AS CARACTERÍSTICAS DA TECNOLOGIA DE PULVERIZAÇÃO DE DETONAÇÃO PARA REVESTIMENTOS À BASE DE CARBONETO DE TUNGSTÊNIO

THE FEATURES OF DETONATION SPRAYING TECHNOLOGY FOR TUNGSTEN CARBIDE BASED COATINGS

ОСОБЕННОСТИ ТЕХНОЛОГИИ ДЕТОНАЦИОННОГО НАПЫЛЕНИЯ ПОКРЫТИЙ НА ОСНОВЕ КАРБИДА ВОЛЬФРАМА

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RESUMO

Foi estudado o efeito de parâmetros chave do processo de pulverização de detonação em revestimentos à base de carboneto de tungstênio e suas propriedades mecânicas, microestrutura e composição de fase. Duas tarefas principais são resolvidas ao desenvolver a tecnologia para pulverizar os materiais contendo carbonetos. A relação é estabelecida entre a composição da fase dos revestimentos à base de tungstênio e sua resistência, dureza e aderência do substrato. Estabelecemos que a dissolução da CC na fase metálica promove o aumento da adesão do substrato, bem como a resistência e a dureza do material de revestimento. É proposto um procedimento de pulverização de revestimentos no modo de redução: isto é, utilizando misturas de gases de trabalho com excesso de acetileno. Impede a descarbonização de carbonetos de WC sob a ação de produtos de detonação e meio ambiente. A heterogeneidade da composição de fases (ambas junto com a espessura da camada e ao longo do diâmetro do ponto de pulverização) é estabelecida. Isso depende de um complexo de fatores que determinam a intensidade de remoção de calor da área de formação da camada. Para otimizar a estrutura e as características mecânicas do revestimento, precisamos controlar a descarbonização do componente de carboneto (WC) e a formação da solução sólida de α -Ni (W) em diferentes estágios de pulverização. Mesmo um desvio menor do conteúdo de carbono leva a uma aparência de grafite ou à formação da frágil fase ($\text{Co}_3\text{W}_3\text{C}$), reduzindo fortemente as propriedades mecânicas.

Palavras-chave: revestimentos de detonação, descarbonização, dissolução de carboneto na fase metálica, resistência de aderência de substrato, modo de pulverização de oxidação e redução, pulverização.

ABSTRACT

The authors studied the effect of key parameters of detonation spraying process on tungsten carbide-based coatings and their mechanical properties, microstructure, and phase composition. Two main tasks are solved when developing the technology for spraying the carbide-containing materials. The relationship is established between the phase composition of tungsten-based coatings and their strength, hardness, and substrate adhesion. It was established that the WC dissolution in the metal phase promotes the increase of substrate adhesion as well as strength and hardness of coating material. A procedure of spraying coatings in the reduction mode is proposed: i.e., using working gas mixtures with excess acetylene. It prevents the decarbonization of WC carbides under the action of detonation products and environment. The phase composition heterogeneity (both along with the layer thickness and along the spraying spot diameter) is established. This depends on a complex of factors that determine the intensity of heat removal from the area of layer formation. For optimizing the structure and the mechanical characteristics of the coating, we need to control decarbonization of carbide component (WC) and formation of α -Ni (W) solid solution at different stages of spraying. Even a minor departure from carbon content leads to either appearance of graphite or formation of

the fragile η' -phase ($\text{Co}_3\text{W}_3\text{C}$), thus strongly reducing the mechanical properties.

Keywords: *detonation coatings, decarbonization, carbide dissolution in the metal phase, substrate adhesion strength, oxidation and reduction spraying mode, spraying spot.*

