

**ELECTRON BEAM TECHNOLOGY FOR DETAILS STRENGTHENING
FOR STEEL INDUSTRY**

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Abstract

The present paper is focused on the advanced deposition technologies, such as electron-beam surfacing in vacuum. Modern electron beam surfacing equipment «LUNa-10» has been developed for iron and steel industry. The present paper contains investigation of properties of composite coatings for different part of metallurgy equipment.

Key words: *electron-beam surfacing in vacuum, composite coatings, metallurgical*

1. INTRODUCTION

Progress in the newest technologies and modern mechanical engineering including ferrous metallurgy is related with wide application in practice of advanced methods of development materials with specified properties and all-round studying of their functional characteristics. Unconventional technologies of materials structure and properties modification of based on processing of details surface by concentrated energy flows (CEF) are actively developed. Laser emission, powerful (high-current) ion beams, high-temperature pulse flows, electron beams are used as CEF. In doing so, extreme conditions of the behavior of thermal physical and micro-metallurgical processes causing formation of a structure-phase state and material properties can be achieved, which never can reach by traditional ways for their obtaining and processing [1]. It is well-known that in metallurgy industry a significant part of the production cost makes expenses for repair of units, the replaceable equipment and spare parts. Thus, the problem of increase of wear resistance of high-wearing details of metallurgical units working under severe conditions: heating, stresses, corrosive medium and other hostilities is the most actual.

So, for example, the major problem in ferrous metallurgy is instability of the blast furnace tuyers subjected to high thermal loadings at the cast iron manufacture. The analysis of tuyer damage reasons and an experience of their operation in blast furnaces at the West-Siberian metallurgical complex has shown that about 50 % of blast furnace idle time occurred because of short service life of tuyers due to an abrasive wear of the top row of tuyers, burning-out (small fracture of the bottom row of tuyers), manufacturing defects, basically, in the field of welded joints. Plural attempts of strengthening coatings deposition by means of plasma metallization, gas-flame spraying have not led to positive results because after short operation of tuyers the coatings were delaminated. Also, there is a critical problem of increase of the copper walls wear resistance of the crystallizer of continuous-casting machines (CCM). The copper having high heat conductivity provides fast formation of a metal crust on a surface of a formed ingot. There is a significant abrasive wear of copper leading change of initial geometry of a crystallizer in the zone of surfaces interaction when metal is going through a crystallizer. Having passed 4-8 cycles of use, after mechanical treatment, copper walls are utilized. In connection with high prices of the copper attempts of reduction of its specific consumption counting upon ton of the melted steel by use of wear resistant types of copper alloys, copper hardening by

means of cold deformation, nickel and chromium plating of a surface of a copper crystallizer, etc. are undertaken. However, such ways of hardening are expensive labour-consuming, and significant temperature gradients in the crystallizers caused by water cooling and mechanical loadings bring to delamination of deposited coatings.

2. FEATURES OF THE TECHNOLOGICAL PROCESS OF THE ELECTRON BEAM FACING IN VACUUM

One of the most perspective directions on increase of steel products durability (forming rolls, exhausters's blades, etc.) and copper products for the metallurgical equipment (tuyers of the blast-furnace production, walls of crystallizers for steel continuous casting) is an application of the electron beam facing (EBF) technology in vacuum for deposition of strengthening coatings on their surface. Coatings formation with necessary structure and properties is provided owing to advantages of the given technology – simplicity, high stability and reliability of electromagnetic scanning system of an electron beam, an opportunity of flexible management due to change of its parameters, wastelessness and an ecological process. By means of EBF technology depending on facing modes, it is possible to realize processes both powder metallurgy and micrometallurgy in an electron beam directly on a detail. Surfacing material is delivered by the powder dispenser into a molten pool taking place on a surface being strengthened by an electron beam. High speed of crystallization promotes forming homogeneous fine-dispersed structure of a deposited layer.

The technology of multi-pass electron beam facing is based on the effect of the concentration of electron beam energy in the micro-volume of molten pool of deposited product. Electron beam scanning along base lines allows a beam repeatedly with frequency of 400 Hz to influence on micro-volume of a molten pool up to the end of the melting process of a metal powder component submitted to a fusion zone and averaging of phase structure of a molten pool micro-volume.

