# Effect of the Material Hardness and Operating Conditions on the Friction and Wear During Lubricated Sliding

**Amar Kumar Jain, Manoj Kumar, and Gananath Doulat Thakre**

## 1 Introduction

Friction and wear are two integral parts of the tribological study of any lubricated contact. Wear is a process by which material gradually removed from the surfaces in contact. It is inevitable when the surfaces are in relative motion. Wear in mechanical systems is evaluated using Archard's law. However, wear of materials is a complex phenomenon and is a function of operating parameters, the environment of operation, material hardness, etc. Friction is the resistive force arising due to the resistance offered by the contacting bodies against the motion. Friction has two basic components, i.e. static and kinetic friction. The friction theories in general state that friction is affected by the applied load and the real area of contact. These theories have been in use since the ages and have formed the basis for the designing of the mechanical systems. However, friction in lubricated contacts is a complex function of, material hardness, surface roughness, lubricant film, operating conditions, etc. In a well-designed tribological system, both friction and wear are assumed to be minimal. However, in real-life situations, both friction and wear are of prominence and detrimental to the system life expectancy. Hence, for thorough know-how of tribo-phenomena occurring inside a contact, it is essential to understand the parameters that influence the tribo-performance of the contact. The studies in the area of

A. K. Jain · G. D. Thakre (✉)
CSIR-Indian Institute of Petroleum, Dehradun 248005, India
e-mail: gdthakre@iip.res.in

A. K. Jain
e-mail: amarkumarjain@yahoo.co.in

M. Kumar
Mechanical Engineering Department, DIT University, Dehradun 248009, India
e-mail: kmanoj1947@gmail.com



P. K. Rakesh et al. (eds.), *Advances in Engineering Design*, Lecture Notes in Mechanical Engineering, https://doi.org/10.1007/978-981-33-4018-3_11

tribology have revealed that the material hardness, along with the operating parameters has a profound influence on the tribo-performance behaviour of the contact [1].

Hokkirigawa et al. [2] with the help of Scanning Electron Microscope (SEM) reported in-situ wear in single point scratch test. The study revealed that the wear mode changed sequentially from ploughing to wedging and then cutting with an increase in penetration. Furthermore, the extent of wear in cutting enhanced with increase in hardness. Kayaba and Iwabuchi [3] reported that in the case of fretting wear, hardness had a minor influence on wear phenomenon. On the contrary, the oxide produced during the process protected the parent surface from wear damage, but caused wear of opposing surface. Adachi and Hutchings [4] observed that in a micro-scale abrasion test, wear rates are insensitive to test conditions in case of rolling particles and the variation in wear resistance is insignificant with hardness. Fang et al. [5] through a three-body abrasion study revealed co-existence of cutting and plastic deformation wear, and the material hardness influenced it. Ajayi et al. [6] proposed that as heat generation exceeds the heat dissipation, the scuffing wear propagates; otherwise, it gets quenched.

Along with material hardness, wear is also influenced by the load and the distance traversed. The study revealed that the contact wears increased with the load. With the increase of load, the actual area of contact increases, thereby increasing the wear. Sudin et al. [7] studied wear in ABS and ABS composite parts and revealed that the applied load and the run time significantly affected the rate of wear and the contact friction. Wear also gets enhanced with enhancement in the sliding distance. Cozza [8] investigated the influence of sliding distance on the abrasive wear. It was reported that an increase in sliding distance resulted in a transition from grooving abrasion to rolling abrasion. Similarly, Okonkwo et al. [9] studied the influence of sliding speed on adhesive wear. The study revealed that the rate of wear is sensitive to the sliding speeds, specifically at lower speeds, but it becomes insensitive with an increase in sliding speeds.

The research studies undertaken in the area of contact friction reveal that the friction decreases with a decrease in applied load and an increase in sliding speeds [10]. Bhushan and Kulkarni [11] reported that friction coefficient starts to increase at critical load, and it also corresponds to the hardness of the specimen. Recently, Thakre et al. [12] investigated the influence of operating parameters on the performance of micro EHL contact. The study revealed that the lube film thickness and contact friction is not only influenced by the load, speed, temperature, but also by the slide-to-roll ratio and the lubricant rheology. Investigations pertaining to the effect of texture on tribo-performance of the contact have been undertaken by various researchers [13–16]. The studies have revealed that the roughness parameters, along with the small and shallow cavities, significantly reduce the contact friction.

