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Development of a Technological Process for Producing and Investigation of Cermet Electrodes Based on TiC–NiCrAl and TiC–NiCrAlY

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Conflicts of interest

The authors declare that there is no conflict of interest.

Statement on the use of artificial intelligence technologies.

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Data availability

All data obtained during this study are included in the published article.

Abstract. This study presents a developed technological process for producing cermet electrodes based on TiC–NiCrAl and TiC–NiCrAlY using self-propagating high-temperature synthesis followed by deformation (free SHS compression), intended for applying coatings via electro spark alloying (ESA). The relevance of the study is determined by the need to create new electrodes with improved physical and mechanical characteristics to enhance the wear resistance and service life of machine components while reducing the cost and energy intensity of protective coating application processes. It is shown that ESA is a promising surface hardening method, the efficiency of which is largely determined by the properties of the electrode materials used. A comprehensive technological scheme is proposed, including the preparation of powder preforms, synthesis and production of compact materials by free SHS compression, and evaluation of their mechanical and structural characteristics. The phase composition was studied using X-ray diffraction (XRD), and the structural features were examined by scanning electron microscopy (SEM). The regularities of the influence of the component composition and parameters of free SHS compression on the structure formation and operational properties of the cermet electrodes have been established. It is shown that the developed approach ensures the production of electrodes with an improved combination of properties, promising for application in ESA technology to enhance the wear resistance and reliability of machine components.

Keywords: electro spark alloying, electrode, cermet composite, self-propagating high-temperature synthesis, SHS compression, titanium carbide

Authors' contribution

Nazarko I.A. — conducting research, writing, preparing an article for publication, methodology, formal analysis; Chizhikov A.P. — conducting research, methodology; Antipov M.S. — conducting research, methodology; Bazhin P.M. — developing a research concept, scientific guidance, writing, formal analysis. All the authors have read the final version of the article and approved it.

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Разработка технологического процесса получения и исследование металлокерамических электродов на основе TiC–NiCrAl и TiC–NiCrAlY

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Заявление об использовании технологий искусственного интеллекта

При создании настоящей статьи технологий генеративного искусственного интеллекта не использовались.

Заявление о доступности данных

Все данные, полученные в ходе этого исследования, включены в опубликованную статью.

Аннотация. Представлен разработанный технологический процесс получения металлокерамических электродов на основе TiC–NiCrAl и TiC–NiCrAlY методом самораспространяющегося высокотемпературного синтеза с последующим деформированием (свободное СВС-сжатие), предназначенных для нанесения покрытий методом электроискрового легирования (ЭИЛ). Актуальность исследования обусловлена необходимостью создания новых электродов с улучшенными физико-механическими характеристиками для повышения износостойкости и долговечности машиностроительных деталей при одновременном снижении стоимости и энергоемкости процессов нанесения защитных покрытий. Показано, что ЭИЛ является перспективным методом упрочнения поверхностей, эффективность которого в значительной степени определяется свойствами применяемых электродных материалов. Предложена комплексная технологическая схема, включающая приготовление порошковых заготовок, синтез и получение компактных материалов методом свободного СВС-сжатия и оценку их механических и структурных характеристик. Фазовый состав изучен методом рентгеноструктурного анализа (РФА), а особенности строения — методом сканирующей электронной микроскопии (СЭМ). Установлены закономерности влияния состава и параметров свободного СВС-сжатия на формирование структуры и эксплуатационные свойства полученных металлокерамических электродов. Показано, что разработанный подход обеспечивает получение электродов с улучшенным комплексом свойств, перспективных для применения в технологии ЭИЛ с целью повышения износостойкости и надежности деталей машиностроения.

Ключевые слова: электроискровое легирование, электрод, металлокерамический композит, самораспространяющийся высокотемпературный синтез, СВС-сжатие, карбид титана

Вклад авторов

Назарько И.А. — проведение исследований, написание текста, подготовка статьи к публикации, методология, формальный анализ; Чижиков А.П. — проведение исследований, методология; Антипов М.С. — проведение исследований, методология; Бажин П.М. — разработка концепции исследования, научное руководство, написание текста, формальный анализ. Все авторы ознакомлены с окончательной версией статьи и одобрили ее.

