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A Statistical Study on the Dry Wear and Friction Characteristics of Al-12.6Si-3Cu- (2-2.6wt. %) Ni Piston Alloys

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Abstract

The present study aims to investigate the effect of Ni addition on the microstructural, physical, mechanical and wear characteristics of Al-12.6Si-3Cu-(2-2.6 wt. %) Ni piston alloys. The microstructural observations shows that the needle like β eutectic silicon's are fragmented, spheroidized and evenly dispersed in the α-Al matrix. The average grain size and degrees of fineness of β-eutectic silicon increased by the increase of Ni from 2 to 2.6 wt. % on the Al-12.6Si-3Cu-Ni (2-2.6 wt. %) Piston alloys. A tremendous increase in the Brinell hardness (49 to 63 BHN) and ultimate tensile strength (96 to 197 MPa) also observed by the addition of Ni weight percentage from 2 to 2.6 wt. % on the Al-12.6Si-3Cu-(2-2.6 wt. %) Ni piston alloys. A Full Factorial design experiment was used to investigate the effect of parameters such as normal load (15-75N), sliding distance (1000-20000 m), sliding velocity (0.8-1.2 m/s), and weight percentage of Ni (2-2.6 wt. %) on the wear loss and friction characteristics of Al-12.6Si-3Cu-(2-2.6 wt. %) Ni piston alloys against En31 Steel counter surface. The normal load (P = 63.49%), sliding distance (P = 28.57%), weight percentage of Ni (P = 4.33%) and sliding velocity (P = 1.63%) are the controlling factors on the wear loss characteristics of Al-12.6Si-3Cu-(2-2.6 wt. %) Ni piston alloys. While normal load (P = 94.96%), sliding distance (P = 1.11%, sliding velocity (P = 0.99%) and the interaction between load and sliding velocity (P = 1.57%) are the controlling factors on the friction behaviour of Al-12.6Si-3Cu-(2-2.6 wt. %) Ni piston alloys within the rage of parameters investigated.

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Keywords: *Piston alloys, Mathematical model, Coefficient of friction, Percentage of contribution*

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1. Introduction

Al-Si-Cu-Ni alloys are widely used in automobile industry for the production of piston and associated components due to its high strength to weight ratio, low density, good castability, low thermal expansion as well as high elevated temperature strength [1,2]Wear behaviour of such alloys have more significance in terms of economic and environmental factors [3].In order to reduce the hydrocarbon emission it is required to reduce the crevice volume of internal combustion engines which leads to the requirement of stronger piston alloy with improved mechanical properties and wear characteristics. Addition of alloying element is one of the most important and practical methods to improve the elevated-temperature properties of Al–Si piston alloys, and many elements have been examined during the past decades[4–8].Nickel has been known as the most important alloying element to improve the properties of Al-Si multicomponent piston alloy. Ni rich intermetallic phases formed by the addition of Ni on such alloys have significant role in the elevated temperature properties [4,6]. The Al_3Ni, Al_3CuNi and Al_7Cu_4Ni phases have much bigger contributions to the elevated temperature properties of Al-Si piston alloys owing to their better thermal stability, mechanical properties, morphologies and distributions[6,9].Factorial designs allows for the simultaneous study of the effects that several factors may have on a process. In a full factorial design experiment, responses are measured at all combinations of the experimental factor levels[10–12].

In this study, attempts were made to investigate the effect of Ni addition on the microstructural, physical, and mechanical characteristics of Al-12.6Si-3Cu-(2-2.6 wt. %) Ni piston alloys. A full factorial design experiments were conducted to analyse the effect of Nickel on the dry sliding and friction characteristics of Al-12.6Si-3Cu-(2-2.6 wt. %) Ni piston alloys under varying parameters.

2. Experimental Details

2.1. Materials Preparation and processing

Table 1. Chemical composition of Al-12.6Si-3Cu-Ni (2-2.6 wt. %) Piston alloys

Piston Alloys	Si	Cu	Ni	Mg	Fe	Mn	Al (Balance)
	wt.%						
Alloy A	12.6	3	2	0.7	0.2	0.07	81.43
Alloy B	12.6	3	2.6	0.7	0.2	0.07	80.83

Deferent types of piston alloys are prepared by using Al-6061 alloy, Al-50%Si master alloy, Al-50%Cu master alloy and Al-20%Ni master alloy.Table.1 describes the chemical composition of piston alloys used in this study. The gravity die casting technique was used to prepare the piston alloys. A melting process was carried out by using diesel fired tilting furnace .The preheated ingots were charged in to the furnace when the crucible attains a temperature of 700°c.The melting temperature was maintained at 750±5°C.The molten melt was continuously degassed by bubbling Ar gas into the melt. The molten metal was poured at temperature of 720-730°C in to the open preheated metal mould and after solidification mould allows to water quenching. The T6 heat treatment process was carried out by using electrical muffle furnace. [9]. The internal structure of cleaned and dried specimens inspected by using optical microscope.