The contact friction and wear in lubricated contact is a complex function of lubricant film thickness, interlayer shearing of lubricating film and the material characteristics and operating conditions. In the study undertaken by Kimura and Sugimura [17], it has been concluded that the fatigue of ridges in the sliding direction results into flake-like wear particles. Moreover, the acids and peroxides present in the lubricant influence wear of the lubricated contact [18]. Recently the influence of nanoparticles and ionic liquids on the friction and wear behaviour of the lubricated contact was investigated [19, 20].

The literature review reveals that a large number of studies have been undertaken to study the effect of the material hardness and the operating parameters on the performance of dry contacts. However, the studies considering the combined effect of hardness and operating parameters in case of lubricated contacts are very limited. In order to have in-depth information on the dependence of the input design parameters on the tribological studies, it is very much essential to utilize the robust statistical tool to generate a reliable correlation. Hence, the present study attempts, investigating the dependency of the material hardness and the operating parameters on the tribology of lubricated contact using the Taguchi method of experiment design. The study undertaken will be of significant importance to design engineers in designing the engineering components.

## 2 Experimental

The experimental investigations were performed on a pin-on-roller tribo-tester shown in Fig. 1. The tribo-tester utilizes a cylindrical flat-ended pin in contact with the cylindrical roller. The flat surface of the pin is mated with the cylindrical surface of the roller in such a way that the axis of pin and roller are perpendicular to each other. The pin was loaded by a pneumatic loading system on the top of the pin. The roller is partially submerged into the lubricant reservoir housed at the bottom of the roller. The roller while in motion builds the lubricating film on its surface.

The contact is lubricated with commercial lubricating oil having physico-chemical characteristics as tabulated in Table 1. The pin is lowered on the roller surface, and the load applied. The experiments were carried out on cylindrical flat-end pins of Φ8 mm and 12 mm length fabricated from materials of different hardness, i.e. spring steel, EN31 and Gun-metal. The contact surface of the pins was mated with a polished EN31 cylinder of Φ50mm and 20 mm width. The contact friction in terms of friction force and the friction coefficient is thus continuously monitored. The wear of the contact was measured by weight loss technique at the end of the test.

The tribological performance of a lubricated contact depends on a large number of parameters viz. material parameters, operating conditions, lubrication, etc. Based on the literature review, the cause and effect diagram has been constructed, as shown in Fig. 2. Among the various influencing parameters, the operating conditions and the material hardness has been selected to investigate their influence on the tribo-performance. The experiments were performed as per the L9 Taguchi orthogonal array. The design parameters selected were applied load, test/sliding duration and the material hardness. The contact friction and the wear were selected as the output parameters. The L9 Orthogonal Array for three input design parameters for three levels is given in Table 2.

