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Investigating The Lubricated Sliding Wear Behaviour of Aluminium Matrix Composite Produced by Stir – Squeeze Cast Process

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Abstract

This investigation makes an attempt to assess the lubricated sliding wear behavior of aluminum matrix composite reinforced with varied weight percent of fly ash particulates as reinforcement using Dimensional Analysis. Through this analytical modeling, the input parameters & the process outcome are linked through an expression so that the wear behavior of the composite under lubrication can be predicted without conducting actual trials for any arbitrary values of the inputs. The produced base metal & composite specimen were subjected to lubricated sliding wear test & were compared with the theoretical wear values generated through analytical modeling using dimensional analysis and the regression equation obtained by Minitab -17 statistical tool to justify the validity of the models. Further validation trials were carried out for the intermediate process variable values and the results of validation trials were justified through R- Tool program.

Keywords: Stir – squeeze cast composite, lubricated Sliding wear, Dimensional Analysis, Mathematical modeling, Minitab analysis, R-tool program

1. Introduction

From the last fifty years, the MMCs have gained premier importance with respect to their processing, characterization and wear analysis to make them more suitable for specific applications. In this regard, dry & lubricated sliding wear response of Metal Matrix Composites (MMCs) and their associated modeling concepts got originated globally by considering different factors (process parameters) and their respective levels. MMCs were produced with various types of particle reinforcements (particle size, shape and volume fraction) and by using fibers and whiskers (size, length and orientation) to achieve homogeneity and directional properties respectively. High performance aerospace structures depend on selection of material, primary fabrication and secondary post-operative processes, cost analysis, modeling and process parameter optimization [1]. Increased market acceptance of MMC's basically depends on their processing, characterization, properties, modeling as well as applications [2]. Corrosive environments demand new MMC's for cold forging tools and for high temperature wear applications [3]. Due to the existence of mechanistic differences in asperity interaction, investigations took a significant importance with respect to the sub-surface structural evolution; the wear studies of aluminum based composites were more inclined towards dry sliding compared to lubricated sliding. Relatively few investigations were recorded pertaining to the sliding wear response of aluminum matrix composites under lubricated situation, especially, to assess the tribo-contact environment with respect to the sub-surface microstructure [4].

The systems like engines, simple bearings are characterized by ultralow wear rates due to modern lubricating system. The lubricant applied depends on the type, chemical and physical nature of the sliding surfaces and of major importance in the investigation. The application of lubricant at the interface reduces the initial metallic contact, drastic reduction in friction by absorbing heat & there by reducing the wear rate. The importance of interface temperature in lubricated sliding was also investigated by using different oils. Under sever conditions of loading; oil film between surfaces reduces friction and wear, similar to hydrodynamic lubrication. Exponential rise in viscosity of the lubricant with elastic deformation and pressure of contact surfaces, giving rise to the elastohydrodynamic lubrication were the chief fact findings of these investigations. However, there was a minor study on the impact of the parameters such as temperature, viscosity, contact pressure, type of lubricant pertaining to practical applications such as mining industry steel industry [5].

All the above investigations were inclined on the assessment of mechanical properties and sliding wear response through various configurations and using lubricating oils. Once again, no investigations were seen to model the lubricated wear behavior or mechanical properties.

Some investigators carried out research to compare the tribological properties of the composite under dry and lubricating situations.

2124 aluminum alloy reinforced with 25 vol.% SiC, produced by powder metallurgy method was investigated for its friction and wear behavior against AISI 1050 steel using block-on-ring setup at temperature range of 25 – 200^{o}C, for varying loads at constant sliding velocity of 2 ms^{-}1. For dry condition at 100°C, both wear rate and wear mechanism showed the transition. It was also observed that, below 100^{o}C, higher wear rate with mild abrasive mechanism in nature was observed with aged specimen of both matrix and composite material than that of non-aged specimen of them. However, both the composite and base material non-aged specimen exhibited severe adhesive mechanism with greater wear rate compared to aged specimen above 100°C. The lower wear rates were recorded under lubricated situation compared with dry condition at room temperature [6].

Mechanically alloyed aluminium-base materials reinforced with 5% vol. of titanium and 5% vol. of aluminum nitride, processed through powder-metallurgy method, was investigated for its friction and wear behavior using pin-on-disk tribometer. Dry wear conditions disclosed its dependency on volume loss measurement whereas usage of track-width method yielded regular wear tracks under lubrication for better accuracy. In general, composites showed higher hardness and greater wear resistance in comparison with matrix material typically at higher load. Base material at a load of 4.90 N under lubricated situation exhibited the wear mechanism transition from mild severe [7].

Above investigations dealt with the sliding wear behavior and wear mechanisms of the composite in both dry and wet mode, but no attempts were observed in promoting modeling aspect for the same.

Similar to modeling approaches of sliding wear of aluminum matrix composites under dry condition, attempts were also made to build simple models to assess the sliding wear behavior of aluminum matrix composites under lubricated situation. Hani Aziz Ameen et al. investigated the lubricated wear rate of both ferrous and nonferrous materials under the impact of sliding speed of about 2.5 to 9 m/sec, time range of about 5-30 minutes and load range of about 0.5 to 2 kg using pin on disc setup. The three different models were developed using least square method to predict adhesive wear rate by varying time factor, sliding speed and loads [8]. In addition to this, wear mechanisms responsible for the damaged surfaces were also discussed. The results also indicated that all three input parameters were directly proportional with the wear rate and the ferrous material exhibited less wear rate in comparison with nonferrous materials.

M. A. Maleque et al. explored an approach of empirical model of wear and friction for the experimental results from palm oil methyl ester (POME) added lubricant to contribute to the understanding of wear and friction process under boundary lubricating condition [9]. In order to develop an empirical model for a general wear and friction equation of ball-plate configuration under 5% POME added lubricant, the specific wear rate against temperature, sliding distance and running time was statistically analyzed using MATLAB and an initial regression equations were obtained. From the fact findings it was concluded that there was least significance of sliding distance and time on the wear of the mating surfaces. The friction equation showed that influence of temperature on the friction coefficient compared to other two variables was greater. It was reasonable to assume that wear and friction of mating materials up to a certain level were mostly controlled by boundary film of the POME even at higher temperature.

