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## **STUDIES OF THE SURFACE FATIGUE LIFE OF NANOLAYER COATED PAIRS**

### **BADANIA POWIERZCHNIOWEJ TRWAŁOŚCI ZMĘCZENIOWEJ SKOJARZEŃ Z NANOWARSTWAMI**

#### **Key words:**

pitting, surface fatigue life, low-friction coatings, PVD, microhardness

#### **Słowa kluczowe:**

pitting, powierzchniowa trwałość zmęczeniowa, powłoki niskotarciowe, PVD, mikrotwardość

#### **Abstract**

The article presents results obtained in studies of surface fatigue life conducted using a specially developed unique method in a model system with a cone and three balls. The studies involved pairs in which the cones were made of 100Cr6 and SW7M steel (hardened) as well as 17HMN steel, which were subjected to low-pressure carburizing with pre-nitriding (PreNitLPC<sup>®</sup>) technology. The results obtained for the pairs were used as a point of reference for pairs in which the test elements were coated with a-C:H:W (WC/C) and additionally, in

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the case of 17HNM steel, with Si-DLC (DLC SiliComp). The temperature of the coating process did not exceed 200°C in all cases, and the coating thickness was in the range of 1.5 –20 µm. The studies were conducted in the presence of pure synthetic oil PAO8.

Based on the studies, it was concluded that thin PVD coatings applied to heavily loaded steel elements of rolling friction joints variously affected the surface fatigue life of the steel coated with them. The observations cannot be unambiguously accounted for by any technological rules, and there is no available physical explanation for their underlying causes.

## INTRODUCTION

One of the effective methods of increasing the life of heavily loaded lubricated machine elements can be the application of thin hard anti-wear coatings with a thickness within the limits of their dimensional tolerance, as enabled by PVD technologies [L. 1, 2, 3], which allows their application to elements with nominal dimensions without their prior special preparation. Such coatings, primarily made of nitride and carbide, based on Ti and Cr, are commonly applied at the present time to technology tools [L. 4].

It is estimated that available technologies make it possible to coat around 80% of tool types, increasing their service life by up to several hundred percent. In machine parts, however, the use of PVD coatings to improve life is still rare, and in heavily loaded friction joints (rolling bearings, conveyor rollers, cogwheels, cam and follower mechanisms, guiding elements in textile machines, etc.), it is minimal, found only in around 2 percent of parts.

The situation can be attributed to the fact that the recent jump in technology in terms of upper layer constitution has not been accompanied by a corresponding expansion of knowledge in the area of friction mechanisms and the wear of the improved friction elements, particularly in heavily loaded lubricated contacts.

An in-depth analysis of the current state of knowledge in the field has shown that the main causes of the *status quo* include the following:

- The lack of theoretical descriptions combining the physicochemical properties of coatings with phenomena constituting friction and wear processes; and,
- The lack of numerical data on the friction and wear behaviour of elements with hard surface layers, particularly heavily loaded lubricated kinematic joints in machines.

Consequently, there are no theoretical foundations for the selection of coating materials for specific technical applications. The selection is performed experimentally, on a trial and error basis.

Model-based studies investigating the scuffing of elements with PVD-applied coatings making up a lubricated concentrated contact have demonstrated a possibility of increasing resistance to scuffing [L. 5, 6], which is one of the main causes of defects to kinematic machine joints. However, satisfactory results obtained in the constitution of surface layers of friction elements through the application of coatings with respect to scuffing are not accompanied by an increase in surface fatigue life, which tends to be decreased. The authors' own studies, aimed at verifying existing literature reports, which are still scarce and conflicting, have shown that elements subjected to surface treatments based on standard PVD coatings significantly reduce resistance to surface fatigue [L. 7, 8]. Consequently, a thesis can be proposed that this is the main reason why they are not applied to lubricated friction joints, especially the heavily loaded types.

The presence of a thin anti-wear coating affects the status of stresses in the upper layer, which determines the resistance of elements to surface fatigue. The most important factors affecting the resistance of machine parts with anti-wear coatings to fatigue wear, according to Stewart and Ahmed [L. 9], include the following:

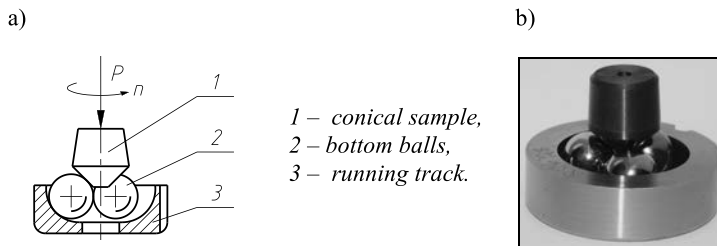
- Coating material,
- Coating thickness,
- Coating structure, and
- Adhesion to substrate.