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Introduction

The application of protective coatings is one of the key areas of modern mechanical engineering technology, since it is the surface layer that, in most cases, determines the wear resistance, strength, corrosion resistance, and overall service life of machine parts and tools [1–4]. Under conditions of intensified operating conditions, increased loads, and stricter reliability requirements, the need for materials capable of maintaining functional properties under the simultaneous influence of mechanical wear, aggressive environments, and elevated temperatures is growing [5–7]. In this regard, the development of new technological approaches to surface modification and the creation of effective protective coatings is a pressing scientific and technical challenge [8; 9].

At present methods such as flame and plasma spraying, electric arc [1; 10] and laser technologies [11], ion-plasma deposition and their various modifications [12] are widely used for applying protective coatings. However, these methods are generally characterized by high equipment costs, significant energy costs, limited mobility and significant thermal impact on the material, which can lead to structural changes and deterioration of the mechanical properties of the base onto which the protective coating is applied [7; 13; 14].

Electric spark alloying (ESA) is considered a promising alternative with a number of significant advantages: localized processing, minimal thermal impact, no need for a vacuum or protective atmospheres, the ability to harden hard-to-reach areas, mobility, and the relatively low cost of the equipment used [1; 15–17]. However, the effectiveness of ESA is crucially determined by the properties of the electrode material, which determine the intensity of mass transfer, the structure of the formed layer, the performance characteristics of the coating and consequently the service life of the part or tool.

The most common electrode materials for ESA are alloys based on tungsten and titanium carbides with a metallic binder (WC–Co, WC–TiC–Co, etc.) [3; 7; 18]. Despite the relatively high

hardness and wear resistance of such materials, they have a number of disadvantages, including the high cost of raw materials, limited corrosion resistance, a tendency to brittle fracture, and insufficient adaptability to changes in alloying conditions. This indicates the existence of a scientific and technological gap associated with the absence of a universal methodology for the targeted design of electrode materials for ESA with an optimal set of properties [19–20].

A promising approach to solving this problem is the use of self-propagating high-temperature synthesis (SHS) [21–22] followed by compression (SHS compression), which allows the production of dense cermet materials with a given phase composition and controlled structure [10; 23–24]. The SHS compression method is characterized by high energy efficiency, technological flexibility, and the ability to vary the component composition over a wide range, which makes it attractive for the development of next-generation electrode materials [25].

The object of study in this research is cermet composites based on the TiC–NiCr system with additional alloying with aluminum and yttrium, intended for use as electrodes for ESA. The central scientific problem is the lack of a comprehensive, experimentally proven technological scheme covering all stages of electrode material creation — from the selection of component composition and SHS compression parameters to the assessment of the physical, mechanical, electrical and structural characteristics of the final product.

The objective of the research is to develop a process for producing and characterizing TiC–NiCrAl and TiC–NiCrAlY-based cermet electrodes using the free SHS compression method for ESA. To achieve this goal, the following tasks were addressed: developing a process method for producing the electrodes; studying their mechanical properties; analyzing their phase composition using X-ray diffraction analysis; and studying their microstructure using SEM to establish composition — structure — property relationships.

The academic novelty of this study lies in its integrated approach to the design and production

of ESA electrodes, implementing a comprehensive process chain from synthesis to functional evaluation. The practical significance of this study lies in the possibility of targeted development of competitive ESA electrodes that enhance wear resistance and extend the life of mechanical engineering components.

1. Materials and methods

Commercial powders of titanium, carbon black (soot), and nickel-chromium alloy (NiCr) with added aluminum and yttrium were used as starting components (Table 1). The Al additive

serves as an additional exothermic agent and structure modifier, while Y is an effective element that improves the boundary structure of carbide grains and the thermal stability of the composite. The component composition and mass ratio of the powders are presented in Table 2.