Disperse-strengthened coatings with a metal matrix based on high-melting wear-resistant compositions (carbides, nitrides, carbonitride, borides) are most demanded for a spreading of constructional application spectrum under conditions of high loading operation. In this case the molten pool with a high-melting component which is not under influence of an electron beam owing to replacing a fusion zone has the high speed of crystallization because of significant heat removal from the molten pool in the volume of a deposited product. And a strengthening high-melting component being simultaneously the center of the crystallization has no time to interact with a melt. Thus, wear-resistant composite coatings with a high level of physicomechanical characteristics are formed on a product surface. Necessary thickness of a deposited layer (0.5-3 mm) is reached due to change of the feed rate of a fusible material or increase in number of passes [2]. EBF technology feature is that between a matrix and a coating an extensive transition zone (0.5-1.5 mm) is formed. Owing to that an opportunity of coatings delamination is excluded. The combination of facing process with the synthesis of a deposited material accompanied by an exothermal effect, also represents the specific interest. All of that makes EBF technology unique as by way of variety of functional properties of powder coatings, and by way of coverings deposition on parts of any alloys and any geometry.

3. THE DEVICE OF ELECTRON BEAM FACING INSTALLATION “LUNA-10”

The electron beam facing technology has been developed at the Institute of strength Physics and Material Sciences of the Siberian Branch of the Russian Academy of Sciences (ISPMS SB RAS). New modification of the electron beam installation – “LUNa-10” (fig. 1), intended for hardening a surface of units and mechanisms of the metallurgical equipment including large-sized products such as copper

crystallizers for steel continuous-casting was put into a practice in the public corporation “ZSMK” in March, 2006. Installation allows forming one- and multilayered coatings for various purposes (strengthening, wear resistant, heat resistant, etc.) on a surface of steel, cast-iron and copper products. It is possible to form coatings on flat surfaces of products (length up to 2100 mm, width – 900 mm, thickness – 200 mm) and bodies of rotation (diameter up to 600 mm and length – 2100 mm) with the help of the installation.

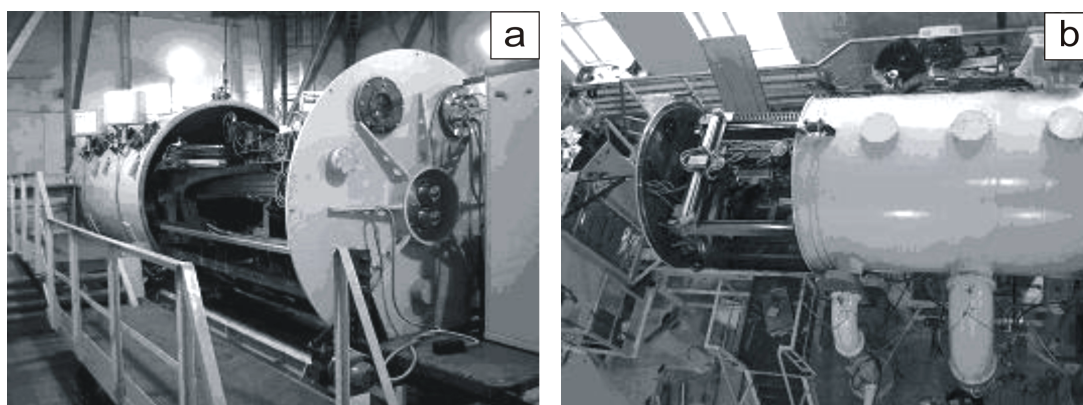


Fig. 1. The device of electron beam facing installation “LUNa-10”: a – side view; b – top view

Installation represents the vacuum electron beam automated system under the computer control. It is equipped by two electron guns that allows to carry out deposition of coatings on two products simultaneously and to raise productivity of the process (fig. 2). Electron guns (1) are inside of the vacuum chamber (2) and can move by means of the two-coordinate manipulator (3) above a surface of a deposited product (4) on the given trajectory set by the operator. Introduction of a deposited material into the melting zone is carried out through the dispenser (5) fixed on a gun. Installation also is equipped by two replaceable manipulators for deposition of coatings on tuyers.

The electron equipment of the installation represents two independent power supply systems of electron guns, control systems of manipulators and vacuum station. Such construction of electron systems allows providing high reliability and maintainability of the installation without long stops of manufacture.