АННОТАЦИЯ

Исследовано влияние основных параметров процесса детонационного напыления покрытий на основе карбида вольфрама, их механические свойства. Определены две главные задачи при разработке технологии нанесения карбидосодержащих материалов. Установлена взаимосвязь между фазовым составом покрытий на основе WC и их прочностью, твёрдостью и прочностью сцепления с подложкой. Установлено, что растворение WC в металлической фазе способствует повышению адгезии подложки, а также прочности и твердости материала покрытия. Предложена процедура напыления покрытий в режиме восстановления: использование газовых смесей с избытком ацетилена. Это предотвращает декарбонизацию карбидов WC под действием продуктов детонации и окружающей среды. Установлена неоднородность фазового состава (как по толщине слоя, так и по диаметру пятна распыления). Это зависит от комплекса факторов, определяющих интенсивность отвода тепла от зоны формирования слоя. Для оптимизации структуры и механических характеристик покрытия необходимо контролировать декарбонизацию карбидного компонента (WC) и образование твердого раствора $\alpha\text{-Ni (W)}$ на разных стадиях распыления. Даже незначительное отклонение от содержания углерода приводит либо к появлению графита, либо к образованию хрупкой η' -фазы ($\text{Co}_3\text{W}_3\text{C}$), что сильно снижает механические свойства.

Ключевые слова: *детонационные покрытия, обезуглероживание, растворение карбида в металлофазе, прочность сцепления с подложкой, окислительный и восстановительный режим напыления, пятно напыления.*

1. INTRODUCTION

The composition coatings based on tungsten carbide (WC) have got the most extensive distribution among those sprayed by the detonation method. The compositions of WC-Co or WC-Ni types are mainly used. The reason is that they ensure very high mechanical properties of the obtained coatings. Owing to the substantial hardness (up to 1300 HV5), such coatings demonstrate very high wear resistance. So they are extensively applied in the aircraft industry and shipbuilding, in the manufacturing of oil production equipment and other branches of machine building. The detonation coatings based on WC with cobalt or nickel have the highest substrate adhesion (up to 200-250 MPa) among the gas-thermal coatings. They are often used where the load on a working surface is of a dynamic character. Owing to high substrate adhesion, the WC-based compositions also serve as sublayers when applying coatings of other materials (Kazanin et al., 2018).

At detonation spraying the coating properties are determined not only by the energy parameters of sprayed particles (their velocity,

mass, temperature) but also by the structural and phase changes occurring in the sprayed material. These changes of the structural-phase states begin even during acceleration of powder particles, continue at the stage of their flying from the gun cut to the substrate surface and come to an end at the formation of the coating layer. There are many publications dealing with the investigation of regularities in variations of phase composition of coatings in the WC-Co and WC-Ni systems. The detonation coatings made of the BK-15, BK-20 and BK-8 powders in the form of a mechanical mixture of WC and Co were studied in the works of Shmyreva (Shmyreva, 1982; Kharlamov, 1985). It was determined that, under the action of high temperatures and oxidizing medium, monocarbide dissociates due to carbon oxidation according to the scheme $\text{WC} \rightarrow \text{W}_2\text{C} \rightarrow \text{W}$. In addition, the diffraction reflections of double carbides $\text{Co}_3\text{W}_3\text{C}$ and $\text{Co}_3\text{W}_9\text{C}_4$ as well as of intermetallic compound Co_7W_6 were revealed. In this case, the content of the above phases varied depending on the spraying modes (especially on the composition of working explosive gas mixture).

The intense processes of carbides decarbonization (down to get tungsten) also dealt

with the investigation of the phase composition of coatings derived from mechanical mixtures of BK type. In this regard, the use of mechanical mixtures as initial powders is least acceptable (Shmyreva, 1980; Shmyreva et al., 1980; Alfintseva et al., 1982). Tret'yakov (1962), Chaporova and Chernyavsky (1975) proposed that in sintered alloys there is a continuous framework (made of WC grains) in whose gaps a cementing metal is located. Apparently, this is the main feature of the mechanism of coating formation using a refractory compound with a metal binder. In this case, the properties of hard alloys of W-C-Co and W-C-Ni ternary systems depend on their structure and phase composition. Based on an analysis of the structural-phase transformations occurring when spraying powders obtained in different ways, it was established that the highest mechanical properties of coatings are achieved for those obtained from the powders prepared by spheroidization in a protective medium (Khamitsev et al., 1987).

