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THE INFLUENCE OF STEEL AND CAST IRON AS SUBSTRATE MATERIALS ON THE MICROSTRUCTURE, MICROHARDNESS AND WEAR RESISTANCE OF NICKEL-BASE Ti-Al PLASMA SPRAY COATINGS

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Abstract

This paper studies the influence of different substrate materials on the phase composition, microstructure, microhardness, and wear resistance of Ni-Cr-B-Si-C-Ti-Al plasma spray coatings. Two types of substrate metals were studied – AISI 1045 steel and Pig-P3 Si grey cast iron. It has been found that in the as-coated condition the surface layers have a phase composition of γ-Ni, $Cr_{23}C_6$, γ-TiAl, TiN, and α-Ti(N, O) on steel substrate, and γ-Ni, α-Ti, TiN, Ni_3B, CrB, $Cr_{23}C_6$, α-Ti(N, O), Ni_3Si on cast iron. The microhardness and wear resistance of the plasma sprayed Ni-Cr-B-Si-C-Ti-Al coatings is tested. The wear volume of the coatings has been tested for up to 60 min. The deposits on cast iron substrates demonstrate lower wear than those on the steel substrate.

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

Introduction. The broad usage of steel and cast iron over the years is primarily because of their suitable mechanical properties and relatively low cost. However, these metals have limited application due to their initial properties,

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such as low hardness, insufficient wear resistance, and poor corrosion resistance. Therefore several post-production methods and techniques have been developed to extend the range of their usage [1,2]. Practically, one effective method for introducing enhanced wear, corrosion, and heat resistant layers on various types of metal substrates is plasma spraying. This method provides control over the production of specific microstructure and mechanical properties by changing the process parameters [3,4]. Thus plasma spray coatings are built to fulfill various application requirements [5,6].

Scientific investigations indicate that mixed crystalline and amorphous structures can be obtained under certain conditions during plasma spraying [7]. This structure determines the mechanical properties and structural stability of the coating. It is well known that the nickel-base plasma coatings with mixed amorphous and crystalline structures have good mechanical, physical, and chemical properties. Therefore nickel and nickel alloys are often used for plasma spraying of substrates made of steel and cast iron to increase their surface hardness, wear, and corrosion resistance [8].

Besides the technological parameters of the coating process, there are external factors related to the base material that may influence the structure, properties, and adherence of the plasma-sprayed coating. Those factors include the chemical composition, surface roughness, temperature, and others of the coated material [9,10].

The present work aims to investigate the influence of AISI 1045 steel, and Pig-P3 Si grey cast iron as substrate materials on the phase transformation, microhardness, and wear resistance of the Ni-Cr-B-Si-C-Ti-Al plasma spray coating.

Experimental. In this investigation, Ni-Cr-B-Si-C-Ti-Al powder was low-pressure plasma sprayed onto rotating substrate specimens. An automated gear set PPS-800 with indirect plasmotron PN-80 was utilized [8]. The chemical composition of the Ni-base alloy powder by wt.% is Ni: 45–50, Cr: 18–20, B: 3–5, Si: 3–5, C: 3–5, Ti: 11–13, Al: 11–13. This substance consists of spherical grains, with a size of 25–40 µm. The substrate materials used for the experiment are steel AISI 1045 and cast iron Pig-P3Si BDS EN 10001. The shape of the specimens is cylindrical with dimensions of 30 mm by length and a 10 mm diameter. Before spraying all samples were ground to the average roughness of Ra < 0.25 µm and cleaned with acetone. All of the plasma-spraying procedures were performed under the following fixed processing parameters:

- Current: 500 A;
- Voltage: 75 V;
- Plasma forming gas flow rate: Ar: 12×10^{-5} m^3/s^{-1}, N_2: 50×10^{-5} m^3/s^{-1};
- Spraying powder consumption: 1.5×10^{-3} k/gs^{-1};
- Spraying distance: 100 mm;
- Transport Ar gas flow rate: 4.25×10^{-5} m^3/s^{-1};
- Traverse speed of the plasmotron: 10 mm/s^{-1}.

The spraying time was 2 min for each specimen. The obtained thickness of the coatings ranges from 280 µm to 320 µm.

X-ray diffraction (XRD) analysis was employed to determine the phase constitution of the coatings. The measurements were performed at room temperature with a Philips XPert PRO analytical X-ray diffractometer, using Cu $K\alpha 1+\alpha 2$ 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 specimens were cut at low-speed, 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 examined optically using a Nikon Eclipse ME 600, 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 performed using 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 = 0.18–0.32 µm. The wear tests were carried out under the condition of a normal load of 50 N, 0.9 ms^{-1} sliding speed for up to 60 min. Every 5 min the weight loss of the samples was measured and converted to wear volume.

