Numerical Simulation of Dry Reciprocating Wear Loss Characteristics of Al 6061 Alloy

B. Sunil, V. R. Rajeev, C. Jaimon, S. Jose

Abstract*— In this paper, attempts were made to develop a numerical wear model. The developed wear model was used to investigate the effect of parameters on the response reciprocating wear loss characteristics of Al 6061 alloy against En 31 hard steel counterface. A Box-Behnken design of experiment was used to investigate the effect of parameters such as normal load (15-45N), reciprocating velocity (0.4-0.6 m/s), and sliding distance (300-500 m) on the response reciprocating wear loss characteristics of Al 6061 alloy. The normal load (Percentage of contribution, P = 34.23%), and reciprocating velocity (P = 43.75%), sliding distance (P = 14.45%) are the controlling factors on the response wear loss behaviour of Al 6061 alloy. The interaction model term between the normal load and reciprocating velocity (P = 3.21%) was the secondary influencing factor on the response wear loss characteristics of Al 6061 alloy within the range of parameters investigated. An optimized sliding condition was identified by the genetic algorithm (GA) approach as load 15N, reciprocating velocity 0.6m/s and sliding distance 300m.

***Index Terms*—Wear loss, Percentage of contribution, Reciprocating tribometer, Genetic algorithm.**

I. INTRODUCTION

Al 6061 alloy is widely used as construction material, usually in the aircraft manufacture and automobile components sector. The Al 6061 alloy is well-suited to the construction of yachts, bicycle frames, motorcycles, scuba tanks, fishing reels, camera lenses, electrical fittings, couplings, bearings and valves. Al 6061 alloy used as a base material for cast alloys and it's composite. Wear behaviour of such alloys have more significance in terms of economic and environmental factors [1]. Santana et al. studied the effect of laser shock processing on the wear and friction behaviour of 6061-T6 aluminium alloy and reported that wear rate decreases as pulse density increases [2].A wear study of laser surface alloying with NiTi using a pin-on-disc tribometer was conducted by Man et al. and found that the wear resistance of the modified layer reached about 5.5 times that of the substrate [3].An enhanced stir casting method was deployed by Gopalakrishnan et al. on Al 6061 matrix titanium carbide particulate reinforced composite, which revealed that the specific strength of the composite increases with higher percentage of TiC addition [4]. Very few studies on wear characteristics were reported under reciprocal sliding conditions where the same material may behave differently compared to unidirectional wear conditions [5, 6]. Andersson et al. employed a wear model to simulate the time dependent wear in a sphere on flat contact [5]. Esteban et al. studied the effect of controlling parameters on the abrasive wear system of Ni-based alloy coatings both with and without WC reinforcement by using a full factorial design. And reported that the abrasive grain size followed by reinforcement were the main controlling parameters for the response abrasive wear characteristics [6]. Rajeev et al. studied the effect of various wear test and material related parameters (applied load, sliding distance, reciprocating velocity, counter surface temperature and weight percentage of silicon) on dry wear behaviour of two Al–Si–SiCp composites under reciprocating conditions by using fractional factorial design. And reported that the applied load, sliding distance, reciprocating velocity and weight percentage of silicon in composite are the four important and controlling factors [7].However, very few of these studies on the effect of parameters were reported under reciprocal sliding conditions where the same materials may behave differently compared to that under unidirectional wear conditions.

In this paper attempts were made to develop a numerical wear model to analyze the dry reciprocating wear loss characteristics of Al 6061 alloy slid against hard En 31 steel counterface and also analyze the effect of parameters such as load, reciprocating velocity and sliding distance on the response wear loss characteristics by design of experiments.

II. EXPERIMENTAL PROCEDURE

A. Materials

Al 6061 alloy supplied by the Hindalco India was selected as the material to study the wear characteristics. The chemical composition of Al 6061 is presented in Table 1.Table 2 shows the physical and mechanical properties of Al 6061 alloy.