Lubricated sliding wear behaviour of AL-25ZN-2CU alloys considering two process variables with three levels were investigated using SAE 20W/40 oil at the rate of 1.5cm^3/hr on the revolving disc. 2-Factor Interaction approach and Archards method were used to carry out both linear as well as nonlinear regression analysis [10]. Experimental results concluded that the contribution of sliding distance was about 79.32% and applied load was about 14.76% on the wear. However, wear rate was found to be virtually independent of sliding speed whose calculated % contribution was just 2.124%.

In the above investigations, it was observed that there were considerable attempts to model the lubricated wear behaviour of the aluminium matrix composite using, least squares method, MATLAB, 2-Factor Interaction approach and Archards method.

In this regard, the present investigation aims at modeling and evaluating the lubricated sliding behaviour of Aluminium Matrix Composite produced by Stir – Squeeze cast technique by making use of Dimensional Analysis, MINITAB – 17 statistical package & R-tool.

2. Materials & Methods

2.1 Fabrication of Composite

20T hydraulic squeeze press was used to fabricate the Al – fly ash composites by melting the LM-25 ingots of about 3 kgs in a graphite crucible inside the three-phase electrical resistance furnace to a temperature of 800^0 C. Preheated (600°C) fly ash particles were added gently along with preheated magnesium pieces to improve the wettability after degassing in 2.5, 5 & 7.5 wt. % respectively. Further, the composite mixture was poured with into the graphite paste coated, cylindrical die cavity of the hydraulic squeeze press with the help of ladle to achieve densification by descending punch. Squeeze pressure of 50 kg/cm^2 was applied for 15 minutes. The melt got solidified in the mould and the casting was allowed to cool gradually to arrive at room temperature [11]. The table 1 provides information about the various process variables and their levels for regular trials & table 2 provides intermediate values for validation trials.

Factors	Unit	Level 1	Level 2	Level 3
Sliding Velocity	m/s	0.9423	1.88	2.8274
Sliding Distance	km	1	2	3
Load	Newton	4.5	9.8	14.7

Table 1: Input parameters and corresponding levels for sliding wear studies

Factors	Unit	Level 1	Level 2
Sliding Velocity	m/s	1.41	2.354
Sliding Distance	km	1.5	2.5
Load	Newton	7.15	12.25

Table 2 **:** Process variables with their values & levels for validation trials

2.2 Theoretical model for Lubricated sliding wear behavior of Aluminum matrix composites using Dimensional Analysis

The following seven parameters were considered.

$\Delta w = f(L, V, D, H, \rho, \gamma)$

Δw – Amount of wear kg
L- Applied load in N (kg-m / s^2)
V- Sliding velocity in m / s
D – Sliding distance in m
H- Hardness of the material in kg / m – s^2
ρ – Density in kg / m^3
γ – Kinematic viscosity of the lubricating oil in m^2 / s
V – Kinematic property
D- Geometrical property
ρ – Fluid property

Hence ρ, V and D are repeating variables & the basic dimensions considered were M, L & T

Total number of parameters 'n' = 7 & Total number of basic dimensions = 'm' = 3
Therefore total number of Π terms = 'n – m' = 7 – 3 = 4 terms

$\Pi_1 = (\rho^{a1}, V^{b1}, D^{c1}, \Delta w)$
$\Pi_2 = (\rho^{a2}, V^{b2}, D^{c2}, L)$
$\Pi_3 = (\rho^{a3}, V^{b3}, D^{c3}, H)$
$\Pi_4 = (\rho^{a4}, V^{b4}, D^{c4}, \gamma)$

Then, solving for $\Pi_1, \Pi_2, \Pi_3, \Pi_4$ by applying basic M, L & T dimensions, we have

$\Pi_1 = \rho^{-1} V^{0} D^{-3} \Delta w \Rightarrow \mathbf{\Pi_1 = [\Delta w / (\rho^* D^3)]}$ **Eq - 1**

$\Pi_2 = \rho^{-1} V^{-2} D^{-2} L \Rightarrow \mathbf{\Pi_2 = [L / (\rho^* V^2 D^2)]}$ **Eq - 2**

$\Pi_3 = \rho^{-1} V^{-2} D^{0} H \Rightarrow \mathbf{\Pi_3 = [H / (\rho^* V^2)]}$ **Eq - 3**

$\Pi_4 = \rho^{0} V^{-1} D^{-1} \gamma \Rightarrow \mathbf{\Pi_4 = [\gamma / (V^* D)]}$ **Eq – 4**

Then formation of new Π term involve

$\Pi_{1(new)} = \phi\, (\Pi_2 * \Pi_3 * \Pi_4)$

$\Rightarrow [\Delta w / (\rho^* D^3)] = \phi [L / (\rho^* V^2 D^2)] * [H / (\rho^* V^2)] * [(\gamma / (V^* D)]$

$\Rightarrow [\Delta w / (\rho^* D^3)] = \phi\, [(L^* H * \gamma) / (\rho^2 * V^5 D^3)]$

$\Delta w = \phi\, [(L^* H^* \gamma * \rho^* D^3) / (\rho^2 * V^5 D^3)]$

$\mathbf{\Delta w = \phi\, [(L^* H^* \gamma) / (\rho * V^5)]}$ **Eq - 5**

Checking for dimensional homogeneity

$M = \phi\, [(MLT^{-2} * ML^{-1}T^{-2} * L^2 T^{-1}) / (ML^{-3} * L^5 T^{-5})]$

$M = \phi\, [M^2 L^3 L^{-1} T^{-5}) / ML^{-3} L^5 T^{-5})]$

$M = \phi [(M^2 L^2 T^{-5}) / (M L^2 T^{-5})]$

$\mathbf{M = \phi\, M \Rightarrow \phi = 1}$

2.3 Lubricated sliding wear studies

From the fabricated composites, cylindrical test specimen (8-10 mm diameter and 30 mm length) were prepared. The prime process variables and the output of the process were identified to frame the design of experiments. Experiments were designed considering Taguchi's full factorial method which comprises L27 orthogonal array. The process outcome was wear in term of kilogram.

