

# THE INFLUENCE OF TUNGSTEN CARBIDE ON THE STRUCTURE AND PROPERTIES OF WEAR-RESISTANT COATINGS PRODUCED BY VARIOUS METHODS (REVIEW)

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## ABSTRACT

Surface coating with wear-resistant materials is a reliable and cost-effective process used for the manufacture and repair of tools, materials and machine components that require desirable surface properties such as resistance to corrosion, erosion and wear. Wear-resistant coatings cover a wide range of applications in many industries, for example, in automotive and aerospace, oil and mining (as components of drill bits or tunneling machines), in the manufacture of cutting tools for processing metal components. This review presents the main types of wear-resistant coatings based on Co, Ni, Fe, Cu, Cr, NiCrBSi, NiCrBSiFe and others with 10% to 90 % tungsten carbide particles in the matrix. By changing the phase composition and surface structure of the material by forming protective coatings, it is possible to achieve a significant increase in operational properties, such as hardness, strength, wear resistance, heat resistance, corrosion resistance, etc. In both wear-resistant coatings and hard alloys, of the three specified carbide phases in the W–C system, namely WC,  $W_2C$  and  $WC_{1-x}$ , WC is the only stable carbide at room temperature, and it is the phase that must be present in wear-resistant coatings in order to obtain optimal properties. Given the rapid development of wear-resistant coatings, this paper provides an overview of the main types of wear-resistant abrasive coatings, application methods and their properties. The results of the above studies may be useful for scientists and engineering staff of enterprises engaged in improving the operational properties of structures for various purposes.

**KEYWORDS:** wear-resistant, composite coatings, tungsten carbide, wear, wear resistance, abrasion resistance, surfacing, microstructure, hardness

## INTRODUCTION

Nowadays wear-resistant coatings are widely used to reduce or eliminate wear, and extend the service life of products. Considering the rapid development of wear-resistant coatings this paper presents a review of basic types of wear-resistant coatings, their properties and application. To achieve a long service life of wear-resistant coatings subject to severe mechanical wear, materials with enhanced properties, such as high hardness and ability to withstand high temperatures, are needed. Tungsten carbide is a material having these properties, but manufacture of a large product from this material is not practically possible or economically feasible, as certain material defects may occur, such as brittleness, considerable weight and high cost. For effective use of material properties the surface of ordinary steel is covered by a composite coating, which allows increasing the strength, reducing the weight and cost owing to higher wear resistance of tungsten carbides. The wear-resistant composite coating can be produced by different methods, including welding (manual arc, consumable and nonconsumable electrode), laser, plasma spraying, magnetron sputtering, etc.

This review presents the possibilities for producing and application of composite coatings, based on the following systems: WC– $W_2C$ , WC–Co, WC–Ni, WC–Fe, WC–Ni–Fe, WC(Co)–NiCrBSiFe, WC–NiCrSiB, which are used to extend the service life of engineering structures subject to wear, erosion and corrosion.

## TUNGSTEN CARBIDE PROPERTIES

Tungsten is a metal element with exceptional mechanical and thermal properties; it has the highest melting temperature of all the metal elements. It combines with carbon to form tungsten carbide [1, 2], which is considered a refractory carbide with melting temperature above 1800 °C. It is characterized by high hardness and satisfactory chemical resistance. Tungsten carbide can exist in the form of two phases: WC and  $W_2C$  with the hardness of 2000–2700 HV [1]. Tungsten carbide can be a monocrystalline WC with carbon content of  $\approx 6.1\%$  or a eutectic WC/ $W_2C$  with carbon content of  $\approx 4\%$ , as one can see in carbon-tungsten phase diagram (Figure 1). Table 1 gives the properties of tungsten and tungsten carbides.

The tungsten carbide, in addition to deposition as part of a coating on the surface, is usually used as cemented carbide in tools from hard metal. In this case the tungsten carbides are sintered with a metal binder, more often cobalt and less often nickel, as these ele-

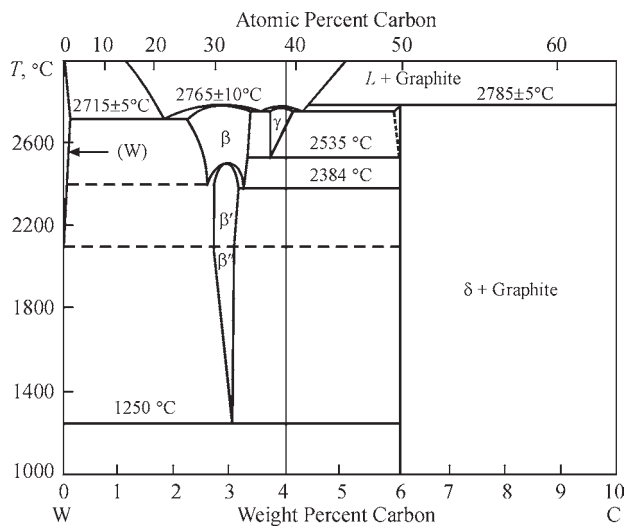


Figure 1. W–C binary diagram [1]

ments provide good wetting of the base metal. To obtain a spherical shape (Figure 2, *a*), the cast carbides are subjected to spheroidization by a plasma torch.

The fused and ground tungsten carbides (FTC) (Figure 2, *b*) are manufactured by melting in an electric arc furnace with further cooling and crushing, and they are characterized by a regular sharp shape. Fused tungsten carbides consist of a eutectic containing WC/W<sub>2</sub>C having a feather-like structure, similar to spherical cast tungsten carbides. Monocrystalline carbides (Figure 2, *c*) have a structure similar to FTC carbides with very sharp edges. As one can see from the Figure, carbide particles look like chipped elements with cracks. Fused WC–Co carbide (PA2) (Figure 2, *d*) also has an irregular shape, but not as sharp as the monocrystalline carbide or FTC. Agglomerated WC–Co carbide (Figure 2, *e*) has particles of a spherical shape with satellites. Investigation of

Table 1. Properties of tungsten and tungsten carbide [2]

Type	Melting temperature, °C	Density, g/cm <sup>3</sup>
W	3410	19.3
WC	2870	17.2
W <sub>2</sub> C	2730	15.8

the carbide cross-section shows the presence of pores during manufacture.

