microstructure as well improves the tribological characteristics.***

Keywords: Al-Si-Ti Alloys, Wear; Orthogonal Array, ANOVA, Taguchi Method

1. Introduction

Aluminium and aluminium alloy are gaining huge industrial significance because of their outstanding combination of mechanical, physical and tribological properties over the base alloys. These properties include high specific strength, high wear and seizure resistance, high stiffness, better high temperature strength, controlled thermal expansion coefficient and improved damping capacity. These properties obtained through addition of alloy elements, cold working and heat treatment. Alloying elements are selected based on their effects and suitability. The alloying elements may be classified as major and minor elements, microstructure modifiers or impurities, however the impurity elements in some alloys could be major elements in others. Now a days the aluminium-silicon alloys found many industrial application[1].

Francis Uchenna et al studied the effect of parameters on dry sliding wear characteristics of Al-Si alloys. Micro structural characterization was done using optical microscope (OM) and scanning electron microscope (SEM). Hardness and wear characteristics of different samples have shown near uniform behaviour. From this experimentation they found that the wear rate decreased when the percentage of silicon increases and wear was observed to increase at higher applied load, higher sliding speed and higher sliding distance. Also they observed that the wear characteristics of Al-14%Si was superior to those of Al-7%Si and Al-12%Si due to the degree of refinement of their eutectic silicon[1]

Riyadh A et al studied the effect of load and speed on sliding friction coefficient using a pin-on-disc Tribometer with three different loads (10, 20, and 30 N) at three speeds (200, 300, and 400 r/min) and relative humidity of 70%. From the experimentation they showed that the wear rate increased with increasing load and decreased with increasing sliding distance, whereas the friction coefficient decreased with increasing sliding speed before a stable state was reached. Also the friction coefficient decreased with increasing load. They suggested that after maintaining appropriate sliding speed and normal load level combination, frictional force and wear rate can be reduced which will improve the mechanical processes[2].

2. Taguchi Technique

The Taguchi technique is a powerful design of experiment tool for acquiring the data in a controlled way and to analyze the influence of process variable over some specific variable which is unknown function of these process variables and for the design of high quality systems [16,17]. This method was been successfully used by researchers in the study of wear behavior of aluminium metal matrix composites [18]. The aim of this technique is to make the products that are robust with respect to influencing parameters. Taguchi creates a standard orthogonal array to accommodate the effect of several factors on the target value and defines the plan of experiment [19,20]. The experimental results are analyzed using analysis of means and variance to study the influence of parameters.

3. Materials and Methods

Different elements were added to Al-Si alloy to improve their properties for variety of application. In this dissertation work Ti is added to Al-Si eutectic alloys. For preparation of testing alloy permanent mould casting process is used. Basic steps in casting process like melting, pouring, cooling, cleaning and inspections were carried out for each alloy. The alloys were prepared from commercially pure aluminum (99.7%), high purity silicon (99.9%) and electrolytic titanium (99.9%). Alloys were melted in an electric furnace at a temperature of 800^0C and poured into a permanent steel mould at was maintain at a temperature of 200^0C for some time then cooled to room temperature. The mould had a cylindrical shape with a length of 160 mm and diameter of 16 mm. Then this components were cut into small pieces and machined to the required shape of pin ie diameter 10 mm and length 30 mm for wear testing purpose. Polishing was done for all pins before wear testing with the help of emery paper of 400, 1000 and 2000 grade. Sample were cleaned in acetone before testing. The counter surface disc of EN-32 steel (0.62%Si-0.35Mn-1.02C-1.05Cr-0.3Ni) was used for experimentation. The chemical compositions of the alloys were determined by atomic absorption analysis method. Approximately 1gm of the alloy sample is weighed out accurately into an acid cleaned dry 200ml conical flask and the alloy is reacted with 30ml of 30% v//hydrochloric acid. After the reaction has almost stopped the mixture is gently heated and 5ml of concentrated nitric acid are slowly added. The clear sample solution is cooled and transferred to a standard volumetric flask and diluted to exactly 100 ml with distilled water. Aliquots of this sample solution may be further, if necessary, in order to bring each metal into the appropriate concentration range for measurement by atomic absorption spectrophotometer.

The experiments were conducted as per the standard L9 orthogonal array for material composition given in table 1. The wear parameters selected for the experiment were sliding speed in m/s, load in N and sliding distance in m. The each parameter was assigned three levels which are shown in Table 2. The standard L9 orthogonal array consists of nine tests as shown in the Table 3. The first column is assigned by sliding speed, second column was assigned by load and third column was assigned by sliding distance. The response studied was wear in terms of grams with the objective of "smaller is the better" type of quality characteristic.