Lubricated sliding wear studies were carried out using lubricated sliding wear test rig as shown in Fig.1 (Ducom instruments). Wear disc was cleaned thoroughly with solvent and clamped on to the holder using four screws. The specimen pins were thoroughly cleaned to remove burs form the circumference using emery paper. The specimen pin was inserted inside the hardened jaws and tightened using specimen holder. Height of the specimen pin above the wear disc was adjusted using height adjustment block where the adjusting block ensures the loading arm is always parallel. Then frictional force and wear displays were set to zero and timer & speed of the disc were set with the required values. Lubrication oil supply was switched on. SAE 20 W 50 lubricant was used which is very widely used in industries for commercial purposes and the constant flow rate of 75 ml / min was maintained throughout.

Fig 2 represents the test specimen thoroughly immersed in the lubricated oil. Kinematic viscosity of the lubricant 20 W 50 used was158.5 mm^2/s. Once the tester was switched on, the monitor starts recording the online graph. At the end of the experiment, sample was removed from the instrument and thoroughly cleaned with the dry cloth. Then hexane was sprayed over the sample and again thoroughly cleaned with another dry cloth and the procedure was repeated for two or three times to remove the oil from the sample completely to record the weight loss of the sample. The trials were repeated for all Taguchi's factorial conditions and the results were tabulated. The procedure was repeated for four different types of composites having 0%, 2.5%, 5% and 7.5% fly ash reinforcement for comparison purpose with the dry sliding wear studies and finally the results were tabulated.

Fig 1: Lubricated wear test rig

Fig 2: Experimental setup for lubricated sliding wear studies

2.4 Density & Hardness tests

By considering radius 'r' of the circular face and height 'h' of the specimen, volume of the fabricated composites and base metal were calculated by using the mathematical formula$V = \pi r^2 h$. Mass of the specimen was noted down using an accurate electronic balance. Finally densities were calculated by dividing mass by volume (gm / cm^3). The density was found inversely proportional to percentage reinforcement of fly ash.

Cylindrical test specimen of 20 mm length and 15 mm diameter as per the ASTM standard were subjected to in order to Brinell hardness tests to assess the significance of reinforcement on the base metal hardness. A steel ball indenter of 10 mm diameter was used to apply the load of 500 kg. BHN was found directly proportional to percentage reinforcement of fly ash.

Both of these results were used successfully in analytical modeling using dimensional analysis

2.5 Modeling studies

i) For regular trials, one analytical (Dimensional analysis) & one empirical model (Minitab – 17 analysis) were attempted

ii) R – tool Program was used to model validation trials.

3. Results & Discussion

3.1Results of lubricated sliding wear studies

The fig.3 depicts graphical representation of lubricated sliding wear studies for base metal LM-25 and the three different composites with varying percentage of fly ash into aluminum matrix. It is evident from the excel chart that introducing the lubricant at the pin – disc interface drastically reduces the amount of heat and friction thereby decreasing the wear rate. Hence lowest wear with the highest % reinforcement was recorded. Considering an example of 27th experimental condition, where all three parameters are high, it was observed that lubricated situation decreases wear about 95 % for base metal and different composites. Similarly when the 18th trial was taken as an example, again it was found that around 95% reduction of wear rate from dry to lubricated situation for all types of specimen [12]. Hence it is well proven that use of lubricant is preferred choice in automobiles where wear, heat and frictional aspects can be regulated very well.

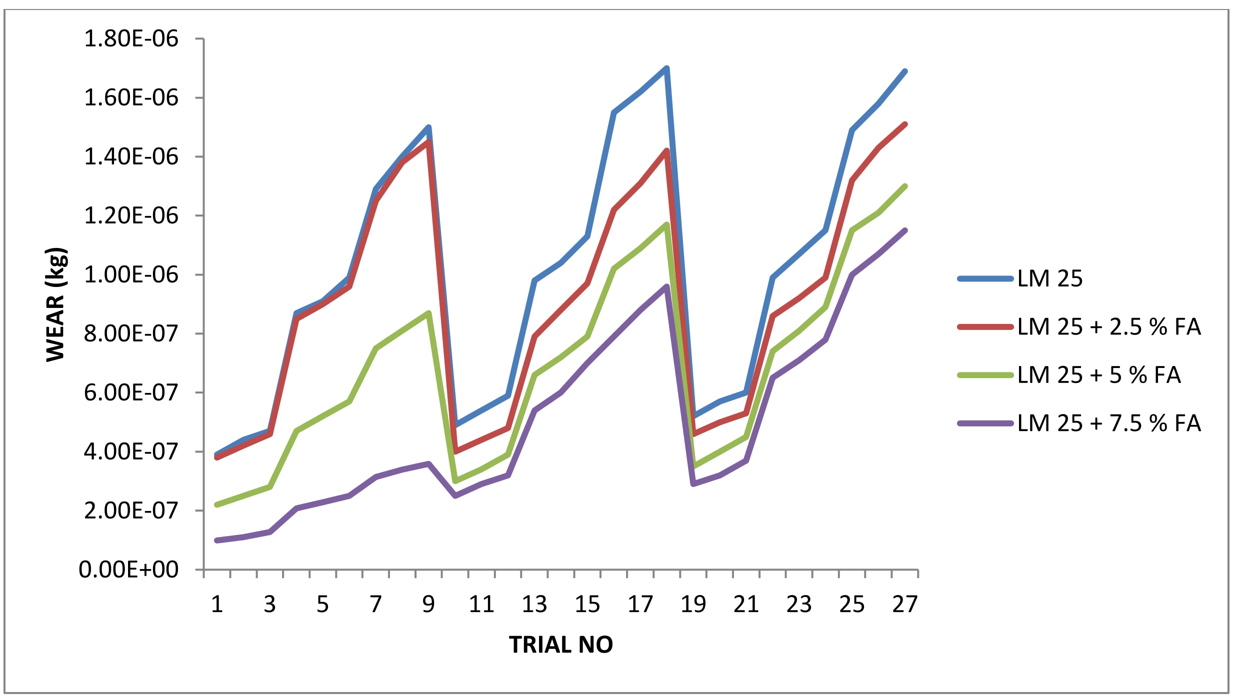


Fig 3: Graphical representation of lubricated sliding wear behavior of base metal & three different composites for full factorial trials

3.2 Results of lubricated sliding wear test for confirmation trials

Confirmation experiments were carried out to verify the repeatability, precision and accuracy of the sliding wear results under lubricated condition for all four materials for the intermediate values of process variables. Similar trends were observed when compared with the regular trials. The 7.5% fly ash reinforced composite recorded lowest wear compared to base metal and other two composites with 2.5% and 5 % fly ash content respectively. This is reflected in fig 4.

