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INFLUENCE OF SLIDING SPEED AND SURFACE ROUGHNESS ON THE FRICTION COEFFICIENT AND WEAR OF TIN COATINGS DEPOSITED AT LOW TEMPERATURE

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Abstract: *Wear behavior of TiN coatings during dry reciprocating sliding against an alumina ball was studied. The research focus was on the influence of sliding speed on friction and wear. In addition, the coatings of different surface roughness were tested in order to find the optimum one. The range of surface roughness analyzed in this research provides insight into a rarely studied domain of fine surface finish. The wear tests were conducted at low load with low sliding speeds in order to determine the wear behavior of TiN coatings in mild conditions. Low values of friction coefficient were obtained, ranging from 0.13 to 0.24. The decreasing trend of the friction coefficient and increasing trend of the wear rate with increase in the sliding speed were observed for the coatings of different surface roughness. The highest friction coefficient was found on the roughest specimen, while the smoothest specimen exhibited the highest wear rate. The different wear behavior is due to different wear mechanisms acting on specimens with different roughness. For the tests conditions and range of surface roughness studied, the coating with roughness of 20 nm has the optimum surface finish. This coating exhibited low friction coefficient and the lowest wear rate. No significant difference in wear behavior was found when sliding transversal and parallel to machining ridges.*

Keywords: *IBAD, TiN, reciprocating sliding, sliding speed, surface roughness*

1. INTRODUCTION

Their high hardness, good adhesion to steel substrates and good thermal and chemical stability make TiN coatings suitable for wear protection of various mechanical components. Although tribological properties of TiN coatings have been widely studied, there is still a number of possible application areas where behavior of TiN coatings during wear is to be investigated. Understanding of wear mechanisms occurring during contact of TiN with other materials plays a great role in expanding its exploitation field [1].

Tribological behavior of coated mechanical components depends on a great number of parameters. For a selected coating it depends on mechanical, physical and chemical properties of counter material, on surface roughness and working conditions (environment, contact geometry, contact pressure). In practice, it is not possible to theoretically link these factors to tribological response of coated elements. True tribological behavior can only be determined experimentally, [2], [3], [4].

Tribological studies of hard coatings are usually conducted by using sliding test with high normal loads and high sliding speeds. On the other hand, mechanical components are often wearing at rates of nanometers per hour. In addition, a number of applications where sliding occurs at low normal loads and low sliding speeds is constantly increasing [5], [6]. Therefore, in this research tribological properties were evaluated using low loads and low sliding speeds.

The coating tribological behavior was studied in reciprocating sliding under milli-Newton loads. Special consideration was given to the influence of sliding speed on a friction and wear of coatings with different surface roughness.

There are several parameters which are applied to quantify the wear performances of hard coatings. A worn volume is the one usually used, although this parameter is not as practical as wear rate [7] which was used in the present study.

2. MATERIALS AND EXPERIMENTAL

Studied coatings were prepared in an Ion Beam Assisted Deposition (IBAD) chamber with a base pressure of 1.5x10-6 mbar. The coatings were deposited at low temperatures around 50^0C. Carburizing steel (20MnCr5) disks were used as a substrate material. The substrates were prepared with three grades of surface roughness: Specimen 1 – substrate ground using 400 grit SiC paper; Specimen 2 - substrate ground using 1500 grit SiC paper; Specimen 3 - substrate polished using 1µm diamond paste.

Substrate hardness was measured by standard Vickers hardness test while coating hardness was assessed by using the "Fischerscope HM2000 S" Microhardness Measurement System.

Friction and wear behavior was evaluated by ball-on-plate nanotribometer. The reciprocating sliding tests were conducted in air at room temperature. An alumina ball with diameter of 1,5mm was used as a counterpart material. The wear tests were performed using the sliding speeds of 10, 15 and 25 mm/s and the applied normal load of 100 mN. A stroke length of 1 mm was used in all tests which were stopped after 3000 cycles. All tribo-tests were repeated two times.

