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STATISTICAL ANALYSIS ON INFLUENCE OF HEAT TREATMENT, LOAD AND VELOCITY ON THE DRY SLIDING WEAR BEHAVIOR OF ALUMINIUM ALLOY 7075

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Abstract. In this paper, the influence of the heat treatment, load and sliding velocity on the wear loss of the Al alloy 7075 was evaluated using a pin-on-disc wear testing rig. Dry sliding wear tests were conducted for three different loads (5, 10, and 15 N) for three different velocities (0.8, 1.6, and 2.4 m/s). Taguchi and Analysis of Variance (ANOVA) techniques were employed to investigate the influence of parameters on the wear loss of Al alloy. Multiple linear regression models were also developed to predict the wear loss of alloys. It was observed that the wear increased with increasing load and sliding velocity. The results showed that T6 Al - alloy aged for 6 hrs exhibited better wear resistance compared to as - cast alloy and T6 alloy aged for 2 hrs. The results reveal that the normal load is the most influencing the wear resistance followed by the heat treatment and sliding velocity. The worn surface morphology was investigated by Scanning Electron Microscope (SEM).

1. Introduction

Since the aluminium and its alloys are widely used in aerospace and automobiles, it is more essential to analyze the wear behavior of alloys. Wear is a removal of material from one or both of two solid surfaces in contact with each other under load and speed. Aluminum alloys of the 7075 series have been considered for structural applications in the automotive industry. Babic [1] conducted the dry and lubricated sliding wear tests to investigate the tribological potential of Zinc- Aluminium alloys using block-on-disc machine over a wide range of applied loads and sliding speeds. They reported that the heat-treated alloy samples attained improved tribological behavior over as-cast ones. Adeyemi Dayo Isadare et al. [2] analyzed an effect of heat treatment on mechanical properties of 7075 aluminium alloy and they reported that the alloying elements lead to increase in the strength through formation of $MgZn_2$ precipitate within the structure as the result of aging heat treatment. It was found that yield strength, ultimate tensile strength and hardness values increases but lowers the ductility and impact strength. Mohit Dhiman et al. [3] analyzed the wear behavior of Al alloy in the as-cast and heat-treated conditions using analysis of variance to find out the factors that affect wear. Md Abdul Maleque and Md Rezaul Karim [4] reported that heat treated composite exhibited better wear resistance compared to as-cast composites. Srecko Manasijevic et al. [5] analyzed the effects of heat treatment on the microstructure and mechanical properties of aluminum piston alloys. They emphasized that it is necessary to find the optimum combinations of the temperature and the time of heat treatment in order to achieve the required performance and economic savings. Amro M. Al-Qutub [6] reported that at high loads and beyond transition region the heat treated composite offers higher wear resistance. G.H. Koch and D.T. Kolijn [7] reported that the significant features of the heat treating process are the solution treatment temperature, the quench rate, the aging temperature and aging time.

Limited attempts [8-9] have been made to investigate the effect of heat treatment on the sliding wear behaviour of Al alloys. Hence it is obvious that there is no clear understanding in the literature regarding the contribution of parameters on the wear of Al alloy. The present work therefore has been undertaken to find the optimal levels of wear parameters such as heat treatment, applied load and sliding velocity on wear loss using Taguchi’s experimental technique. The analysis of variance (ANOVA) is employed to analyze the contribution of the parameters on the wear loss. The worn surface morphology was investigated by Scanning Electron Microscope (SEM).

2. Experimentation

(i) Heat treatment process. The studies were carried out on the aluminium alloy 7075.The composition of the Al alloy 7075 is given in Table 1.

Table 1.

Element	Al	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Pb	Ca	Ni
Wt.%	Rest	0.05	0.11	1.35	0.02	2.31	0.27	5.61	0.05	0.02	0.013	0.001

T6 (precipitation heat treatment) was carried out on AA7075 specimens for two different aging durations, 2 hrs and 6 hrs respectively. In the first stage (solution treatment) , Al alloy was heated above the solvus temperature 470 ºC and soaking them at this temperature for 1 hour in the muffle furnace and cooled by rapid quenching in water. In the second stage (age hardening), solution treated Al alloy subjected to a age hardening by heating them to 120 °C, holding them at this temperature for two different aging durations (2 hour and 6 hours) then followed by air cooling to room temperature.