Table 1 Chemical Composition of Al 6061 alloy (wt. %)

Alloy	Si	Cu	Mg	Cr	Fe	Mn	Al
Al-6061	0.6	0.35	0.11	0.08	0.7	0.15	98.64

Table 2 Physical and Mechanical properties of Al 6061 alloy

Density	2.7g/cc
Hardness	60BHN
Ultimate Tensile Strength	310MPa
Modulus of Elasticity	68.9GPa
Poisson's Ratio	0.33

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B. Pin-on-Reciprocating Plate Tribometer

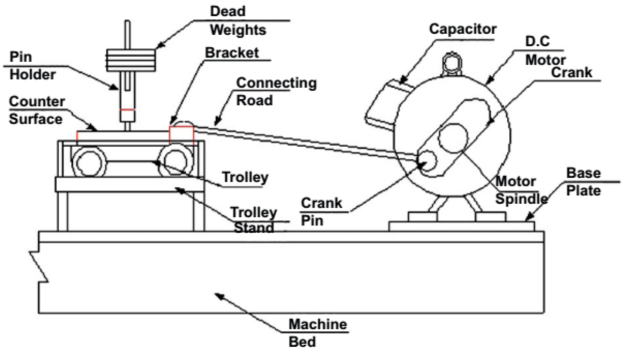

Fig. 1 Schematic diagram showing the front view of reciprocating wear test rig.

A pin-on-reciprocating plate tribometer was used to analyse the wear loss characteristics of Al 6061 alloy as per the ASTM G 133-05 standard. Fig. 1 shows the schematic representation of a pin-on-reciprocating tribometer. The Al 6061 pin specimen having a dimension of 6 mm diameter and 30 mm length was held on a reciprocating En31 hard steel counterface. Load on the pin was exerted by dead weights through lever arm. The plate attached on a trolley was reciprocated against the stationary pin through a slider crank mechanism. The stroke length of the plate was fixed at a length of 100mm. In order to identify the wear loss characteristics of Al 6061 alloy a single pan electronic weighing machine (Zhimadzu) with a least count of 0.1mg was used to measure the initial and final weight of the pin specimen. The difference in the weight of specimen before and after test was a measure of sliding wear loss [7].

C. Numerical Wear Model

A finite element technique was implemented in this work and developed a numerical wear model based on the Bayer exponential form in order to calculate the dry sliding wear loss characteristics of the Al 6061 alloy against En31 hard steel counterface. The commercially available software package MSC Marc/Mentat was used to develop numerical wear model. It was assumed that the deformation state was plane strain rather than three dimensional. This assumption helped in reducing the level of complexity in modelling.

D. Plan of experiments

In this study response surface methodology such as Box-Behnken design was adopted to analyze the effect of parameters as applied load (N), reciprocating velocity (m/s) and sliding distance (m) on the response wear loss characteristics of Al 6061 alloy sliding against En31 hard steel counter face. Being an independent quadratic design Box-Behnken design does not relate to any factorial designs. The peculiarity of the design is that the treatment combinations are located at the midpoint of edges of the process space. The other peculiarities of being rotatable and having statistical missing corners may be used by the experimenter to avoid the combined factor extremes. These properties prevent a potential data loss in those cases [8]. Table 3 shows the actual and coded independent variables. The sliding wear test results were subjected to the analysis of variance [9].

Table 3 Process parameters and their levels in terms of coded and actual values.

Factors	Units	Actual levels		
Coded levels		Low (-1)	Intermediate (0)	High (1)
A:Load	N	15	30	45
B:Reciprocating Velocity	m/s	0.4	0.5	0.6
C:Sliding Distance	m	300	400	500