A eutectic alloy of WC–W<sub>2</sub>C (relit) is one of the promising traditional wear-resistant materials for metal product protection from wear [3, 4]. This is a eutectic alloy of WC+W<sub>2</sub>C tungsten mono- and semi-carbides with the melting temperature of 2735 °C and the microhardness in the range of 1000–2400 *HV* (depending on the manufacturer) [4]. The initial eutectic alloy of WC–W<sub>2</sub>C tungsten carbides was produced by off-center spraying of castings produced in the Tamman furnace at the temperature of 3100 °C. Argon, nitrogen and argon-nitrogen mixture were used as the plasma-forming gas in the proportion of 50:50. Vickers hardness of the eutectic alloy of WC–W<sub>2</sub>C system, produced by off-center spraying, differs essentially, depending on the change of protective and plasma-forming gas environment and powder particle dispersion. The finest fine-crystalline structure is observed in an alloy, produced in the protective environment of argon with nitrogen as the plasma-forming gas. It was established by the method of quantitative metallographic analysis that increase in the mechanical properties correlates with reduction in the ratio between the quantity of W<sub>2</sub>C, WC and WC<sub>1-x</sub> phases, thickness of phase interlayers in the grains and their

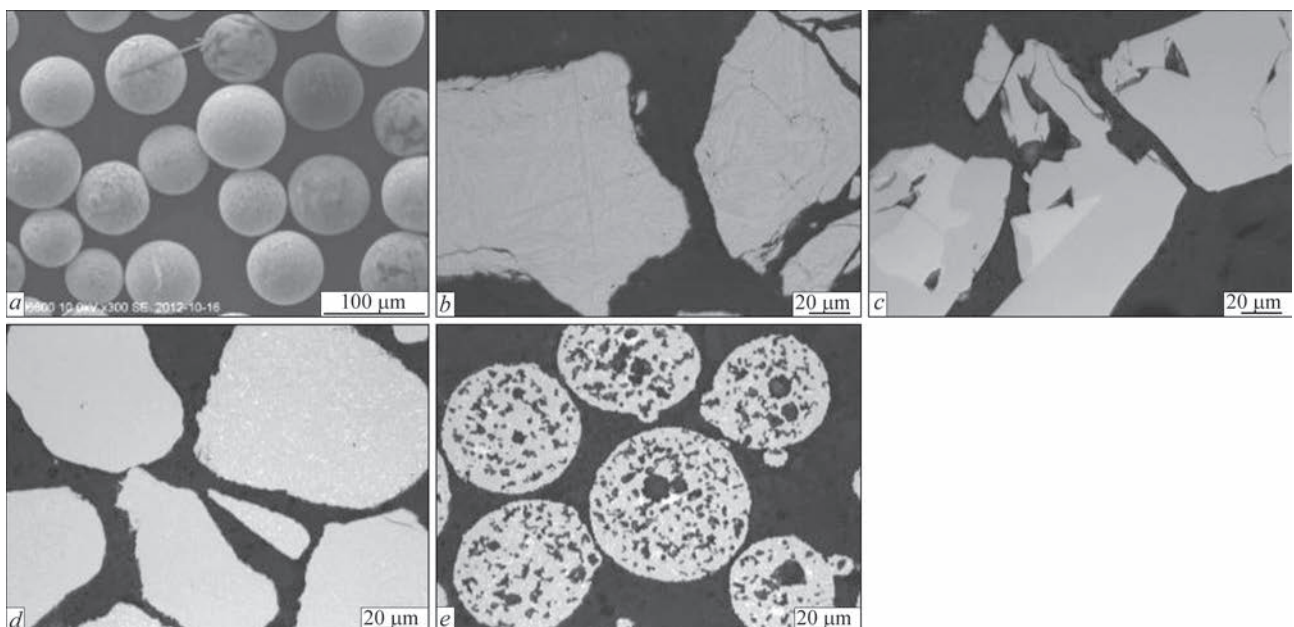


Figure 2. Appearance of tungsten carbides: spherical cast carbide (*a*); fused and crushed tungsten carbide (FTC) (*b*); monocrystalline tungsten carbide (*c*); WC–Co carbide (PA2) (*d*); agglomerated WC–Co tungsten carbide (*e*) [1]

**Table 2.** Properties of matrix coatings [5]

Carbide	Crystalline lattice type	Microhardness, MPa	Density, g/cm <sup>3</sup>	Melting temperature, °C
WC	Hexagonal	17000	15.70	2600
W <sub>2</sub> C		30000	17.15	2850

morphology [3]. W<sub>2</sub>C quantity is reduced with increase in the cooling rate that leads to an increase in the hardness of the alloy, which contains fine particles of the relit powder. Reduction in the hardness of the relit powder particles is due to the predominant loss of carbon during spraying and an increase in the quantity and dimensions of the W<sub>2</sub>C phase.

Technology of the process of off-center thermal spraying of fused tungsten carbide ingots allows producing powder with spherical particles of 50–1000 μm size in a vacuum chamber [4]. The hardness and increased strength properties of the spherical granules of tungsten carbide largely depend on the stoichiometric composition of WC+W<sub>2</sub>C eutectic alloy. Maintaining a ratio within 78–82 % W<sub>2</sub>C and 18–22 % WC in combination with a fine-grained structure, forming as a result of high crystallization rates, provides the granule microhardness above 3000 HV. Note that the microhardness of tungsten carbides, produced by other methods, is much lower: crushed WC+W<sub>2</sub>C (1800–2300 HV), crystalline WC (1900–2150 HV) and spherical fused WC+W<sub>2</sub>C (1900–2800 HV) [4]. Fused tungsten carbides with ground or spherical granules, are used for surfacing the drilling tools.

### MODERN DEVELOPMENTS FOR COATING DEPOSITION BY FLAME SURFACING

At present the method of manual flame surfacing has become widespread due to the ease of equipment operation, high coating capacity, and local heating of the surfaced material. Powders of Relit LKV “Z”-2, Relit LKV “Z”-6, Relit LKV (S) and VSNGN-88 grades (nickel-based alloys and cast tungsten carbides) have a high hardness and wear resistance and they can be used as additives during deposition of wear-resistant coatings [5]. It is known that the cast tungsten carbide powders consist of several phases, so that the pres-

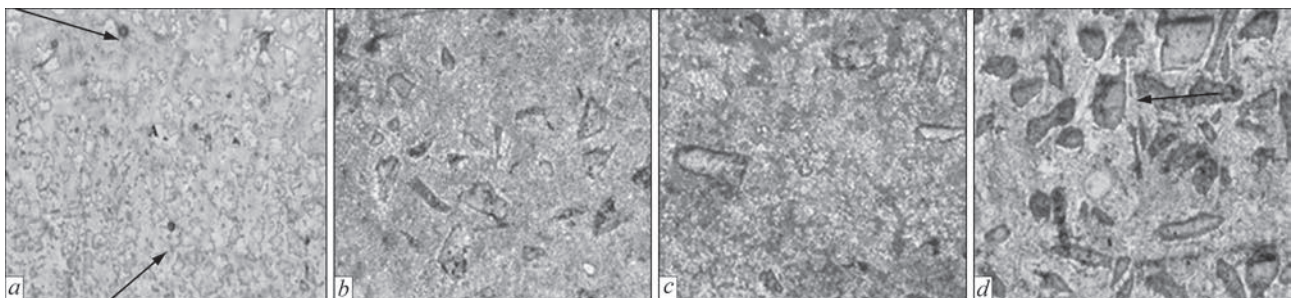
ence of a phase with the highest hardness is important. The data on microhardness of various phases of cast tungsten carbide are presented for clarity in Table 2.

Relit LKV “Z”-2, Relit LKV “Z”-6 powders have the same phase composition, but W<sub>2</sub>C content in Relit LKV “Z”-2 (64.8 wt.%) is higher than that in LKV “Z”-6 (59.4 wt.%). The granulometric composition of these powders differs significantly. They can be used as a coating for drilling tool body [5].

