

The effect of gas atmosphere on the coating formation by electric arc surfacing with cermet SHS electrodes of the $\text{TiB}_2\text{--Co}_2\text{B}$ composition

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Abstract: Due to their unique properties, metal-matrix composite materials, when used as a surfacing material for electric arc surfacing, provide high properties of the deposited layers. SHS-extrusion is a promising method for a wide range of surfacing metal-matrix electrodes. The gas environment of surfacing affects the quality of coatings formed by SHS electrodes, their microstructure and properties. In this paper, cermet SHS electrodes of the $\text{TiB}_2\text{--Co}_2\text{B}$ composition obtained by SHS-extrusion were used to form protective coatings on a steel substrate by electric arc surfacing in an argon atmosphere and in a nitrogen atmosphere. The elemental and phase composition, as well as the microstructure of the deposited layers, were investigated. Based on the conducted studies, the influence of the gas atmosphere on the formation of the structure of cermet coatings was established. It is shown that, despite the similar phase composition, there are fundamental differences in the microstructures of the deposited coatings, which are caused by the partial fusion of the tungsten electrode and the transfer of the electrode material in the coating during surfacing in an argon atmosphere. The maximum values of the microhardness of coatings deposited in a nitrogen atmosphere exceed the maximum microhardness of coatings obtained by surfacing in an argon atmosphere by 200–450 HV.

Keywords: cermet electrodes; SHS-extrusion; SHS electrodes; protective coatings; electric arc surfacing; borides, gas atmosphere.

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Влияние газовой атмосферы на формирование покрытий в процессе электродуговой наплавки металлокерамическими СВС-электродами состава $\text{TiB}_2\text{--Co}_2\text{B}$

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Аннотация: Благодаря своим уникальным свойствам металломатричные композиционные материалы при использовании их в качестве наплавочного материала для электродуговой наплавки могут обеспечить высокие свойства наплавленных слоев. Перспективным методом получения широкого спектра наплавочных металломатричных электродов является СВС-экструзия. Газовая среда наплавки оказывает влияние на качество формируемых СВС-электродами покрытий, их микроструктуру и свойства. В настоящей работе металлокерамические СВС-электроды состава $\text{TiB}_2\text{--Co}_2\text{B}$, полученные методом СВС-экструзии, применены для формирования защитных покрытий на стальной подложке методом электродуговой наплавки в атмосферах аргона

и азота. Исследовались элементный и фазовый составы, а также микроструктура наплавленных слоев. На основании проведенных исследований установлено влияние газовой атмосферы на формирование структуры металлокерамических покрытий. Показано, что несмотря на схожий фазовый состав, существуют принципиальные различия микроструктур наплавленных покрытий, которые обусловлены частичным оплавлением вольфрамового электрода и переносом электродного материала в покрытие при наплавке в атмосфере аргона. Максимальные значения микротвердости покрытий, наплавленных в атмосфере азота, превышают максимальную микротвердость покрытий, полученных при наплавке в атмосфере аргона, на 200...450 HV.

Ключевые слова: металлокерамические электроды; СВС-экструзия; СВС-электроды; защитные покрытия; электродуговая наплавка; бориды; газовая атмосфера.

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1. Introduction

Metal-matrix composite materials (MCMs) with reinforcing ceramic particles are widely used in various fields of modern industry. This is due to the fact that, combining the advantages of metals and ceramic materials, MCMs have high indicators of such characteristics as hardness, fatigue strength, wear resistance, heat resistance and thermal stability [1–5]. A promising application of MCMs is the deposition of protective coatings by the method of electric arc surfacing, which serves as a simple and effective way to improve the performance characteristics of the treated surfaces [6–9]. To prevent oxidation of the molten electrode material and the substrate material by air oxygen, surfacing is carried out in protective gas atmospheres. To create a protective atmosphere, gases such as inert argon [10–12] and carbon dioxide are used [13, 14], however, their mixture is used most often [10, 15, 16]. Surfacing in an environment of active gases, such as nitrogen, enables not only to protect the deposited coating from oxidation, but also to additionally alloy it [17, 18].