(ii) Dry sliding wear test. A pin-on-disc apparatus which is shown in Fig. 1 was employed to conduct the dry sliding wear tests. Hardened steel (65 HRC) counter disc of 100 mm track diameter and 8 mm thick was used. Specimens of 10 mm diameter and 25 mm height were prepared and the pin surfaces were polished by emery paper. The tests were conducted at 27 °C room temperature and 55 % relative humidity for 30 minutes. The wear loss of the pins was recorded by measuring the height loss of the material in terms of μm. Each test was repeated three times and the mean values were taken into consideration.

Fig. 1. Pin-on-disc apparatus.

3.Taguchi method

Taguchi’s parameter design is a systematic methodology to find out the optimum levels of parameters which have an influence on the process and its performance. In this study, “smaller is better” S/N ratio was considered to find the optimum parameters because smaller wear loss was desirable. Mathematical equation of the S/N ratio for “smaller is better” can be represented in the equation (1).

$$\frac{S}{N} = -10Log\left(\frac{1}{n}\sum_{i}\frac{1}{Y_i^2}\right), \quad (1)$$

where Y is the observed data and n is the number of observations.

Wear tests were conducted as per the L9 orthogonal array. The chosen parameters and levels are presented in Table 2. The corresponding measured wear loss values and Taguchi's S/N ratios are presented in Table 3.

Table 2. Parameters and levels

Level	Heat treatment (A)	Load, N (B)	Sliding Velocity, m/s (C)
I	As – cast alloy	5	0.8
II	T6- 2 hrs	10	1.6
III	T6- 6 hrs	15	2.4

Table 3. Measured values and S/N ratios for wear.

Exp. No	Parameters			Values	
	Heat treatment (A)	Load, N (B)	Sliding Velocity, m/s (C)	Wear (μm)	Signal / Noise Ratio
1	As – cast	5	0.8	216	-46.6891
2	As – cast	10	1.6	239	-47.568
3	As – cast	15	2.4	262	-48.366
4	T6- 2 hrs	5	1.6	206	-46.2773
5	T6- 2 hrs	10	2.4	223	-46.9661
6	T6- 2 hrs	15	0.8	232	-47.3098
7	T6- 6hrs	5	2.4	198	-45.9333
8	T6- 6hrs	10	0.8	213	-46.5676
9	T6- 6hrs	15	1.6	227	-47.1205

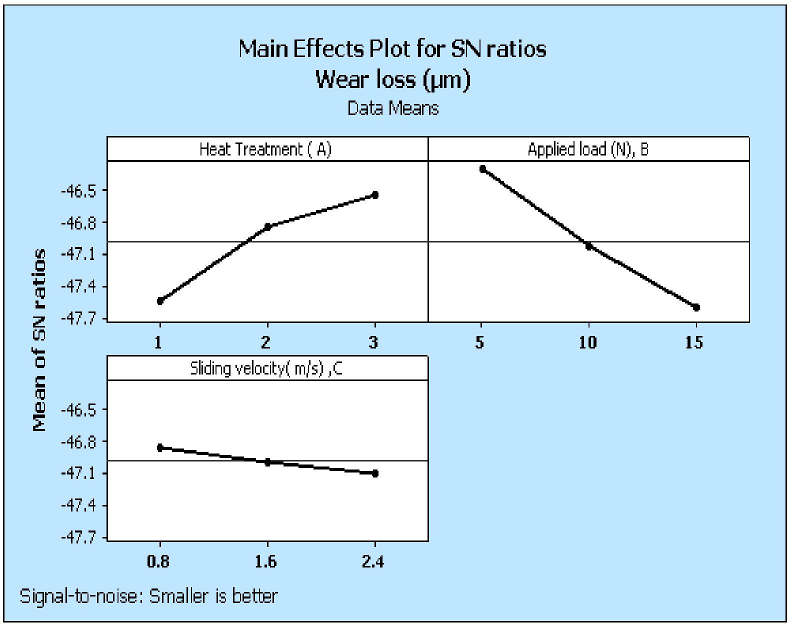

Fig. 2. Response diagram for Signal to Noise Ratios.

