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A METHOD FOR THE ASSESSMENT OF THE ROLLING CONTACT FATIGUE OF MODERN ENGINEERING MATERIALS IN LUBRICATED CONTACT

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Summary

It is widely recognised that apart from scuffing, rolling contact fatigue (RCF) is one of the most predominant failure types in highly loaded non-conformal friction joints. The fatigue life of machine parts depends on many factors that can be divided into three groups: design, technology and operating conditions. The main factors influencing pitting are material properties, the geometry of the tribosystem, surface finish, dimensional precision, and working conditions as well as the physicochemical properties of the lubricant.

The aim of this paper is to present the experimental method for determining fatigue life of modern engineering materials in lubricated rolling contact. The developed method allows an investigation into the effect of all these factors on rolling contact fatigue (pitting). The method is employed by using a modified four-ball testing machine denoted as T-03. The modification embraces the replacement of testing specimens. The upper ball is replaced with a cone that can be made of various materials. The method exhibits good resolution and is time and cost effective. It was successfully applied to the investigation into various types of surface coatings including single, multilayer and duplex coatings. This method can be employed by using a widespread four-ball apparatus.

Key words: *rolling contact fatigue, thin, hard coatings, pitting, oil additives, lubricants*

1. Introduction

Rolling contact fatigue (pitting) is a phenomenon of great practical significance in many engineering applications involving concentrated contacts. It is one of the dominating forms of the wear of components in transmissions like toothed gears and rolling bearings [1]. Rolling contact fatigue is responsible for the failure of rolling element bearings, gears, and camshafts. It may be defined as cracking (pitting) limited to the near-surface layer of bodies in rolling/sliding contact. The description of the pitting wear is presented in the paper [2]. These studies indicate that pitting can be initiated either beneath the contacting surface (classical subsurface), where the maximum stress occurs, or at the surface, where a surface defect such as grinding marks, nicks, corrosion pits, etc., contribute to crack initiation. Examples of a gear and a race worn due to pitting are presented in Fig. 1.

a) b)

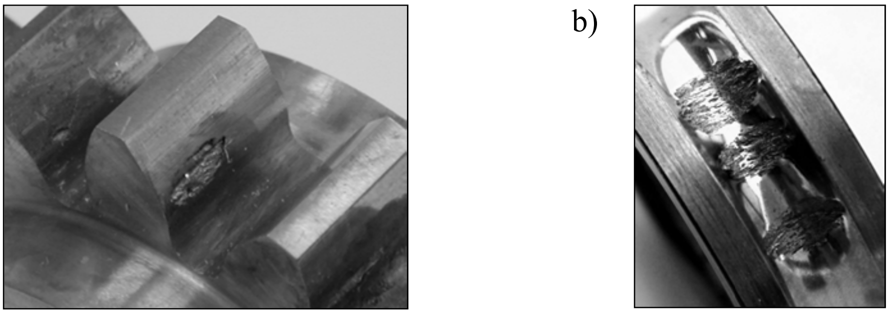


Fig. 1 Pitting wear: a) on a pinion gear, b) on bearing race

Pitting is a form of wear typical of heavily loaded surfaces working in rolling contact and is caused by the cyclic contact stresses that lead to crack initiation. The lubricant is pressed into a crack at a very high pressure (existing in the EHL contact), making them propagate, which is additionally intensified by the adsorption of active additives on the crack faces leading to easier decohesion of the material. Finally, the process results in breaking a piece of material away from the surface. The example of a cross-section of pitting wear is depicted in Fig. 2.

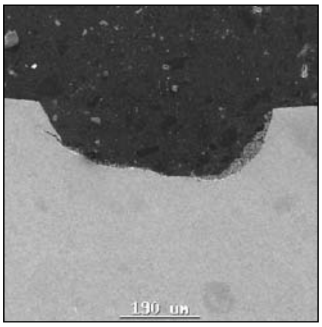


Fig. 2 Cross-section showing pitting on a 100Cr6 steel test cone (SEM image)

The fatigue life of machine parts depends on many factors that can be divided into three groups: design, technology, and operating conditions [3]. The main factors influencing pitting are material properties, the geometry of the tribosystem, surface finish, dimensional precision, and working conditions as well as physicochemical properties of the lubricant.