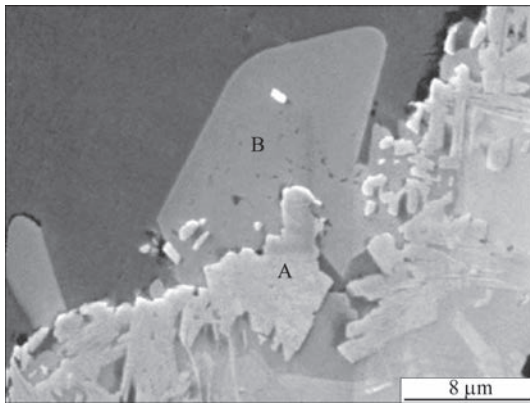
Note that WC/Co concentration in NiCrBSi–WC/Co powder influences the physical and mechanical properties of the coatings after their deposition [6]. The concentration may vary from 0 % WC/Co in the mixture up to 50 % WC/Co. Combinations of WC and Ni coatings with WC concentrations of 0, 12.5, 25 and 50 % are characterized by different microstructure (Figure 3).

Coating wear resistance depends on the percentage of WC. It is shown that higher mass wear of the coating was observed at greater loads in alloys with an increased amount of WC. This is attributable to WC dissolution in the main matrix. WC dissolution reached 12.5 % (according to [6]), resulting in greater mass wear of the coating.

Compared to other processes, much larger WC particles can be used during the coating deposition to create a metal layer with a higher wear resistance. A wear-resistant coating from tungsten carbide/copper (WC/Cu) was deposited on a steel substrate using furnace brazing [7]. Relatively large WC particles (up to 850 μm) were used for reinforcement. The particles were saturated with a copper-based brazing filler metal with satisfactory toughness. A composite coating was formed, which is characterized by strong adhesion to the base metal. Microstructural studies showed that wear of the deposited coating depends on the carbide size and distribution. Figure 4 shows the



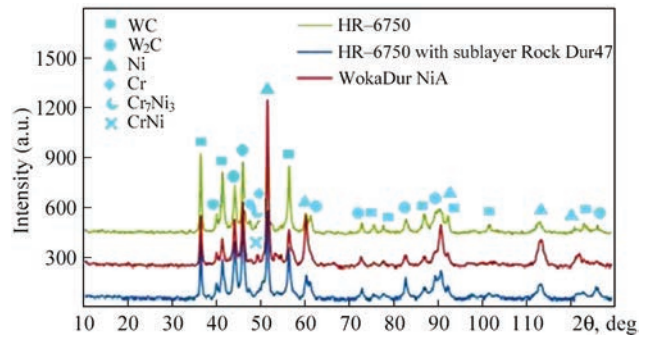
**Figure 3.** Microstructure of coatings with different WC concentrations: 1060 alloy (a); 1060 alloy with 12.5 wt.% WC (b); 1060 alloy with 25 wt.% WC (c); 1060 alloy with 50 wt.% WC (d) [6]



**Figure 4.** Microstructure ( $\times 5000$ ) of the carbide/matrix interface [7] microstructure of the area of the carbide and matrix interface. Table 3 gives the results of chemical analysis obtained by energy-dispersive spectroscopy (EDS) of areas A and B. A small quantity of Cu, Mn and Ni is present on the interface in zone A, indicating that the Cu alloy has melted and is diffusing into the WC, eventually forming a satisfactory metallurgical bond on the contact surface.

The strength of adhesion of the coating to the base metal varies, depending on the soaking time during surfacing. EDS analysis of area B shows that there is a certain quantity of Fe which dissolves in the molten alloy and eventually forms a new phase with WC. Test results [7] for the composite coating showed a higher wear resistance than that in several widely used WC-6Co alloys. A relatively large average size of the carbides is an effective factor in improvement of the abrasive wear resistance, as it is harder to remove the particles from the matrix.

Work [8] is devoted to investigation of composite coatings for drilling tools, namely those of WokaDur NiA and HR-6750 grades, containing cast tungsten carbide in the form of grains with particles of up to 800  $\mu\text{m}$  size, uniformly distributed in the nickel alloy matrix, and HR-6750 alloy with Rock Dur sublayer, which are deposited by the method of thermal surfacing on different steel substrates of St. 45 and St. KhVG grades (Figure 5). Investigations of the microstructure (Figure 5) and element distribution in the



**Figure 6.** X-ray patterns of samples with coating applied on St. 45 and St. KhVG steel substrates [8]

**Table 3.** EDS-analysis of the interface between the carbide and the matrix [7]

Element	Carbide/matrix interface (A)	Phase in the matrix (B)
W	89.08	59.99
Cu	4.24	5.98
Mn	0.47	4.04
Ni	2.74	13.04
Fe	3.46	22.15

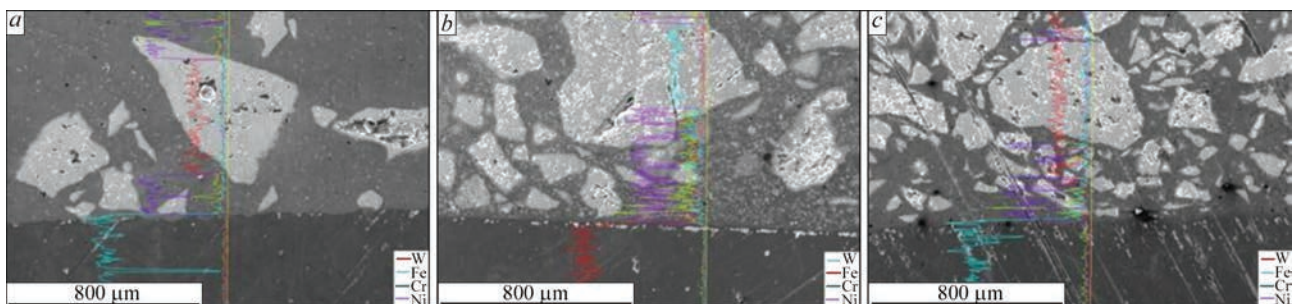
**Table 4.** Elemental analysis of matrix coatings [8], wt.%

Coating	Ni	Cr
HR-6750	81.09	18.91
HR-6750 sublayer Rock Dur 47	85.56	14.44
WokaDur NiA	91.03	8.97

coating revealed the difference in the nickel and chromium concentration (Table 4).

Proceeding from the results of X-ray structural analysis, it was determined (Figure 6) that WC,  $\text{W}_2\text{C}$ , Cr,  $\text{Cr}_7\text{Ni}_3$  and CrNi phases are present in samples with HR-6750 coating and Rock Dur 47 sublayer.

The ratio of WC and  $\text{W}_2\text{C}$  phases in these samples is different. In HR-6750 sample the WC phase predominates over  $\text{W}_2\text{C}$ , and in the sample with Rock Dur 47 sublayer the relationship is inverse. WC,  $\text{W}_2\text{C}$ , and CrNi phases were found in samples with WokaDur NiA coating. During investigations it was established that microhardness of the produced coating matrices



**Figure 5.** Element distribution over the surface: WokaDur NiA-St. 45 (a); HR-6750-St. 45 (b); Rock Dur 47 with HR-6750-St. KhVG (c) [8]

is equal to 590–660  $HV$ , and microhardness of tungsten carbide particles is 2145–2455  $HV$  [8].