In the present work, we investigated the effect of the most significant parameters of the process of detonation spraying (namely, the composition of working explosive mixture and the degree of detonation gun filling) on the character and intensity of structural-phase changes at the formation of coatings and, consequently, on their quality. Variation of the phase composition of coatings along the layer thickness and spraying spot diameter was also studied.

2. MATERIALS AND METHODS

The WC-based materials were sprayed using the "Ob" and "Plakart-D3" automatic detonation plants. Their construction makes it possible to vary over a wide range the composition of working explosive mixture and the degree of plant gun filling as well as other parameters of the spraying process. The plants are equipped with manipulators that provide rotation of the sprayed detail with different frequencies and reciprocating motion with different speeds. The spheroidized BH-20 powders (WC + 20% Ni) and BK-20 powders (WC + 20% Co) prepared according to the Technical Specifications TY 48-19-381-85 (producer the LLC "Technicord") were used as the starting powder materials. The mechanical properties of the obtained coatings were estimated from the substrate adhesion and strength of the coating material as well as by measuring the Vickers hardness (HV5). The

substrate adhesion (σ_{sa}) was determined using the pin method for a party of 5-7 samples (Figure 1). The bush and pin were made of steel C45E4 (EN 10027). The coating material strength was determined using a particular procedure for a sample party of 5-7 pieces (Figure 2).

After spraying a layer 0.5-0.6 mm thick onto a revolving sample, the coating was polished using a circular grinding machine, the outer diameter of the sample was measured at a junction between the left and right parts, and the coupling bolt was unscrewed. Then the coating was destroyed by a tensile testing machine. The strength of the coating material was determined from the ratio between the sample breaking strength and the area of ring cross-section of the coating layer.

The X-ray phase analysis of the starting powders and coatings was performed using an *ALRX'TRA* device (produced by Thermo Fisher Scientific, Switzerland) with a copper anode ($\text{Cu}_{K\alpha}$). The mode of taking X-ray patterns was as follows: 25 mA, 40 kW (1.0 kWA). The sizes of horizontal collimator gaps (limiting the vertical X-ray beam divergence) were 1.0 mm and 1.0 mm. The detector gaps (0.9 mm and 0.5 mm) limited the registered radiation, thus providing a resolution of $0.11^\circ 2\theta$ when registering the diffraction maxima. In the vertical direction, the beam was restricted by the Soller gaps (angular divergence of 1.5 deg). When taking X-ray patterns, we used a discrete mode of counter motion (with a pulse collecting time of 2 s per point).

The starting powder specimens were put into a standard cuvette until complete filling. The diffraction pattern was registered at the average recording speed (0.8 deg/min); this provided the required sensitivity. The coatings were studied directly from the surface as well as after polishing until the required depth.

To perform X-ray phase analysis, we used the program *Crystallographica Search-Match* Version 3, 1, 0, 0 Copyright © 1996-2008, Oxford Cryosystems (CSM 3.10) and the database of the reference X-ray patterns ICDDPDF-2 (2010). The search report was prepared using the CSM 3.10 program after choosing the reference X-ray patterns that described the phase composition of the studied materials in the most detail.

3. RESULTS AND DISCUSSION:

The practice of determining substrate adhesion of the WC-based coatings using pin

samples demonstrated that, as a rule, the separation occurs over the coating material near the end surface of the pin rather than over the substrate-coating interface (the cohesive separation) (Figure 3). This means that the weakest spot for coatings of the WC-Co and WC-Ni types in the "substrate-layer" system is just the coating. Therefore, when choosing the parameters of the spraying process, the emphasis should be placed upon obtaining a high-quality layer whose properties are maximally close to those of sintered hard alloys. A typical structure of a WC-based detonation coating (Figure 4) is very similar to the structure of sintered hard alloys. Despite the radical difference in the methods of obtaining, in this case, one can also observe the sufficiently uniform distribution of carbide grains in the metal component as well as the formation of WC solid solutions in Co or Ni (though to a lesser extent than at sintering). In this case, the dependence of mechanical properties on phase composition remains (Dmitriev et al., 2011; Orlov et al., 2003).