Nowadays, technology offers numerous modern engineering materials. Among other engineering solutions, the ones that demonstrate a very high potential are the thin hard coatings deposited at low temperatures (below 200°C). Potentially, these coatings can be successfully deposited on heavily loaded machine parts such as gears or rolling bearings. The main factor hampering the application of thin coatings on heavily loaded elements is poor behaviour under cyclic stress conditions. Unfortunately, it is impossible to predict the fatigue life of modern engineering materials with various possible surface treatments on the basis of numerical calculations [4]. Furthermore, it is virtually impossible to predict the time to pitting wear based only on the material properties of the tribosystem. In practice, the resistance to pitting failure of various tribosystems can be compared only experimentally.

To perform testing, it is necessary to conduct tests on real components like bearings [5] or gears [6]. In practice, the component tests are usually limited to validation testing, because they are very time consuming and much more expensive than model testing.

Nowadays, there are a lot of different methods for testing rolling contact fatigue. Pitting can be tested in point or linear contacts. In model testing, in point contact, the most popular tribosystems are the four-ball apparatus and the rod-two-ball apparatus (Table 1); whereas in linear contact, rod-rollers and roller-roller tribosystems can be used (Table 2). There are also many testing rigs adjusted to individual requirements [7].

Table 1 The most popular testers for investigation into rolling contact fatigue in point contacts

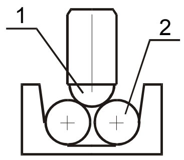
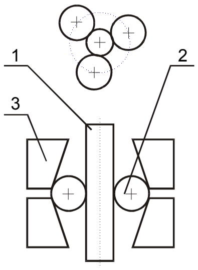
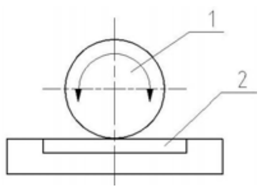
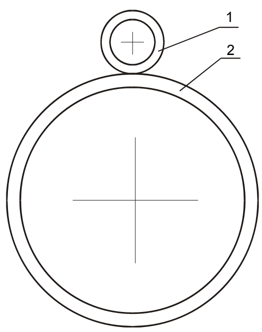
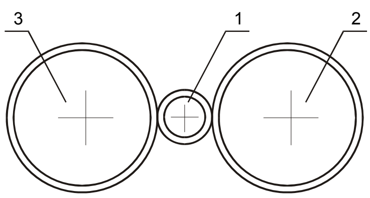
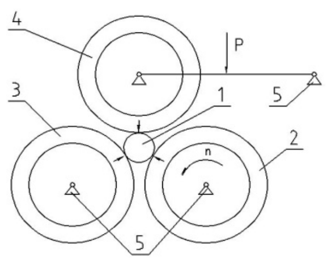
Testing rig	Schematic diagram	Operating conditions	Source
four - ball apparatus		Contact: point Specimens: balls ½” Max. Hertzian pressure: 8.7 GPa 1 - upper ball 2 - lower balls	[1]
rod - three balls		Contact: point Specimens: rods Max. Hertzian pressure: 5.5 GPa 1 - rod 2 - balls 3 - tapered races	[8]
CTD-ROLL rolling contact testing device		Contact: point Specimens: balls 1 – ball 2 – testing sample	[9]

Table 2 The most popular testers for investigation into rolling contact fatigue in linear contacts

Testing rig	Schematic diagram	Operating conditions	Source
roller - roller		Contact: linear Specimens: roller Max. Hertzian pressure: 2.3 GPa 1 - specimen 2 - supporting disk	[10]
rod - two rollers		Contact: linear Specimens: rods Max. Hertzian pressure: 7.52 GPa 1 - rod 2, 3 - rollers	[3]
rod - three rollers		Contact: linear Specimens: rods 1 - rod 2, 3 - rollers 4 - loading roller 5 - support	[8]