Scanning electron microscope (SEM JEOL JSM 6460 LV) was applied to investigate morphology of worn zones. Specimen surface roughness and morphology of worn zones were evaluated by VEECO di-CPII atomic force microscope (AFM). All images were acquired in contact AFM mode using a symmetrically etched silicon-nitride probe. The scan size was 90x90 µm^2 while scan rate and set point were kept at 0.5 Hz and 225 nN respectively.

Worn volume "*V*" was determined by measuring the worn channels produced during reciprocating sliding and including the dimension of the alumina ball. The representative worn volume was calculated for a worn channel length of 90 µm, since all channels were imaged using 90x90 µm^2 scan sizes. Sliding distance "*s*" was calculated by multiplying the length of scanned area with the number of sliding cycles. The specific wear rate "*K*" was calculated for all regimes according to equitation (1)

$$K = \frac{V}{F \cdot s} \quad (1)$$

where "*F*" presents applied normal force, "s" sliding distance, and "*V*" worn volume which was calculated by equitation (2).

$$V = L \times \left(r^2 \times arcsin\left(\frac{x}{2r}\right) - \frac{x^2}{4tan(arcsin\left(\frac{x}{2r}\right))} \right) \quad (2)$$

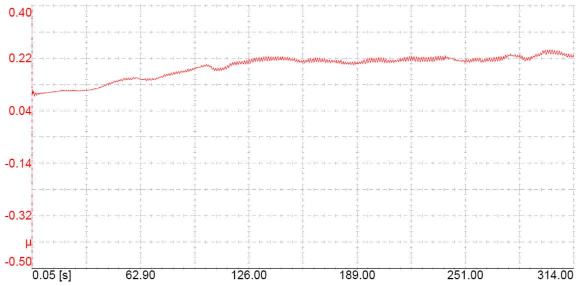
where "*L*" presents worn channel length, "*r*" radius of alumina ball, and "*x*" worn channel width.

3. RESULTS AND DISCUSSION

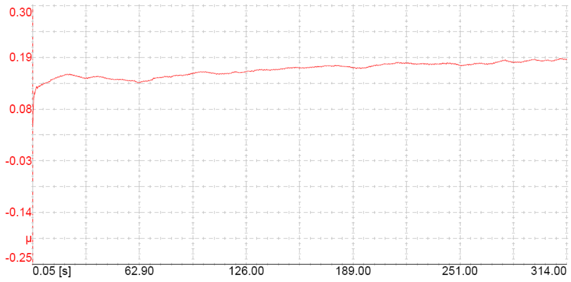
The Vickers hardness of hardened steel substrates was measured prior to the deposition process. The surface hardness of 740HV features a material with high load bearing capacity, appropriate for hard coating substrate. The coating hardness was measured to a value of 1920HV, which is rarely achieved by deposition at nearly room temperature. The coating thickness of 1 µm was measured for all studied specimens. The thickness was assessed by SEM examination of specimen cross section.

The surface topography of as-deposited coatings was imaged by the AFM. The following values of average roughness were obtained: Specimen 1 Ra = 53 nm; Specimen 2 Ra = 20,1 nm and Specimen 3 Ra = 3,5 nm. These values correspond to the one usually obtained by fine grinding or honing. The fine surface finish used in the present study was rarely applied in previous studies of tribological behavior of TiN coatings during reciprocating sliding.

Figure 1 shows the friction vs. the sliding time curves of TiN coatings tested at a load of 100 mN with a sliding speed of 15 mm/s. The friction coefficient showed similar behavior for all specimens and for different regimes applied during testing. The beginning of the sliding was characterized by very low values of the friction coefficient (as low as 0.1). All friction curves exhibit two stages, running-in stage and steady-state stage. The typical transition stage is not evident. In the running-in stage the friction coefficient smoothly increases with sliding distance. The smooth increase of friction coefficient is a desirable property for the practical application of TiN coatings. In the steady-state stage the friction coefficient is oscillating around approximately constant value. This stage appears after deformation of asperities of contacting surfaces. The typical transition stage is absent; in the presented curves the transition stage is basically an extension of the running-in stage. The sliding distance at the running-in stage increased with decreasing the coating roughness. For the smoothest specimen the friction coefficient maintains its growing tendency (Figure 1c) even after reaching the maximum sliding distance used during the wear tests.



a)



