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RESEARCH

Standardization in Tribology

Lorena Deleanu[a,*], Constantin Georgescu[a], George Cătălin Cristea[a,b], Traian Florian Ionescu[a,c], Guglea Dionis[a,d], George Ghiocel Ojoc[a], Dumitru Dima[e], Iulia Paduraru[f]

[a] *Dunarea de Jos University, Faculty of Engineering, Galati, Romania,*
[b] *National Institute for Aerospace Research "Elie Carafoli", INCAS, Bucharest, Romania,*
[c] *Romanian-British School, Galati, Romania,*
[d] *TopConstruct SRL, Cahul, Republic of Moldavia,*
[e] *Dunarea de Jos University, Faculty of Sciences and Environment, Galati, Romania,*
[f] *Dunarea de Jos University, Transfrontier Faculty, Galati, Romania.*

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* Corresponding author:

Lorena Deleanu
E-mail: lorena.deleanu@ugal.ro

A B S T R A C T

This paper presents an analysis of standards applied in tribology, especially concerning materials, test methods and failures of machine components, related to exploitation under load and motion. By the help of their own research and based on open literature, the authors justify the use of standards in tribology, but also the researchers' initiative to develop new and more particular test methods and materials with application in tribology, starting from the already standardized ones. The market asks for products that could be rapidly and efficiently assessed by standards, but laboratory work ask for standards in order to compare old and new, original solutions. Thus, using standards does not block the researchers' work, but helps to point out the new solution and even to develop new materials and test methods that accelerates the introduction of these new solution in actual applications. There are given examples of applying standards in tribology laboratories and how they are used or extend in order to point out a beneficial aspect of the tribological behavior.

1. INTRODUCTION

Definition of tribosystem is clear, but the formulation could be simpler or more detailed. The authors present several variants in order to see the meaning that this system implies interactions caused by movement, load, materials and environment.

In 1978, Horst Czicosh introduced the concept of tribosystem, as a particular system formulated in order to analyze, explain and improve it by tribological characteristics (friction, wear and all processes caused by tribological actions). The trybosistem should be characterized by its structure (components, properties of them and their interaction inside the system) and by its functions (inputs, outputs and functions that allow for transferring input parameters as output parameters in order to fulfil the scope of the system [1]. Inputs having a bad influence of outputs were named "disturbances" (vibrations, not-beneficial external thermal sources, materials called impurities etc.). The outputs have to be analyzed as a set with required parameters (functions) and intrusive ones or losses (loss of energy by friction, heating etc., loss of material by wear and loss of qualities, such as viscosity modification for fluid, structural and shape changes for solid bodies etc.).

A year later, Deutsches Institut fur Normung had released, DIN 50320:1979 Wear Terms Systematic Analysis of Wear Processes Classification of Wear Phenomena. DIN 50322:1986 Wear, wear testing categories also clarified the concept of tribosystem but also explained terms related to tribology. Even withdrawn now, these pointed out the organization on levels for tribosystems, level ranking being promoted also by professor Czicosh [1,2].

In Romania, tribology was promoted by professor Dan Pavelescu [3], professor Nicolae Tipei [4] and professor Ioan Crudu [5] and standards, especially related to wear, were elaborated or adopted as Romanian standards by the Romanian Institute for Standardization (now, ASRO [6]) more of those before 1990 being withdrawn [7], but several are still active [8].

Peter Blau, coeditor-in-chief of Wear journal has a PhD in metallurgical engineering from Ohio State University, hold a position at the now the National Institute of Standards and Technology (NIST), defined the tribosystem as a tribological system that consists of at least two contacting bodies and any environmental factor that affects their interaction [9].

The American standard ASTM G40-17 defines the tribosystem is "any system that contains one or more triboelements, including all mechanical, chemical and environmental factors relevant to tribological behaviour" [10]. The triboelement refers to "one of two or more solid bodies that comprise a sliding, rolling, or abrasive contact, or a body subjected to impingement or cavitation.

„Like other detrimental influences on material performance, such as corrosion or biodegradation, both friction and wear result from exposure of the material to a particular set of conditions. They do not therefore represent intrinsic material properties, but are ''system dependent attributes'' of tribosystems and must be measured under well-defined test conditions" [11].

Decomposability is a characteristic that help tribologist to organize a system in subsytems, of different levels, and that could be analyzed and improved as tribosystems.

Do we need standards/norms in tribology? This is a basic question to get an answer in this paper. The authors respond with a strong YES.

And the arguments are as following. For a tribosystem, there could be different solutions concerning selection of materials, their shapes, based on their tribological performances. The users are interested in saving money, energy and maintenance time, in increasing operating regimes in order to increase productivity. Thus, the tribological characteristics should be evaluated, based on the same norm or standards. Even if the researchers would like to perform particular tests, adapted for a particular tribological application, they have to compare the former solution with their new one. It is high probability that the old solution to have been tested under standard conditions. Thus, in order to point out their new solution, they have to test it according to standards because the former information will become a reference to which they compare to. They could report a new test method, supplementary to the standard ones to point out specific tribological characteristics of the new proposed design. Examples of promoting standards for a more convenient and largely accepted study and assessment of tribological features are ASTM G77-98 Standard Test Method for Ranking Resistance of Materials to Sliding Wear Using Block-on-Ring Wear Test [12] and ISO 14577-1, Metallic Materials. Instrumented Indentation Test for Hardness and Materials Parameters. Part 1: Test Method [13].

In 2022, Garabedian et al. [14] introduced a concept about data reported in tribology, FAIR data, meaning "Findable, Accessible, Interoperable and Reusable" data, and this team agrees that there is a lack of data base that could improve knowledge on tribological processes and phenomena. The team mentioned an example for the pin-on-disk tests.

2. CASE STUDIES

2.1 ISO 14830-1:2019 Condition monitoring and diagnostics of machine systems

The word “tribology” is found in only one standard title, ISO 14830-1:2019 Condition monitoring and diagnostics of machine systems — Tribology-based monitoring and diagnostics — Part 1: General requirements and guidelines [15]. But it does not mean that tribological characteristics are not included in standards. Words like wear, friction, lubrication or lubricants are subject of interest in standards.

Which standards are needed in a design based on tribological criteria like reducing wear or and/friction, damages caused by motion under load, with or without lubrication? Figure 1 presents the tribosystem and how engineering could analyse it.

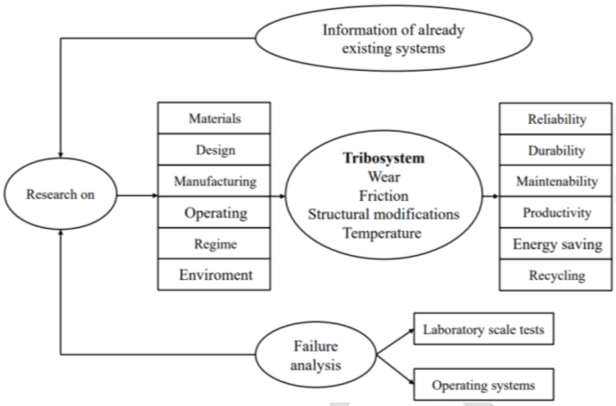


Fig. 1. Factors took into account when conducting a research or an investigation on a tribosystem.

And it is useful to list family of standards related to design exploitation and testing having in mind tribological aspects:

- standards for materials and coating,
- standards for evaluating failure of components,
- standards related to components design (gear, rolling bearings, sealings, chains etc.)
- standards related to manufacturing related to surface quality that is of exquisite importance in tribocontacts,
- standards related to lubricants and their performances,
- standards that offers methods of mea-suring wear of particular friction couple,
- standards for ranking couple of materials based on tribological parameters obtained by laboratory method or/and simplified tribotesters,
- standards for evaluating the durability of lubricants,
- standards for characterizing surface quality (defining roughness and waviness parameters), only recently used in evaluating worn surfaces.