In addition, substrate characteristics are a very significant factor related to the life of coated elements [L. 10]. As the authors claim, the key feature in this group is the hardness of the material to which a coating is applied. Because the PVD coating application technology takes place at elevated temperatures, which can result, among others, in the tempering of upper layers that contributes to a decrease in hardness, the tests presented below focus on determining the effect of substrate hardness on the pitting of test elements.

## METHODOLOGY AND TEST OBJECTS

The purpose of the tests was to determine the effect of the hardness of surface layers of steel elements constituted by various methods, operating in a lubricated concentrated contact, on surface fatigue life (pitting).

Tribological tests were conducted using a four-ball tester equipped with a rolling friction joint (Fig. 3), consisting of three steel balls rolling along a special running track and powered by a rotating sample in the form of a cone [L. 8].



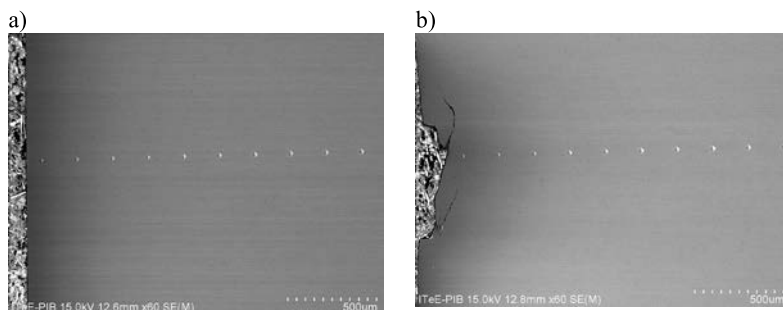
1 – conical sample,  
2 – bottom balls,  
3 – running track.

**Fig. 1. Upgraded friction joint of T-03 test rig intended for fatigue wear investigation of materials used in heavily loaded rolling elements: a) schematic view, b) photograph**  
Rys. 1. Zmodernizowany węzeł tarcia aparatu T-03 do badania zużycia zmęczeniowego materiałów stosowanych na wysokoobciążone elementy toczne: a) schemat, b) fotografia

The test objects were samples made of 100Cr6 bearing steel and SW7M tool steel, both heat treated, and 17HNM steel – heat and chemically heated, with an applied a-C:H:W coating. Before coating application, the 17HNM steel was subjected to low-pressure carburizing with pre-nitriding (PreNitLPC<sup>®</sup>) [L. 11, 12]. Steel carburizing was performed at 1000°C, and the resulting thickness of the carburized coating in the test samples was in the range of 0.65–0.70 mm. The prepared samples were provided with a low-friction a-C:H:W coating, and 17HNM steel was additionally coated with Si-DLC (DLC SiliComp). The temperature of the coating application process did not exceed 200°C in all cases. The thickness of coatings on the friction surfaces of the samples was approx. 2 μm.

The reference for the investigated material pairs was a pair of uncoated samples. The investigated pairs were lubricated with PAO 8, which is a pure synthetic oil without any additives. The determinants of life used for the investigated pairs were the operating times of the lubricated rolling friction joint until the occurrence of pitting. For each material pair, a total of 24 experimental runs were conducted, culminating with the occurrence of pitting on the sample (cone).

The distribution of hardness in the surface layers of the samples was determined by means of a Microhardness Tester FM-800 from Future-Tech. Microhardness distribution in the surface layers of the samples was investigated on specially prepared polished sections of the samples after tribological tests. For each sample, two series of hardness measurements were performed along a straight line at a section of 1.8 mm (Fig. 2) with a stroke of 0.2 mm. One series involved measurements in an area that had not been exposed to any effects of external forces “before the test,” and they describe the distribution of hardness after all technological treatments. The other series focused on an area that was deformed as a result of friction interactions during the test and in which the sample surface layers became reinforced “after the test.”



