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MICROSTRUCTURE AND MECHANICAL PROPERTIES OF Ni-WC THERMAL SPRAYED COMPOSITE COATINGS

ABSTACT

The paper presents results of investigations of the microstructure and selected properties of improved composite coatings consisting mainly of nickel matrix reinforced by WC particles. The coatings were obtained by flame spraying of powders mixture on non-alloy steel substrates with following material remelting. Structural investigations were performed using both optical and electron microscopy. The distribution of microhardness and abrasion resistance of deposited coatings were also determined. The complex structure of coatings and resulting high wear withstand are the consequence of an intensive action of liquid matrix with dissolving tungsten carbide particles and formation of secondary phases.

Keywords: Composite coatings, thermal spraying process, Ni-WC, microstructure

INTRODUCTION

Composite coatings (CCs) built of a metallic matrix strengthened with hard particles of transition metal carbides have significantly higher properties when compare to pure metal ones. They combine the features of a relatively elastic metal matrix with high abrasion resistance particles of the reinforcing phase. Such materials are implemented in particular at the conditions of abrasive load in elevated temperatures, for example in the power or mining industries. Strengthening effect of the metal matrix is often obtained by additions of tungsten carbide particles, chromium carbide or titanium carbide ones [1-3]. Thick coatings of order of several mm are produced by overlaying techniques, including plasma transferred arc welding from powder mixtures [4, 5]. In turn, coatings of smaller thicknesses designed to large surfaces can be deposited by different techniques of spraying, including flame spraying, HVOF, HVAF, plasma spraying, cold spraying and arc spraying [6, 7]. Spraying process is characterized by a much higher efficiency than hardfacing. Sprayed layers are successfully applied into molds for compacting ceramic products, turbine blades, aircraft landing gears, etc. [8-10], significantly increasing their service time.

The matrix materials of sprayed coatings are generally based on iron, nickel or cobalt. The presence of hard carbide particles in the matrix results in faster appearance of mechanically mixed layers (MML), containing in-situ formed complexive oxides in dry sliding wear conditions with further stabilization of these MMLs [6, 11-14]. These effects increase the wear resistance of the material: the presence and the rate of fracture of MML have a greater impact onto it than the bulk properties of the coating material. The wear behaviour of CCs depends on the carbides amount, their size and distribution, as it was evidenced for cold sprayed and flame sprayed Ni base - WC CCs [11, 13, 15]. Nickel alloys with cast WC particles are more wear resistant than agglomerated ones due to their multi-modal size distribution and lower so called mean free path between particles [11]. CCs designed for the service at elevated temperatures are based mainly on Ni-Cr-B-Si matrix [6, 16-18]. Chromium increases hardness and promotes resistance for high temperature corrosion, boron serves as a melting temperature depressant whereas silicon gives self-fluxing properties.

The quality of flame-sprayed coatings closely depends on the particles' velocity from the torch to the modified surface. The higher particle energy, the lower the porosity of the deposited layer and its oxidation, and also higher adhesion to the substrate material is achieved. The continuous boundary between the reinforcing phase particles and metal matrix is of prime importance in composite layers. Only then the material can carry higher loads than the monolithic metal layer due to ability of transferring the load from the matrix to the reinforcing phase particles. In the case of an impact load, a transition zone at the interface between the reinforcing phase and the matrix phase is desirable. The nature of the interface between the matrix and the strengthening phase depends on the time and temperature of formation of the composite coating and the chemical affinity of both constituents to each other. Sprayed layers are always porous and have the lamellar structure of deformed grains. Since the time of contact between liquid metal droplets and solid refractory particles in the course of spraying is relatively short, the wettability based on chemical interaction between phases can be often problematic resulting with weak particles - metal bonds according to the fundamentals of liquid metal - solid phase interaction [19, 20]. Another possible problem may cause a poor adhesion of a sprayed deposited layer to the substrate.

Improvement of the above listed properties of sprayed coatings can be achieved by remelting the layer. Then the porosity is significantly eliminated as well as the incompatibilities at the boundary of the matrix with the strengthening phase. In addition, this variant makes it possible to obtain coatings of greater thickness without being delaminated. Remelting by means of flame, furnace, electric resistance and laser are employed for this purpose (see, for example, comparison of them applied for sprayed NiCrBSi coatings [21]).