III. RESULTS AND DISCUSSIONS

A. Wear Loss Characteristics

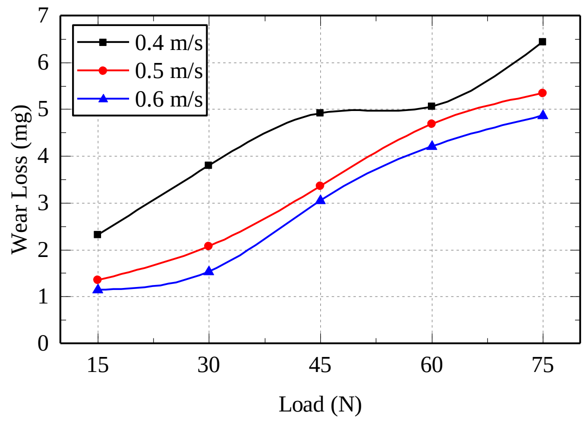

Fig.2 Wear loss characteristics of Al 6061 alloys as a function of load under a constant sliding distance of 300m.

A single variable approach wear study was conducted in order to analyze the wear loss characteristics of Al 6061 alloy.Fig.2 shows the wear loss characteristics of Al 6061 alloy as a function of load from 15 to 75 N under a constant sliding distance of 300m.It has been observed that the wear loss characteristics of Al 6061 alloy increases with increase of applied load irrespective of the reciprocating velocity. The increase of load causes an increase in sliding contact area and the excess of plastic deformation which promote the extent of wear debris formation leading to a high wear rate [10]. The plot also indicate that the wear loss decreases by the increase of reciprocating velocity in all load conditions. Increase in reciprocating velocity was attributed to the higher interfacial temperature which results an extent of oxidation of the Al 6061 alloy. The thicker glazed oxide layer will act as wear protective layer and thereby lower the wear rate [11].

B. Numerical Wear Model

Fig.3a shows the developed numerical wear model. The numerical model contain four different components such as pin, pin holder, reciprocating plate and plate support of a pin-on-reciprocating plate tribometer. Each component was separately modeled and finally assembled. The finite element mesh as shown in Fig.3a has 350 elements and 471 nodes. The pin and plate plane strain geometries were modeled with marc quad4 type 11 element. Element type 11 is a four-node, isoparametric, arbitrary quadrilateral written for plane strain applications. As this element uses bilinear interpolation functions, the strains tend to be constant throughout the element. The pin and plate contact bodies were derived from meshed deformable bodies, while the holder and support were modelled as rigid geometric bodies. Separate contact interactions are derived for the meshed, rigid and their combinations.

Fig.3 Initial numerical wear model a) initial geometry and mesh b) after global remeshing.

A contact table was derived for defining the number of potential contact pairs. In order to apply the translation and load on the pin, a control node was provided for the rigid pin holder. Fig. 3b shows the global remeshing criteria used to do the wear simulation. With automatic global remeshing, steps are taken to make sure contact conditions are preserved and incorrect penetrations are removed in the new mesh. This is achieved by correcting the nodal position after a new mesh is created. After the global remeshing the total element in the model has changed from 350 to 450.Mechanical wear was modelled by determining the stress on the surface and using it in a subsequent wear calculation.

$$\dot{w} = \frac{K}{H} * \sigma^m * f_{rel}^n \qquad (1)$$

Where $\dot{w}$, K, H, σ and $f_{rel.}$ are the rate of change of wear in the direction normal to the surface, wear coefficient, hardness of the pin, normal stress, relative reciprocating velocity respectively. The m and n indices are the stress and relative velocity exponents derived from the experimental data.

The wear was converted in to an incremental form. In the modified wear model normal stress was used instead of normal force for the calculation of wear as local quantity. The incremental wear calculation is performed at the nodal points that are in contact. The incremental wear is calculated as $\dot{w}\Delta t$. And the wear is accumulated as;

$$w_{n+1} = w_n + \dot{w}\Delta t \qquad (2)$$

The total accumulated wear can be interpreted as the distance a node would move due to wear and indicates a volume loss. The total volume loss due to wear is calculated per contact body. Surface fitting method was used to find the values of K, m and n by surface curve fitting method. The corresponding values of k, m and n are 2.229e-5, 0.7463 and -1.138 respectively. Table 4 shows the validation of the numerical wear model at different combinations of load, reciprocating velocity and sliding distance with experimentally obtained data. Fig.4 shows the wear loss characteristics of Al 6061 alloy in experimental and numerical wear model. It has been observed that the error percentage of wear loss at run order 1 and 10 was very high since the range of parameter was out of range. It revealed that the resulting values for the exponents are usually valid only within the range of the experiments [12].