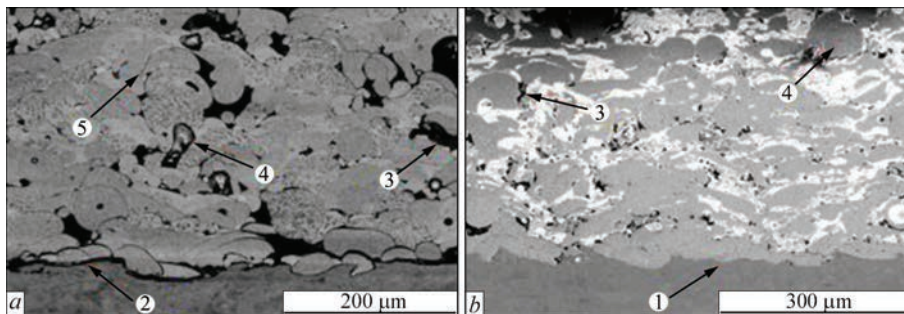
### MODERN DEVELOPMENTS IN THERMAL SPRAYING OF COATINGS

Nowadays thermal spraying is the leading method, which allows avoiding abrasive wear of materials for many days, high-temperature corrosion, erosive wear and stresses due to extension of the service life of the material during operation. The hard alloy coatings produced by thermal spraying typically have the thickness of 100–500  $\mu\text{m}$ . Thus, thermal spraying (HVOF — high-velocity oxy-fuel spraying and HVAF — high-velocity air-fuel spraying) allows implementing the functionality of the hard alloys on the surface of large parts, which cannot be manufactured by the powder metallurgy method for engineering and economic reasons.

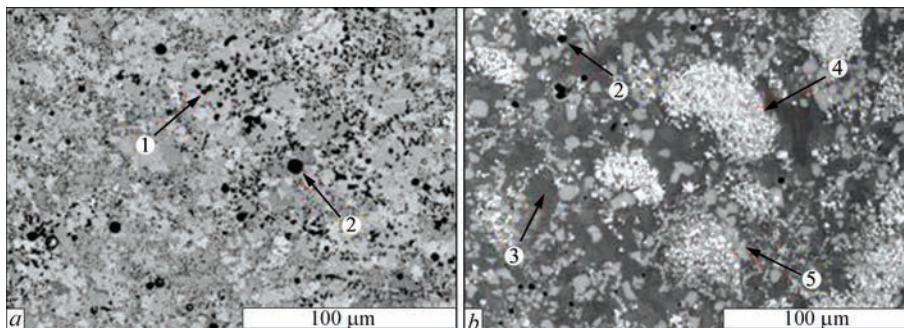
The HVOF method was used to apply WC–10Ni and WC12Co coatings on a blade from steel (BS 3100 GR A3 cast steel) 200–300  $\mu\text{m}$  thick [9]. The characteristics of the carbide phase and morphology of the Ni/Co matrix revealed a similar distribution of the reinforced particles of tungsten carbide in the metal matrix. The visible size of the carbide grain is smaller for WC–12Co and it is equal to 2.3  $\mu\text{m}$  on average, whereas in WC–10Ni coating the size is increased to 2.7  $\mu\text{m}$ . It is shown that the wear rate of WC–12Co coating is much lower than that of WC–10Ni. This is related to the fact that the WC–12Co combination

ensures a high hardness, which is close to 1700  $HV$ , compared to WC–10Ni (1500  $HV$ ) [9]. Wear characteristics and adhesion strength of the carbide coatings, produced using HVOF, are improved by further heat treatment after spraying. Further heat treatment is usually used for modification and correction of the microstructure and phase composition after coating deposition using HVOF and HVAF [10, 11].

Testing (for wear resistance, frictional properties) of thermally sprayed carbide alloys based on WC–17 % Co, WC–10 % Co 4 % Cr, WC–15 % Ni–MoCrFeCo,  $\text{Cr}_3\text{C}_2$ –25 % NiCr, (Ti, Mo)(C, N)–37 % NiCo, NiCrSiB and AISI 316L systems produced by HVOF method and plasma spraying of  $\text{Cr}_2\text{O}_3$  demonstrated wonderful properties, and they can be recommended as a replacement of the traditional surface treatment [12]. They successfully passed the wear tests by the following methods: abrasion resistance of the coatings on dry sand/rubber wheel according to ASTM G-65; wet slurry erasure according to ASTM G-75 and sliding wear behaviour during pin-on-disc testing according to ASTM G-99. Owing to brittle cracking susceptibility,  $\text{Cr}_2\text{O}_3$  ceramic coating deposited by plasma spraying can be recommended only for pure abrasive wear conditions. Tested metal coatings with HVOF-sprayed NiCrSiB and AISI 316L did not have sufficient wear resistance compared to the traditional surface treatment, so they should not be used in more severe conditions [12].



**Figure 7.** Microstructure of NiCrBSiFeC (a); NiCrBSiFeC–WC(Co) (b) coatings: 1 — substrate-coating interface; 2 — oxides; 3 — pore; 4 — unmelted particle; 5 — interface [13]



**Figure 8.** Microstructure of remelted NiCrBSiFeC (a); NiCrBSiFeC–WC(Co) (b) coatings: 1 — block precipitates; 2 — round pore; 3 — matrix; 4 — unmelted WC carbides; 5 — molten WC carbides [13]

**Table 5.** Chemical composition of WC electrode [14]

Element	W	C	Mn	Si	Fe
Composition, %	60.2	3.1	1.5	0.4	Bal.

WC(Co) addition to NiCrBSiFeC leads to producing a composite coating with higher hardness and wear resistance [13]. According to microstructural studies (Figure 7) of the sprayed layers, the coating is characterized by a general lamellar structure with pores, oxides and unmelted particles.

After remelting (Figure 8) the block precipitates disappeared completely, and the surface roughness dropped abruptly for NiCrBSiFeC coatings and for NiCrBSiFeC–WC(Co).

Investigation results show that both NiCrBSiFeC and composite coatings led to a significant increase in the steel substrate hardness and improvement of wear resistance due to formation of precipitates with a high hardness, which are well dispersed in the crystal structure [13].