For the production of cermet surfacing electrodes, the SHS-extrusion method is quite promising [19]. This method combines two processes in one stage: self-propagating high-temperature synthesis (SHS) [20] of MCMs, and extrusion of hot reaction products through a forming die. The synthesis of the material and the formation of the final product take a few seconds. This approach makes it possible to obtain a wide range of metal-matrix composite materials with a uniform distribution of reinforcing particles in the matrix and the required set of physical and mechanical properties.

Currently, there are quite a lot of studies on the development and preparation of new compositions of electrode MCMs using the SHS-extrusion method [19, 21–23], promising for the application of protective coatings by the method of electric arc

surfacing (EAS). Earlier, in [24], a protective coating was obtained on a titanium substrate by the method of electric arc surfacing with SHS electrodes based on the TiB-Ti system. It is shown that, as a result of surfacing of the SHS electrode material, a high-quality coating with a continuous fusion zone was formed on the substrate, the microhardness of the deposited layers reached 1420 HV. In [25], electrodes based on the MAX-phase of the Ti-Al-C system, obtained by SHS-extrusion, were used as a filler material for surfacing. The microstructure of the deposited coatings has been studied in detail. It is shown that as a result of surfacing at currents of 40–80 A, the initial MAX-phase decomposes and titanium carbide and aluminide phases are formed in the coatings. The authors of [26] investigated the possibility of creating protective coatings by surfacing with SHS electrodes $\text{TiC-W}_2\text{C-Co}$. The deposited layer had a microhardness of 940 HV, and the microhardness of carbide grains in the coating structure reached 1400 HV. In [27], industrial tests of the welded sections of a jaw crusher with SHS electrodes of the STIM group were successfully carried out. The microhardness of the deposited layer was 650–700 HV. Thus, in the cases mentioned above, the coatings applied by electric arc surfacing with SHS electrodes had a high quality and increased microhardness.

The available research in this area has shown the possibility of using metal-matrix composite SHS electrodes as surfacing for creating protective coatings. Expanding the list of SHS surfacing electrodes and studying the effect of various gas atmospheres on the coating formed during surfacing will ensure the selection of the most suitable material for creating protective coatings in accordance with the operating conditions of the surfaces to be deposited.

The purpose of this study is to produce metal-matrix SHS electrodes of $\text{TiB}_2\text{-Co}_2\text{B}$ composition by SHS-extrusion method for surfacing and to study the

effect of a gas atmosphere of argon and nitrogen in the process of electric arc surfacing with SHS electrodes on the features of the formation of cermet composite coatings on a steel surface. A study of the phase and elemental composition, microstructure of SHS electrodes and coatings was carried out depending on the environment in which the surfacing was carried out; the distribution of microhardness from the surface of the deposited layer to the steel substrate was measured.

2. Materials and methods

2.1. Materials

Powders of titanium (PTS, 98 wt. %, 280 μm , JSC Polema, Tula, Russia), boron (B-99A, 99.5 wt. %, 10 μm , JSC Aviabor, Dzerzhinsk, Russia) and cobalt (PK-1u, 99.35 wt. %, 71 microns, GC "MetallEnergoHolding", Yekaterinburg, Russia) were used. The initial components were taken in the ratio required for the formation of strengthening phases TiB_2 and Co_2B in the titanium matrix, wt. %: 39.4 wt. % Ti, 42.8 wt. % Co, 17.8 wt. % B. The formation of the metallic matrix of the composite electrode was provided by an excess of metallic titanium in relation to the stoichiometry of the reaction: $\text{Ti} + 2\text{B} \rightarrow \text{TiB}_2$. The powders were mixed for 12 hours to achieve uniformity in the composition of the powder mixture. From the obtained powder mixture, according to the standard technique, the initial blanks in the form of tablets with a diameter of 25 mm were pressed to carry out the synthesis of the electrode material in the SHS mode. To ensure a stable course of the self-propagating high-temperature synthesis process, the tablets were pressed to a relative density of 0.6.