**Fig. 2. Photograph showing the locations of microhardness measurements on the samples: a – before the test, b – after the test**

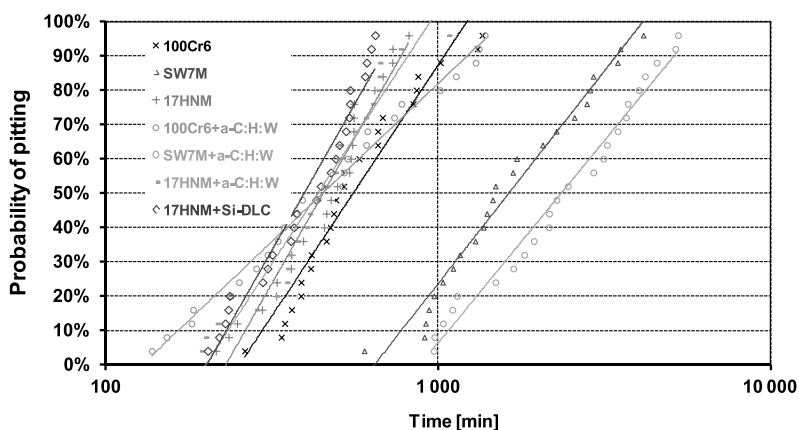
Rys. 2. Przykładowe zdjęcie obrazujące miejsca pomiaru mikrotwardości na próbkach; a – przed testem, b – po teście

The surface of the polished sections of the samples was evaluated using a SU-70 (FE-SEM) field emission scanning electron microscope from Hitachi.

## TEST RESULTS

### Surface fatigue life

The results of tests investigating the surface fatigue life of the studied material pairs are shown in **Fig. 3** and in **Fig. 4**, and calculated life values ( $L_{10}$ ) with their limit values and the scatter coefficient  $W=L_{90}/L_{10}$  are listed in **Table 1**.



**Fig. 3. Results of tests investigating the surface fatigue life of test elements in combination with 100Cr6 steel balls lubricated with PAO 8 synthetic oil**

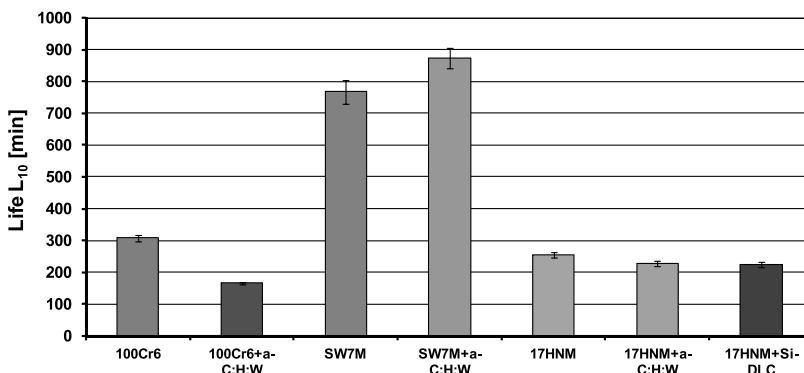
Rys. 3. Wyniki badań powierzchniowej trwałości zmęczeniowej badanych elementów w skojarzeniu z kulkami stalowymi ze stali 100Cr6 smarowanymi olejem syntetycznym PAO 8

**Table 1. List of  $L_{10}$  surface life values for the investigated pairs**Tabela 1. Zestawienie powierzchniowej trwałości  $L_{10}$  badanych skojarzeń

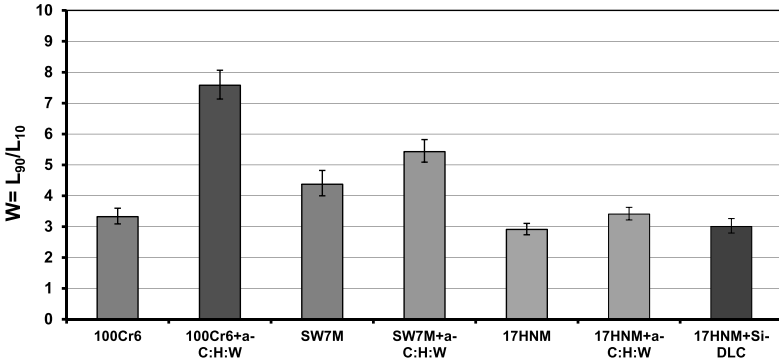
Sample material	100Cr6	SW7M	17HNM	100Cr6+ a-C:H:W	SW7M+ a-C:H:W	17HNM + a-C:H:W	17HNM + Si-DLC
$L_{10}$ [min.]	318.51	718.58	264.79	169.96	906.91	235.03	234.24
	308.09	684.39	255.07	165.57	873.93	226.95	225.04
	297.38	649.60	244.74	161.23	840.43	218.52	215.31
$W = L_{90}/L_{10}$	3.32	4.37	2.91	7.58	4.93	3.41	3.01