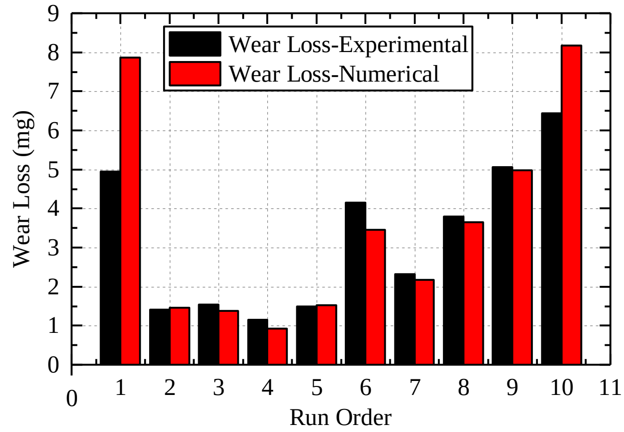

Fig.4 Experimental and numerical wear loss as a function of run order.

Table 4 Experimental and numerical wear loss characteristics of Al 6061 alloy

Run Order	Load	Reciprocating Velocity	Sliding Distance	Wear Loss	
	(N)	(m/s)	(m)	Experimental	Numerical
1	30	0.2	200	4.94	7.86
2	15	0.4	200	1.405	1.46
3	45	0.6	200	1.54	1.38
4	15	0.6	300	1.15	0.92
5	15	0.6	500	1.49	1.52
6	45	0.6	500	4.145	3.45
7	15	0.4	300	2.32	2.17
8	30	0.4	300	3.79	3.64
9	45	0.4	300	5.06	4.98
10	75	0.4	300	6.43	8.17

C. Statistical Analysis

The developed numerical model was used to investigate each array of the response surface methodology as shown in Table 5. The design has 13 rows and nine columns. The experiment consists of 13 tests (each row in the design arrays) and the columns 6 to 8 were assigned with actual value of parameters. The purpose of the statistical analysis of variance (ANOVA) was to investigate which parameter and their interactions are significantly affect the response wear loss characteristics of Al 6061 alloy, under the confidence level of 95%. Table 6 shows the summary statics of the design model and clearly indicate that the two factor interaction (2FI) model was the best suggested for the response wear loss characteristics with larger R^2 value of 0.9565. Table 7 shows

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Table 5 Experimental factors of a Box Behnken design for the response wear loss of Al 6061 alloy.

Run Order	Block	Coded Factors A:Load	Coded Factors B:Reciprocating velocity	Coded Factors C:Sliding Distance	Actual Factors A:Load (N)	Actual Factors B:Reciprocating velocity (m/s)	Actual Factors C:Sliding Distance (m)	Response Wear Loss(mg)
1	Block 1	-1	-1	0	15	0.4	400	2.887
2	Block 1	1	-1	0	45	0.4	400	6.547
3	Block 1	-1	1	0	15	0.6	400	1.219
4	Block 1	1	1	0	45	0.6	400	2.765
5	Block 1	-1	0	-1	15	0.5	300	1.349
6	Block 1	1	0	-1	45	0.5	300	3.059
7	Block 1	-1	0	1	15	0.5	500	2.244
8	Block 1	1	0	1	45	0.5	500	5.088
9	Block 1	0	-1	-1	30	0.4	300	3.637
10	Block 1	0	1	-1	30	0.6	300	1.532
11	Block 1	0	-1	1	30	0.4	500	6.035
12	Block 1	0	1	1	30	0.6	500	2.554
13	Block 1	0	0	0	30	0.5	400	3.01

