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# The effect of depth of surface layers constituted by vacuum technologies on pitting

**B. Majkowska [a], W. Piekoszewski [b], M. Szczerek [b], E. Wołowiec [c,*]**

[a] Department of Materials and Welding Engineering, Faculty of Mechanical Engineering, Gdansk University of Technology, ul. Narutowicza 11/12, 80-233 Gdańsk, Poland

[b] Institute for Sustainable Technologies - National Research Institute, ul. Pułaskiego 6/10, 26-600 Radom, Poland

[c] Institute of Materials Science and Engineering, Lodz University of Technology, ul. Stefanowskiego 1/15, 90-924 Łódź, Poland

* Corresponding e-mail address: emilia.wolowiec@p.lodz.pl

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## ABSTRACT

**Purpose:** The paper presents the results of a study of the effect of vacuum technologies of formation of surface layers on pitting of associated elements in a lubricated, heavy-load rolling contact.

**Design/methodology/approach:** Samples of 16MnCr5 vacuum-carburised steel, 100Cr6 bearing steel as well as elements of 100Cr6 steel with deposited coatings of titanium nitride (TiN) and chromium nitride (CrN) of various depths have been examined. The contact under examination was lubricated with RL 144 standard mineral oil with no additives.

**Findings:** The study has shown that increase in a PVD coat depth is accompanied by decrease in the fatigue friction pair.

**Research limitations/implications:** The elements after cutting-edge surface processing may have lower surface fatigue strength. It is one of the reasons for them not being used in lubricated friction parts of machines, especially high-performance ones.

**Originality/value:** The study has shown a significant and varied effect on pitting of vacuum technologies of surface layer deposition in associated elements in concentrated rolling contact

**Keywords:** Thermo-chemical treatment; Vacuum technologies; PVD coatings; Pitting; Surface fatigue strength

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MATERIALS MANUFACTURING AND PROCESSING

## 1. Introduction

The main problem faced by users of high-performance friction pairs with lubricated concentrated contact is their durability. A failure of a kinematic friction pair (a toothed gear, a rolling bearing, a cam-follower pair, etc.) usually makes a device inoperable for a long period of time and results in increase in the operation costs. A general tendency to reduce costs in practice means miniaturisation of devices, which in



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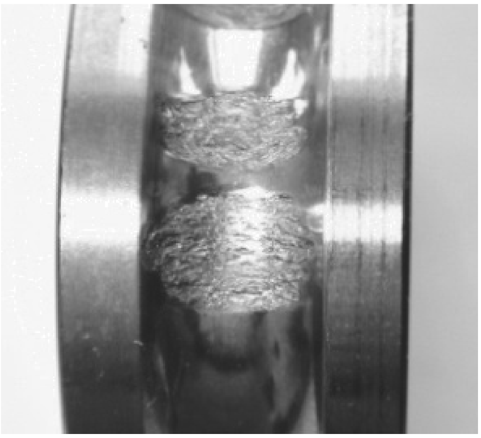
consequence increases the power transferred by kinematic friction pairs. Increase in the load transferred through the pairs is associated with the risk of fatigue of the working surfaces of friction elements.

Pitting is a form of wear of surface layers of lubricated parts of machines, which manifests itself in formation of hollows on friction surfaces of bearing and toothed wheels (Fig. 1). The latent wear process is continuous and it results from accumulation of energy in the surface layer; after its certain level is exceeded, it manifests itself in chipping [1,2].

There is a common opinion in centres which construct and design of high-performance friction pairs that the capabilities of classic materials - in terms of durability and strength - have reached their limit. Methods of increasing wear strength with potential for the future are cutting-edge methods of formation of surface layers of machine parts, which include vacuum methods (carburising, nitriding, PVD/CVD coatings) [3-10].

a)



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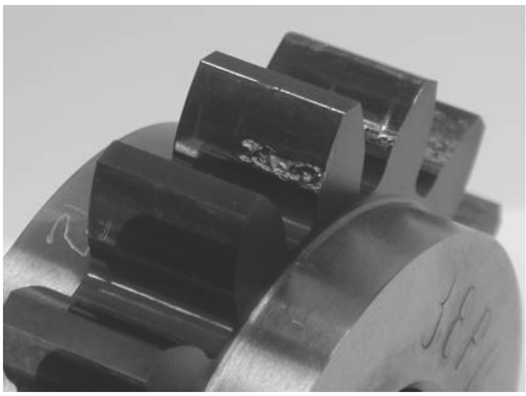


Fig. 1. Machine elements with traces of surface damage caused by pitting: a) a ball bearing race, b) tooth wheel

The depth of a coating/layer significantly affects surface fatigue wear (pitting). It should be noted when discussing the issue that three effect zones can be identified for each type of surface layer (the zone which deforms in the same way as the substrate material, the transition zone and the zone which deforms in the same way as the surface layer). They have been discussed in detail in the monograph by M. Szczerek [2], who has shown the extent of strains and deformations in the contact zone to be considerably dependent on the elasticity and the layer depth as well as on the load, i.e. on the conditions of the contact operation.

