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Comparison of a tribological model and real component test methods for lubricated contacts

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Abstract. The work is aimed to the comparison of tribological performance of lubricated surfaces sliding against each other in laboratory (model test) and real component working conditions. An emphasis is also made on the possibility to use environmental friendly lubricants. The efficiency of using some particular test devices is considered on the basis of available techniques and methods to study lubricated contacts. The implementation of different scales of measurements into the process of materials performance evaluation under tribological conditions is shown to be essential for the reliable assessment of multi-body systems reliability and durability.

Key words: lubrication, model testing, component testing.

1. INTRODUCTION

The assessment and improvement of performance are continuing processes in products and technologies development [1–3]. The way how well the product or process performs influences the satisfaction of the customer (end user) that in its turn stimulates the supplier (or service provider) to ensure high level of product quality. For further development of the processes and for innovation it is required to look beyond the existing knowledge. Simulation, testing, surface characterization and analysis are tools enabling verification of emerging ideas (that are the source of innovation) before implementing them into real products.

The importance of tribological investigations is supported by the fact that approximately 95% of all machine problems are related to fatigue fracture and tribology phenomena like friction and wear [4]. Already in about 2400 BC an improvement of sliding contacts for transportation of large stone blocks during erection of legendary Egyptian pyramids was achieved through the application of lubricants [5]. The search for higher load carrying capacity of lubricated contacts is stimulated by the necessity to minimize the size of machine components. This decreases material consumption by the production of the component itself and leads to significant improvement of efficiency, fuel economy and reduction of green-gas effects in applications that are driven by the necessity of weight reduction. The high load carrying capacity and other specific properties of engineering surfaces are crucial in automotive, aerospace and industrial applications (power trains, turbines, formula F1 car, mining machinery bearings and other components) [6].

The current work has the aim to give some insight into the potential of the research for longer lifetime performance and reliability of lubricated contacts. The Institute for Sustainable Technologies (ITEE, Poland) and SKF Engineering and Research Centre (The Netherlands) are respectable representatives of a governmental institution and an industrial research centre, accordingly. Both institutions participate in the Sixth Framework Programme, Marie Curie research training network WEMESURF with the topic of the current paper being one of the research tasks. The main questions that will be answered are the following.

1. What are model and component tests? Is it possible to skip one of them doing research on lubricated contacts?
2. How to utilize the information obtained from model and component tests? How is it possible to determine the reason of failure?
3. Why cooperation between governmental institutions and industrial research centres is important?

The content and structure of the work is built up to serve as a reference material for students and engineers interested in research on tribology in general and lubricated contacts in particular. It contains some specific information that may be of interest for researchers working in the same or related research areas. The complete description of the results will be available at the end of the WEMESURF project in year 2010 in the form of the final report.

2. THE ROLE OF THE MODEL, COMPONENT TESTING AND SURFACE ANALYSIS

Tribological research is performed at different scales ranging from 10^{-9} to 10^{12} m including molecular, asperity, contact, component, machinery, plant, national, global and universe studies [7]. Tribotests could be classified by rising of the degree of realism (i.e., how closely they imitate the conditions of a real application) as model, simplified component, component, sub-system, bench and field tests. The comparison between model and component testing with more evaluation aspects is given in Table 1 [8]. In a model test both tribosurfaces are replaced by simulated components. Semitribocouple and full tribocouple tests, where only one or both of the surfaces are represented by real components, are called a simplified component and a component test, respectively [9]. Surface characterization and analysis, model and component tests scale from the molecular size up to the size of a component that may be up to several metres.

In general, the process of observation, understanding and reproducing of the mechanisms and reasons of failure in real components, including theoretical modelling, is summarized in Fig. 1.

