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The New Methods for Scuffing and Pitting Investigation of Coated Materials for Heavy Loaded, Lubricated Elements

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1. Introduction

In modern technology due to the increase of the unit pressure, velocities, and hence temperatures in the tribosystems of machines, a risk of two very dangerous forms of wear exists. These forms are scuffing and pitting.

Scuffing is a form of wear typical of highly-loaded surfaces working at high relative speeds. Scuffing is considered to be a localised damage caused by the occurrence of solid-phase welding between sliding gear flanks, due to excessive heat generated by friction, and it is characterised by the transfer of material between sliding surfaces. This condition occurs during metal-to-metal contact and due to the removal of the protective oxide layer of the metal surfaces (Burakowski et. al., 2004).

A typical scuffing zone of gear teeth (Michalczewski et al., 2010) is illustrated in Fig. 1.



Fig. 1. A typical scuffing wear of gear teeth

Another form of wear is rolling contact fatigue (pitting). Pitting is a form of wear typical of highly-loaded surfaces working at a sliding-rolling and rolling contact, e.g. such components in transmissions like toothed gears and rolling bearings (Torrance et al, 1996). It is caused by the cyclic contact stress, which leads to cracks initiation (Libera et al., 2005). The lubricant is

pressed into the cracks at a very high pressure (elastohydrodynamic lubrication), making them propagate. Finally, cyclic stress results in breaking a piece of material off the surface. Examples of a gear and a race worn due to pitting (Michalczewski et al., 2010) are presented in Fig. 2.



Fig. 2. The pitting wear: a) on a pinion gear, b) on a bearing race

For many engineering materials, further improvement of their properties through a modification of their microstructure, chemical composition, and phase composition, is practically impossible. In this situation the most effective way of improving mechanical properties of various engineering components is the modification of surface properties by the deposition of PVD/CVD coatings (Michalczewski, 2008). One of the most important characteristics of these coatings is the fact that its thickness, usually in the range from 1 to 5 μm , is located in the field of dimensional tolerances of typical machine elements.

There are many successful applications of thin hard PVD/CVD coatings in various technical devices like engines, pumps, compressors. However the problem of application of such coatings for heavy-loaded friction parts (e.g. gears, bearings) is still open - the share of mechanical components that are coated is extremely small (less than 2%). Why? The service life of heavy-loaded machine parts is essentially determined by two types of tribological failures: scuffing which is a severe form of mechanical wear, and pitting which is a surface fatigue phenomenon. Up to now, there was a lack of verified laboratory test methods intended for correlated determination of coating material and lubricating media on scuffing and pitting resistance of heavy-loaded system. So, the selection of coating material and technology was realised mainly basing on very expensive and long-term practical component research and the results are frequently contradictory (Szczerek, Michalczewski, & Piekoszewski, 2009).

The evaluation of friction and wear characteristics of PVD/CVD coatings is only possible on the way of experimental research. The experimental research of friction and wear of interacting surfaces is realised by means of a special device called tribotester. The new test methods and testing machines have been developed based on the achievements of the System for Tribological Research (SBT) implemented in the Tribology Department at the Institute for Sustainable Technologies - National Research Institute (ITeE-PIB), Radom, Poland (Szczerek, 1996). The SBT system was developed on the basis of the combinatorics that enables to reduce the tendency which is widely known as "testing rush".

For the purpose of the tribological research in the areas mentioned above, two tribological devices have been developed:

- The T-02U Universal Four-Ball Testing Machine,
- The T-12U Universal Back-to-back Gear Test Rig.

The set of methods and devices intended for the comprehensive tribological evaluation of PVD/CVD coatings is presented in Fig. 3.