2.2. Method of products obtaining

In this paper, metal-matrix composite electrodes with TiB_2 and Co_2B strengthening particles for electric arc surfacing (hereinafter referred to as SHS electrodes) with a diameter of 3 mm and a length of more than 150 mm were obtained by SHS-extrusion. The SHS-extrusion of the electrode material took place in several stages. The thermally insulated pressed blanks were placed in an installation for SHS-extrusion (Fig. 1). The combustion reaction was locally initiated on the surface of the upper end of the pressed tablet using a tungsten wire. A few seconds after the passage of the combustion wave throughout the sample (delay time), pressure P was applied to the synthesis products. Under the applied pressure, the hot synthesized material was compacted and extruded through the forming die. The synthesis of the material

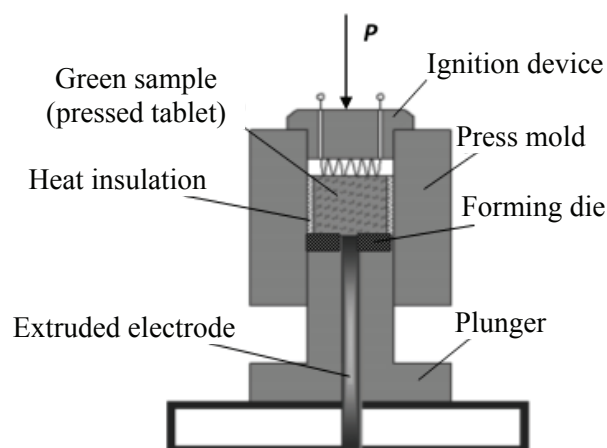


Fig. 1. Schematic representation of the installation for SHS-extrusion

in the combustion mode was carried out due to the occurrence of an exothermic chemical reaction of the interaction of titanium and boron powders: $\text{Ti} + 2\text{B} \rightarrow \text{TiB}_2$.

2.3. Method of coatings obtaining

Samples of protective composite coatings were obtained by the method of electric arc surfacing with cermet SHS electrodes on a steel plate of St3 grade with a thickness of 4 mm. Surfacing was carried out in one pass according to the most optimal conditions established empirically: in an argon atmosphere at a current of 70 A and in a nitrogen atmosphere at a current of 80 A as a filler material. Fig. 2 shows a diagram for the process of electric arc surfacing. An SHS electrode was uniformly fed into the combustion zone of an electric arc excited between the tungsten electrode and the steel substrate. The SHS electrode was fed manually. Under the influence of the temperature of the electric arc, the substrate material was partially melted, and a weld pool was formed. A shielding gas was supplied to the

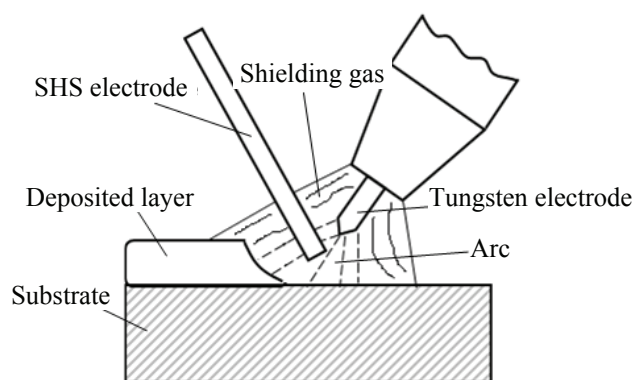


Fig. 2. Scheme of electric arc surfacing in a gas atmosphere

surfacing zone under pressure, due to which the arc column and the molten weld pool were isolated from the gases that make up the air. The surface of the deposited layers had no defects visible to the naked eye. There were no cracks, pores or craters on it.

2.4. Characterization methods

To study the microstructure, elemental and phase composition and microhardness of SHS electrodes for electric arc surfacing and deposited coatings in the transverse and longitudinal sections, metallographic thin sections were prepared. The microstructure and elemental composition of SHS electrodes and coatings were investigated in cross section by scanning electron microscopy (SEM) and energy dispersive analysis (EDA) on a Zeiss Ultra plus ultra-high resolution field emission scanning microscope based on Ultra 55 (Germany) equipped with an energy dispersive microanalyzer.