Table 1: Chemical Composition of Materials

Material	*Chemical Composition in Wt.%*
A	Al-0.582%Si-0.016%Zn-0.004%Pb-0.192%Fe
B	Al-**11.362%Si**-0.038%Zn-0.012%Pb-0.51%Fe
C	Al-11.437%Si-0.01%Zn-0.017%Pb-0.242%Fe-**0.47%Ti**

Table 2: Testing Parameters and their Values

Factors	*Level 1*	*Level 2*	*Level 3*
Sliding Velocity (m/s)	1.571	2.095	2.618
Load (N)	29.43	39.24	49.05
Sliding Distance (m)	2827	3771	4712

Table 3: Orthogonal Array (L_9) of Taguchi for Wear Test

L_9 Tests	*Sliding Velocity (S)*	*Load (L)*	*Sliding Distance (D)*	*Wear of Al (mm^3)*	*Wear of Al-Si (mm^3)*	*Wear of Al-Si-Ti (mm^3)*
1	1.571	29.43	2827	0.0075	0.0054	0.0042
2	1.571	39.24	3771	0.0193	0.0166	0.0107
3	1.571	49.05	4712	0.0323	0.0285	0.0224
4	2.095	29.43	3771	0.0084	0.0056	0.0045
5	2.095	39.24	4712	0.0258	0.0172	0.0144
6	2.095	49.05	2827	0.0208	0.0138	0.0119
7	2.618	29.43	4712	0.0111	0.0096	0.0088
8	2.618	39.24	2827	0.0086	0.0072	0.0061
9	2.618	49.05	3771	0.0201	0.0151	0.0111

4. Result and Discussions

4.1 S/N Ratios Analysis

The influence of control parameters such as sliding speed (S), load (L) and sliding distance (D) on wear was been evaluated using S/N ratio response analysis. Process parameter settings with the highest S/N ratio always yield the optimum quality with minimum variance [20]. The sliding wear quality characteristic selected was smaller is the better type and same type of response was used for signal to noise ratio which is given below.

$$\eta = -10\log_{10}\left\{\frac{1}{10}\sum_{i=1}^{n} y_i^2\right\}$$

The S/N ratio response was analyzed using the above Equation for all nine tests and presented in Table 4. Figures 1, 2 and 3 show the main effects plots of S/N ratios for aluminium and its alloys graphically. From the figures it is evident that the average mean wear of aluminium is 0.0171 grams, where as for the Al-Si alloy it is 0.0132 grams and same for Al-Si-Ti alloy is 0.0104 grams. This shows that wear resistance of Al-Si-Ti alloy is more than that of Al and Al-Si alloys.

Table 4: S/N Ratio for Al and its Alloys

L_9 Tests	*S/N Ratio for Al (db)*	*S/N Ratio for Al-Si (db)*	*S/N Ratio for Al-Si-Ti (db)*
1	42.4988	45.3521	47.5350
2	34.2889	35.5978	39.4123
3	29.8159	30.9031	32.9950
4	41.5144	45.0362	46.9357
5	31.7676	35.2894	36.8328
6	33.6387	37.2024	38.4891
7	39.0935	40.3546	41.1103
8	41.3100	42.8534	44.2934
9	33.9361	36.4205	39.0935