Due to ambiguous and contradictory literature reports [10-12] on the issue, the authors decided to elucidate the problem by experiment. For anti-wear coatings, increase in fatigue wear strength has been observed mainly in elements whose coating depth did not exceed 1 µm. A thin coating more often deforms with no loss of cohesion [13,14]. According to K. Holmberg and A. Matthes [15], thin coatings have their own compressive stress, which makes them more resistant to fatigue wear. Different reports have also been published, e.g. theoretical calculation for a TiN coating suggest that increased surface fatigue strength can also be achieved for coatings deeper than 3 µm. [16]. However, this has not been confirmed experimentally.

An analysis of literature reports shows that the process of vacuum carburising has an advantageous effect on formation of compressive stress in the surface layer of elements being processed [17], which positively affects surface fatigue strength. The value of the stress and the diffuse layer thickness depends mainly on the process parameters.

This study has examined the effect of a vacuum-carburised layer depth and typical PVD (CrN and TiN) coatings on surface fatigue strength (pitting) of elements which operate in a lubricated rolling contact.

## 2. Study methodology

The tribological examination was conducted in a modified four-ball apparatus, developed and produced at the Institute for Sustainable Technologies. Both the modernised apparatus and the modified study methodology have been presented in a number of publications [17-19]. The examination involved conducting 24 test runs of elements in the rolling contact in the presence of a lubricating agent, at constant set load and constant rotational speed, with continuous measurement of amplitude of vibrations generated in the friction pair, measurement of the time of each test run, developing Weibull distribution and determination of the friction pair strength based on it.

Fatigue strength was characterised with so called 10% strength, abbreviated as $L_{10}$. It is the period of operation of lubricated rolling elements of a friction pair, in which 10% of their population has been damaged.

The test runs were conducted in the following conditions:

- initial load of the friction pair: 3,924 N,
- rotational speed of the spindle: 1450 ± 50 rpm,
- initial load of the friction pair: 981 N,
- ambient temperature: 23 ± 2ºC.

## 3. Study objects

The study association included a conical sample made of the material under examination and three 1/2" balls made of 100Cr6 steel which rolled in a special track (Fig. 2).

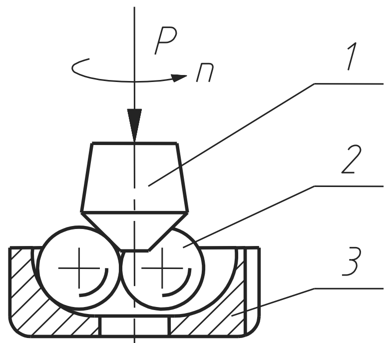
Samples for coating deposition were made of 100 Cr6 bearing steel because of its uniform structure after thermal processing. For this reason, it is suitable as a reference material and it has been chosen as the basic material for coating deposition. Moreover, 100 Cr6 steel is commonly used for elements of rolling bearings and it has been thoroughly tested for its fatigue strength [20-25]. The samples were covered with single-layer coatings of titanium nitride (TiN) and chromium nitride (CrN).

The TiN and CrN coatings were deposited in the PVD process by the vacuum arch method. The TiN coatings had the following depth: 0.65, 1.0, 2.0 and 2.14 μm, whereas the CrN had the following depths: 0.25, 0.8, 1.2 and 1.6 μm. All the deposition processes were conducted below the temperature at which phase transitions take place in the substrate material (ca. 180ºC).

The vacuum-carburised samples were made of 16MnCr5 steel, and the vacuum-carburising process itself was conducted by the FineCarb method [26-28]. The depth of diffusion layers was equal to 0.4, 0.5, 0.6 and 0.7 mm.