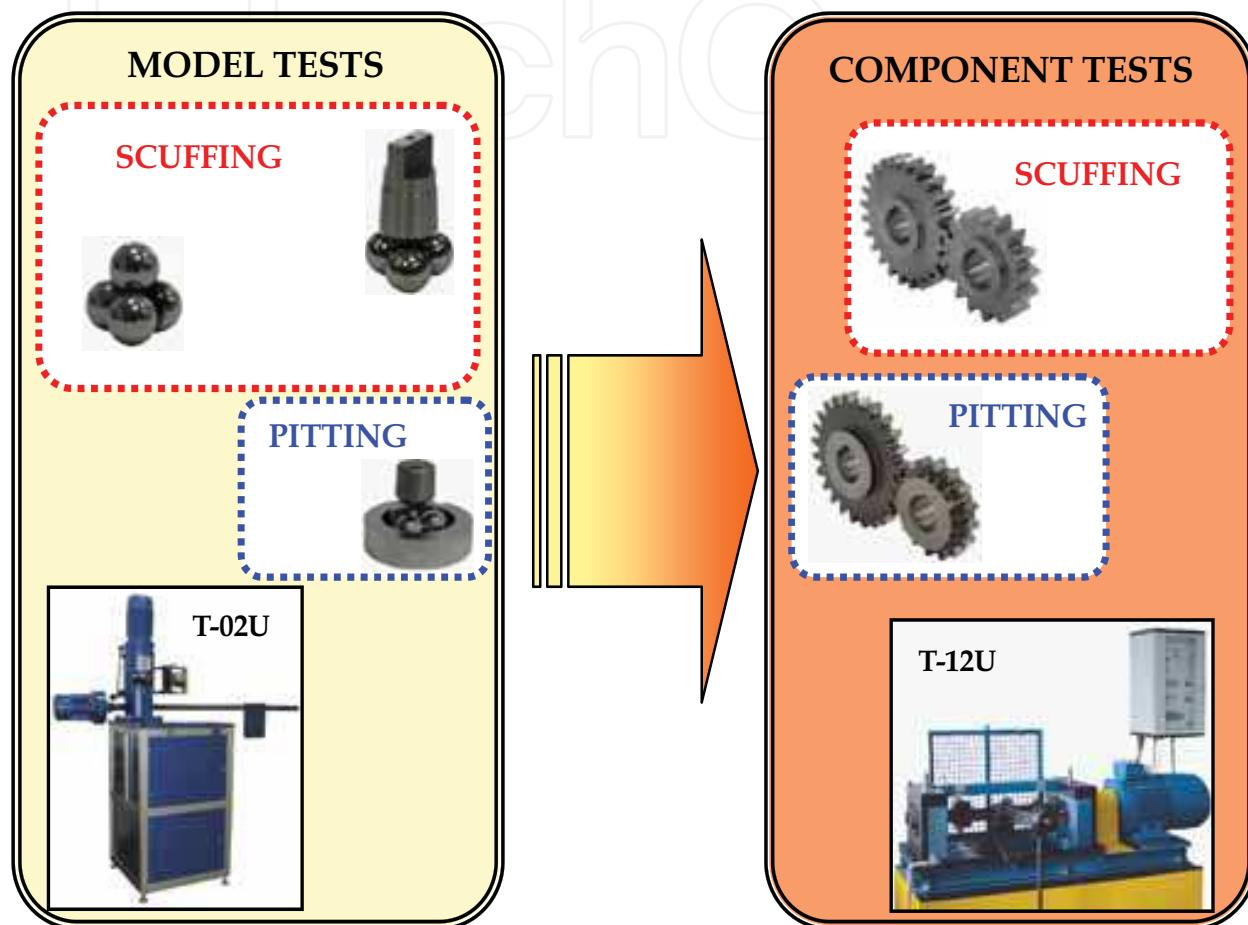


Fig. 3. The tribological methods and devices developed intended for comprehensive tribological evaluation of elements covered with PVD/CVD coatings

By means of this set, low-friction and antiwear PVD/CVD coatings can be evaluated from micro to macroscale in model and component tests (Antonov et al., 2009).

Using new devices, five test methods, giving the possibility of comprehensive testing of various low-friction and antiwear PVD/CVD coatings intended for machine elements, were developed. They are as follows:

- The model method for the evaluation of scuffing in the four-ball tribosystem,
- The model method for the evaluation of scuffing in the cone-three balls tribosystem,
- The model method for the evaluation of pitting wear in the cone-three balls tribosystem,
- The component gear method for the evaluation of scuffing resistance of gears,
- The component gear method for the evaluation of pitting wear of gears.

The new test methods and the new devices for the experimental evaluation of friction and wear of low-friction and antiwear PVD/CVD coatings are described below.

2. Model methods and T-02U Universal Four-Ball Testing Machine for evaluation of scuffing and pitting resistance of PVD/CVD coatings

2.1 Model scuffing tests in four-ball and cone-three balls tribosystems

For evaluation of scuffing resistance of lubricants, coatings, and engineering materials two tribosystems were employed: four-ball and cone-three balls. In typical four-ball test balls are made of chrome alloy 100Cr6 bearing steel, with diameter of 12.7 mm (0.5 in.). Surface roughness is $R_a = 0.032 \mu\text{m}$ and hardness 60 to 65 HRC. In the new method the investigated coating can be deposited on the ball or on the cone. Furthermore the cone can be made of various engineering material, not only of bearing steel.

The four-ball and cone-three balls tribosystems are presented in Fig. 4.

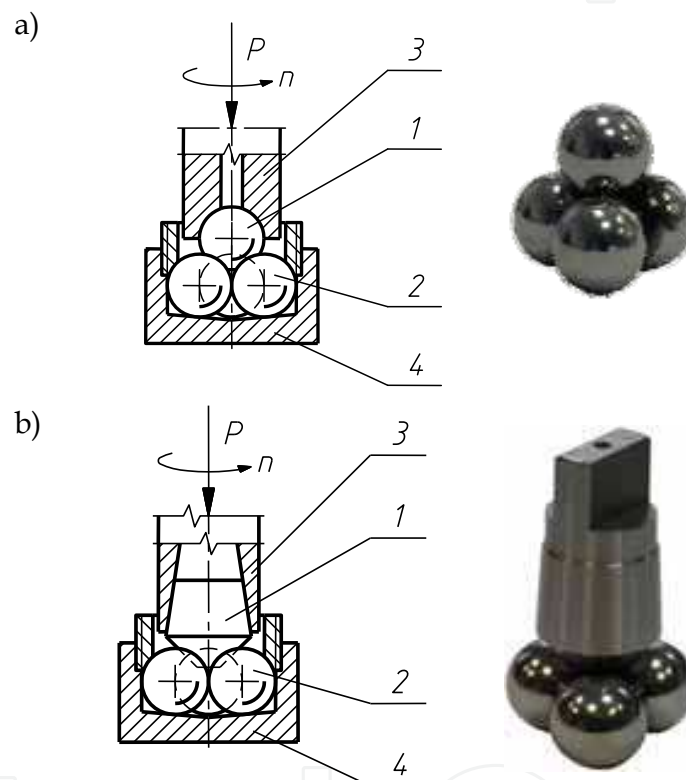


Fig. 4. Model tribosystems for testing scuffing: a) four-ball tribosystem: 1- top ball, 2- lower balls, 3- ball chuck, 4 - ball pot, b) cone-three balls tribosystem; 1 - top cone, 2 - bottom balls, 3 - ball chuck, 4-ball pot

The three stationary, bottom balls (2), having a diameter of 0.5 in., are fixed in the ball pot (4) and pressed against the top ball or cone (1) at the continuously increasing load P . The top ball/cone is fixed in the ball chuck (3) and rotates at the constant speed n . The tribosystem is immersed in the tested lubricant. During the run the friction torque is observed until seizure occurs.

The test conditions are as follows: rotational speed: 500 rpm, speed of continuous load increase: 409 N/s, initial applied load: 0 N, maximum load: 7200 ± 100 N.

The methods are described in detail in works (Szczerek & Tuszynski, 2002) and patented (Polish Patent No. 179123 - B1 - G01N 33/30). A friction torque curve (M_t) obtained at the continuously increasing load (P) is shown in Fig. 5.