An analysis of test results shows that the highest fatigue life was obtained for the pairs in which the samples were made of SW7M tool steel. Only in this case, was the application of a coating found to have increased the life of the pair by approx. 30%. The coating on 100Cr6 steel triggered a marked decrease in surface fatigue life (by approx. 45%), whereas for the a-C:H:W and Si-DLC coatings applied to 17HNM carburized steel, the decrease was, respectively, 6 and 11%, in relation to uncoated pairs. The findings are consistent with the tendency observed and reported in study [L. 13].

With respect to such a high decrease in pitting resistance noted for the a-C:H:W-coated pair in relation to the results presented in this study, it is presumed that the coating application was performed without following strict technological requirements which are put forward as being necessary in treatments of this type. The above claim can be corroborated by the scatter coefficient value obtained for the test results (Fig. 5) which, for that particular pair, is over twice as large as for the uncoated pair. It needs to be noted that the application of a coating in all other studied pairs caused only a slight change in the coefficient.

**Fig. 4.  $L_{10}$  surface fatigue life of investigated samples in combination with 100Cr6 steel balls lubricated with PAO 8 synthetic oil**

Rys. 4. Powierzchniowa trwałość zmęczeniowa  $L_{10}$  badanych próbek w skojarzeniu z kulkami stalowymi ze stali 100Cr6 smarowanymi olejem syntetycznym PAO 8

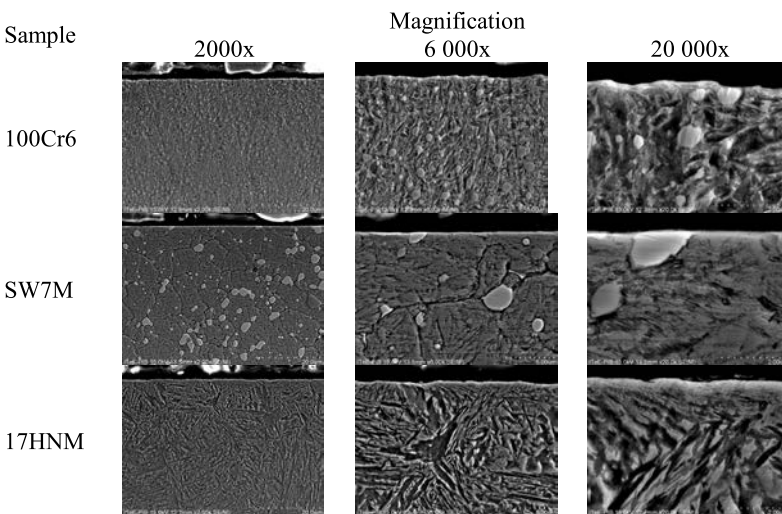


**Fig. 5. Scatter coefficient values obtained for surface fatigue life  $W = L_{90}/L_{10}$  in the studied material pairs**

Rys. 5. Wartości współczynnika rozrzutu powierzchniowej trwałości zmęczeniowej  $W = L_{90}/L_{10}$  badanych skojarzeń materiałowych

What is surprising, however, is that the fatigue life of SW7M steel turned out to be almost three times higher than 100Cr6 steel. An analysis of polished sample sections performed with a scanning microscope (**Fig. 6**) reveals differences in steel morphology that stem not only from the chemical composition but also from the heat and chemical treatment, which has a considerable effect on the hardness of surface layers. Pitting resistance is known to be very strongly correlated with the hardness of layers, as shown in prior publications [L. 13, 14].

For that reason, sample hardness measurements were carried out, and their results are presented below.