Three bearing balls with the nominal diameters of 1/2", made of 100Cr6 bearing steel in class precision 16 (PN-83/M-86452), were used as counter samples in the fatigue strength tests. The surface roughness, characterised by the Ra parameter, was equal to 0.032 μm, and the material hardness - 62-64 HRC.

a)




1-conical sample, 2-lowerballs, 3-track

b)

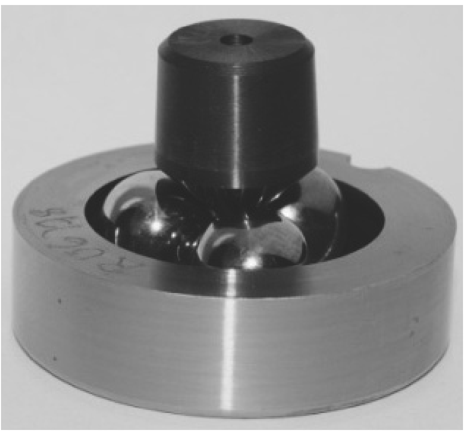


Fig. 2. A friction pair of a T-03 apparatus used in studying surface fatigue wear of materials used for high-performance rolling elements: a) diagram, b) view

For all the associations under study, only the sample had surface friction layers formed by vacuum technologies. In order to avoid the effect of the type of lubricating agent on the test result, a standard oil RL 219, with no additive, with the viscosity of 49.31 mm$^2$/s at the temperature of 40 °C, was used to lubricate the material associations.

## 4. Results of the wear tests

The results of material association tests in which a cone was covered with TiN coatings are shown in Fig. 3 and Fig. 4. The results show unambiguously that the coating depth significantly affects the time of pitting initiation. A thicker coating decreases the fatigue strength of the friction pair under examination. The difference is clearly seen in the data presented in Fig. 4. It must be stressed that the strength $L_{10}$ of association *100Cr6-100Cr6* (as the reference base) and *TiN 0.65 - 100Cr6* is of the same order, although the coating decreases it nearly two-fold.

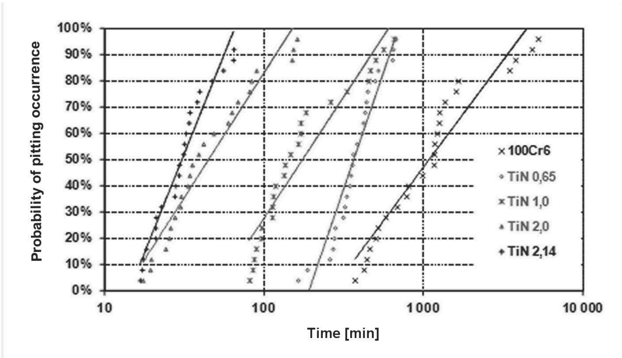



Fig. 3. Results of fatigue tests for material associations steel-steel (100Cr6) and steel - TiN coating (different coating depth, μm), lubricated with mineral oil, RL 219

Coatings of the depth of more than 1 μm dramatically decrease the strength as compared to the associated elements without coatings (Table 1).

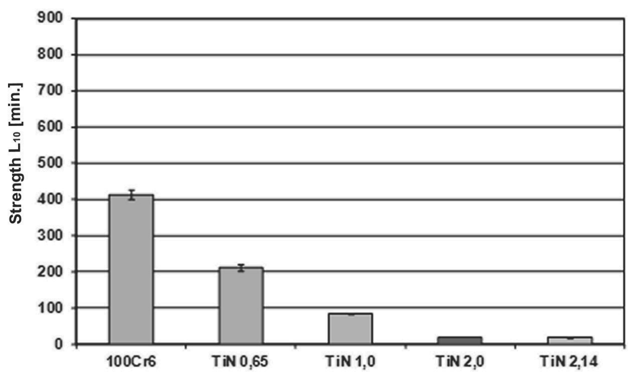



Fig. 4. Fatigue strength of material associations steel-steel (100Cr6) and steel - TiN coating (different coating depth, μm), lubricated with mineral oil, RL 219



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Table 1.
A listing of $L_{10}$ values and its upper and lower limits of the confidence interval for steel-steel (100Cr6) and steel-TiN coating material associations (different coating depth, μm), lubricated with mineral oil RL 219

| Cone/coating material ⇒ | | 100Cr6 | TiN 0.65 | TiN 1.0 | TiN 2.0 | TiN 2.14 |
|---|---|---|---|---|---|---|
| Strength [min] | $L_{10G}$ | 427.71 | 221.04 | 85.65 | 19.80 | 17.89 |
| | $L_{10}$ | 413.25 | 211.56 | 84.60 | 19.35 | 17.58 |
| | $L_{10D}$ | 399.86 | 201.28 | 83.64 | 18.91 | 17.29 |

Tests of the friction pair with deposited CrN coatings confirmed the effect of coating depth on its strength, observed for TiN coatings. The results of the fatigue tests of friction pairs with CrN coatings lubricated with oil *RL 219* are shown in Fig. 5 and Fig. 6.