Results and discussion. To inspect the microstructure of the plasma sprayed layers, cross-sections of the coated samples were prepared. Visual observations on the cross-sections showed that the coatings had good appearances without visible cracks or cohesion losses. Figure 1 shows the microstructures of coatings formed on a substrate of steel (Fig. 1a) and cast iron (Fig. 1b). The microstructures exhibit the typical heterogeneous nature of coatings produced by plasma spraying. The deposited melted powder particles are visible in the shape of light and dark layers, while the partly melted or non-melted particles have a round or spherical shape. Also, pores and cavities are distinguishable in some areas (Fig. 1c, d).

Under the microscope, three zones are distinguishable on the treated samples – coated layer, interface, and substrate metal. The coatings obtained on cast iron are more homogeneous than those on a steel substrate. It was observed that the bonds between steel substrates and plasma spray layers are good without any pores, cracks, or other faults. The bonds between the coatings and cast iron substrates look similar, but inclusions and interruptions were detected on the substrate surface. The phases composition of the splat Ni-base coatings is analyzed using XRD. Figure 2 shows diffraction patterns of plasma sprayed layers on samples of steel (Fig. 2a), and cast iron (Fig. 2b).

Quite broad diffraction peaks are visible in the coatings obtained on the steel

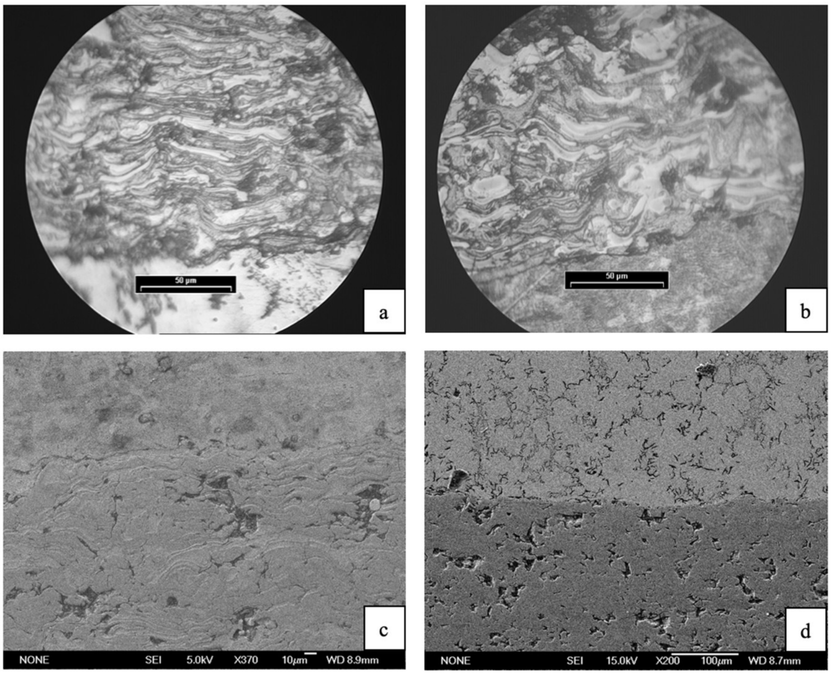

Fig. 1. Microstructure of Ni-Cr-B-Si-C-Ti-Al plasma sprayed coatings on (a) steel, (b) cast iron, observed under an optical microscope, and (c) steel, (d) cast iron, using SEM backscattered imaging

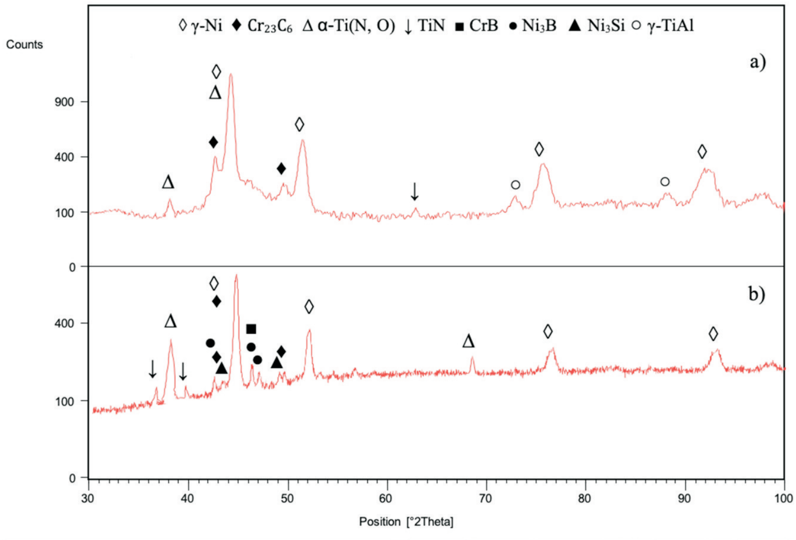

Fig. 2. X-ray diffraction pattern in the range of 30 to 100 (2θ, CuK_α radiation) for coatings on (a) steel substrate, and (b) cast iron substrate

samples. This indicates the presence of microcrystalline structures. The broad peak around and overlapping with the {111}Ni peak, which is the highest peak in all diffraction profiles, also shows the presence of an amorphous phase. Most peaks from minority phases in the coatings on cast iron are in close proximity, with a small relative intensity than the major fcc peaks. This low relative intensity of these phases ($Cr_{23}C_6$, Ni_3B, CrB, TiN) indicates their presence in small volume fractions. The main element of the structure of the coatings on both the steel and cast iron substrates is the γ-Ni solid solution. For the coatings produced on steel samples, microcrystalline and amorphous phases are present. In addition to those on the substrates of cast iron Ni_3B, CrB, and $Cr_{23}C_6$ are available.