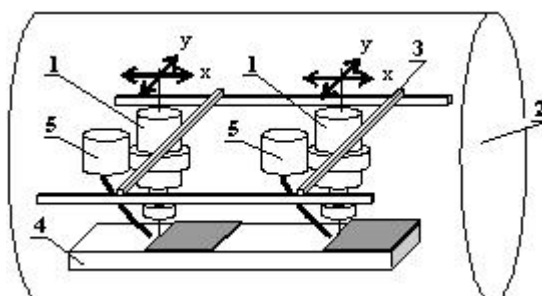


Fig. 2. The Scheme of a placement and movement of electron sources into the installation “LUNa-10”

Control of the installation is carried out by two consoles representing panel computers. The software of the consoles allows to control a vacuum system, manipulators, electron guns in an automatic mode, and to carry out automatic check of the elements providing the control of emergencies, such as power down, an emergency stop of pumps. Control of a technological cycle of coatings deposition and its modes is carried out by the consoles. Sources with the plasma emitter manufactured by public corporation "ELION" have been used for forming an electron beam. These sources do not contain getting hot electrodes and parts that makes to their less sensitive to chemically active and refractory vapor of the processed materials in comparison with thermo-cathodic ones. They are capable to work without application of special measures on the emitter protection in a wide range of pressure and under conditions of intensive gas emissions in a molten zone. At the same time sources with the plasma emitter have a high life-time, and relative to common technical characteristics and geometrical parameters of a beam are good as well as thermo-cathodic sources.

4. COATINGS ON COPPER PARTS OF THE METALLURGICAL EQUIPMENT PRODUCED BY EBF

In the work results of coatings research obtained by EBF technology on a surface of various details of the metallurgical equipment are presented. For obtaining coatings the powder nickel-chromium alloys and also composite powders based on high-melting borides, titanium carbonitrides with metal binder of various structures have been used. For formation of strengthening coatings on furnace tuyer throats the manufactured nickel-chromium alloys as well as composite powders on their basis with titanium and niobium carbides have been used. Appearance of a furnace tuyer throat with a coating strengthened by EBF is presented in figure 3.

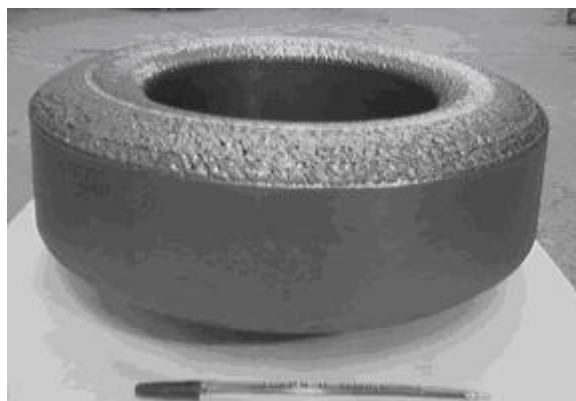


Fig. 3. Furnace tuyer throat strengthened by EBF

Fusion of composite powders was carried out at working pressure $P=10^{-1}$ Pa with a tuyer preheating by an electron beam up to 300°C. Required thickness (1.5-2 mm) of a coating was obtained by two passes (the quantity of passes depends on the rate of substrate replacing and submitted powder). During the process of coatings formation the temperature of a tuyer reached 500-600°C.

Metallographic and X-ray phase analyses of the coatings have shown that during the fusion the dendrite shaped structure of γ -solid solution based on the Ni with uniform distribution of microhardness in a depth of the deposited layer ($H\mu=5600-6500$ MPa) was generated. The structure of

coatings contains borides and carboborides $(\text{Cr}, \text{Ni})\text{B}_2$, $(\text{Cr}, \text{Ni})_5\text{B}_3$, carboboride eutectics like $\text{Me}_7(\text{CB})_3 + \gamma$, which content defines hardness and wear resistance of a deposited layer. In Fig. 4 the microstructure of the interface “substrate (copper tuyer) – coating (PGSR-4)” and the microstructure of a coating surface are presented.

