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Sliding Wear of Coated Prealloyed Sintered Chromium Steel

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Abstract: The present paper deals with the sliding wear behaviour of prealloyed chromium sintered steel with graphite powder added in the amount of 0.7 %. The wear characteristics, such as profilograms, wear tracks morphology and wear curves of the sintered specimens and Physical Vapour Deposition (PVD) coated were investigated through pin-on-disk tests. The specimens were sintered in pusher furnace at the temperature of 1180 °C for 40 minutes in an atmosphere of 25 % H_2+75 % N_2. The results of profilograms, the wear curves and the wear tracks showed positive effect of coating on the wear resistance of the tested specimens.

Trošenje uslijed klizanja na presvučenom pred-legiranom sinteriranom krom čeliku

Izvornoznanstveni članak

Sažetak: Ovaj rad se bavi karakteristikama kliznog trošenja pred-legiranog sinteriranog krom čelika s dodatkom grafitnog praha u iznosu od 0,7%. Obilježja trošenja, kao što su profilograf, morfologija tragova trošenja i krivulje trošenja sinteriranih uzoraka i uzoraka fizikalno presvučenih u parnoj fazi (PVD) su istraživani pomoću pin-disk tribometra. Uzorci su sinterirani u potisnoj peći na temperaturi od 1180 °C tijekom 40 minuta u atmosferi 25% H2 75% N2. Rezultati profilograma, krivulja trošenja i tragovi habanja pokazali su pozitivan učinak prevlake na otpornosti na trošenje testiranih uzoraka.

1. Introduction

The mechanism of wear is very complex and the theoretical background is not easy as well. It should be understood that the real area of contact between two solid surfaces compared with the apparent area of contact is invariably very small, being limited to points of contact between surface roughness. The load applied to the surfaces will be transferred through these points of contact and the localized forces can be very large [1].
The wear properties of PM materials are complex phenomena that are influenced by several factors like pores, microstructure and subsequent treatments such as sintering conditions, heat treatment and surface modifications. The pores act as crack initiators, the distribution of stress is inhomogeneous across the cross section of the investigated material and reduces the effective load bearing area [2]. Besides porosity [3], the microstructure of the steel matrix has a significant effect on mechanical behaviour as well wear and fatigue characteristics [4, 5]. Sliding wear is generally referred to as a type of wear generated by the sliding of one solid surface along another. Sliding wear problems may occur also in other types of wear such as erosion, cavitation, abrasion, oxidative wear, fretting and corrosion [1].

One of the intrinsic advantages of PM is the possibility to produce sintered alloys with optimal chemical composition; moreover a suitable modification of functional surfaces may determine a sensibile upgrade in the properties of low alloyed steel.
In particular TiCN-based coatings, typically deposited as 2-12 μm thick films, show a friction coefficient against steel counterparts between 0.35 and 0.4 [6, 7]. The development of titanium carbon nitride (TiCN) coating is aimed at improving the wear resistance of investigated materials.
In PM area, the possibility of improving the wear resistance is to use ceramic or intermetallic compound powders to produce composites; nevertheless embrittlement in such composites usually occur. In addition, other methods, such as electroless coating, flame spray processing has not proven to be very effective. It is therefore necessary to develop novel materials or techniques to solve this problem.
The contribution deals with the wear behaviour of the prealloyed chromium sintered steel parts after the TiCN

Symbols/Oznake

PM	- powder metallurgy - metalurgija praha		**Greek letters/Grčka slova**
PVD	- physical vapour deposition - fizikalno presvlačenje u parnoj fazi	μ	- friction coefficient, - koeficijent trenja, -
Ra	- profile surface roughness, μm - hrpavost površine profila, μm		
V	- velocity, $m \cdot s^{-1}$ - brzina, $m \cdot s^{-1}$		
Δm	- mass loss, mg - gubitak mase, mg		
l	- Sliding distance, mm - Udaljenost klizanja, mm		

PVD coating. The wear characteristics and wear tracks morphology of the coated parts was performed in comparison with the as-sintered state.

2. Materials and experimental methods

The starting powders used in the analysis were: prealloyed iron powder containing of 1.5 % Cr and 0.2 % Mo (commercially prealloyed Astaloy CrL powder produced by Höganäs AB, Sweden), natural CF-4 graphite powder with particle size less than 40 μm added in the amount of 0.7 %, and HW wax in the amount of 0.8 % as lubricant. Powder mixtures were homogenized in a Turbula mixer. Cylindrical specimens (ϕ 40x30 mm^2) were compacted to the green density of ~7.0 $g \cdot cm^{-3}$ using a uni-axial hydraulic press. The specimens were sintered in industrial pusher furnace CREMER at the temperature of 1180 °C for 40 minutes in an atmosphere of 25 % H_2 + 75 % N_2 (the inlet dew point was -55 °C). The heating and cooling rates were about ~10 °C/min.