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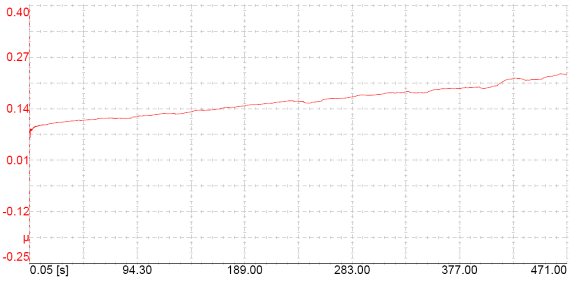

c)

Figure 1. Evolution of the friction coefficient for different specimens, v=15mm/s, F=100mN

Figure 2 summaries the friction coefficient of TiN coatings with different roughness in function of speed applied during the tribo-tests. The obtained low values of friction coefficient are typical for TiN coatings sliding against Al_2O_3 [8]. Low friction coefficient can be explained by the presence of an oxide tribolayer on the coating surface during sliding [10]. Formation of TiO_2 layer on TiN coating surface is common for sliding conditions used in the present study [15]. During reciprocating test with shorter stroke lengths temperature rises which favors tribochemical interaction between sliding pairs and surrounding atmosphere. The TiO_2 layer has low shear strength [11], [12] which leads to a low friction force [13], [14].

The friction coefficient decreases with increase in the sliding speed for all specimens (Figure 2). This is contrary to findings of S.Y. Yoon et al [9] who studied wear of TiN coatings. At higher sliding speed the tribolayer forms more easily [16], it increases in thickness and keeps the friction coefficient low. The smoother surfaces give a lower friction coefficient, see Figure 2. There was no significant difference in friction coefficient of Specimen 2 and Specimen 3. It appears that below a certain roughness, here Ra about 20 nm, the friction is less influenced by surface roughness. During sliding contact, asperities of two bodies in contact interact with each other. This interaction can results in plastic deformation of asperities of one or both bodies. For rougher surfaces higher energy is required for asperity deformation resulting in higher friction.

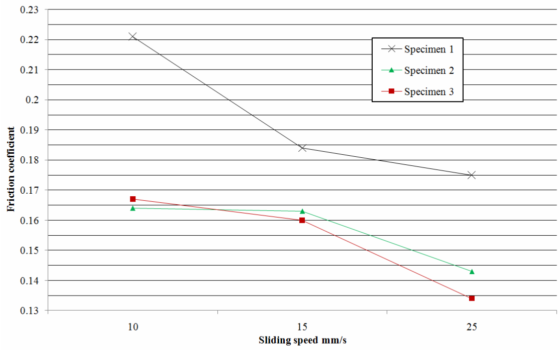

Figure 2. Friction coefficient of TiN coatings with different roughness in function of sliding speed

In addition to friction coefficient, wear loss is the other important parameter for practical application of hard coatings. The wear loss is often presented by worn volume. However, specific wear rate is more practical parameter for wear characterization. In order to calculate specific wear rates it is necessary to measure the worn channels. The accurate measurement of produced channels by optical or scanning electron microscopy is not an easy task (see Figure 3). In order to overcome this problem atomic force microscopy has been applied in the present study.

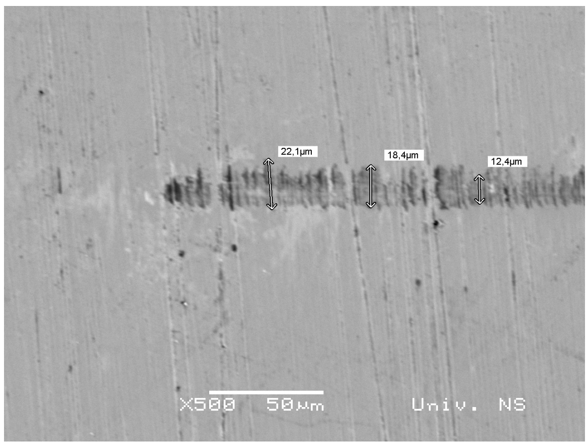

Figure 3. SEM micrograph of worn channel generated on Specimen 2, F=100mN, v=10mm/s