As soon as the theoretical idea is emerged, it is necessary to prove it by practical test. The model test usually involves standard test specimens and could be executed in short time and without significant expenses that is extremely important in conditions when delay in introduction of the product to the market could mean the loss of a sufficient part of the profit. In some conditions it is possible to make several tests on one sample. The test samples could be smaller than the real component and of simple geometry that makes the test more convenient and enables to raise the level of control of conditions and of tracking

Table 1. Comparison between model and component tests

	Model	Component
Degree of realism	Lower	Higher
Duration of the test	Several minutes–several hours	Several days–several months
Cost of the test	Lower	Higher
Level of the test conditions control	Higher	Lower
Ability to study individual, isolated wear mechanisms	Higher	Lower

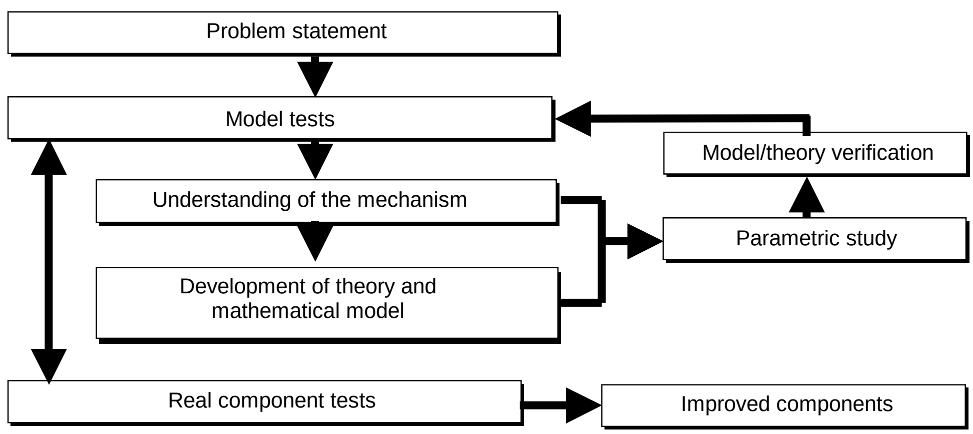


Fig. 1. A schematic overview of the learning process to improve the performance of machine components.

the tribosystem behaviour. It is possible to test the tribosystem in a variety of conditions to evaluate the responsible effects and mechanisms. Only some of the initial ideas provide significant advantages that were expected. Reliable and cost-effective model tribotesters and standardized procedures for the evaluation of suitable tribosystems enable to save resources and to avoid expensive testing of real components.

After the elimination of the unjustified ideas, the most promising ones are tested by means of component tests. A real component test requires the components to be produced, which significantly raises the price of testing. It is usually possible to make only one test of each component; however, for statistical reasons, more tests are recommended. The test is run under required conditions until the component fails or shows a decrease of the performance level. The testing of components (like gears, bearings, etc) under the conditions that are very close to those of real application enables one to improve the quality of the scientific theories and model tribotest results and to avoid the expensive stop of real machines due to malfunctioning of the component or the necessity to make frequent replacements due to deterioration.

In order to understand the mechanisms that are responsible for the machine component performance, the surface characterization is needed. Surface characterization and analysis are usually done on the surfaces of the real component and the model test specimens on atomic, molecular and asperity levels to give information about surface geometry, physical and chemical state. Due to the high precision and resolution, the sample is required to be fixed firmly to the measuring (or observation) device. The state of the surface, determined before and after the experiments, can give the insight to the changes in the surface properties as the result of applying the specific test conditions. Surface investigations enable to prove the model and component results as well as to enhance their quality, providing additional information.

3. EQUIPMENT FOR LUBRICATED CONTACT RESEARCH

The devices and methods for the whole spectrum of operations required for production of engineering surfaces and lubricants, their testing and characterization in selected governmental and industrial research centres are given in Table 2. It is a short presentation that is grouped and described with emphasis on the features that are relevant to lubricated contact studies of model and component testing.

The industrial centre has devices that are more specialized for the realization of specific tasks, related to their product. Governmental institution owns the devices capable to study a wide range of tribological systems and geometries; it is also capable to produce engineering surfaces of required properties.