Standards for evaluating failure of components present test methodologies for actual parts of the systems and the market has been asking for them because of the important role place of these components for their reliability, durability, safety and price. There are several examples: ISO 24469 Road wear test of studded tyres (under development) [16], ISO/AWI 14242 Implants for surgery — Wear of total hip-joint prostheses with four parts [17], ISO 23160:2011 Watch cases and accessories — Tests of the resistance to wear, scratching and impacts [18], ISO/CD 10545-22 Ceramic tiles — Part 22: Determination of resistance to wear with a multi-attribute method [19] etc.

An inventory of keywords related to tribology, (Table 1) revealed that there are not so many standards for this field, 1065, this representing only 4.30% of the number of ISO standards, 24728 in 18.04.2023 [20].

Table 1. Words related to tribology, in ISO standards titles.

Term	Number of ISO standards
Tribology	1
Friction	141
Wear (all)	270
Friction and wear	19
Lubricants	200
Damage	316
Friction coefficient	20
Four ball	2
GPS, surface	85
Tribological	11

The newest standard related to tribology is the only standard that has the word "tribology" in title, ISO 14830-1:2019 Condition monitoring and diagnostics of machine systems. Tribology-based monitoring and diagnostics. Part 1: General requirements and guidelines. As one may notice this could have more than one part dealing with diagnosis and survey of systems that have to pay attention to tribological processes and phenomena.

The machine monitoring is very important that evolution of parameters could announce a severe failure or an abnormal functioning. This standard proposes that tribology and lubricant-based monitoring "comprising the activities of monitoring, reporting and responding to information obtained from the analysis of lubricating oils, hydraulic fluids and greases" could help in increasing reliability and durability of systems. Nowadays, the monitoring of tribosystem is easier to do, due to very adaptive instruments to measure very complex characteristics that have been developed, but the accent is on lubrication system and lubricants, not taking into account other tribological aspects [10].

Part 2 is still under development, ISO/PWI 14830-2 Condition monitoring and diagnostics of machines systems — Tribology-based monitoring and diagnostics — Part 2: Wear debris analysis [21]. The subject has been in the researchers' focus for more than a half century, as wear debris analysis could help having a realistic diagnosis on malfunctioning and failure of the tribosystem [22-25].

2.2 Four ball tests and ISO 20623:2017

ISO standard related to the four-ball tribotester is only one, ISO 20623:2017 Petroleum and related products. Four-ball method (European conditions) [26] A very similar standard is promoted in USA: ASTM D2266-01 (2015) Standard test method for wear preventative characteristics of lubricating grease (four-ball method), Determination of the extreme-pressure and anti-wear properties of lubricants [27]. But the testing methodology is similar in ISO 26422:2014 Petroleum and related products. Determination of shear stability of lubricating oils containing polymers [28]. This method uses a tapered roller bearing. And the results allow for predicting the permanent viscosity loss of an additivated lubricant in service. This parameter, viscosity modifications caused by using a lubricant in high-shear rate regime is important and it is the subject of another standard ISO 20844 [29], but the test method implies lower shear rates that are not realistic for tribosystems like gears, chains, sliding bearings and roller bearings.

First edition of ISO 20623 was released in 2003, even if the four-ball test, initially developed by Shell Oil Company, also named Shell test, has been known and applied several decades before this first edition of the standard.

Other organizations of standardization have standards using the four-ball tester:

- ASTM D2783: EP Test for lubricating fluids [30],
- ASTM D2596 for grease [31],
- IP 239:2020 Determination of extreme pressure and anti-wear properties of lubricating fluids and greases. Four ball method (European conditions) [32],
- DIN 51350-02: Extreme pressure properties test for liquid lubricants [33],
- ASTM D4172:21 Standard Test Method for Wear Preventive Characteristics of Lubricating Fluid (Four-Ball Method) (ASTM D2266:01 being dedicated to greases) [34, 35],
- ASTM D5183:21a Standard Test Method for Determination of the Coefficient of Friction of Lubricants Using the Four-Ball Wear Test Machine, with a method for measuring the coefficient of friction of lubricants [36],
- DIN 51350-03: Testing of lubricants - Testing in the four-ball tester - Part 3: Determination of wearing characteristics of liquid lubricants [37].

The American standard ASTM D2783 [30] recommends this method for determining two parameters, load-wear index (formerly Mean-Hertz load) and weld point by means of the four-ball extreme-pressure (EP) tester.

ISO 20623:2017 modified the first edition by

- enlarging the types of lubricants to all liquid ones, including greases, whereas the first edition was applied “only to fire-resistant hydraulic fluids” [26],
- refining the procedures,
- specifying better the ball material, “chromium steel AISI 52100 — EN 10027 100CR6 (1.3505)”,
- including calculations for wear test parameters,
- deleting the calibration procedure of the friction recorder springs because the producers of four-ball machine [38-42] could offers their own solutions for measuring the friction coefficient and other test parameters (angular speed, load etc.).

The standard ISO 20623 recommends four parameters, one less than the American standard (which defines LNSL), but the international standard defines the initial seizure load as the lowest force for which seizure occurs. ISO 20623:2017 intended to give test methodology using four-ball machine for determining extreme-pressure and the anti-wear properties for all types of lubricants, based on a single rotational speed of 1450 r/min.

Table 1 gives the test conditions of standards that use four-ball tester. The American standards were revised in 2020-2021 and in this table conditions for American standards are those before their last revision. Table 2 presents the parameters that are measured or calculated using the four-ball machine. Even if there were selected a few documents, it is obvious that research enlarges the testing parameters in order to point out particular tribological behaviour of lubricants and even ball material.

The mean wear scar diameter (MWSD) remains a relevant parameter of the test, but there are parameters that are measured or calculated in order to emphases the differences in tribological behaviour of the tested lubricants, including friction coefficient, the wear rate of the MWSD, the temperature evolution during the test or at the test end.

Table 2 . Lubricant properties evaluation by the different methods.

Standard	Lubricant property
ISO 20623	LWI, WL, ISL, MWSD
ASTM D2262	MWSD* under 392 N load
ASTM D4172	MWSD* (mm) for 147 N to 392 N
ASTM D2596	WL (N), LWI (N), LNSL (N)
ASTM D2783	WL (N), LWI (N)
IP 239	WL (N), LWI (10 s or 60 s), ISL (N), MWSD* (mm) (10 s, 60 s or 60 min)
DIN 51350-2	WL (N)
DIN 51350-3	MWSD* (150 N or 300 N, 60 min)
DIN 51350-4 [43]	WL (N)
DIN 51350-5 [44]	MWSD* (150 N, 300 N or 1 000 N)

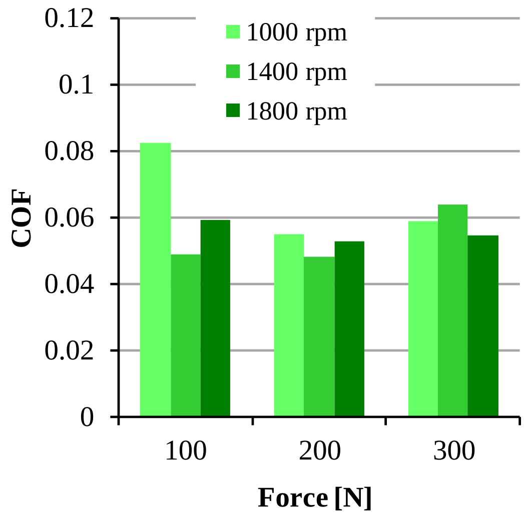
*MWSD – an anti-wear characteristic, mean wear scar diameter, for short duration (10 s or 60 s) and long duration (60 min), WL – load-wear (curve), LWI – load-wear index, LNSL - last non-seizure load, ISL – initial seizure load.