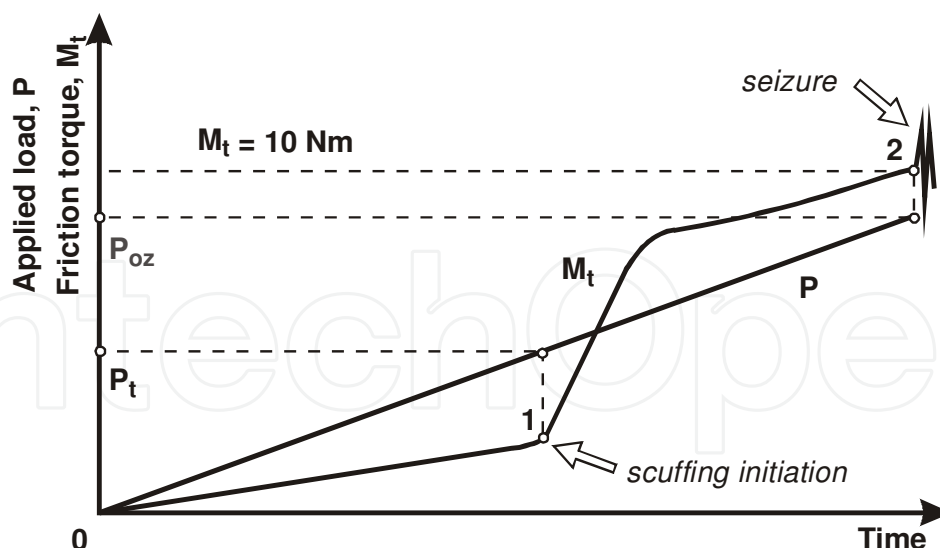


Fig. 5. Simplified friction torque curve (M_t) obtained at continuously increasing load (P); 1 - scuffing initiation, 1-2 - scuffing propagation, 2 - seizure (exceeding 10 Nm friction torque)

Scuffing initiation occurs at the time of a sudden increase in the friction torque - point 1. The load at this moment is called the *scuffing load* and denoted P_t .

According to the new test method, the load still increases (over a value of P_t) until seizure occurs (i.e. friction torque exceeds 10 N m - point 2). The load at this moment will be called the *seizure load* and denoted P_{oz} . If 10 Nm is not reached, maximum load (c.a. 7200 N) is considered to be the seizure load (although in such a case there is no seizure). For every tested lubricant the so-called *limiting pressure of seizure* (denoted p_{oz}) should be calculated. This value reflects the lubricant behaviour under scuffing conditions and is equal to the nominal pressure exerted on the wear scar surface at the moment of seizure or at the end of the run (when seizure has not appeared). The limiting pressure of seizure is calculated from the equation (1):

$$p_{oz} = 0.52 \frac{P_{oz}}{d^2} \quad (1)$$

where:

p_{oz} - limiting pressure of seizure, N/mm²,

P_{oz} - seizure load [N],

d - average wear scar diameter measured on the stationary balls, mm.

The 0.52 coefficient results from the force distribution in the four-ball tribosystem. The higher p_{oz} value, the better action of the tested lubricant under scuffing conditions is.

The developed test methods were successfully used for testing the scuffing resistance of components with thin hard coatings (thickness of 2 μ m) deposited by PVD/CVD method. The example of their application (Michalczewski et al., 2010) is presented in Fig. 6.

Wear scars images on lower balls from scuffing tests for steel-steel and CrN-CrN tribosystems are presented in Fig. 7.

The developed test methods have the resolution, not achieved by the other methods, good enough to differentiate between coatings, engineering materials and lubricants (Piekoszewski, Szczerek & Tuszynski, 2001). What is more, they are fast and inexpensive. So, these test methods can be effectively used to select the optimum substrate-coating-lubricant combinations best suited for highly loaded machine components (Michalczewski et al., 2009a).

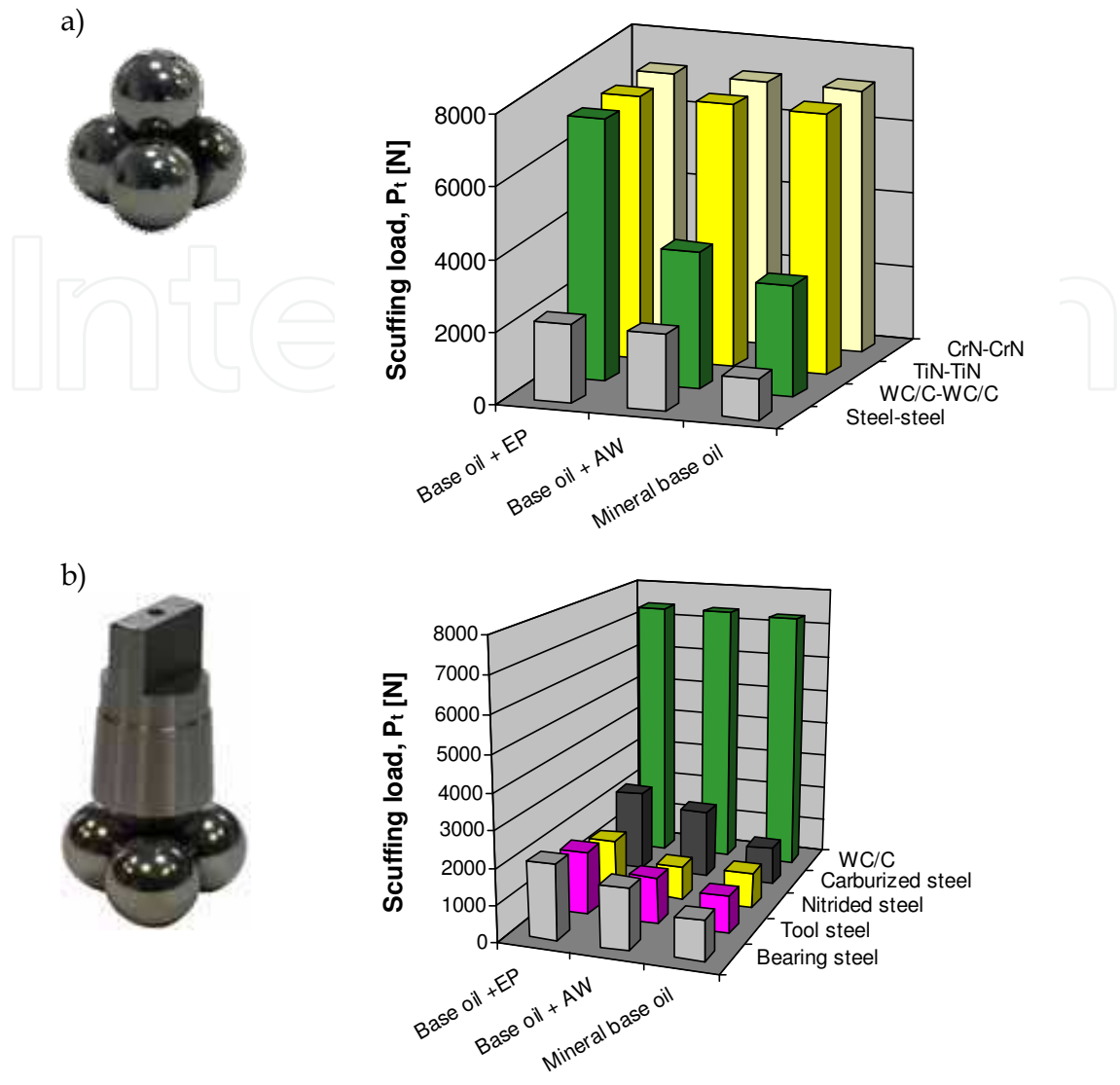


Fig. 6. Results from scuffing tests for lubricants, engineering materials and thin hard coatings: a) modified four-ball scuffing test, b) cone-three balls scuffing test

