Vol. 43, No. 3 (2021) 442-451, DOI: 10.24874/ti.907.06.20.02

Tribology in Industry

www.tribology.rs

RESEARCH

Analysis of Friction and Wear as a System Response Using Indigenously Fabricated Tribometer

K.R. Shah[a,*], A. Shukla[b], N.S. Patel[a]

[a] *Mechanical Engineering Department, Faculty of Technology, Dharmsinh Desai University, Nadiad, Gujarat, India,*
[b] *Shah Schulman Centre for Surface Science & Nanotechnology, Dharmsinh Desai University, Nadiad, Gujarat, India.*

Keywords:

Tribopair
Tribotesting
Friction
Wear
Tribometer

* Corresponding author:

Kavit R. Shah
E-mail: krshah.mech@ddu.ac.in

Received: 17 June 2020
Revised: 1 September 2020
Accepted: 23 February 2021

A B S T R A C T

In this paper, tribometric characteristics of the steel-brass and steel-aluminium tribopairs were studied under different interaction parameters through varying operating conditions. An indigenous tribometer was developed using ASTM G77 protocol to estimate friction and wear characteristics for steel-brass and steel-aluminium tribopairs. Results presented here show the importance of the tribotesting of tribological properties, namely friction and wear due to complex nature of system induced interdependencies. Stribeck curve was plotted by varying the speed at a constant load for a specific tribosystem using the indigenously developed tribometer. Finally, simplified tribosystem diagram has been proposed for a better understanding of friction and wear as a system response in the tribotesting.

1. INTRODUCTION

Tribology is a science of concurrent studies of three properties in a mechanical system, namely, friction, wear, and lubrication. In order to improve the life of entire machine, and the efficiency of the mechanical process it is performing, the tribology-based concepts are applied in such a way that the friction between components remains optimally less, and also that negligible wear takes place of the sliding machine components. To achieve this lubrication is applied in various parts [1].

The journey of word tribology started when Peter Jost reported that the giant economic benefits could be reaped through proper application of lubrication in order to control friction and wear related issues in the machines [2]. One of the important aspects of tribology is its interdisciplinary nature, as it deals with interacting surfaces in relative motion, where the possibilities of wide variety of surfaces and multitude of influencing factors makes it a complex phenomenon. This stronger and complicated interplay and dependencies between constituent components gives rise to system approach in dealing with tribology [3]. In last five decades numerous experiments were carried out in variety of conditions based on this system approach or extension of it. The complex nature of friction and wear has been discussed by many researchers with respect to different tribosystems in the past [4]. In one such study, friction and wear were claimed as tribo-system generated responses which are reasonably related to each other and not as the material's properties of tribopairs under consideration [5]. Further, it was reported that no universal predictive theory can be proposed for friction due to numerous potential factors which can influence friction in a wide spectrum of physical situations [6]. This assumption was found in agreement with conclusions derived by Feynman in relation to the importance of friction data produced in the laboratory [7]. Moreover, the importance of wear classification of tribopairs in relative motion was discussed in the context of system approach. Recently, it was reported that the tribosystem is one of the important factors which affects repeatability and reproducibility of wear data produced at the laboratory level [8,9].

Another prominent aspect of Tribology is Tribotesting, which is carried out to ascertain different parameters related to different tribopairs for a particular tribosystem or tribo-mechanical system [10,11]. Friction and wear are two crucial entities in tribotesting which are estimated at various stages, namely, laboratory tests, model tests, component-system-machinery bench tests to machinery field tests. Devices used to estimate tribometric characteristics are referred as tribometers [6,12].

Further, transient processes involved in friction and wear focused on interdisciplinary approach which can help to solve problems related to tribological properties. It was also observed that when improved tribological data when it applied to actual conditions resulted in failure of the system much rapidly which again proved the importance of data produced in the laboratory condition must be understood properly [13,14]. It is observed that comparatively large amount of work is being carried out in the area of tribotesting and huge amount of friction and wear related studies are being published across the globe. In most of the analysis, tribological properties were studied by altering different parameters of a tribosystem, namely, tribopair, operating parameters and various types of lubricants as interaction parameters. After introduction of nanofluid, the numbers of experimental analysis were conducted due to inherent complex characteristics of nanofluid itself. All these studies mainly focused on understanding different wear mechanisms which took place during working conditions. It is believed that interdependency of friction and wear are fundamentally required to part found missing in the most of these studies carried out on standard available tribometers.

Many researchers discussed about the fundamental aspects of tribometer and how different types of tribometer can be used to satisfy their basic research needs. Different types of tribometers can be developed and tested based on the application where the tribopair is to be used. Number of researchers developed their own tribometers for friction and wear analysis due to unavailability of the suitable tribometer in the market for a given tribopair [7,15]. Considering friction and wear as system response, it was observed that variety of tribometers customized and fabricated depends upon user application. For example, in the space and dental applications environmental parameters are crucial along with load as a operating parameter and friction drives and brake materials as a triboelements [16-20].