The difference in the structure of the produced coatings is most likely a result of the different heat conductivity (λ) and heat capacity (cp) of cast iron and steel. Since cast iron is the worse conductor of heat as a consequence the heat dissipation, crystallization, and phase formation of the plasma sprayed coatings are influenced. This confirms the importance of the substrate material in the production of the coatings. The influence of the substrate metal on the mechanical properties, including hardness and wear resistance of the Ni-base plasma-sprayed coatings, is observable in Fig. 3 and Fig. 4.

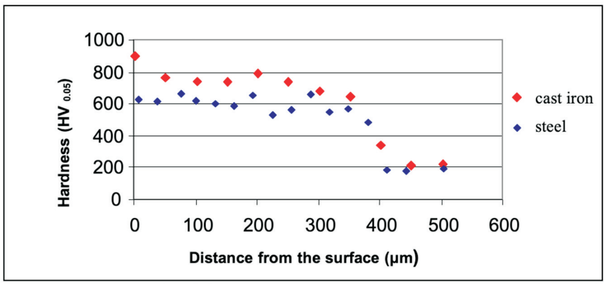

Fig. 3. Microhardness profiles of plasma-sprayed Ni-Cr-B-Si-C-Ti-Al coatings on AISI 1045 steel and cast iron Pig P3 Si

According to the results depicted in Fig. 3, the microhardness of the obtained coatings on the cast iron alloy is marginally higher than that on the steel substrate. The surface microhardness of the coatings splat on cast iron ranges from 650 to 920 HV, while that on the steel substrates is between 600 and 680 HV. In some points of the coatings on steel samples, there are microhardness readings from 1000 to 1100 HV. The highest values ranging from 1500 to 1700 HV are measured in some light non-homogeneous grains of coatings sprayed on cast iron. Such high local hardness values confirm the XRD analysis, which reports the presence of carbide, nitride, and boride phases in the coatings.

The results from the wear resistance test of the plasma sprayed coatings accordingly to the substrate metal are shown in Fig. 4. They indicate that during the first 30 min of wear testing, the wear volume of the coated layers on

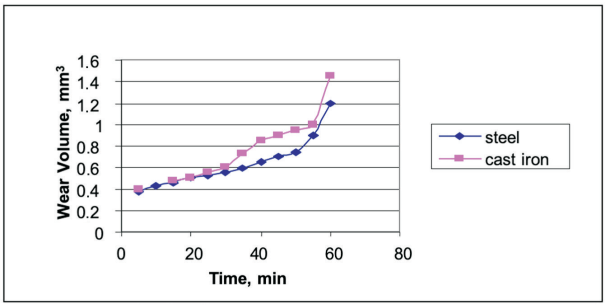

Fig. 4. Wear volume after abrasive wheel test of plasma-sprayed Ni-Cr-B-Si-C-Ti-Al coatings on AISI 1045 steel and cast iron Pig-P3Si

each type of substrate is almost identical. In the interval 35th to 55th min, the coatings splat on steel substrates is more resistant to the ware than those laid on cast iron. At the end of the wear testing period, the wear depth is 6.2×10^{-2} mm. Probably in this period, because of the friction heat, the amorphous state undergoes phase transformations, and the cohesion strength between the lamellas in the coating reduces, causing reduction of the cast iron sample wear-resistance. The presence of γ-TiAl, TiN, $Cr_{23}C_6$, and α-Ti(N, O) in the coating on the steel sample considerably increases its wear resistance.

Conclusions. The substrate material is an important factor for the production of plasma-sprayed Ni-Cr-B-Si-C-Ti-Al coatings. Depending on the base metal, the phase composition is different and consequently the properties of the coating. In as-coated condition the surface layers acquired on steel consist of crystalline and amorphous phases including γ-Ni, $Cr_{23}C_6$, γ-TiAl, α-Ti(N, O), TiN, while the phases present on cast iron are γ-Ni, $Cr_{23}C_6$, α-Ti(N, O), TiN, Ni_3B, Ni_3Si, CrB.

Considering microhardness, the layers obtained on cast iron demonstrate higher microhardness in the range from 650 to 920 HV, while the microhardness on the steel substrates is between 600 and 680 HV. During the wear resistance testing from the beginning of the process up until the 30th min the coatings on both substrate materials wear off almost identically. From the 35th min of wear testing until the end of the process the wear resistance of the coatings on steel is better than that on the cast iron substrate.

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