Reciprocating Wear of a A390 Aluminium Alloy Under Varying Stroke Length: A Statistical Analysis to Deduce the Factor Contribution

Harish T V, V R Rajeev

Abstract: ***Stroke length is one of the significant factors contributing wear loss in bidirectional sliding condition. Most of the research works on reciprocating sliding reported increase in wear loss with stroke length. However, in all these studies the reciprocating frequency was constant for the set of stroke lengths studied. Experimental proof needed whether increase in wear is due to increase in stroke alone. Statistical analysis on wear data can reveal the relative contribution of each of the factors individually and in combination. Present work reports the reciprocating wear study of A390 alloy on an in house developed tribometer with reciprocating sliding motion. The average relative velocity of sliding, distance slid and duration of test kept constant in the first set of experiments. Three stroke lengths of 50 mm, 100 mm and 150 mm was attempted. Normal loads tried were 15 N, 30 N, 45 N, 60 N and 75 N. Experiments repeated for average relative sliding velocities of 0.2 m/s, 0.3 m/s and 0.4 m/s. Wear test conducted under a constant load of 45 N, average sliding speed of 0.4 m/s for three sliding distances of 400m, 800m and 1200m. Statistical analysis then performed on the wear data to obtain factor contribution on wear loss. The results proved that wear loss does not increase with stroke length alone.***

Index Terms: ***average velocity, frequency, reciprocating wear, sliding distance, statistical analysis, stroke length.***

I. INTRODUCTION

Engineering applications like engines, reciprocating pumps, linear motion guide-ways of machine tools etc have material pairs with relative sliding motion. Sliding causes friction and material loss by wear. Wear-loss between the sliding pairs determines their safe working life. Therefore, it is utmost importance to have a thorough understanding of parameters and their ranges on wear loss. Operating wear parameters are normal load, sliding speed, distance slid, temperature, surface finish and type of contact. Stroke length is another operating factor if the relative motion is reciprocating [1]. Reciprocating sliding contact results in higher wear rate than unidirectional sliding and one of the phenomenons experimentally identified was Bauchinger effect [2]. It was reported [3] that, wear rate varied with position of contact along the stroke length. Maximum wear under dry reciprocating sliding condition in that experiments occurred at the extremities of the stroke length. Hence, adduced that wear rate had direct correlation with deceleration and stroke length instead of sliding velocity. Definition of tribological properties is complete only if it relies on a systems concept. Illustration of tribological testing covering topics from specimen preparation, tribometers, test parameters, measurement of wear and friction are available in [1, 4, 5]. The authors could not find literature on systems approach to reciprocating wear study but combination of one or two factors. Investigators [6, 7] have experimentally proved that wear loss increases with average speed under reciprocating sliding condition. Higher velocity demands more acceleration, which in turn raises the energy dissipated per cycle. Most of frictional energy converted to heat that eroded material strength and increased wear. In [8], it was experimentally established that, wear loss decreased with speed initially and after a particular speed, it increased. Strain rate and heat buildup were the reasons indentified. Strain rate increased with sliding speed raising the hardness or flow strength. This resulted in a lower wear rate since the true area of contact also reduced. As speed increased further, frictional temperature got larger lead to softening the materials. True area of contact increased due to softening that resulted in higher wear rate. Strain rate was more predominant than the temperature up to a critical sliding speed, above which the temperature effect dominated. By experiments [9, 10], it was demonstrated that wear loss increased with sliding distance. In [11], explained the two-stage variation of wear with sliding distance for steel. Initially wear was severe due to insufficient frictional temperature for oxide formation. As time / distance of sliding progressed, frictional temperature increased causing accelerated production of oxides. Oxides that sheared easily acted as solid lubricant, which reduced wear rate. With increased sliding distance, wear increased due to higher frictional temperature. For Al - 12 % wt Si alloy, the wear rate and coefficient of friction increased with sliding distance [12]. Reasons explained where, softening of mating materials due escalation in frictional heating with sliding distance. There was rise in wear rate with sliding distance for a steel pin [13]. The increased deposit of pin material on the counter surface with time caused increased wear rate [13]. Wear rate variation with stroke length had be previously investigated by several researchers. At smaller stroke lengths, oxidative wear mechanism responsible for wear [14]. The sequence of wear was (1) fresh surface roughness spoiled by the plastic deformation of asperities (2) initial adhesion and mechanical