The recent trend in tribology is percolating through macro scale systems to micro and nanoscale systems with the advancements of measurement techniques and miniaturization. The Tribological effects transcend beyond geometrical boundaries to span over nanotribology to teratribology [21]. At nano level, the scale effect on frictional behaviour of different pair developed new area referred as nanotribology where it was shown that how friction behaviour changes at reduced dimensions [22]. Later on, similar studies were transformed to new era called Tribotronics which is widely used to reduce friction and wear related problems using electronics [23]. Recently, many researchers found improved performance of a nanofluid based tribosystem compared to conventional which motivate us to fabricate inhouse tribometer for better understanding of tribological properties in case of nanofluid based tribosystem [24].

Thus, In the present analysis basic experiments of friction and wear were carried out for two metal pairs under varying interaction parameters using indigenously fabricated tribometer. Based on these data, tribological properties and their relationships are discussed with respect to the proposed tribosystem. Repeatability of experiments were checked based on the G77 protocol and stribeck curve which was plotted by varying the speed at a constant load. At last, the simplified tribosystem diagram has been introduced with given due importance in top-down & bottom up tribotesting methodology.

2. MATERIALS AND METHODS

2.1 Experimental Setup

Tribometers are used to estimate tribological properties like friction and wear between triboelements at different operating conditions. Standard tribometers are available in the market as well as customized tribometers are produced based on researcher's requirement. Here a new tribometer was fabricated as per the ASTM G77 standard for ranking two material pairs at different operating conditions [9, 27].

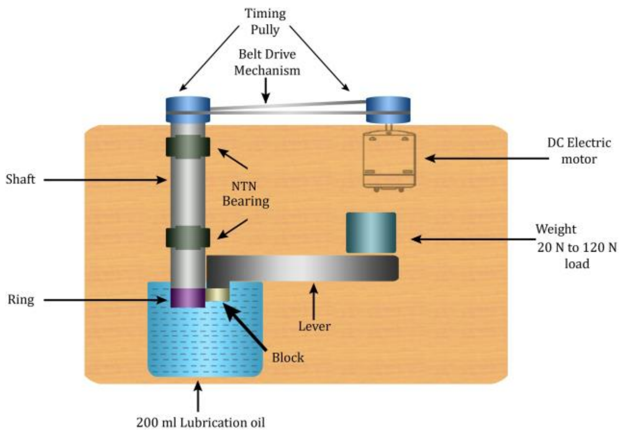

Fig. 1. Schematic diagram of indigenously fabricated tribometer.

Tribometer was fabricated for block and ring type of geometry which can operate in the range of 20 N load to 120 N load and speed upto 1000 RPM. Schematic diagram for the same is shown in Fig.1. Experiments were carried out in accordance with the procedure mentioned in ASTM G77 standard protocol which is used to rank different metals at different operating condition. Friction measurement was conducted using load cell mounted in the structure. Friction measurement concept was taken from the literature which is as shown in Fig. 2. Initial experiments were performed to check repeatability of the test-rig. To conduct these experiments, the shaft made from SS410 was taken as steel ring and the metal blocks, namely, aluminium and brass were chosen. This material pairs were selected in such a way that the block materials should wear out against the shaft either in dry or lubricated condition.

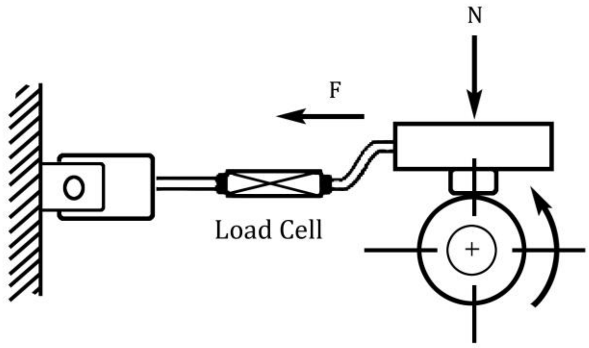

Fig. 2. Friction Measurement Technique [12].

2.2 Methodology and Experimental

To perform experiments various tribological parameters were selected as shown in Table 1. Here, tribopair steel-brass (SB) and steel-aluminium (SA) tested under boundary and lubricated condition considering different operating conditions.

Table 1. Testing Parameters using System Theory

Structral Parameter	Steel-Brass and Steel-Aluminium as a Tribopair
Operational Parameters	20 N, 40 N, 80 N load 400 RPM and 800 RPM speed
Interaction Parameter	1) Dry condition 2) Low and high viscosity oil as a lubricant condition
Tribometric charactersitics	Friction and wear
Enviormental condition	Room Temperature

Wear loss was measured using weight loss method on weighing machine having accuracy of 0.1 mg. Temperature was measured by means of digital pyrometer at starting and end of the experiments in a lubricated testing condition.