The phase composition of SHS electrodes for surfacing was determined using X-ray phase analysis. The phase composition of the deposited coatings was investigated layer by layer in the cross section with a step of 1 mm. X-ray phase analysis was carried out on an ARL X'TRA X-ray diffractometer (XRD) (Thermo Fisher Scientific, Switzerland) in Fe-K α radiation (anode – Fe), the sensitivity of the method is 5 wt.%.

The microhardness of SHS electrodes was determined in cross section using the Vickers method. The microhardness of the deposited coatings was determined in the plane perpendicular to the plane of the substrate. The measurements were carried out using a PMT-3 microhardness tester with a load of 0.5 N.

3. Results and Discussion

In accordance with the EDA results, the elemental composition of the SHS electrode consists of three initial elements: titanium, cobalt, and boron. It should be noted that these elements are uniformly distributed over the entire volume of the electrode material. According to the findings of XRD (Fig. 3) and SEM (Fig. 4), the microstructure of the filler SHS electrodes for surfacing was homogeneous and was represented by strengthening particles of titanium boride TiB₂ and cobalt boride Co₂B, uniformly distributed in the titanium matrix (Ti). The particles were in the form of polyhedrons. Along with the target hardening phases, a by-product of the synthesis of the electrode material was formed – the TiCo₂ phase. The microhardness of SHS electrodes was 1066–1947 HV.

The thickness of the coatings obtained by the EAS method with cermet SHS electrodes on a steel substrate was 3.0–3.5 mm in argon and 2.7–3.2 mm in nitrogen.

According to the EDA results, deposited coatings in different gas atmospheres had an identical elemental composition, which includes the following elements:

- titanium (Ti), boron (B) and cobalt (Co), introduced into coatings with the material of the SHS electrode being welded;
- iron (Fe) entering the coatings as a result of substrate melting;
- tungsten (W), which was found in coatings due to partial melting of a non-consumable tungsten electrode. To a greater extent, this occurs with EAS in an argon atmosphere.