The closer the coating structure and phase composition come to those of sintered material (Figure 5), the higher have to be the strength of the layer itself and adhesive strength of engaging with the sprayed surface as well as hardness and other service properties. It is known that a two-phase structure composed of the γ -phase (representing a solid solution of WC in β -cobalt) and WC phase is the most favorable to sintered hard alloys of the WC-Co type (with respect to their mechanical properties) (Chaporova et al., 1959; Tret'yakov, 1976). However, for the ternary W-C-Co system, this two-phase region is very narrow, and obtaining of the mentioned structure is only provided by the stoichiometric content of carbon. Even a minor departure from carbon content ($\pm 0.07\%$ for the BK-15 alloys) leads to either appearance of graphite or formation of the fragile η' -phase ($\text{Co}_3\text{W}_3\text{C}$), thus strongly reducing the mechanical properties.

Under detonation spraying, when the heated powder particles are subject to oxidizing action of detonation products and ambient air, a coating formation, as a rule, occurs at carbon deficiency. Partial decomposition of monocarbide with the formation of complex carbide compounds takes place at the stage of acceleration and heating of particles inside the gun of the detonation plant. The decarbonization process persists during particles flying behind the gun cut and at coating formation on the substrate surface. Shown in Figure 6 is an X-ray pattern of

detonation coating made of the spheroidized BK-20 powder.

The detonation products may represent an oxidizing, neutral, or reduction medium depending on the composition of working the explosive gas mixture. In this case, the structural-phase changes in the sprayed material may flow in different ways (in particular, decomposition of monocarbide may continue with different intensity) (Gridina and Andreev, 2016).

To determine the degree of influence of the working mixture composition on the phase composition (and consequently on the mechanical characteristics of coatings), spraying was performed at stoichiometric ($\text{C}_2\text{H}_2:\text{O}_2 = 1.0:2.5$) and equimolar ($\text{C}_2\text{H}_2:\text{O}_2 = 1.0:1.0$) ratios of acetylene and oxygen, as well as at the $\text{C}_2\text{H}_2:\text{O}_2 = 1.2:1.0$ ratio, i.e., at possible formation of free carbon (carbon black). In the latter case, a reduction medium arises in the plant gun, and the spraying mode may be conventionally called the reduction mode. Usually the working mixtures close to the equimolar composition ($\text{C}_2\text{H}_2:\text{O}_2 = 1.0:1.05\text{--}1.15$) are used at the spraying of WC-based coatings. At such composition, the velocities of detonation wave and detonation products flow, as well as the degree of powder particles heating, are close to their maximum values. A small excess of oxygen in the mixture ensures reliable operation of the electric candle in the ignition chamber of the plant, thus preventing black carbon precipitation at the electrodes.

The construction of the detonation plants used by us makes it possible to spray coatings with the enriched acetylene mixtures with $\text{Q}_{\text{C}_2\text{H}_2}:\text{Q}_{\text{O}_2} = 1.2:1.0$, where Q is the gas consumption per cycle of plant operation. This is because, when filling the gun with working gases, a mixture that is locally enriched with oxygen is formed in the area of the candle. Table 1 presents the mechanical characteristics of coatings prepared from the spheroidized BH-20 powder at different compositions of the working explosive mixture. The degree of gun filling with the working mixture was the same (53%). One can see from Table 1 that spraying of coatings with the working mixtures enriched with acetylene makes it possible to profoundly improve their mechanical characteristics (especially substrate adhesion and strength of coating material).

The results of X-ray phase analysis of coatings obtained with the working mixtures of stoichiometric composition (oxidative mode) and those enriched with acetylene (reduction mode)

make it possible to explain the growth of strength characteristics by the corresponding structural-phase changes.

It is shown in Figures 7, 8, and 9 the X-ray patterns of the starting powder and coatings. Table 2 presents the results of quantitative analysis of the phase components and changes of the parameter "a" of the crystal lattice of a solid solution of tungsten in nickel based on the α -Ni phase (Fm3m). An appreciable difference in WC content and change of parameter "a" of nickel unit cell are well detected when comparing the phase compositions of powder and coatings. The increase of the parameter "a" indicates a degree of tungsten dissolution in nickel, while a distinction in WC content points to different intensities of monocarbide oxidation.

