



Process Parameters Optimization of Pin and Disc Wear Test to Minimize the Wear Loss of General-Purpose Aluminium grades by Taguchi and Simulation through Response Surface Methodology

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Abstract

Mechanical parts are frequently subjected to friction which generates heat at the contact zones, resulting in wear of the parts which reduces the components life and leads to the higher power consumption. Because of their exceptional characteristics, aluminium (Al) and its alloys find a wide range of applications in industry and daily life. These alloys range from the 1xxx series to the 7xxx series. However, research is continuously being performed to develop superior, low-cost, high-strength alloys that provide the best wear outcomes. In the present study, an attempt has been made to optimize the process parameters on pin and disc wear test as per American Society for Testing and Materials (ASTM) standard Grain size (G)99-05 on 2xxx series alloys – Aluminum Al 2011, Al 2014, and Al 2024. The results reflect that, the parameter disc speed has the greatest influence on the wear loss of the specimen and the material type has the least effect at 95% the confidence level. In the present work, the optimum combination of parameters determined through the Taguchi and Response Surface Methodology (RSM). It is proved from the work among the three materials (Al 2011, Al 2014, and Al 2024) considered for the analysis, the material Al 2024 exhibits the lowest wear loss.

Keywords: Al alloys; Optimization; RSM; Taguchi Method; Wear loss.

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1. Introduction

Aluminium is one of the lightest engineering metals, with a strength-to-weight ratio that exceeds that of steel.^[1] An aluminium alloy is a chemical compound in which other elements are mixed with pure aluminium to improve its properties and strength. Copper, magnesium, iron, silicon, tin, zinc, and manganese are among the other elements, accounting for 15% of the total weight of the alloy. Alloying necessitates a thorough mixing of pure aluminium with these other elements while it is still molten. The primary alloying element added to aluminium alloys allows them to be

classified into a variety of groups. These groups represent the characteristics of the material, such as its ability to respond to mechanical and thermal treatment. Aluminium alloys are typically assigned a four-digit number, with the first digit identifying the alloy series and characterizing its main alloying elements.^[2]

In this work, we have considered 2xxx series aluminium alloy. The main alloying element in the 2xxx series aluminium alloy is copper, and this series can be significantly strengthened through solution heat-treating. These alloys lack the atmospheric corrosion resistance of many other aluminium alloys but have a good combination of strength and toughness. To greatly resist corrosion, these alloys are typically clad with a high purity alloy or a 6xxx series alloy. Alloy 2024, possibly the most well-known, is used as an aircraft alloy. Aluminium alloy 2024 is widely used as structural parts in the aerospace industry due to its excellent combination of strength and fatigue resistance. Age hardening can alter the microstructure and mechanical behaviour of Aluminium alloy 2024. A high

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strength-to-weight ratio metal with finely dispersed precipitates was obtained after an appropriate heat treatment process. However, the ductility of Aluminium alloy 2024 makes it difficult to form complex-shaped parts using traditional cold forming processes. As a result, in order to reduce spring back in the forming process, some thin-walled and complex-shaped parts are machined from solid blocks of metal. For some applications, the machining process contributes to 90% material waste, with associated energy and cost.^[3]

Wear is defined as a process in which a solid's surfaces or bounding faces interact with its working environment, resulting in dimensional loss and/or material loss.^[4,5] A pin-on-disc machine is used to measure the dry sliding wear resistance at room temperature.^[6] Loads, speed, temperature, kind of counter body, and type of contact are all aspects of the working environment that effect wear. The loss of material during wear is indicated in terms of volume in the results of standard wear tests. When comparing the wear resistance capabilities of materials with considerable changes in density, the volume loss gives a more accurate picture than the wear loss. The secondary stage is shortened as environmental circumstances become more severe, such as increased temperatures, strain rates, stress, and slide velocities, and the primary stage merges with the tertiary stage, shortening the working life dramatically. Surface engineering techniques are employed to reduce material wear and increase its useful life.^[7-13]