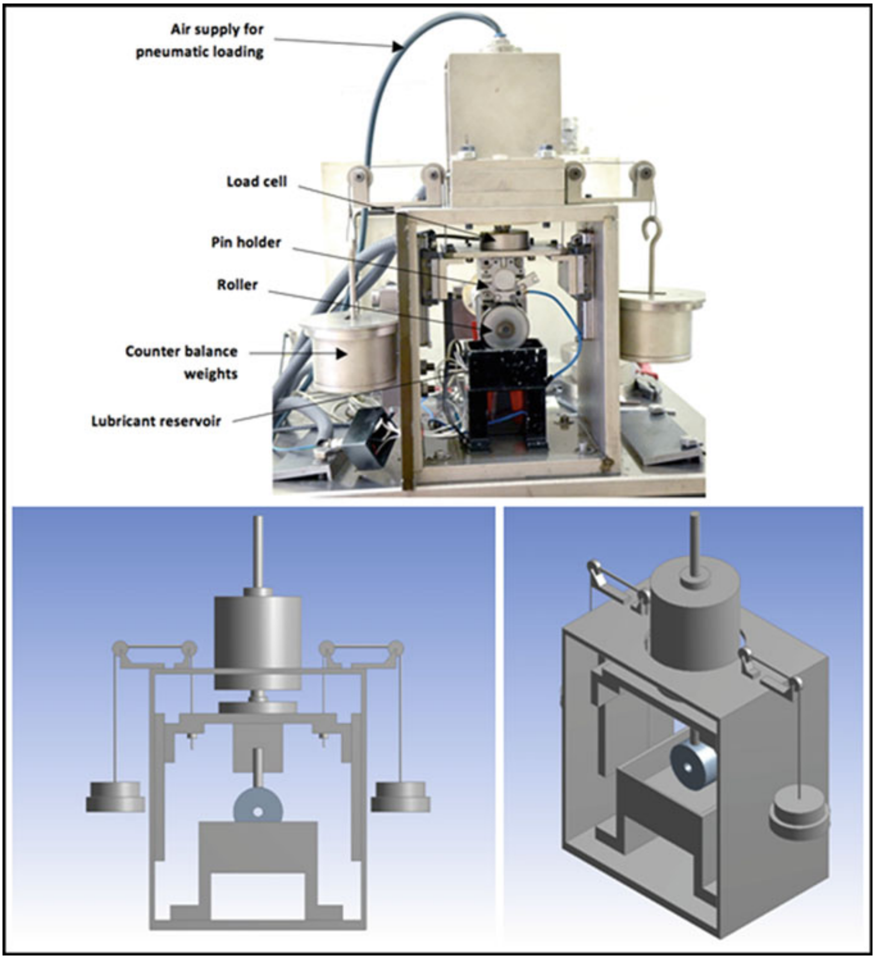


**Fig. 1** Pin-on-Roller tribo-tester

**Table 1** Lubricant properties

| Kinematic viscosity (cSt) | | Density @15 °C (kg/l) | Pour point (°C) | Flash point (°C) |
|---|---|---|---|---|
| @40 °C | @100 °C | | | |
| 74.4 | 13.1 | 0.840 | −39 | 215 |

The experimental results thus obtained were then subjected to statistical analysis and signal/noise (S/N) ratio determined. The S/N ratio is given by;

$$S/N = -10\log_{10}\frac{1}{a}\sum_{i=1}^{a} b^2 \tag{1}$$

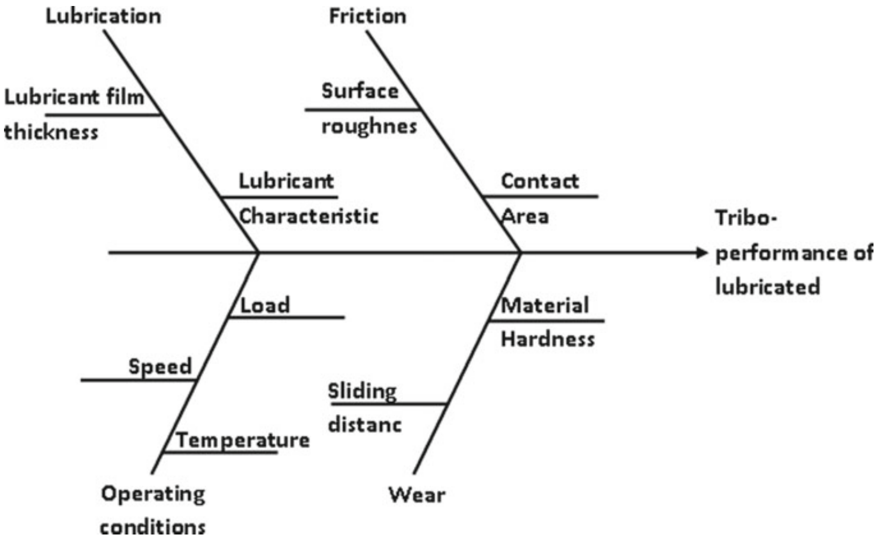


**Fig. 2** The cause and effect diagram

**Table 2** Experimental design matrix

| Experiment No. | Load (N) | Time (min) | Hardness (HRC) |
|---|---|---|---|
| 01 | 100 | 30 | 27.96 |
| 02 | 200 | 60 | 27.96 |
| 03 | 300 | 120 | 27.96 |
| 04 | 100 | 60 | 34.29 |
| 05 | 200 | 120 | 34.29 |
| 06 | 300 | 30 | 34.29 |
| 07 | 100 | 120 | 58.59 |
| 08 | 200 | 30 | 58.59 |
| 09 | 300 | 60 | 58.59 |

where '$a$' represents a number of experiments, and '$b$' is the number of the response value. The ratio is used to optimize the quality characteristics. In the present case, the criterion of smaller the S/N ratio better will be the tribological performance has been considered.