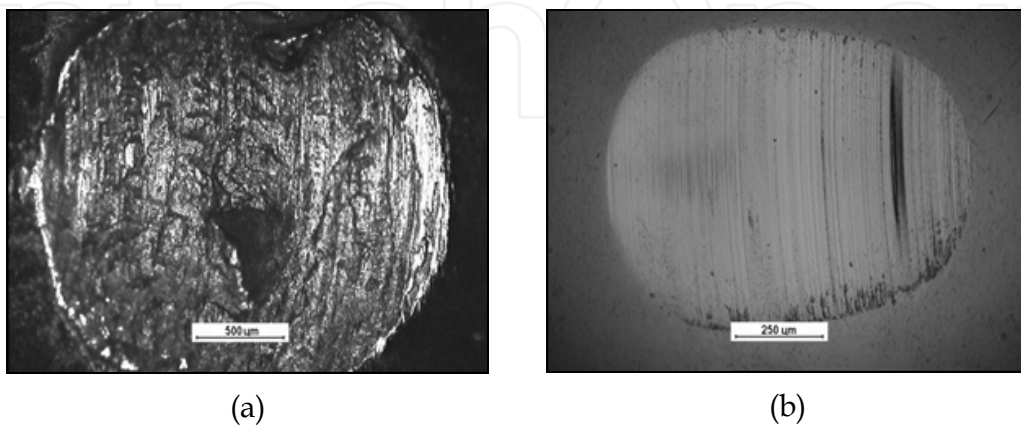


Fig. 7. Wear scars images on lower balls from scuffing tests for: a) steel-steel, b) CrN-CrN (four ball test, mineral base oil without lubricating additives)

2.2 Model method for evaluation of pitting wear in cone-three balls tribosystem

The cone-three balls test method is generally based on IP 300 standard (Rolling contact fatigue tests for fluids in a modified four-ball machine). The main change is the geometry of the contact of the rolling elements. The upper ball was replaced with a special cone (Michalczewski & Piekoszewski, 2006). The cone can be made of any material. The cone-three balls tribosystem is presented in Fig. 8.

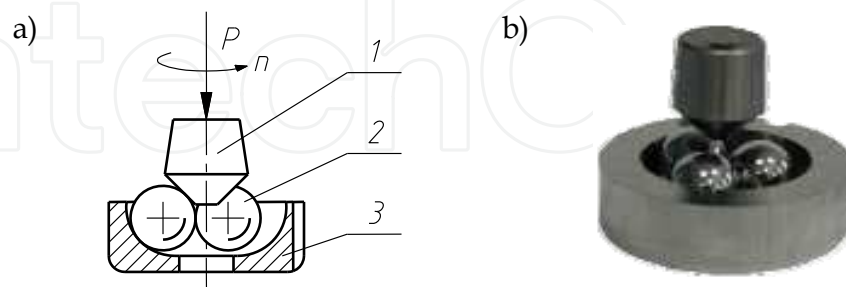


Fig. 8. Cone-three balls tribosystem: a) scheme, b) photograph; 1- cone, 2 - balls, 3 - race

The tribosystem consists of a rotating cone (1) loaded against three balls (2) which are able to rotate in the race (3). The specimens are immersed in the tested lubricant. During the run the vibration level is monitored until pitting occurs.

The tested cones are made of the tested material. The test balls are made of 100Cr6 chrome alloy bearing steel. For each test the new set of balls should be used. According to the method the test conditions are 3924 N (400 kg) load and 1450 rpm top cone speed. 24 top cone failures are necessary to assess the performance of the lubricant and the material. The tested materials can be compared on the basis of L_{10} or L_{50} values as well as scatter factor K. The value of L_{10} represents the life at which 10% of a large number of cones made of the tested material would be expected to have failed. The value of L_{50} relates in a corresponding manner to the failure of 50% of tested cones. The higher L_{10} and L_{50} value, the better the resistance of the tested material to pitting is.

The developed test method was successfully used for testing the fatigue life of components with thin hard coatings deposited by PVD/CVD method and presented in.

The results from pitting tests for uncoated steel and steel coated with single and low-friction coatings are presented in Fig. 9.

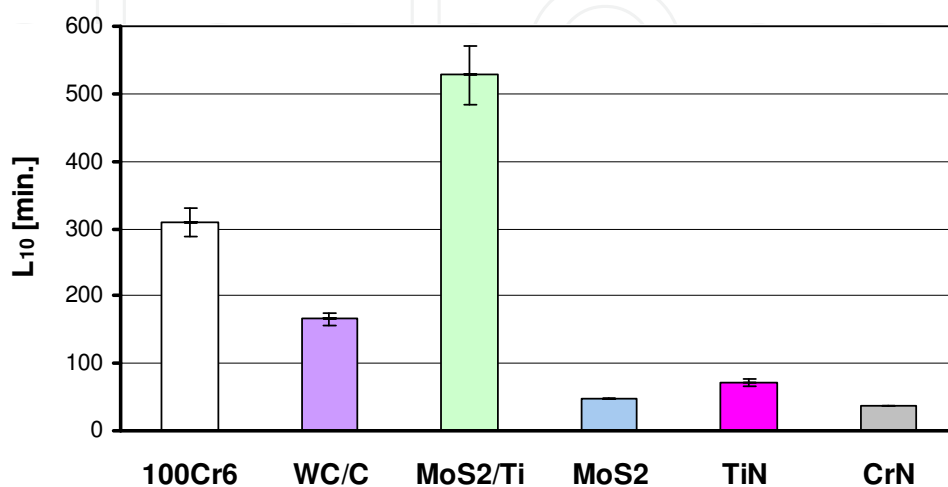


Fig. 9. Results from pitting tests for 100Cr6 steel covered with thin, hard coating

The SEM images of wear on the test cone from pitting tests for 100Cr6 steel covered with WC/C coating are presented in Fig. 10.