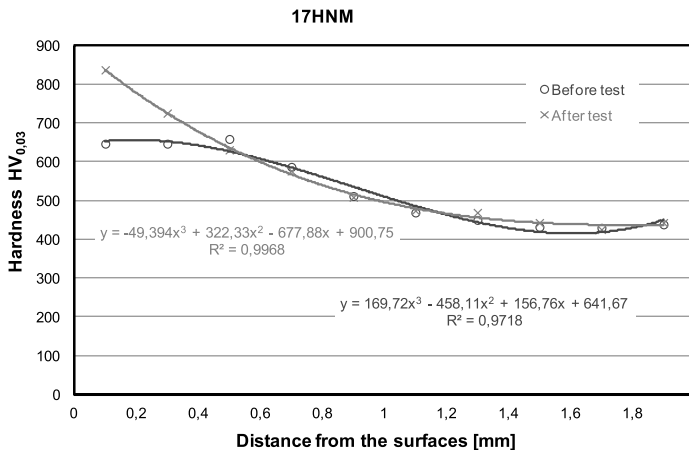


**Fig. 6. Scanning microscope images of the polished sections of uncoated samples**

Rys. 6. Zdjęcia zglądów próbek bez powłoki wykonane na mikroskopie skaningowym

### Measurements of surface layer microhardness

As indicated in the preliminary section, hardness distribution in the surface layers was investigated on specially prepared polished sections of samples, following tribological tests (evaluating life). An example of microhardness distribution into the material “before the test” and “after the test” for 17HNM-carburized steel is shown in **Fig. 7**.



**Fig. 7. An example of hardness distribution in the surface layer of a carburized 17HNM steel sample**

Rys. 7. Przykładowy rozkład twardości w warstwie powierzchniowej próbki ze stali 17HNM nawęglanej

The trend lines for hardness distribution determined for 100Cr6 and SW7M steel before tribological tests are similar whether the samples are coated or not (**Fig. 8**), even though both steel types differ markedly in terms of hardness. As shown by measurements, the hardness of different sample types across the studied range of layer thicknesses demonstrates little variation; however, the application of a coating results in hardness reduction. As expected, the samples made of 17HNM steel show the highest hardness in the carburized zone; however, as the distance from the surface increases, there is a rapid decrease in hardness. Moreover, it is interesting to note that hardness is slightly higher in SW7M steel with an applied a-C:H:W coating and 17HNM steel coated with Si-DLC in relation to uncoated samples – as opposed to the samples made of 100Cr6 steel. A characteristic feature of SW7M steel is that it has the highest hardness that does not change across the entire thickness range of the upper layer. As seen in **Fig. 9**, it was only in the case of that steel that surface treatment, including the application of coatings, did not lead to a change in microstructure. The fact that hardness decreases with depth into the



upper layer is associated with decreasing resistance to shear stresses, the maximum of which – in a concentrated contact – lies at a certain depth below the surface.

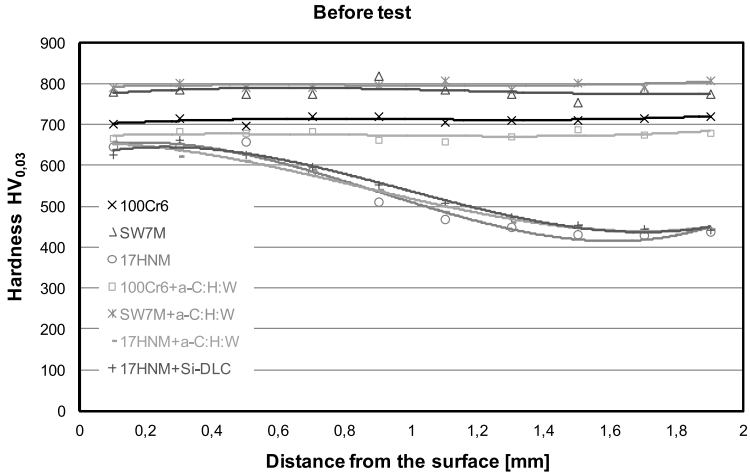


Fig. 8. Curves illustrating the distribution of hardness in the surface layers of test samples before tribological tests

Rys. 8. Krzywe obrazujące rozkład twardości w warstwach powierzchniowych badanych próbek przed testami tribologicznymi