Subsequently, Analysis of Variance (ANOVA) was performed to determine the input factors that significantly influence the performance characteristics. The domain was established for lower values of output parameters in the entire factor space. The data obtained were further analysed using normal probability plots. The regression analysis was performed on experimentally obtained results to establish the quadratic equations for friction and wear prediction. The experiments were designed using Minitab v17 software.

## 3 Results and Discussion

The contact friction along with wear for different operating conditions as per the Taguchi experimental design is given in Table 3. The results reveal that the coefficient of friction and the weight loss due to wear varies with input design parameters of the experimental design. The contact wear is directly proportional to the applied load and distance travelled.

However, material hardness has a reverse impact on wear. With an increase of load, the actual contact area increases and the lubricant film thickness decreases. Therefore, the metal-to-metal contact increases resulting in an increase in wear. Same is the case with the sliding time. As the contact traverses longer distance with time, the wear of the contact increases with time. However, in the case of hardness, the wear decreases with hardness. As the hardness increases, the material becomes more brittle, and its wear due to adhesive mechanism becomes negligible.

The probability of abrasive wear increases, but due to the presence of lubricant film this chance diminishes. Hence, wear decreases with an increase in hardness. As per the classical theories of friction, the contact friction increases with load and hardness and decrease with sliding distance.

However, the values of S/N ratio can provide a better understanding of the design parameters and friction/wear behaviour of the contact. The values of S/N ratio in graphical form are shown in Fig. 3. Considering the criterion of smaller the better, the parameter setting for lower wear and fiction are H3-L1-T2 and H2-L1-T3, respectively.

The results indicate that by increasing the material hardness, wear gets reduced. A lower load and moderate sliding distance too results in lower wear. In the case of friction, it is observed that moderate material hardness results in lower friction. Friction increases at the higher hardness and also a lower material hardness result in higher friction because of the increase in adhesive forces. The friction decreases with rising in load and sliding distance. As the sliding distance increases, smoothening of asperities takes place, which in turn results in lower friction values.

**Table 3** Friction and wear of the contact

| Experiment No. | Coeff. of friction | Weight loss due to wear (mg) |
|---|---|---|
| 01 | 0.085 | 0.25 |
| 02 | 0.103 | 0.25 |
| 03 | 0.069 | 4.9 |
| 04 | 0.056 | 21.1 |
| 05 | 0.051 | 57.2 |
| 06 | 0.111 | 27.9 |
| 07 | 0.080 | 0.25 |
| 08 | 0.076 | 0.1 |
| 09 | 0.072 | 0.17 |