The degree of tungsten dissolution in nickel depends on the degree of powder particles melting at spraying, i.e., on the degree of their heating. To determine the dependence of the mechanical properties of coatings on the degree of heating of starting powder particles, spraying was performed with different degrees of gun filling with the working gas mixture. In this case, the ratio between the consumption of acetylene and oxygen ($Q_{C_2H_2} : Q_{O_2} = 1.2:1.0$) remained the same (reduction mode) (Table 2).

The results of investigating the mechanical properties of coatings are presented in Table 3. One can see from Table 3 that the mechanical characteristics of coating improve as the degree of powder particles melting increases. However, one should bear in mind that the intensity of monocarbide decomposition increases with temperature. As a result, the strength properties and hardness are disappearing. At the same time, the total coating hardness and strength may grow due both to increase of metal phase microhardness at the dissolution of the carbide component and reduction of the intensity of carbides decarbonization. Table 4 presents the data of quantitative X-ray phase analysis of the starting BH-20 powder and coatings obtained at 43% and 65% gun filling in the reduction mode of spraying. Table 5 presents the parameters of unit cells of the WC, W_2C , W, and tungsten solid solution in nickel α -Ni (W).

It should be noted that the process of $WC \rightarrow W_2C \rightarrow W$ decomposition may proceed either entirely (until tungsten formation) or partially (limiting to the appearance of W_2C). In the first case formation of the solid solutions α -Ni (W) is possible (Epicier et al., 1988; Kurlov and

Gusev, 2007; Tellgren et al., 1986; Yvon et al., 1968). This can lead to some decrease in hardness but may promote an increase in strength (Abe and Tanabe, 1985; Buschow et al., 1983; Dubrovinsky and Saxena, 1997; Suzuki et al., 1985). It seems that just this can explain a small hardness decrease for the coating sprayed in the reduction mode as compared with the hardness level for coating sprayed in the neutral mode (see Table 1). With a considerable quantity of W_2C in a coating, the total hardness may remain almost the same, but the strength decreases due to polycarbide fragility. Hence, when choosing the modes of the WC-based coating spraying process, the optimal combination of the factors (related to both mutual dissolution and WC decarbonization) is required (Fang et al., 2009; Litasov, 2010; Metcalfe, 1947; Schuster et al., 1976; Taylor, 1985).

A coating of spheroidized BH-20 powder was sprayed onto the stationary steel plates (size of 30x20x3 mm) to study phase composition in depth of the sprayed layer as well as along the diameter of the sprayed spot. Spot spraying was performed in practically the neutral ($Q_{C_2H_2}/Q_{O_2} = 1.0/1.05$) and reduction ($Q_{C_2H_2}/Q_{O_2} = 1.2/1.0$) modes. The degree of gun filling with the working gas mixture was 53%. A coating was sprayed by 150 shots of the detonation plant and shown in Figure 10 is the characteristic crater shape of a spraying spot. Such a spot profile is owing to the process modes, the granulometric composition of the starting powder and the features of its insertion into the gun of detonation plant. In this case, the maximum layer thickness was in the lower part of the spot and was equal to 0.55-0.6 mm. The spraying spot surface was conventionally divided into three areas (from the center to periphery): the central (5 mm from the center), upper and lower parts.

After obtaining a spraying spot, an X-ray phase analysis of the central part of its surface (called site 0) was performed. Because of the crater shape of the spot, X-ray exposure of the peripheral areas was problematic due to considerable alteration of the angles of reflection. Then the coating was subjected to triple polishing. A layer 0.15-0.2 mm thick was removed at each act of polishing. An X-ray phase analysis of the upper, central and lower surface areas of the spot was performed after each act of polishing, and then the average Vickers hardness was determined in each area (Chaporova et al., 1960; Kharlamov, 1978).