Part of specimens was then coated by PVD of TiCN layers of 2 μm thickness synthesized at 250 °C by evaporating a Ti (99.5 %) in N_2/C_2H_2 plasmas. The process and equipment are described in [8]. Wear tests were carried out by means of a pin-on-disk. The disc was the investigated material and the counter face was WC-Co pin having a rounded shape on top with ϕ 3 mm. The counter - pin was changed after the end of each test and was weighed. All wear tests were performed in air without lubrication. An applied load used in all wear tests was 15 N. The rotation speed of the disc was 300 rpm. Each test was interrupted after 100, 300, 600, 1100 and 2100 meters of sliding distance; the disc (tested specimen) was weighed using a precision weighing to determine the evolution of wear (weight loss) during the test.

The wear tracks morphology was observed using light microscopy and SEM JEOL 7000F. The apparent hardness HV10 and the microhardness HV 0.025 using digital tester LECO LM 700 were measured.

The profile unevenness after the wear test was expressed by the arithmetical mean deviation of the profile surface roughness, Ra. The profile surface roughness is the average arithmetical deflection from all unevenness from the central line in the measured length. Ra was measured by tangent profilometer, Hommel Tester T1000.

3. Results and discussion

3.1. Microstructure

The microstructure of the tested steel resulting from the sintering at the temperature of 1180 °C consists of upper and some lower bainite, **Figure 1**.

The apparent surface hardness for both coated and as-sintered samples was in the range of 188-193 HV10, the microhardness measured on the metallographic sections perpendicular to the tested surface was different in the areas near the surface, 189-191 HV0.025, in the core of the samples was 287-302 HV0.025, which corresponds to decarburization during the sintering. The depth of decarburization was 100 microns. The microstructure in decarburized depth consisted pearlite and some ferrite.

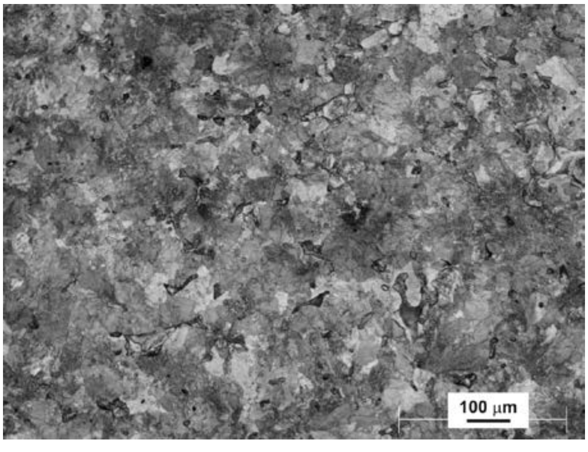

Figure 1. Microstructure of the prealloyed steel.

Slika 1. Mikrostruktura predlegiranog čelika.

In the chromium alloyed steels decarburization is mainly due to the reaction of carbon with chromium oxide. The surface chemistry evolution on sintering Cr steels is mainly governed by the local atmosphere formed in the interconnected pores at high temperature, in which carbon and carbon monoxide play a predominant role along with addition of 0.7 % C [9-11].

3.2. Surface roughness and friction coefficient

The topography of the surface with different surface qualities can be easily expressed as the surface profile parameters Ra [12-15]. The values of surface roughness, Ra, were 1.16 microns for TiCN coated samples and 1.32 microns for as-sintered samples. **Figures 2a, b** shows the profilogram and wear tracks for coated and as-sintered specimens.

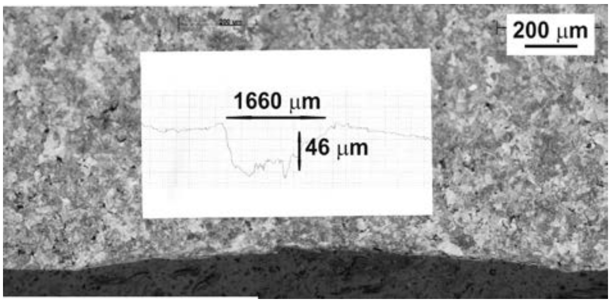

Figure 2a. The profilogram and wear track of coated specimen

Slika 2a. Proflogram i staza trošenja na presvučenom uzorku.

