

# MODIFICATION OF COATING-SUBSTRATE SYSTEMS UNDER THE ACTION OF COMPRESSION PLASMA FLOW

*V.M. Astashynski, I.G. Gimro, A.M. Kuzmitski, E.A. Kostyukevich, A.V. Kovyazo, A.A. Mishchuk, V.V. Uglov\*, V.M. Anishchik\*, N.N. Cherenda\*, E.K. Stalmashonak\**

*Institute of Molecular and Atomic Physics, National Academy of Sciences of Belarus, Minsk, Belarus, e-mail: ast@imaph.bas-net.by; \*Belarusian State University, Minsk, Belarus*

The results of studying changes in physical and mechanical properties of coating-substrate systems subjected to the compression plasma flow are presented. The possibility for doping the substrate both with pre-deposited coating components and with plasma-forming substance during liquid-phase mixing and resolidification of near-surface layers melted by the compression plasma flow is shown.

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## INTRODUCTION

The material modification by high-energy flows of charged particles is the prospective tendency in the modern solid-state physics. Of processing methods the widest recognition received those using lasers, plasma flows, and beams of charged particles such as ions and electrons [1-4]. The material being treated first melts, then rapidly cools and finally resolidifies from liquid phase. High cooling rates of molten layers produce a variety of novel metallurgical microstructures, as well as stable and/or metastable, nanocrystal and amorphous phases. Along with the usual modification, it is possible to carry out the doping of working surfaces with various components by means of treating the coating-substrate system via the melting of the coating and the near-surface layer of the substrate followed by fast diffusion of components in the melt. The purposeful injection of alloying elements into the surface layer of metals allows to produce various structures and thus to select the required physical and mechanical operating properties.

In the present work the results of investigations on the structure and the mechanical properties of titanium-on-steel and chromium-on-steel systems subjected to the compression plasma flow (CPF) are presented.

## EXPERIMENTAL

Cr (about 2.5  $\mu\text{m}$  thick) and Ti (about 1.0  $\mu\text{m}$  thick) layers have been deposited on carbon steel St3 (0.2 C, 0.2 Si, 0.5 Mn, in wt.%) using the CAVD method (cathodic arc vapor deposition) with the following operating parameters: arc current of 100 A, bias voltage of  $-120$  V, deposition temperature and time of  $450^\circ\text{C}$  and 10 min, respectively. The specimens were subjected to CPF. The experiments were performed in a "residual gas" mode in which the vacuum chamber was filled with nitrogen up to the preset pressure of 400 Pa. The plasma flow parameters are as follows: pulse duration  $\sim 100$   $\mu\text{s}$ , plasma velocity  $(5-6)\cdot 10^6$  cm/s, electron concentration  $(4-7)\cdot 10^{17}$   $\text{cm}^{-3}$ , dynamic plasma pressure and temperature 1.5 MPa and 2-3 eV, respectively. The incident flow energy density is equal to 13 J/cm<sup>2</sup> per pulse. The chosen mode of thermal action, according to estimated calculations, corresponds to the melting of both a film and a substrate.

The phase composition was investigated by X-Ray diffraction (XRD), using the  $\text{CuK}\alpha$  radiation. The surface morphology and cross-sections were analysed with the help of scanning electron microscopy (SEM), using a LEO1455VP device equipped with EDX. The element composition was determined by Auger-electron spectroscopy (AES), using a PHI-660 device. The microhardness was tested with a Vickers indentor under a load ranging from 0.2 to 2 N. The tribological test was of "pin-on-plane" type, dry sliding dynamic friction. The friction coefficient was determined at the reciprocal sliding and carried out at room temperature ( $22\pm 1^\circ\text{C}$ ) and at the relative humidity  $50\pm 5\%$ . The linear velocity was 4mm/s. The pin was made of a hard alloy BK8 (92% WC, 8% Co) with a hardness of 36.75 GPa. The load on the pin was 1 N.

## RESULTS AND DISCUSSION

During the CPF treatment of the coating-substrate system the melting of the surface layer occurs and then, upon completing the action of plasma pulse, its resolidification takes place. A wave-like structure observed on sample surfaces is due to the solidification of the liquid metal. SEM-analysis shows that the surface of samples subjected to processing, contains cellular structure areas with a cell size up to 1  $\mu\text{m}$  (Fig. 1) formed at a stage of solidification of the overcooled liquid.

In the initial state low-carbon steel has a ferrite-pearlite structure. Ferrite peaks are observed on the X-ray diffraction pattern (Fig. 2). XRD does not reveal a cementite component of pearlite due to high dispersion of  $\theta\text{-Fe}_3\text{C}$  carbide.