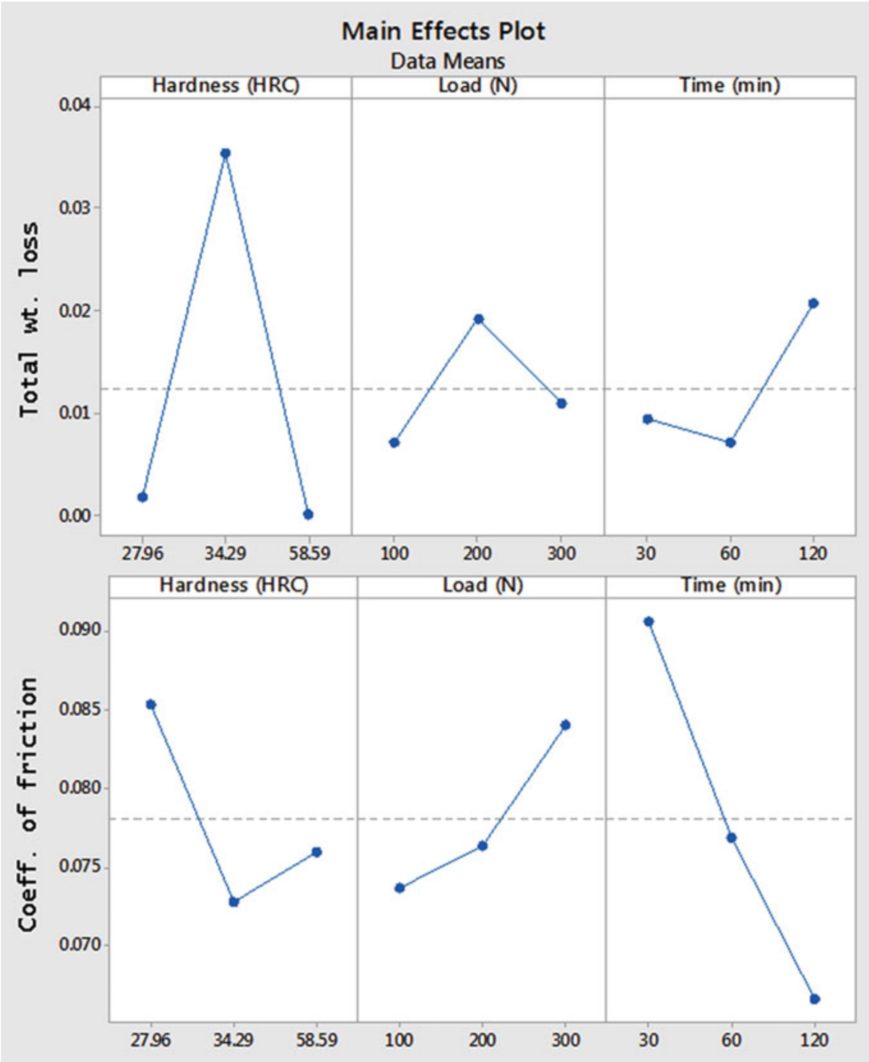


**Fig. 3** Main effects plot for wear and friction

Figures 4 and 5 represent the response surface plots for the wear and contact friction over the input parameters. The surface plots confirm the findings observed from the principle effect analysis. The normal probability plots for the residuals and the predicted response of wear and friction are shown in Figs. 6 and 7. When the normal probability plots closely follow the mean line, this represents a good agreement between the experimental findings. Figures present the agreement with those of mean line.

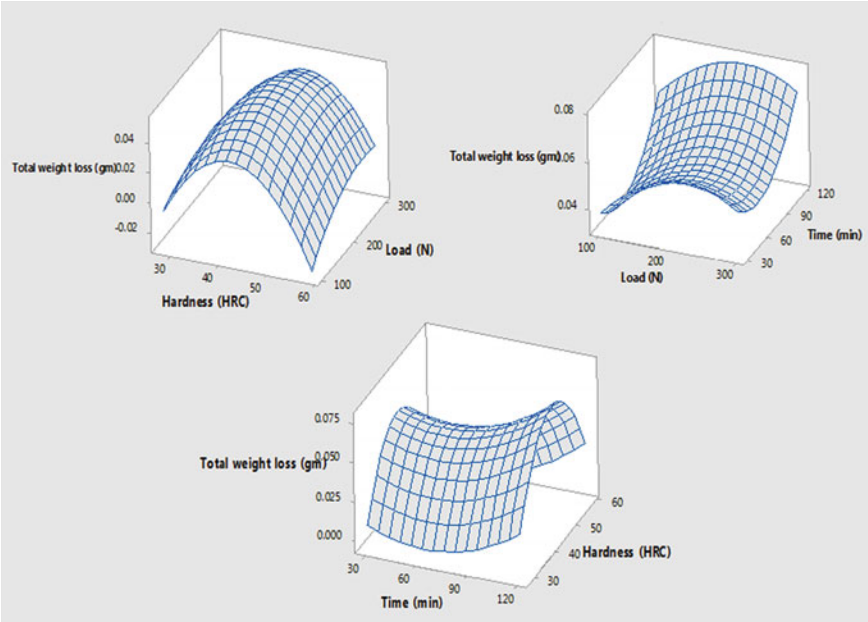


**Fig. 4** Response surfaces for wear behaviour versus input parameters

Subsequently, with the use of regression analysis quadratic equations for the contact friction and wear with input parameters as variables have been determined. The regression equations thus obtained are;

$$\mu = 0.1708 - 0.006570H + 0.000956W - 0.001309t + 0.000069H^2 - 0.000001W^2 - 0.000002t^2 - 0.000009H^*W + 0.000030H^*t \quad (2)$$

$$\text{Wt.loss} = -0.03245 + 0.01734H + 0.000276W - 0.001063t - 0.000221H^2 - 0.000001W^2 + 0.000007t^2 - 0.000007H^*W + 0.000006H * t \quad (3)$$

In the above equations, $H =$ hardness of the material in HRC, $t =$ time in minutes and $W =$ load in Newton.