Table 2. Equipment related to surface engineering, characterization and lubricated contact condition testing

Devices and methods	Capabilities and features
Material (surface) and lubricant production and characterization	
Surface engineering equipment (physical vapour deposition (PVD)[G], nitriding[G, I], carburizing[G, I], thermal treatment[G, I], casting[G], etc.)	Modification of surface properties (mechanical, chemical, tribological, etc.)
Characterization and analysis of engineering surfaces (measuring optical microscope with extended focus imaging[G, I], scanning electron microscope (SEM)[G, I], energy dispersive X-ray spectroscope (EDS)[G, I], atomic force microscope (AFM)[G, I], glow discharge optical emission spectroscopy (GDOES)[G], contact profilometer[G, I], white-light confocal optical profiler[I], scratch tester[G, I], instrumented indentation nanoscale tester[G, I], hardness testers[G, I], etc)	Obtaining of high-magnification images, elementary composition of the surface layer and depth profiling, measurement of surface geometry and roughness parameters in contact and non-contact mode, mechanical properties
Lubricant preparation and analyses (mixing[G, I], heating[G, I], stirring devices[G, I], rheometer[G, I], infrared spectrometry[G, I], etc)	Providing required viscosity characteristics (e.g. viscosity index), chemical composition, additive chemistry, additive concentration
Model tribotesting	
Non-conformal contact systems/tribometers (Four-ball[G, I], Cone-three Ball[G], Ball-on-Plate[I], Three Cylinder-Cone[G], Block-on-Ring[G], Ball-on-Disk[G, I], Journal and Vee Block[G], Crossed-Cylinders[G])	Dip or drop lubrication. Sliding, rolling, controlled ratio of rolling/sliding conditions. Continuous, reciprocating movement mode. Environmental control (temperature, humidity, pressure). Controlled input parameters (load, sliding/rolling velocity, temperature, duration).
Conformal contact systems/tribometers (Block-on-Ring[G], Pin-on-Disk[G, I])	Measured output parameters (friction force, friction coefficient, linear wear, heat generation, vibration, in-situ lubricant film thickness measurements[I]).
Component tribotesting	
Gear test rig[G] (FZG Back-to-Back type) Hip joint test rig simulator[G] Tap, chasing tool, screw joint tester[G] Various bearing testers[I]	Real components are tested; by selecting the component geometry, test conditions and surface preparation it is possible to promote and intensify the required wear mode

[G] available in the governmental research institution.
[I] available in the industrial research centre.

4. CASE STUDIES

In the following section, two examples on how to improve the performance of lubricated contacts are presented. The procedure of selection the methodology and the devices for solving these tasks is outlined. It gives an overview of how the problem is tackled and the potential solution through the model and component testing is offered.

4.1. Coating for environmentally friendly transmission systems

Nowadays, the additives used for non-coated gears, working under heavy-loaded conditions, are harmful for the environment (are not ecologically friendly due to the presence of S, P, Zn, Cl elements and their compositions), intensify the corrosion of the elements and it is required to reduce their content. Also, it is of interest to substitute the mineral and synthetic oils that are showing the best performance by vegetable oils that are ecologically more friendly and belong to the class of renewable resources. The aim of this case study was to improve the load carrying capacity of gears, to make it possible to use eco-friendly lubricants and to reduce the content of additives.

Two-stage experiment plan, including model and component tests, was performed. The industrial partner was able to supply special bearing balls for testing that shows good opportunity for cooperation. The coating was also developed in cooperation with the industrial partner. The multilayer nano-composite coatings were deposited by PVD technology on bearing balls.

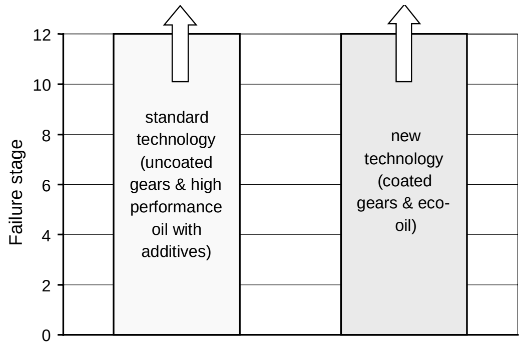
It is well known that the durability of gears depends on two phenomena (mechanisms): scuffing of mating elements and rolling contact fatigue – pitting [10]. The scuffing resistance was measured using the T-02 model tester employing four-ball tribosystem in a sliding contact. The T-02 tester has the possibility of continuously increasing the load during a run enabling to determine the scuffing resistance, characterized by scuffing load and the so-called limiting pressure of seizure [11]. This method, developed by ITEE, is more time and cost effective (enable to save up to 80% of resources) and has better resolution of tribosystem properties than the analogous model test (ASTM D2783-03). As much as 300 tests were necessary that needed 3 months of testing.