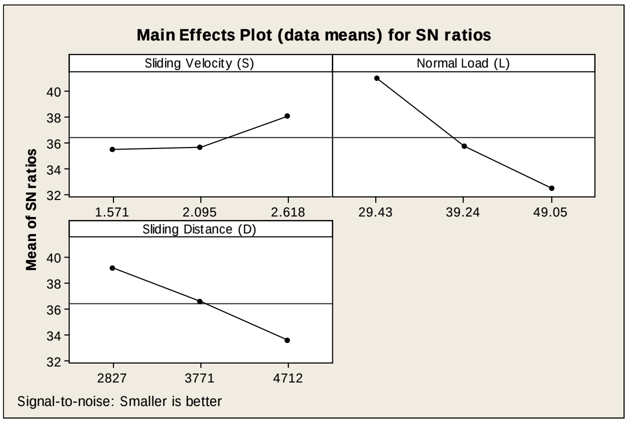

Figure 1: S/N Ratios of Al

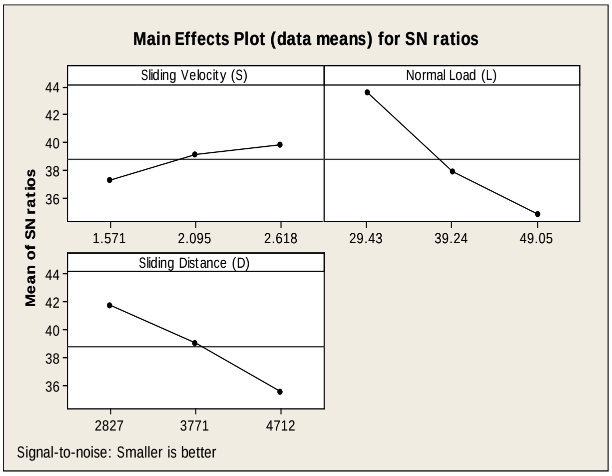

Figure 2: S/N Ratios of Al-Si Alloy

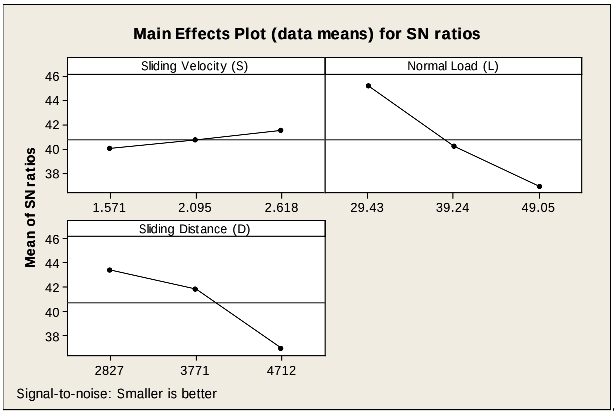

Figure 3: S/N Ratios of Al-Si-Ti Alloy

4.2 ANOVA Analysis

The analysis of variance (ANOVA) was used to analyze the influence of wear parameters like sliding speed, load and sliding distance. The ANOVA establishes the relative significances of factors in terms of their percentage contribution to the response. This analysis was carried out for a level of significance of 5% (i.e., the level of confidence 95%). Tables 5, 6 and 7 show the results of ANOVA analysis of Al, Al-Si and Al-Si-Ti alloys respectively. We can observe from the ANOVA analysis (Table 5) that the sliding speed, load and sliding distance have the influence on wear of aluminium material. The last column of the Tables 6 and 7 indicate the percentage contribution of each factor on the total variation indicating their degree of influence on the result. One can observe from the ANOVA Table 5 that the load (58.29%) and sliding distance (29.03%) have great influence on the wear of the aluminium material. The Table 6 shows ANOVA analysis of Al-Si alloy. From the results, it is found that load (51.80%) and sliding distance (32.27%) have great influence on the wear of the Al-Si alloy. Similarly Table 7 shows ANOVA analysis of Al-Si-Ti alloy. From the results, it is found that load (49.75%) and sliding distance (39.79%) have great influence on the wear of the Al-Si-Ti alloy.

Table 5: ANOVA Table of Al Material

Source	*DOF*	*Seq SS*	*Adj SS*	*Adj MS*	*F*	*P*
Sliding Velocity (S)	2	0.0000689	0.0000689	0.0000345	24.56	0.039
Normal Load (L)	2	0.0003586	0.0003586	0.0001793	127.77	0.008
Sliding Distance (D)	2	0.0001800	0.0001800	0.0000900	64.14	0.015
Error	2	0.0000028	0.0000028	0.0000014		
Total	8	0.001604				

Table 6: ANOVA Table of Al-Si Material

Source	*DOF*	*Seq SS*	*Adj SS*	*Adj MS*	*F*	*P*
Sliding Velocity (S)	2	0.0000624	0.0000624	0.0000312	28.15	0.034
Normal Load (L)	2	0.0002266	0.0002266	0.0001133	102.27	0.010
Sliding Distance (D)	2	0.0001420	0.0001420	0.0000710	64.09	0.015
Error	2	0.0000022	0.0000022	0.0000011		
Total	8	0.0004332				

Table 7: ANOVA Table of Al-Si-Ti Material

Source	*DOF*	*Seq SS*	*Adj SS*	*Adj MS*	*F*	*P*
Sliding Velocity (S)	2	0.0000214	0.0000214	0.0000107	11.81	0.078
Normal Load (L)	2	0.0001297	0.0001297	0.0000649	71.47	0.014
Sliding Distance (D)	2	0.0001041	0.0001041	0.0000520	57.34	0.017
Error	2	0.0000018	0.0000018	0.0000009		
Total	8	0.0002571				

4.3 SEM Analysis

The mechanism of material removal during wear process of the aluminium is by plastic deformation and gouging. The wear resistance of the composite material is improved due to the presence of hard AlSiTi particles in the material. The wear process in the material is by plastic deformation, gouging and reinforcement particles will crush to very minute particles and form a very thin sub surface layer. Figures 4 and 5 show the micro structure of the aluminium and its alloys.