Friction force was estimated using load cell and converted it in to coefficient of friction using software as shown in Fig. 3 which is a part of tribometer as shown in Fig. 4.

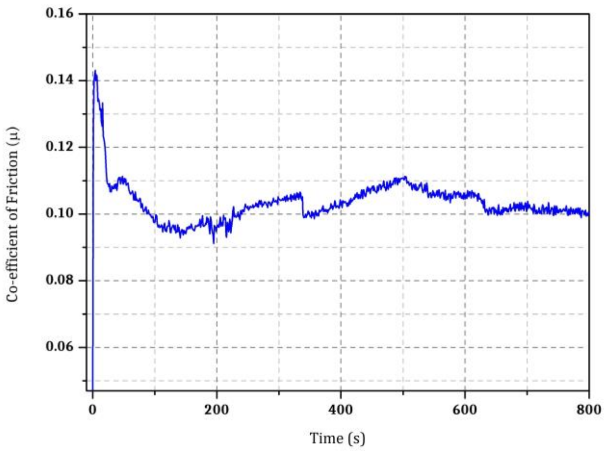

Fig. 3. Coefficient of friction diagram.

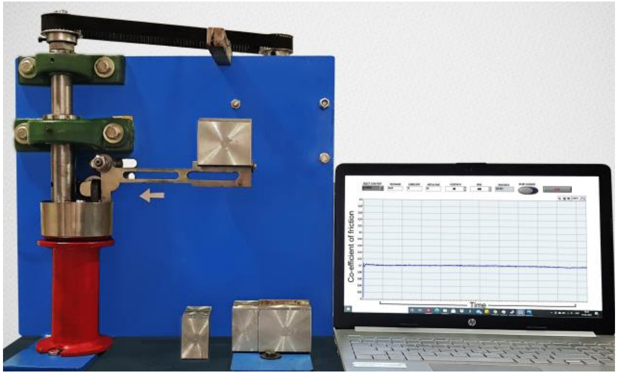

Fig. 4. Actual photograph of Tribometer.

Repeatability of the experimental setup was checked using steel brass material pairs at 80 N load and 500 RPM for 600 meters sliding distance. Here, 20 tests were carried out under the same operating parameters to estimate the tribometric characteristics. Furthermore, sliding distance was taken 1000 m for lubricated condition and 300 m for dry condition.

3. RESULTS AND DISCUSSION

3.1 Repeatability of experiments

First of all, to produce technical data of friction and wear, repeatability of the instrument was studied using method explained in the ASTM standard G77. Based on that at same operating conditions, experiments were conducted 20 times and statistical analysis of friction and wear data was carried out using Minitab software. First, Anderson-Darling test (A-D test) was carried out with 95% confidence interval to identify that the data are normally distributed or not. For that purpose, the Histogram plots of wear loss and friction data were plotted based on same sets of experiments which are shown in Fig. 5 & 6.

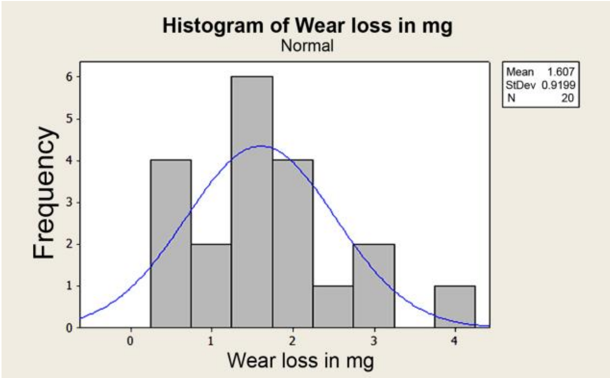

Fig. 5. Histogram of Wear loss based on 20 sets of Experiments.

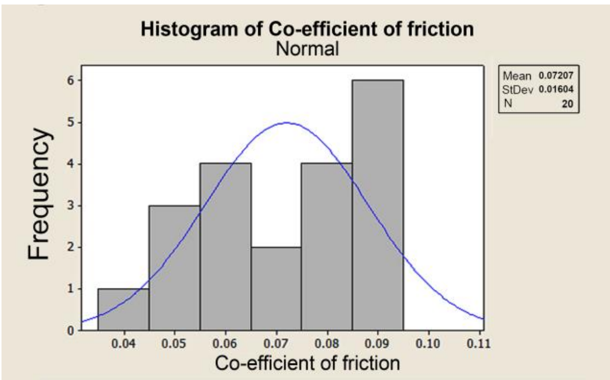

Fig. 6. Histogram of Coefficient of friction based on 20 sets of Experiments.