#### MODERN DEVELOPMENTS IN COATING DEPOSITION BY ARC WELDING METHOD

There is an opinion among many researchers that the surfacing methods and parameters have an essential influence on the productivity of the process of producing the coating. The arc welding method is cost-effective, compared to other coating methods. In [14] the influence of prior heat treatment of the base material on the microstructure of a blade with the deposited tungsten carbide (WC) was studied. Tungsten carbide was applied on the surface of a carbon steel blade using the arc heating technology, to improve its wear resistance. Preheating of the base metal — the blade was performed with a torch for 3–5 min (temperature was 300 °C) before coating deposition. The electrode designed for edge surfacing, is a WC placed into a steel tube (350 mm length, 6 mm diameter). WC ma-

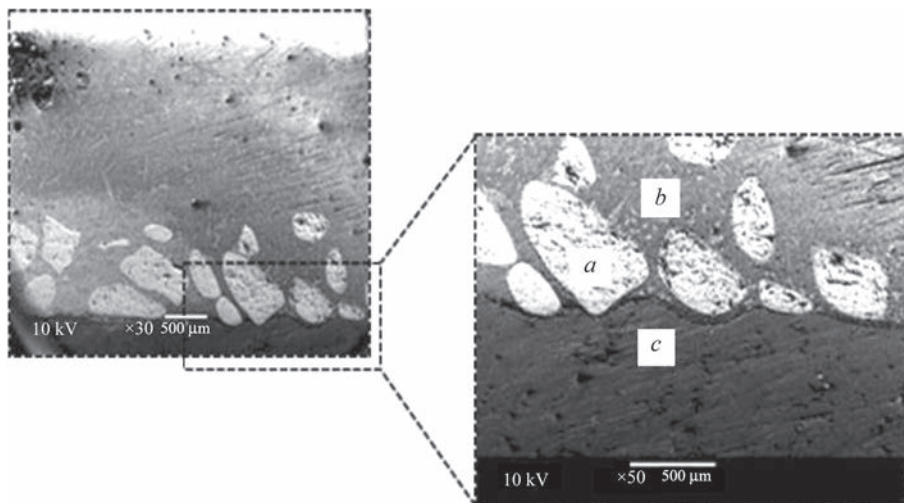
terial (Table 5) with a high hardness has excellent wear- and corrosion resistance, which is suitable for application in an abrasive medium.

The surfaced sample structure (Figure 9) has three main zones: carbide (*a*), non-carbide matrix (*b*) and substrate (*c*). Carbides of different size in the coating area are concentrated in the coating lower part on the coating-substrate interface at the depth of approximately 1 mm.

Researchers determined that base material treatment ensures sufficient thermal energy, which promotes greater growth of the carbide phases in the entire coating area with uniform distribution of smaller carbide particles in the non-carbide area. The carbide area demonstrates a higher hardness value (1795 *HV*), than does the non-carbide area (814 *HV*) [14]. The non-carbide zone consists of W and Fe, which points to a close arrangement of the carbide and the binder. Prior heat treatment of the base material envisages a uniform distribution of the WC carbide phases over the coating surface, which may improve the coating hardness and increase the wear resistance and the service life of the surfaced blade edge.

To prevent excess wear of the coating, the research is mainly focused on studying and determining the materials resistant to abrasion. To study the mechanism of wear of a roller cutter drill bit the hard alloy wear-resistant coating was deposited on the drill teeth [15]. Investigations showed that the microstructure can be conditionally divided into three zones: coating (zone A), transition zone (B) and body of the tooth base (C). Figure 10 shows the microstructure of the sample and the interface between the tooth body and a mixed zone after carbide coating deposition on the tooth by the melting method.

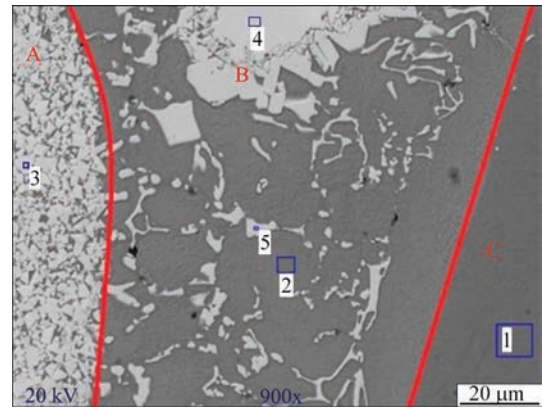
It is shown that the carbide coating contains the following components: WC granules of 100–300 µm size, held together by a cobalt binder; polycrystalline

**Figure 9.** Surfaced sample microstructure: carbide zone (*a*), non-carbide zone (*b*) substrate (*c*) [14]

WC of 10–100 μm size with a binder, which joins the WC granules and polycrystals based on Co and Fe (matrix), and also contains WC nanoparticles of 0.06–0.25 μm size. Zone 2 (Figure 10) shows that this is steel with an increased content of Mn, Co and W (Table 6), which entered the transition zone from the carbide coating based on a cobalt alloy, in which the tungsten carbide particles are distributed. Analysis of zones 3 and 5 confirms it.

Results of Vickers microhardness tests showed that the average hardness of the tooth base is 328 HV, whereas the hardness of the carbide coating of the tooth will be much higher, up to 2200 HV (1667 on average) [15].

At present the new methods of repair of the worn areas of the drill bits with deposition of a wear-resistant coating allow effectively solving a number of problems on wear of the blades and bodies under the conditions of hydroabrasive wear, corrosion, etc. In order to study the wear-resistant protective coatings under the conditions of hydroabrasive wear, composite materials containing tungsten carbides on different bases were selected, namely nickel-based TeroCote 7888T (Castolin), iron-based Relit “LZ-117” (Ukraine) and Diamax M (Castolin) [16]. The deposition of the layers on the test samples made from St. 45 was performed by nonconsumable tungsten electrode arc method in commercial grade argon as the shielding gas. Microsections with the deposited layer were prepared to determine the microstructure. Metallographic studies showed that the deposited layer and the base metal are connected by a thin transition layer of diffusion origin, indicating that the base metal sur-



**Figure 10.** Tooth microstructure: 1 — substrate (tooth base steel); 2 — WC matrix of the coating in the transition zone; 3 — WC; 4 — WC in the transition zone; 5 — WC in the transition zone; zones: A — coating; B — transition zone (mixing zone); C — substrate (tooth body) [15]

face melting and the filler metal dissolution in it did not take place (Figure 11).

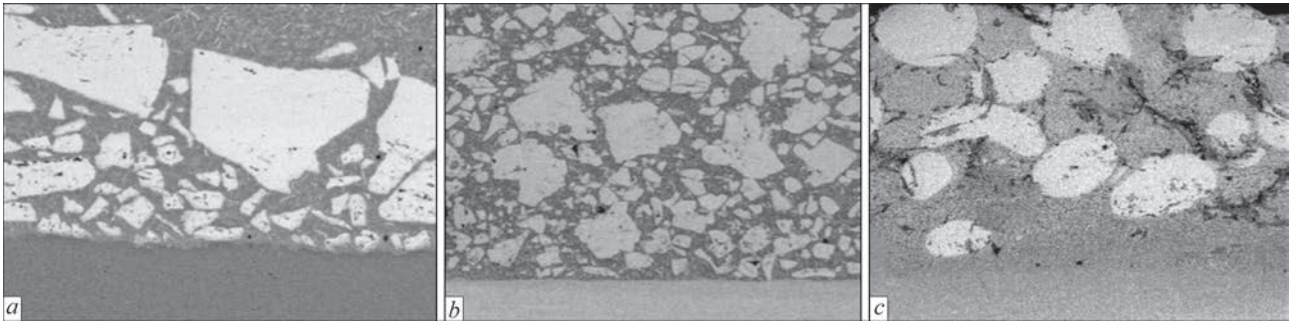
Results of hardness tests (HRC) of the deposited layers showed that at surfacing the St. 45 steel (standard) using Diamax M and Relit “LZ-11-7” filler materials, the coating hardness is on average by 15–20 % higher than when TeroCote 7888T is used [16]. Wear-resistance tests revealed that the hydroabrasive wear resistance of TeroCote 7888T nickel-based corrosion-resistant protective coating with crushed particles of tungsten carbide exceeds the wear resistance of iron-based Relit “LZ-11-7” (spherical granules of tungsten carbide) and Diamax M (crushed particles of tungsten carbide 1.5 and 2.0 times, respectively) [16]. Figure 12 shows average values of wear of the depos-