Although it is feasible to establish a robust design by employing expensive components, high-quality materials, or even managing process factors, these solutions are rarely cost-effective, hence the Taguchi approach is the most cost-effective way in Design of Experiments.^[14,15] Dr. Genichi Taguchi discovered a number of novel statistical tools, methodologies, and concepts for improving product quality that are based on statistical theory of design of experiments.^[16,17] Taguchi explains how he came up with his method by adopting a design of experiment that create a method that can withstand a wide range of environments and variations and reduce the goal value to reduce fluctuation.^[18,19] Taguchi approach is chosen since it is a cost-effective method.^[20] The action of making the best or most effective use of a situation or resource is known as optimization.^[21,22]

So far optimization of process parameters for pin and disc wear testing in Al alloys 2011, 2014 and 2024 has not been done. The results of this work throw the light on the selection of combination of process parameters to obtain the minimum

wear rate when a particular material has been selected for any application which is similar to testing condition.

2. Experimental section

2.1 Material preparation

Commercially available Aluminium alloys 2011, 2014 and 2024 were utilized to carry out the experiment in this work. Chemical composition for the specimens used are presented in [Table 1](#).

2.2 Experimental work done

To better understand the dry sliding wear pattern (mass loss) of 2011, 2014, and 2024 series aluminium alloys, experiments were conducted on a pin-on-disc type wear and friction monitor [DUCOM, India make; Model: TR-201CL] machine which is equipped with a data acquisition system.

For testing the material's wear behavior, pin type specimens with 10 mm diameter and 30 mm length were used. In the wear test, a hardened steel disc (EN31) served as the counter surface. The test was carried out with various loads of 1000, 2000, and 3000 grams at disc speeds of 200, 400, and 600 rpm for sliding distances of 50, 70, and 90 mm. The experiment was carried out at room temperature (30 °C) with a relative humidity of 60–65%. The specimen's initial weight was determined using an electronic weighing machine. The wear test was performed 30 minutes after the initial run for each 1000, 2000, and 3000 grams when the pin specimens were completely in contact with the disc surface. In each test, the specimen was removed after running the fixed sliding distance, cleaned with acetone, dried, and weighed to determine the mass loss due to wear.

Based on the literature, process parameters are selected to carry out the experimentation. The considered process parameters and their levels are presented in [Table 2](#).

3. Results and discussion

3.1 Design of experiments (DOE)

For the present experimentation, the experiments were designed using design of experiments (DOE) methods. The combination of process parameters to each of the experiment has been obtained by using Taguchi L27 array. The combination of parameters of all 27 experiments and results obtained are presented in [Table 3](#) and the regression equation obtained is presented in [equation 1](#).

$$W = - 0.0231 + 0.000045 S + 0.000006 L + 0.000196 T + 0.000219 TD - 0.00206 M \tag{1}$$

Table 1. Chemical composition of the Aluminium alloy 2011, 2014 and 2024.

Al alloy	Si %	Fe %	Cu %	Cr %	Mg %	Mn %	Ti %	Zn %	Bi %	Pb %	Others %
2011	0.40	0.70	5-6	-	-	-	-	0.30	0.2-0.6	0.2-0.6	0.15
2014	0.5-1.2	0.70	3.9-5	0.10	0.2-0.8	0.4-1.2	0.15	0.25	-	-	-
2024	0.50	0.50	3.8-4.9	0.10	0.3-0.90	1.2-1.8	0.15	0.25	-	-	-

Table 2. Parameters and their levels.

Sl. No	Variables	A	B	C
1	Speed (S) (rpm)	200	400	600
2	Load (L) (g)	1000	2000	3000
3	Time (T) (min)	30	60	90
4	Track Diameter (TD) (mm)	50	70	90

In order to establish if a statistically significant link between the response and predictors is seen or not, we need to recognize the p-value coefficient and compare the p-values coefficient with our α -level value (typically < 0.05). The α levels are likely, if a zero hypothesis is valid, to reject the zero hypothesis, which means that an important link can be established if there is not a real one. This probability (α) is also termed the meaning level. Table 4 represents the P values obtained for the present work. Since all the P values are lesser than 0.005 there is a significant link between the predictors

and response.