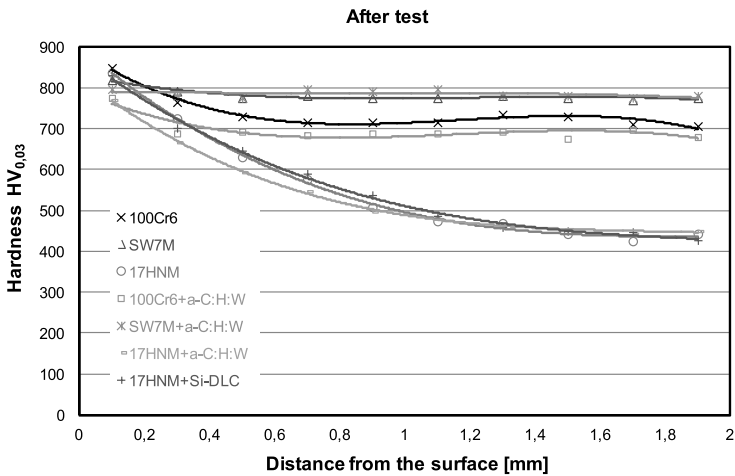
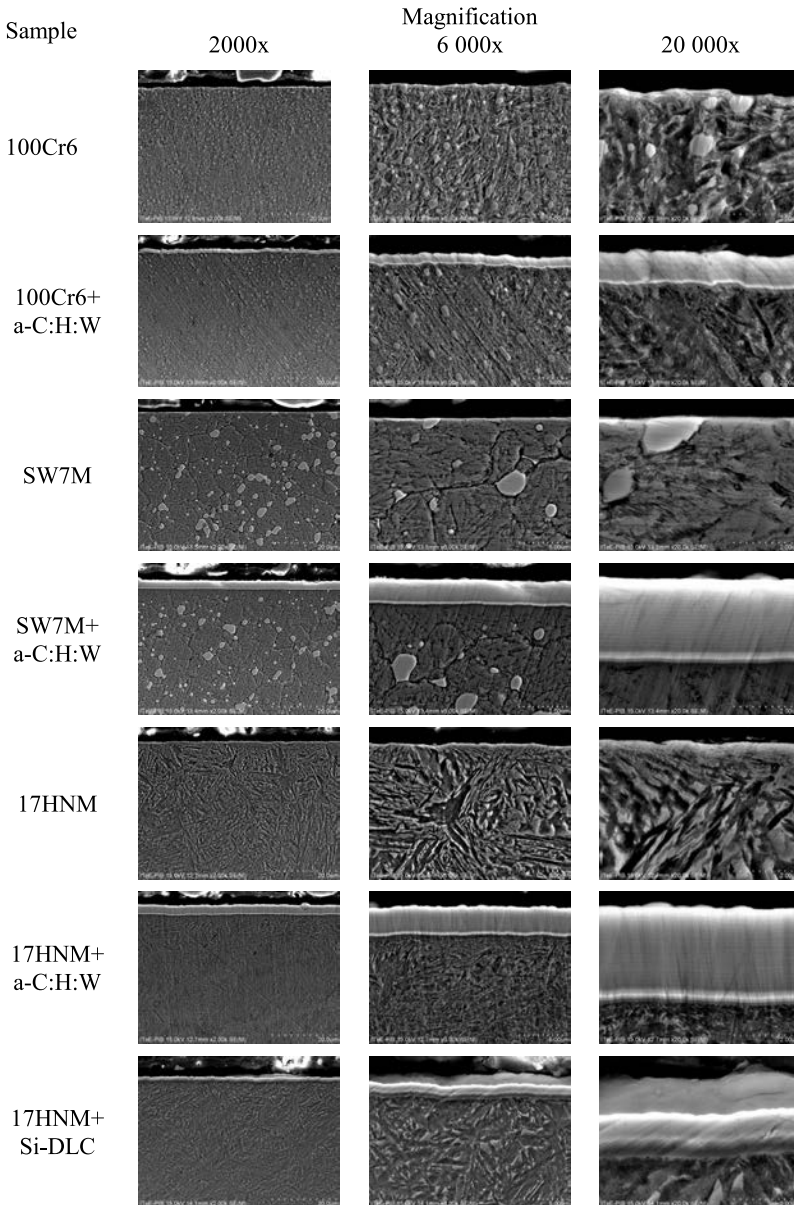


Fig. 9. Curves illustrating the distribution of hardness in the surface layers of test samples after tribological tests in the friction zone