Each of the presented methods has some limitations. Some of the methods are intended for evaluating only the effect of oils (e.g. the four-ball method, where the balls are made only from one material – 100Cr6 bearing steel), others are used only for evaluating materials (e.g. the rod-roller method, where one oil is specified). All the above methods are employed by using non-standard specimens and equipment which results in low reproducibility and repeatability. To overcome these limitations, a new, fast, simple and low-cost experimental method is required.

The new method is based on the commonly used four-ball method intended for oil testing. The modification embraces the replacement of testing specimens. The upper ball is replaced with a cone that can be made of various engineering materials.

2. The principle of the new test method

The procedure for the determination of the test method is generally based on the IP 300 standard (Rolling contact fatigue tests for fluids in a modified four-ball machine). The method is described in details in the monograph [12]. The method is carried out using a cone-three-ball tribosystem presented in Fig. 3.

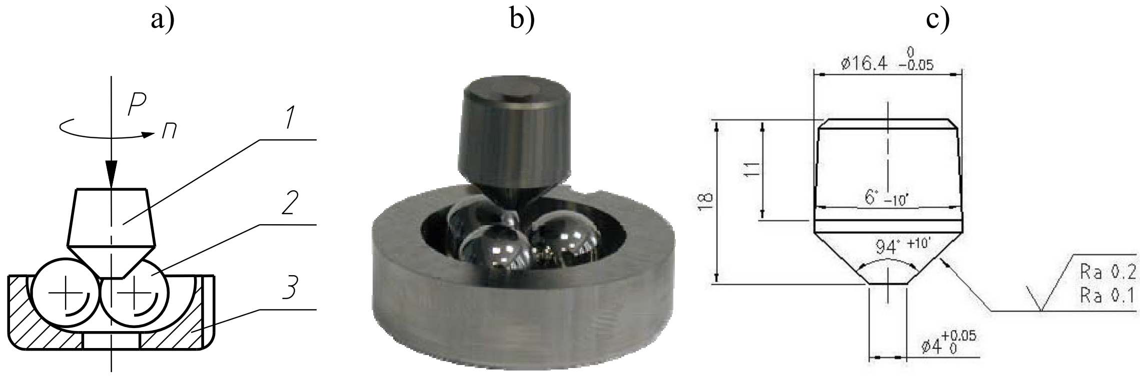


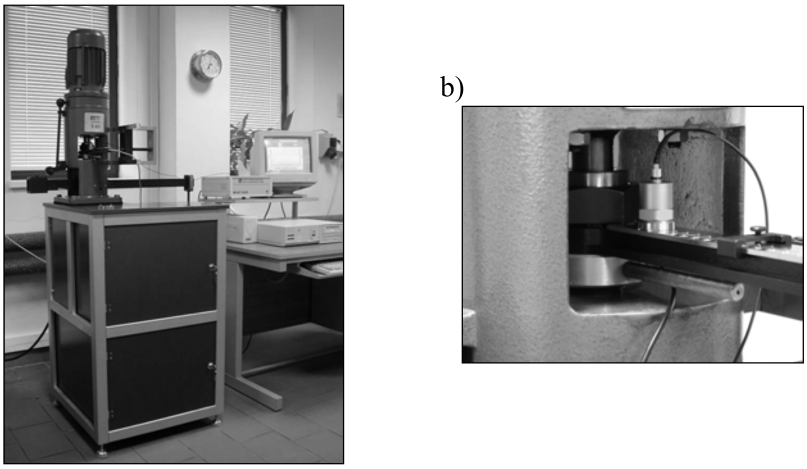
Fig. 3 Cone-three ball tribosystem: a) scheme, 1- cone, 2 - balls, 3 – race, b) photograph, c) cone dimensions

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

The cones are made of the material to be tested. The test balls are made of 100Cr6-chrome alloy bearing steel. New balls are used for each test.