The friction coefficient (COF) could be reported as:

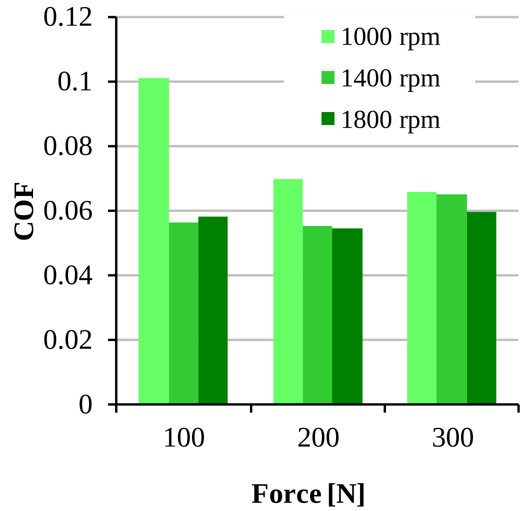
- the average value of all values recorded during the test, this being of interest for systems that start and stop frequently,
- extreme values, maximum and minimum, the first being of more interest in selecting motors actuating the tribosystem,
- the average value during last 5 minutes or 10 minutes of the test (this is of interest as representative for a stabilized regime).

Figure 2 presents the average values of COF for the rapeseed oil, tested following the procedure in ISO 20623:2017, but with different rotational velocities, test duration being 1 h. Also, for the easy of results analysis, the rotational velocity of the main shaft of the four-ball tester was selected at 1400 rpm, this being a deviation of -3.44% of the standard one, 1450 rpm, considered acceptable.

What parameters were kept from the standards? The time of a test was 1 h; of course, the sliding distance is longer for the higher rotational velocity (1800 rpm) and lower for 1000 rpm. The balls have the parameters recommended in standards and they were supplied in set of 4 balls by SKF and the quantity of lubricant was that mentioned in standard.



(a) Average values for all test duration



(b) Average values for the last 10 minutes

Fig 2. Friction coefficient of soybean oil

Thus, only the tests done at 1400 rpm could be considered in agreement with the standard. The other tests were proposed to point out that soybean oil has a good behavior from the friction point of view, except for low force (F=100 N) and low velocity (1000 rpm). Also, giving values for the last 10 minutes and comparing them to average values on the entire test, the researcher [45] point out that this vegetable oil has very short running-in period that do not influence the average value of COF, meaning this oil generates a partial or full film even from the beginning of the operating time. This is a characteristic of many vegetal oils, also mentioned by [46-48].

Many researchers have enlarged the range of sliding velocity in order to assess the tribological behaviour of lubricants, knowing that velocity is a key-factor in generating the fluid film that would reduce both friction and wear [49, 50, 51]. But test conditions in already published scientific papers are so different that a comparison of the results is difficult to be done. For instance, Table 3 presents several research reports with results obtained on four-ball machine and the test conditions.

The standards dealing with tests on four-ball machine (Table 4) recommend methods with different output parameters, determined for specified test conditions or ranges of the input parameters (lubricant, rotational speed, load, duration, fluid temperature or enclosure temperature).

Table 3 . Conditions in four-ball tests from relevant references.

Lubricants / additives/ lubricant temperature	Balls	Velocity [rpm] or [m/s]	Load [N]	Time	Reference / Year
Rapesed oil, olive oil, soybean oil, corn oil	SKF, as in standard ISO 20623:2017 Φ12.7 mm ±0,0005 mm HRC 62	800 rpm (0.30 m/s), 1200 rpm (0.46 m/s)	140 N, 200 N, 260 N;	1 h	[46]
Soybean oil (black carbon, graphene, graphite)		1000 rpm 1400 rpm 1800 rpm	100 N, 200 N, 300 N	1 h	[45]
Rapeseed oil (ZnO, TiO_2)			100 N, 200 N, 300 N nonseizure load 850 N	1 h 60 s	[47]
Rapeseed oil (h-BN, graphene, h-BN+graphene)		600 rpm, 1000 rpm 1400 rpm 1800 rpm 2200 rpm	100 N, 200 N, 300 N	1 h and L=ct (1933 m)	[48]
			nonseizure load 850 N	60 s	
Transol 150 oil	ball hardness 24–62 HRC	1450 rpm	till 800 N, in steps	10 s	[52]
gear liquid paraffin base oils Sulphurized isobutylene (SO) and dibutyl phosphite (DBP) initial oil temperature, 20 °C	GCr 15 steel Φ12.7 mm	1500 rpm (0.576 m/s)	40 kgf	20 min	[53]

PAO6 / Carbon quantum dots doped with silver / 10 °C, 100 °C, 200 °C, 300 °C	GCr15 steel* Φ12.7 mm, 62-64 HRC	1450 rpm	392 N	0.5 h	[54]
			Non-seizure load	10 s	
Transesterificated soybean oil, room temperature	Φ12.7 mm, 68 HRC, steel EN31	1200 rpm	392 N	1 h	[55]
refined, bleached, deodorised palm kernel oil (CuO and graphite) /at 75°C	Φ12.7 mm, AISI 52100 steel, 64–66 HRC	1,200 rpm	392 N	1 h	[56]
palm kernel methyl ester (viscosity improver ethylene-vinyl acetate copolymer), 35°C		1760 rpm	40 kgf till failure	10 s	[57]
lithium grease, 150N oil / stearic acid modified TiO2	Φ12.7 mm	1,200 rpm	196 N		[58]
Microemulsions: hydrogenated base oil + (water + 0.03 mol/L Na_2SO_4 and emulsifier)	Not reported ASTM D4172	Not reported ASTM D4172	392 N	30 min	[59]
Base lubricant not specified SiO2-coated WO_3 nano-particle (~70 nm), 75°C.	Not reported	1,200 rpm	147 N	60 min	[60]
10w40 oil / nano-Ag/MWCNT / 75 ± 1 °C	GCr15 steel*, Φ12.7 mm, 61–65 HRC.	1,200 rpm	392 N,	1 hour	[61]
mineral and synthetic ester base oils /copper nanoparticles / 75°C	ASTM D4172	1200 rpm (0.46 m/s)	392 N	1 h	[62]
hazelnut oil /zinc dialkyl-dithiophosphate (ZDDP) / 75°C, 27-62°C (severe test)	Φ12.7 mm HRC 64.98	1,200 rpm	392 N	3,600 s	[63]
		1,7606±40 rpm	6 kgf – 800 kgf	10 s	

*Steel GCr15 (China standard); MWCNT – multi-wall carbon nanotubes

Table 4 . Test conditions of standards that use four-ball tester (adapted from [26]).