Preliminary preparation of components (step 2). To eliminate the influence of adsorbed moisture on dosing accuracy and combustion stability, all powders were subjected to isothermal aging in a SNOL-3.5 drying oven at a temperature of 50 ± 2 °C for 24 hours. This mode was chosen to minimize the risk of surface oxidation of the powders, which can occur at high temperatures.

Table 1. Powder Characteristics

Powder	Powder Brand/Grade	Reagent Purity, %	Particle Size, μm
Ti	PTS-1	99,0	45
C	P-803	99,1	1
NiCr	PR-12Kh18N10T	97,0	45
NiCrAl	METCO-451	97,0	56
NiCrAlY	AMDRY-962	97,0	53

Source: by I.A. Nazarko.

Table 2. Mass Ratio of Powder Components

№	Designation	Content of Initial Reagents, wt., %				
		Ti	C	NiCr	NiCrAl	NiCrAlY
1	TiC–NiCr	56	14	30	–	–
2	TiC–NiCrAl	56	14	–	30	–
3	TiC–NiCrAlY	56	14	–	–	30

Source: by I.A. Nazarko.

Batch preparation procedure (step 3). The calculated mass of each component was weighed on a CAS MWP-1500 laboratory balance with an accuracy of 0.1%. Mechanical mixing was carried out in a ball mill for 4 hours. Grinding media were cylinders made of 12Kh18N10T steel with a mass-to-mass ratio of 3.5:1. After mixing and sifting through a 2.5 mm sieve to remove grinding media, the mixture is returned to the drying oven for 2 or more hours to remove excess moisture introduced during mixing.

Procedure for producing powder blanks (step 4). The batch blanks (presses) were produced

using cold uniaxial pressing on a Hercules-40 hydraulic press. To study the combustion temperature and rate, 25 mm diameter blanks were prepared. Pressure was varied to produce blanks with a relative density in the range of 50–75% of the theoretical value. To obtain compacts, batch blanks with dimensions of 60×90×12 mm were prepared, achieving the optimal relative density. The formed blanks were visually inspected for cracks and delamination.

Methodology for Determining Temperature and Combustion Rate (Step 4.1). The temperature and combustion rate were determined using the following method. Two VR5/VR20 tungsten-

rhodium thermocouples, mounted vertically and 10 mm apart, were placed in a charge blank (weight 35 g, diameter 25 mm). Their signals were recorded using a QMBOX1-40-50 ADC. The passage of the combustion front through each thermocouple was recorded as a change in temperature. The combustion rate was calculated as the ratio of the distance between the thermocouples to the time interval between these events.

XRD and SEM methods (Step 7.1). To determine the phase composition of the synthesized materials, X-ray diffraction analysis was performed on a DRON-3 diffractometer. Qualitative identification of the phases was performed based on the position of diffraction peaks in the obtained X-ray diffraction patterns, and their relative content was estimated based on the intensity of the reflections. The microstructure of the samples was examined using a LEO 1450 scanning electron microscope.

Measurement of mechanical properties (Step 7.2). The mechanical properties of the

obtained samples were determined using a Nano-scan-4D dynamic nanohardness tester: hardness (H), elastic modulus (E), elastic recovery (η), and plastic and elastic deformation work. Indentation was performed in accordance with ISO 14577-1:2002 on polished cross-sections of the samples in the central part under a load of 0.5 N using a Berkovich diamond tip. The loading time was 10 s, the hold time under load was 2 s; the distance between indentations was not less than: $x = 15 \mu\text{m}$ and $y = 12 \mu\text{m}$.

2. Results

This work involved the development and optimization of a process for producing TiC–NiCr electrodes alloyed with aluminum and yttrium. A general diagram of the developed and optimized multi-stage process, reflecting the sequence of operations and feedback loops for adjusting parameters, is presented in Figure 1.