A comparative assessment of the results obtained from the experiments and those obtained from the regression equation is shown in Fig. 8. The comparison reveals that the developed equation can predict the tribo-performance of lubricated point contact efficiently.

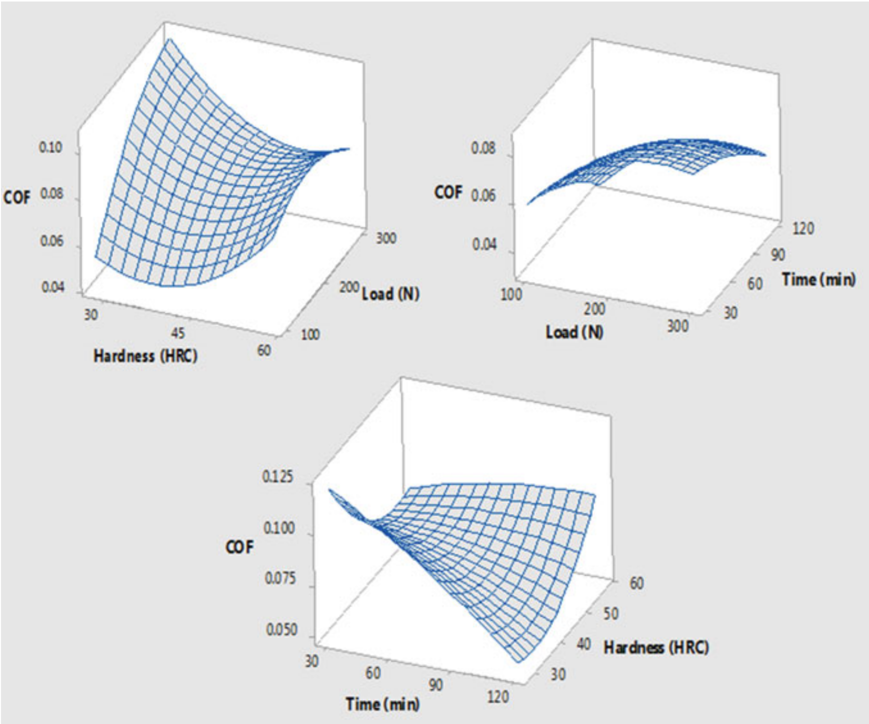


**Fig. 5** Response surfaces for friction behaviour versus input parameters

## 4 Conclusions

An experiment-based study utilizing the concept of Taguchi design of experiments has been performed to study the influence of operating and material parameters on tribo-performance behaviour of the lubricated contact in sliding. Concerning the study undertaken following salient conclusions have been made;

- The contact wear is influenced by applied load, distance traversed and the material hardness. Wear decreases with an increase in hardness. Lower wear can be observed at lower loads and moderate sliding distances.
- A lower value of contact friction is obtained at lower loads and higher sliding distances. However, in order to have lower friction, the material hardness has to be moderate.
- The empirical relations for the contact wear and friction with applied load, sliding distance and material hardness as input variables have been presented. The empirical relations can provide useful information on the contact friction wear for the considered design parameters.