Standard	Lubricant	Type of test	Load (N)	Duration	Rotational speed (rpm)	Temperature, °C
ISO 20623:2017	**any**	Test A – Load-Wear Index (LWI)	400 ± 5 N (start) Until ball welding	10,0 ± 0,2 s or 60,0 ± 0,5 s	1450	Not specified
		Test B – wear-load (curve)	100 N steps up to 1 000 N 250 N steps up to 3 000 N 500 N steps up to 8 000 N	10 ± 0,2 s or 60 ± 0,5 s		
		Test C – wear, liquid grease	100 N and 300 N 100 N, 300 N, 1000 N	No time imposed		
ASTM D2266	Grease	Wear	392	60 min	1 200	75
ASTM D4172	Oil	Wear	147 (A) 392 (B)	60 min	1 200	75 75
ASTM D2596	Grease	EP	59 to 7 848 N	10 s	1 770	19 to 35
ASTM D2783	Oil	EP	59 to 7 848 N	10 s	1 760	18 to 35
IP 239	Grease — oil	Wear EP	60 to 7 940	60 min 10 s or 60 s	1 450	Not specified
DIN 51350-2	Oil	Weld load	2 000 N to 12 000 N	60 s	1 450	18 to 40
DIN 51350-3	Oil	Wear	150 (A) 300 (B)	60 min	1 450	18 to 40
DIN 51350-4	Consistent lubricant	Weld load	2 000 to 12 000	60 s	1 450	18 to 40
DIN 51350-5	Consistent lubricant	Wear	150 (C), 300 (D) 1 000 (E)	60 min, 60 min 60 s	1 450	18 to 40

EP – extreme pressure

These outputs could be determined for quality control during production and asked for the same reason by clients or other involved parts (as professional associations, organization of consumers and environment protection). Of course, researchers may add input parameters (as, for instance, additive concentration), and may use different ranges of input parameters as compared to those in standards, may change test principle, for instance, introducing the constant sliding distance and not duration for a test, for evaluating lubricants at different rotational speeds or changing the material the balls are made of (specialists are interested in ceramic or composite balls). Several studies introduced analyses of 3D roughness parameters measured or calculated for the entire wear scars on the fixed balls, as in [45,47].

Table 5 presents the average value of MWSD for two sets of tests, one with test duration constant (1 hour), the other one with sliding distance constant (L=1933 m, this corresponding to 1400 rpm or a sliding velocity of 0.53 m/s, conditions that could be considered very close to those in ISO 20623:2017). For lower sliding velocity than 0.53 m/s, here 0.38 m/s, an increase with 29.22% of the sliding distance, produced an increase of MWSD with 5.96% for F=100 N, with 23.27% for F=200 N and with 19.56% for F=300 N. For higher velocity than 0.53 m/s, the difference between MVSD for constant duration test and constant distance test are very small [48], this could be explained by the fact that a higher velocity is more favorable to generate continuous fluid film and, thus, to reduce abrasive wear induced by direct contact between balls.

Table 5 . Values of MWSD for tests with 1 h and tests with L=ct [47].

Force [N]	WSD [mm]		
	0.38 m/s		0.53 m/s
	t=ct (1 h) L=1368 m	L=ct L=1933 m	t=ct (1 h) L=1933 m
100	0.331	0.352	0.381
200	0.412	0.537	0.528
300	0.518	0.644	0.621

From this example, it is obvious that test conditions have to be clearly mentioned in a scientific report in order to compare them to other results in the literature.

Also, there could be reported consequences of other parameters related to the test:

- evolution of roughness parameters on the wear scars, depending on test conditions (velocity, load, environment or/and lubricant temperatures) [45, 47],
- wear rate of the MSWD, defined as

$$w(\mathrm{MWSD}) = \frac{\mathrm{MWSD}}{\mathrm{F}\times\mathrm{L}}, \quad (1)$$

where F is the load on the tribotester and L is the sliding distance during the test; this is a relevant parameter for tests with the same duration (usually 1 h), but with different sliding velocities [64,65],

- oil film strength (OFS) or lubricant film strength (LFS), defined as

$$\mathrm{OFS} = \frac{0.409\times F}{A_{MWSD}}, \quad (2)$$

where F is the load applied on the four-ball tester and $A_{MWSD} = \pi \times MWSD^2/4$ is the equivalent area of the wear scar, considered as a circle with the value of MWSD for the load F.

OFS correlates influence of several characteristics of the lubricant and solid bodies in contact under load [66]:

- finishing quality of the surfaces (roughness);
- shear stress within the lubricant film;
- viscosity change due to temperature characterizing the stable regime.

Figure 3a presents the average values of MWSD for two tests. Even if there are plotted on the same figure, only the values for the same velocity can be compared, the standard value for the sliding velocity being 0.53 m/s, corresponding to 1400 rpm at machine shaft.

For the same velocity, it is obvious that MWSD is proportional to load. For the other two sliding velocities, the sliding distance run for 1 h is different. In order to compare the wear in this type of tests, another parameter is introduced, the wear rate of MWSD, w(MWSD) (Fig. 3b).

One may notice that the lower values are obtained for the higher values of both load and velocity and that high wear rate of MWSD is for the lowest tested velocity (0.38 m/s), meaning that, for the same sliding distance, the lower rate of MWSD of the balls is obtained for operating with high load (F=300 N) and high velocity (v=0.69 m/s).

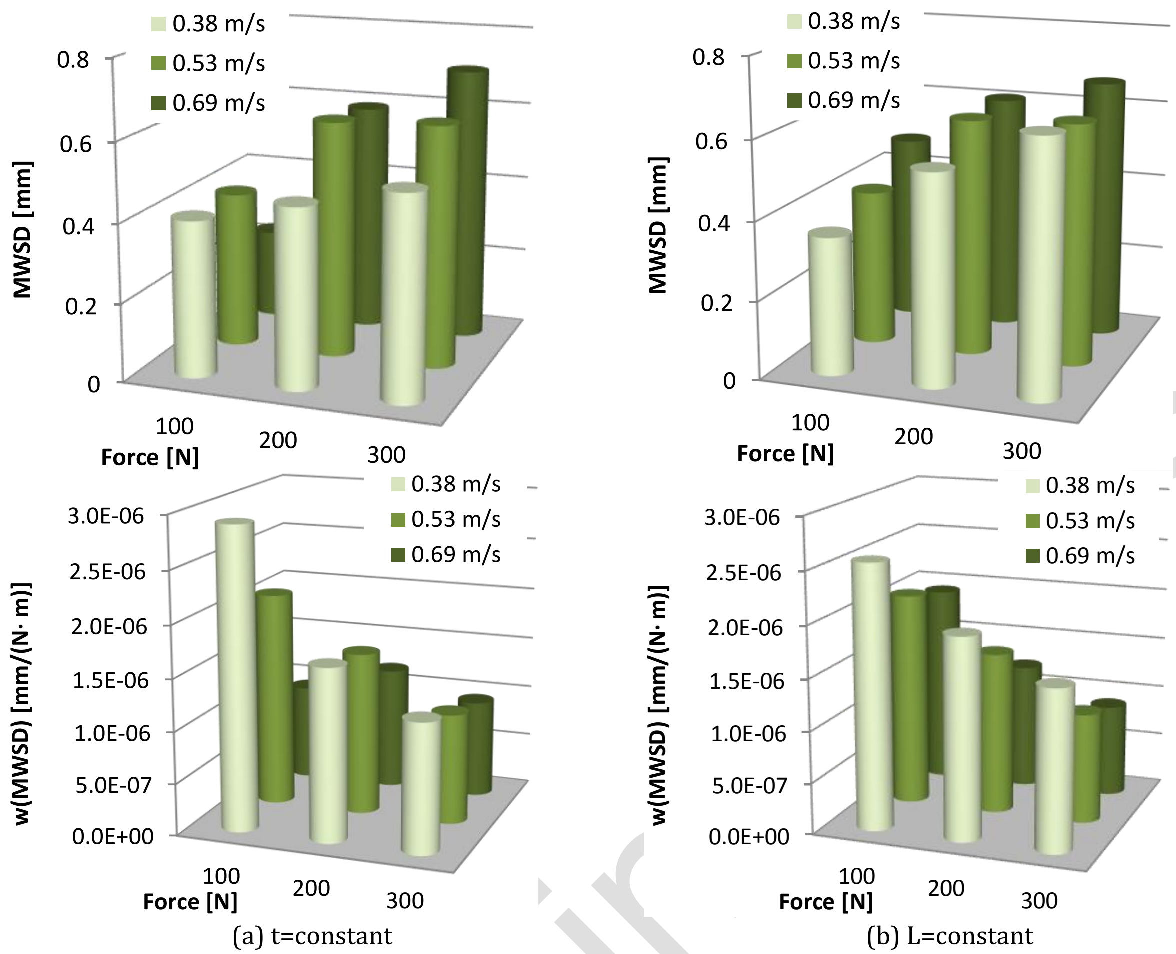


Fig. 3. Comparison of wear parameters for test done with t=ct (1 h) (left graphs) and tests done with L=ct (1993 m) (right graphs); tested lubricant: rapeseed oil [47,48].