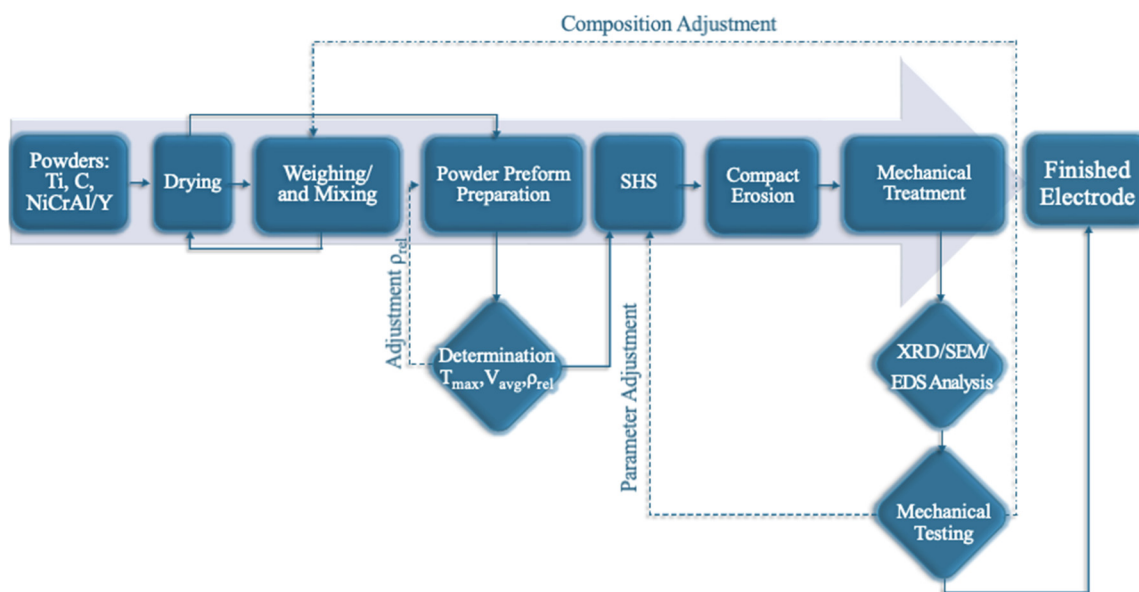


Figure 1. Flowchart of the electrode production process by SHS compression

Source: by I.A. Nazarko.

During the initial stages of the technological process (stages 1–3 in Figure 1), the initial powder reagents are prepared and processed in accordance with their mass ratios given in Table 2. The powder

mixture is used to prepare blanks of specified shapes and sizes for combustion characterization and compact production under free SHS compression conditions. The critical factor determining

the suitability of the synthesized material for plastic deformation after the combustion wave has passed is the temperature and time conditions of its production, which directly depend on the combustion parameters of the charge blank. These parameters are significantly influenced by the relative density of the charge blank, which is preliminarily selected experimentally prior to the SHS compression process.

To select the optimal density, combustion characterization studies were conducted in this work (stage 4.1). In this work, we experimentally investigated workpieces based on the TiC–NiCrAl (relative density 0.68–0.76) and TiC–NiCrAlY

(0.69–0.77) systems. For each composition, the maximum temperature ($T_{\max}$) and combustion rate (V) were determined based on the obtained experimental thermograms. Summary graphs of the dependences of these parameters on relative density are shown in Figure 2.

After selecting the optimal parameters for the blank, compacts are produced using free SHS compression (Stage 5). A blank (Figure 3) with optimal density is initiated at the end by a tungsten coil to initiate combustion. When the combustion front has traversed the entire volume, but the product is still in a high-temperature plastic state, pressure is applied to it by the press plunger.