the result of ANOVA analysis for the response wear loss characteristics of Al 6061 alloy. The "p-value" mentioned in the table 7 suggests the significance of model and interaction terms. Significant model terms are those having p-value less than 0.05 at 95% confidence level. The seventh column of the Table 7 shows the percentage of contribution, P (%), of each factor on the total variation indicating the degree of influence on the result It can be observed from the ANOVA Table 7, that the load, reciprocating velocity, sliding distance are the significant model terms influencing the response wear loss characteristics of Al 6061 alloy. Whereas the interaction between the load and reciprocating velocity have a significant influence on the response wear loss characteristics of Al 6061 alloy. It can be observed from Table 7 that the reciprocating velocity (P = 43.75%), normal load (P = 34.23%) and sliding distance (P = 14.45%) are the main controlling parameters for the response wear loss characteristics of Al 6061 alloy. The interaction model term between load and reciprocating velocity (P = 3.21%) had the significant influence on the response wear loss characteristics of Al 6061 alloy.

Table 6 Model summary statics of the response characteristics weight loss of Al 6061 alloy

Model	Std. Dev.	R^2	$R^2_{Adj.}$	$R^2_{Pred.}$	Remarks
Linear	0.54	0.9243	0.8991	0.834	
2FI	0.35	0.9565	0.9347	0.896	Suggested
Quadratic	0.17	0.9975	0.9901	N/A	

D. Multiple Linear Regression Model

An appropriate RSM model was generated by considering the correlation between the response wear loss and its parameters such as load, reciprocating velocity and sliding distance.

In terms of coded factors after removing the insignificant factors the final model of the response wear loss equation as follows.

$$Wear\ Loss = 3.23 + 1.22A - 1.38B + 0.79C - 0.53AB \pm \varepsilon \qquad (3)$$

In terms of actual factors after removing the insignificant factors the final model of the response wear loss equation as follows.

$$Wear\ Loss = -0.774 + 0.257A - 3.22515B + 0.0079C - 0.35234AB \pm \varepsilon \qquad (4)$$

Where A is the load (N), B is the reciprocating velocity (m/s) and C is the sliding distance (m). First, to check the reliability of the statistical analysis, the diagnostic graphs were used to analyze the data.

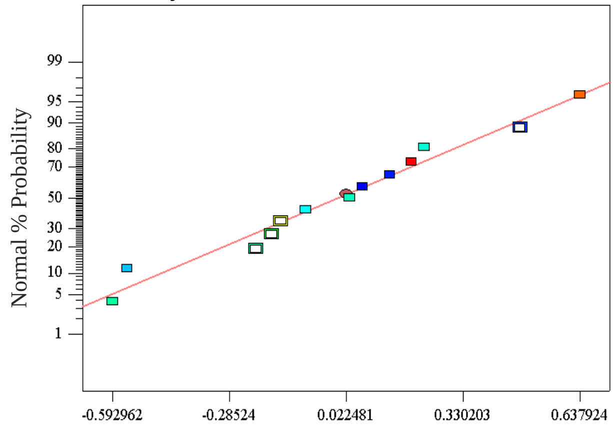

Fig.5 Normal probability plot of the effects for Box-Behnken design of the response weight loss.

Fig. 5 shows the normal probability plot in which the experimental points lay around the straight line, which indicates that the experimental points follow the normal distribution and fit the model. This graph can be taken as an indication that the experiments were well conducted and the results have no significant error [13]. Fig.6 shows the predicted values of the response wear loss characteristics

Table 7 ANOVA Table for a Box-Behnken response surface methodology for the response wear loss characteristics Al 6061alloy.