2.2. Wear test

A pin-on-disc wear test rig was used to investigate the dry wear characteristics of Al-12.6Si-3Cu-(2-2.6 wt. %) Ni piston alloys in accordance with the ASTM G99-05 standards. A cylindrical pin of 6.0 mm diameter and length 30 mm cut from the heat treated samples was held on a rotating En 31 steel disc of diameter 200mm and having a hardness of 60HRC. All the tests were carried out using piston alloy pin with an applied load in the range 15–75N and sliding velocity of 0.8–1.2 m/s range. In order to measure the wear loss the initial and final weight of the pin specimen before and after the test are measured by a single pan electronic weighing machine (Zhimadzu) with least count of 0.01mg. After every test as per the design matrix the pin specimens were removed and weighed to measure the wear loss due to wear. The frictional force was measured by using a load cell attached to the lever arm and the data acquisition system.

2.3. Plan of experiments

A full factorial design was used to analyse the effect parameters such as load, sliding velocity, sliding distance and weight percentage of Ni on the responses wear loss and coefficient of friction of Al-12.6Si-3Cu-(2-2.6 wt. %) Ni piston alloys. The experiment consists of 16 tests (each row in the 2^4 design arrays) and the columns were assigned with actual value of parameters. The experiments were conducted as per the design matrix with the level of parameters given in each array row as shown in Table 2. The study of dry sliding wear behaviour of the alloys, and its significance lies in direct industrial applications such as in industrial machineries and passenger cars where the wear intensive region of the liner represents the upper section (top) against the cast iron cylinder. The combustion pressure acting radially on the piston ring is converted into normal force, and it generally lies between 15 and 100 N. Hence, applied load in this study was taken as the first wear and friction test parameter with the low and high levels, which were fixed as 15 and 75 N, respectively. The low and high ranges of sliding distance in this case study were kept at 1000 and 2000 m, respectively[13]. In order to compare the continuous and reciprocating wear characteristics of Al-12.6Si-3Cu-(2-2.6 wt. %) Ni piston alloys it was planned to select the range of sliding velocity as 0.8 to 1.2 m/s. The limit of weight percentage of Ni in this study was kept in the range of 2- 2.6 wt. %.

3. Results and discussion

3.1. Microstructure characteristics

Fig.1 shows the as cast microstructure of piston alloys. The average grain size varies with respect to the addition of Ni. The microstructure consists of α- aluminium dendritic halos with eutectic Si and complex intermetallic compounds segregated into the inter-dendritic regions. The changes on the size and shape of the eutectic Si is obvious after the heat treatment. The plate-like eutectic Si in the as cast condition is broken into small particles. That is, the Si particles break down into smaller fragments and become gradually spheroidized. The changes in size and morphology

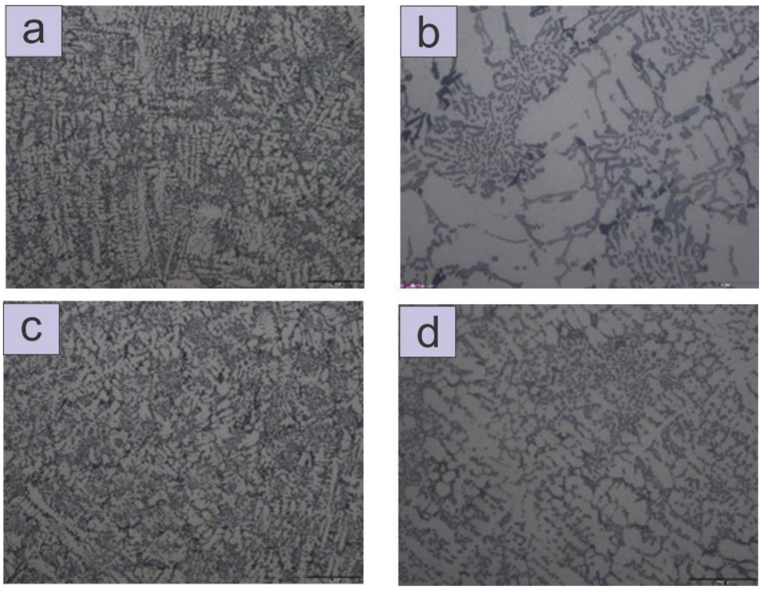

Fig.1. (a-b)Optical microstructure of Alloy A, (c-d) Optical microstructure of Alloy B.