The results of A-D tests are presented in the tabular form as shown in Table 2. The p-values for coefficient of friction and wear loss are 0.111 (>0.005) and 0.399 (>0.005) respectively. Therefore, the null hypothesis i.e. the distribution of data follows normal distribution is accepted. Now confidence interval for mean values of coefficient of friction and wear loss can be calculated using formula given for normal data. The 95% confidence interval for mean value of wear loss is 1.176 mg to 2.073 mg. The mean value of 20 sets of observations for wear loss is 1.607 mg which falls within the interval limit. Similarly, 95% confidence interval for mean value of coefficient of friction is 0.064 to 0.079 and the mean value of 20 sets of observations for coefficient of friction is 0.072 which is also well within the interval limit.

Table 2. Confidence Interval for mean value of Coefficient of Friction and Wear Loss

Results	Observations	p-value of (Anderson-Darling Test)	Sample mean ($\bar{x}$)	Standard dev. of sample (s)	Confidence Interval	
					Lower bound	Upper bound
COF	20	0.111	0.072	0.0160	0.064	0.079
Wear Loss (in mg)	20	0.399	1.607	0.9199	1.176	2.073

Hence, it is manifested that the instrument has very little inherent variability and capable to demonstrate high repeatability [26].

3.2 Tribotesting

After verifying the test-rig as per the ASTM standards, the experiments were conducted to measure the friction and wear. The testing was carried out on two different tribo-pairs, namely, steel-aluminium and steel-brass pairs at different speeds and loads in the presence of various interaction parameters. Here, three different types of tribo contacts were chosen to vary the interaction parameters, namely, dry contact and lubricated contact using low viscosity oil and high viscosity oil. Initially, the tribometric characteristics analyses were performed for both the pairs under dry conditions considering specific sliding distance. As can be seen from Table 3, it is clear that for steel-brass pair the coefficient of friction found to be decreased with increase in load and speed, whereas the wear loss found to be increased under the similar conditions. On the other hand, in the steel-aluminium pair the changes in the tribometric characteristics are found almost opposite to that of the steel-brass pair under dry condition.

Once the results obtained from dry conditions, further experiments were conducted for both steel-aluminium and steel-brass pair under the presence of low viscosity oil. Interestingly, the variation in friction and wear were found again different than the dry contacts as can be seen in table 3. Here, it is seen that with increase in load from 20N to 40 N at 400 RPM, friction and wear both increased whereas at 800 RPM contradiction was found in the behaviour of friction and wear characteristics. Moreover, friction was increased when speed increased from 400 RPM to 800 RPM at 20 N load. However, at the same conditions the wear loss was decreased. In addition, this trend was not remained same at 40 N load when speed increased from 400 RPM to 800 RPM where both friction and wear found to be decreased.

Table 3. Results of Friction and wear for different interaction parameter

Tribo pair	Interaction Parameter	Load in N and Speed in RPM	Tribometric Characteristics	
			Coefficient Of Friction	Wear Loss In (mg)
Steel-Brass	Dry	40-300	0.3206	11.33
		40-600	0.2648	19.82
		80-300	0.246	15.1
		80-600	0.209	21.64
	Lubricated Low Viscosity of oil	20-400	0.085	1.13
		20-800	0.12	1.22
		40-400	0.1076	4.54
		40-800	0.0857	2.36
	Lubricated High Viscosity oil	20-400	0.0975	0.01
		20-800	0.092	0.1
Steel-Aluminium	Dry	40-300	0.3888	0.96
		40-600	0.4136	2.35
		80-300	0.3983	1.11
		80-600	0.4738	0.74
	Lubricated Low Viscosity of oil	20-400	0.05	0.94
		20-800	0.055	0.88
		40-400	0.1239	5.63
		40-800	0.1214	1.9
	Lubricated High Viscosity oil	20-400	0.1645	0.64
		20-800	0.18	0.67

To further check these highly unpredictable tribometric characteristics, the experiments were performed in the presence of highly viscous oil. Surprisingly, the changes in friction and wear were found different than the dry condition and lubricated condition using low viscous oil which can further be observed in the Table 4-7. The different behaviour of friction and wear may be probably due to the presence of different interaction parameters present in each tribo-pair.