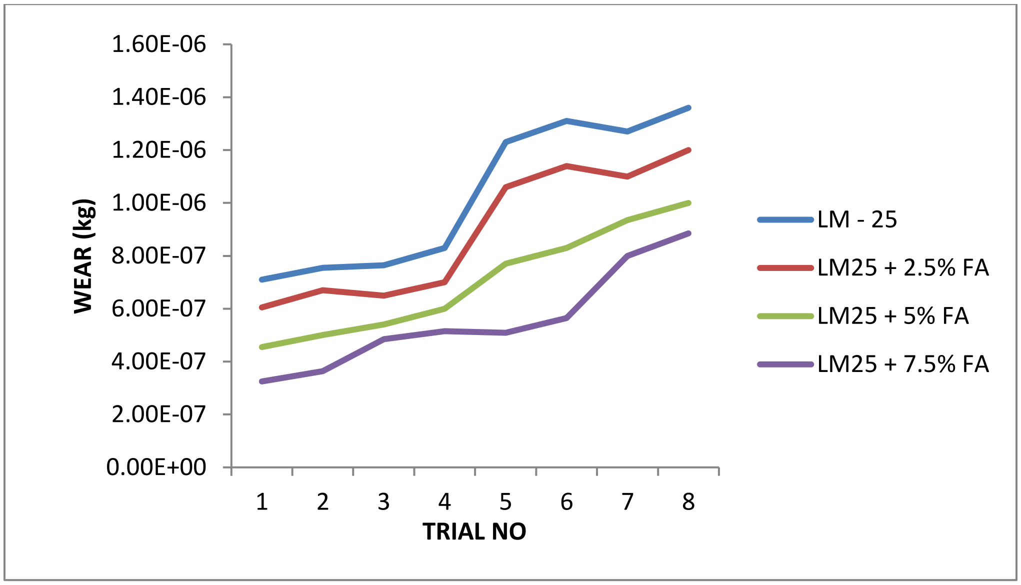


Fig 4: Graphical representation of lubricated sliding wear behavior of base metal & three different composites for confirmation trials

3.3 Results of Dimensional Analysis for lubricated sliding wear studies

Using the expression 5 of the section 2.2, the dimensional constant 'ϕ' value for all twenty seven full factorial trials were calculated for all four materials under lubricated situation. A common'ϕ' value was estimated for a fixed speed & specific sliding distance and load range combination. This common 'ϕ' value was then used to estimate wear values theoretically and compared with experimental wear to calculate the percentage error. It was found that the constant 'ϕ' – value was directly proportional to sliding velocity & percentage reinforcement of the composite whereas inversely proportional to wear rate.

Figures 4 – 7 exhibit results of dimensional analysis for base metal LM – 25 and three composites with 2.5, 5 & 7.5 wt. % fly ash reinforcement produced by stir – squeeze cast method under lubricated sliding situation. Error analysis was carried out using the formula

% Error = [(Actual wear – Theoretical wear) / Actual wear] * 100

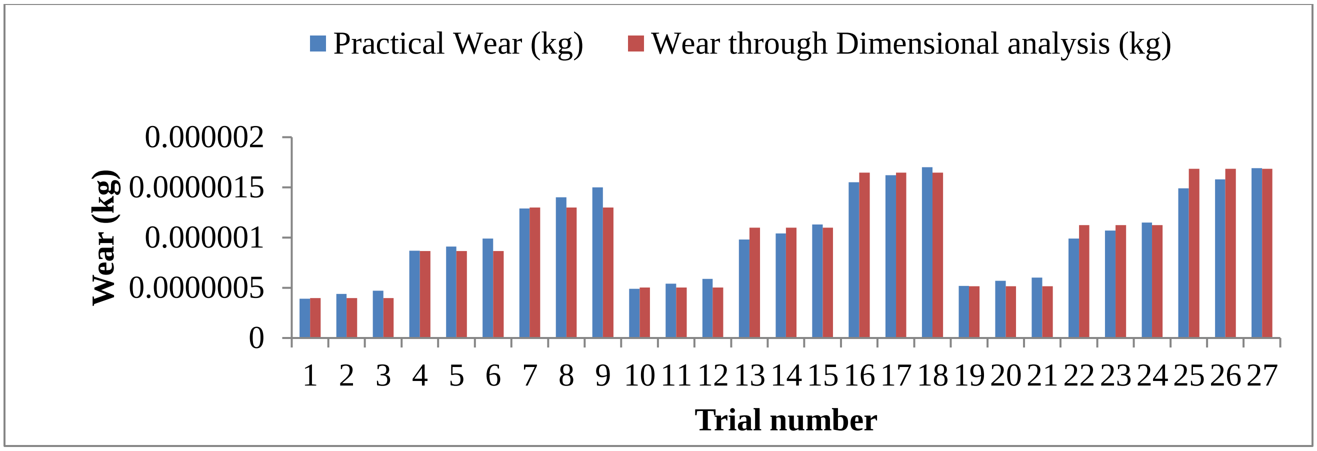


Fig 4: Bar chart for dimensional analysis of base metal LM-25 under lubricated sliding