In the present work, laminated thick composite coatings based on Ni with the addition of WC particles were produced on the carbon steel surface by means of a classical flame spraying method. After that the layers were additionally remelted also by flame to enhance their adhesion to substrate, their structure and properties. The method was selected due to its economy and versatility as sliding wear behaviour of coatings depends only in a small extent on such a choice [21]. As it results from the earlier research on overlaying [5, 22-23], in order to avoid the sedimentation effect of high density WC particles, three layers of different composition were deposited onto the substrate prior the remelting. Additionally, a wide range of strengthening phase size with low mean free path between particles were expected as a result of dissolution and separation of small WC grains from the supersaturated solution. The microstructure and behavior of such upgraded composite coatings were analyzed in terms of their application to parts of machines exposed to large abrasive loads.

EXPERIMENTAL PROCEDURE

Composite layers were sprayed onto S355J0 grade carbon steel of 10x50x150 mm size. Prior to the experiment, surfaces of steel substrates were subjected to abrasive blasting.

Two types of powders were used to produce composite coatings. The first was a nickel-based powder contained 16-17% Cr, 3.3% B, 3.8% Si and 0.8-1% C (wt %, nickel - balance) while the second with the same chemical composition with the addition of 0.8-1% W and 35 wt. % of irregular-shape tungsten carbide particles.

The spraying process was carried out using CastoDyn DS 8000 torch in 3 stages by following parameters: acetylene pressure 0.7 bar, oxygen pressure 4 bar, air pressure 1 bar, distance of torch from the substrate surface 200 mm. After pre-heating the substrate, first layer was deposited by using Ni-based powder without refractory particles. The second major layer was formed then using Ni-based powder with WC addition. Finally, pure Ni-based powder was sprayed again. After completing the spraying process, the whole 3-layered coating was remelted with the same torch.

RESULTS AND DISCUSION

Microscopic observations conducted with the unarmed eye did not show any welding incompatibilities in the obtained coatings (Fig. 1) The layers were free from cracks and porosity, and their face was smooth. A typical cross-section of the received composite layer is shown in Fig. 2. A uniformly thick coating is visible throughout the whole profile. Light, irregularly shaped tungsten carbide particles are distributed against the matrix background. In turn, Fig. 3 shows the region close to the boundary between the coating and steel substrate. The interface is clearly continuous without welding defects such as sticking and gas bubbles. It indirectly proves the good adhesion of the composite coating to the steel substrate.
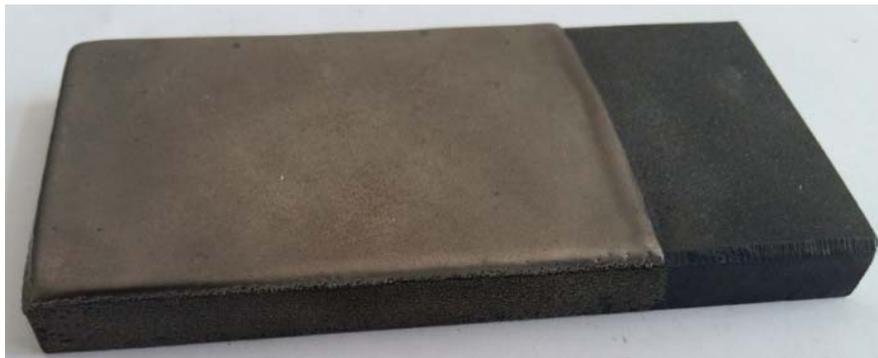
**Fig. 1.** Sample surface after spraying and remelting
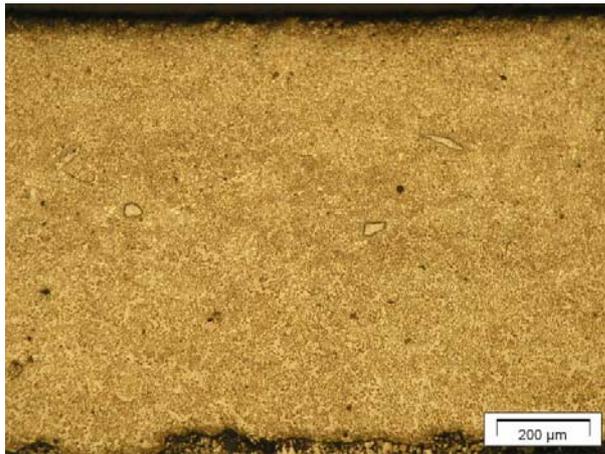
**Fig. 2.** Cross-section of a Ni-WC composite coating
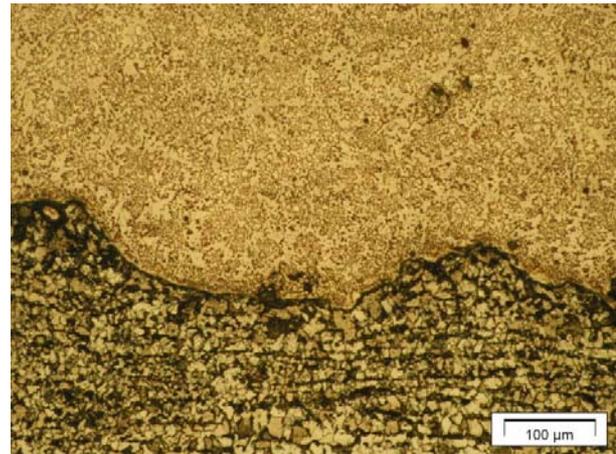
Fig. 3. Interfacial boundary composite coating - steel substrate