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wear (3) abrasive and oxidative wear at higher stroke lengths. In [15], higher stroke length resulted in larger wear particles and increased content of counterface material in debris. Reduced debris buildup on the counterface resulting in earlier abrasion of the steel specimens at higher stroke length was the reason. Lesser number of stress reversals per unit sliding distance at larger stroke length resulted in reduction in inclined cracks at larger stroke length. Increase in stroke length did not produce an increase in the wear volume at every time but depended on wear mechanism [16]. For smaller stroke lengths wear particles were oxides and smaller in diameter due oxidation mechanism. At larger stroke length, metallic wear mechanism dominated that produced larger wear particles. Energy dissipated per cycle multiplied with stroke length that resulted in escalated wear volume [17]. This energy estimated by taking the product of frictional force and stroke length. In fretting, [18], as stroke length increased there was transformation of wear regimes from partial slip to mixed fretting and then to gross slip under a given contact load. As per [19] wear mechanism changed to a combination of oxidation and delamination wear from local adhesive damage giving an increased the coefficient of friction (CoF) and wear volume with stroke length. Wear mode changed from stick to gross slip as stroke length increased [20].

The wear rate as per Archard equation [21,22] is:

$$V = \frac{KPD}{3H} \tag{1}$$

$$K = \frac{3VH}{PS} \tag{2}$$

Where, 'V' volume of material lost, 'P' is the normal load, 'S' is the total sliding distance and 'H' is the lower hardness of the materials pair and 'K' the wear coefficient. In most of the equations 'S' replaced by sliding velocity and wear loss expressed in per unit sliding distance. If, in reciprocating wear tests, frequency of reciprocation and test duration is a constant, then increasing stroke length the wear will increase. This is because of the sliding distance increased with stroke length at constant frequencyAs per the (1), wear should increase with normal load. Raising load (2 - 65 N) increases wear of an Al-Si alloy [23]. At lower loads smooth surfaces obtained due to abrasion of asperities by hard particles producing fine debris. As load increased, the wear debris grew larger. At higher loads, gross plastic flow mechanism produced debris of large flakes. The formation of surface craters with increased loads was the deciding factor of wear mechanism. Delamination was the major mechanism identified. Load and sliding distance together affected wear more [12]. Wear, as a system concept requires establishment of relationships between parameters. In the reciprocating wear, stroke length is an important parameter.Most of the research works on reciprocating sliding reported show increase in wear loss with stroke length. However, in all these studies the reciprocating frequency was constant for the set of stroke lengths in each study. It is worth noting that, sliding distance and relative velocity increased with stroke length when frequency of sliding was a constant. Increase of wear loss with increase in sliding distance is a proven phenomenon. Statistical analysis on wear data can reveal the relative contribution of each of the factors individually and in combination. The authors as a part of their reciprocating wear studies of aluminium alloys conducted wear studies of A390 alloy at average sliding speeds of 0.2 - 0.4 m/s, stroke lengths 50 - 150 mm, normal loads 15 - 75 N and total sliding distances 400 - 1200m. The results analyzed statistically to identify the relative significance of each factor on the wear loss. It was found that stroke length is dominant factor if factors are load, speed and stroke length for a fixed sliding distance. If stroke length and sliding distance varied then sliding distance dominated.

II. EXPERIMENTAL SETUP

A. *Fabricated Reciprocating Tribometer*

In house fabricated pin-on-plate reciprocating tribometer Fig. 1 used in this study. A drill chuck (1) of 12 mm capacity (here after called specimen holder) was used to hold the specimen in the form of pin of diameter 6 mm and length 30 mm. The counter surface (2) was EN 32 steel plate of 10 mm thickness fixed on top of trolley (5). The specimen holder fixed on the loading arm (3). The loading arm hinged on a point (14) and was able to swing about the pillar (15) to transmit the frictional force. The lateral frictional force transferred to the load cells by stopper pins (13) on both sides of the loading arm. Counter weights (4) of required quantity attached to free end of the loading arm to balance loading arm. The drive for the tribometer was an AC motor (ABB make, model M2BA 112 M-6) (9). The rotational speed controlled by a VFD drive (ABB make, model ACS550-01-05A4-4) (10). Crank disc (11) used to convert rotary motion to reciprocating motion. Motion transmitted to the trolley (5) through a connecting rod (12). The stroke length of reciprocation of trolley was equal to diameter of the point on which connecting rod end fixed on the disc. The trolley movement on the tabletop (8) guided by a projection on the table (7). The load hanger was loaded with desired weight (6). The normal load acting on the pin arrived considering advantage. When the motor powered, the crank disc rotated at the set RPM and the trolley reciprocated for the set stroke length and average velocity. The whole setup mounted on top of a lathe bed to arrest vibration. Test specimen, in the cylindrical shaped pin of 6 mm diameter, fixed in the specimen holder. As the trolley moved, the pin slid on the counter surface on trolley top.