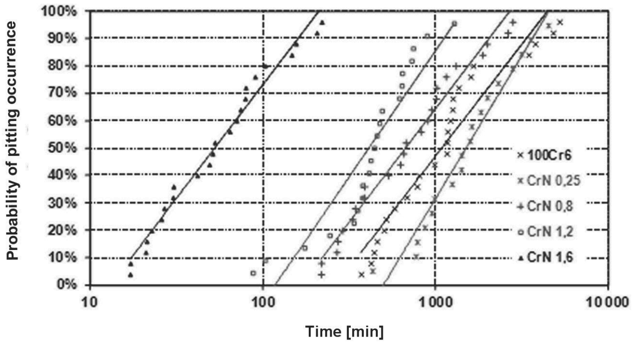


Fig. 5. Results of fatigue tests for material associations steel-steel (100Cr6) and steel - CrN coating (different coating depth, μm), lubricated with mineral oil, RL 219

Only for associations with an element coated with CrN with the thickness of 0.25 μm was the strength of the association nearly twice as high as for the steel association, whereas the strength for the other associations with that coating - like for elements with a TiN coating - a thicker CrN coating significantly decreases the fatigue strength (Fig. 6). Strength $L_{10}$ of an association with deposited coating of *CrN 0.8 - 100Cr6* is nearly twice lower than strength of the steel elements. Increasing the coating depth to ca. 1.6 μm results in its dramatic (nearly 20-fold) decrease as compared to steel (100Cr6) elements association with no coating (Table 2).

The nature of the trend line of surface fatigue strength of associations with PVD coating as a function of their depth is shown in Fig. 7.

This has also confirmed that the beneficial effect of a very thin coating (referred to by the authors of [19]) with the depth of about 0.25 μm is a result of hindering propagation of surface cracks, which increases the strength of elements with such coatings.

The test results for the associations in which the cone was vacuum-carburised are shown in Fig. 8 and Fig. 9. They also show that the depth of a carburised layer affects the time of pitting initialisation, but it is not as varied as for PVD coatings. The diagram in Fig. 9 shows that the association in which the sample was coated with a 0.5 mm deep carburised layer was the most resistant to pitting. A thicker diffusion layers decreased the fatigue strength of the friction pair under examination.

It must be stressed that strength $L_{10}$ of friction pairs with carburised elements as compared to bearing steel associations is of the same order, although it decreases with increasing coating depth (Table 3).

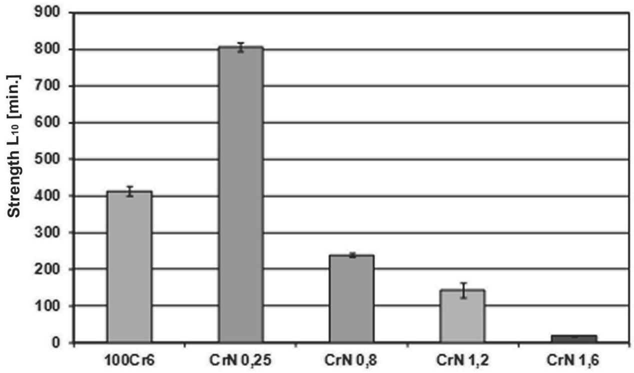


Fig. 6. Fatigue strength of material associations: steel-steel (100Cr6) and steel - CrN coating (different coating depth, μm), lubricated with mineral oil, RL 219

Table 2.
A listing of $L_{10}$ values and its upper and lower limits of the confidence interval for steel-steel (100Cr6) and steel-CrN coating material associations (different coating depth, μm), lubricated with mineral oil RL 219

| Cone/coating material ⇒ | | 100Cr6 | CrN 0.25 | CrN 0.8 | CrN 1.2 | CrN 1.6 |
|---|---|---|---|---|---|---|
| Strength [min.] | $L_{10G}$ | 427.71 | 817.98 | 244.28 | 162.91 | 19.16 |
| | $L_{10}$ | 413.25 | 806.23 | 238.79 | 143.69 | 18.73 |
| | $L_{10D}$ | 399.86 | 794.64 | 233.53 | 123.18 | 18.32 |