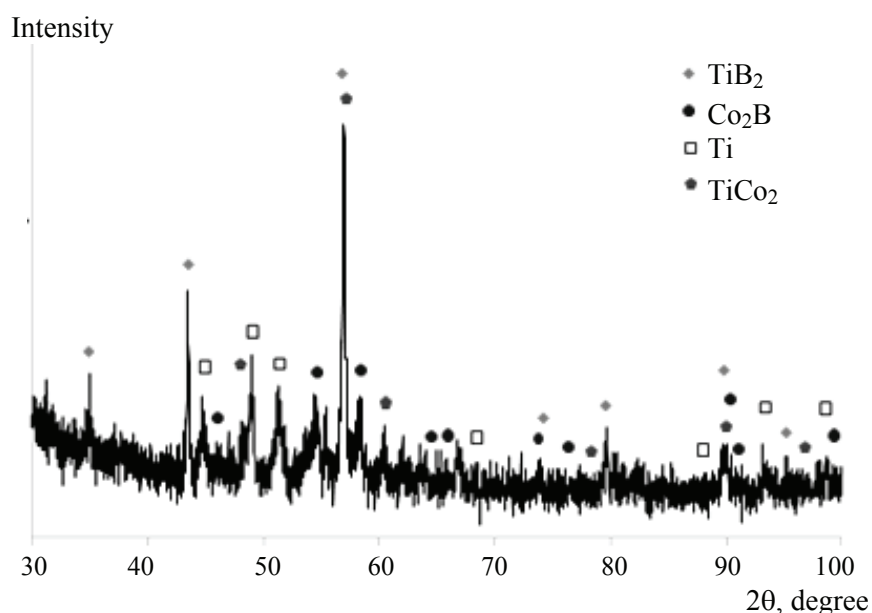


Fig. 3. XRD pattern of SHS electrodes for electric arc surfacing

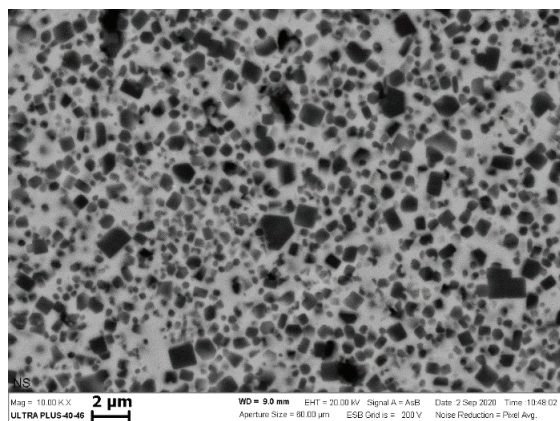


Fig. 4. Microstructure of SHS electrodes for electric arc surfacing

Layer-by-layer XRD showed (Fig. 5) that a complex phase composition was formed in coatings deposited in different atmospheres, including the following phases:

- phases that were part of the deposited electrode – TiB_2 and Co_2B ;
- phases formed as a result of the interaction of the iron of the substrate with titanium and cobalt of the SHS electrode – FeTi and Co_3Fe_7 ;
- the phase formed during the transition of tungsten to the coating – W_2CoB_2 ;
- solid solution of titanium in iron – $\text{Fe}_{0.975}\text{Ti}_{0.025}$;
- titanium Ti ;
- cobalt Co .