of the discontinuous silicon phase are significant since they have a direct influence on the tensile properties. The massive rod like Si particles has been changed to a fine spherical shape besides the intermetallic phases distributing evenly along the grain boundaries. The intermetallic phases and the eutectic Si are the main elevated-temperature strengthening phases in Al-Si piston alloys, especially Ni- rich phases. At elevated temperature, the thermally stable Ni-rich phases could impose drag on boundaries and hinder the slide of α-Al grains. Therefore, Ni-rich phases can be called the main strengthening phases in Al-Si piston alloys at elevated temperature.

3.2. Statistical analysis

The purpose of the statistical analysis of variance (ANOVA) is investigate to which parameter is significantly affect the wear and friction characteristics of Al-12.6Si-3Cu-Ni (2-2.6 wt. %) piston alloys, with a confidence level of 95%.Table 3 shows the result of ANOVA analysis for the wear and friction coefficient of Al-12.6Si-3Cu-Ni (2-2.6 wt. %) piston alloys. From these tables the significant and insignificant model terms and interaction terms are identified through the value of "prob>F". Significant model terms are being "prob>F" values less than 0.05.In the ANOVA analysis response wear loss ranges from 4.61 to 52.285 and a ratio of maximum to minimum response is 11.34, that recommends a power transformation with λ=0.09.

It can be observed from the ANOVA Table 3a that the load, sliding velocity, sliding distance and weight percentage of Ni are the significant model terms influencing the dry wear characteristics of Al-12.6Si-3Cu-Ni (2-2.6 wt. %) piston alloys. The column 7 of the ANOVA analysis of wear loss result of piston alloys (Table 3a) indicates the percentage of contribution (P) of each factor on the total variation indicate their degree of influence on wear loss. It can be observed from the Table 3a that the Load (P=63.49%), Sliding Distance (P=28.57%), weight percentage of Ni (P=4.33%) and Sliding velocity (P=1.63%) are the controlling factors on the wear loss behaviour of Al-12.6Si-3Cu-Ni (2-2.6 wt. %) piston alloys. These results indicate that the Load, sliding distance , weight percentage of Ni and sliding velocity are the factors greatly influence the wear characteristics of Al-12.6Si-3Cu-Ni (2-2.6 wt. %) piston alloys. The error contribution was 1.98%.

Table 2. Experimental factors of the a full factorial design (FFD) for the wear loss and coefficient of friction of Al-12.6Si-3Cu-(2-2.6) wt. % Ni piston alloys

Run order	Factors				Responses	
	Load, A (N)	Sliding Velocity, B (m/s)	Sliding Distance, C (m)	Weight Percentage of Ni. D (wt. %)	Wear loss, Δm (mg)	Coefficient of Friction,μ
1	15	1.2	2000	2.6	11.53	0.4042
2	15	0.8	2000	2	18.35	0.3848
3	75	1.2	2000	2.6	28.56	0.2632
4	75	0.8	2000	2.6	45.28	0.2866
5	15	1.2	1000	2	7.9	0.3934
6	75	0.8	1000	2	28.69	0.3124
7	15	0.8	2000	2.6	14.53	0.3797
8	75	1.2	2000	2	50.59	0.2628
9	15	1.2	2000	2	17.04	0.3864
10	75	1.2	1000	2	21.3	0.29
11	15	0.8	1000	2.6	6.68	0.3986
12	15	1.2	1000	2.6	4.61	0.3838
13	15	0.8	1000	2	6.84	0.3934
14	75	0.8	1000	2.6	20.78	0.3014
15	75	1.2	1000	2.6	18.38	0.2733
16	75	0.8	2000	2	52.29	0.2869

It can be observed from the Table 3b that the load, sliding velocity, sliding distance and the interaction between load and sliding velocity are the significant model terms, which influence the friction characteristics of Al-12.6Si-3Cu-Ni (2-2.6 wt. %) piston alloys. It can be observed from the Table 3b that the load (P=94.96%), sliding distance

(P=1.11%, sliding velocity (P=0.99%) and the interaction between load and sliding velocity (P=1.57%) are the controlling factors on the friction behaviour of Al-12.6Si-3Cu-Ni (2-2.6 wt. %) piston alloys. The result indicating that the load, sliding distance, sliding velocity and the interaction between load and sliding velocity are the predominant factors greatly influencing the friction behaviour of Al-12.6Si-3Cu-Ni (2-2.6 wt. %) piston alloys. The error contribution was 1.87%.