The microstructure of the two different areas in the bulk of the coating is shown in Fig. 4. A multiphase structure with a clear segregation of alloy constituents is visible near the interface (Fig. 4a). No primary tungsten carbide particles are observed in this zone but a few scattered gas bubbles are noticeable. Fig. 4b shows the structure from the middle zone of the coating. Undissolved tungsten carbide particles of irregular shape are visible in the multiphase matrix. Small gas pores are also observed. A clear transition zone appears at the interface between the WC and Ni matrix. It is an evidence of the intense interaction of the carbide with the liquid Ni alloy.
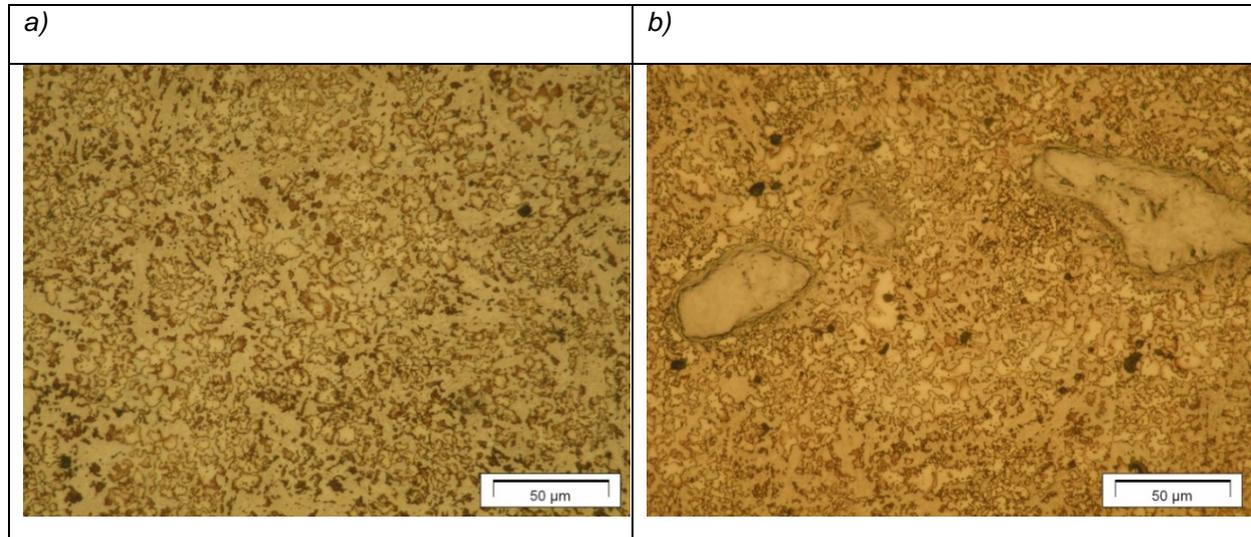
Fig. 4. Microstructure of the composite coating in the area of: a) close to the boundary with the substrate, b) middle zone.