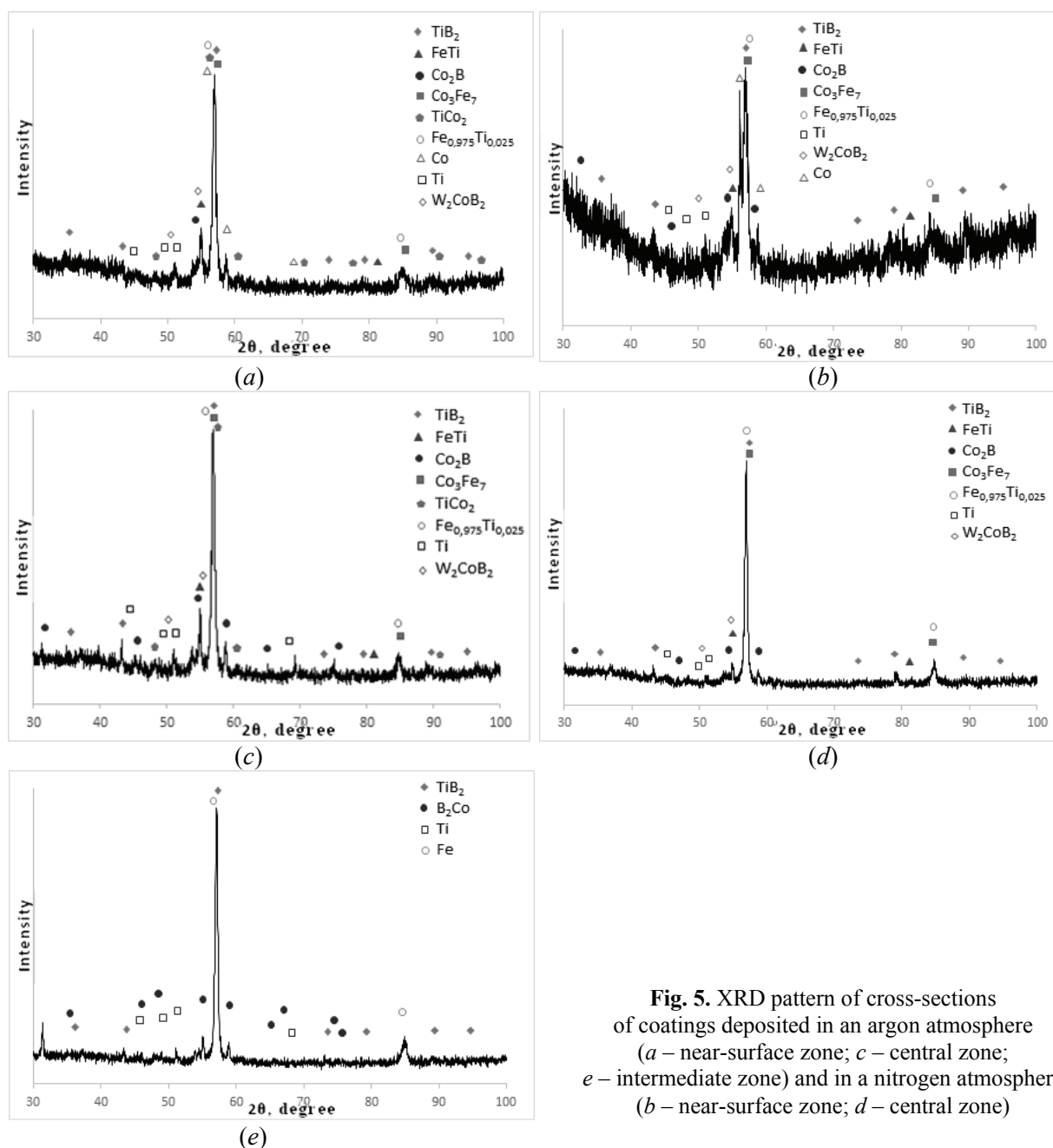


Fig. 5. XRD pattern of cross-sections of coatings deposited in an argon atmosphere (a – near-surface zone; c – central zone; e – intermediate zone) and in a nitrogen atmosphere (b – near-surface zone; d – central zone)

In addition to the indicated phases, in the coatings deposited in an argon atmosphere, TiCo_2 was found – a phase that is part of the deposited SHS electrode, which, when deposited in a nitrogen atmosphere, apparently decomposes. Cobalt Co was observed only in the near-surface layers of the coatings; otherwise, the phase composition of the coatings remains unchanged up to the transition zone. It should be noted that nitrogen-containing phases were not observed in the coatings, although, as a rule, nitrogen is an active gas.

The transition zone of coatings deposited in a nitrogen atmosphere at a given step of layer-by-layer XRD was not investigated. However, its presence is evident from the SEM results. Fig. 6 shows typical images of microstructures in the cross section of specimens deposited in an argon atmosphere and in a nitrogen atmosphere.

As can be seen from Fig. 6, the microstructure of the deposited coatings is fundamentally different from each other, although it has a similar phase composition. In the microstructure of coatings

deposited in a nitrogen atmosphere, there are few tungsten-containing inclusions and they are concentrated at the periphery; in the rest of the coating, the tungsten content is up to 5 wt.%. When surfacing in an argon atmosphere, tungsten is distributed over the entire deposited layer (Figs. 6a and 6b).

The structure of the deposited coatings has a layered structure. Several zones can be distinguished in it: a near-surface zone with large structural components, followed by a zone in which the refinement of structural components is observed, a transition zone is observed at the boundary of the surfacing and the substrate. The high rate of heat removal promotes the formation of a finely dispersed structure in the region close to the substrate, the size of the structural components becomes larger when approaching the coating surface. At the interface between the substrate and the deposited layer, a transition layer is formed due to mutual diffusion (Figs. 6c and 6d).