2.3. Wear tests

One of the most used tribotester for dry or lubricated contact is pin-on-disk, included in the American standards, ASTM G133-22 Standard Test Method for Linearly Reciprocating Ball-on-Flat Sliding Wear [67], ASTM F732-17 Standard Test Method for Wear Testing of Polymeric Materials Used in Total Joint Prostheses [68] and ASTM G99-17 Standard Test method for wear testing on a pin-on-disk test apparatus [69].

ISO elaborated similar standards for this test, namely, ISO 7148-1:2012 Plain bearings. Testing of the tribological behaviour of bearing materials. Part 1: Testing of bearing metals [70] and ISO 7148-2:2012 Plain bearings. Testing of the tribological behaviour of bearing materials. Part 2: Testing of polymer-based bearing materials [71]. Now these are revised and they will be released taking into account up-to-date references and progress in measuring and calculated tribological parameters.

Like ISO 7148, ASTM G99-17 describes the test procedure and tribotester, but they do not introduce constraints for researchers that would like to modify test configurations and parameters in order to report original or/and adequate tests for the application in view.

“Wear results are usually obtained by conducting a test for a selected sliding distance and for selected values of load and speed” [69]. A report on interlaboratory measurement series has a ball-on-disk tester and the test conditions were: F=5-10 N, v=0.1 m/s (very low considering possible applications of such contact), T =23 °C, relative humidity 12% to 78 %; laboratory atmosphere; sliding distance 1000 m; wear track (nominal) diameter R=32 mm, materials: steel AISI 52 100 and alumina α-Al_2O_3.

This type of test has the objective to rank the friction couples, lubricated or not, and to evaluate, at least qualitatively, the influence of test parameters. This method, like many other test methods, does not try to analyse all the actual conditions characterizing the operating regime of an actual tribosystem. As the test has characteristics that are not met in practice (such as ratio of contact area to friction path that is very small as compared to actual ones, different shapes and volumes, usually larger, of the triboelements). Even if there is a ball or a cylinder on plan contact in actual applications, the heat generating by friction would have different influence on the mechanical properties of the solid bodies and lubricant, especially when dealing with polymeric materials that are poor thermal conductive, the results of the tests could not be the same with those obtained in real exploitation of the tribosystems, but, usually, the test tendency will be kept and also the damages at micro-level are similar.

Test conditions may be modified, depending on the researcher's objective.

Even if the tester has only two simple components, a disk and a pin, both of cylindrical shapes, there are numerous factors influencing its tribological behaviour. Specialists recommend to design a test plan and the bodies in contact (pin and disk) to approximate, as much as possible, the actual contact. The parameters that have to be taken into account when using this type of tribotester are:

- pin shape: the standards do not impose its shape, but, usually, it is a sphere, a cylinder, rarely a lens,
- the friction couple: as there is two bodies in contact, it could be three cases: both bodies are made of the same material (it is not usual), the disk is made of the harder material (for instance, steel) or the pin is made of the harder material (usually this pin is made of steel, cylindrical rollers from rolling bearings); the tribological behavior for the same pair of materials is different depending on which material is used for each triboelement, especially for materials with high difference in hardness. When using the softer material for manufacturing the pin, the wear is "faster" for it, its shape is changing, thus, modifying the pressure distribution on contact area; if the disk is made of the softer material, than a ploughing wear track will be generated;
- the position of the pin related to disk: pin and disk axis are overlapped only for reciprocating tests, but for sliding tests, the pin axis is positioned at a certain radius from the centre of the disk. The issue is that the relative sliding velocity between pin surface and disk surface is not constant: the most outlying point of the pin from the disk axis will have the highest velocity and the nearest point of the pin to the disk axis will have the lowest velocity. Results are reported to the sliding velocity of the pin centre, but this influence is more severe when the pin has large diameter (d) and the disk has a small diameter (D), meaning that their ratio, d/D, will influence the results; this influence is lower for lubricating contact if the fluid film is generated,
- disk location; if the pin is on the top of the disk, the wear debris will have the tendency to be re-engaged in contact; if the disk is positioned above the pin, these debris will fall ant this arrangement avoid the re-entrance of debris in contact,
- the thermal effect: for the same pair of materials, the radius of pin to the disk centre is important. Greater the radius, cooling of the contact area is more effective, as the time between contacting the same position on the disk is longer and heat generated by friction could be more efficient evacuated. For metallic materials this influence is lower, but for polymeric material it could be very important. But the disk dimensions are constraint by tribometer design, manufacturing method, thermal properties of the materials in contact (knowing that polymeric materials have poor thermal conductivity as compared to metallic ones),
- regime parameters, here including especially the different sliding distance and environment from standard laboratory values. For instance, standards recommend 1500 m of sliding, but there were reported longer sliding distance for friction couple that have low wear rates or damage processes that occur with an incubation period long enough to overpass 1500 m.

To overcome these inconveniences, there is another test for ranking materials, using their tribological characteristics, ASTM G77-17 [72], with block-on-ring test. The advantage is that the rotational component is usually an external ring of a tapered rolling bearing and the block has small dimensions, allowing for investigations at micro scale by electron scanning microscopy, energy-dispersive X-ray spectroscopy etc.

ISO 7148-2:2012 [71] proposes five types of tribotester for sliding movement, that may be used for any combinations of materials, but especially for friction couple that has at least one body made of polymeric materials (polymers, blends, composites):

- test method A - pin-on-disk,
- test method B - block-on-ring,
- test method C — plain bearing-on-shaft,
- test method D — sphere-on-prism,
- test method E — rotation under thrust load.

For pin-on-disk, the material of interest could be used to made either the disk or the pin. The results of these two cases could very a lot. For instance, Maftei [73] conducted a study for evaluating the influence of adding micros glass beads in PA6 and the disk was manufactured from this polymer or its composites and the pin was a roller from a cylindrical roller bearing, made of steel grade for rolling bearing.

Andrich et al. [74] reported results on block-on-ring tester for composites based on carbon fabrics and polymers, with these test parameters: normal force F= 100 N, sliding speed v=0.13 m/s, the dry sliding distance being L=9504 m. Contact length was 10 mm. These testing conditions guarantee a maximum mean temperature of the block specimen of 50 °C.

Pin or ball-on-disk could be also used for evaluating the tribological behaviour of lubricants.

The influence of additives (nature, concentration, size) on greases have been investigated on a block-on-ring tester in [75]. There were studied the tribological characteristics when adding MoS_2 and CaF_2 in a lithium soap grease. Test parameters were: 200 rpm to 800 rpm, meaning v=0.53 m/s to 2.5 m/s, and contact loads of 72 N, 108 N and 144 N, test duration 600 s, meaning that wear should be compared by wear rates, not by direct material loss of the block as sliding distances depend on sliding velocity.