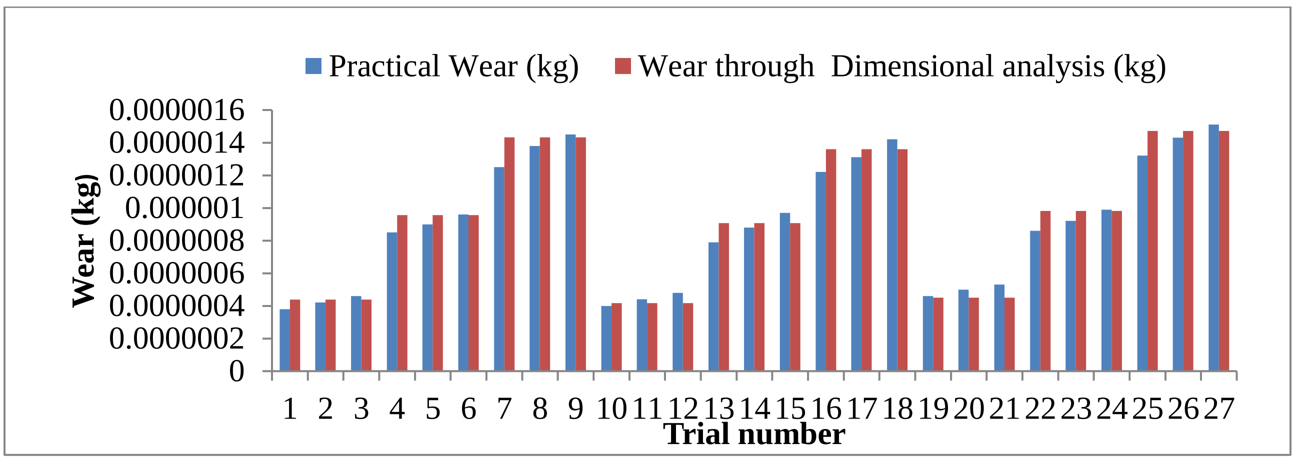


Fig 5: Bar chart for Dimensional analysis of aluminum matrix composite with 2.5 % fly ash under lubricated sliding

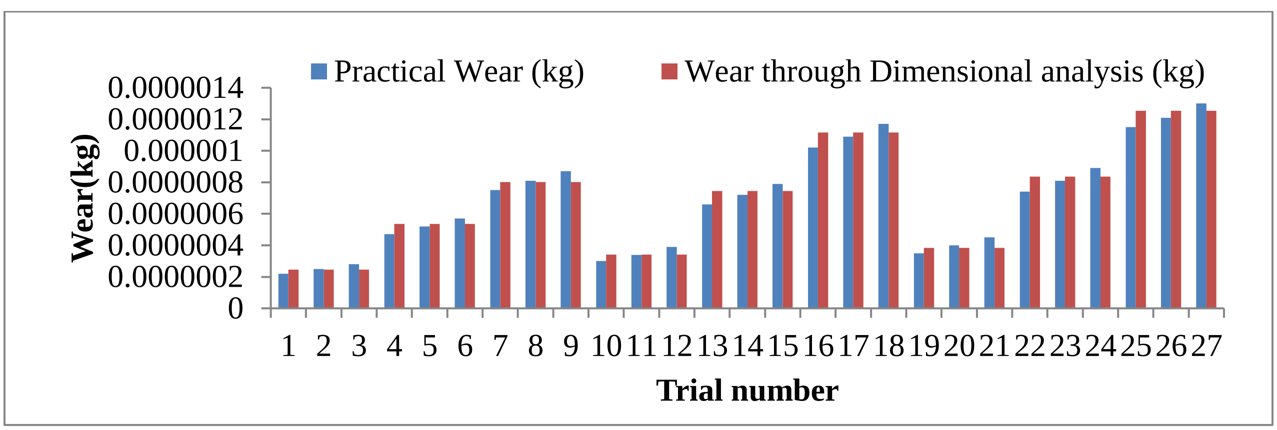


Fig 6 Bar chart for Dimensional analysis of aluminum matrix composite with 5 % fly ash under lubricated sliding

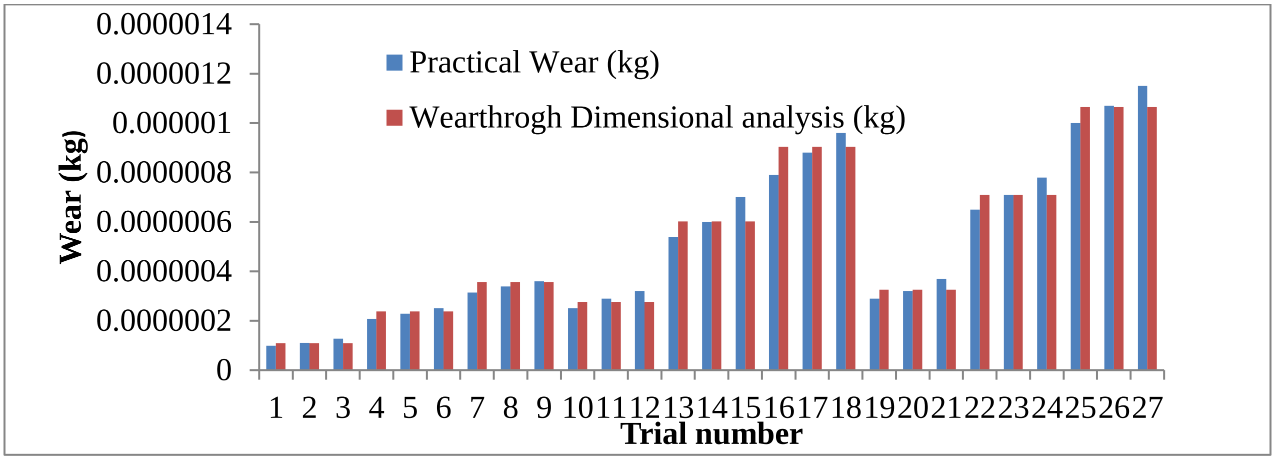


Fig 7. Bar chart for Dimensional analysis of aluminum matrix composite with 7.5 % fly ash under lubricated sliding

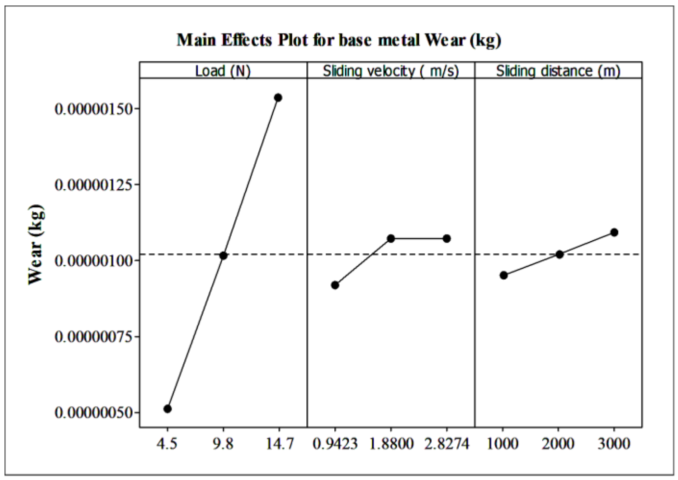
The inherent problem of MMC's is to justify the uniform distribution of reinforcement phase. The bar charts clearly indicate that the deviations are well within -15 to +15 %. Hence validity of the model is justified.