Normal probability graph of the experiment is shown in Fig. 1, since there in no any sign of skew in the probability line, the line is indicating the normality in distribution of the data. The graph does not show any slope other than the factors in interest. This indicates that, there is no effect of any undiscovered variables or other major variables that influence the response.

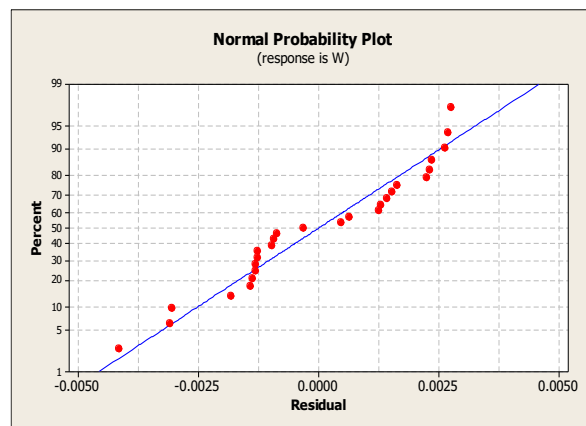


Fig. 1 Normal probability plot of residual.

Table 3. Combination of parameters and results.

Sl. No	Speed (S) (rpm)	Load (L) (g)	Time (T) (min)	Track Diameter (TD) (mm)	Material (M) (no.)	Wear Loss (WL) (g)
1	200	1000	30	50	1	0.008
2	200	1000	30	50	2	0.003
3	200	1000	30	50	3	0.001
4	200	2000	60	70	1	0.025
5	200	2000	60	70	2	0.023
6	200	2000	60	70	3	0.021
7	200	3000	90	90	1	0.039
8	200	3000	90	90	2	0.036
9	200	3000	90	90	3	0.033
10	400	1000	60	90	1	0.029
11	400	1000	60	90	2	0.027
12	400	1000	60	90	3	0.025
13	400	2000	90	50	1	0.031
14	400	2000	90	50	2	0.032
15	400	2000	90	50	3	0.030
16	400	3000	30	70	1	0.027
17	400	3000	30	70	2	0.026
18	400	3000	30	70	3	0.024
19	600	1000	90	70	1	0.039
20	600	1000	90	70	2	0.037
21	600	1000	90	70	3	0.035
22	600	2000	30	90	1	0.041
23	600	2000	30	90	2	0.039
24	600	2000	30	90	3	0.037
25	600	3000	60	50	1	0.043
26	600	3000	60	50	2	0.040
27	600	3000	60	50	3	0.039

Table 4. Regression Table – P-values.

Predictor	Coef	SE Coef	T	P
Constant	-0.023102	0.002776	-8.32	0.000
S	0.00004472	0.00000258	17.33	0.000
L	0.00000572	0.00000052	11.08	0.000
T	0.00019630	0.00001721	11.41	0.000
TD	0.00021944	0.00002581	8.50	0.000
M	-0.0020556	0.0005162	-3.98	0.001

The main effect plot of the experiment is illustrated in Fig. 2. The slope of the graphs indicates that, for the present experimentation condition the parameter speed has most significant effect on the wear hence any small variation in this parameter will cause the major difference in the wear of the components. Hence the drastic variation of this parameter is barred. The second parameter which is having the considerable amount of effect is the operating time and the least effecting parameter is the material type.

Fig. 3 shows the interaction plot of the present experimentation. It evident that the parameter material type does not have any interaction with any other parameters considered. Except that, all other input parameters exhibit the mutual interaction over the output parameter. Hence the

variation in the output obtained is not the result of variation of one input parameter but it is a combined effect of all other parameters which are in consideration.