Table 4. ANOVA analysis for wear.

Factor	DoF	SS	F-Value	P value	Pc, %
Wear					
A - Heat treatment	2	1100.67	26.21	0.037	37.59
B - Load	2	1704.67	40.59	0.024	58.21
C - Sliding velocity	2	80.67	1.92	0.342	2.76
Error	2	42.00			1.4
Total	8	2928.00			100

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

4. Results and discussion

From the response diagram of S/N ratio (Fig. 2), it was found that the optimum parameters were T6 heat treated Al alloy aged for 6 hrs, load (5 N) and sliding velocity (0.8 m/s) in minimizing the wear of the Al alloy. ANOVA was performed with the help of the software package MINITAB15. The p-value is used to test the significance of each parameter. When the P-value is less than 0.05, then the parameter can be considered as statistically highly significant. It was observed from the Table 4 that heat treatment and applied load on the wear loss have less than 0.05, which means that they are highly significant at 95 % confidence level. The last column of the Table 4 shows the percentage contribution (Pc %) which indicates the degree of influence of the parameters on the wear loss. It can be observed that the load (58.21 %) was the major contributing factor followed by heat treatment (37.59 %) and sliding velocity (2.76 %) influencing the wear loss.

Results infer that as the normal load increases wear increases irrespective of heat treated specimens. It was observed that the precipitated heat treated (T6 aged for 6 hrs) Al alloys have higher wear resistance than the precipitated heat treated (T6 aged for 2 hrs) and as –cast Al alloy specimens. The improvement in the wear resistance of precipitated heat treated alloys owing to fine precipitate dispersion which is associated with solubility of the alloying elements during heat treatment process. It can also be observed that the wear resistance of the Al alloy increases as aging duration increases. This can be attributed to the fact that the formation of more intermetallic precipitates when the ageing duration was increased. AA7075 alloy which has major alloying elements such as zinc and magnesium enhances the wear resistance through the formation of $MgZn_2$ intermetallic phases during heat treatment. The similar observation was made by Dursun Özyürek et al. [10]. They reported that small and homogenously dispersed intermetallic compounds precipitates formed in AA6063 aluminium alloy with T6 heat treatment were compared to the T5 heat treatment. Fine-grained materials resist the dislocation during sliding since they have more grain boundaries which increase the materials to be harder and stronger [11].

The effect of normal load and sliding velocity on the wear loss of T6 Al alloy (aged for 6 hrs) is shown in Figure 3.It can be observed that when the load was increased from 5 to 15 N at constant sliding velocity of 2.4 m/s, wear of Al alloy increased by 20 % i.e. from 198 μm to 239 μm. Figure 3 also demonstrates that the wear of Al alloy is apparently to have increasing trend with increase in sliding velocity. Wear increased from 219 μm to 239 μm when the sliding velocity was increased from 0.8 m/s to 2.4 m/s at a constant load of 15 N. It can be noted that the wear increased (10 %) when increasing the sliding velocity from 0.8 m/s to 2.4 m/s. It could be attributed to the fact that an increase in sliding velocity causes rise in temperature at the interface resulting in the softening tendency of Al alloy which increased adhesion at the sliding contacts.

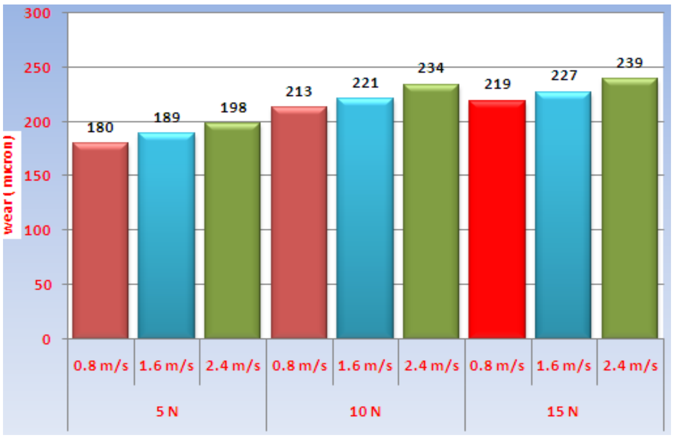

Fig. 3. Effect of heat treatment, load and sliding velocity on wear of Al alloy.