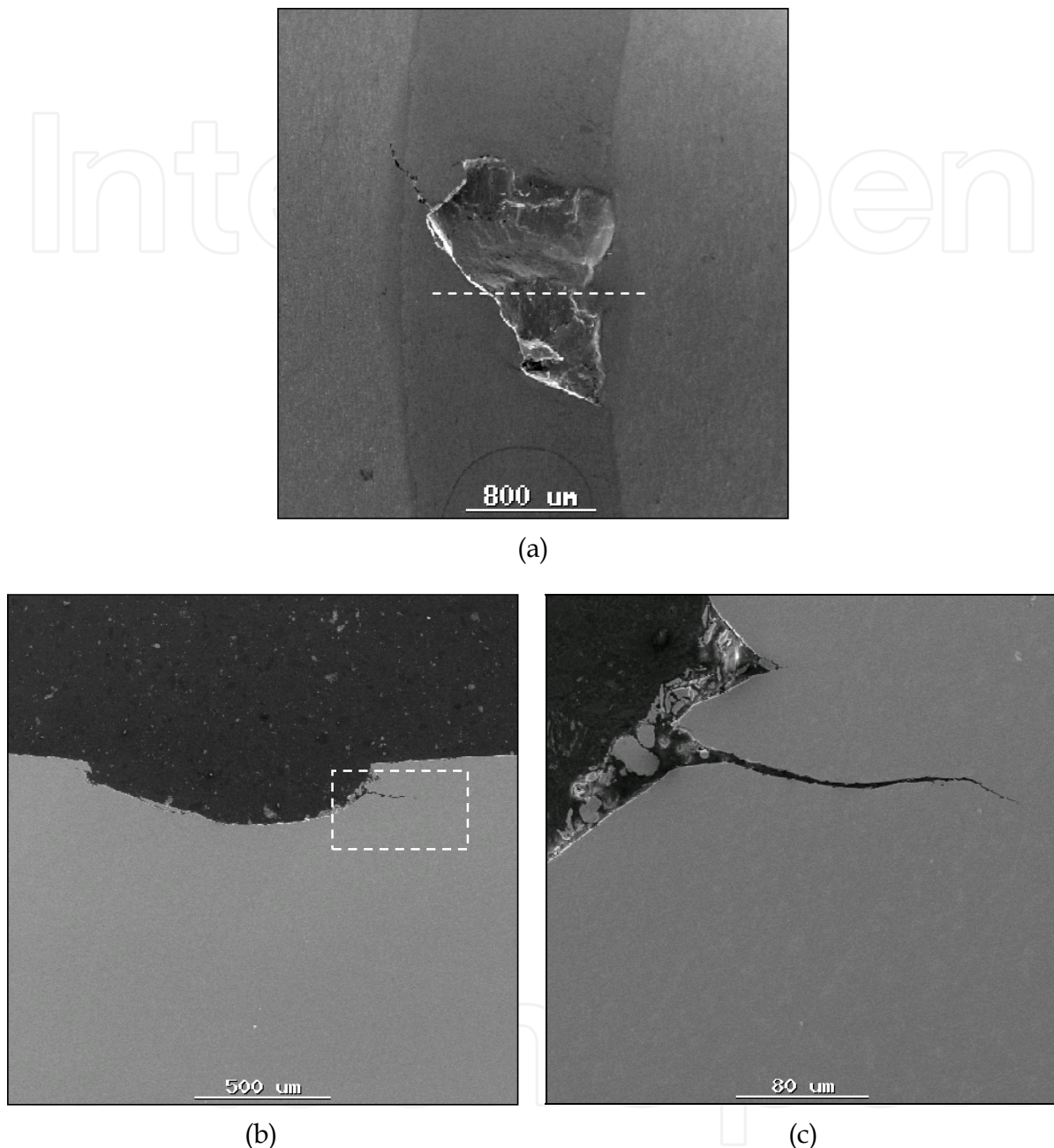


Fig. 10. The pitting wear on the test cone: a) upper view, b) cross-section, c) enlargement of selected fragment (WC/C coated cone, RL-144/4 mineral oil)

The results indicate beneficial impact of low friction coatings on pitting wear (e.g. MoS₂/Ti coating).

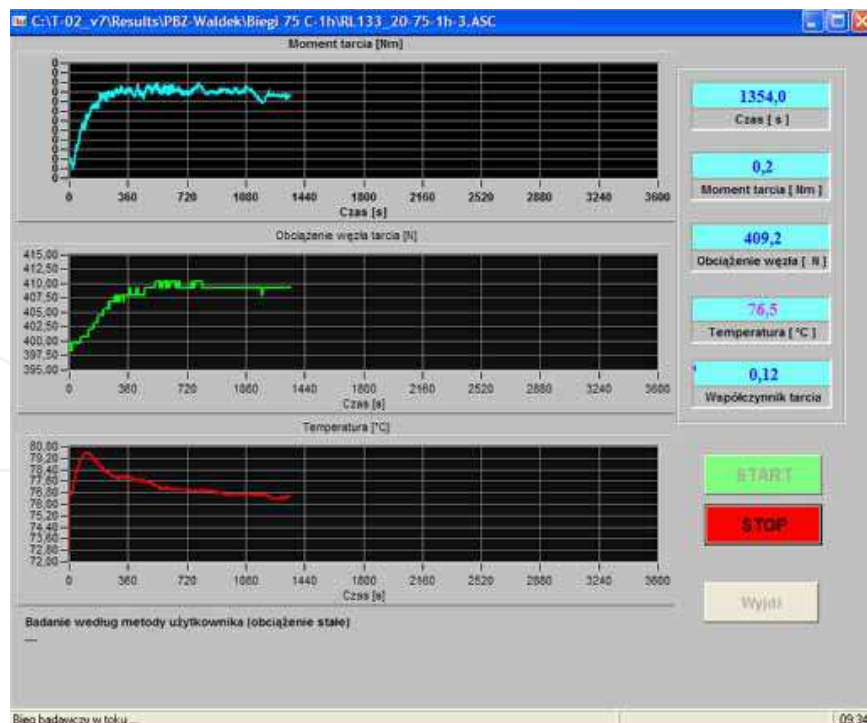
The presented method for testing pitting in cone-three balls tribosystem can be applied to testing fatigue wear of various materials, surface coatings as well as various lubricants. In comparison to other existing methods the new method gives better resolution and is time- and cost-effective.

