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THE INFLUENCE OF SUBSTRATE MATERIALS ON THE MICROSTRUCTURE, MICROHARDNESS AND WEAR RESISTANCE OF NICKEL-BASE PLASMA SPRAY COATINGS

Hristo Skulev[#], Deyan Veselinov

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Abstract

This paper studies the influence of the substrate material on the phase composition, microstructure, microhardness, and wear resistance of Ni-Cr-B-Si-WC ($Ni_{95}Al_5$) coatings. Three types of substrates were studied, AISI 5060 Steel, SAE J431 automotive gray cast iron, and Ti-6Al-4V. It has been found that in the as-coated condition the surface layers have a phase composition of crystalline γ-Ni solid solution, amorphous, Ni_3B, CrB, and $Cr_{23}C_6$. There are different changes of the surface after 80 min abrasive wheel.

Key words: plasma spray, nickel alloy, wear, cast iron, steel

Introduction. Steel, cast iron, and titanium have been amongst the most widely used materials for various industrial applications during the last two decades. However, their low hardness and wear resistance in their raw state limit their application [1–3]. Hard Ni-base coatings produced by plasma spraying are employed to minimize friction, lower wear, and reduce tribological requirements for the base material like steel, cast iron, and titanium [4,5]. Among all other deposition processes, plasma spraying is known for its attractiveness to many industries

[#]Corresponding author.

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because of the simplicity of application, versatility of materials, high deposition efficiency, cost-effectiveness, and intriguing coating properties [6,7]. This method allows controlling the production of coatings with specific microstructure and mechanical properties according to the application requirements entirely by changing its processing parameters [8,9].

Investigations show that mixed crystalline and amorphous structures can be obtained during plasma spraying under certain conditions [10]. These structures determine the mechanical properties and structural stability of the produced coating. The crystalline phase of nickel-base coatings has a face-centred-cubic (fcc) structure. Also, the nickel-mixed amorphous and crystalline structure has good mechanical, physical, and chemical properties [11].

This work report aims to investigate a case of the influence of steel, cast iron, and titanium substrates on the phase transformation of the Ni-base coating during as-sprayed and next wear test.

Experimental. In the current experiment, a nickel-chromium alloy powder was low-pressure plasma sprayed onto the surface of rotating substrates. The used computerized equipment set is PPS-800 with indirect plasmotron PN-80 [11]. The chemical composition of the used Ni alloy powder by wt.% is Ni: 65 ± 1, Cr: 18 ± 1, B: 4.5 ± 0.5, Si: 4.5 ± 0.5, C: 4 ± 1, WC: 3, $Ni_{95}Al_5$: 5. It consists of spherical grains, with a size of 25–40 µm.

The substrate materials used in this study are three types: AISI 5060 Steel, SAE J431 automotive gray cast iron, and titanium alloy Ti-6Al-4V (ISO 5832-3:2016). The shape of the specimens is cylindrical with dimensions of 30 mm by length and a 10 mm diameter. Before spraying, all samples were cleaned with acetone and sandblasted. All plasma-spraying procedures performed are under the following fixed processing parameters:

– Current: 450 A;
– Voltage: 70 V;
– Plasma forming gas flow rate: Ar: 20 slpm, N_2: 8 slpm;
– Powder flow rate: 45 g/min;
– Spraying distance: 120 mm;
– Transport gas flow rate: Ar: 3.5 slpm;
– Traverse speed of the plasmotron: 10 mm/s^{-1}.

The spraying time was 2 min for each sample. The thickness of the coatings thus obtained is within the range of 250–300 µm.

The phase constitution was determined using X-ray diffraction (XRD) analysis. All of the performed measurements were at room temperature with a Philips X Pert PRO analytical X-ray diffractometer, using CuK$\alpha 1 + \alpha 2$ radiation from an angle of 30 to 100 degrees (2θ) with a step size of 0.01 (2θ) and a counting time of 100 s/step.

Cross-sections from the coated samples were low-speed cut, mechanically ground, and polished with a diamond suspension having a particle size of 0.1 µm.

The microstructures obtained in the as-coated state were studied optically using a Nikon Eclipse ME 600 microscope, and LUCIA software was used for image analysis. SEM analysis was performed at 15 kV, using a JEOL-6400 SEM at room temperature.

The microhardness of the samples was measured using a Mitutoyo HM-124 testing machine. A Knoop indenter with a load of 0.05 kg for 10 s was applied at selected spots from the surface to the middle of the cross-sections to generate microhardness profiles.

Wear tests were conducted with a dry plane sliding abrasive wear tester. The sample of the wear couple is a No. 320 carborundum disk with a diameter of 60 mm and a roughness of Ra = 0.15–0.25 μm. The wear tests performed were under the condition of a load of 50 N, 0.9 ms^{-1} sliding speed, for up to 80 min. The weight loss of the samples was measured every 5 min and converted to wear volume.