5. Multiple linear regression model

Multiple linear regression equations were done to establish the correlation among the parameters on the response. The value of regression coefficient, R^2 (0.963) is in good agreement with the adjusted R^2 (0.9426) for wear loss of the alloy. It can be seen that the values of R^2 and adjusted R^2 are close to unity and models would provide better elucidation of the relationship between the parameters on the response.

The regression equation developed for wear loss of Al alloy is

$$W = 209 - 13.2\,(A) + 3.37\,(B) + 4.58\,(C), \tag{2}$$

where, W= Wear loss; A- Heat treatment, B-Applied load, N, C- Sliding velocity, m/s.

It was observed from the Eq. (2) that the coefficients associated with applied load (B) and sliding velocity (B) are positive. It infers that the wear loss decreases with decreasing applied load and sliding velocity. Wear resistance increases with heat treatment aging duration.

6. Confirmation test

The confirmation experiments were carried out according to the Table 5 and results were presented in the Table 6. Typical superimposed curves of wear of Al alloy 7075 are shown in Figure 4 which was taken from the wear test rig after the test duration of 30 minutes. The experimental values for the wear of the alloy and calculated values from the regression equation are nearly same with least error (± 4 %). The resulting equations seem to be capable of predicting the wear loss to the acceptable level of accuracy.

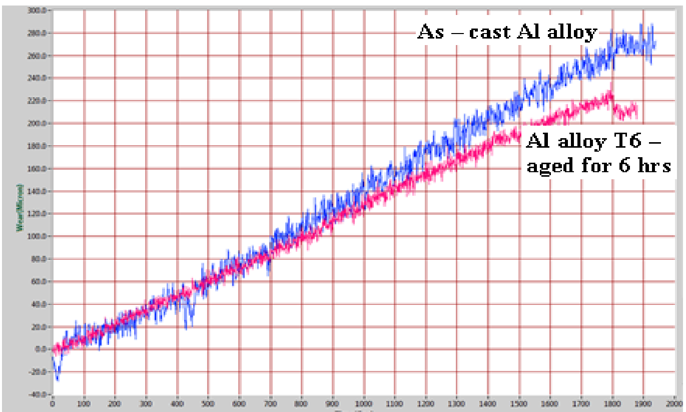

Fig. 4. Typical superimposed curves of wear of as – cast Al alloy and Al alloy T6 – aged for 6 hrs against steel as a function of constant sliding velocity of 2 m/s at 15 N.

Table 5. Parameters used in the confirmation test.

Test	Heat treatment (A)	Applied load (B), N	Sliding velocity (C), m/s
I	As - cast alloy	15	2
II	T6- 6 hrs	15	2

Table 6. Results of confirmation tests.

Test I			**Test II**		
Wear Loss					
Model equation	Expt.	Error, %	Model equation	Expt.	Error,%
255.51	260	1.75	229.11	220	3.97

7. Worn surface morphology

Additional wear tests were conducted at the optimum parameters (applied load 5 N and sliding velocity 0.8 m/s) for as – cast Al alloy, T6 – aged for 2 hrs and Al alloy – aged for 6 hrs. The SEM images of the worn surface are shown in Figs. 5-7.

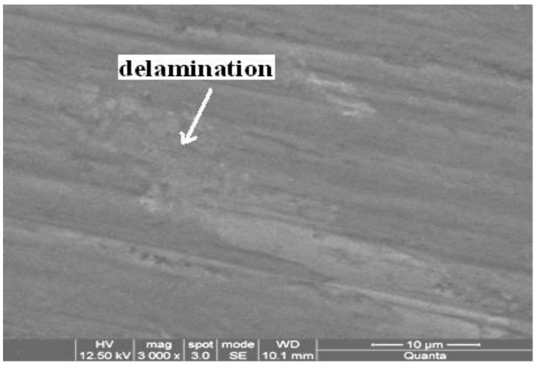

Fig. 5. SEM micrograph of the worn surface of the Al alloy (as - cast) at a normal load of 5 N with 0.8 m/s sliding velocity.