3.4 Results of Minitab Analysis

Figures 8a -8d and 9a – 9d represent main effect plots and interaction plots for overall lubricated sliding wear behavior of the base metal and composites (2.5, 5 & 7.5 % fly ash content) respectively. The main effect plots exhibit complete spread of the process. The steeper slope for the load parameter indicates its greater effect on the wear output. For sliding velocity parameter, base metal LM - 25 exhibits narrow spread zone between from 0.9423 to 1.88 m/s and remains parallel from 1.88 – 2.8274 m/s zone. The slope drops from 0.9423 to 1.88 m/s zone and show an ascending trend from 1.88 – 2.8274 m/s zone for 2.5 % fly ash composite. This is basically due the application of the lubricant at the interface which absorbs friction and dissipates the heat generated between the sliding pair. A very thin lubrication film is maintained at the interface and this reduces the physical contact between the sliding pair. Hence the plot remains parallel. There after the slope finds more inclination for the other two composites due to the increased load which presses the pin against the disc more firmly. This gives rise more area of contact and hence pressure increases. The sliding distance show the similar minimum inclination for all four materials because, applied lubricant not only absorb heat and friction also take out the minute chips of material removed from the pin. Hence wear will be minimal with the increased time factor since application of lubricant is continuous.

In interaction plots, base metal LM – 25 exhibits almost merging of lines between sliding velocity from zone 1.88 to 2.8274 m/s zone and sliding distance. Hence there could be very little interaction effect between them over the wear output. Except this all other lines remain parallel indicating no interaction effect of parameters over the output. The composite with 2.5 % fly ash reinforcement, shows all three

lines being merged to represent very little crossover so that there can be minimum interaction between the sliding velocity and sliding distance. The composite with 5 % fly ash reinforcement show all parallel lines indicating clearly no interaction effects between input parameters over output. Composite with 7.5 % fly ash reinforcement shows very slight convergence at 0.9423 to 1.88 m/s zone with the applied load. This signifies very little interaction effect among sliding velocity and the load on the output.
The reason for minimum slope in main effects plot and very little interaction in interaction plots was due to the application of the lubricant, the wear drastically get reduced by 95 % compared with dry sliding situation for similar operating conditions [12].



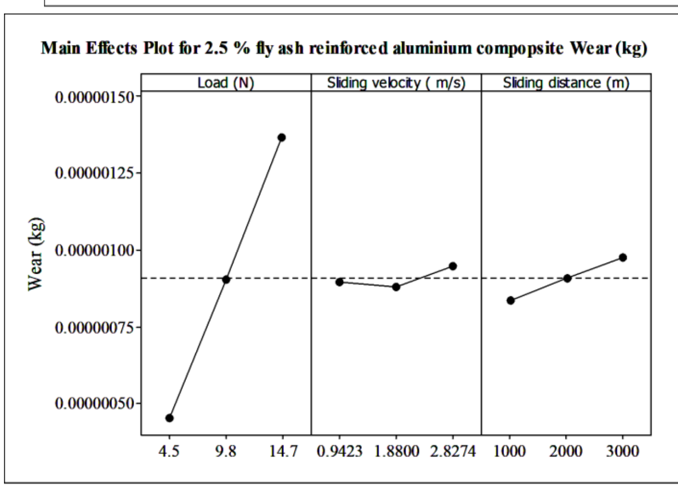
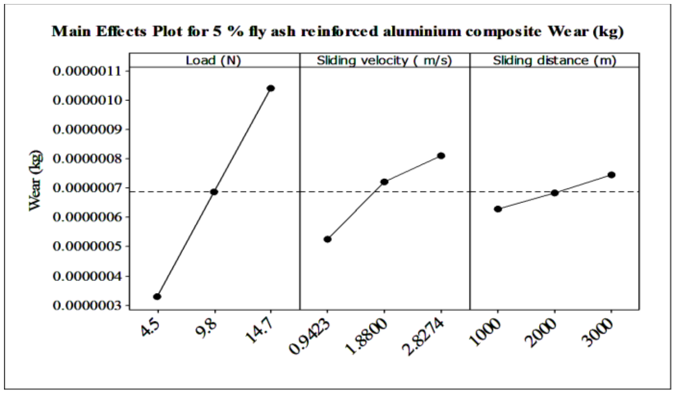


Fig 8a

Fig 8b



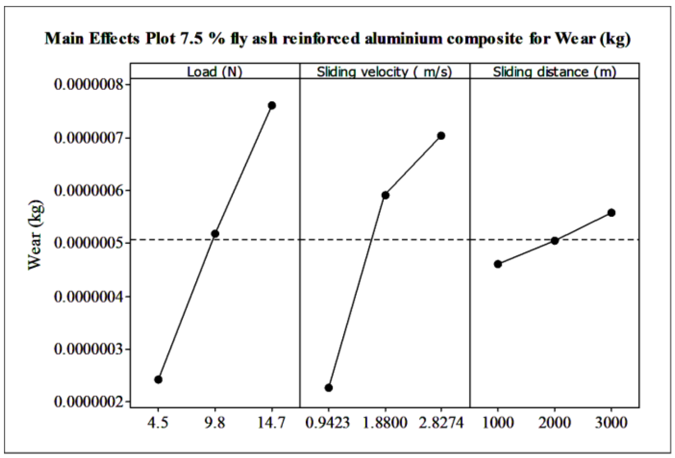
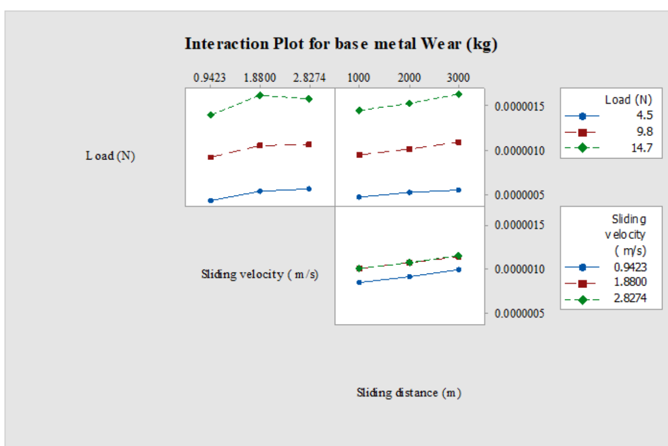