Results and discussion. For studying the splat microstructures of the coated layers, cross-sections were prepared carefully. The visual observations of the cross-sections showed that the coatings have good appearances without cracks or signs of adhesive loss. Figure 1 shows obtained microstructures of the plasma sprayed coatings on steel, cast iron, and titanium substrates, respectively. The microstructures exhibit the typical heterogeneous nature of plasma spraying. The melted powder particles in the deposit are visible as light and dark layers, while non-melted and partly melted particles have a spherical or round form. In some areas, there are pores and cavities. Three zones are distinguishable in the image: coated layer, interface, and substrate metal. The coatings obtained on the titanium substrates appear to be more homogenous than those on steel and cast iron substrates. It was found that the connections between the plasma sprayed coatings and all the studies substrates are without pores, cracks, and other faults.

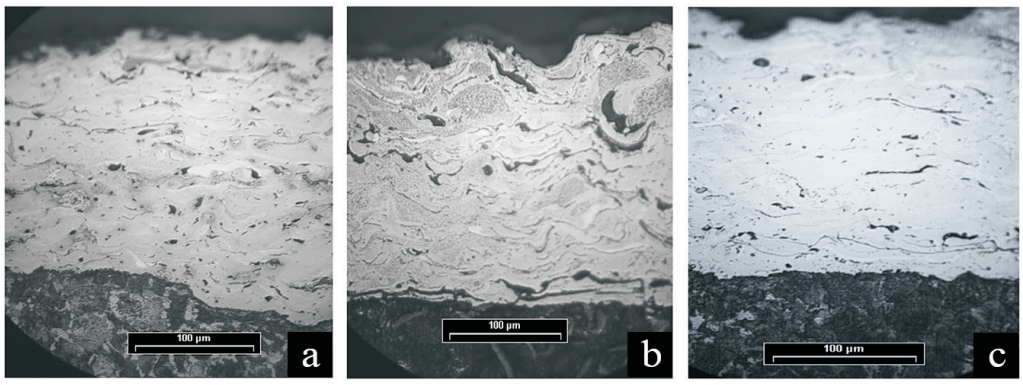


Fig. 1. Microstructure of the Ni-base plasma powder coating on: (a) steel, (b) cast iron, and (c) titanium substrates

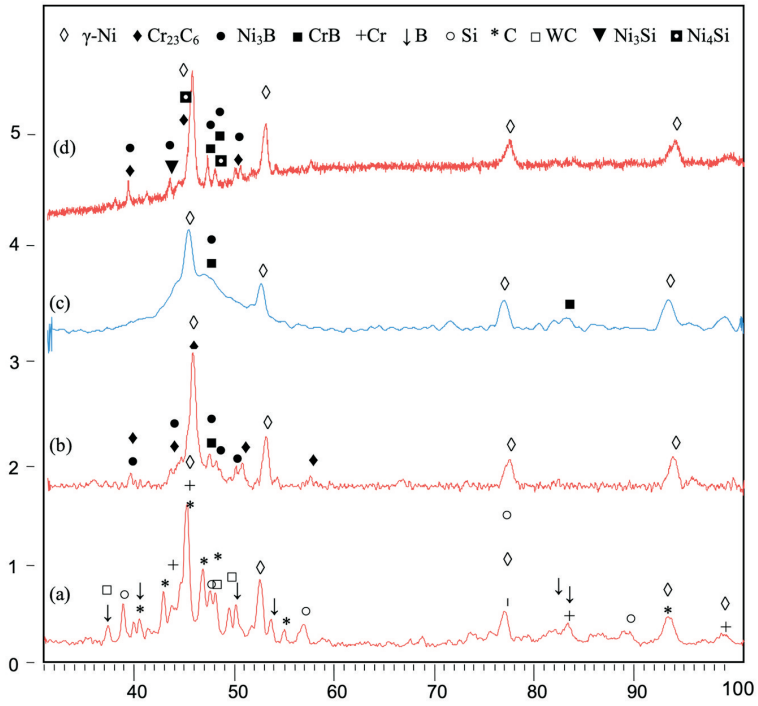


Fig. 2. As-sprayed phase composition of Ni-Cr-B-Si-C-WC-($Ni_{95}Al_5$): powder (a) and coating on SAE J431 automotive gray cast iron (b), AISI 5060 Steel (c), and Ti-6Al-4V (d) substrate

The phases in the initial powder and the Ni-base coatings were analyzed by XRD. Figure 2 shows diffraction patterns of plasma sprayed coatings on steel, cast iron, and titanium substrate samples. The diffraction pattern of the Ni powder is available in Fig. 2a. The main fcc peaks of the coatings correspond to those of the powder. The coating diffraction peaks are considerably broad on all steel samples, which is typical of microcrystalline structures.