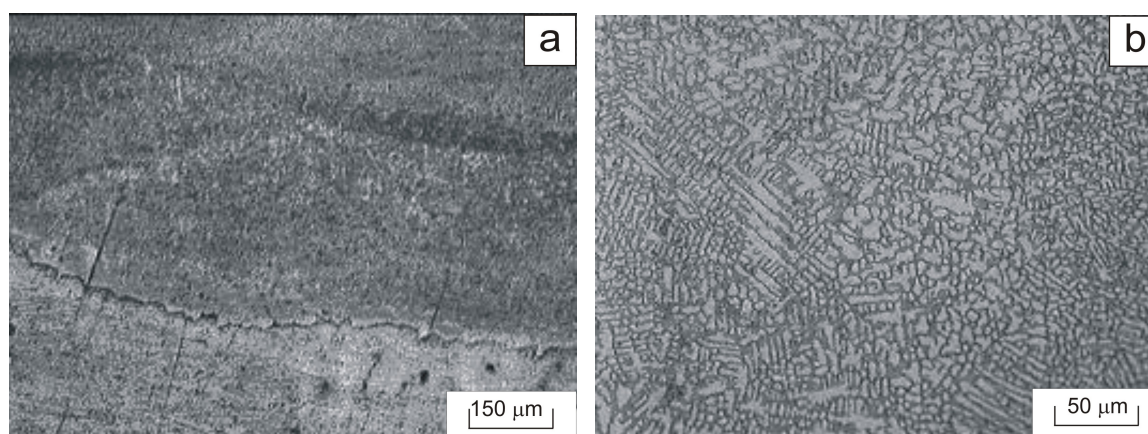


Fig. 4. Microstructure of EBF- coating of the alloy PGSR-4 on a surface of the copper tuyer (a- interface; b- surface coating)

Results of abrasive wearing test (State Standard 23.208-79) have shown that the factor of wear resistance of the EBF-coatings on the basis of Ni-Cr an alloy makes 5-6.7 K_w .

Now, EBF technology is successfully used in public corporation “ZSMK” for hardening furnace tuyer throats by an electron beam with usage of the installation LUNa-10” and allows to lower by a factor of ten their annual need.

Basic features of coatings deposition on massive (200 kg), "cold" surfaces having a big area (0.5 m^2) (crystallizers for steel continuous-casting) have demanded serious improvement of the equipment and additional technological researches. Thus, it was necessary to take into account that facing is conducted practically under condition of "an infinite thermal capacity» that demands an increase in density of a beam capacity in the zone of the electron beam and crystallizer interaction for obtaining a molten pool. This, in turn, should lead to local increase in the melting temperature of the copper exceeding the boiling one.

Owing to thermal losses in a melt formed under the effect of an electron beam on a massive crystallizer, only a part of the installed capacity is useful. The calculations resulted in the work [3] have shown that from thermal losses of a melt the most essential are capacity losses for radiation and copper evaporation. The maximal losses of capacity for evaporation do not exceed 100 Wt (q_s – the specific latent heat of fusion and q_v – the specific latent heat of evaporation were not considered) and the size of a molten pool liquid metal increases from 5 mm^2 (at heating of a crystallizer sample up to 200°C) up to 12 mm^2 (at the heating – up to 500°C).

Experimental researches and theoretical calculations have shown that under EBF in the zone of an electron beam interaction with the crystallizer surface, the area of overpressure of the order 3-5 atm. is formed that does not make it possible to use the classical scheme of this technology. In this case a part of the sprayed powder does not get to the molten pool and is rejected aside by copper particles flow evaporating from the surface of a molten pool and reducing operating ratio of a deposited material. To

avoid that, the complex technology including gas-flame sputtering of coatings with subsequent fusion by an electron beam has been developed for coating deposition. Ni-Cr-coatings reinforced with dispersed titanium and niobium carbides by thickness of 0.8 ± 0.2 mm were sputtered on a strengthened surface by gas-flame method, then, they were fused by an electron beam. As a result of application of the complex technology qualitative coatings free of defects and pores were formed with hardness $H_{\mu} = 4100\text{--}4500$ MPa. In doing so, there was no deformation of the copper matrix and coating cracking that, possibly, is connected with rather small thickness of the deposited strengthened layers and low thermal (structural) stresses in the system “substrate – coating”.