Fig 8c

Fig 8d

Fig 8 a-d: Main effects plots of base metal and three different composites



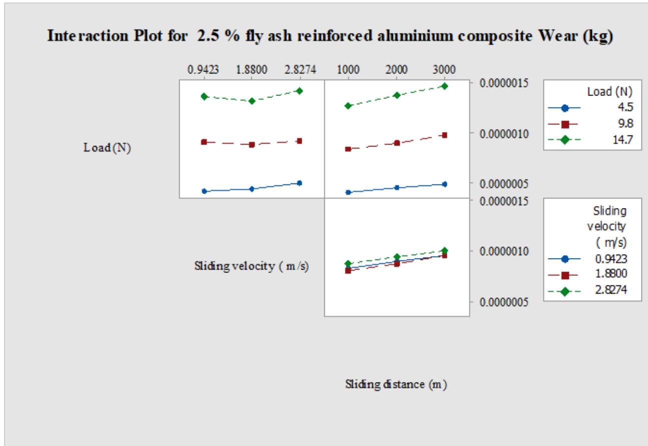
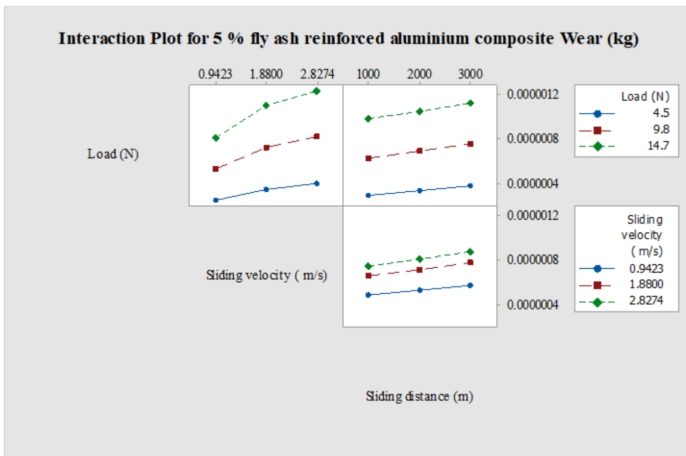


Fig 9a

Fig 9b



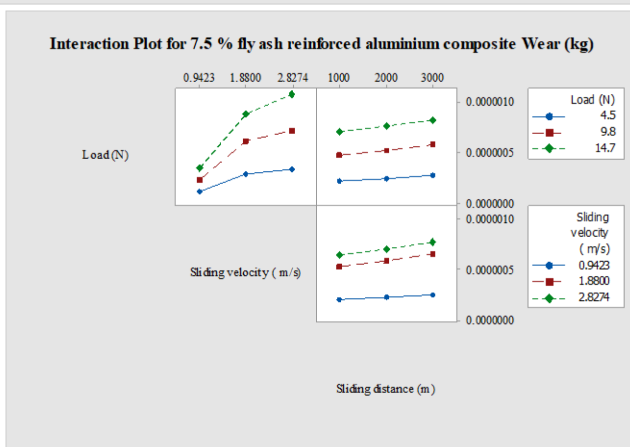


Fig 9c

Fig 9d

Fig 9 a-d: Interaction effects plots of base metal and three different composites

3.5 Results of R – tool program for validation trials

The R- tool program was executed to generate regression equations used to estimate the theoretical wear of four materials in lubricated condition and the same were compared with experimental results. Finally percentage of error was calculated to assess the efficiency of the model and found varying between -8% to +8%. These results are represented in figures 10 – 13