Constantin Georgescu [76] reported results on block-on-ring testing of PBT and PBT-base materials (blends with PTFE, composites with micro-glass beads and a hybrid polymeric material with 10% PTFE and 10% glass beads), for different sliding distances (2.5 km, 5.0 km and 7.5 km), closer to actual applications as compared to other sliding distances ranged between 1500-2500 m (Figure 4).

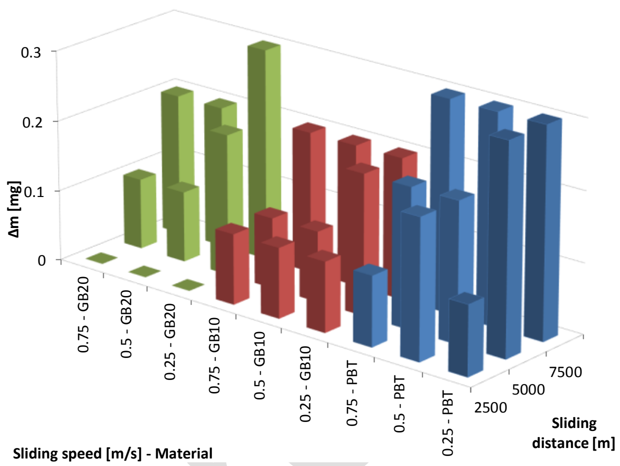


Fig. 4. Wear as mass loss of the block, from tests with steel ring and block made of PBT-base materials: PBT – polybuthylene terephthalate, GB10 – composite PBT + 10%wt micro glass beads, GB20 – composite PBT + 20%wt micro glass beads [76].

Test conditions were: contact length of 4 mm, sliding speed 0.25 m/s, 0.5 m/s and 0.75 m/s, normal load being 1 N, 2,5 N and 5 N. Except for the composites with 20%wt glass beads that has a very low wear in test of 2500 m, the mass loss of the block is lower as compared to the composite with 10%wt glass beads, for this one the influence of sliding velocity being almost indistinguishable on the plot in figure 4.

Ball-on-disk tribometer was used for a sliding distance of 2500 m, for evaluating the wear and friction of the ball made of bio-ceramics and disk made of rolling bearing steel [77], the test parameters being 6 mm track radius, under loads of 3 N, 6 N and 10 N), and sliding velocity of v=0.25 m/s.

Zhao et al. [78] reported the influence of adding 0.05 wt% graphene, 1 wt% ZDDP and their mixtures in PAO4 base oil. The tests were carried out on a ball-on-disk tribotester, with reciprocating movement, under normal force of 30 N, 80 N, 155 N and 310 N. The result revealed that the friction coefficient of graphene/ZDDP blend was slightly higher than that obtained with PAO4 oil under high load and wear was much reduced for all test parameters, the wear rate being lower with 77% as compared to that of PAO4 oil, under a normal force of 30 N.

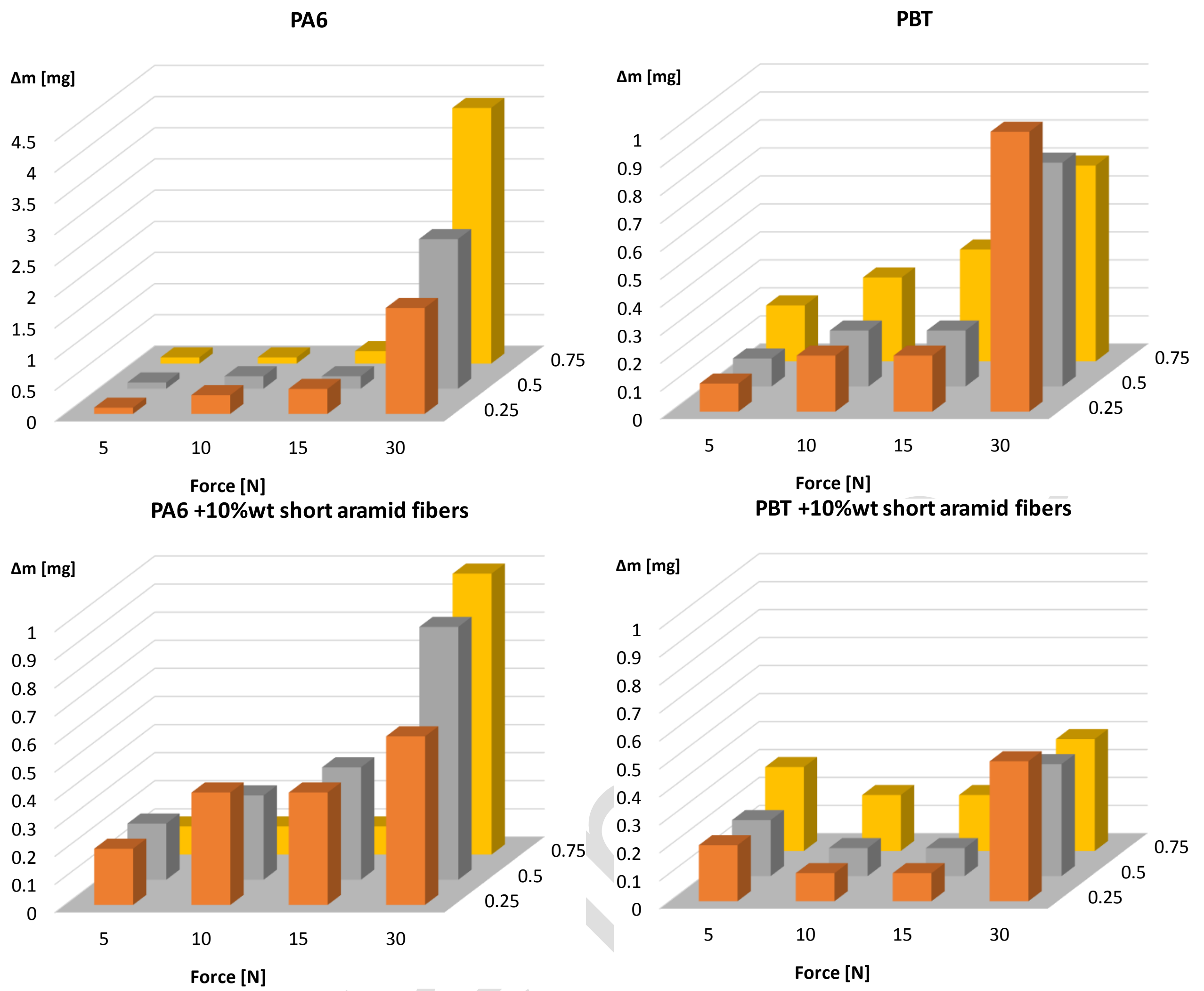


Fig. 5. Results of block-on-ring tests, done for a set of values for normal force and sliding velocity, the sliding distance being 5000 m [79].

Mihail Botan [79] used the same tribosystem [76], block-on-ring with 4 mm line contact between polymeric block and steel ring, to test the addition of short aramid fibres in matrices made of PA6 and PBT, respectively, for 5000 m dry sliding distance (figure 5). The test results pointed out that, for this tribosystem, load of 30 N caused a severe wear, higher for the composites with PA6 matrix and that influence of sliding velocity on wear is lower for the composites with PBT matrix. Thus, the composite made of PBT and 10% aramid fibres had a better tribological behavior, especially for wear and this could replace components made of PA6 with the same reinforcement.