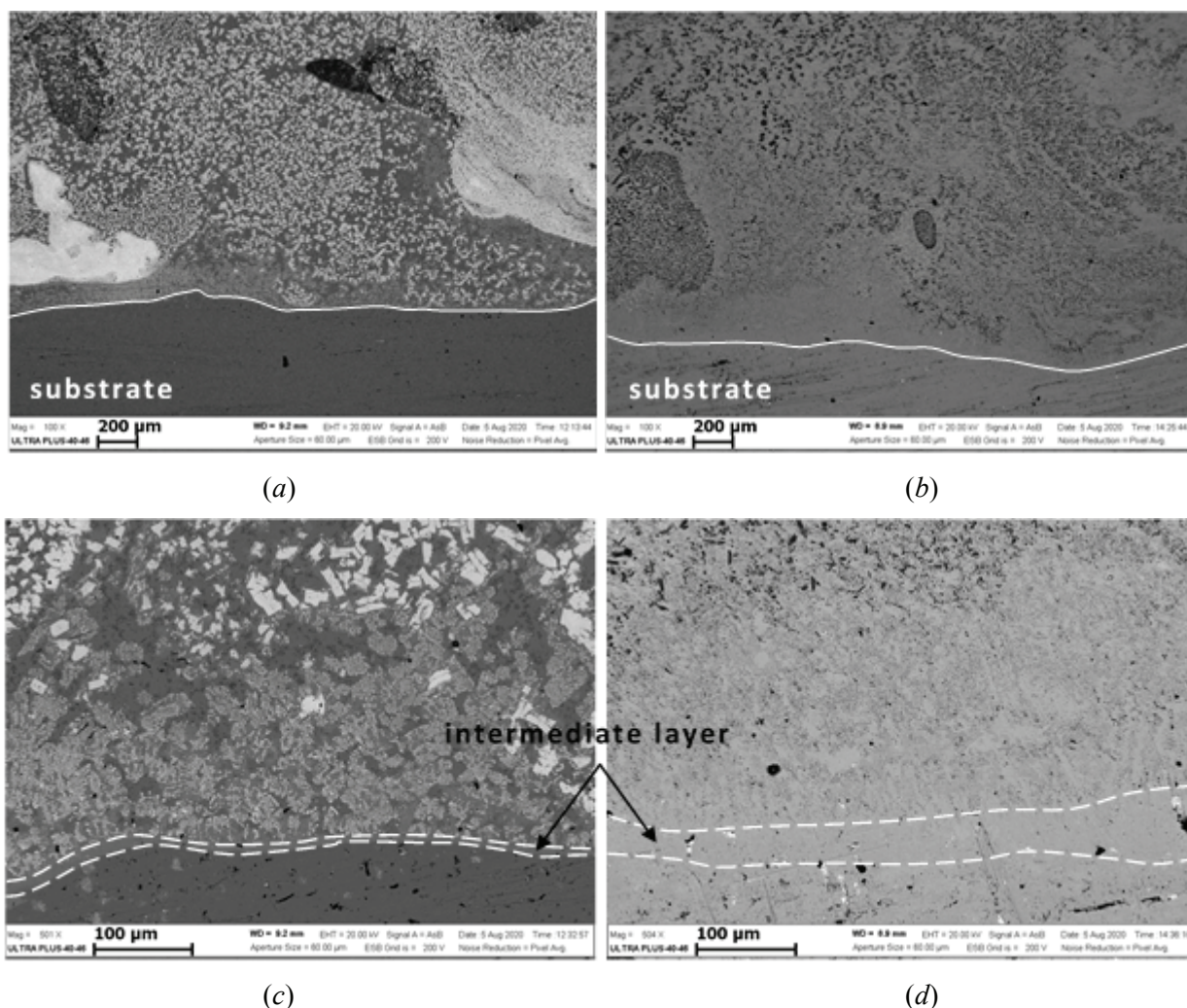


Fig. 6. Microstructure of coatings deposited in an argon atmosphere (a, c) and in a nitrogen atmosphere (b, d)

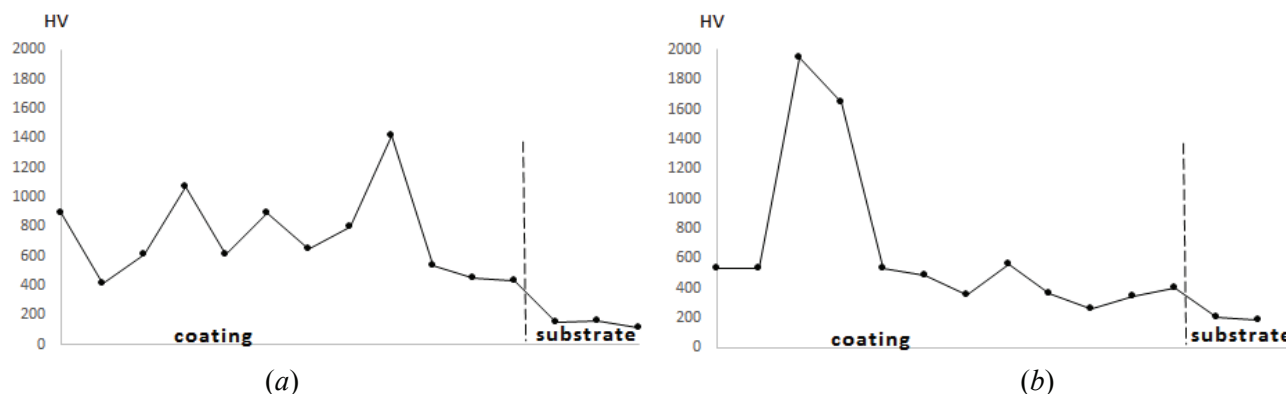


Fig. 7. Change in microhardness of coatings deposited in an argon atmosphere (a) and in a nitrogen atmosphere (b) from the surface of the deposited layer to the steel substrate