5. COMPOSITE COATINGS BASED ON THE TITANIUM BORIDES FOR HARDENING BLADES OF EXHAUSTER.

The technology for reconstruction of worn out machine and mechanism steel parts of the wide nomenclature (exhauster blades, face seal, forming rolls) and for hardening of new ones has been developed in ISPMS SB RAS. The chemical and phase composition of a coating was chosen in view of operating conditions of a concrete detail. So, hardening blades of exhauster (fig. 5) which are subjected to an intensive influence of an erosive, abrasive and impact character has been realized by deposition on their surface of composite coatings based on the titanium diborides (borides) by fusion of the mixture of thermoreacting powders FeB-FeTi, and also powders based on the (self-propagating high-temperature synthesis) SHS-composite ($\text{TiB}_2\text{-Fe}$) with a metal binder.

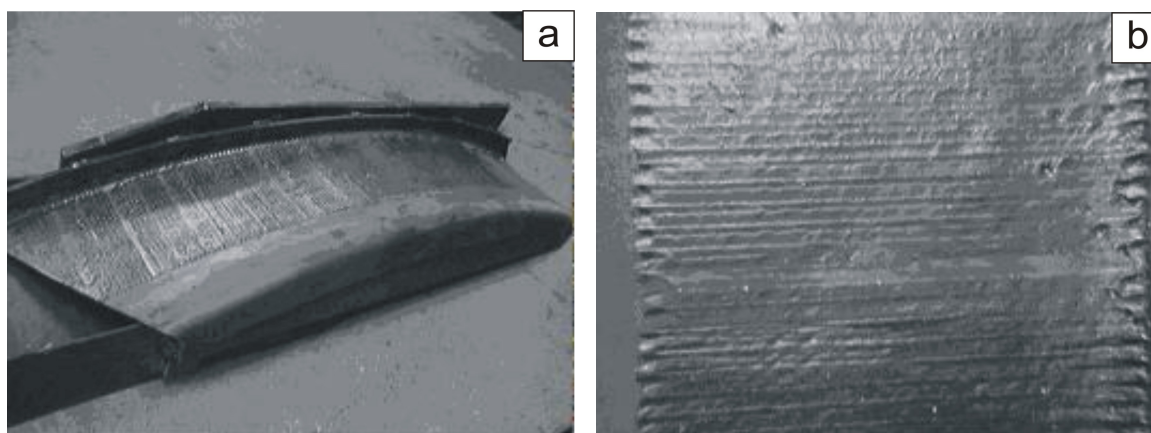


Fig. 5. Appearance (a) and a fragment (b) of the exhauster's blade after EBF

In figure 5, as an example, the microstructure of a coating formed by a mechanical mixture of powders $(\text{TiB}_2\text{-Fe})_{\text{SHS}}$ - PG-US-25 is resulted. The choice of structure of a metal binder of a fused powder based on the titanium diboride is caused by expediency of designing on its basis of coatings with a high-alloyed metal matrix. In this connection as a material of the binder the high-chromium alloy PG-US-25 known in mechanical engineering as a high wear-resistant constructional material has been used. The chemical composition of the powder PG-US-25 is presented in a table 1.

The chemical composition of high-chromium iron of the type PG-US-25

Table 1

Type of powder	Mass fraction of chemical elements, %							Hardness HRC
	C	Cr	Ni	Si	Fe	W	Mn	
PG-US-25	4.4-5.7	35-41	1.0-1.8	1.6-2.6	Base	-	to 2.5	33-35 HRB

Three variants of powders with the different content of the high-chromium alloy PG-US-25 (30, 50, 70 mass %) in a fused mixture have been prepared for electron beam facing. Concentration parities of initial components in the powder mixture $(\text{TiB}_2\text{-Fe})_{\text{SHS}}$ – PG-US-25 have been chosen experimentally with the purpose of obtaining optimum structures with the high level of hardness and wear resistance. Study of coatings structure has shown that under the facing as a result of the crystallization of a melt formed on the exhaustor surface with the powder $(\text{TiB}_2\text{-50\%Fe})\text{-70 \% PG-US-25}$ the metal binder of a coating is saturated by a lot of superfluous high melting combinations of titanium borides, chromium and titanium carbides (fig. 6).