The Anova table is presented in Table 5, from the table it is clear that all the considered parameters are having the significant effect on the wear. The most significant parameter is disc speed this may be because of the fact that, as the disc speed increases, there is a quick rise in the temperature at the contact region. This rise in temperature will leads to decline in the strength of the material due to which the bonding between the atoms diminishes quickly. The increases in the operating time will leads to increase in the contact time between disc and specimen again which increases the temperature at the contact area which leads to fast wear of the specimen. Hence the operating time reflects as the second highest influencing parameter. As the load on the specimen increases, the contact pressure between the disc and specimen enhances due to which there is a hike in the wear. Since the material is removed in the form of the powder, the removed material will stick to the disc surface which will reduce the fresh surface contact of the disc and specimen. When the track diameter increases, there is a less collection of the powder material over the contact region which opens the fresher region of the disc to the specimen which leads to the escalation in the wear. Finally, the

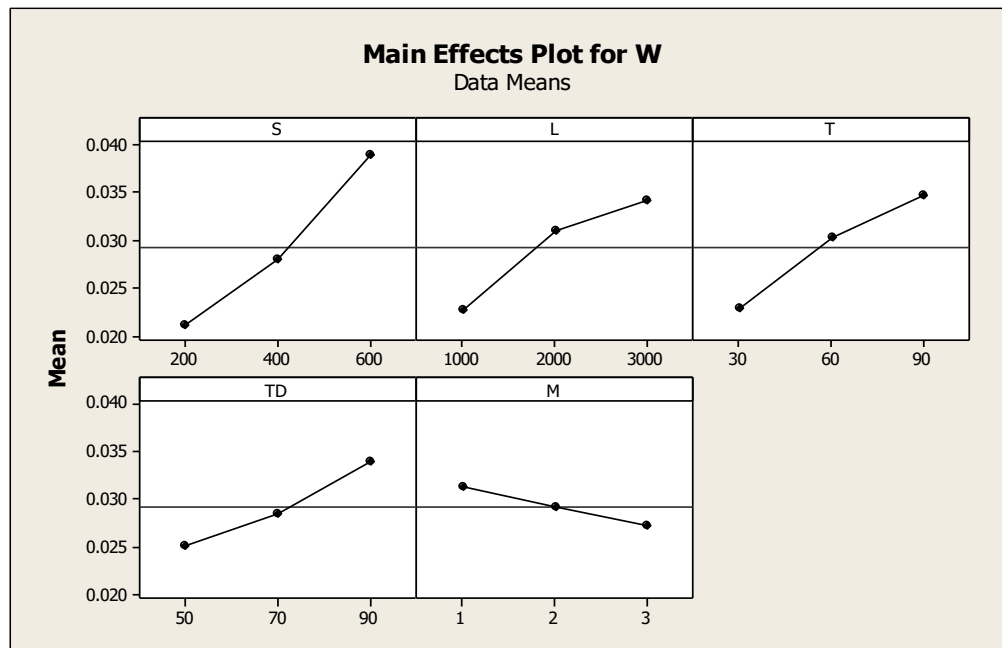


Fig. 2 Main effects plot for wear loss (data means).

Table 5. Analysis of variance for wear loss, using adjusted Sum of Squares (SS) for tests.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
S	2	0.0014654	0.0014654	0.0007327	768.27	0.000
L	2	0.0006303	0.0006303	0.0003151	330.45	0.000
T	2	0.0006367	0.0006367	0.0003184	333.83	0.000
TD	2	0.0003534	0.0003534	0.0001767	185.28	0.000
M	2	0.0000761	0.0000761	0.0000380	39.88	0.000
Error	16	0.0000153	0.0000153	0.0000010	-	-
Total	26	0.0031772	-	-	-	-