3. INVESTIGATING TRIBOLOGICAL FAILURE AND STANDARD TERMINOLOGY

There are standards that propose terms and definitions of tribological failures, even if there are variants of naming and explaining damages in triboelements.

Here, we mentioned the definition of failure, given by Tallian [80]: "a failure mode is the physical condition of a component resulting from a specific physical failure process". The author of the relevant "Failure Atlas for Hertz Contact Machine Element" classified failures related to the investigated machine component and its specific design, materials and operating conditions. There are catalogued six types of tribological failure: wear, with two variants (mild and severe – galling and skid marking), fretting wear, spalling (hertzian contact fatigue) and surface distress (surface fatigue). This is quite different from Table 7, presenting types of wear, but sections allocated to these failures are very detailed in describing the damage appearance, causes and remedies for reducing damage and increasing the machine component durability.

ASTM G40-22 Standard - Terminology Relating to Wear and Erosion has "the purpose ... to encourage uniformity and accuracy in the description of test methods and devices and in the reporting of test results in relation to wear and erosion" [81].

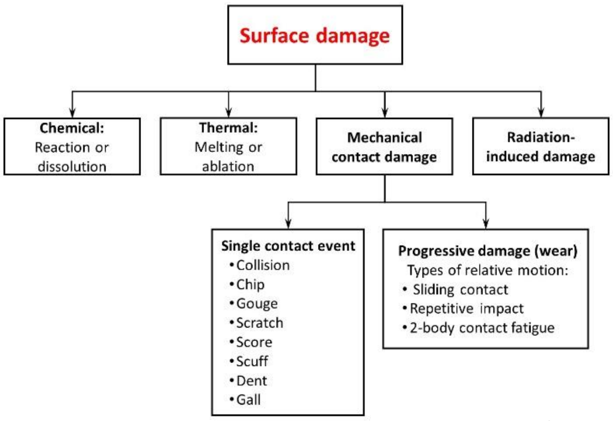


Fig. 6. Surface damage [9].

Peter Blau [9] proposed to organize damages based on type of interaction between the elements of a tribosystem: chemical, thermal, mechanical and radiation-induced (Fig. 6). For all possible combinations of 2, 3 and 4 types of wear (as surface damage), mathematically, it results 15 types of damage. Also, he appreciates the importance of logical diagnosis of tribological issues (wear, heating, malfunctioning), based on ranking criteria for damages and failures. He expressed very well the issue of analysing these damages, "the multidisciplinary nature of tribology has led to the inconsistent use of wear and surface damage terminology in reports, articles, handbooks, and even textbooks" [9].

He gives an example of inconsistency in the well-known reference book, ASM international handbook on failure analysis and prevention. The chapter on "wear failures" proposes five types of wear: abrasive wear, erosive wear, corrosive wear, erosion–corrosion and surface fatigue [82].

But the chapter, "Failures of rolling element bearings" [83], distinguishes 13 types of wear (see Table 6, column 2).

Table 6. Types of wear.

Wear failures [82]	**Failures of rolling element bearings** [83]	**Wear failures** [84]	**Failures of gears** [85]	**Wear failures** [93,94]
1	2	3	4	5
abrasive wear erosive wear corrosive wear erosion–corrosion surface fatigue	false brinelling, true brinelling, electrical pitting flaking fluting fretting indentation skidding scuffing sliding smearing softening spalling	abrasive wear with hard granular material abrasive wear from hard particles trapped between moving surfaces adhesive wear from rubbing bearings, fretting cavitation erosion particle erosion surface fatigue	normal wear (polishing) moderate and destructive wear scoring interference wear abrasive wear corrosive wear flaking fluting burning surface fatigue initial pitting destructive pitting spalling	abrasion, adhesion fatigue tribo-corrosion

At chapter dedicated to "Failures of Gear" [84], also 13 types of wear are listed, several being variant versions of fatigue (flaking, surface fatigue, initial pitting, destructive pitting, spalling).

Neal [85] gave, at page 8, three main types of wear (abrasion, adhesion and erosion-fatigue), but at page 16, he introduced 7 main types.

Stachowiack and Batchalor [86] identified five major types of wear mechanisms in surface damage: abrasion, erosion, adhesion, corrosion and fatigue. Due to the space dedicated to this paper, there will be discussed only several terms for rolling bearings' failures and damages.

In ISO 15243:2017 [87], there is no "wear" types, but failure modes of the rolling bearings, wear being only one of six types of failure. But except corrosion that could happen also in static conditions, all other damages or failures imply tribological aspects (lubrication, overload, shocks and overheating during operation, impurification by dust, wear debris).

It is interesting that fretting is included as corrosion failure. The authors consider that this particular type of wear is the synergic results of combining two causes: oscillatory movement under load, thus, fatigue, and corrosion caused by high temperature generated in contact. But the definition of fretting is related to tribology and wear "Fretting corrosion occurs in fit interfaces between components that are trans-mitting loads under oscillating contact surface micromovements. Surface asperities oxidize and are rubbed off and vice versa; powdery rust develops (fretting rust, iron oxide)" [87].

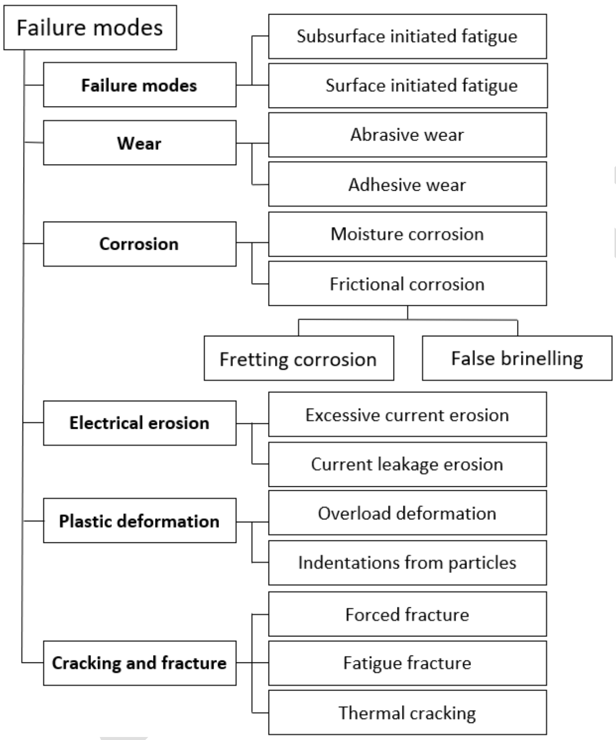


Fig. 7. ISO classification of failure modes for rolling bearings, after [87].

SKF brochure [88], that also presents classifications from ISO 15243:2017 (Fig. 7), gives the following explanation: "fretting corrosion occurs when there is relative movement between a bearing ring and its seat on a shaft or in a housing. Fretting is usually caused by a too loose fit or form inaccuracies. The relative movement may cause small particles of material to become detached from the bearing surface and its seat. These particles oxidize quickly when exposed to air and the result is iron oxide". This definition is accompanied by a very suggestive sketch of the fretting process, followed by an image that values "a thousand words".

This brochure also introduces "frictional corrosion" (one may also say tribocorrosion), having as variants fretting corrosion and false brinelling [88].