2.3 T-02U Universal Four-Ball Testing Machine

The methods for evaluation of pitting and scuffing resistance of PVD/CVD coatings is realised by means of T-02U Universal Four-Ball Testing Machine (Michalczewski et al., 2009b). The photo of the machine is presented in Fig. 11. The tribotester is equipped with a computer-aided system of control and measurements.



(a)



(b)

Fig. 11. T-02U Universal Four-Ball Testing Machine: a) photograph, b) computer screen during data acquisition

A very wide range of lubricants can be tested using the T-02U Machine, e.g.: gear oils, hydraulic-gear oils, motor oils, eco-lubricants, non-toxic lubricants, new EP additives, cutting fluids, and greases. Many test methods described in international and national standards can be performed - ISO 20623, ASTM D 2783, D 2596, D 4172, D 2266, D 5183, DIN 51350, IP 239, IP 300, PN-76/C-04147. They concern the determination of the influence of the tested lubricants on scuffing, pitting, friction coefficient, and sliding wear, at ambient and elevated temperatures.

3. Component methods and T-12U Universal Back-to-back Gear Test Rig for evaluation of scuffing resistance and rolling contact fatigue of PVD/CVD coated gears

In research where high reliability is at stake, there is a tendency to use such test specimens that are similar to real machine components. The gear testing is incomparably more expensive and time consuming than tests carried out on simple specimens. But the main advantage is better reliability of the results obtained.

Concerning the most dangerous kinds of wear of gear wheels, two types can be specified: scuffing and pitting. These forms have been described previously in this study.

3.1 Component method for evaluation of scuffing resistance of gears

The test method for the evaluation of scuffing resistance of gears has been originally developed by FZG (Gear Research Centre) at the Technical University of Munich. This method was adapted for investigation of PVD/CVD coated gears at ITeE-PIB.

All test gears are case carburised, with HRC 60 to 62 surface hardness and case depth of 0.6 to 0.9 mm. "A" test gears are cross-Maag's ground, and their tips are especially shaped to achieve high sliding velocities, hence the tendency to scuffing. The tested PVD/CVD coating can be deposited on one or both gears - Fig. 12.



Fig. 12. Coated test gears used for testing scuffing - type A

The only limitation is the deposition temperature that should be below 180°C, which is connected with thermal stability of gear material.

Special coated gears (e.g. A20 type) are run in the test lubricant, at constant speed for a fixed time, in dip lubrication system. From load stage 4 the initial temperature is controlled. The

oil is heated up to 90°C. Loading of the gear teeth is raised in stages. During the running time of each load stage the oil temperature is allowed to rise freely. After load stage 4 the pinion gear teeth flanks are inspected for damage and any changes in tooth appearance are noted. The maximum load stage is 12. If the summed total width of the damaged areas on all the pinion gear teeth faces is estimated to equal or exceed one gear tooth width then this load stage should be taken as the failure load stage (FLS). Additionally the oil temperature, vibration level and motor load during the test can be measured.

The main advantage of the method is the possibility of scuffing testing of various materials, surface coatings as well as various lubricants intended for heavy-loaded friction joints. Furthermore the test can be realised by means of the worldwide popular back-to-back gear test rig manufactured by many producers.

Load stage	Hertzian stress at pitch point p_{max} [MPa]	The type for tooth failure			
		uncoated steel	a-C:H:W	a-C:Cr	a-C:H
4	621	light grooves	light scars	face polished	none
5	773	light grooves	light scars	face polished	none
6	927	light grooves	light scars	face polished	none
7	1080	light grooves	light scars	face polished	light scars
8	1232	grooves	light scars	face polished	light scars
9	1386	scuffing strips	light scars	face polished	light scars
10	1538	wide scuffing areas	light scars	wide scuffing areas	light scars
11	1691		light scars		numerous scars
12	1841		light scars		numerous scars

Table 1. The teeth failure at load stage for various DLC coatings (gears lubricated with eco-oil)

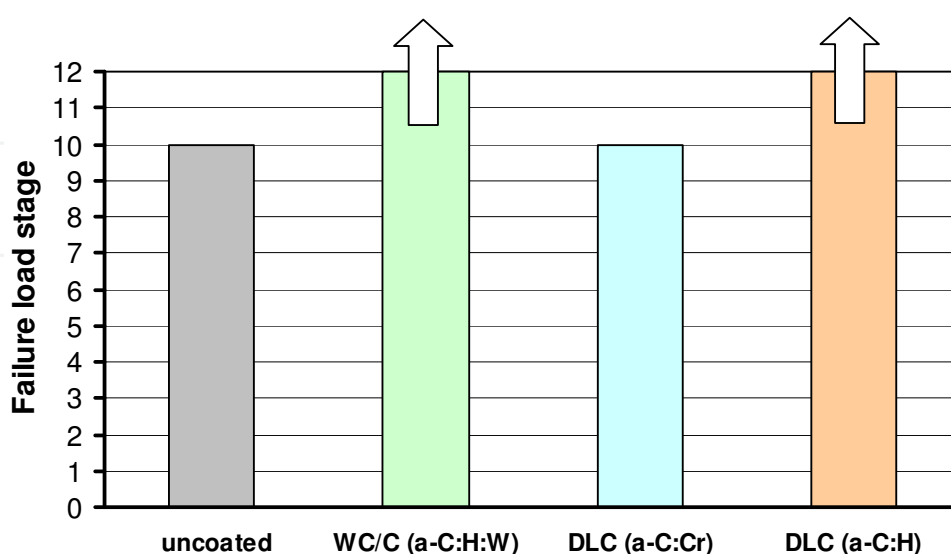


Fig. 13. Failure load stages for uncoated steel gears and for teeth coated with DLC coatings lubricated with eco-oil (A/8.3/90 method)

The test method has been successfully used for extensive research to determine the effect of ecological gear oils on scuffing resistance of coated gears and for the selection of coating types for gear applications. An example of the research on gear oils is presented below.