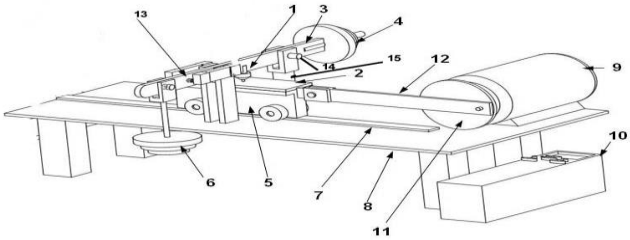

Figure 1: Schematic diagram of the reciprocating tribometer

B. *Wear Testing*

The wear test specimen (6 mm diameter and 30 mm long) was the machined from A390 aluminium alloy castings by Electric Discharge Machining (EDM). The alloy had the following composition.

Table 1: alloy composition

Element	Al	Cu	Mg	Si	Zn	Others
Wt %	77.40	5.00	0.90	18.0	0.50	rest

Initially specimens thoroughly cleaned by using acetone and dried. Weight of specimens measured using a Shimadzu Micro-analytical Balance having 5 digits accuracy for a gram. Subsequently specimens mounted on the specimen holder. Normal load applied by placing weights on hanger considering the advantage. When the motor powered, specimen pin slid over the counter surface, sliding continued for specific period to achieve the desired sliding distance at the desired average sliding speed. Once the sliding distance achieved, the motor stopped, test specimens removed, cleaned with acetone, dried and weighed again to record the wear loss (weight loss). The process repeated for all the runs. The parameters varied were stroke length, velocity and normal load. A set of experiments performed at constant load of 45 N (being the centre value of the range 15 - 75 N) and at constant speed of 0.4 m/s for studying the effect of variation in sliding distance. The test parameter ranges fixed based on the consideration expressed in [24] and is given the Tables 2 and 3. The test parameters and results summarized in Tables. 4, 5, 6 and 7.

Table 2 : Parameter values for the first set of experiments

Parameter	Unit	Values
Normal load	N	15, 30, 45, 60 & 75
Avg. velocity	m/s	0.2, 0.3 & 0.4
Stroke lengths	mm	50, 100 & 150
Sliding distance	m	400

Table 3 : Parameter values for the second set of experiments

Parameter	Unit	Values
Normal load	N	45
Avg. velocity	m/s	0.4
Stroke lengths	mm	50, 100 & 150
Sliding distance	m	400, 800 & 1200

Table 4: Wear loss at average speed of 0.2 m/s and 400 m sliding distance

Normal load in N	Wear loss in gram at stroke length of		
	50 mm	100 mm	150 mm
15	0.00435	0.00478	0.00337
30	0.00643	0.00593	0.00386
45	0.00727	0.00631	0.00398
60	0.00801	0.00669	0.00478
75	0.00955	0.00715	0.00484
Frequency	2.00 Hz	1.00 Hz	0.67 Hz

Table 5: Wear loss at average speed of 0.3 m/s and 400 ,m sliding distance

Normal load in N	Wear loss in gram at stroke length of		
	50 mm	100 mm	150 mm
15	0.00505	0.00461	0.00282
30	0.00556	0.00492	0.00351
45	0.00612	0.00535	0.00462
60	0.00652	0.00561	0.00494
75	0.00669	0.00572	0.00536
Frequency	3.00 Hz	1.50 Hz	1.00 Hz

Table 6: Wear loss at average speed of 0.4 m/s and 400 m sliding distance

Normal load in N	Wear loss in gram at stroke length of		
	50 mm	100 mm	150 mm
15	0.00420	0.00320	0.00350
30	0.00636	0.00378	0.00367
45	0.00846	0.00483	0.00436
60	0.00903	0.00565	0.00496
75	0.00968	0.00584	0.00548
Frequency	4.00 Hz	2.00 Hz	1.33 Hz