In SKF brochure [88], adhesive wear has a synonym, smearing. The standard ISO 15243:2017 has a synonym for smearing: skidding: "adhesive wear is a type of lubricant-related damage that occurs between two mating surfaces sliding relative to each other. it is characterized by the transfer of material from one surface to another (smearing)". It is typically accompanied by frictional heat that could, sometimes, temper or reharden the mating surfaces. The frictional heat produces local stress concentrations, which could cause cracking or spalling in the contact areas. Smearing is not common under normal operating conditions." ISO 15243:2017 defines adhesive wear (smearing) in rolling bearings as "the damage that occurs when two inadequately lubricated surfaces slide against each other under load". Smearing causes material from one surface to be transferred to another, leaving a "torn" appearance [87]. In Torrington's brochure for failure and damage of rolling bearings [89], there is introduced fretting corrosion (fretting supposes the existence of chemical changes of wear debris, especially oxidations, and of superficial layers of bodies in contact). But there is no reference to adhesive wear, even if this process is included in poor lubrication consequences and use the term "spall". But the term is also used for explaining the detaching of the material from the raceway, when submitted to overload that will cause also overheating that is favorable to pick off debris due to adhesion resulted from overheating or/and overloading.

The Koyo's brochure on the same subject [90] does not have adhesive wear", but it has "fretting" and "smearing". The fretting is defined as "a phenomena which occurs when slight sliding is repeatedly caused on the contact surface. On the fitting surface, fretting corrosion occurs, generating a rust like powder. If bearings receive a vibration load when they stop or operate, slight sliding occurs in the section between the rolling element and bearing ring due to elastic distortion". Even if the definition is not the same as those from above, it is clear and the photos supporting it are representative.

The FAG's brochure [91] mentions "seizing" as adhesive process (not using adhesion, but cold welding) and "fretting corrosion". Representative photos are selected to explain these processes.

INA's brochure [92] presents five main types of failures for rolling bearings: running marks, fatigue, wear, corrosion and erosion, overload. Wear includes abrasive forms like polishing, mild to severe abrasion, false brinelling, smearing (mild and severe, with cracking after re-hardening) and fretting corrosion (also named frictional corrosion].

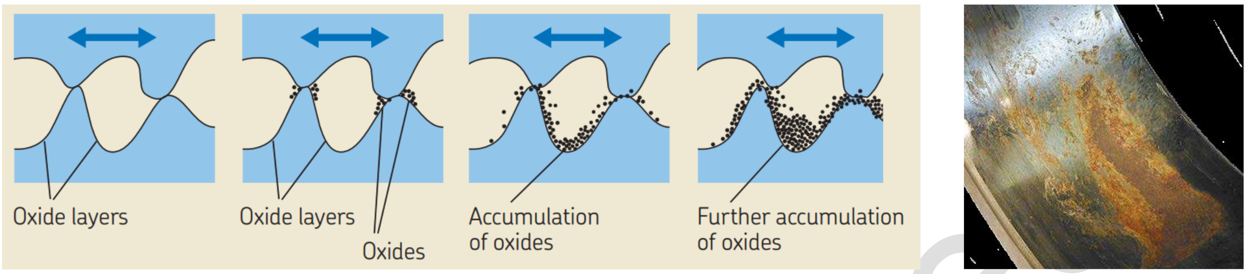


Fig. 8. Fretting damaging process [90]: a) Suggestive sketch, b) Fretting corrosion on an inner ring bore resulting from heavy load or inadequate shaft seat.

Based on relevant books [44,80,86,95,96], standards [71,81,87], scientific papers [97-100] and producers' brochures [88-92] and analyzing the definitions of failure in the standards [87], [101-105] on damage and wear of machine components, the authors consider that the standard terminology for tribology failures and damages has not been fixed yet and it is possible not to be in the following years because of different terms in use for different machine components. Thus, it is recommended to use a term for a tribological failure and to give the definition and classifications needed for better understanding the described issue. Also, as it is said, a photo (at macro or/and micro scale) will clarify and mark off what the report on a failure wanted to underline.

The conclusion for this section is concentrated in Figure 8, from [106], where standardization is a compulsory chain link in analyzing any failure, including those involving tribological processes and phenomena.

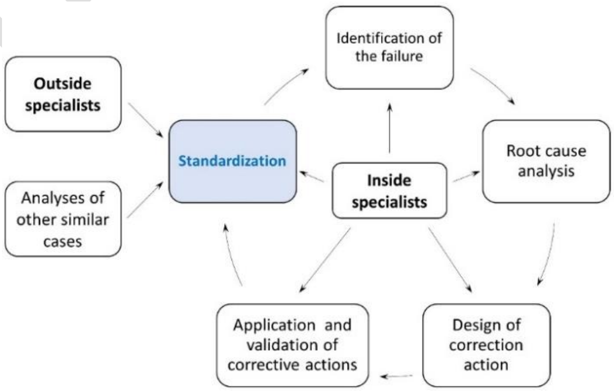


Fig. 9. A chart flow of analyzing failure [106].

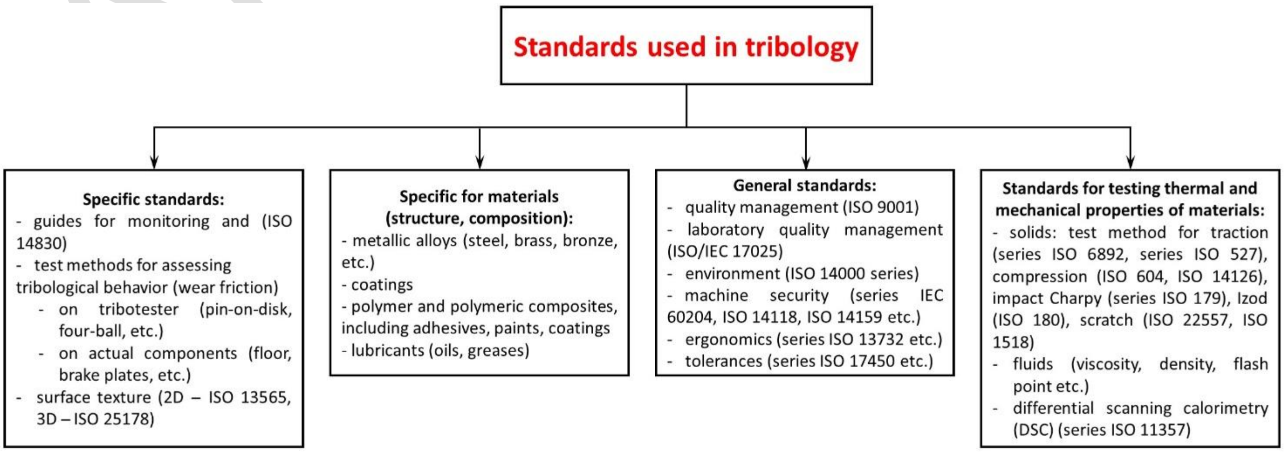


Fig. 10. Standard families used in tribology

4. CONCLUSION

In tribology, standards help researchers to have reference test methods that enable to compare the older solutions to the new ones, but the tribologists could use new method of testing and investigating to point out the progress. On the market, standards are trusted especially by industrial specialised clients and they could verify the quality of products or services by the help of a third party that would confirm or not the parameters obtained by applying standard test method.

In tribology, standards are used at different levels (Fig. 10):

- the general one, meaning general procedures that offer quality and trust (like ISO 9001, ISO 17025),
- standards dealing with assessing tribological behaviour (solid bodies and lubricants), especially by friction coefficient and wear and
- standards assisting a tribological research (for instance, standards for determining thermal and mechanical properties, necessary in calculating or ranking tribosystems).

The authors recommend to start a research study or a design by adding the following question to the main issues of the theme. What standards are needed to fulfil the research or the design and what parameters will have to be determined by the help of standards. Of course, there is enough "space" to have original ideas about how to solve the research or the design.

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