The fatigue life (pitting) was characterized by the 10% fatigue life (life at which 10% of the test samples, lubricated by selected lubricant, would be expected to have failed) according to IP 300 standard, using the T-03 four ball model tester [12].

The mechanochemical interaction between oil and gear materials was studied using SEM/EDS, AFM, GDOES, and optical microscopy.

The results obtained by model testers with different base oils (mineral, synthetic and vegetable) on scuffing and pitting of uncoated and coated elements allowed to eliminate the lubricants and coatings with the lowest performance levels and to select the promising ones for further component tests.

The load-carrying capacity of lubricated gears (component test) was investigated using the T-12 Back-to-Back Gear Test Rig, employing test conditions according to DIN 51 354 and IP 334 standards, procedure A/8,3/90. The results are presented in Fig. 2.



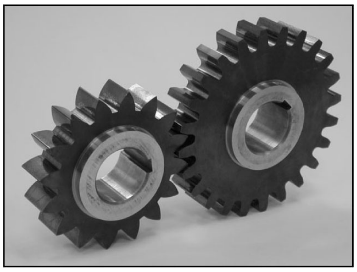


Fig. 2. Results from FZG tests: gears lubricated with commercial high-performance oils with additives, and coated gears lubricated with vegetable-based oil without the additives show the maximum performance level.

The failure load stage, obtained for the coated test gear, lubricated by the eco-oil without any AW/EP additives, is the same or better than that of commercial gear oils containing toxic AW/EP additives. Both tribosystems have not failed during the test under highest applied load available according to the standard. Furthermore, the heat generated and vibration level were lower for coated gears lubricated by the eco-friendly oil [13]. The tests are time-consuming and only 10 tests were completed during 1 month of testing that is about 10 times slower compared to model testing.

The component tests of selected coatings in combination with vegetable oil have shown that under extreme pressure conditions low-friction coatings can take over the functions of AW/EP additives that enables to use eco-friendly lubricants.

4.2. Effect of oil polarity on fretting performance

The fretting is usually successfully avoided during the normal functioning of the components, however, it can cause excessive damage during idle time, for example, in car bearings during their transportation by railroad or when the wind-mill is stopped due to inappropriate wind conditions, but components continue to suffer from vibration induced by wind [14,15].

Polarity of the oil was found to be important since it influences the activity of the additive–surface interaction [16]. In order to study isolated effect of the base oil polarity on action of additives (and additive combinations), two oils, similar in properties but being polar (diethylene glycol) or non-polar (hexadecane) were studied with respect to fretting performance. The result of this investigation is to be used during formulation of real lubricants along with other substantial properties, specific for each real application such as viscosity, chemical composition, thermal and oxidative stability, compatibility, biodegradability, toxicity, etc.

The model fretting rig results, evaluated with Ball-on-Plate configuration, showed that the polarity of the base oil determines the affinity of the additive to be functioned on the tribological surface, thereby effecting the formation of protecting reaction layer and the fretting process (Fig. 3).