To carry out the new test method, a modified four-ball apparatus equipped with a pitting detector is needed as presented in Fig. 4.

b)



a)

Fig. 4 T-03 pitting tester: a) test rig, b) location of vibration detector

The test conditions are 3924 N (400 kg) load, which provides a maximum Hertzian stress on the top cone of 7.32 GPa. The cone rotational speed is 1450 rpm. Pitting is detected by a special system with a vibration sensor (Fig. 4b), which automatically stops the machine when the predefined level of vibrations (RMS value) is achieved. 24 runs are necessary to assess the performance of a lubricant and a material. An example of pitting wear is shown in Fig. 5.

a) b) c)

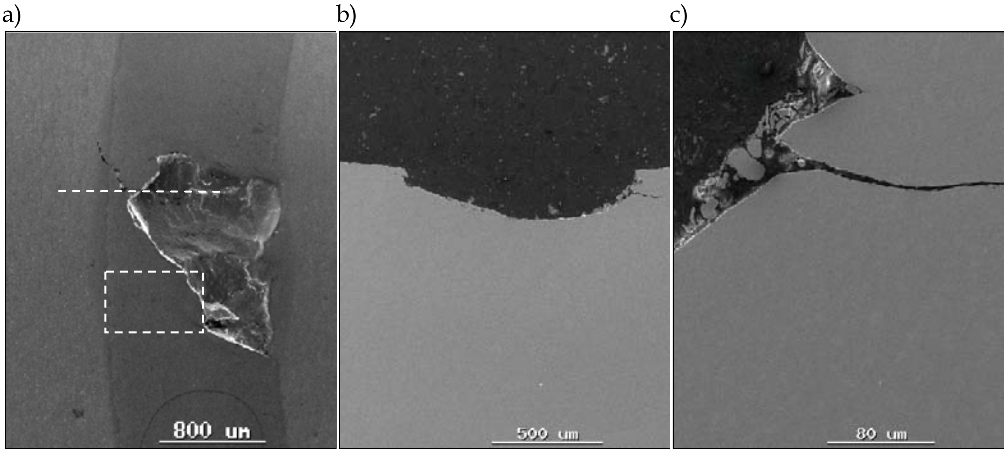


Fig. 5 Pitting wear on a test cone: a) upper view, b) cross-section, c) enlargement of selected fragment (WC/C coated cone, RL-144/4 mineral oil)

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 is the resistance of the tested material to pitting.

To complete the test method the following four steps have to be made:

STEP 1. Performing at least 24 tests for each material. Pitting is detected by a special system with a vibration sensor that automatically stops the machine when pitting occurs.

STEP 2. Re-listing the 24-run duration times in increasing order. Plotting the estimated cumulative percentage failed versus the time to pitting on Weibull co-ordinates and fitting a straight line to the points – Fig. 6.