Source	Sum of Squares	DF	Mean Squares	F-Value	Probability (P-value)	% of Contribution	Remarks
Model	33.28	4	8.32	43.93	< 0.0001		significant
A-Load	11.91	1	11.91	62.89	< 0.0001	34.23	
B-Reciprocating velocity	15.23	1	15.23	80.39	< 0.0001	43.75	
C-Sliding Distance	5.03	1	5.03	26.55	0.0009	14.45	
AB	1.12	1	1.12	5.9	0.0413	3.21	
Residual	1.52	8	0.19				
Cor. Total	34.79	12					

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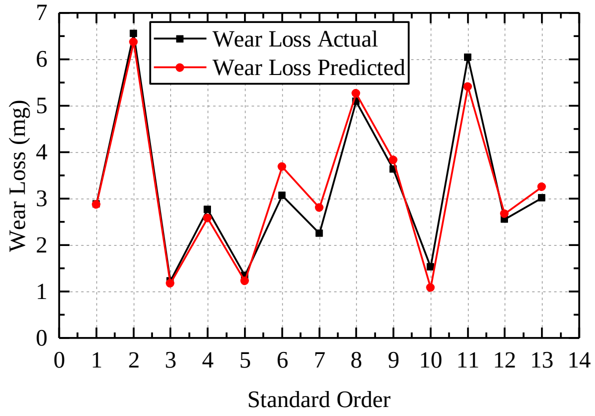

Fig.6 Actual vs. predicted values of the response wear loss.

from the multiple linear regression equation and the actual experimental values. The effect of each experimental parameters and its interactions on the response wear loss characteristics were revealed by means of effect plots as shown in Fig.7-8. Fig.7a shows the effect plot of wear loss

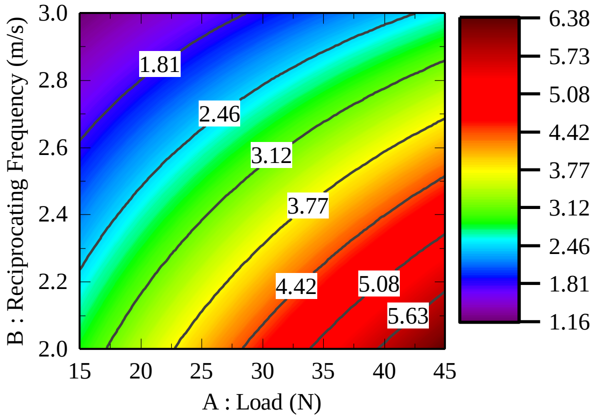

Fig.8 Interaction plot between load and reciprocating velocity, for the response characteristics wear loss of Al 6061 alloy.

These trend and observations agrees well with results reported by many researchers[9,14,18].Fig.8 shows the interaction plot between the load and reciprocating velocity. The interaction model term such as between load and reciprocating velocity significantly contribute to the response wear loss characteristics at confidence level of 95%.The

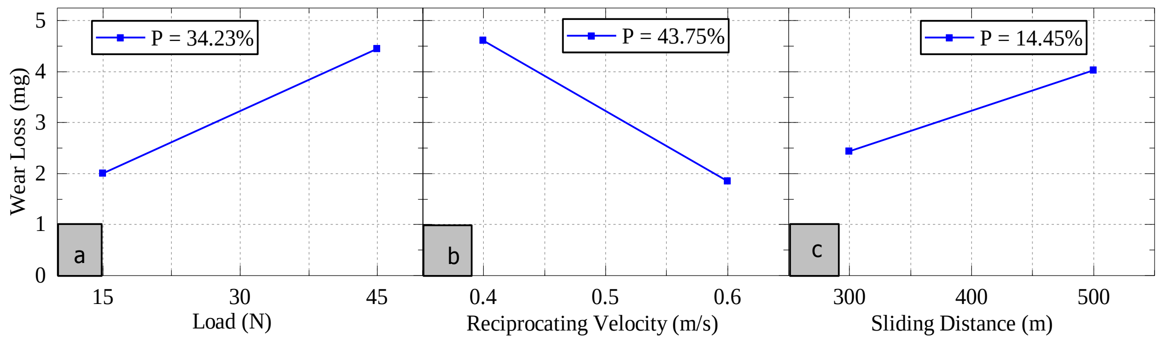

Fig.7 Main effects plots for the response characteristics wear loss of Al 6061 alloy (P-percentage of contribution).

with respect applied load.