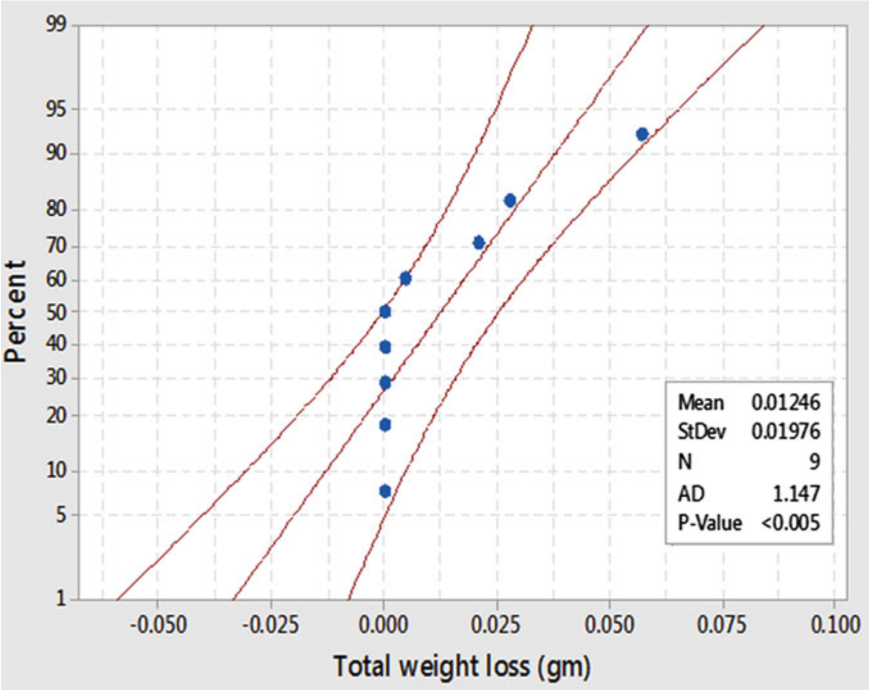


**Fig. 6** Normal probability plot for wear response of the contact

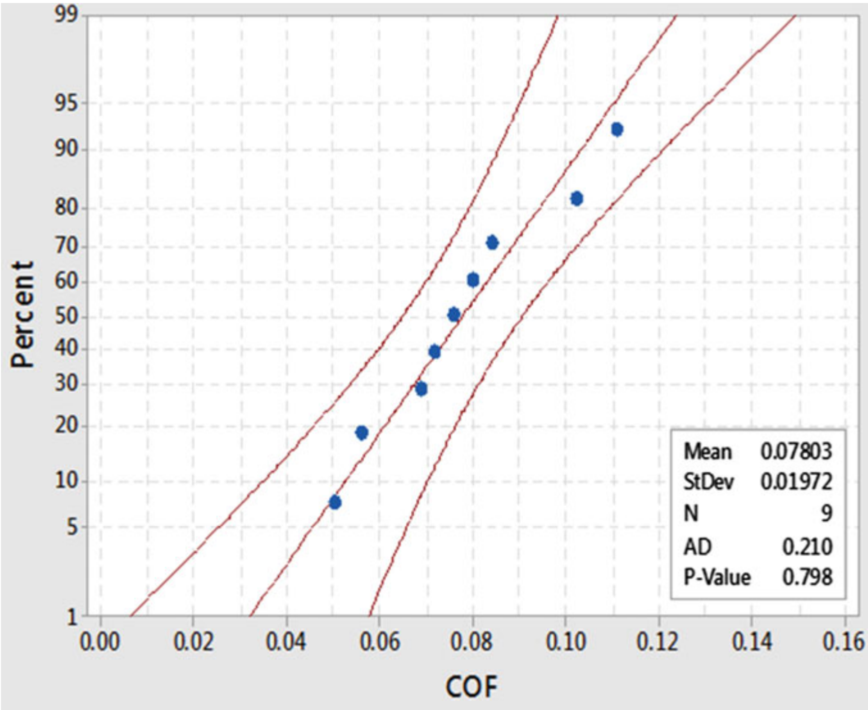


**Fig. 7** Normal probability plot for friction response of the contact

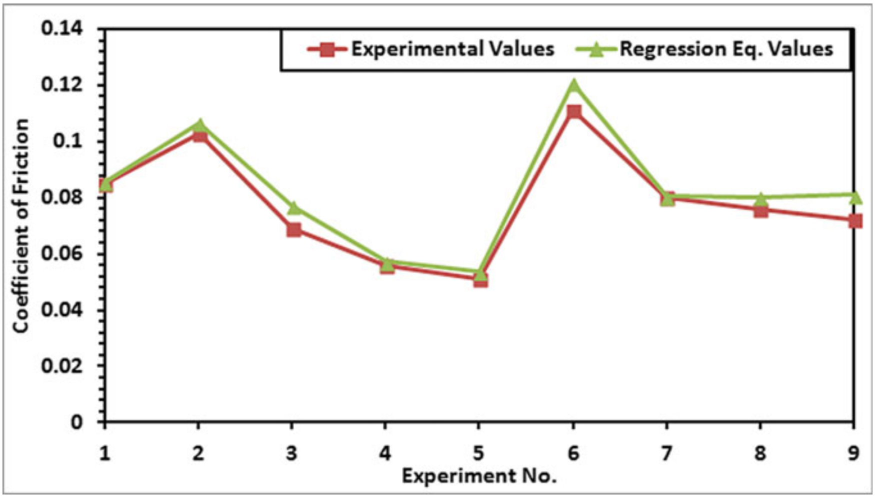


**Fig. 8** Comparative assessment of experimental and regression values

**Acknowledgements** The authors thank Director, CSIR-Indian Institute of Petroleum, Dehradun, India for the financial support to carry out the experimental work and also to publish the findings.