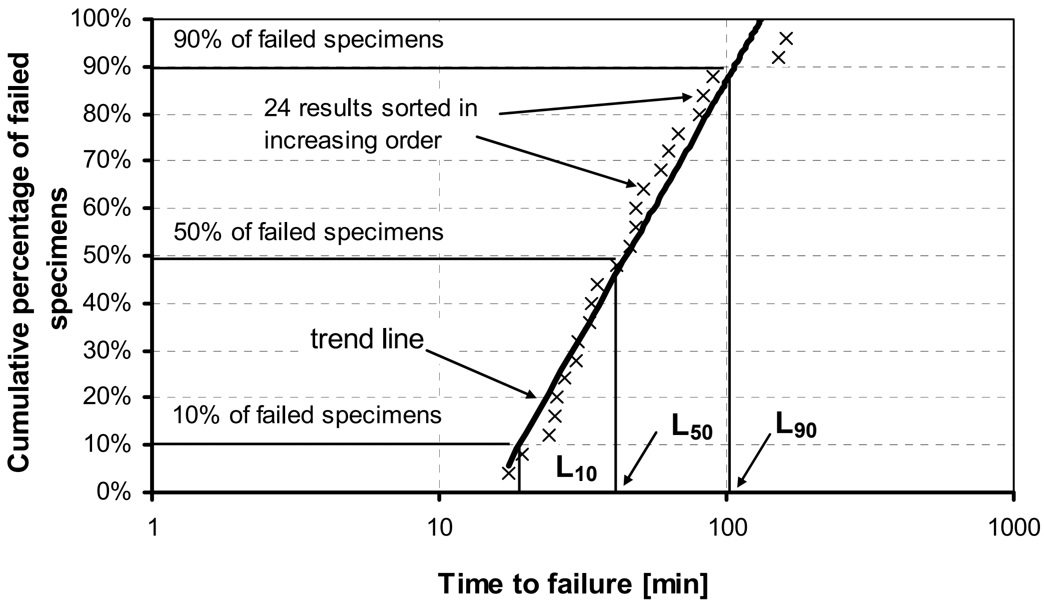


Fig. 6 The method of calculating L lives

STEP 3. Reading out the L_{10}, L_{50}, and L_{90} lives from the plot and calculate confidence intervals for 90% probability.

STEP 4. Calculate the scatter factor W by using the following equation:

$$W = \frac{L_{90}}{L_{10}} \tag{1}$$

The longer the L_{10}, L_{50}, and L_{90} life, the better is the resistance to rolling contact fatigue of the tested tribosystem. The lower W factor, the smaller scatter of the results; thus, the better is the reliability of the tested materials.

3. Comparison of rolling fatigue lives and scatter factor for four-ball tribosystem and cone-three ball tribosystem

The new method was compared to the standard four-ball method (IP 300). In both cases, the same load (3924 N and 5886 N) and rotational speed (1450 rpm) were applied. The tribosystems were lubricated with the RL 144 reference mineral oil (mineral oil without additives, viscosity 7.2 mm^2/s at 100°C). Balls and cones were made of chrome bearing steel (100Cr6). The ball roughness (about $R_a = 0.032$ μm) was lower than the cone roughness ($R_a = 0.1$ μm).

The results are presented in Fig. 7 and summarised in Fig. 8.

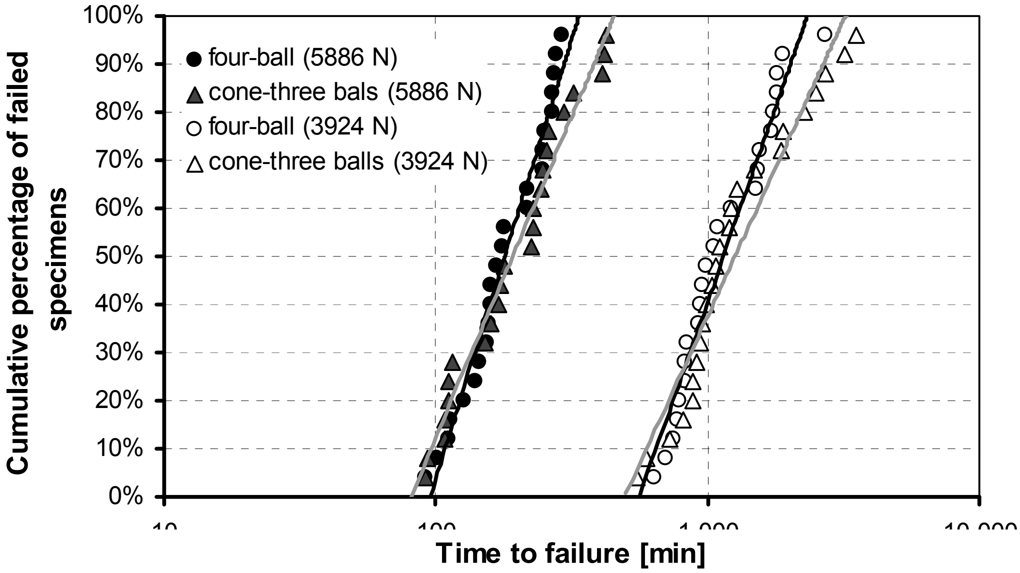


Fig. 7 The cumulative percentage of failed specimens for four-ball tribosystem and cone-three ball tribosystem (100Cr6 steel, RL-144/4 mineral oil)