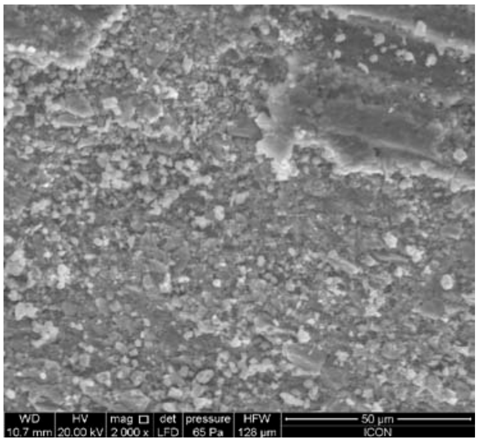

Figure 4: SEM of Al-Si-Ti Alloy

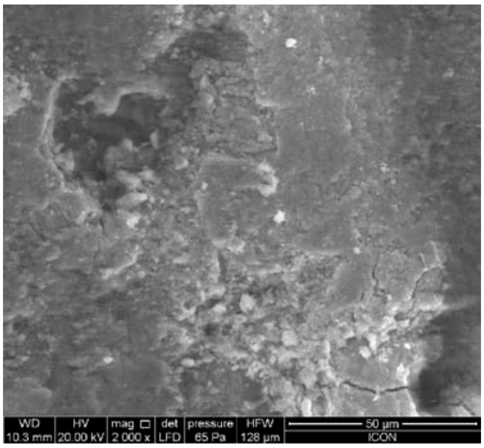

Figure 5: SEM of Al-Si Alloy.

4.4 Multiple Linear Regression Analysis

A multiple linear regression analysis attempts to model the relationship between two or more predictor variables and a response variable by fitting a linear equation to the observed data. In order to establish the correlation between the wear parameters: sliding velocity (S), normal load (L), sliding distance (D) and the wear (mass loss) in grams, the multiple linear regression model was used.

Wear of Al (gms) = – 0.0224 – 0.00614 S + 0.000785 L + 0.000006 D…………………………………….…………...(I)
S = 0.00193595 R-Sq = 96.9% R-Sq (adj) = 95.1%

Wear of Al-Si-Ti (gms) = – 0.0182 – 0.00592 S + 0.000625 L + 0.000005 D……………………………..…………..(II)
S = 0.00145777 R-Sq = 97.5% R-Sq (adj) = 96.1%

Wear of Al-Si-Ti (gms) = – 0.0162 – 0.00360 S + 0.000474 L + 0.000004 D………………………………………...(III)
S = 0.00172548 R-Sq = 94.2% R-Sq (adj) = 90.7%

Equation (I), (II) and (III) shows the regression equations for Al, Al-Si and Al-Si-Ti respectively. In this study, results obtained from wear in good agreement with regression models (R^2=0.942). It can be noted that since the value of regression coefficient for the model is 0.942, the wear data were not scattered. Since both the values are reasonably close to unity, models provide a reasonably good explanation of the relationship between the independent factors and the response.

It can be observed from (III) for Al-Si-Ti alloy that the coefficient associated with sliding velocity (S) is negative. It indicates that the wear of the material A decreases with increasing sliding velocity. Conversely the wear rate of the material A increases with increasing the applied load (L) and sliding distance (D) since the coefficient associated with the applied load and sliding distance are positive.

5. Conclusion

The following conclusions, from the experiential investigation can be made about the friction and sliding wear behavior of Al, Al-Si Eutectic alloy and Al-Si Eutectic alloy in addition of Titanium as a grain structure modifier under the selected ranges of normal loads and sliding velocities.

1. The DOE technique is successfully used to dry and wet sliding wear behaviour of , Al-Si Eutectic alloy and Al-Si-Ti Eutectic alloy.
2. The ANOVA analysis shows that the normal load (58.29 %) and sliding distance (29.03 %) have significant influence on wear of aluminium in dry condition. The same analysis shows that the normal load (51.80 %) and sliding distance (32.27 %) have significant influence on wear of aluminium-silicon eutectic alloy in dry condition. Similarly for Al-Si-Ti alloys, the ANOVA analysis shows that the normal load (49.75 %) and sliding distance (39.79 %) have significant influence on wear in dry condition.
3. The wear resistance of Al-Si-Ti alloy is more than that of Al-Si alloy and Al in dry condition. The average mean wear of aluminium is 0.0171 grams, where as for the Al-Si, it is 0.0132 grams, similarly for Al-Si-Ti, it is 0.0104 grams for dry condition.
4. A multiple linear regression model was developed to predict the wear rate of the composites. The closeness of the results of predictions based on calculated S/N ratios and experimental values show that the Taguchi experimental design technique can be used successfully for both optimization and prediction.
5. Analysis of worn surfaces revealed that at lower load, oxidation was the dominant wear mechanism, whereas at higher load, delamination and adhesion were found to be dominant for the alloys. It was found that mild wear occurs at high velocity and lower applied load, whereas severe wear occurs at high velocity and higher applied load.
6. As a result, it is found that the parameter design of the Taguchi method provides a simple, systematic, and efficient methodology for the optimization of the wear test parameters.

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