In both cases, both when surfacing in an argon atmosphere and when surfacing in a nitrogen atmosphere, the coatings have high adhesion strength due to the formation of a transitional diffusion layer. The transition layer is represented by a solid solution of titanium and cobalt in iron with fine inclusions of tungsten in the first case, and boron-containing inclusions in the second case. Nitrogen cladding promotes the formation of a wider transition layer. Its thickness is on average 60 μm , while for surfacing in an argon atmosphere it is 15 μm .

All deposited coatings have increased microhardness throughout the entire thickness compared to the microhardness of the steel substrate, which is 160–200 HV (Fig. 7). The scatter in the microhardness values of the deposited coatings is due to the fact that the microhardness measurements were carried out over the entire surface of the section, the indenter got both directly into the matrix and strengthening particles, and into the interphase boundaries. Thus, when the indenter enters the grains of strengthening particles, the microhardness reaches 1200–1500 HV for coatings deposited in an argon atmosphere, and 1700–1950 HV for coatings deposited in a nitrogen atmosphere. Due to solid solution hardening, the matrix solution of the deposited coating has microhardness values above 400 HV. When moving from the coating surface to the substrate, the microhardness of the specimens deposited in an argon atmosphere remains high and sharply decreases on going to the substrate material. In the case of surfacing in a nitrogen atmosphere, a gradual decrease in microhardness values is observed due to a wider transition zone.

4. Conclusions

Metal-matrix composite SHS electrodes with strengthening particles TiB_2 and Co_2B for surfacing protective coatings were obtained by SHS-extrusion.

It was found that, as a result of SHS-extrusion of the electrode material, a homogeneous structure is formed throughout the entire volume, and in addition to the target strengthening phases, a side TiCo_2 phase is formed.

The possibility of using metal-ceramic electrodes of the $\text{TiB}_2\text{--Co}_2\text{B}$ composition, obtained by the SHS-extrusion method, as a filler material in the electric arc surfacing of protective coatings has been investigated. The influence of the gas atmosphere on the thickness of the deposited layer has been studied. It was found that as a result of surfacing, coatings of different thicknesses are formed: in argon – up to 3.5 mm, in nitrogen – up to 3.2 mm.

It has been found that the qualitative elemental composition of the coatings does not depend on the surfacing atmosphere and includes 5 elements (iron, titanium, cobalt, boron, tungsten), but has quantitative differences: the argon atmosphere is more conducive to the transition of tungsten into the coating.

It is shown that the deposited coatings have a similar phase composition, except that during surfacing in a nitrogen atmosphere, the TiCo_2 phase is not formed in the coating.

It has been found that the microstructure of the coatings in both cases is layered; a diffusion transition layer is formed, which increases the adhesion strength of the coating to the substrate. Under conditions of surfacing in a nitrogen atmosphere, a diffusion layer is formed, the width of which is 4 times greater than when surfacing in an argon atmosphere. It is shown that the size of inclusions decreases from the surface of the deposited layer to the steel substrate.

It has been found that the atmosphere of electric arc surfacing with cermet SHS electrodes influences the microhardness of the coatings that reaches

1500 HV when surfacing in argon and 1950 HV in nitrogen, which is more than 7 times higher than the microhardness of the steel substrate.

The studies have shown that the use of cermet SHS electrodes based on strengthening TiB₂ and Co₂B particles for electric arc surfacing on a steel surface in various gas atmospheres makes it possible to obtain a deposited layer with a low level of defects, and deposited protective coatings with high microhardness values can be promising for increasing the service life of working surfaces of steel parts in conditions of abrasive wear.

5. Funding

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6. Conflict of interests

The authors declare no conflict of interest.

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