Table 4. Relation between friction and wear for two tribopair under dry condition

Under Dry Condition	Steel-Brass	Steel-Aluminium
Friction	Less	Higher
Wear	Higher	Less

Table 5. Effect of speed and load on Friction and wear on steel aluminium pair

Steel-Aluminium Pair	SA	Friction	Wear
Load increases	At 400 RPM	↑	↑
(20 N to 40 N)	At 800 RPM	↑	↑
Speed increases	At 20 N	Negligible effect	↓
(400 to 800 RPM)	At 40 N	Negligible effect	↓

Table 6. Effect of speed and load on Friction and wear on steel Brass pair

Steel-Brass Pair	SB	Friction	Wear
Load increases	At 400 RPM	↑	↑
(20 N to 40 N)	At 800 RPM	↓	↑
Speed increases	At 20 N	↑	↓
(400 to 800 RPM)	At 40 N	↓	↓

Table 7. Effect of friction and wear for steel-brass and steel aluminium pair under viscous condition

Under Viscous Condition	Steel-Brass	Steel-Aluminium
Friction	Less	Higher
Wear	Less	Higher

In order to further analyse the behaviour of friction and wear, the Stribeck curve was plotted. As can be seen in Fig. 7, the Stribeck curve was plotted four times for steel-brass pair by varying the speed from 0 to 600 RPM at 60N load. It is revealed from Fig. 7 that the coefficient of friction initially found to be higher. It can also be observed further from Fig.7 that the coefficient of friction decreased as the sliding speed increased. At one stage the coefficient of friction reached the minimum value and after that it increased with increase in speed. This variation of friction shows that the overall trend of the Stribeck curve is in well agreement with the theoretical one.

From Stribeck curve it is observed that the coefficient of friction initially at low speed is found to be high and with increase in speed at one stage it reaches minimum value.

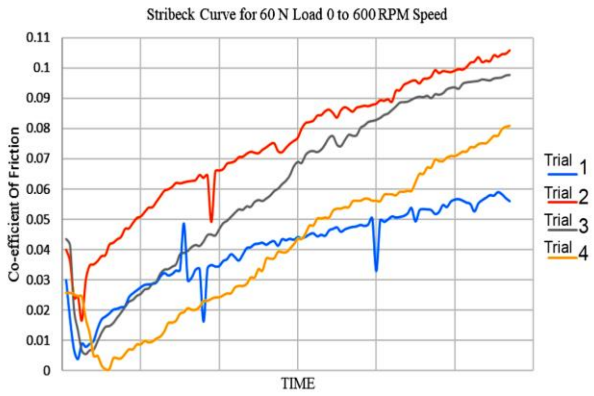

Fig. 7. Nature of Stribeck curve plotted for from varying speed from 0 to 600 RPM at 60 N load under 22 Cst viscosity of oil.

This kind of changes in friction particularly happens when the system is in boundary or near to mixed film lubrication region. After reaching the minimum level, the friction value increased continuously with increase in speed in hydrodynamic region. This shows that the alteration in friction depends on the regime in which the system runs. It can also be understood from the experiments that there is no direct relationship between friction and wear phenomenon. This makes it clear that the wear estimation along with the friction is very crucial from better understanding of the system behaviour [27]. Table 8 shows the wear coefficient range for different interaction parameters gives the tentative indication of the wear regime in which the system ran during experimentation. The combine information of stribeck curve and wear regime may give an additional degree of freedom from systems design point of view.

Table 8. Range of wear coefficient for different interaction parameter

Interaction Parameter	Wear Coefficient Range	Wear Regime [28]
Dry	2.19E-05 to 7.13E-04	Boundary and Mild
Low viscosity oil	1.56E-07 to 1.32E-05	Boundary
High Viscosity Oil	1.74E-05 to 5.56E-05	Boundary

3.3 Proposed Simplified Tribosystem

Based on the analysis of experimental results, it is evident that the friction and wear are system response. Moreover, each system may behave in a different manner from tribometric characteristics point of view. Any tribosystem itself consists of various other smaller tribosystem and entire product's performance depends on all individual tribosystem through which entire product is produced. Therefore, one needs to be cautious while implementing the friction and wear data generated at the laboratory level experiments into the larger scale system design. Due to the inherent interdependency the improper tribological design of any of the components may lead to the failure of entire product. To explain this failure and inefficiencies or losses for a tribosystem, in a machine Fig 8. depicts simplified illustration. Wherein, in working condition the friction between triboelements causes energy losses and that may result in structural changes called wear. This wear causes the changes in topography of the surfaces in contact which will further alter the friction. This process continues until the steady state condition is achieved and at one stage severe wear takes place which can result in catastrophic failure [4,12].