As a result of the treatment of the titanium-on-steel system the disappearance of titanium peaks and the displacement of ferrite peaks towards the lowest angles are observed in the XRD pattern (Fig. 2). So there is an increase in the lattice parameter, which can be caused by the replacement of iron atoms by titanium atoms having a greater atomic radius, and this results in the formation of solid Fe-Ti solution. Also the interaction of the nitrogen plasma with system elements is established, in particular, XRD shows the presence of titanium nitride diffraction peak TiN (111) (Fig. 2). The visual proof of TiN formation is the appearance of a characteristic golden

color on the sample surface. Thus, the modified layer analyzed by X-ray radiation contains high nitrogen concentration sufficient to form titanium nitride. Titanium penetrates into the iron lattice as an overdimensional impurity during the cooling and resolidification of the iron-titanium mixture.

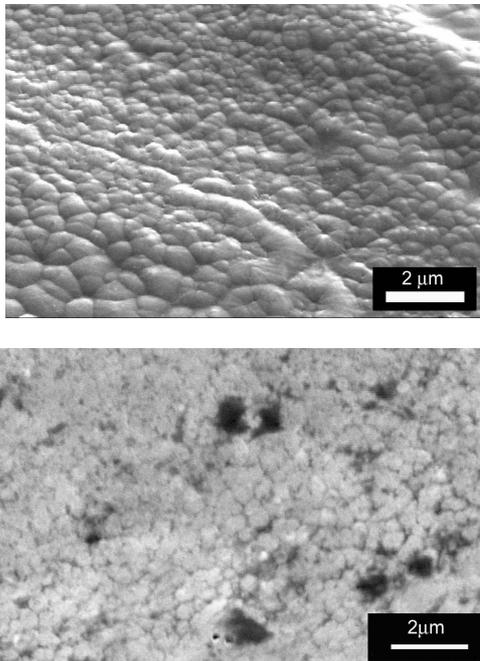


Fig. 1. Surface morphology of treated Ti/steel (a) and Cr/steel systems (b)

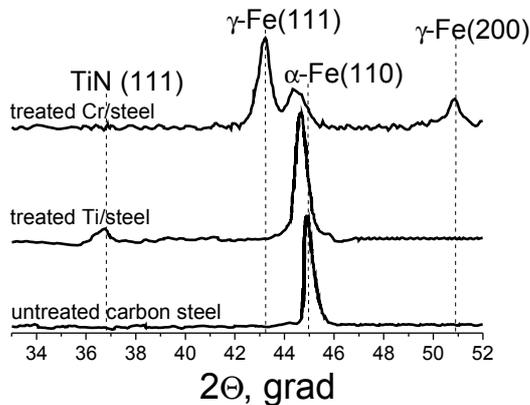


Fig. 2. XRD patterns of treated samples

On the contrary, the XRD data (Fig. 2) reveal that the treatment of the chromium-on-steel system with nitrogen plasma results in the formation of doped austenite:  $\gamma$ -Fe(Cr, N, C). It is worth noting the role of Cr as a stabilizing element.

The analysis of the element concentration profiles obtained by AES shows the mixing of the various components of the systems, as well as the nitrogen incorporation. For example, the nitrogen concentration in

the near-surface layer of mixed Cr/steel system exceeds 15 at.%.

SEM observations of cross-sections of treated samples show that the surface layer (~15 μm in thickness) is modified. What is more, titanium and chromium are present throughout thickness of modified areas, falling down at the modified layer–base material interface, whereas the thickness of as-deposited titanium and chromium coatings does not exceed 1.0 and 2.5 μm, respectively.

As a result of the treatment, phase and structure transformations occurred, giving rise to a change in mechanical properties. The microhardness of samples is given on Fig. 3. One can note a significant increase in microhardness of samples subjected to CPF. Moreover, the treated chromium/steel system exhibits the maximum hardness value, exceeding by more than two times hardness of carbon steel. The enhanced microhardness is due to the creation of faulted structure and phase composition changes: the presence of a  $\gamma'$ - phase, solid Fe-Ti solution and TiN in the modified layers, and to possible formation of fine-dispersed nitrides.