Research conducted using scanning electron microscopy on non-etched specimens revealed the presence of dark particles of irregular shape on the background of light matrix - Fig. 5. These separations were observed throughout the cross-section of the coatings and their distribution is fairly even. In addition, in the middle of this section there are light partially dissolved irregular tungsten carbide particles - Fig. 5b. At the tungsten carbide-matrix interface, a reaction zone with a slightly darker color is visible. Small precipitations with the same color as the reaction zone are located around the large carbide particles.

a)

b)
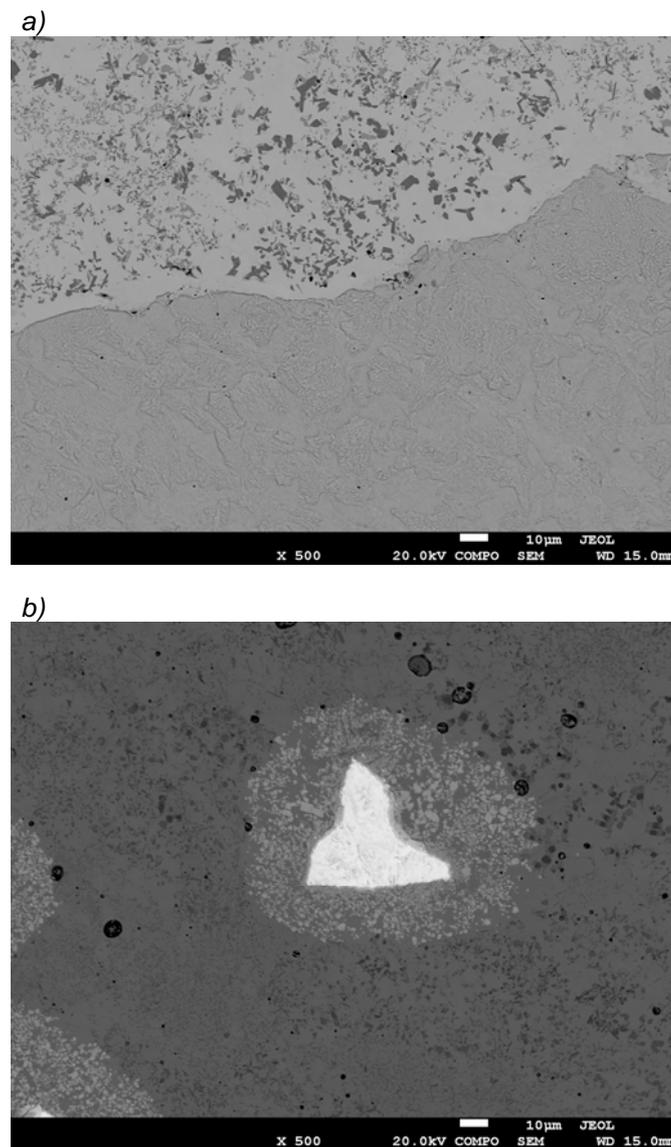
Fig. 5. Microstructure of coatings: a) dark precipitates at the border with the substrate, b) large WC agglomerate partially dissoluted with a "halo" of secondary crystallized phase

The results of the linear distribution of elements from these characteristic areas are shown in the form of concentration profiles along the line perpendicular to the substrate border (Fig. 6) and the line crossing the tungsten carbide-matrix interface (Fig. 7). The study has shown that these dark irregular precipitates distributed in the matrix are rich in chromium - Fig. 6. The high chemical affinity of chromium to carbon suggests the formation of chromium carbides during the remelting process. In turn, relatively smooth transitions of tungsten, carbon, nickel and chromium concentration profiles confirm the presence of a reaction zone at the interface between tungsten carbide and the matrix. This indicates the intense interaction of the metallic liquid with the carbide with its dissolution. As a result, new phases around the undissolved WC particles crystallize from the supersaturated solution. Research shows that these new phases are rich in tungsten but also contain nickel and chrome.