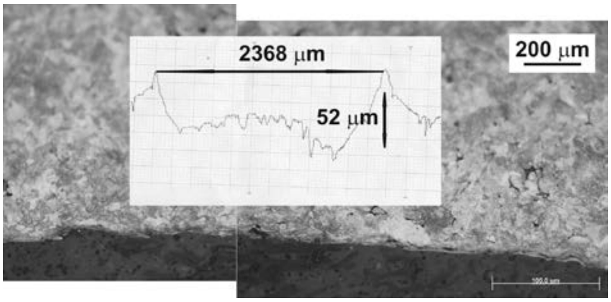

Figure 2b. The profilogram and wear track of as-sintered specimen

Slika 2b. Profilogram I staza trošenja na sinteriranom uzorku.

The mean calculated values of the width and depth were recorded. The contact surfaces between materials and counterpart have important influence on the friction coefficient. Contact surface for both conditions has non-linear relations and the dry friction coefficient also depends on the characteristics of the tested interfaces. Lim et al. [16] suggested that the friction coefficient depends strongly on the roughness at low velocities ($V < 1$ ms^{-1}) for unlubricated contact between a pairs of sliding surfaces. The friction coefficient plotted as a function of the sliding distance for coated samples and as sintered samples is presented in **Figure 3**.

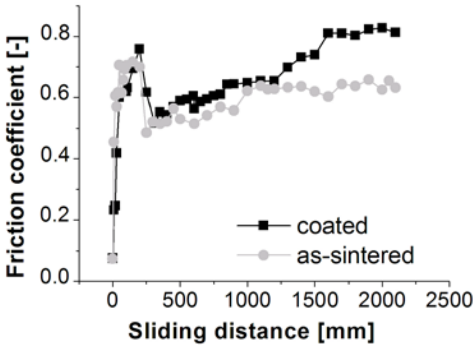

Figure 3. Friction coefficient for both investigated materials

Slika 3. Koeficijenti trenja dvaju ispitivanih materijala.

As it can be seen from plot, the friction coefficient rises after the beginning of the test up to the maximum value, then decreases and again slightly increases up to the sliding distance of 1000 mm. In the as-sintered materials the friction coefficient reaches the steady-state and remains stable until the end of the test. On the contrary, for coated materials further slightly increases up to the steady-state at the sliding distance of 1600 mm. The results show higher values of the friction coefficient for coated material and relate the friction to the forces required to make the asperities on one surface ride over another. The oxide films formed on the worn surface in as-sintered material can become as solid lubricant reducing adhesion and decreasing the friction coefficient, such as present in [17].

The tendency of wear curves (mass loss versus sliding distance) recorded for coated and as-sintered samples during the pin on disc test are shows in **Figure 4**.

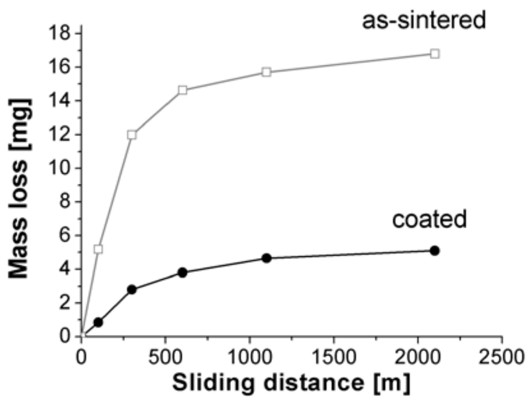

Figure 4. Tendency of wear curves of investigated materials

Slika 4. Trend krivulja trošenja ispitivanih materijala.

According to data in **Figure 4** the lower mass loss exhibited by coated specimens for all wear sliding distances. Wear curves show similar increase trends up to the sliding distance of 300 meters, for higher sliding distances the differences increase. At 2100 meters the differences are more than 3 times. The results indicate that no delamination of the coatings occurred during the sliding test: the PVD layer was free of cracks and pores. The wear track morphology for both systems are in **Figures 5a, b**.