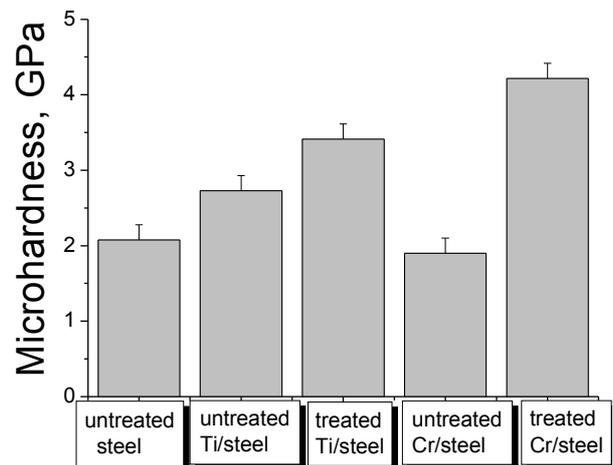


Fig. 3. Microhardness of treated samples

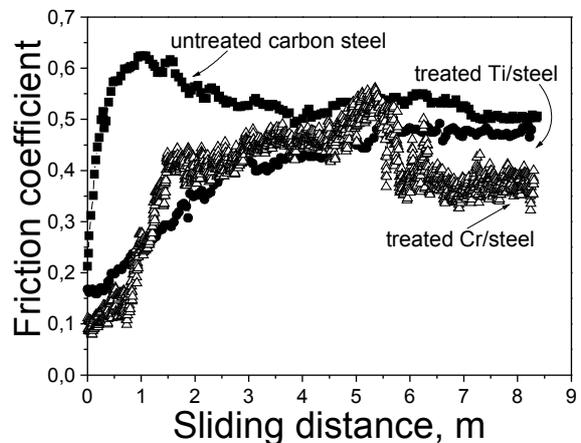


Fig. 4. Friction coefficient versus sliding distance

Investigations of the friction coefficient dependence on the sliding distance reveal an improvement in tribological properties of treated samples (Fig. 4). The tribological curves of treated samples feature significant decrease in the friction coefficient as compared to the initial stage of friction, i.e. wear-in stage of treated samples continues a longer time in comparison with untreated one. The presence of a developed surface on treated samples and enhanced surface hardness both lead to the decrease in the pin contact area under sliding and consequently to the reduction of the friction coefficient.

#### CONCLUSION

The modification of carbon steel with pre-deposited titanium and chromium coatings by nitrogen CPF leads to the melting of the near-surface layer and the liquid-phase mixing of the coating with the matrix substance; to the creation of a cellular structure on the surface (cell size up to 1  $\mu\text{m}$ ); to the production of deep ( $\sim 15 \mu\text{m}$ ) modified layers alloyed by titanium and chromium. After the treatment of the Ti/steel system phase composition is represented by solid solution Fe-Ti and nitride TiN. The presence of Cr in treated system serves as a stabilizing factor for the formation of doped austenite. Phase and structural changes result in an increase in microhardness of treated systems (by 1,5 times) in comparison with the hardness of the initial state of used carbon steel and in the reduction of friction coefficient at the initial stage of friction.

Thus, it is shown that compression plasma flows allow producing highly alloyed surface layers with improved mechanical properties.

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#### МОДИФИКАЦИЯ СИСТЕМ ПОКРЫТИЕ-ПОДЛОЖКА ВОЗДЕЙСТВИЕМ КОМПРЕССИОННОГО ПЛАЗМЕННОГО ПОТОКА

*В.М. Асташинский, И.Г. Гимро, А.М. Кузьмицкий, Е.А. Костюкевич, А.В. Ковязо, А.А. Мицюк, В.В. Углов, В.М. Анищук, Н.Н. Черенда, Е.К. Стальмошенок*

Представлены результаты исследований изменения физико-механических свойств систем покрытие-подложка при воздействии на них компрессионным плазменным потоком. Продемонстрирована возможность легирования материала подложки как компонентом предварительно нанесенного покрытия, так и рабочим веществом плазмы, в процессе жидкофазного перемешивания и перезатвердевания расплавленных под действием компрессионного плазменного потока приповерхностных слоев.

#### МОДИФІКАЦІЯ СИСТЕМ ПОКРИТТЯ-ПІДКЛАДКА ВПЛИВОМ КОМПРЕСІЙНОГО ПЛАЗМОВОГО ПОТОКУ

*В.М. Асташиньський, І.Г. Гімро, А.М. Кузьмицький, Є.А. Костюкевич, А.В. Ковязо, А.А. Мицюк, В.В. Углов, В.М. Анищук, Н.Н. Черенда, Е.К. Стальмошенок*

Представлено результати досліджень зміни фізико-механічних властивостей систем покриття-підкладка при впливі на них компресійним плазмовим потоком. Продемонстровано можливість легування матеріалу підкладки як компонентом попередньо нанесеного покриття, так і робочою речовиною плазми, у процесі рідкофазного перемішування і перезатвердіння розплавлених під дією компресійного плазмового потоку приповерхніх шарів.