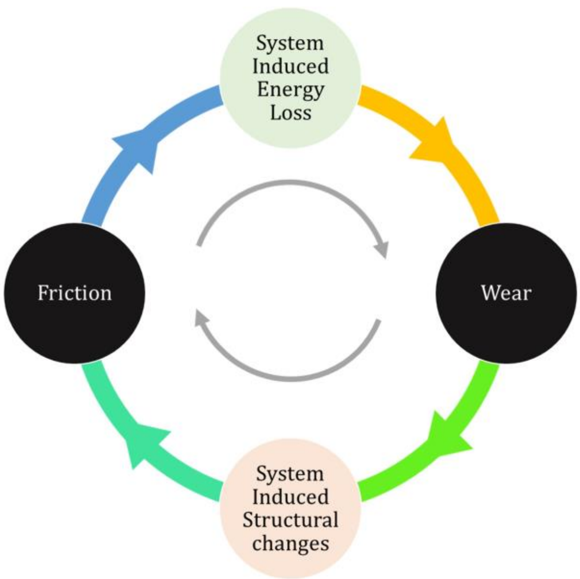

Fig. 8. Interdependency of Friction and wear based on system theory

From the present experimental analysis, it is observed that friction and wear are system response and based on the system theory it is referred as basic tribometric characteristics [3,4]. The general tribosystem diagram can be shown as Fig. 9 (a) which indicates basics of any tribosystem in simplistic manner but does not throw light on how various components of the tribosystems are inter-related. This simplified tribosystem diagram needs to be updated by incorporating various elements in apt tier. Tribotesting system designed based on such diagram shall provide wholesome data analysis.

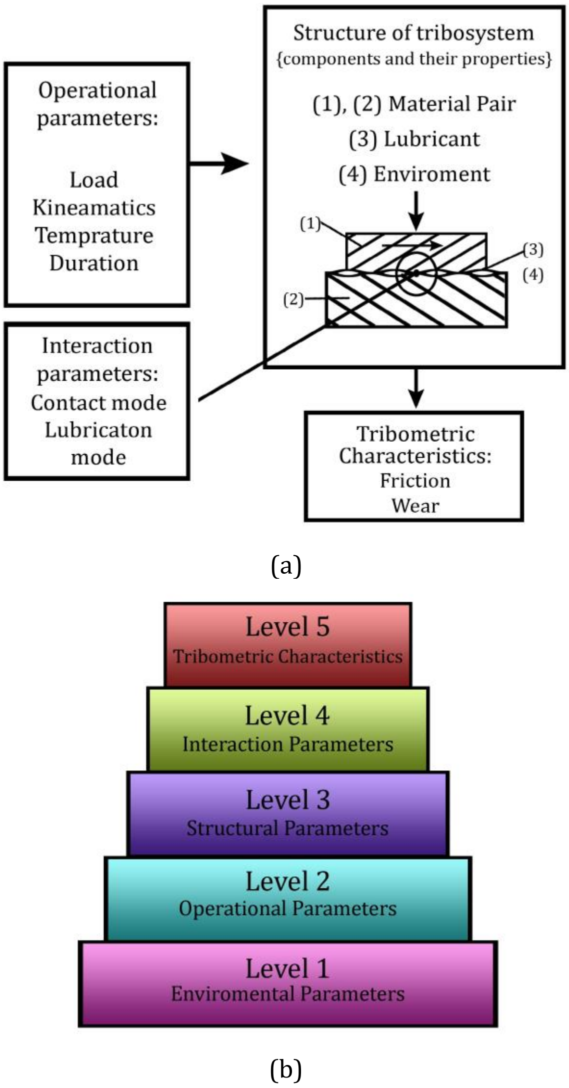

Fig. 9. (a) Existing tribosystem diagram [3,12], b) Level based simplified tribosystem diagram

Previously, various science and technology community studied the concept and application of tribology in design. But, the use of system theory was rarely applied in tribological characteristics analysis. So, in order to understand the system theory in effective way, the simplified tribosystem diagram has been introduced. Recently, it was also observed that the many researcher published research articles related to nanofluid based system to study the tribological properties. In some of these study, different nanoparticle based tribological properties were compared where understanding and application of system in all those studies were missing [29-31]. So tribotesting must be designed in such a way that the tribological data produced in laboratory can effectively be used for further application.

Thus, the novel simplified tribosystem diagram (STD) has been proposed here as shown in Fig. 9 (b). The suggested simplified diagram gives the idea about how various components of tribosystems are inter-related. This simplified hierarchical diagram suggests that the any change in lower level will result in the change at upper level. This means that the alteration at any level from environmental conditions to interaction parameters will affect the results of tribometric characteristics. The performance of any mechanical system will be directly affected by its environmental condition like vacuum, temperature, magnetic field, seawater etc. Equipment designed at atmospheric condition may not work properly when used at higher temperatures. Thus, from design of experiments perspective point of view, the environmental condition (level 1) has to be fixed first. After fixing up the environmental conditions (level 1), the operating parameters like speeds and loads are to be selected. Thereafter, based on operational parameters (level 2) structural parameters (level 3) like tribopairs should be selected. Lastly, to achieve better performance for prolong period of time, tribosystem should be designed considering appropriate interaction parameters (level 4). After finalizing all these parameters, tribometric characteristics (level 5) are to be evaluated by tribotesting of them. In the suggested simplified diagram level 1 is kept broader with respect to level 2 and so on. The reason behind to do so is that any change in lower level can affect the selection procedure of the next level and ultimately it affects the parameter of level 5 which are tribometric characteristics. So, the level-based approach in this fashion gives an idea about the importance of tribological properties with respect to other parameters. It must be remembered that friction and wear are only two basic and widely studied tribometric characteristics. Apart from these characteristics, noise, vibration and so many other parameters are there which can be studied for effective working of the tribosystem [3].