The method has been applied for selecting a proper DLC coating for increasing the scuffing resistance of gears. The results from gear tests are presented in Table 1 and Fig. 13.

For uncoated gears lubricated eco-oil the 10th failure load stage only was achieved. The application of the coating (a-C:H:W or a-C:H) increased the scuffing resistance of gears. They passed the maximum 12th stage without scuffing. Only a-C:Cr coating did not improve the scuffing resistance of the tested gears.

The photographs of teeth surfaces after tests for tested DLC coatings (gears lubricated with eco-oil) are presented in Fig. 14.

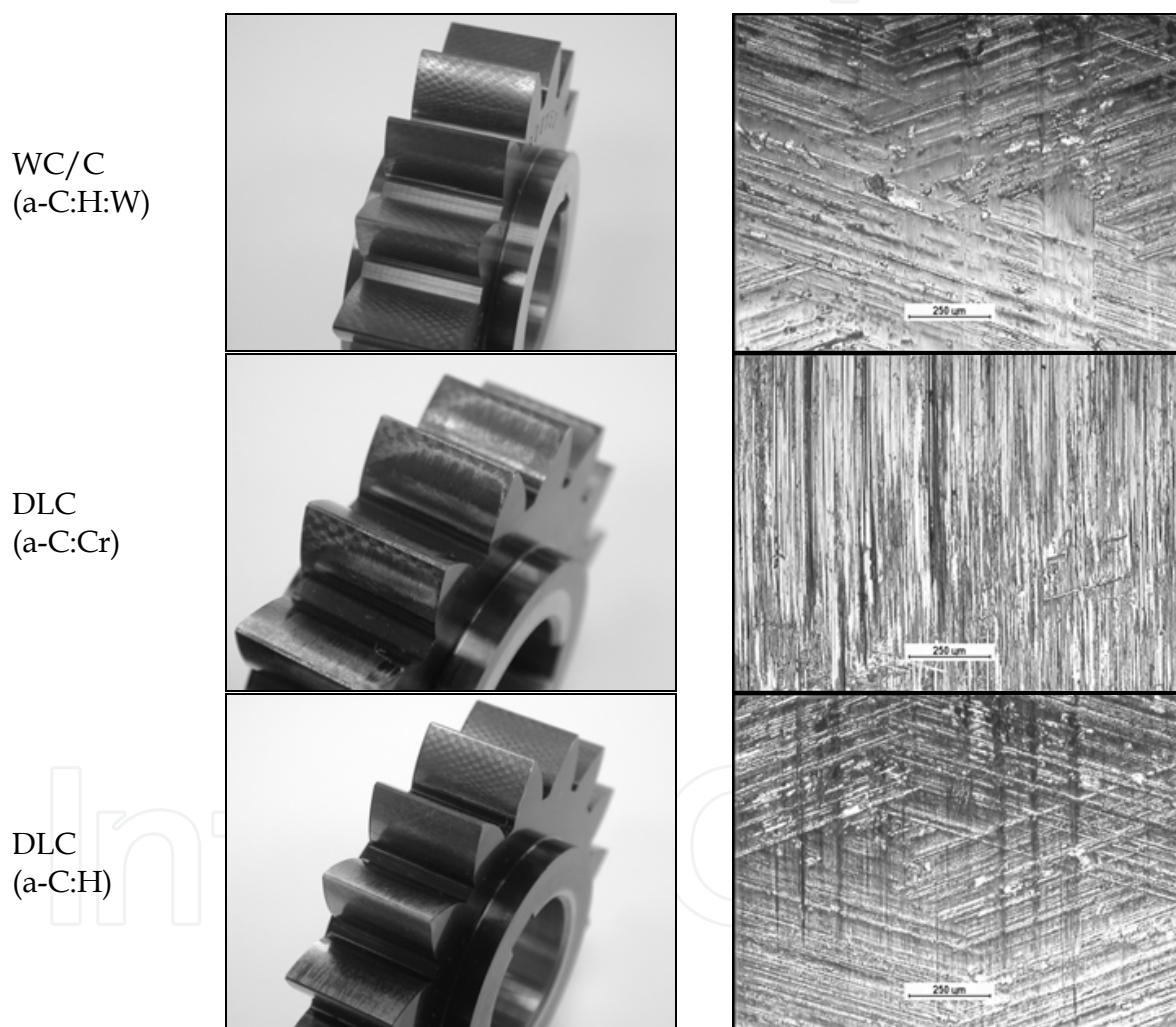


Fig. 14. The photographs of teeth surfaces after tests for various DLC coatings (gears lubricated with eco-oil)

The presented component method for evaluation of scuffing resistance of gears have been applied for developing a new solution for manufacturing steel heavy-loaded machine components covered with low friction coatings that enables increase service life of components and allows lubricating with environmentally friendly oils. This will increase the reliability of machines and reduce pollution of the environment by oil.

3.2 Component gear method for evaluation of pitting wear of gears

Similarly to scuffing gear tests, the method for evaluation of pitting wear of gears has been originally developed by FZG (Gear Research Centre) in the Technical University of Munich. This method was also adapted for the investigation of PVD/CVD coated gears at ITeE-PIB.

The experiments are performed using the single-stage pitting test procedure (PT C/10/90) in an FZG type gear test rig, using C-PT gears – Fig. 15.

Special coated gears (C-PT type) are run in the lubricant test, at constant speed for a fixed time, in dip lubrication system. The load stage is 9 or 10 giving 302 Nm and 372 of torque respectively. The oil is heated up to 90°C. The oil temperature is controlled and kept at constant level. The inspection of gears is performed every 7 or 14 hours.



Fig. 15. Coated test gears used for testing pitting – type C-PT

The result of the tests is the LC_{50} fatigue life, related to 50% probability of failure. LC_{50} is defined as the number of load cycles when the damage area of the most damaged tooth flanks exceeds 4% (about 5 mm²). The total test time of each run is limited to 40 millions load cycles at pinion (300 operating hours). In some cases other criteria can be used. At least three valid runs are necessary to calculate the LC_{50} parameter.