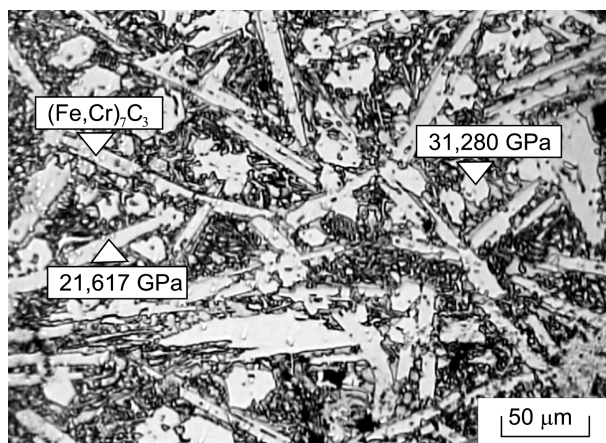


Fig. 6. Surface microstructure of the coating $(\text{TiB}_2\text{-50 \% Fe})\text{-70 mass \% PG-US-25}$

The metallographic analysis has shown that in case of the melt oversaturation with carbon in the combination with chromium and boron when the facing mixture contents 70 mass %. PG-US-25 has resulted during the facing in formation of the eutectic structure of a matrix. Values of microhardness in its various sites differ and are in a range ($H=6\div13$ GPa). Characteristic feature of the given structure is presence of carbides $(\text{Fe, Cr})_7\text{C}_3$ of thin needle-shaped plates having in width no more than 12 microns. Alongside with primary carbides $(\text{Fe, Cr})_7\text{C}_3$ and hardness $H=21\div27$ GPa, there also are carbide grains having rounded and six-sided form with raised hardness ($H=28\div37$ GPa) in the structure. Their size made 8-30 microns. It is established that under electron beam facing of the powder with the concentration ratio of initial components $(\text{TiB}_2\text{-Fe})_{\text{SHS}}$ – 70 mass % PG-US-25, the maximal values of hardness and wear resistance of coatings ($H_\mu=15\text{-}20$ GPa; $K_w=14.4$) are reached.

6. COMPOSITE COATINGS ON THE BASIS OF THE TITANIUM CARBONITRIDES FOR HARDENING FORMING ROLLS, FACE SEALS AND EXCAVATOR BUCKET CROWNS

Dispersed strengthened composite materials including bonding material and reinforcing solid particles of metalloceramics is of great interest in connection with a creation of hardening and wear-resistant coatings on a surface of metals and alloys which essentially increase service life of details at the normal and high temperatures. These materials represent heterogeneous system which is often characterized by thermodynamic instability which consequence is interfacial interaction of components during obtaining and operation of composite coatings, and occurrence of undesirable phases at the interface reducing the operating characteristics.

New surfacing composite materials in which as a strengthening phase has been chosen the titanium carbonitride with the equimolar composition ($\text{TiC}_{0.5}\text{N}_{0.5}$), having high thermodynamic stability and low factor of friction in comparison with carbides and nitrides of metals have been developed at the ISPMs SB RAS. The content of the titanium carbonitride in the sprayed charge was varied within the limits of 20-40 mass %. As a binder the nitrogenated chromium-manganese steel of austenite class CR20NMn20 (the content of nitrogen in a binder of a deposited composite made 0.4-0.8 mass %) and the martensite fast-cutting steel R6M5 [6] have been used. Composite powders have been obtained by a method of a self-extending high-temperature synthesis.

Research of coatings CR20NMn20+40 % $\text{TiC}_{0.5}\text{N}_{0.5}$ has shown that gradient structures with a variable chemical composition in the depth of a layer are formed during the electron beam facing. Actually the structure of a coating surface layer represents the duplex structure in which titanium carbonitride particles are in regular intervals distributed in an austenite matrix taking about half of the coating (fig. 7).

According to the micro- X-ray spectral analysis there are particles of a solid phase representing composition $\text{TiC}_{0.5}\text{N}_{0.5}$ and complex phases $(\text{Ti-Fe-Cr-Mn})\text{C}_x\text{N}_y$ in deposited coatings [5]. The given circumstance, probably, is caused by local high-energy influence of an electron beam therefore there is a partial disintegration of nonstoichiometric carbonitrides with formation of the complex structure containing Ti, Fe, Mn, Cr, N, C.