Table 6 presents the results of an

investigation of the phase composition of the coating and measuring its hardness along with the layer thickness and spot diameter in the neutral spraying mode. One can see from Table 6 that the phase composition and average hardness vary in both the layer thickness and in different parts of the sprayed spot. For instance, the content of the WC phase in the central part of the spot is maximum at the unpolished surface, decreases in the middle part of the layer and then again increases as the substrate is approached. It seems that such character of variation of monocarbide content may be explained by alteration of conditions of heat removal from the zone of coating formation as the layer thickness increases. The most intense heat removal occurs at the first shots through the substrate at the initial stage of spraying process when the zone of coating formation has not warmed up yet (site 3) as well as at the end of the process when heat supply into the zone of coating formation ceases, and cooling occurs mainly due to ambient air (site 0).

The average hardness in the upper part of the spraying spot is substantially less than in the central and lower parts; this trend remains after every act of polishing. Taking into account the form of spraying spot profile, one can conclude that at every shot of the detonation plant the most significant amount of heat transferred by the particles of sprayed powder comes to spot periphery (notably to its lower part). Correspondingly the process of coating cooling is going on slower in the above region. This affects the intensity of the $WC \rightarrow W_2C \rightarrow W$ oxidation process and formation of α -Ni (W) solid solutions. It should be noted that the α -Ni (W) content is the highest in the upper part of the spraying spot; this is noticed in all sites after polishing. At the same time, a difference in the WC phase content in different parts of the spot is not such considerable.

It seems that, at more intense cooling of coating in the upper part of the spot, formation of α -Ni (W) occurs more quickly than the monocarbide decomposition. A quantitative ratio between the forming phases determines the average level of hardness along the sprayed layer thickness as well as at the spraying spot areas.

At spot spraying in the reduction mode ($Q_{C_2H_2}/Q_{O_2} = 1.2/1.0$), the degree of heating of powder particles and their velocity somewhat decrease. When approaching the substrate surface, the lighter particles travel to the spot periphery owing to the gas flow. So the central

part of the spot is formed mostly by the big and medium particles. Some decrease of the temperature of powder particles may lead, on the one hand, to a drop of coating density, and, on the other hand (with allowance made for the presence of a reduction medium in the gun in a given spraying mode), to a decrease of intensity of WC decarbonization.

The results of the investigation of the phase composition of the coating and changing its hardness along the layer thickness and spot diameter in the reduction spraying mode are presented in Table 7. One can see from Table 7 that in the given spraying mode, the content of WC phase is considerably higher than in the neutral mode. This is observed over all spot areas and after every act of polishing. In addition to that, the content of α -Ni (W) solid solution is at approximately the same level (20-30%) in the neutral and reduction spraying modes. This seems to be owing to the solubility limit of tungsten in nickel.

When comparing the characteristics of coatings obtained in the neutral and reduction spraying modes, one can notice that they have the minimum hardness in the upper spot part. The maximum hardness of the coating sprayed in the neutral mode is achieved in the lower spot part. For the coating sprayed in the recovery mode, the central part is the hardest. It is evident that coating hardness depends on its phase composition which, in its turn, is determined by the rate and completeness of the phase transformations occurring at a given spot point at coating formation. A number of factors exert a complex impact on the proceedings of the given processes. These are as follows:

- the granulometric composition of the starting powder and the degree of heating of particles of different sizes in the gun of detonation plant;
- the chemical composition of detonation products of the working gas mixture and the characteristic of the medium in the gun (oxidizing, neutral, reduction);
- the mass of sprayed material that transfers heat into a defined area of the substrate surface at each shot;
- the distance from the point of surface hardness measurement to the spot geometric center;
- the operation rate of the detonation plant.

Because of a combination of the above factors, the coatings sprayed in the neutral mode have a higher hardness level in the middle and

lower spot parts. However, the coatings sprayed in the reduction mode have the higher inherent strength and substrate adhesion (see Table 1); this is determined by the phase composition in the spot central part. This may be explained by the considerably higher (more than double) content of the WC phase. Obviously, the minimum degree of monocarbide decomposition promotes the increase of the coating material strength. Taking into account the cohesive character of pin separation when determining substrate adhesion, one can also explain the higher σ_{sa} level at spraying in the reduction mode.