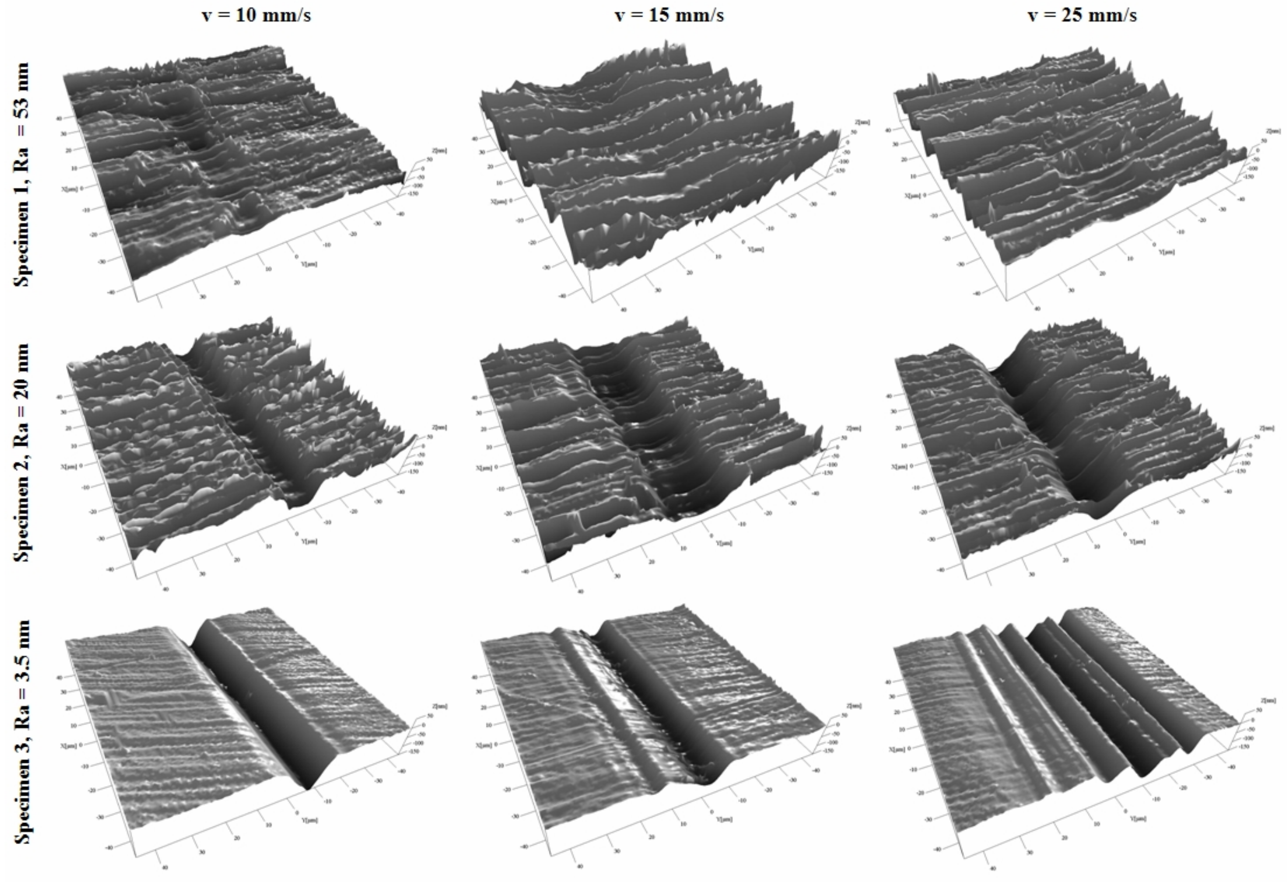

Figure 4. Morphology of the worn zones generated on TiN coatings of different roughness by reciprocating sliding with different sliding speeds

Figure 4 illustrates morphology of worn zones formed on all tested specimens by sliding with different speeds at load of 100 mN. The mild loading conditions applied did not produce any sign of hazardous wear. There were neither cracks, flakes nor fragmentation in the worn zones of studied specimens. This behavior can be attributed to high coating toughness which was confirmed by qualitative indentation tests conducted in our previous research [17]. The maximum wear track depth was around 150 nm which is far less from the coating thickness of 1 μm. The wear debris were not present inside the worn zones.