Table 7: Wear loss at average speed of 0.4 m/s and normal load of 45 N

Total sliding distance in m	Wear loss in gram at stroke length of		
	50 mm	100 mm	150 mm
400	0.00846	0.00483	0.00436
800	0.01444	0.00704	0.00781
1200	0.02076	0.01359	0.01250
Frequency	4.00 Hz	2.00 Hz	1.33 Hz

III. RESULTS AND DISCUSSION

Tables 4, 5, 6 and 7 show the wear loss at different values of wear parameters. Analysis of Variance (ANOVA) is best suited to understand the interactions and dominance of various factors on wear [25]. Understanding the two-factor interaction effects and individual factors was the aim of the analysis. The interval plots made to see the significant variation at any particular value of parameters.For the first set of tests, three variables selected and were stroke length, load, and average velocity. The Fig. 2 gives details of this. In this, wear loss decreases with stroke length and increases with normal load. The interaction plot in Fig. 3 shows the wear loss decreases with increase in stroke length but increases with normal load. Fig. 4 presents the decreases of wear loss with increases in stroke and speed.Reduction in wear loss with increasing stroke length and velocity could be due to the reduced number of stress reversals per unit sliding distance at larger stroke length as reasoned in [15]. The Fig. 6 substantiates this. It is an interval plot of wear at 95% confidence interval for the mean wear at different frequencies (range represents the variation due to load and stroke length). Frequency estimated by dividing average velocity by twice the stroke length. Higher speeds reduced the depth of wear damage due to frictional heating [28]. This reduces the wear at higher speeds.

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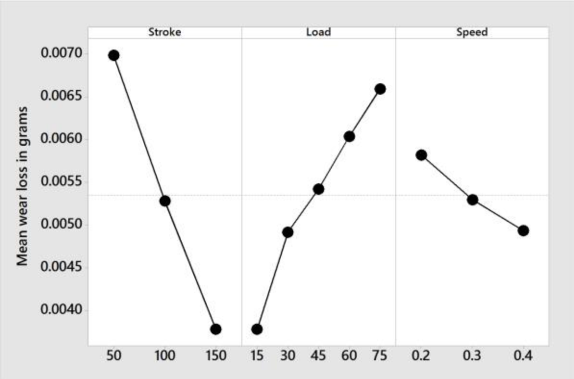

Figure 2: Main effects plot of the first set of experiments (400 m)

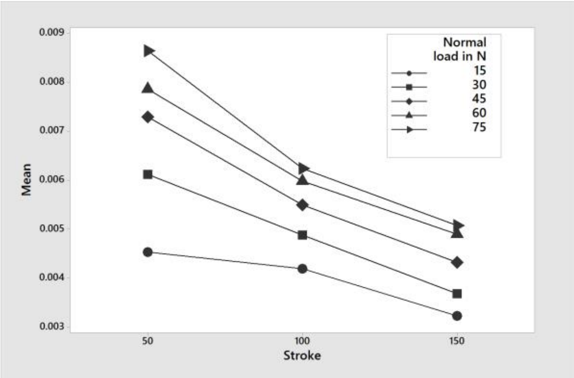

Figure 3: Interaction plots from the mean of wear at 0.2, 0.3 & 0.4 m/s average sliding speed and sliding distance of (400 m)

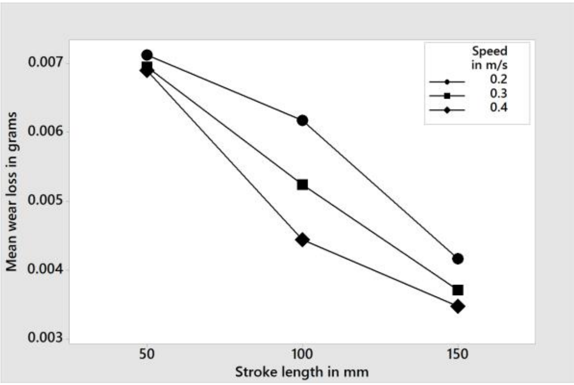

Figure 4: Interaction plots from the mean of wear at normal loads 15 - 75 N and sliding distance of (400 m)

As the stroke, length decreased for a constant speed the frequency of reciprocation increased. The strain-hardening rate was higher at higher frequencies that increased the wear loss. At 4 Hertz (50 mm stroke length) of reciprocating frequency, the wear loss was higher. At lower loads and higher frequencies, the vibration might have separated the contact surfaces and thus lowered interaction. At higher loads, contact was more conformal and caused more wear. At lower frequencies, the reversals reduced hence, the lower wear at low frequencies.