It is clear that the results obtained for the four-ball tribosystem and the cone-three ball tribosystems are very similar. For a more precise comparison, the L_{10} and L_{50} lives and W for 5886 N and 3924 N were calculated and presented in Fig. 8.

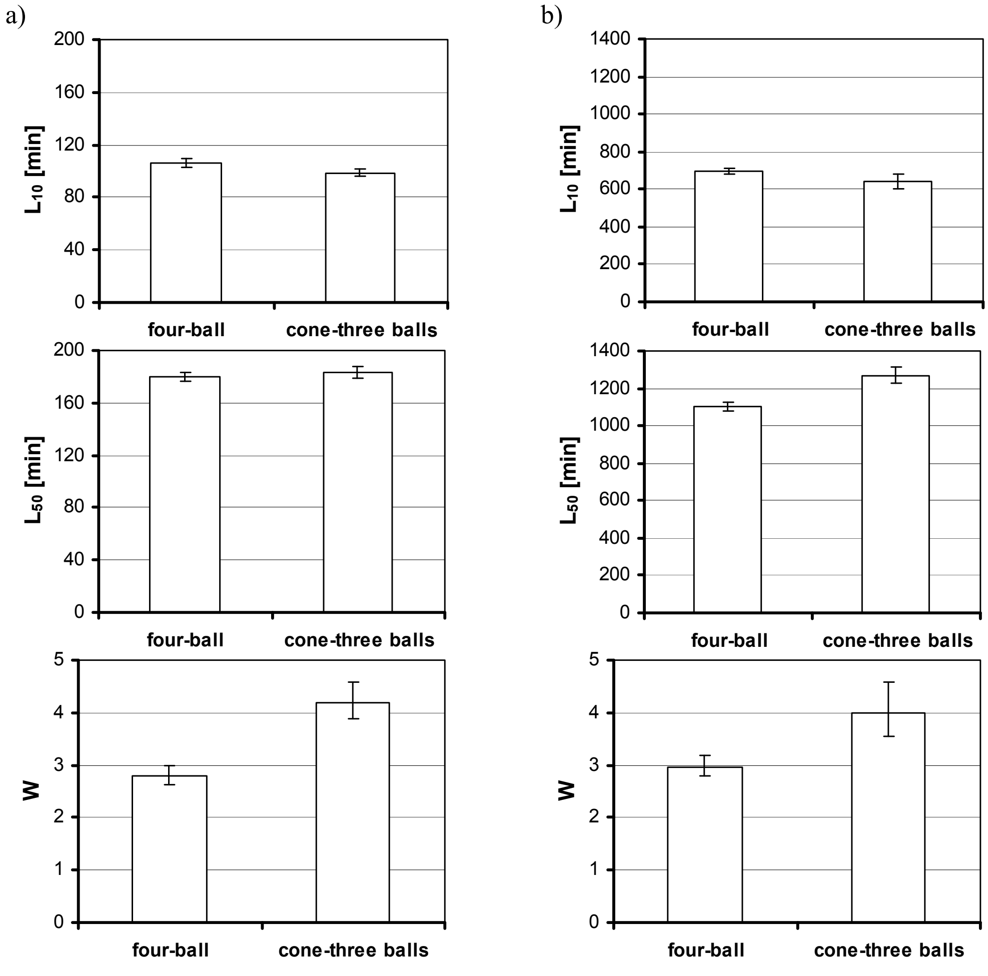


Fig. 8 The results of L_{10} and L_{50} lives and W for a) 5886 N and b) 3924 N (100Cr6 steel, RL-144/4 mineral oil)

For both loads (5886 N and 3924 N) the rolling contact fatigue L_{10} lives were almost equal to the cone-three ball tribosystem. Only in one case, for 3924 N, the L_{50} life was a bit higher for cone-three ball than for the four-ball tribosystem.