$S = 0.000976578$ $R\text{-Sq} = 99.52\%$ $R\text{-sq (adj)} = 99.22\%$

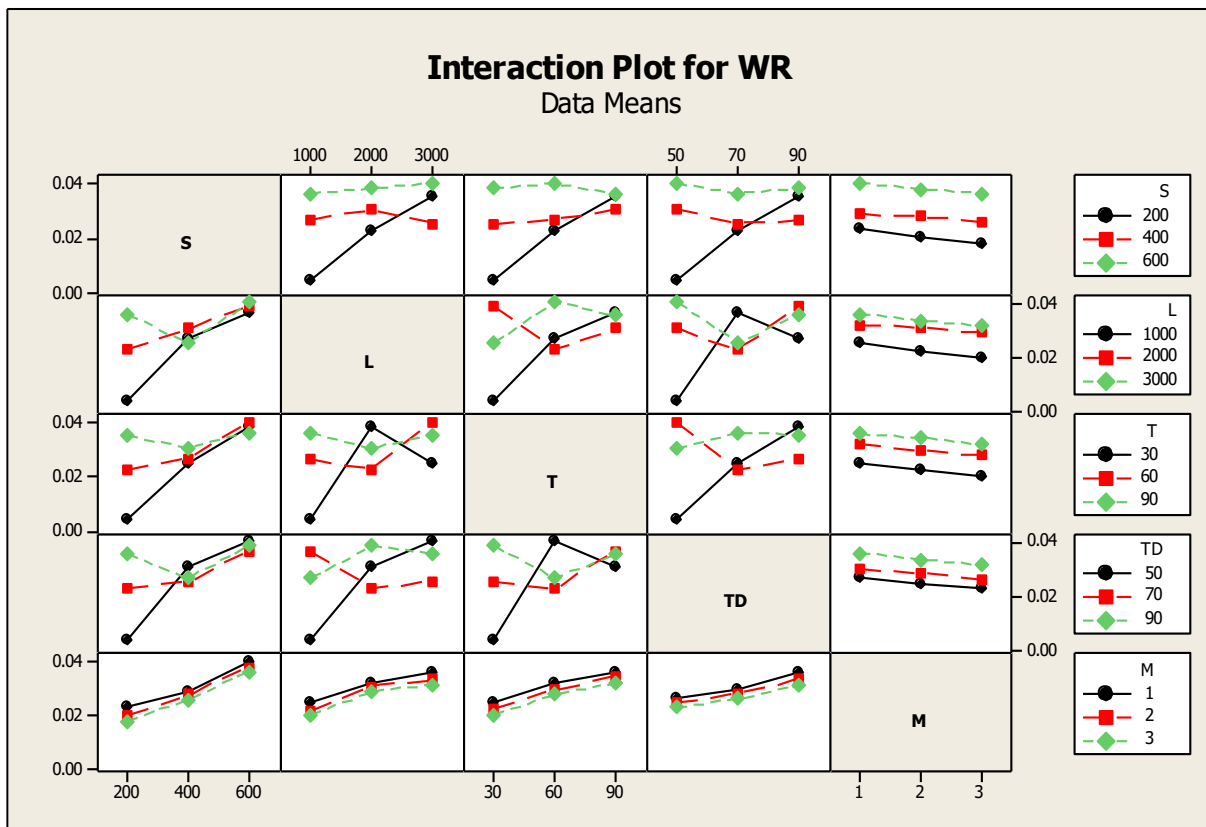


Fig. 3 Interaction plot for wear loss.

material type is also having the least effect on the wear because of the composition of the alloy. The Al alloy 2024 shows the lower wear in comparison with the other alloy 2011 and 1014. This could be because of higher amount of Mg and Mn present in the alloy.

3.2 Optimization by Taguchi method

The response table of the experimentation is presented in Table 6 from the table the optimum combination of parameters to obtain the minimum wear loss is: S=200 rpm, L=500 g, T=15min, TD=20mm and M= Al alloy 2024.

Response optimizer of the experimentation is shown in Fig. 4 the optimization of the process parameters to achieve the lower wear loss is illustrated in the red color which is same as obtained by the Taguchi method.

Table 6. Response table for means.