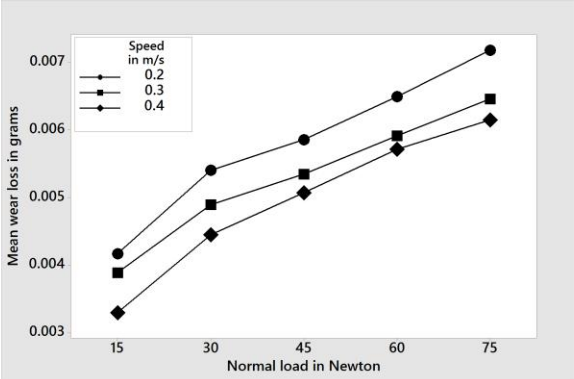

Figure 5: Interaction plots from the mean of wear at stroke lengths 50, 100 and 150 mm and sliding distance of (400 m)

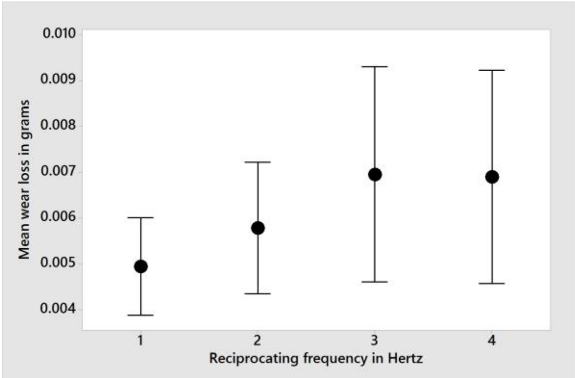

Figure 6: Interval plot from the mean of wear at 0.2,0.3 & 0.4 m/s average sliding speed, 50mm, 100mm and 150mm stroke length and sliding distance of (400 m) and at 95% confidence interval

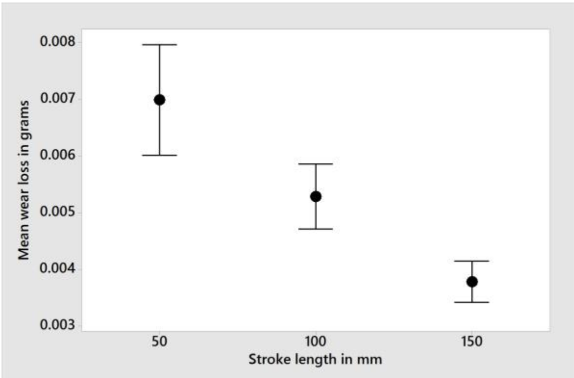

Figure 7: Interval plot from the mean of wear at 0.2,0.3 & 0.4 m/s average sliding speed and loads 15 - 75 N and a sliding distance of (400 m) and at 95% confidence interval

The comparison of speed and load as in Fig. 5 establishes that, compared to speed, load contributes more to wear loss and at higher loads, the variability was more due the combination of load velocity. The reasons could be same as in [8]. At lower speeds strain rate causes hardening hence wear loss variation due to load only. At higher speeds, frictional temperature softens materials hence the wear loss due to combined effect of load and velocity. Fig. 8 shows interaction effect of speed and wear. This confirms the explanation in [8] on the effect of speed

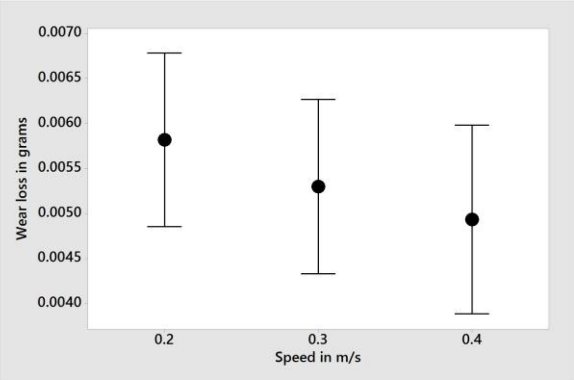

Figure 8: Interval plot from the mean of wear at 50 mm, 100 mm and 150 mm stroke length and 15 - 75 N and a sliding distance of (400 m) and at 95% confidence interval