Tungsten partially dissolved in the nickel matrix additionally strengthens it. A slight presence of iron in the alloy evidences a local melting of the steel substrate during the process.

a)

b)

c)

d)

e)
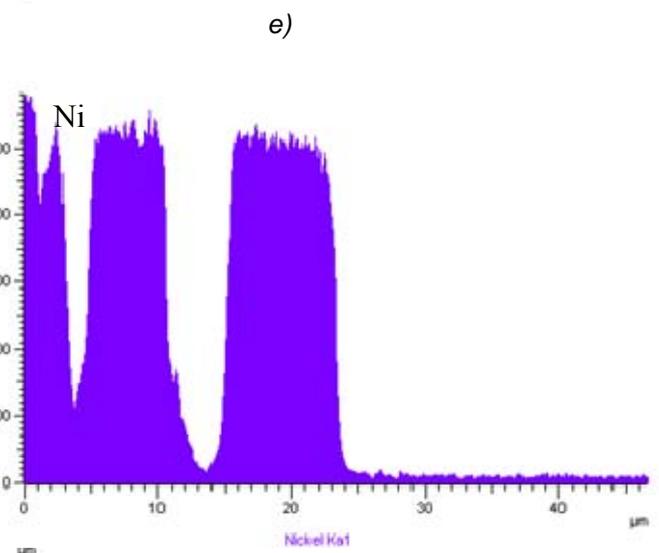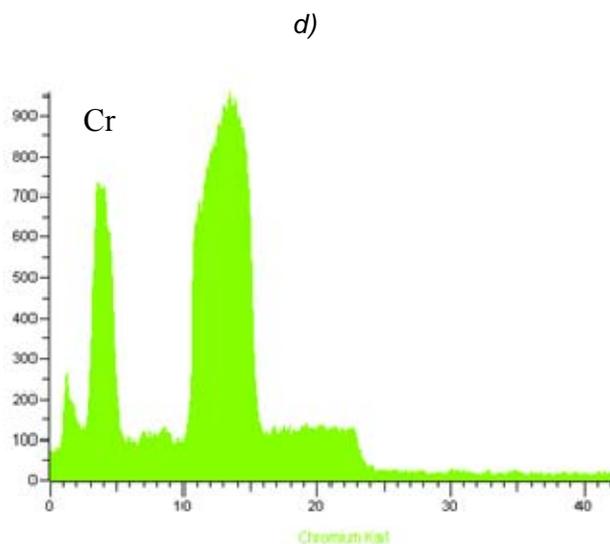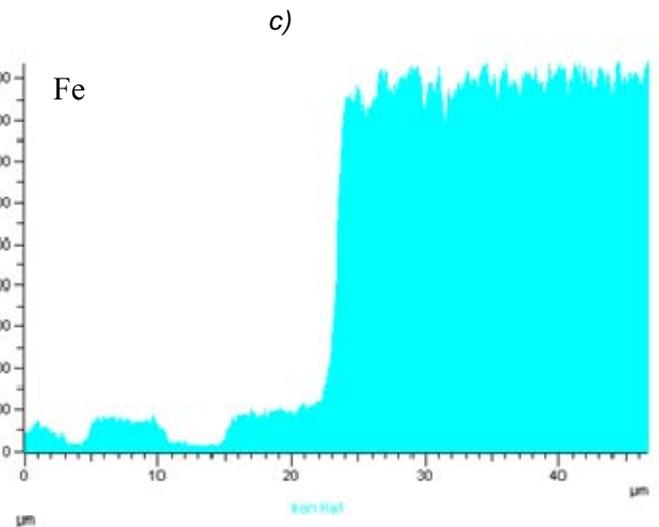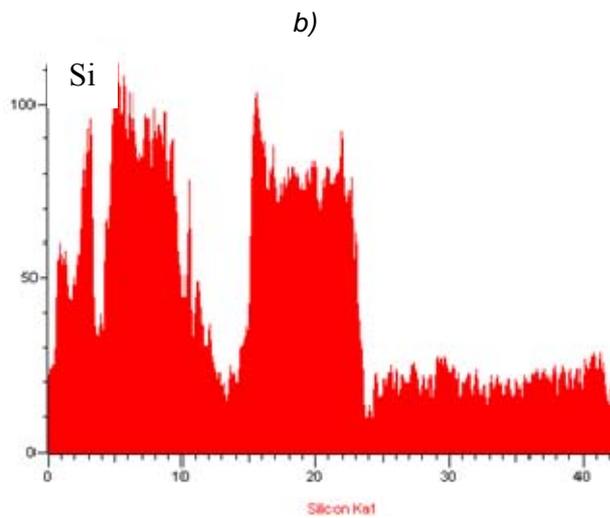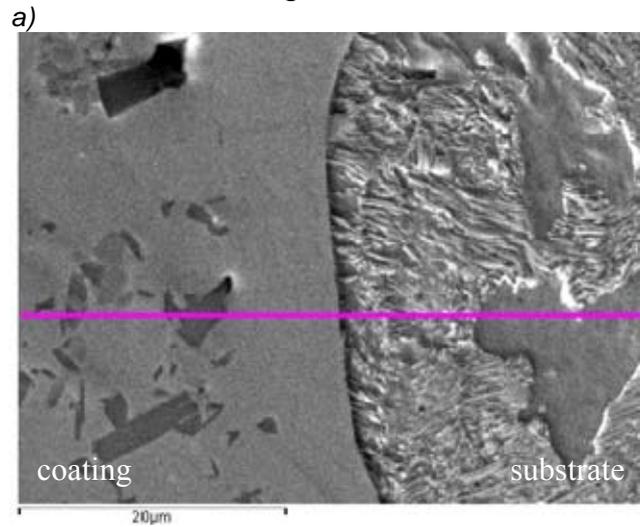
Fig. 6. Viscinity of coating-substrate interface (a) and linear distributions of silicon, iron, chromium and nickel (b - e, respectively)