4. CONCLUSIONS:

1. When spraying the WC-based detonation coatings, their mechanical properties are determined by two main processes:

- carbide component dissolution in the metal phase; this promotes the increase of substrate adhesion as well as strength and hardness of coating material;
- decarbonization of carbides under the action of detonation products and environment; this exerts a negative influence on the coating quality.

2. To decrease the intensity of monocarbide decomposition, the spraying process should be realized in the reduction mode, i.e., using working gas mixtures with excess acetylene.

3. When spraying coatings onto a stationary substrate, the phase composition in the emerging spraying spot varies along both its thickness and diameter and depends on a complex of factors that determine the intensity of heat removal from the area of layer formation. The mechanical characteristics of coating in different spot areas and along the layer thickness change correspondingly.

4. When developing technology for carbide-containing coatings spraying onto specific details, a search is required for optimal ration between the processes of decarbonization of carbide component (WC) and formation of α -Ni (W) solid solution at different stages of spraying.

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Table 1. The mechanical characteristics of coatings made from the spheroidized BH-20 powder sprayed at different compositions of the working explosive mixture

The ratio between the consumption of acetylene and oxygen	The average strength of substrate adhesion (σ_{sa}), MPa	The average strength of coating material (σ_B), MPa	The average Vickers hardness, HV5
Oxidation mode, $Q_{C_2H_2}/Q_{O_2} = 1.0/2.5$	63.04 ± 1.19	122.9 ± 21.1	866 ± 16.6
Neutral mode, $Q_{C_2H_2}/Q_{O_2} = 1.0/1.05$	118.68 ± 3.8	355.8 ± 19.3	960.6 ± 37.8
Reduction mode, $Q_{C_2H_2}/Q_{O_2} = 1.2/1.0$	137.5 ± 3.84	411.6 ± 22.5	921.6 ± 26.1

(σ_B) – tensile strength.

(σ_{sa}) – strength of substrate adhesion

Table 2. The content of the main phases in the starting BH-20 powder and coatings in the oxidation and reduction spraying modes

	The phase composition, atomic%				The parameter "a" of the Ni lattice – phases
	WC	W ₂ C	W	Ni	
Starting powder	83.8	Traces	No	16.2	α -Ni (Fm3m)-W 3.5661
Oxidation mode, $Q_{C_2H_2}/Q_{O_2} = 1.0/2.5$	62.0	No	22.0	16.0	3.6417
Reduction mode, $Q_{C_2H_2}/Q_{O_2} = 1.2/1.0$	73.0	3.0	No	23.0	3.6059

Table 3. The mechanical characteristics of coatings made from spheroidized BH-20 powder sprayed at different degrees of gun filling with the explosive gas mixture

Degree of gun filling, %	The average strength of substrate adhesion	The average strength of coating material	The average Vickers hardness, HV5
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	(σ_{sa}) , MPa	(σ_B) , MPa	
30	89.8 ± 10.4	143.0 ± 21.1	693 ± 47
43	94.7 ± 1.3	156.0 ± 19.0	846 ± 35
65	108.5 ± 2.7	216.2 ± 22.5	1124 ± 35

(σ_B) – tensile strength.

(σ_{sa}) – strength of substrate adhesion

Table 4. The data of quantitative X-ray phase analysis of the starting BH-20 powder and coatings obtained at different degrees of filling gun of the detonation plant with the explosive gas mixture

No	Item	The degree of gun filling, %	Phase composition, atomic%			
			WC	W ₂ C	W	α -Ni (W)
1	Starting powder BH-20	-	84.1	3.1	No	12.8
2	Coating	43	73.15	2.0	2.1	20.8
3	Coating	65	71.4	5.75	5.01	17.7

Table 5. The parameters of unit cells of the WC, W₂C, W and NiW phases in the starting BH-20 powder and coatings at different degrees of gun filling

No	Item	The cell parameters of phases					
		α -Ni (W)	W	WC		W ₂ C	
		a[A]	a[A]	a[A]	c[A]	a[A]	c[A]
1	Reference quantity	3.5239	3.1648	2.900	2.8310	2.980	4.7100
2	Starting powder	3.566	No	2.914	2.843	2.989	4.714
3	Coating, 43% filling	3.603	3.162	2.907	2.839	2.980	4.724
4	Coating, 65% filling	3.624	3.168	2.916	2.845	2.990	4.735