The machining ridges formed during specimen preparation were not worn away. Detailed analysis of areas inside and outside the wear tracks revealed drop in surface roughness. The maximum depth (R_{pv}) of the same machining ridges was lower inside the wear track. The machining ridges were flattened by plastic deformation and mild wear. The depth of worn channels was larger than the maximum depth of machining ridges. This suggests that machining ridges were pressed into the surface before being worn and plastically deformed.

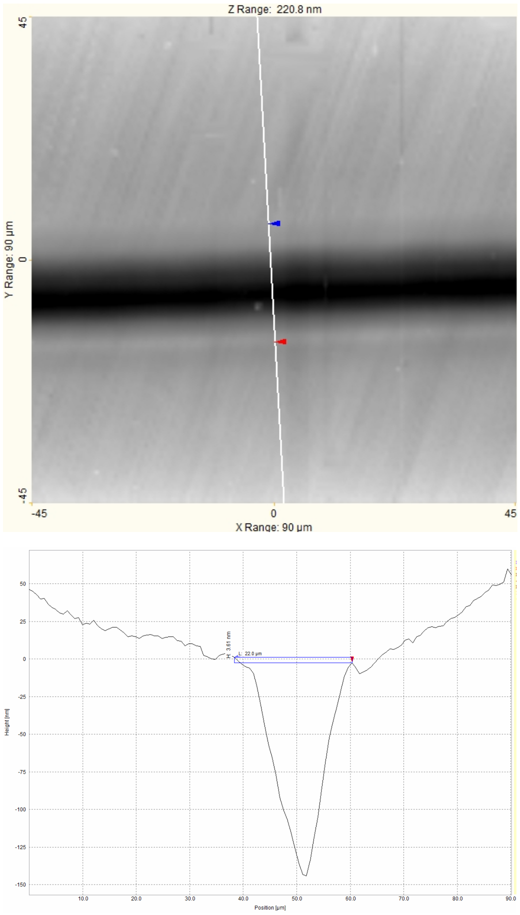

Figure 5. Measurement of wear track width

According to the SEM and AFM analyses there was no sign of wedge formation during wear. A wedge, which should be generated at the end of the wear track, forms when brittle coating is unable to absorb the load by its plastic deformation.

The worn zones produced during wear at different sliding speeds differ in size, morphology and roughness (Figure 4). Increase in the sliding speed led to increase in width and depth of wear tracks. The dimensions of worn channels were measured by applying appropriate image processing software. Figure 5 shows the measuring method applied. The conducted measurements provided the data for calculation of specific wear rates.

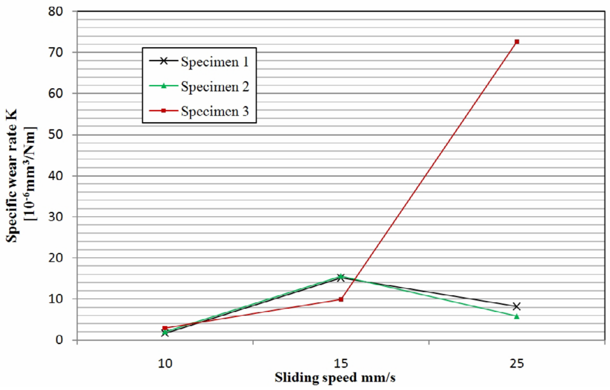

Figure 6. Specific wear rate of TiN coatings with different roughness in function of sliding speed

According to literature, a decrease of the wear rate with decrease in the friction coefficient should be expected [16], [17]. Nevertheless, such relationship cannot be taken as a rule of thumb for all material combinations in sliding contact [18], [19]. Figure 6 presents wear rates of coatings with different surface roughness in function of sliding speed applied during reciprocating sliding tests. The wear rate increases with increase in sliding speed and reaches a maximum of $72.3x10^{-6}$ mm^3/Nm at the smoothest specimen tested with sliding speed of 25 mm/s. The obtained wear rate values are comparable to those usually observed for TiN coatings sliding against Al_2O_3 [8]. The two rougher specimens (Specimen 1 and 2) behaved similarly during sliding wear tests and exhibited almost same values of specific wear rates. It appears that when sliding is conducted on surfaces of $R_a \approx 25$ - 50 nm the surface roughness does not affect the coating wear behavior significantly. In addition, for sliding speeds bellow 15 mm/s the wear rate is less affected by the surface roughness.