Level	Speed	Load	Time	Track Diameter	Material
1	0.02100	0.02267	0.02289	0.02522	0.03133
2	0.02789	0.03100	0.03022	0.02856	0.02922
3	0.03889	0.03411	0.03467	0.03400	0.02722
Delta	0.01789	0.01144	0.01178	0.00878	0.00411
Rank	1	3	2	4	5

3.3 Simulation through Response Surface Methodology (RSM)

In the optimizer plot there is a provision to move the red bar from the lowest range to the highest range. As the red bar of

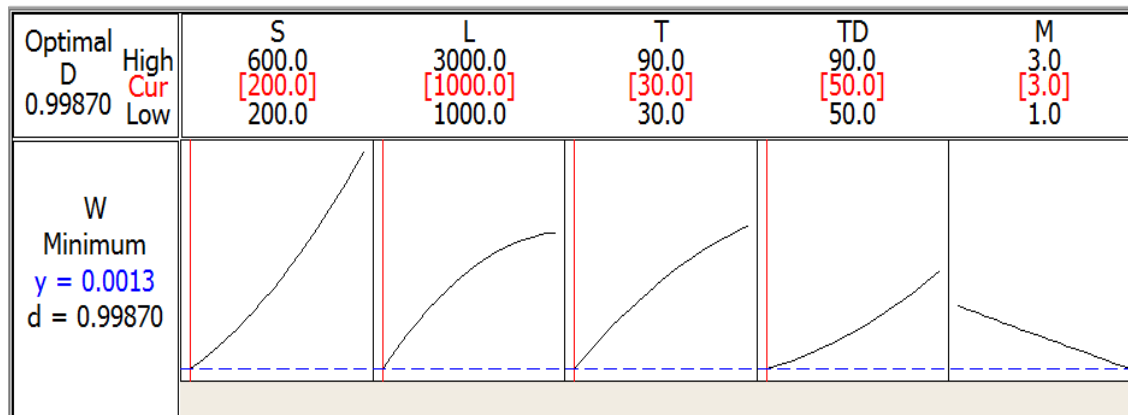


Fig. 4 Optimization plot of wear loss.