The main advantage of the method is the possibility of comprehensive testing on various low-friction and antiwear PVD/CVD coatings intended for heavy-loaded machine elements. The method is realised by means of the worldwide popular back-to-back gear test rig.

The test method has been successfully used for extensive research to determine the effect of low-friction and antiwear coatings on pitting wear. An example of the research on gear oils is presented below.

The results indicate that for the coated/coated pair (pinion and wheel coated) and coated pinion/steel wheel pair a significant decrease in the fatigue life compared to the uncoated gears was obtained – Fig. 16.

The best results were obtained in the case of the steel pinion/W-DLC coated wheel – even fourfold increase in the fatigue life was observed. This shows a very high potential of the application of DLC coatings for gears.

Thanks to the component gear method for the evaluation of pitting wear of gears, it was possible to overcome the main factor hampering application of thin coatings on heavy loaded elements for many years i.e. their poor behaviour under cyclic stress conditions. This new method will allow for selection of low-friction and antiwear PVD/CVD coatings intended for manufacturing of steel heavy-loaded machine components. This will increase the service life of components and allow for the application of environmentally friendly oils. This will increase the reliability of machines and reduce environmental pollution.

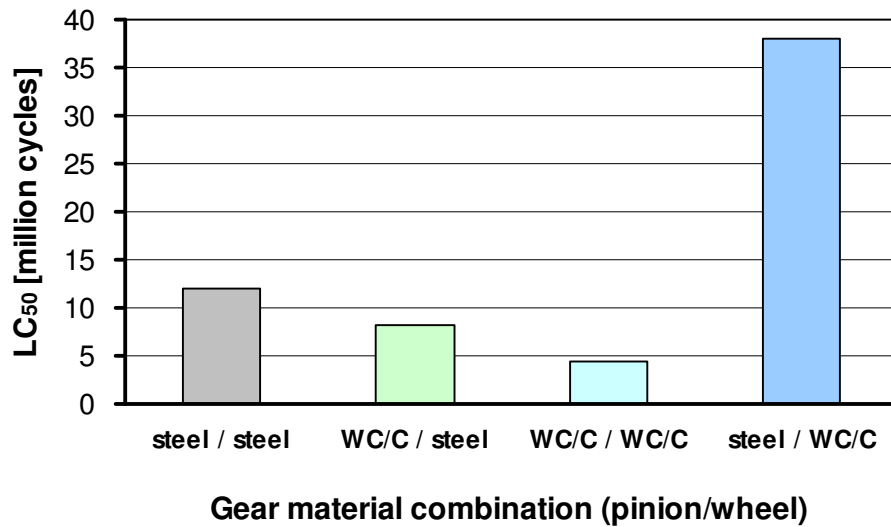


Fig. 16. Fatigue life LC₅₀ for various pinion/wheel gear material

3.3 T-12U Universal Back-to-back Gear Test Rig

The T-12U Universal Back-to-back Gear Test Rig makes it possible to investigate both aforementioned forms of wear. The photo of the tester is presented in Fig. 17.



Fig. 17. T-12U Universal Back-to-back Gear Test Rig

The tribotester is equipped with a microprocessor-aided controller and as an option, it may also be equipped with a computer-aided measuring system.

A very wide range of lubricants can be tested using the T-12U Test Rig, e.g.: gear oils, hydraulic-gear oils, eco-oils, non-toxic oils, and new EP additives. What is more, there is a possibility of testing modern engineering materials and surface coatings intended for gear manufacturing. Many test methods described in international and national standards can be

performed - ISO 14635-1, 14635-2, 14635-3, CEC L-07-A-95, L-84-02, DIN 51354, IP 334, ASTM D 5182, D 4998, PN-78/C-04169, FVA information sheets: 2/IV (1997), 54/7 (1993), 243 (2000). For the last few years, the T-12U Rig has been successfully used at ITeE-PIB for the extensive research to determine an effect of modern gear oils (including ecological oils) on different forms of gear tooth wear, as well as possibility of improving the gear life by the deposition of low-friction coatings.

4. Conclusion

Presented methods give the possibility of comprehensive testing on various low-friction and antiwear PVD/CVD coatings intended for machine elements. All the presented methods and both tribotesters i.e. T-02U Universal Four-Ball Testing Machine, T-12U Universal Back-to-back Gear Test Rig have been implemented at the Tribology Laboratory of ITeE-PIB and successfully verified. They are employed to perform various kinds of projects e.g. grants, R&D projects, ordered by the Polish government and international projects (COST Actions, 6th EU Framework Programme). They are also used to realise research orders from Polish industry (especially small and medium size enterprises) and the scientific sector (research institutes, technical universities).

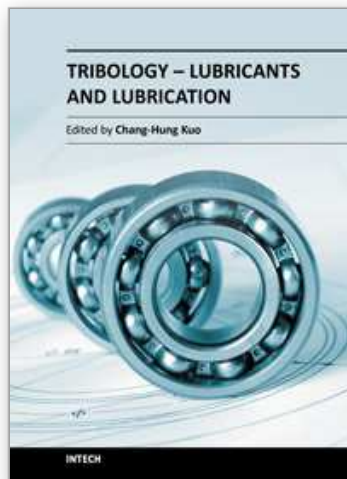
The new methods exhibit very good resolution and precision comparable to standardised test methods and are time and cost effective. Furthermore the cone-three ball method gives the possibility of testing fatigue wear of any coating and substrate material. Basing on the elaborated methods the optimal selection and development of PVD/CVD technologies applied for extension of the life of the heavy-loaded friction joints as well as the elimination of toxic lubricating additives have been obtained.

The further development of tribological devices is performed in the frame of Strategic Programme "Innovative Systems of Technical Support for Sustainable Development of Economy," which is currently realised at the Institute for Sustainable Technologies-National Research Institute (ITeE-PIB) in Radom, in Poland. The Programme is realised within the framework of the Innovative Economy Operational Programme co-funded from European structural funds. The greatest emphasis is put on the development of advanced machines for testing spur gears and rolling bearings under extreme conditions.

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In the past decades, significant advances in tribology have been made as engineers strive to develop more reliable and high performance products. The advancements are mainly driven by the evolution of computational techniques and experimental characterization that leads to a thorough understanding of tribological process on both macro- and microscales. The purpose of this book is to present recent progress of researchers on the hydrodynamic lubrication analysis and the lubrication tests for biodegradable lubricants.

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