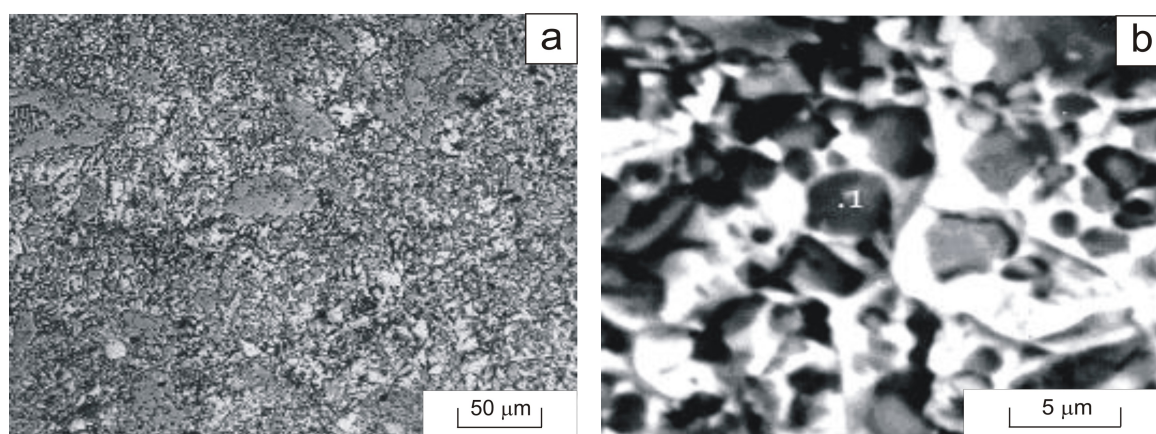


Fig. 7. Microstructure of EBF-coating CR20NMn20+40 % $\text{TiC}_{0.5}\text{N}_{0.5}$ after hardening:
dark segments (1) - $\text{TiC}_{0.5}\text{N}_{0.5}$; light segments – matrix

Microdurometric analysis (fig. 8) has shown that with growth of the titanium carbonitrides content the microhardness of a binder material (H_{μ}) increases that is caused with additional alloying of a solid solution by alloying elements of unstable carbides and nitrides which have dissolved under facing. The more titanium carbonitrides with nonstoichiometric structure is in a composite coating, the more an alloying degree of a melt.

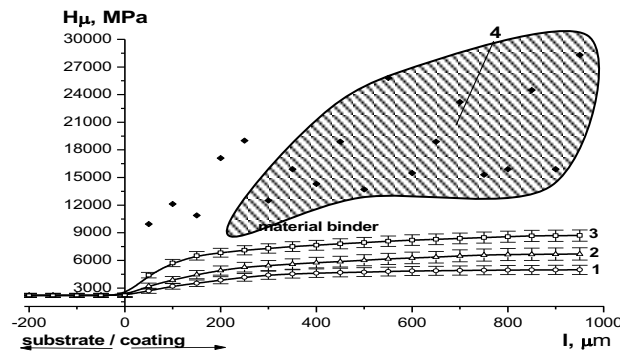


Fig. 8 Distribution of microhardness H_{μ} in transition region “low-carbon steel – EBF-coating”: 1 – CR20NMn20; 2 – CR20NMn20+20%TiCN; 3 – CR20NMn20+40%TiCN; 4 – field of the solid phase.

The hardness of a strengthening phase in coatings (the shaded area) is in a range 10000 - 28000 MPa. Such scattering values of a hardness is connected with formation during the facing of some solid solutions of the titanium carbonitrides of various stoichiometry and other complex structures based on the titan that proves by X-ray analysis of coatings phase compound.

Hardness and relative wear resistance of deposited coatings depending on the content of a solid phase are shown in table 2. From the table it is visible that with growth of a content of the titanium carbides (up to 40 wt %) increases both hardness and abrasive wear resistance of the coatings.

ABRASIVE WEAR RESISTANCE OF COATINGS

Table 2

Coating structure	Hardness, HRC	Relative wear resistance
Reference steel 45	130 HV	1.0
CR20NMn20	30	1.2
CR20NMn20+20%TiCN	41	3.2
CR20NMn20+40%TiCN	50	10.5

Composite coatings Cr20NMn20+40TiC_xN_y and R6M5+30%TiC_xN_y also have been used for hardening an experimental batch of bucket teeth of earth-moving technique manufactured by "Kamatsu". Coatings put on a forward part and lateral faces of a tooth. Thickness of a coating made ~2 mm. Excavator tooth made from steel SCM415H whose chemical composition is presented in table 3.