Table 6. Variation of the phase content and the average hardness of coating made from the BH-20 powder along the layer thickness and sprayed spot diameter in the neutral spraying mode ($Q_{C_2H_2}/Q_{O_2} = 1.0/1.05$)

Sprayin g spot area	Site 0 unpoli shed surface				Site 1 after the first polishi ng					Site 2 after the second polishi ng					Site 3 after the third polishi ng				
	W C	W ₂ C	W	α - Ni (W) %	W C	W ₂ C	W	α - Ni (W) %	HV 5	W C	W ₂ C	W	α - Ni (W) %	HV 5	W C	W ₂ C	W	α - Ni (W) %	H V5
Upper part	%	%	%	%	%	%	%	%		%	%	%	%		%	%	%	%	
Cent ral part	42 .3	17. 6	14 .7	25 .4	24 .8	17. 2	28 .2	29 .8	78 3	24 .5	15. 4	28 .9	31 .1	76 5	30 .5	15. 7	23 .5	30 .3	75 0
Low er part					26 .6	20. 9	28 .8	23 .7	92 1	29 .5	23. 1	26 .4	21 .0	10 12	30 .7	19. 9	26 .0	23 .4	88 4
					26 .6	28. 0	28 .4	17 .1	10 24	29 .7	19. 6	27 .6	23 .1	10 58	32 .6	16. 0	27 .2	24 .2	98 0

Table 7. Variation of the phase content and the average hardness of coating made from the BH-20 powder along the layer thickness and sprayed spot diameter in the reduction spraying mode ($Q_{C_2H_2}/Q_{O_2} = 1.2/1.0$)

Sprayin g spot area	Site 0 unpoli shed surface				Site 1 after the first polishin g					Site 2 after the second polishin g					Site 3 after the third polishin g				
	W C	W ₂ C	W	α - Ni (W) %	W C	W ₂ C	W	α - Ni (W) %	HV 5	W C	W ₂ C	W	α - Ni (W) %	HV 5	W C	W ₂ C	W	α - Ni (W) %	HV 5
Upper part	%	%	%	%	%	%	%	%		%	%	%	%		%	%	%	%	
Cent ral part	76. 1	3.2	1. 4	19. 2	59. 2	6.8	3. 9	30. 0	80 0	68. 7	6.9	3. 9	20. 5	78 8	68. 8	6.3	4. 0	20. 9	76 8
Lower part					62. 3	7.1	5. 0	25. 6	92 0	68. 1	6.4	4. 4	21. 1	86 0	66. 8	6.9	4. 9	21. 4	95 3
					60. 7	6.1	5. 4	27. 8	82 4	68. 0	6.1	4. 5	21. 5	78 6	68. 3	5.9	4. 4	21. 4	68 7*

*The coating thickness in this measurement is insufficient to determine HV5.

Figure 1. A pin sample to determine substrate adhesion strength. 1 – bush; 2 – conical pin; 3 – stop nut; 4 – washer

Figure 2. A sample to determine the coating material strength. The material of the left and right parts of the samples holder is steel 45. 1 – left part; 2 – right part; 3 – coupling bolt

Figure 3. A characteristic appearance of the conic pin end of the sample after substrate adhesion strength testing of coatings made from WC-based powders

Figure 4. The typical structure of a detonation coating from spheroidized BK-20 powder

Figure 5. The X-ray pattern of a sintered hard-alloyed BK-8 plate

Figure 6. The X-ray pattern of a detonation coating from spheroidized BK-20 powder

Figure 7. The X-ray pattern of the starting BH-20 powder

Figure 8. The X-ray pattern of a coating from BH-20 powder sprayed in the oxidation mode

Figure 9. The X-ray pattern of a coating from the BH-20 powder sprayed in the reduction mode

Figure 10. A characteristic form of a coating spot from the spheroidized BH-20 powder sprayed onto a stationary substrate