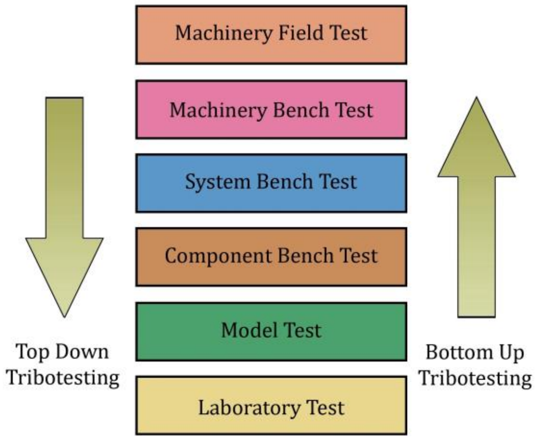

Fig. 10. Scales of Tribotest [4,12].

The extensive research on nanofluids and its applications makes it possible to use nanofluid either in a nano system or in a macro system. In both the cases understanding of this simplified tribosystem diagram helps researcher in designing tribotesting which may help to produce useful data. Moreover, to translate results obtain in the laboratory researchers normally follow bottom-up model for tribotesting. However, in many cases top-down approach for tribotesting successfully applied. Fig.10 illustrate hierarchy of tribotesting with top down and bottom-up approaches. [12, 32].

4. CONCLUSION

From the present experimental analysis using indigenously developed tribometer and past studies, the following conclusions can be drawn:

Tribotesting is carried out in order to check/evaluate compatibility of triboelements for specific tribosystem under different operating conditions based on product's service conditions. And when such different tribosystems are successfully tested, entire product's life cycle improves based on tribological design.

The experimental analysis of friction and wear underlines the importance of fundamentals of tribosystems based on tribotesting.

The proposed tribometer meets the ASTM standard G77 protocol of 95% confidence level as shown by A-D tests and is capable to carry out comparative ranking of tribopairs based on friction and wear analysis.

Further studies will be focused on experimental analysis of nanofluid based tribosystem using indigenously developed instrument where the level-based system theory will be given due importance while designing the experiments.

Acknowledgement

IIT Delhi for faculty summer research fellowship program where author got opportunity to learn about tribology in ITMMEC center. Dr. T.C.S.M Gupta from Apar Industry and Dr. Deepak Kumar from IIT Delhi for their positive feedback towards fabricating inhouse tribometer.

REFERENCES

[1] P.L. Menezes, M. Nosonovsky, S.P. Ingole, S.V. Kailas, M.R. Lovell (Eds.), *Tribology for scientists and engineers,* Springer, 2013.

[2] H.P. Jost, *Lubrication: Tribology; Education and Research*, Great Britain: Department of Education and Science, 1966.

[3] H. Czichos, *Tribology: a systems approach to the science and technology of friction, lubrication, and wear*, Elsevier, 2009.

[4] P.J. Blau, *Tribosystem analysis: a practical approach to the diagnosis of wear problems*, CRC Press, 2016.

[5] K. Kato, *Wear in relation to friction—a review*, Wear, vol. 241, iss. 2, pp. 151-157, 2000, doi: 10.1016/S0043-1648(00)00382-3

[6] P.J. Blau, *The significance and use of the friction coefficient*, Tribology International, vol. 34, iss. 9, pp. 585-591, 2001, doi: 10.1016/S0301-679X(01)00050-0

[7] P.J. Blau, *Friction science and technology: from concepts to applications*, CRC Press, 2008.

[8] M. Varenberg, *Towards a unified classification of wear*, Friction, vol. 1, no. 4, pp. 333-340, 2013, doi: 10.1007/s40544-013-0027-x

[9] P.J. Blau, *Lessons learned from the test-to-test variability of different types of wear data*, Wear, vol. 376, pp. 376-377, 2017, doi: 10.1016/j.wear.2016.11.012

[10] H. Czichos, *The principles of system analysis and their application to tribology*, ASLE Transactions, vol. 17, iss. 4, pp. 300-306, 1974, doi: 10.1080/05698197408981470

[11] D. Klaffke, *Fundamentals of tribotesting*, Tribotest, vol. 6, iss. 4, pp. 373-385, 2000, doi: 10.1002/tt.3020060406

[12] G. Totten, *ASM handbook, Volume 18: Friction, lubrication, and wear technology,* ASM international, Cleveland, 1999.