The result scatter of the cone-three ball tribosystem is at a very low level and is similar to the results obtained for the four-ball tribosystem. The main difference is in the scatter factor W, which in all cases, was higher for the cone-three ball systems than for the four-ball tribosystem. It probably resulted from the differences in the surface quality of the used parts. The surface quality of the ball is better than for the cone.

4. Application of the new test method

The elaborated test method was successfully used for testing the fatigue life of components with thin coatings deposited by using the PVD/CVD method.

The new method was used for

- comprehensive research on rolling contact fatigue of steel components with typical PVD coatings (e.g. TiN, CrN) [11],
- the testing of rolling contact fatigue of steel components with low-friction PVD coatings (e.g. WC/C MoS_2/Ti) [12],
- the testing of the effect of base oils (mineral, synthetic and vegetable) on pitting of uncoated and a-C:H:W coated elements [13],
- understanding the materials behaviour in lubricated contact to improve the performance of machine components [14].

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

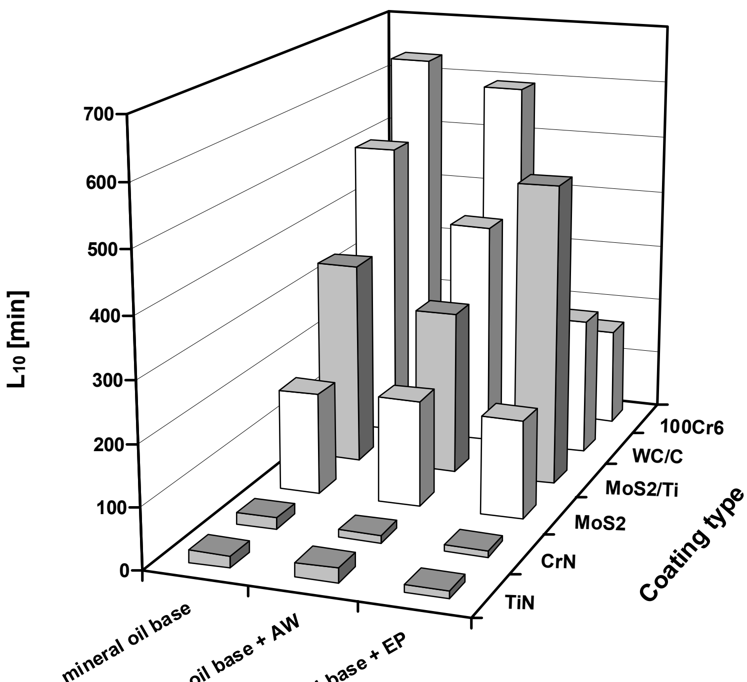


Fig. 9 The results of L_{10} lives for various coatings and lubricants [12]

The practical effect of high importance is the selection of PVD coatings with satisfactory resistance to pitting. It was also indicated that the deposition of PVD coatings on such steel elements can eliminate the classical, mostly non-ecological lubricants.

5. Conclusions

The authors developed a method for investigating rolling contact fatigue (pitting) of engineering materials in point contact. The method is employed by using a modified four-ball testing machine. The modification refers to the replacement of the upper ball with a cone that can be made of various engineering materials.

The new method was successfully applied to testing fatigue wear of various materials, surface coatings, and various lubricants. In these tests, the method exhibited satisfactory scatter of results and was time and cost effective.

In comparison to the numerous existing methods performed by using custom-made equipment the new method uses a modified widespread four-ball apparatus giving much higher reproducibility and repeatability of the results.

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