The increasing trend of wear loss with the increase of applied load was due to the excessive plastic deformation of the asperities which cause the extent of wear debris formation leading to the higher wear rate. High plastic deformation of the worn surface due to the increase of load leads to localised heating which makes the alloy more ductile and consequently adhesive wear occurs [10,14,15].

Fig.7b shows the effect of reciprocating velocity on the response wear loss. A decreasing trend of wear loss with an increasing reciprocating velocity was observed. At higher reciprocating velocities, the interfacial temperature become very high which result an increased oxidation of the aluminium alloy. These results indicate the formation of thicker oxide layer known as tribolayer at the sliding interface which results a reduced wear rate. These trend and observation agrees well with results reported by many researchers [7,11,16,17].

Fig.7c shows the effect of sliding distance on the response wear loss. As sliding distance increase the wear loss found to be increasing and the same was attributed to the prolonged interaction between the asperity to asperity contacts under a steady state wear regime.

interaction model term between load and reciprocating velocity reveals that the reduced wear loss was obtained at

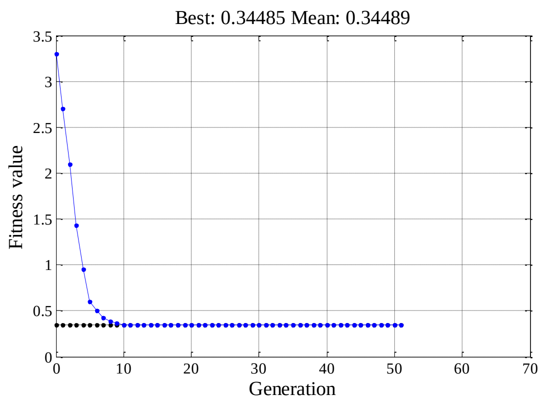

Fig.9 Fitness curve for population size of 50 for the response wear loss.

low levels of load and high levels of reciprocating velocity.

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These findings also pointed that the mild wear occurred within the range of parameters investigated.

E. Optimization for the Response Wear Loss Characteristics

In order to find the optimum sliding condition that leads to the minimum wear loss the so far discussed mathematical model was combined with a developed Genetic Algorithm. Genetic algorithm (GA) is a very powerful and versatile technique, motivated by the principles of genetic and natural selection. It is a combination of Charles Darwin's principle of 'natural selection' and 'survival of the fittest' with computer constructed evolution mechanism to select better offspring from the parent population.

Table 8 GA parameters

Subject	Values
Population size	50
Crossover rate	1
Mutation rate	0.1
Number of generations	70

Then the information is exchanged randomly among parents, expecting a superior offspring [19].The design was generated and analyzed using MATLAB statistical package. Generally, genetic algorithm uses selection, crossover and mutation operation to generate the offspring of the existing population. The significant parameters in GA are the population size, cross over rate, mutation rate, number of generations etc. and their values are given in Table 8.Fig.9 shows the fitness evolution over this period. The response wear loss of Al 6061 alloy was 1.15 and 0.92 for the experimental and Numerical value respectively which was further optimized into a value of 0.345 by the GA under the optimized sliding condition of load 15N, reciprocating velocity 0.6m/s and sliding distance of 300m.

IV. CONCLUSION

In this study a numerical wear model has been developed and the influence of factors and there interactions on the response wear loss characteristics of Al 6061 alloy sliding against hard En 31 steel counterface have been investigated. The developed numerical wear model validated with the experimental data. The proposed numerical wear model was demonstrated in the analysis of Box-Behnken design of the response surface methodology. It can be observed that the reciprocating velocity (P = 43.75%), normal load (P = 34.23%) and sliding distance (P = 14.45%) are the main controlling parameters for the response wear loss characteristics of Al 6061 alloy. The interaction model term between load and reciprocating velocity (P = 3.21%) had the significant influence on the response wear loss characteristics of Al 6061 alloy. An optimized sliding condition was identified by the GA as a load of 15N, reciprocating velocity 0.6m/s and sliding distance of 300m.

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