a)

b)

C

c)

W

d)

Cr

e)

Fe

f)

Ni
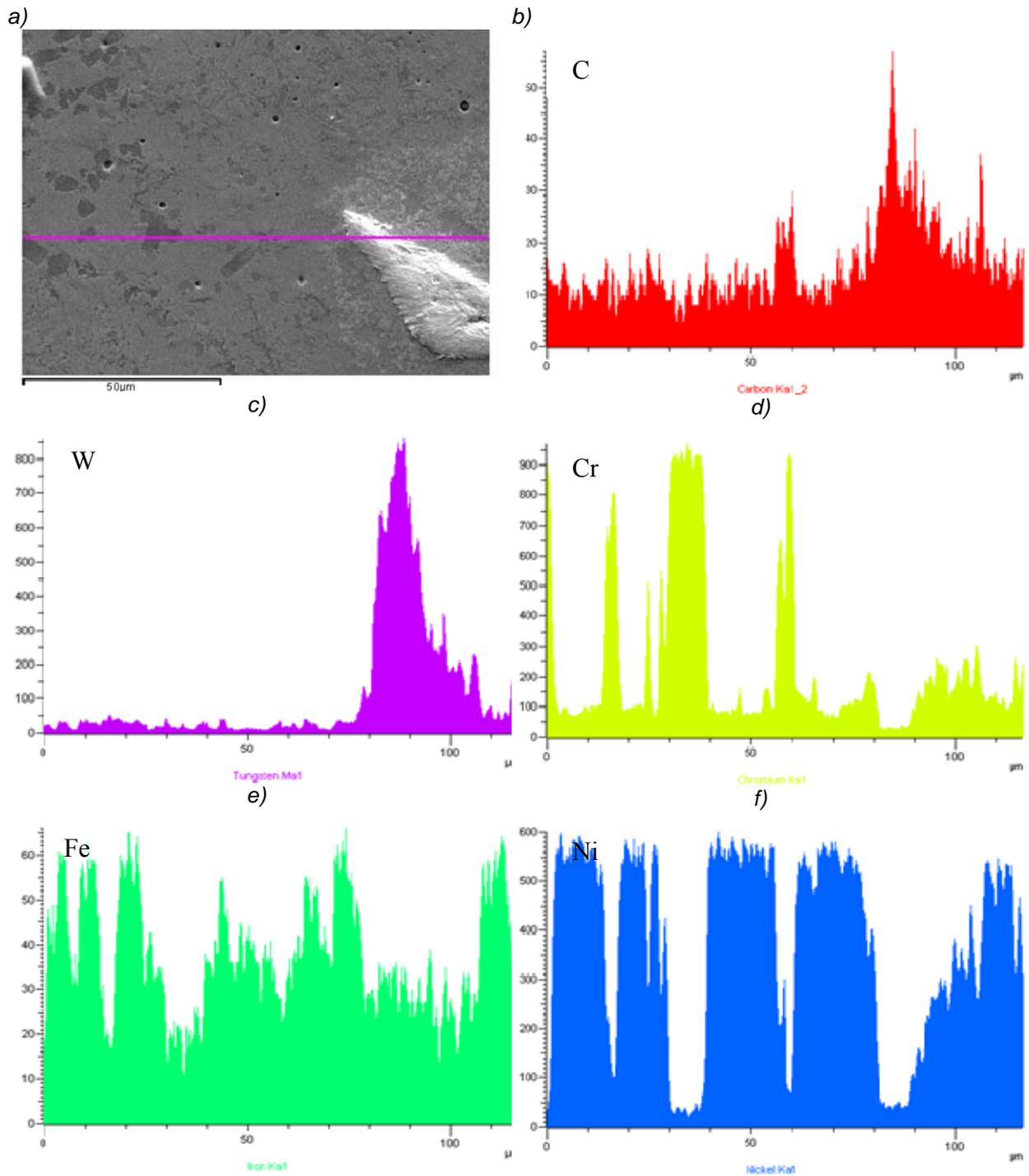
Fig. 7. Line of analysis (a) and concentration profiles of carbon, tungsten, chromium, iron and nickel along it (b - f)