**Table 6.** Elemental composition of material in different areas of the tooth [15]

Element	Location								
	Error	1		Error	2		Error	3	
		Concentration			Concentration			Concentration	
		at.%	wt.%		at.%	wt.%		at.%	wt.%
Si	0.403	0.497	0.250	–	–	–	–	–	–
Mn	0.431	0.347	0.342	1.031	2.445	2.244	–	–	–
Fe	6.218	95.876	95.958	5.772	90.158	84.128	0.594	2.913	0.903
Ni	0.944	3.279	3.450	0.494	0.958	0.940	–	–	–
Co	–	–	–	1.055	3.397	3.345	–	–	–
W	–	–	–	1.566	3.014	9.343	2.627	97.087	99.097

**Table 6. Cont.**

Element	Location					
	Error	4		Error	5	
		Concentration			Concentration	
		at.%	wt.%		at.%	wt.%
Si	–	–	–	–	–	–
Mn	–	–	–	0.778	2.503	1.284
Fe	–	–	–	3.462	55.166	28.772
Ni	–	–	–	–	–	–
Co	–	–	–	0.678	2.345	1.291
W	5.563	100.0	100.0	2.196	39.986	68.653



**Figure 11.** Microstructure ( $\times 100$ ) of the metal of coatings produced using the following filler materials: TeroCote 7888T (a); Diamax M (b); Relit “LZ-11-7” (c) [16]

ited layer of composite alloys during hydroabrasive wear depending on the friction path.

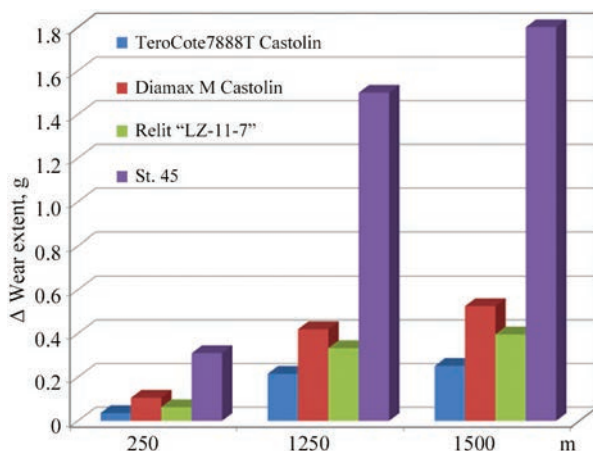
Based on the results of investigations of hydroabrasive wear of the composite materials, the best result was shown by the Tero-Cote 7888T corrosion-resistant composite (Castolin). Corrosion-resistance studies of the metal with the deposited layer of Tero-Cote 7888T were conducted under the laboratory conditions, which simulate the drill bit operation during drilling of the well (temperature, chemical composition, presence of wear, etc.). Results of the conducted studies showed [17] that application of the protective coating deposited using Tero-Cote 7888T allows lowering the corrosion rate of the drill tool working parts from 30Kh steel almost 35 times, which will promote extension of its service life.

Proceeding from the investigation results [16, 17] it was determined that during surfacing by the TIG method using Tero-Cote 7888T, a uniform distribution of the tungsten carbide particles through the entire volume of the deposited layer takes place during the deposited layer formation, which leads to a uniform hardness distribution by the coating depth.

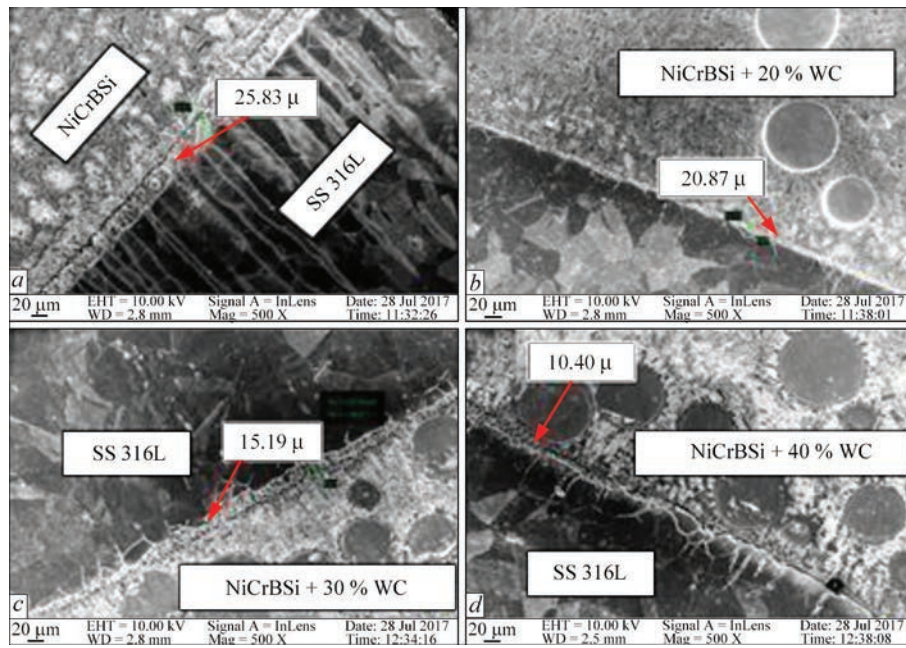
Previous works report on the manufacture of NiCrBSi–WC composite coating by different methods and its mechanical properties. None of the works, however, gives any data on the hardness, phase

structure analysis or cross-sectional morphology of NiCrBSi and NiCrBSi–WC composite. No studies of the influence of WC particles on the thickness of the interface of NiCrBSi–WC composites have been performed, either. In [18] the influence of different weight percentage of WC particles on the thickness of the interface of NiCrBSi–WC composites and its characteristics in case of friction wear were studied. NiCrBSi alloy in the initial state and NiCrBSi alloy reinforced by different weight content (20, 30 and 40 %) of tungsten carbide (WC), were deposited on 316L stainless steel using the process of plasma transferred arc welding (PTAW). Austenitic stainless steel 316L (SS-316L) with plate size of  $50 \times 50 \times 30$  mm was used as the substrate for deposition. The samples were made with 4 mm average thickness of the coating, using a two-pass arc welding process. Before the surfacing process the SS 316 L substrates were first heated to  $400^\circ\text{C}$  to reduce the probability of hot cracking, and after surfacing the samples were cooled naturally. The cross-sectional microstructures of NiCrBSi and NiCrBSi–WC coatings demonstrate the structure of equiaxed austenite grains (Figure 13).