The broad peak around and overlapping with the $\{111\}_{Ni}$ peak, the highest peak in all diffraction profiles, also the presence of an amorphous phase are visible. Most of the peaks from minority phases in the coating on cast iron and titanium are in close proximity, with small relative intensity compared to the major, fcc peaks. The low relative intensity from these phases ($Cr_{23}C_6$, Ni_3B, CrB, Ni_3Si, and Ni_4Si) indicates their small volume fractions. The basic phase of the structure of the coatings on steel, cast iron, and titanium substrates is the γ-Ni solid solution. For the coating on steel samples microcrystalline γ-Ni, Ni_3B, CrB and amorphous phases are present. In addition to those, on the samples of cast iron, $Cr_{23}C_6$ phases are observed (Fig. 3b), and on the titanium substrates (d) - $Cr_{23}C_6$, Ni_3B, CrB, Ni_3Si, Ni_4Si phases are registered.

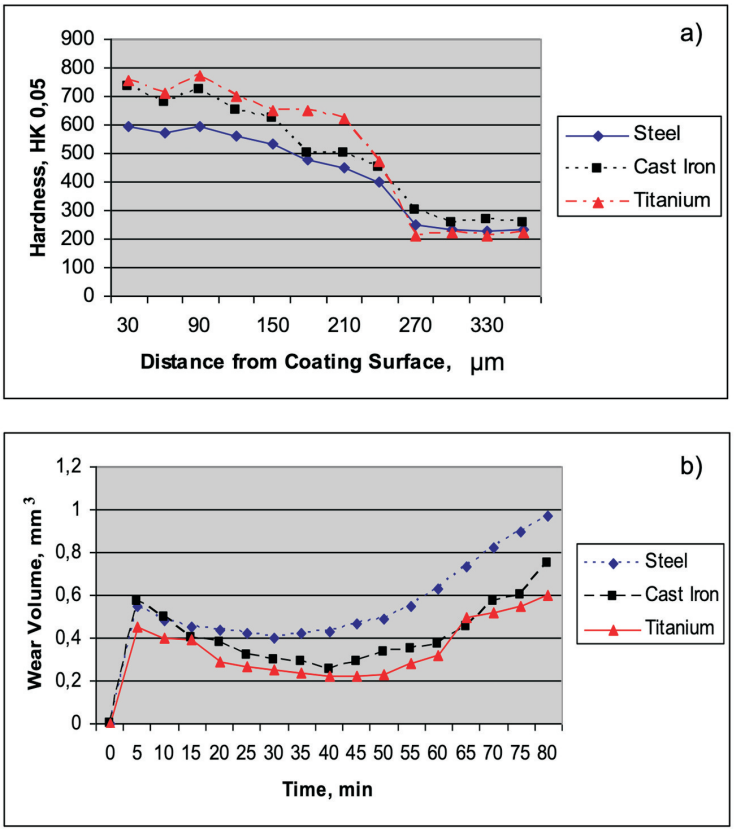


Fig. 3. Microhardness profiles (a) and wear volume after abrasive wheel test (b) of Ni-base coatings on plasma sprayed substrates of AISI 5060 steel, SAE J431 automotive gray cast iron and Ti-6Al-4V

This difference in the coating structures is probably due to the dissimilar heat conductivity (λ) and heat capacity (cp) between cast iron, titanium, and steel. That confirms the base material is indeed a significant factor for the coating structural formation. The influence of the substrate material on the mechanical properties such as hardness and wear resistance of the Ni-base plasma powder coatings is revealed in Fig. 3. Figure 3a illustrates that the microhardness of the coatings obtained on the titanium alloy is higher than on gray cast iron and steel. The measured surface hardness values of the plasma sprayed layers range between 700–890 $HK_{0.05}$ on titanium, from 680 to 840 $HK_{0.05}$ on cast iron, and the deposits on steel demonstrate 600–780 $HK_{0.05}$.