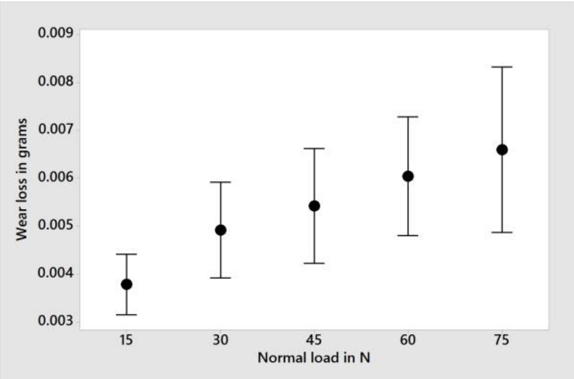

Figure 9: Interval plot from the mean of wear at 50 mm, 100 mm and 150 mm stroke length and speeds 0.2 , 0.3, 0.4 m/s and a sliding distance of (400 m) and at 95% confidence interval

At higher frequency of reciprocation contact area reduces due to the forced disengagement of contact surfaces by vibration. Some other reasons given in the paper were due to the instantaneous reduction of operative normal force. This is due to (i) superposition of static and dynamic force generated during vibration, (ii) reversal of the friction vector, (iii) local transformation of vibration energy into heat energy and (iv) reciprocating frequency nearing to resonance frequency [26]. Modal frequency of frictional contact could change due to change in contact condition [27]. Effect of vibration on wear loss in the present experiments is as in Fig. 7. The range of variation in wear rate was higher at 50 mm stroke length. This could be due to increased reciprocating frequencies at lower stroke lengths. The highest frequency of 4 Hz would have been nearer to the natural frequency of the structure. The Fig. 9 shows lower variation of wear at lower loads. This might have due reduction in conformal contacts resulting in reduced effect of vibration or stroke length. The contact became more conformal at higher loads. Hence, the significance of frequency and stroke length on wear dominated at higher loads. Separate set of experiments conducted to understand the effect of sliding distances and stroke length (Table. 7) on wear loss. Here load and average sliding velocity kept constant at 45 N and 0.4 m/s respectively. Obeying the Archard equation (1) and (2) wear increased with distance. Fig. 10 shows that, sliding distance is dominant that stroke length with speed and load are constant. Fig. 11 gives the indication frequency effect on wear with distance

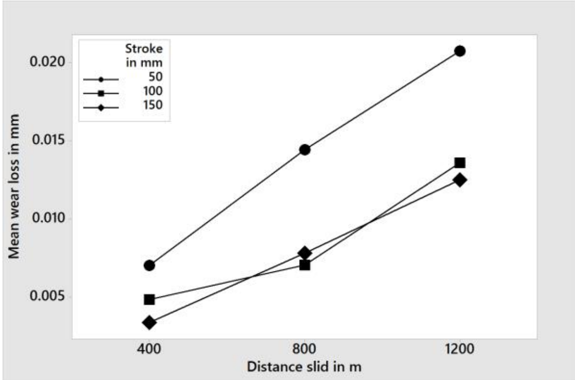

Figure 10: Wear loss at different sliding distances at 45 N normal load and a average velocity of 0.4 m/s

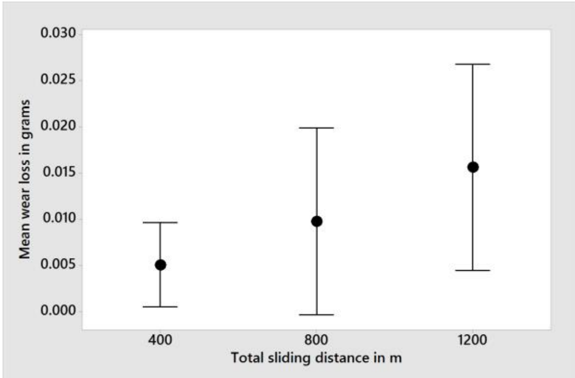

Figure 11: Interval plot from the mean of wear at 400 m , 800 m and 1200 m of sliding distances and normal load of 45 N at 95% confidence interval