According to the cross-sectional microstructure studies, the NiCrBSi–WC composites demonstrate dispersion of spheroidal WC particles in the NiCrBSi matrix. Presence of parallel lines on the substrate points to banding of grains formed during PTAW. The austenite grain boundaries are distinguished as long grains between the component phases. More over, recrystallized grains of a larger size formed on the interface of NiCrBSi and NiCrBSi–WC composites. The austenite grain boundaries are outlined by an alloy of chromium and iron carbides with the base metal oxides. The interface is observed as a clearly defined zone with intermetallic elements, formed by NiCrBSi and SS 316 L components. The hardness of NiCrBSi composites increases significantly with increase of the quantity of WC particles due to smaller dissolution of WC particles relative to NiCrBSi. For NiCrBSi-(20 %) WC composites better wear properties were obtained compared to other composites [18].



**Figure 12.** Wear of the deposited layer of composite materials and St. 45 [16]



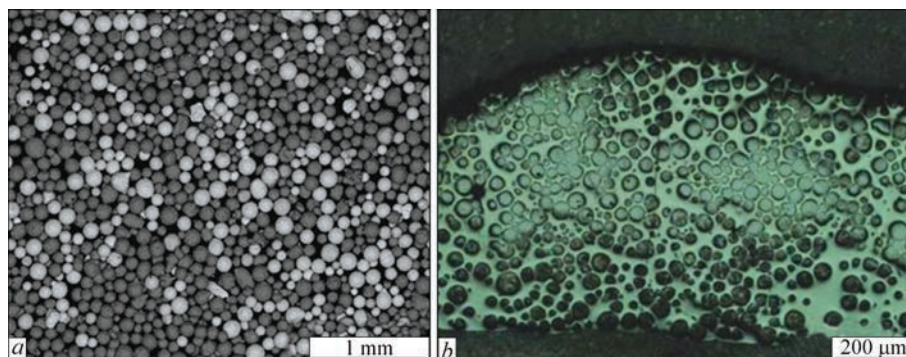
**Figure 13.** Image of the cross-section of the following composites: NiCrBSi (a); NiCrBSi–(20 %) WC (b); NiCrBSi–(30 %) WC (c); NiCrBSi–(40 %) WC (d) [18]

### MODERN DEVELOPMENTS IN COATING DEPOSITION BY LASER SURFACING METHOD

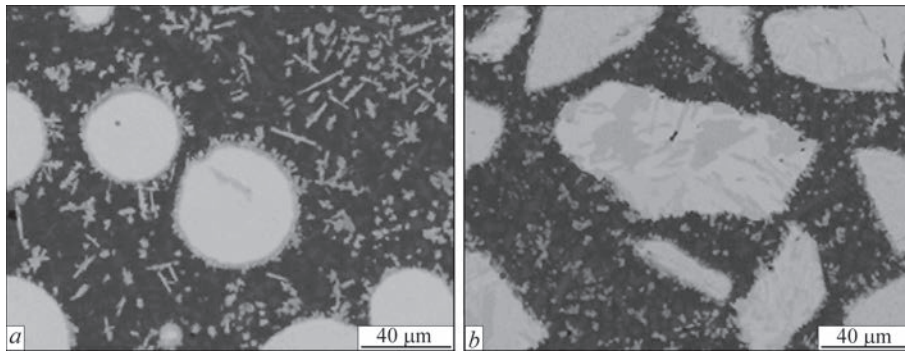
The literature most often reports on the following coating methods: welding (manual arc, consumable and non-consumable electrode), plasma, thermal, flame surfacing, etc. Unlike the traditional coating methods, the laser surfacing method provides a metallurgical bond with the substrate and its minimal remelting. There exist many publications, where the authors describe the metal-matrix composite coatings (MCC). Due to the presence of hard carbide particles, such as WC, VC, etc. the MCC have much better wear resistance. The microstructure of this type of coatings is similar to that of sintered materials. Up to now the majority of the studies were focused on manufacture of Fe- or Ni-based MCC. A smaller number of papers, however, present manufacturing the MCC from Co-based alloys, in particular from Stellite-6 alloy. Paper [19] presents the properties of wear-resistant coatings applied on steel by laser surfacing method by pow-

der technology. Low-carbon steel sheet of 20×20×5 mm size was used as the substrate. Stellite-6 spherical powder with average particle size of 50 μm was applied as the coating material. The Stellite-6/WC powder mixture was blown into the melt pool by the carrier-gas (helium). The powderlike mixture particles had the size of 25–125 μm and a spherical shape (Figure 14, a).

The microstructure of the composite coating of Stellite-6 metal matrix, reinforced by tungsten carbide particles, is shown in Figure 14, b. A very large quantity of the tungsten carbide particles in Stellite-6 matrix was found. The carbides did not melt, and the produced coating had a microstructure similar to that of sintered carbides. A non-uniform distribution of the carbide particles was observed (Figure 14, a). One can see that the two powders mixed poorly. This, probably, affected the coating microstructure. A characteristic feature of all the composite coatings is the dendrite microsegregation, which is a result of different cooling rates, and, hence, different crystallization of the matrix in the coating cross-section [19]. The



**Figure 14.** Coating structure: shape and size of powder mixture particles (a); Stellite-6/WC produced using a 550 W laser beam with scanning speed of 400 mm/min (b) [19]



**Figure 15.** Microstructure of coatings produced by laser surfacing using spherical (a) or irregularly-shaped (b) tungsten carbides, with Ni + 60 wt.% alloy [20]

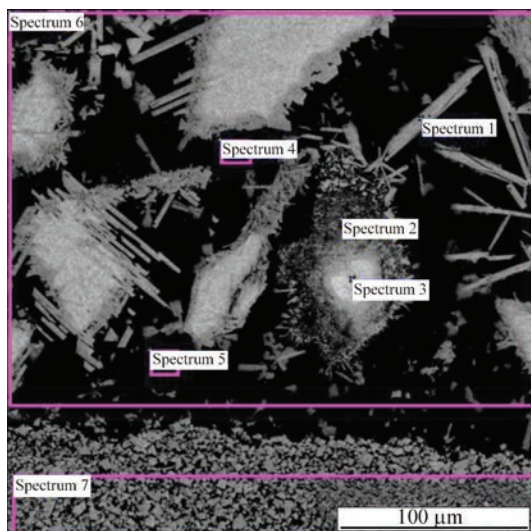
differences in the matrix microstructure are the most noticeable around the tungsten carbides, as well as on the interface between the coating and the steel substrate. It is shown that the presence of WC particles in Stellite-6 matrix has a positive effect on the mechanical properties, but it has a negative impact on the corrosion resistance of the produced surface layers, compared to the non-reinforced coating. X-ray phase analysis confirmed the presence of the hard phases ( $WC$ ,  $W_2C$ ,  $M_7C_3$  and  $M_{23}C_6$ ) in the matrix, which influence the significant increase in the coating microhardness. Hardness measurement within the coating matrix showed that the coating material is characterized by the same hardness (close to  $700 HV$ ), and the WC particle hardness is  $2500 HV$  [19].