Moreover, the microhardness readings in some points of the coatings splat on steel samples range from 850 to 1100 $HK_{0.05}$. The highest microhardness values were 1700–1900 $HK_{0.05}$, measured in some light non-homogeneous grains of coatings sprayed on the titanium alloy and cast iron substrates. Such local

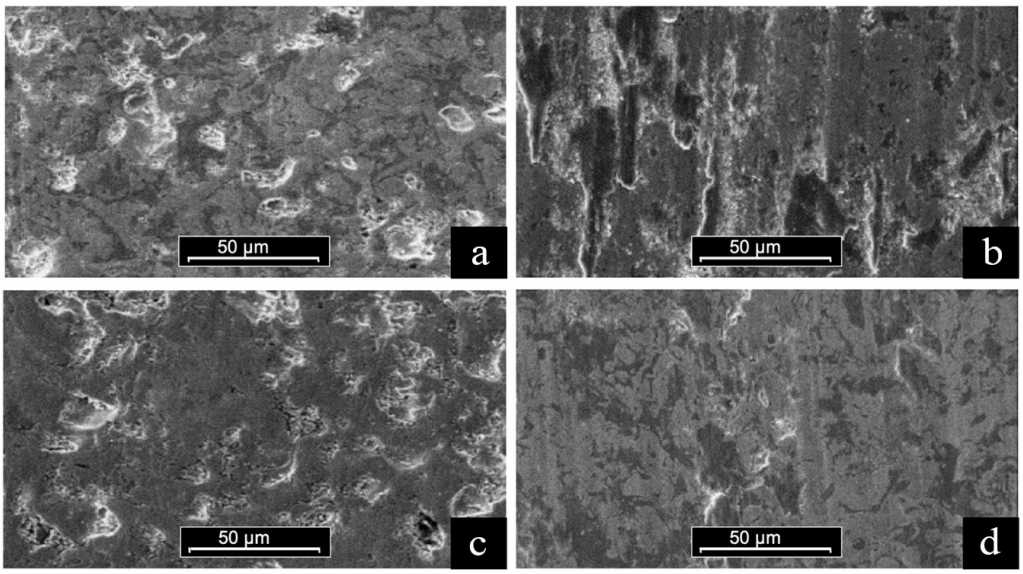


Fig. 4. SEM images of the surfaces of Ni-Cr-B-Si-C-WC-($Ni_{95}Al_5$) based coatings: (a) on AISI 5060 steel substrate prior to test, (b) scar after test, (c) on Ti-6Al-4V substrate prior to test, (d) composite scar after 80 min abrasive wheel test

points of high microhardness values confirm the presence of carbide, silicate, and boride phases in the coatings, as indicated in the XRD analysis.

The results from the abrasive wheel test of the plasma sprayed coatings according to the substrate metals are shown in Fig. 3(b). They reveal that wear occurring in the first 5 min of testing is almost the same in all the investigated cases. Furthermore, the tendency of wear of the coatings from 5 to 80 min is similar for the AISI 5060 steel, SAE J431 automotive gray cast iron, and Ti-6Al-4V substrate. However, the wear volume of the deposits on the titanium substrate is lower than that on cast iron and steel. At 80 min, the wear depth is 5.85×10^{-2} mm^3. That is about two-thirds of the coating on the steel substrate. In this period, presumably due to the friction heat, the amorphous state undergoes phase transformations, and the cohesion strength between the lamellas in the coating reduces. As a result, it is causing a reduction of the wear resistance of the steel samples. The presence of higher quantities of Ni_3B, CrB, Ni_3Si, Ni_4Si, and $Cr_{23}C_6$ in the coatings on the cast iron and Ti-6Al-4V samples considerably increases their wear resistance compared to the steel substrate. Figure 4 displays SEM images of plasma sprayed coatings on steel and titanium samples used in this experiment before and after wear testing.

Conclusions. The substrate material exerts influence on the phase composition of the plasma sprayed coatings. In as-coated conditions, the surface layers have a phase composition of crystalline γ-Ni solid solution and amorphous phases Ni_3B, $Cr_{23}C_6$ on the used steel substrate metal, γ-Ni, Ni_3B, CrB, on the gray cast

iron, and Ni_3B, $Cr_{23}C6$, Ni_3Si, Ni_4Si on the titanium alloy. The microhardness of the plasma sprayed nickel-base coatings is higher when splat on titanium alloy Ti-6Al-4V for up to 890 $HK_{0.05}$, slightly lower on cast iron, and the lowest values are found in the coated steel, about 600 $HK_{0.05}$.

Regarding wear resistance, the plasma sprayed coatings have a similar trend. At the beginning of the wear testing process for up to 5 min, the wear losses for grey cast iron and steel substrates are almost identical, while those on titanium are less. After the 15th min of the wear tests, the coatings on AISI 5060 steel wear off faster in time. The coated layers on the titanium alloy and the gray cast iron show similar resistance to wear with a slight advantage for those on titanium. Overall the coatings on SAE J431 gray cast iron and Ti-6Al-4V demonstrate significantly better wear resistance than those on the steel substrate.

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Institute of Metal Science, Equipment and Technologies
with Hydro- and Aerodynamics Centre "Acad. A. Balevski"
Bulgarian Academy of Sciences
67 Shipchenski prohod Blvd
1574 Sofia, Bulgaria
e-mail: skulev@ims.bas.bg
dveselinov@ims.bas.bg