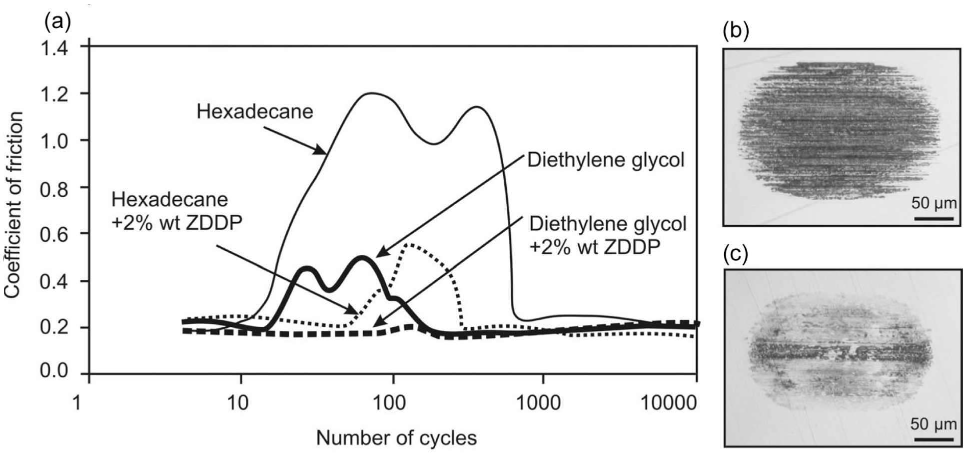


Fig. 3. Effect of ZDDP additive on fretting performance. Material of ball and plate – 100Cr6, duration – 10^4 cycles, frequency – 20 Hz, maximum Hertzian stress – 1 GPa, amplitude – 80 μm. (a) Evolution of friction coefficient during test; (b) pure diethylene glycol; (c) diethylene glycol with 2%wt ZDDP additive.

It is shown in Fig. 3 that polar oil (diethylene glycol) with additive (ZDDP) under specified conditions has low and stable coefficient of friction that results in low surface damage. On the other hand, the same additive used along with the non-polar base oil (hexadecane) shows the rise in the coefficient of friction and is inefficient in protecting the surfaces against deterioration.

Surface characterization using SEM-EDS showed that depending on the type of additives used, the thickness and the composition of the reaction layer, formed on the contacting surfaces, are different. The model test results are now under further continuous proving by various real component tests that in addition to other wear mechanisms experience fretting [[15]]. The understanding of responsible mechanisms, the specifying of required properties and composition of reaction layer will lead to the development of the procedure for the selection of lubricants for various bearing applications that may experience fretting conditions.

5. CONCLUSIONS

The tribosystem, incorporating eco-friendly lubricant and coated elements, exhibits required level of performance. This is an example of how the implementation of model testing accelerates the development of a potential solution to increase the performance of lubricated machine elements, which also give positive impact from the economical and environmental point of view.

The fretting model rig allows studying of separate mechanisms of fretting under high level of test condition control. These results are under continuous validation in various component bearing applications that may experience fretting.

Industrial centres commonly use the devices that are more specialized for realization of specific tasks related to their product. Governmental research institute owns the testers for studying the tribological systems and geometries in a wide range of conditions; the engineering surfaces of required properties can also be produced and tested. That indicates that the potential cooperation between both institutions can enhance their understanding required for improving the performance of lubricated machine elements. An industrial centre can widen the range of test facilities through collaboration with the governmental institution. This will lead to the knowledge exchange, which raises the possibility of applying scientific discoveries in industry.

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Määrdeaine keskkonnas töötava reaalse detaili triboloogiliste tingimuste reprodutseerimine laboratoorse seadme abil

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On näidatud, et olulist osa töötavast määrdeaine keskkonnast on võimalik laboratoorsetes tingimustes hoolikalt valitud metoodikaga edukalt reprodutseerida. On välja töötatud uus, pidevalt kasvava koormusega laboratoorne seade, sest olemasolevate meetodite kasutamisel saadud tulemused ei võimalda leida vajalikku korrelatsiooni. Katseseadme abil leiti, et hammasratta kontaktpinnale pihustatud teemandisarnase süsiniku kile (DLC) võimaldab loobuda keskkonnaohtlike lisandite kasutamisest määrdeainetes. Laboratoorsed tulemused kinnitavad hammasrataste katsetamistulemusi. On näidatud, et laboratoorsed seadmed võimaldavad uurida tribosüsteemi (kontakteeruvad detailid, määrdeained, tingimused) üksikuid eriomadusi (näiteks õli polaarsuse mõju fretingule), mis on keeruline ülisuure tuuleveskilaagri puhul. On leitud, et koostöö tööstusettevõtte ja teadusorganisatsiooni vahel võimaldab suurendada tööstusettevõtte uurimispotentsiaali ja lihtsustada innovatsiooniprotsessi.