The wear-resistant coatings deposited with the laser, can consist of different types of tungsten carbides (spherical and crushed), added to the NiCrBSiCFe metal matrix [20]. With optimal process parameters a coating 0.85–1 mm thick without cracks is produced, which has excellent adhesion to the substrate, up to 60 wt.% carbide content and 40–55 HRC hardness. Microstructural study of the coating demonstrates the

presence of spherical or crushed tungsten carbides and dispersed phases in the metal matrix (Figure 15).

The coating microstructure shows that the carbide particles partially dissolve around the perimeter, and the carbide phase forms around them, growing into the metal matrix. The structure of the crushed carbide powder consists of  $WC$  needles in the  $W_2C$  matrix. As regards the wear resistance, it is shown that the  $W_2C$  phase is harder, but it is also more brittle than the  $WC$  phase [20]. Moreover, the  $W_2C$  phase more readily dissolves in the metal matrix during laser surfacing than does the  $WC$  phase. A higher degree of tungsten carbide dissolution in the metal matrix is harmful for two reasons: it leads to lowering of the matrix strength and, as a result, to high susceptibility to cracking during surfacing, as well as to a loss of service properties of the ceramics as the reinforcing phase. With optimal parameters of laser surfacing, a certain dissolution of the tungsten carbide particles in the nickel-based matrix takes place, which causes formation of finely-dispersed mixed carbides in the metal matrix and increase in the carbide phase in the metal matrix around the primary carbides.

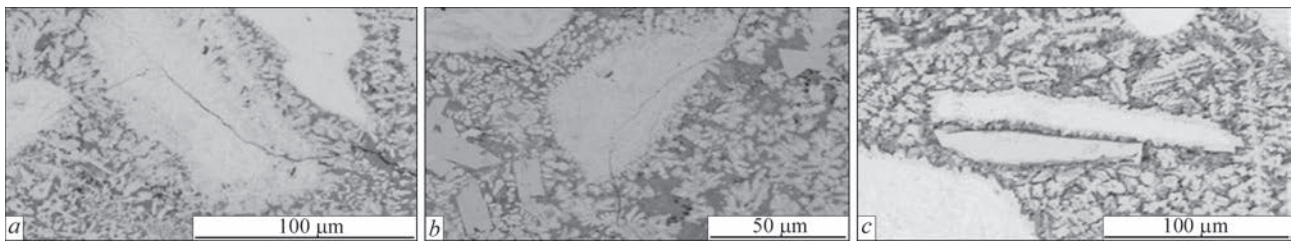
Such features of the coating structure formation were observed at application of TeroCote 7888T abrasive material (Castolin), which is a nickel core, coated by a composites self-fluxing alloy. The latter contains a large quantity of chipped tungsten carbides of an irregular shape, distributed in the nickel-based alloy matrix (Ni–Cr–B–Si system) [21]. The deposited layer structure consists of tungsten carbide particles of an irregular geometric shape and different sizes, which are distributed in the nickel-chromium matrix. Moreover, inclusions of a needlelike phase are observed, which precipitates in the form of dispersed particles around the perimeter of the tungsten carbides (Figure 16). This



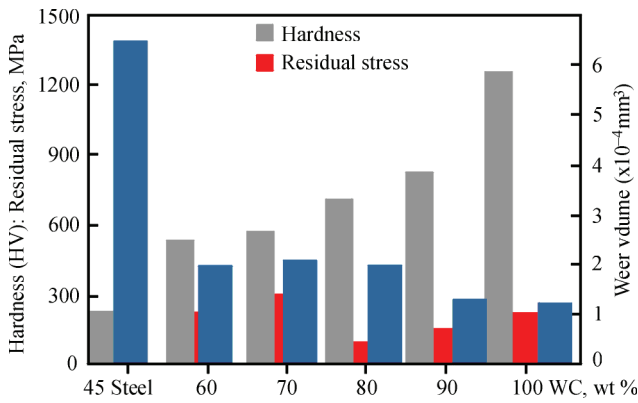
**Figure 16.** Microstructure of TeroCote 7888T layer deposited on VK10 alloy [21]

**Table 7.** Analysis of Co ratios for WC mixtures [22]

Symbol	Element weight, %				
WC	100	90	80	70	60
Co	0	10	20	30	40



**Figure 17.** Microstructural evolution of the coatings: 100 % WC (a), 80 % WC–20 % Co (b) and 60 % WC–40 % Co (c) [22]



**Figure 18.** Results of measuring the wear volume, hardness and residual stresses in the cladding layer with different WC compositions [22]

is indicative of the presence of diffusion processes during heating and of the matrix interaction with the tungsten carbides and their partial dissolution.

Paper [22] gives the results of studying the mechanical properties of the coatings with different percentage of Co and WC additives. A coating with different weight content of Co additive in powdered WC was applied onto metal samples from steel 45 by laser surfacing. WC/Co powder mixtures consisted of powders of WC and Co alloys with 0.125 up to 0.300 mm particle size. Table 7 shows the mixture proportions: 100 % WC; 90 % WC–10 % Co; 80 % WC–20 % Co; 70 % WC–30 % Co and 60 % WC–40 % Co.

Results of microstructural studies of the coatings (Figure 17) show that the high residual stresses cause considerable cracking in 100 % WC, while the cracking activity decreases at addition of 20 % cobalt to WC.

The coating zone microstructure mainly consists of rod-like dendrites and finer eutectic at 100 % WC, while the coating zone at 60 % WC–40 % Co mainly contains austenitic dendrites and block-like carbides. Figure 18 shows the histograms of hardness, wear volume and residual stresses in samples produced with different quantity of Co in the WC.

Finally, increase of the quantity of Co in the WC did not lead to reduction of the residual stresses, because of a smaller quantity of brittle carbide. The microhardness of the surfaced layer with the laser coating at 80 % WC–20 % Co is higher by 850 HV, than that of the substrate of 221 HV [22]. On the whole, the optimal effectiveness of laser deposits is reached with success using a composition of 80 % WC, mixed with 20 % Co.

## CONCLUSIONS

Different methods (flame, arc, laser surfacing, thermal spraying) are considered for producing composite wear-resistant coatings, operating in an abrasive environment and enhancing the operational properties of the products. A structure of composite coatings based on Co, Ni, Fe, Cu, NiCrBSi, NiCrBSiFe with different ratio of the tungsten carbides was produced. It is shown that the mechanical properties of the coating are improved with reduction of the ratio of the quantity of  $W_2C$  WC and  $WC_{1-x}$  phases in the eutectic alloy of WC– $W_2C$  system. The technological characteristics of wear-resistant coatings are given, which depend on the parameters of the technological process of their deposition. Investigations are currently underway to improve and enhance the functional properties of wear-resistant coatings.

The results of the conducted studies may be useful for scientists and engineering personnel of enterprises engaged in enhancing the performance of structures for various purposes.

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#### CONFLICT OF INTEREST

The Authors declare no conflict of interest

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