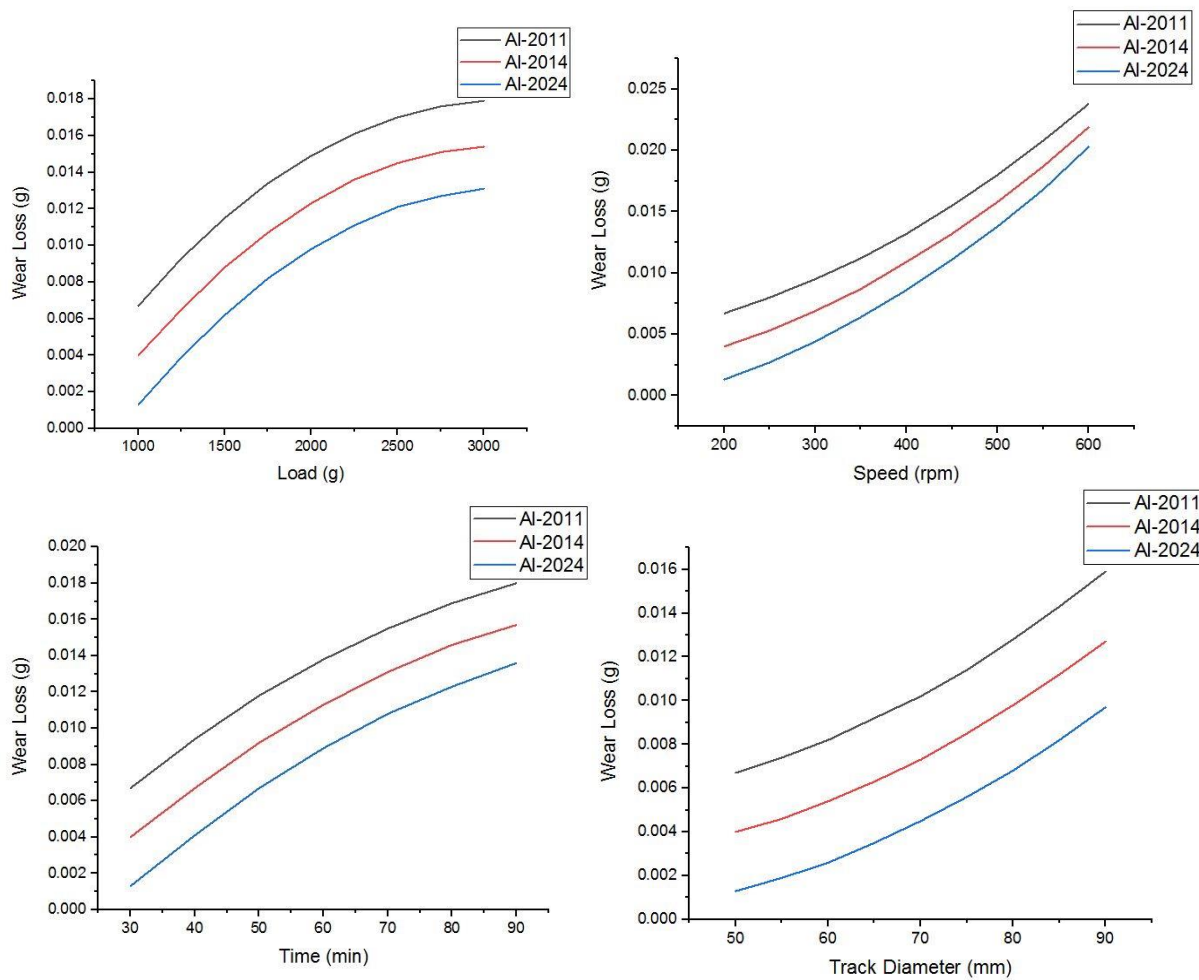


Fig. 5 Wear Loss with respect to speed, load, time and track diameter.

each parameter is moved, the corresponding y value (wear loss) will be displayed. By moving and fixing the bar at different intermediate values, the corresponding wear loss are tabulated. Once the required number of intermediate values are tabulated, the graph of wear loss versus each parameter is plotted. The plots which are plotted to each parameter are represented in Figs. 5(a), (b), (c) and (d). By referring to the appropriate graph, the wear loss for any intermediate values required parameter can be obtained.

3.4 Confirmation tests

The confirmation tests were carried out after the comprehensive simulation for wear loss vs all independent parameters had been constructed. The wear loss calculated from the simulated graphs for the given set of parameters (speed = 200 rpm, load = 2500 rpm, time = 90 min, track diameter = 90mm, specimen Al2011) is 0.038 g. The acceptance level is 97%, and the confirmation test result obtained for the identical set of parameters is 0.037 g. Similarly, the wear loss value obtained from the graph for the combination of parameters (speed = 300 rpm, load = 1000 rpm, time = 30 min, track diameter = 30 mm, and specimen is Al2024) is 0.009 g. The wear loss value for the same combination is 0.0087 g, and the acceptance level is 96.6 %,

according to the confirmation test results. These two confirmation tests show that the stated range is correct.

4. Conclusions

Among the considered parameters, the disc speed has the significant effect on the wear loss and the material type is the least effecting parameter. Except the material type, other parameters exhibit the mutual interaction effect. Thus, variation of one parameter will influence the effect on another parameter. Compared to alloys 2011 and 2014 the alloy 2024 exhibits the least wear loss and this is purely because of its composition. For the present experiment work, to achieve the least wear loss, the optimum combination of parameters obtained by both response table and the response optimizer is: S=200 rpm, L=500 g, T=15min, TD=20mm and M= Al alloy 2024. The simulation graphs drawn through RSM can be used to predict the wear loss at any intermediate values of considered parameters. The confirmation tests reveals that the acceptance level of the results obtained from the simulation graphs are more than 90%.

Conflict of interest

There are no conflicts to declare.

Supporting information

Not applicable.

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