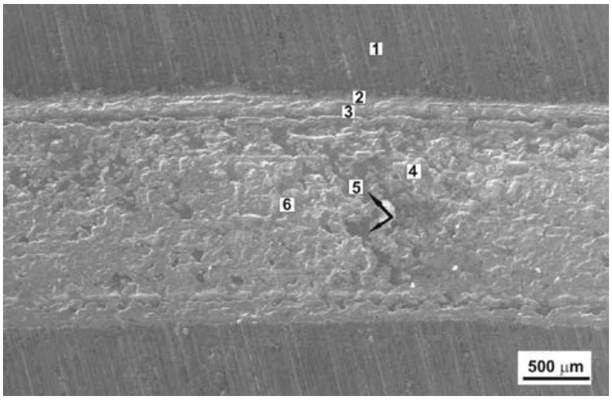

Figure 5a. Wear track of coated material

Slika 5a. Staza trošenja presvučenog uzorka

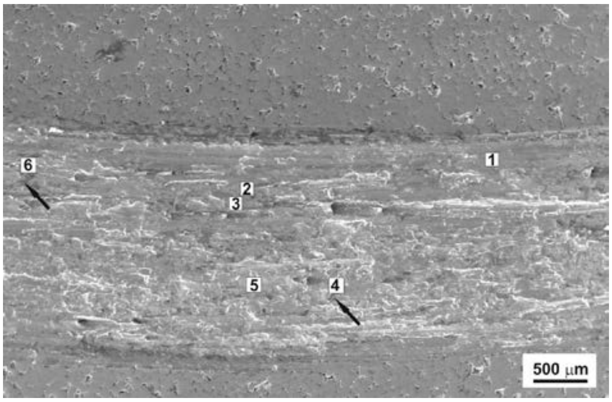

Figure 5b. Wear track of as-sintered material

Slika 5b. Staza trošenja sinteriranog uzorka

Detailed microscopic analyses showed evident features of delamination effect of plastic deformation. The morphology of the wear track for both specimens was similar to the features of localised plastic deformation resulting in some isolated damaged islands corresponding to the responsible microstructure.
The results of EDX analyses are recorded in **Table 1**.

Table 1. EDX analyses of investigated materials

Tablica 1. EDX analiza istraživanih materijala

coated	Ti [%]	Cr [%]	Mo [%]	W [%]
1	16.01	1.46	1.13	2.28
2	0.31	1.8	0.12	0.85
3	0.21	1.6	0.21	1.13
4	1.62	1.71	0.28	6.67
5	2.13	1.44	0.20	19.19
6	0.16	1.95	0.13	0.89
7	71.65	0.93	0.14	0.81
as-sintered	**Ti [%]**	**Cr [%]**	**Mo [%]**	**W [%]**
1	-	1.57	0.64	4.13
2	-	1.58	0.75	0.59
3	-	1.06	0.70	-
4	-	1.39	0.15	13.85
5	-	1.07	0.53	-
6	-	1.28	0.83	22.97

EDX analyses were performed in different areas of the wear tracks for the investigated samples. Wear tracks of coated specimen mainly consist of Ti fragments from TiCN coating with smaller particles identified as chromium oxides. It is known that chromium is used as alloying elements; certain precautions have to be considered in order to avoid oxidation of these elements during the powder fabrication as well as during subsequent processing stages. An oxide layer is inevitably formed during the water atomisation because of the interaction of the molten metal droplets with water or steam. EDX analyses showed the presence of Ti (from TiCN coating) in the coated specimen, but also the presence of tungsten carbides (from the counterface pin), in the case of both samples. An interesting feature of the worn tracks is the presence of tungsten carbides, the bright particles scattered on the surface of the wear tracks (arrows in both **Figures 5a, b** and in detail are showed in **Figure 6**).

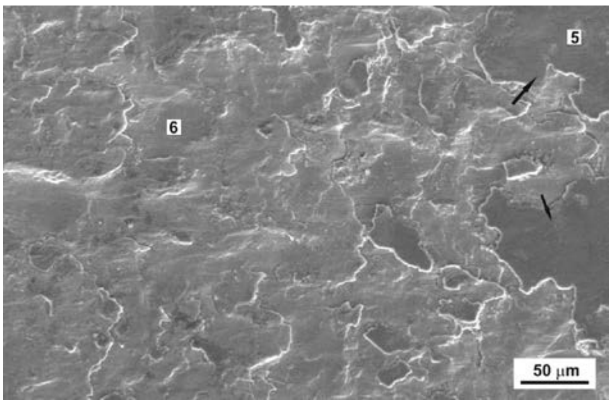

Figure 6. Detail of the presence of tungsten carbides, coated specimen, points are the same as in **Figure 4a**

Slika 6. Detalj prisustva volframovog karbida na presvučenom uzorku, točke su istovjetne **Slici 4a**.

These carbides come from the counterface pin, indicating that a good adhesion is established between the two mating surfaces of the investigated alloy and pin.
The presented results show that the application of TiCN coating via PVD technique are interesting due to wear characteristics (friction coefficient, mass loss) of investigated sintered steel. On the other hand, the influence of surface modification on the wear characteristics still requires further investigation in ferrous PM areas, because the information on the wear properties of iron base steels with carbon contents scarce up to the present.

4. Conclusion

In this work, the tribological behaviour of sintered steels, in the as sintered state and after a PVD coating was investigated by a pin-on-disk test, as well as the morphologies of the wear tracks. Shallows with evident features of plastic deformation at the worn surface, in the dominant bainitic microstructures were detected. The coating of the investigated prealloyed steels increases the wear resistance in comparison with the as-sintered state according to the wear curves. Microstructural and EDX analyses confirmed that delamination and oxidation wear are the main wear mechanism in wear tests. Finally, the surface modification via PVD coating increased the wear resistance of the sintered specimens.

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