3.3. Multiple linear regression model

Table 3
ANOVA table for the response characteristics wear loss and coefficient of friction of Al-12.6Si-3Cu-(2-2.6) wt. % Ni piston alloys.

Source	Sum of Squares	DOF	Mean Square	F Value	p-value Prob > F	% of Contribution
(a) **Response: Wear loss of Al-12.6Si-3Cu-(2-2.6) wt. % Ni piston alloys**						
Model	0.108463	4	0.02711	136.66	0.0001	significant
A-Load	0.07025	1	0.07025	354.07	0.0001	63.49
B-Sliding Velocity	0.001808	1	0.00180	9.1105	0.0117	1.63
C-Sliding Distance	0.03161	1	0.03161	159.32	0.0001	28.57
D-weight percentage of Ni	0.004796	1	0.00479	24.172	0.0005	4.33
Residual	0.002182	11	0.00019			1.98
Cor. Total	0.110646	15				
Coefficient of variation = 1.09, R^2 = 0.9803, R^2 adjusted = 0.9731, Predicted R^2 = 0.9583, Adequate precision = 35.217						
(b) Response: Coefficient of friction of Al-12.6Si-3Cu-(2-2.6) wt. % Ni piston alloys						
Model	0.046678	5	0.00933	107.29	0.0001	significant
A-Load	0.044912	1	0.04491	516.19	0.0001	94.46
B-Sliding Velocity	0.00047	1	0.00047	5.3997	0.0425	0.99
C-Sliding Distance	0.000526	1	0.00052	6.0404	0.0338	1.11
D- weight percentage of Ni	0.000023	1	2.33 e^{-05}	0.2675	0.6162	0.05
AB	0.000747	1	0.00074	8.5816	0.0151	1.57
Residual	0.00087	10	8.7 e^{-05}			1.83
Cor. Total	0.047548	15				
Coefficient of variation = 2.76, R^2 = 0.9817, R^2 adjusted = 0.9726, Predicted R^2 = 0.9532, Adequate precision = 23.372						

Equation 1-4 shows the correlation between wear loss and friction test parameters such as load sliding velocity, sliding distance and weight percentage of Ni in terms of coded and actual terms. The statistically significant terms were included in the model. In terms of coded factors, the final models of response equations are as follows.

$$\Delta m^{0.09} = 1.295 + 0.066A - 0.0106B + 0.0444C - 0.017D \pm \varepsilon \quad (1)$$

$$\mu = 0.337 - 0.052A - 0.005B - 0.0057C - 0.0068AB \pm \varepsilon \quad (2)$$

In terms of actual factors, the final models of response equations are as follows:

$$\Delta m^{0.09} = 1.24833 + .0022087A - 0.053449B + 0.00009\,C - 0.05771D \pm \varepsilon \quad (3)$$

$$\mu = 0.41947 + .000632A + 0.024279B - 0.0000116\,C - 0.001145AB \pm \varepsilon \quad (4)$$

Substituting the measured values of the variables in the multiple linear regression models, the wear loss and friction coefficient of Al-12.6Si-3Cu-Ni (2-2.6 wt. %) piston alloys can be calculated within the range of factors investigated. The effect of factors on the wear loss and friction coefficient is presented in Fig.2 and Fig.3.It can be observed from Fig.2d that increase of load leads to a significant increase of wear loss. There is a slight decrease in wear loss of Al-12.6Si-3Cu-Ni (2-2.6 wt. %) piston alloys due to the increase of sliding velocity (Fig.2a).Fig.2b shows that the wear loss increases by the increase of sliding distance due to the fact that the prolonged interaction time of asperities increases . It is attributed to the increased oxidation of Al alloys as a results of higher interfacial temperature caused by increased frictional heating and localization of heat. It can be observed that an increase of weight percentage of Ni (Fig.2c) results a decrease in the wear loss. This decrease of wear loss achieved by comminute and well dispersed Si particles in the α-Al matrix by the increase of Ni weight percentage, which also improves the hardness. By the increase in degrees of fineness of these strengthening particles avoiding the massive detachment of particles thus diminishing the three body abrasion wear mechanism[16]. It can be observed from Fig.3a that an increase of normal load causes a significant decrease in the coefficient of friction. While increase in the sliding velocity(Fig.3b) and sliding distance(Fig.3c) shows a slight decrease in the case of coefficient of friction of Al-12.6Si-3Cu-Ni (2-2.6 wt. %) piston alloys. Whereas the effect of weight percentage of Ni are marginal. The combined effect of load and sliding velocity (Fig.3d) tends to decrease the friction coefficient.