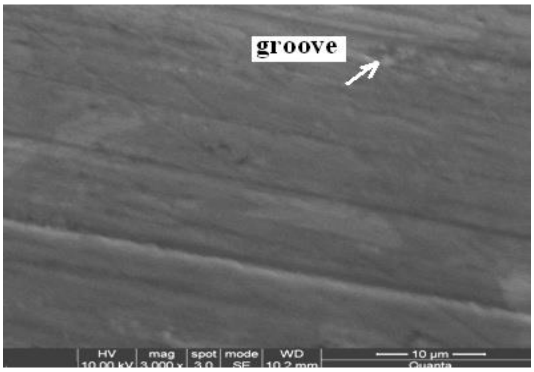

Fig. 6. SEM micrograph of the worn surface of the Al alloy (T6 – aged for 2 hrs) at a normal load of 5 N with 0.8 m/s sliding velocity.

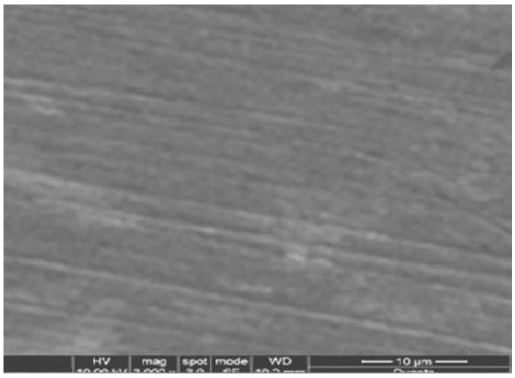

Fig. 7. SEM micrograph of the worn surface of the Al alloy (T6 – aged for 6hrs) at a normal load of 5 N with 0.8 m/s sliding velocity.

It was observed from the Fig. 5 that the plastic deformation was found to be more extensive and delamination type wear was also noticed on the worn surface of the alloy resulting in formation of sub surface cracks. It can be seen from the Fig. 6 that the groove size and sliding marks appear more severe at the lower ageing duration T6 alloy – aged for 2 hrs.

It was seen from the Fig. 7 that sliding marks are appeared mostly parallel to the sliding direction. Small grooves and scratches appeared on the worn surface of the T6 alloy – aged for 6 hrs when it was subjected to 5 N load and sliding velocity of 0.8 m/s. Hence abrasion was dominant under low load and velocity conditions. The worn surfaces morphologies of as – cast alloys pointed out more ductile mode of fracture than the heat treated alloys.

The worn surface of the precipitated heat-treated (aged for 6 hrs) specimen was noticed to be smoother than those of the precipitated heat-treated (aged for 2 hrs) specimen. It reveals that the T6 – aged for 6 hrs has enhanced the wear resistance compared to T6 – aged for 2 hrs. This can be attributed to the formation of more intermetallic precipitates when the ageing duration was increased. The enhanced tribological behavior of the heat-treated Al alloys could be attributed to finer and more uniform distributed micro constituents and reduced cracking tendency. Hence, ageing duration enhances the precipitation hardening by the formation of $MgZn_2$ intermatallics which act as obstacles to dislocation during sliding.

8. Conclusions

Optimal conditions for attaining minimum wear loss are obtained using Taguchi S/N ratio analysis.

From the Taguchi results, it can be found that the optimum parameters were load (5N), sliding velocity (0.8 m/s) and T6 Al alloy aging period of 6 hrs in minimizing the wear of the composites

From ANOVA analysis, it was found that, the most significant influencing parameter on wear loss is the load, which accounts for 58.21 % of the total effect, followed by the heat treatment (37.59 %) the sliding velocity (2.76 %). It was observed that the wear loss increases with the increase in normal load and sliding velocity. The results also clearly demonstrate that the wear resistance of the precipitated heat-treated Al alloys is significantly higher as compared to that of the as - cast Al alloys within the observed range of applied load and velocity. The wear resistance of Al alloy increased with increasing aging duration. It can be concluded that T6 heat treatment (aged for 6 hrs) could be an effective method in enhancing the wear resistance of Al alloys significantly.

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