The microhardness of the matrix of composite coatings was measured using the Vickers method along a line perpendicular to the boundary with the substrate. The results are shown in Fig. 8. The microhardness of the composite coating varies in the range of 650 - 830 $\mu HV_{0.1}$ units depending on the place of a measurement (it is a composite) but all values are significantly larger than these of the steel substrate (130 – 180 $\mu HV_{0.1}$). The effect is obviously a result of both the matrix solution strengthening with alloying elements and of the presence of secondary crystallizing phases based on chromium and tungsten.
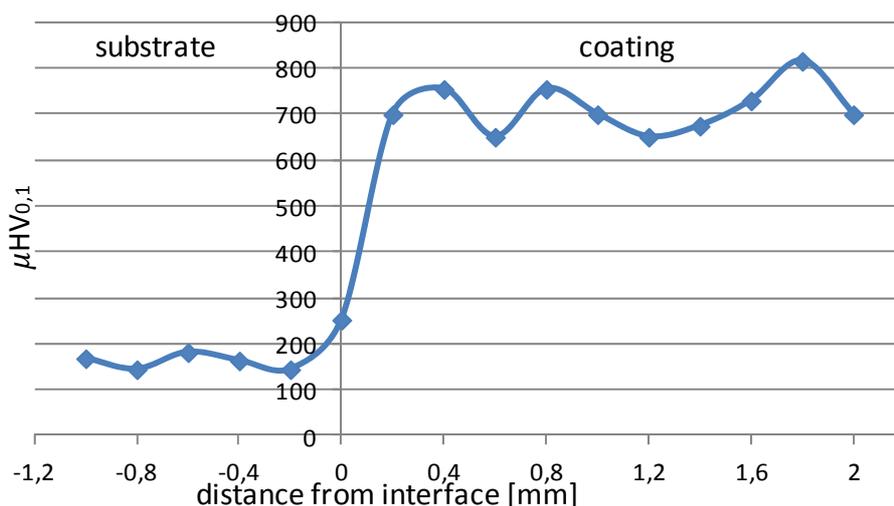

Fig. 8. Results of microhardness test perpendicular to the coating-substrate interface

The test of abrasion resistance was carried out in accordance with ASTM G65 standard at a special stand on samples with dimensions of 25x76 mm. The cutting of the samples was carried out using an electrospark cutting machine. The surface of specimens was prepared by grinding prior to testing according to the standard recommendations. Procedure A was employed assuming a sample pressure of 130N and a rotations number equal 6000. Such configuration of parameters allows to obtain a total frictional distance of 4309 m in 30 min.