As already mentioned, the highest wear rate was calculated for the smoothest specimen. This value was significantly higher than wear rate values of other samples. Although the wear tracks formed on the smoothest sample tested with speed of 25 mm/s were the widest, they were also of the most irregular shape (Figure 4). The more the profile of the wear track deviate from the arc-like shape, the greater error is incorporated in calculation of the specific wear rate. Therefore, it is to believe that the actual wear rate of the Specimen 3 tested with 25 mm/s should be at least half of the calculated one. Since there is no great difference in the wear rate of the two rougher specimens, the high wear rate value determined for the smoothest specimen could be considered as the experimental scatter. However, the sliding tests were conducted two times, and both times the same results were obtained.

This result is contrary to usually observed increase of the wear rate with increase in the surface roughness [22]. Higher stresses, which are present on rougher surfaces, can lead to formation of cracks and flakes, coating fragmentation, formation of fatigue pits, and as a result to more severe wear. Neither of these defects was observed in the present study. The higher ware rate on the smoothest specimen can be explained in the following manner. During the test with the same applied load and the same sliding speed the same amount of energy is dissipated. On the rougher specimens the large amount of the energy is used for deformation of the machining ridges, while on the smoothest specimen almost all energy is used for formation of micro grooves present in the wear track of this specimen (see Figure 4). The difference in the wear rates was a consequence of different wear mechanisms acting on the tested specimens. While ridge deformation and mild abrasion were acting on the rougher specimens, abrasion was the dominant wear mechanism on the smoothest specimen.

According to the results of this investigation, for the conditions applied, the Specimen 2 has the optimum surface finish. This specimen exhibited low friction coefficient and the lowest wear rate. Although the polished specimen exhibits the lowest friction coefficient, the costs of its machining are not justified in term of high wear rate it displays in sliding wear. These findings are of practical importance for application of TiN coating as a wear resistant coating.

The roughest specimen was submitted to further examination of the relation between sliding direction and machining ridges. There was no significant difference in the friction coefficient when sliding transversal (0.221) and parallel (0.222) to the ridges. Such behavior is preferred in industrial applications as the relation between loading direction and machining ridges does not have to be considered during the designing stage of a particular part.

4. CONSLUSIONS

Tribological behavior of the TiN coatings of different roughness has been investigated on a reciprocating sliding against Al2O3 ball. The effect of sliding speed on the wear behavior of the coatings is discussed. The following conclusion can be drawn based on the experimental results:

- Low values of friction coefficient were obtained, ranging from 0.13 to 0.24. Low values of the friction coefficient are attributed to presence of titanium oxide inside the wear tracks.
- The friction coefficient of coatings with different roughness decreases with increase in sliding speed. The roughest specimen exhibited the maximal friction coefficient. For R_a below 20 nm the friction coefficient is less affected by surface roughness.
- Increase of wear rate with increase in sliding speed was observed. The highest value of wear rate was calculated for the smoothest specimen. There was no significant difference in wear behavior of specimens with average roughness between 20 and 50 nm. For this range of surface roughness, the wear rate is less affected by sliding speed applied during the tests.
- There was no sign of crack and flake formation, fragmentation or fatigue pit formation on any of tested specimens. The wear mechanism of the TiN coatings deposited on rough substrates was plastic deformation of machining ridges combined with mild abrasion, while abrasion was the dominant wear mechanism on the smoothest specimen.
- The specimen with average surface roughness of 20 nm has exhibited the best tribological behavior. The low friction coefficient was observed and the lowest wear rate was calculated for this specimen.
- The change of sliding direction relative to the direction of machining ridges does not influence the wear behavior significantly.

In order to construct wear maps, the future research will be oriented to studying the coatings deposited on substrates with wider range of surface roughness in tests with wider range of sliding speeds.

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