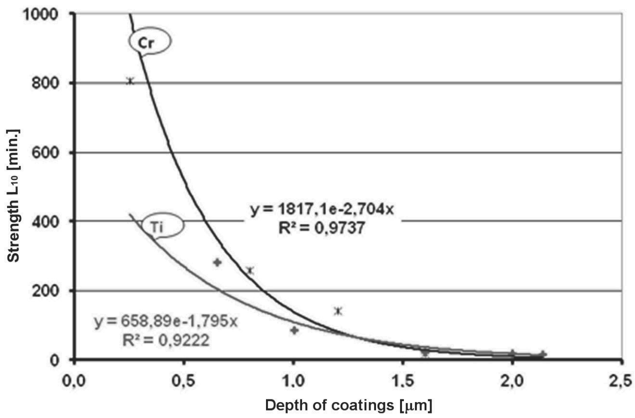


Fig. 7. The relationship between fatigue strength $L_{10}$ and the depth of a coating deposited on a steel sample

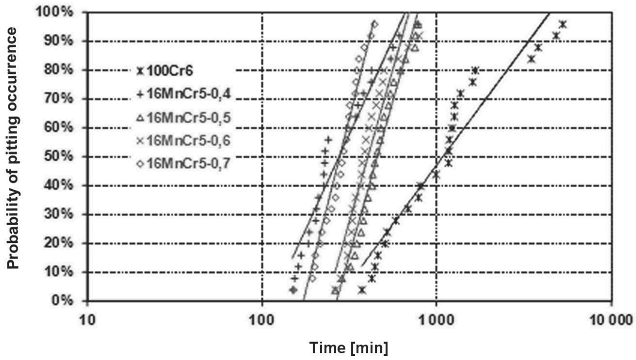


Fig. 8. Results of fatigue strength tests of associations: steel-steel (100Cr6) and steel-carburised steel 16MnCr5 (different depths of carburised layer, mm), lubricated with standard mineral oil (with no oiliness improvers) RL 219

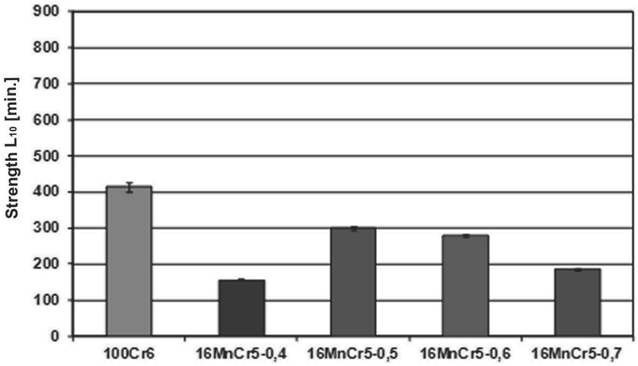


Fig. 9. Fatigue strength of associations: steel-steel (100Cr6) and steel-carburised steel 16MnCr5 (different depths of carburised layer, mm), lubricated with standard mineral oil (with no oiliness improvers) RL 219

Table. 3.
A listing of $L_{10}$ values and its upper and lower limits of the confidence interval for steel-steel (100Cr6) and steel-carburised steel 16MnCr5 (different depths of carburised layer, mm), lubricated with mineral oil RL 219

| Cone/coating material ⇒ | | 100Cr6 | 16MnCr5 | | | |
|---|---|---|---|---|---|---|
| | | | 0.4 | 0.5 | 0.6 | 0.7 |
| Strength [min.] | $L_{10G}$ | 427.71 | 158.96 | 304.30 | 284.11 | 188.50 |
| | $L_{10}$ | 413.25 | 156.95 | 299.09 | 280.17 | 185.21 |
| | $L_{10D}$ | 399.86 | 155.03 | 293.71 | 276.14 | 181.75 |

## 5. Conclusions

The study has shown a significant and varied effect on pitting of vacuum technologies of surface layer deposition in associated elements in concentrated rolling contact.

The results of the tribological tests of the associated elements with coatings deposited by PVD technologies have shown without doubt that increase in depth of anti-wear coatings (TiN and CrN) results in decrease in surface fatigue strength. The decrease is exponential and depends on the coating type.

Associations with vacuum-carburised elements of a friction pair had lower strength as compared to bearing steel associations, but the surface fatigue strength of the associations was not so varied as for associations with PVD coatings. It must also be stressed that the optimum depth of a carburised layer for this type of association was equal to 0.5 mm.

The authors claim that the tests, whose aim was to verify the scarce and contradictory literature reports, have shown that elements after cutting-edge surface processing (e.g. vacuum thermochemical processing, PVD coatings) have lower surface fatigue strength. It is one of the reasons for them not being used in lubricated friction parts of machines, especially high-performance ones.

## Acknowledgements

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