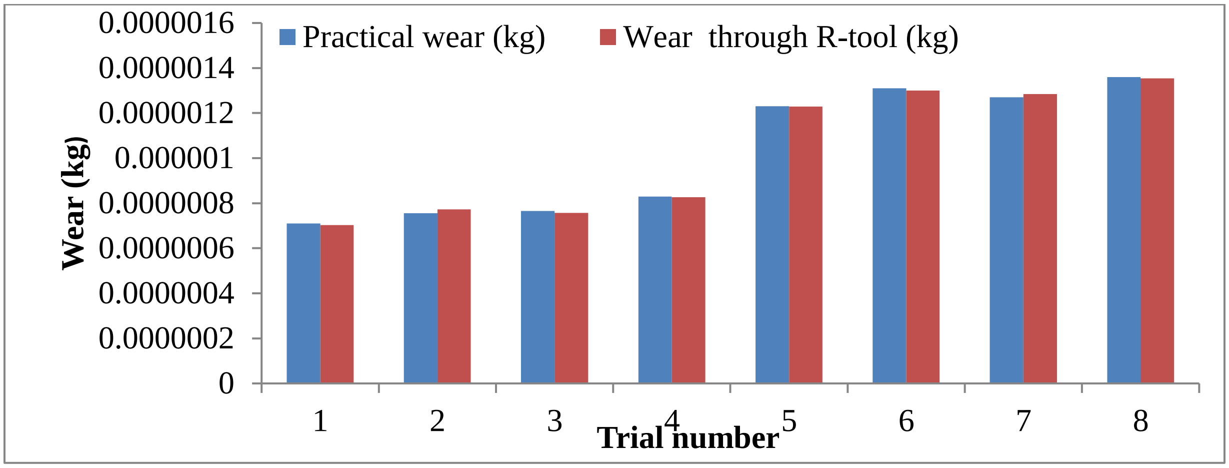


Fig 10: R-Tool regression analysis for base metal LM-25 under lubricated sliding

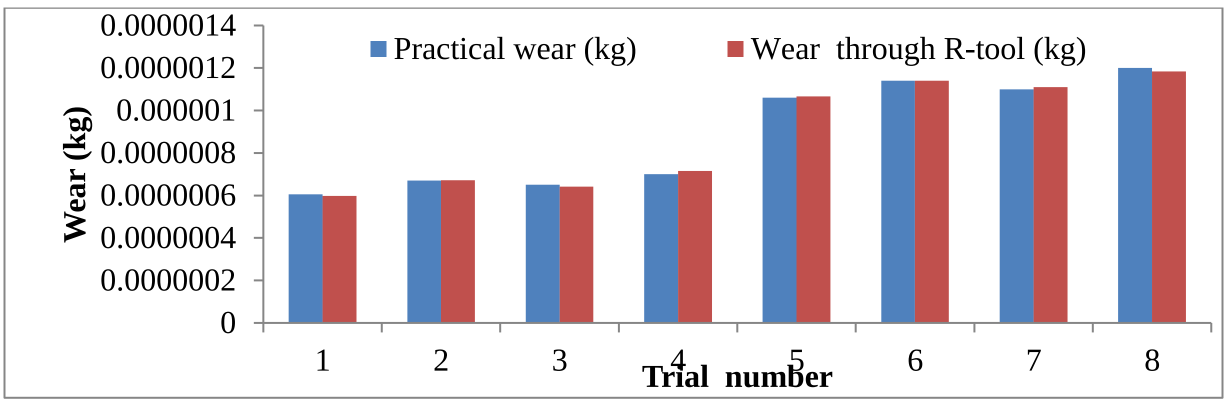


Fig 11: R- tool regression analysis for aluminum matrix composite under lubricated sliding with 2.5 % fly ash reinforcement

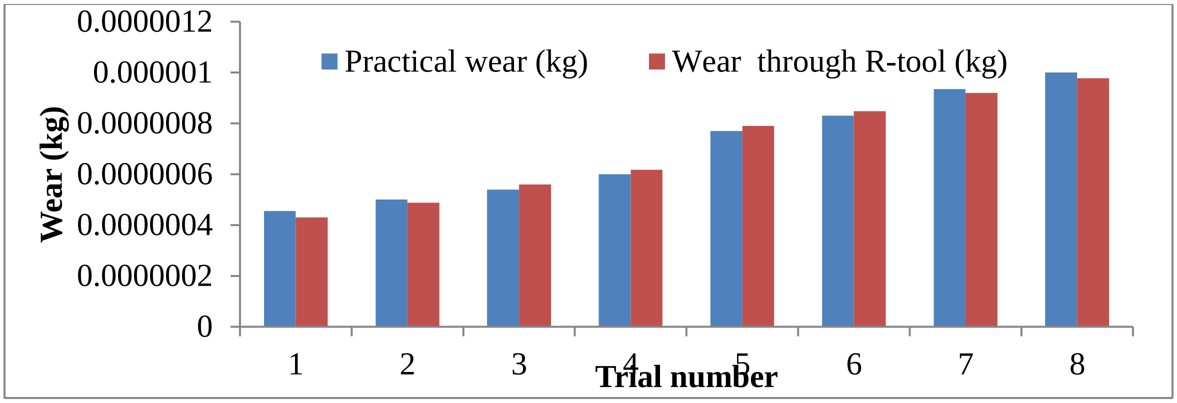


Fig 12: R- tool regression analysis for 5 % fly ash reinforced aluminum matrix composite under lubricated sliding

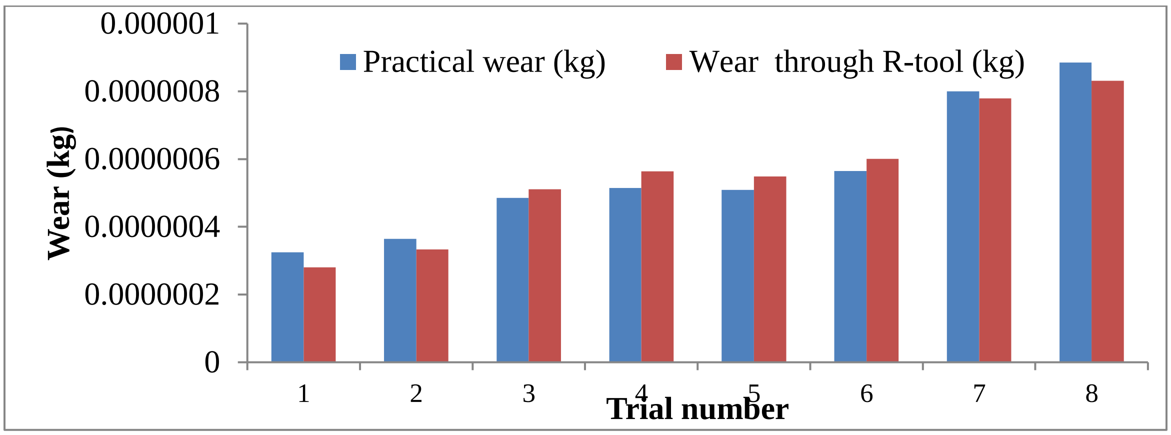


Fig 13: R- tool regression analysis for aluminum matrix composite under lubricated sliding with 7.5 % fly ash reinforcement

4. Conclusion:

- The Stir – Squeeze cast aluminum composites were successfully fabricated to improve the density of composites. It was conferred that squeeze casting technique played its role in improving density to a greater extent when compared with stir – cast composite of similar reinforcement under same operating conditions. Even, BHN also got increased for similar conditions in squeeze cast composites [13].
- Present investigations showed that fabricated squeeze cast composites were superior when compared with the hardness of composites with greater percentage SiCp reinforcement [14] and hybrid composites [15].
- Complete full factorial lubricated sliding wear studies were carried out to compare the results with the dry sliding wear response for the same materials and identical operating conditions. All four materials recorded greater wear resistance under lubricated sliding compared with dry sliding condition [12].

- It was observed that application of lubricant at the interface of the stationary pin and the rotating disc has lowered the friction and the generated heat due to sliding action; thereby increasing the wear resistance of the composite to a greater extent compared with dry sliding situation. Application of the lubricant has reduced the wear rate by 95 %. Hence effective usage of lubricant justifies the application for automotive industries in improving wear resistance of the two parts under sliding action.
- Out of three modeling methods used, Minitab analysis gave more nearer values to the theoretical wear, followed by dimensional analysis and R – tool programming respectively.
- This can be implemented to any manufacturing activity to predict the output for random input values without conducting actual trials. The alternate modeling methods can be evaluated along with cost analysis to obtain optimization.

5. Scope for future work:

An attempt can be exercised to conduct the lubrication sliding wear studies by applying super fluids instead of lubricants which possess zero kinematic viscosity

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