## References

1. Stachowiak G, Batchelor AW (2013) Engineering tribology. Butterworth-Heinemann
2. Hokkirigawa K, Kato K, Li ZZ (1988) The effect of hardness on the transition of the abrasive wear mechanism of steels. Wear 123(2):241–251
3. Kayaba T, Iwabuchi A (1981) Effect of the hardness of hardened steels and the action of oxides on fretting wear. Wear 66(1):27–41
4. Adachi K, Hutchings IM (2005) Sensitivity of wear rates in the micro-scale abrasion test to test conditions and material hardness. Wear 258(1–4):318–321
5. Fang L, Zhou QD, Li YJ (1991) An explanation of the relation between wear and material hardness in three-body abrasion. Wear 151(2):313–321
6. Ajayi OO, Lorenzo-Martin C, Erck RA, Fenske GR (2011) Scuffing mechanism of near-surface material during lubricated severe sliding contact. Wear 271(9–10):1750–1753
7. Sudin MN, Ramli FR, Alkahari MR, Abdullah MA (2015) Comparison of wear behavior of ABS and ABS composite parts fabricated via fused deposition modelling. Int J Adv Appl Sci 5(1):164–169
8. Cozza RC (2015) Effect of sliding distance on abrasive wear modes transition. J Mater Res Technol 4(2):144–150
9. Okonkwo PC, Kelly G, Rolfe BF, Pereira MP (2016) The effect of sliding speed on the wear of steel–tool steel pairs. Tribol Int 97:218–227
10. Kakaš D, Škorić B, Mitrović S, Babić M, Terek P, Miletić A, Vilotić M (2009) Influence of load and sliding speed on friction coefficient of IBAD deposited TiN. Tribol Ind 31(3–4):3–10
11. Bhushan B, Kulkarni AV (1996) Effect of normal load on microscale friction measurements. Thin Solid Films 278(1–2):49–56
12. Thakre GD, Sharma SC, Harsha SP, Tyagi MR (2015) A parametric investigation on the microelastohydrodynamic lubrication of power-law fluid lubricated line contact. Proc Inst Mech Eng, Part J: J Eng Tribol 229(10):1187–1205
13. Sedlaček M, Podgornik B, Vižintin J (2009) Influence of surface preparation on roughness parameters, friction and wear. Wear 266(3–4):482–487
14. Chouquet C, Gavillet J, Ducros C, Sanchette F (2010) Effect of DLC surface texturing on friction and wear during lubricated sliding. Mater Chem Phys 123(2–3):367–371
15. Tang W, Zhou Y, Zhu H, Yang H (2013) The effect of surface texturing on reducing the friction and wear of steel under lubricated sliding contact. Appl Surf Sci 273:199–204
16. Thakre GD, Sharma SC, Harsha SP, Tyagi MR (2016) A theoretical study of ionic liquid lubricated μ-EHL line contacts considering surface texture. Tribol Int 94:39–51
17. Kimura Y, Sugimura J (1984) Microgeometry of sliding surfaces and wear particles in lubricated contact. Wear 100(1–3):33–45
18. Newley RA, Spikes HA, Macpherson PB (1980) Oxidative wear in lubricated contact. J Lubr Technol 102:539–544
19. Sharma V, Timmons R, Erdemir A, Aswath PB (2017) Plasma-functionalized polytetrafluoroethylene nanoparticles for improved wear in lubricated contact. ACS Appl Mater Interfaces 9(30):25631–25641
20. Mu Z, Zhou F, Zhang S, Liang Y, Liu W (2005) Effect of the functional groups in ionic liquid molecules on the friction and wear behavior of aluminum alloy in lubricated aluminum-on-steel contact. Tribol Int 38(8):725–731