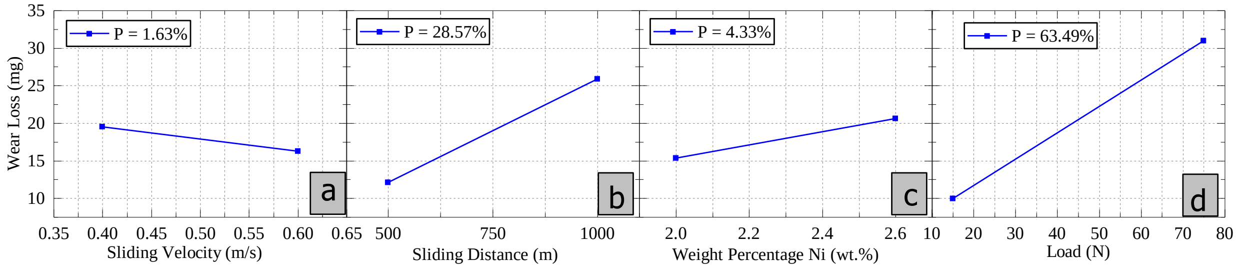

Fig.2. Effect of a) sliding velocity, b) sliding distance, c) weight percentage of Ni, d) normal load on the wear loss characteristics of Al-12.6Si-3Cu-Ni (2-2.6 wt. %) piston alloys.

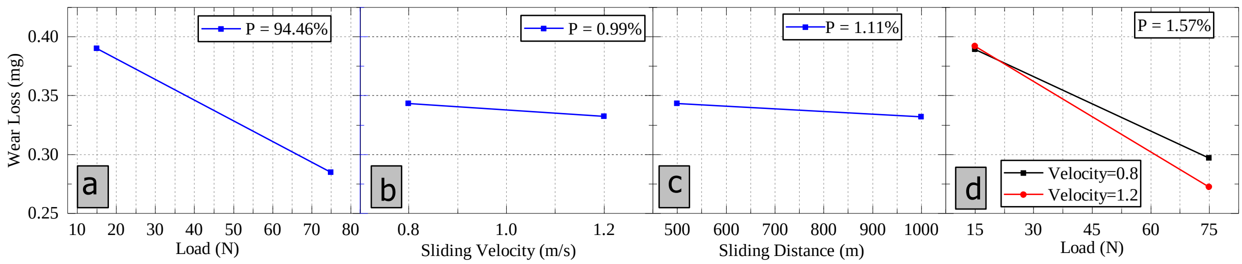

Fig.3. Effect of a) normal load, b) sliding velocity, c) sliding distance, d) the interaction between normal load and sliding velocity on the response coefficient of friction of Al-12.6Si-3Cu-Ni (2-2.6 wt. %) piston alloys

4. Conclusion

A full factorial design experiments were conducted to analyse the effect of Nickel on the dry sliding and friction characteristics of Al-12.6Si-3Cu-Ni (2-2.6 wt. %) piston alloys under varying test parameters. The investigated conclusions are listed here. Normal load (P = 63.49%), Sliding velocity (P = 1.63%), sliding distance (P = 28.57%), and weight percentage of Ni (P = 4.33%) are the significant model terms influencing the dry wear loss characteristics of Al-12.6Si-3Cu-Ni (2-2.6 wt. %) piston alloys. Normal load (P = 94.96%), sliding velocity (P = 0.99%), sliding distance (P = 1.11%) are the main controlling parameters which exerts a strong effect on the friction behaviour of Al-12.6Si-3Cu-Ni (2-2.6 wt. %) piston alloys, within the range of parameters investigated. The interaction between load and sliding velocity (P = 1.57%) are the significant interaction model terms, which influence the friction characteristics of Al-12.6Si-3Cu-Ni (2-2.6 wt. %) piston alloys. The established equations clearly demonstrate that the high Nickel content in Al-12.6Si-3Cu-Ni (2-2.6 wt. %) piston alloys exhibited higher wear resistance in the selected experimental domain.

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