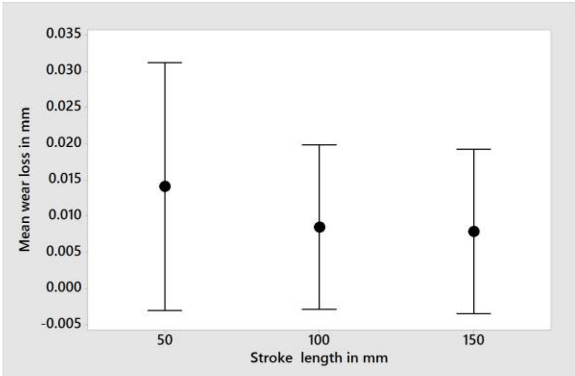

Figure 12: : Plot of 95% Confidence Interval of Stroke length (mean of wear at sliding distance 400 m, 800 m ,1200 m, normal load of 45 N and average sliding velocity of 0.4 m/s)

At shorter distance 400 m, though the frequency of reciprocation was 4.00 Hz, 2 Hz and 1.33 Hz for the three stroke length, the variation was not large as compared to 800 m and 1200 m and may be due to the less strain hardening [8] lower stress reversals [15] and lower temperature caused lesser oxidation[14]. As the sliding distance increased, the difference of wear loss increased due to increased difference of strain hardening rate, stress reversals, temperature buildup between the stroke lengths. Fig. 12 reveals how stroke length can induce the variation. At smaller stroke length difference of wear loss caused due to difference of strain hardening rate, stress reversals, temperature buildup at different sliding distance is larger. When sliding distance increase, the incremental effect of these parameters diminishes and sliding distance becomes a dominating factor.

Table 8: Analysis of Variance for Wear for First set of data

Source	DF	SS	MS	F	F (α=0.01)
Speed	2	5.91E-06	2.96E-06	82.1	6.23
Stroke	2	7.72E-05	3.86E-05	1,072.0	6.23
Load	4	4.20E-05	1.05E-05	291.7	4.77
Speed* Stroke	4	2.98E-06	7.44E-07	20.7	4.77
Speed* Load	8	2.44E-07	3.10E-08	0.9	3.89
Stroke *Load	8	1.26E-05	1.57E-06	43.7	3.89
Error	16	5.81E-07	3.60E-08	1.0	
Total	44	1.41E-04			
S = 0.000190523 R-Sq = 99.59% R-Sq(adj) = 98.87%					

Table 9: Analysis of Variance for Wear for Second set of data

Source	DF	SS	MS	F	F (α=0.01)
Stroke	4	1.03E-04	2.57E-05	17.1	7.00
Distance	2	1.88E-04	9.42E-05	62.9	8.65
Error	8	1.20E-05	1.50E-06		
Total	14	3.03E-04			
S = 0.00122394 R-Sq = 96.05% R-Sq(adj) = 93.08%					

The analysis of variance performed on the two sets of data. The critical value for F statistics fixed for a significance level of 0.01. Table. 8 shows the variances for first set. Since F value for stroke is the most significant factor causing wear. The other ranks are load, speed, interaction of stroke & load, and speed & stroke in the descending order. Interaction effect of speed is not significant and neglected. Table. 9 shows the variances for second set. F value for distance was higher than stroke hence is the most significant factor causing wear when distance and stroke length was changed. Interaction effect stroke-distance was negligible hence not considered.

IV. CONCLUSIONS

Experiments conducted and results analyzed statistically to evaluate the dominance and interaction of various parameters on reciprocating wear. The conclusions of the research are as follows.

1. The load is major factor affecting the wear loss for all stroke length and velocities considered. This is due to the direct relationship of contact area with normal load.

2. The wear loss reduces as velocity of reciprocation increases for the velocity range considered (0.2 m/s to 0.4 m/s). Depth of matrix softening due to frictional heating reduces with speed [28].

3. The sliding distance increases wear loss. For smaller stroke length, higher velocity or frequency needed to achieve the same distance and speed. This promotes the synergistic effect of load and velocity, which creates higher wear loss.

4. The differential effect of stroke length on wear loss diminishes as sliding distance increase since variation induced due to stroke length may have reached saturation as distance exceeded 800 m.

5. Variance analysis reveals the relative dominance of stroke length in the considered range of stroke length, speed and load for a constant sliding distance. When sliding distance was 400 m, frictional heat produced varied with stroke length. When stroke length increases to 800 m and above the accumulated heat energy was higher and hence the change in wear loss induced by sliding distance variation got dominance over stroke length.

As an extension of this work with more factorial experiments needed, that varies stroke length and other parameters simultaneously. That can bring out the relative dominance of distance with other parameters.

V. ACKNOWLEDGMENT

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