[13] K.C. Ludema, *Transient processes as impediments to modelling,* Tribology Series, vol. 43, pp. 13-22, 2003, doi: 10.1016/S0167-8922(03)80030-5

[14] Q. Ahsan, A.S.M.A. Haseeb, E. Haque, J.P. Celis, *Wear failure of a leaded bronze bearing: Correlation between plant experience and laboratory wear test data,* Journal of materials engineering and performance, vol. 12, no. 3, pp. 304-311, 2003, doi: 10.1361/105994903770343150

[15] G. Stachowiak, A.W. Batchelor, *Experimental methods in tribology,* Elsevier, 2004.

[16] W.R. Jones, S.V. Pepper, M.J. Jansen, Q.N. Nguyen, E.P. Kingsbury, S. Loewenthal, R.E. Predmore, *A new apparatus to evaluate lubricants for space applications—the spiral orbit tribometer (SOT*), SAE Technical Paper, pp. 1048-1053, 2000, doi: 10.4271/2000-01-1828

[17] S.T. Patton, J.S. Zabinski, *Advanced tribometer for in situ studies of friction, wear, and contact condition—advanced tribometer for friction and wear studies,* Tribology Letters, vol. 13, no. 4, pp. 263-273, 2002, doi: 10.1023/A:1021063326225

[18] S.K. Sinha, S.L. Thia, L.C. Lim, *A new tribometer for friction drives,* Wear, vol. 262, iss. 1-2, pp. 55-63, 2007, doi: 10.1016/j.wear.2006.03.056

[19] E. Sajewicz, Z. Kulesza, *A new tribometer for friction and wear studies of dental materials and hard tooth tissues,* Tribology international, vol. 40, iss. 5, pp. 885-895, 2007, doi: 10.1016/j.triboint.2006.09.006

[20] G. Purcek, H. Yanar, *Development of Multifunctional tribometer: design concept*, Proceedings on Engineering Sciences, vol. 1, no. 1, pp. 31-38, doi: 10.24874/PES01.01.004

[21] K. Holmberg, *Reliability aspects of tribology*, Tribology International, vol. 34, iss. 12, pp. 801-808, 2001, doi: 10.1016/S0301-679X(01)00078-0

[22] B. Bhushan, J.N. Israelachvili, U. Landman, *Nanotribology: Friction, wear and lubrication at the atomic scale*, Nature, vol. 374, pp. 607-616, 1995, doi.: 10.1038/374607a0

[23] C. Zhang, Z.L. Wang, *Tribotronics—A new field by coupling triboelectricity and semiconductor,* Nano Today, vol. 11, iss. 4 , pp. 521-536, 2016, doi: 10.1016/j.nantod.2016.07.004

[24] N.S. Patel, D. Vakharia, G. Deheri, *Hydrodynamic journal bearing lubricated with a ferrofluid,* Industrial Lubrication and Tribology, vol. 69,

iss. 5, pp. 754-760, 2017. doi: 10.1108/ILT-08-2016-0179

[25] ASTM G77-2010, *Standard Test Method for Ranking Resistance of Materials to Sliding Wear Using Block-on-Ring Wear Test*, 2010.

[26] M.D. Petty, *Calculating and using confidence intervals for model validation,* Fall Simulation Interoperability Workshop, pp. 37-47, 2012.

[27] J.P. Davim, *Tribology for engineers: A practical guide,* Elsevier, 2011.

[28] G.W. Stachowiak, *Wear: materials, mechanisms and practice,* John Wiley & Sons, 2006.

[29] S.S. Murshed, P. Estellé, *A state of the art review on viscosity of nanofluids,* Renewable and Sustainable Energy Reviews, vol. 76, pp. 1134-1152, 2017, doi: 10.1016/j.rser.2017.03.113

[30] S. Shahnazar, S. Bagheri, S.B.A. Hamid, *Enhancing lubricant properties by nanoparticle additives,* International journal of hydrogen energy, vol. 41, iss. 4, pp. 3153-3170, 2016, doi: 10.1016/j.ijhydene.2015.12.040

[31] W. Dai, B. Kheireddin, H. Gao, H. Liang, *Roles of nanoparticles in oil lubrication,* Tribology International, vol. 102, pp. 88-98, 2016, doi: 10.1016/j.triboint.2016.05.020

[32] S.M. Muzakkir, K.P. Lijesh, H. Hirani, G.D. Thakre, *Effect of cylindricity on the tribological performance of heavily loaded slow-speed journal bearing*, Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology, vol. 229, iss. 2, pp. 178-195, 2015, doi: 10.1177/1350650114548053