Chemical composition of steel SCM415H

Table 3

C, %	Si, %	Mn, %	Cr, %	Mo, %	Fe, %	S, %	P, %
0.13-0.18	0.15-0.35	0.60-0.85	0.90-1.20	0.15-0.30	Oct.	<0.030	<0.030

To have comparative data the given strengthened teeth of different structures have been simultaneously placed on one excavator bucket with a reference tooth (steel SCM415H). Natural tests of the tooth with coatings have been carried out within 82 hours for sand (SiO_2) and within 77 hours – for «clay + rocky ground» by machine RS200-6. The sizes of a rocky ground particles made 20~30 sm.

The full-scale test results demonstrate that the teeth with Cr20NMn20+40 % TiC_xN_y coatings are worn out 3.7 times less when operating in «clay + rocky ground» and 1.86 times less for sand (SiO_2) as compared to teeth without facing. These coatings have significant advantages over R6M5+30 of % TiC_xN_y working under conditions of the impact-abrasive wearing (fig. 9).

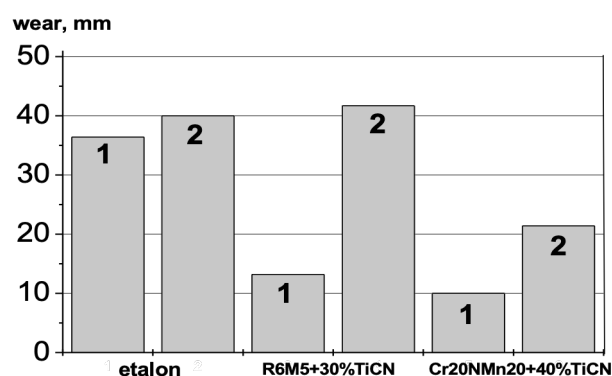


Fig. 9 Wear of excavator tooth crowns with EBF-coating working in different media: 1 – clay + rocky ground; 2 – sand (SiO_2).

The developed compounds of composite coatings with the titanium carbonitrides have been used for hardening forming rolls (fig. 10, a.), face seal (fig. 10, б.) and washers of tribodevices. Industrial tests in conditions of public corporation "ZSMK" have shown that service life of forming rolls and face seals with coatings R6M5-40%TiCN has increased by 3-6 times, and use of the strengthened washers of tribodevices of the rolling mill 450-2 has allowed to let out 27000 tons of rod without regrounding.

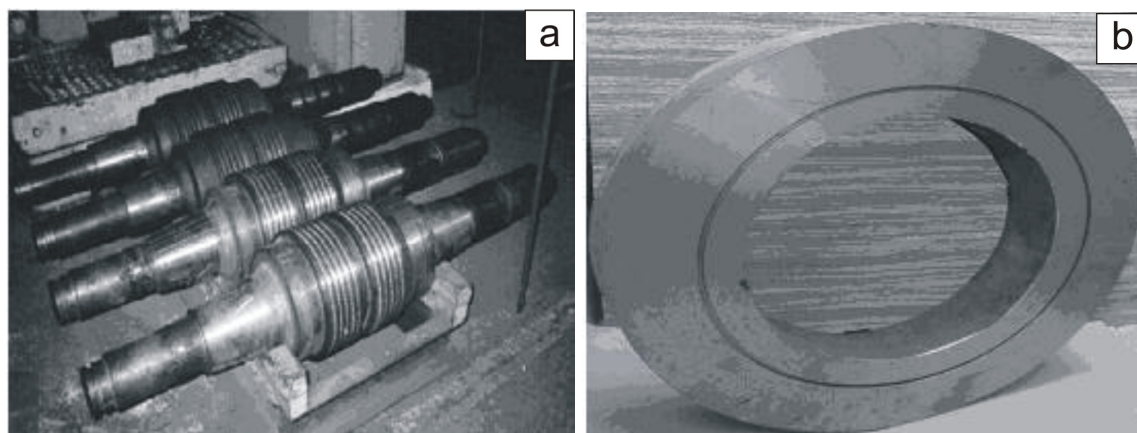


Fig. 10. Forming rolls (a) and face seals at the roller snips for metal cutting (b) with EBF-coatings R6M5-TiCN.

In the conclusion, one should notice, that resulted above methods of coating deposition are high technology to be constantly developed and improved. Experts of our institute are ready to cooperate in this direction with representatives of industries of any specialization, irrespective of patterns of ownership.

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