The reference material was S355J0 steel. The wear was defined as the weight loss of the samples which were weighed with an accuracy of 0.001g before and after abrasion time. Comparative results of abrasion resistance are presented in Figs. 9 and 10. The data show that the abrasion resistance of Ni - WC composite coating is more than four times higher than that of S355J0 steel. The increased abrasion resistance of composite coatings corresponds with microhardness measurements.
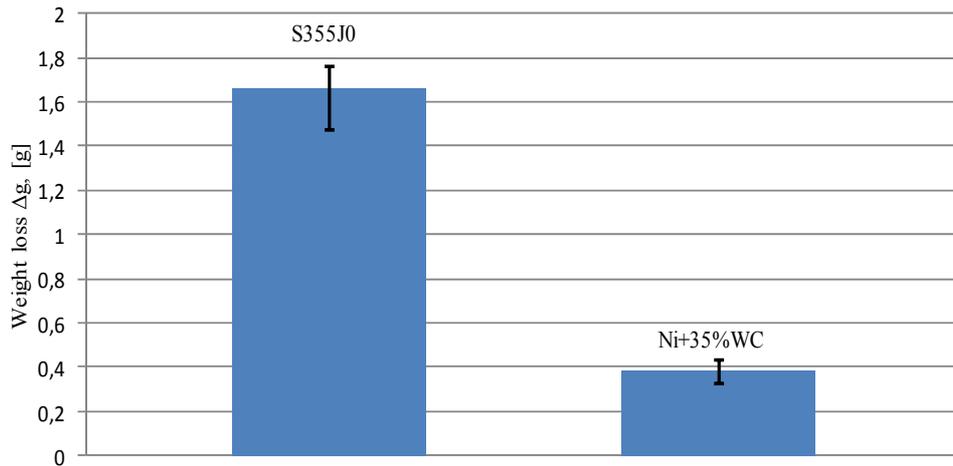
Fig. 9. Results of wear tests

As it is seen from Fig. 10, in the case of Ni alloy -WC composite coating the wear mechanism is mainly based upon fragmentation of hard particles with micro-groves formation in the matrix whereas in the reference steel uniform volume wear took place. Alloying of nickel matrix and in particular the appearance of evenly distributed hard precipitates based on chromium along with the presence of insoluble tungsten carbide particles effectively block the removal of tested material.
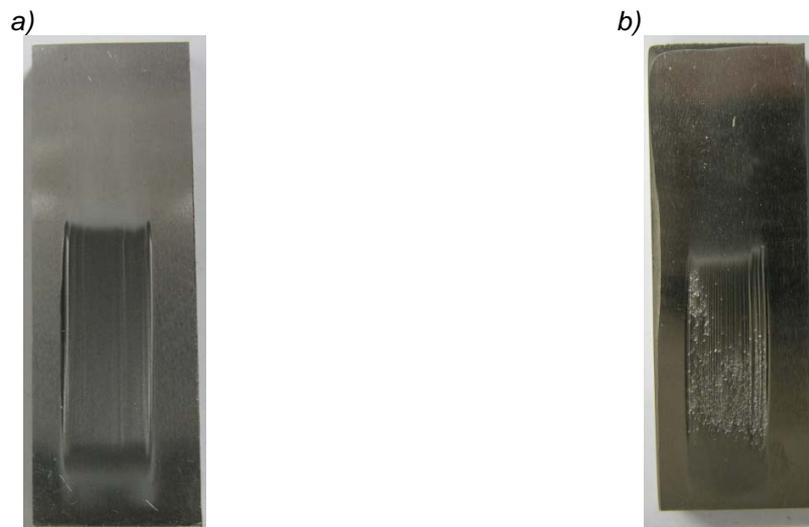
Fig. 10. The view of samples after the wear test: a) S355J0 steel, b) Ni-WC coating

SUMMARY

- Improved Ni - WC composite coatings were obtained as a result of flame spraying of powders with following remelting of the deposited layers. They feature by the recurrent thickness and the lack of welding incompatibilities, both at the interface with the substrate and in the bulk.
- The coatings have multi-phase structure as a result of intensive interaction of components in the course of the process. Tungsten carbide particles dissolve partially in the nickel-

base liquid. New phases rich in chromium are formed and also another ones on tungsten base crystallized from the supersaturated solution.
− Covering the S355J0 steel surface by the composite Ni-WC layer obtained by the presented spraying means increases four times its abrasion resistance.

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