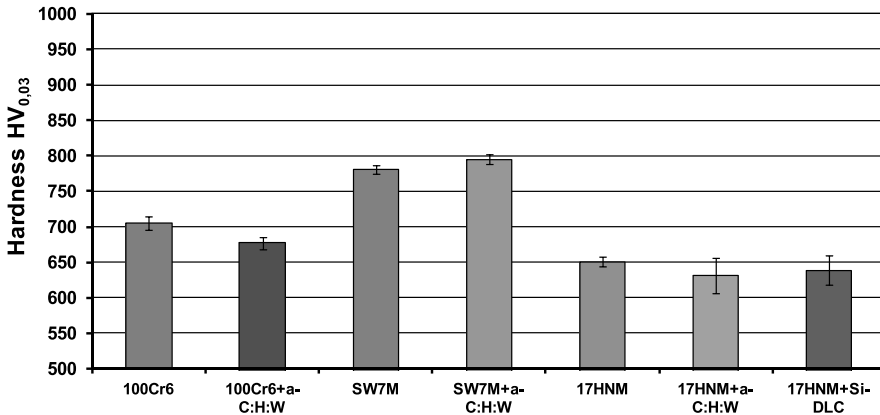
Rys. 9. Krzywe obrazujące rozkład twardości w warstwach powierzchniowych badanych próbek po testach tribologicznych w obszarze tarcia

**Figure 9** shows hardness distribution curves that were generated after the completion of tribological tests. On that basis, it can be stated indisputably that, following tribological tests, the upper layer of samples becomes hardened.



**Fig. 10. Scanning microscope images of the polished sections of samples**  
Rys. 10. Zdjęcia zglądów próbek wykonane na mikroskopie skaningowym

The mean values of hardness determined for the test samples before tribological tests are shown in **Fig. 11**. They were obtained from the first three measurements counting from the surface. As a result, the scatter of mean values for 17HNM steel samples is decidedly higher than for other samples.



**Fig. 11. Statement of mean microhardness values determined for the test samples**

Rys. 11. Zestawienie średnich wartości mikrotwardości badanych próbek

Comparing the results of life ( $L_{10}$ ) tests (**Fig. 4**) and microhardness tests (**Fig. 11**), it is evident that the surface fatigue life is dependent on and proportional to the hardness of the upper layers in the samples.

## CONCLUSIONS

The study yielded the following findings:

- PVD coatings applied to steel elements operating in a lubricated concentrated contact affect pitting to various extents, and there is no adequate physical explanation of the causes of the finding; therefore, there are no technological rules unambiguously accounting for the observation.
- Surface treatments in the case of steel, where they cause a change in structure and an associated reduction in hardness and its decrease with depth into the upper layer, make it impossible to take advantage of the favourable effect of an improved surface fatigue life that is achievable by the application of a coating.
- Aside from studies focused on life, it is necessary to conduct wide ranging analytical studies aimed at explaining such diverse behaviours of coated steel elements operating in a lubricated concentrated contact. It must also be emphasized that the studies confirmed a prior observation made by the authors with respect to the need to maintain the hardness of

surface layers in elements coated with low-friction coatings within a very narrow range of values. The above, however, requires compliance with rigorous technological regimes for substrate preparation and coating application.

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## Streszczenie

W artykule zaprezentowano wyniki badań powierzchniowej trwałości zmęczeniowej własną, unikatową metodą, w modelowym układzie stożek trzy kulki. Przeprowadzono badania skojarzeń, w których stożki wykonane były ze stali 100Cr6 i SW7M hartowanej oraz stali 17HMN, które poddano technologii nawęglania niskociśnieniowego wspomaganego azotowaniem PreNitLPC<sup>®</sup>. Wyniki tych skojarzeń były bazą odniesienia dla skojarzeń, w których elementy testowe pokryte były powłoką a-C:H:W (WC/C) i dodatkowo w przypadku stali 17HMN powłoką Si-DLC (DLC SiliComp). Temperatura procesu nanoszenia powłok we wszystkich przypadkach nie przekraczała 200°C, natomiast ich grubość zawarta była w przedziale 1,5÷2,0 µm. Badania przeprowadzono w obecności czystego oleju syntetycznego PAO8.

Na podstawie przeprowadzonych badań stwierdzono, że cienkie powłoki PVD nanoszone na wysokoobciążone stalowe elementy tocznych węzłów tarcia w zróżnicowany sposób wpływają na powierzchniową trwałość zmęczeniową pokrytej nimi stali.