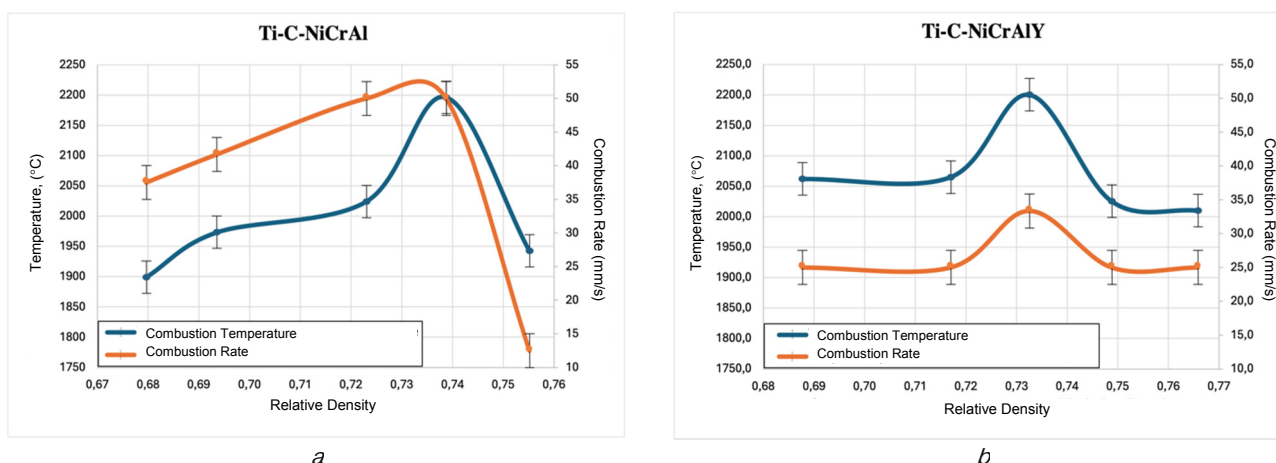


Figure 2. Combustion temperature and velocity as functions of the relative density of the billet for the following compositions:

a — TiC–NiCrAl; *б* — TiC–NiCrAlY

Source: by I.A. Nazarko.

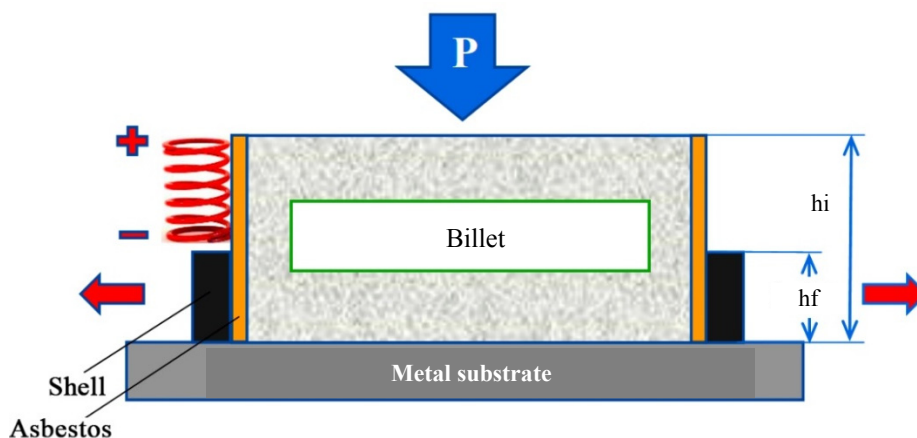


Figure 3. Schematic of the powder billet before free SHS compression

Source: by P.M. Bazhin.

The key optimized parameters are the magnitude of the applied pressure and the delay time between the combustion wave's passage through the entire sample and the onset of compression. Correct selection of these parameters eliminates macropores and achieves high density. Immediately after pressing, to relieve thermal stress, the sample is subjected to low-temperature treatment at 500°C, followed by slow cooling (~12 hours). After the furnace has cooled, the resulting compacts are subjected to rough machining (Stage 6) on a plane-parallel grinding machine to remove surface defects. In order to obtain the required dimensions, the resulting compact is subjected to electrical discharge cutting at the next stage.

The resulting samples were then subjected to a comprehensive analysis to evaluate their structure and properties. This study included structural phase analysis, and SEM analysis was used to study the structure, determine the distribution and sizes of the main phases and alloying elements (Al, Y).

The mechanical properties of the obtained materials were also tested. Key parameters include microhardness, elastic modulus, and others. This stage is crucial for the entire optimization cycle. If the results do not meet the target indicators, the process returns to the previous stages, as shown in the flowchart (see Figure 1) by the dotted arrows. Adjustments can be made in two directions: first, by changing the synthesis modes (pressure and delay time) or by returning to the initial adjustment of the initial powder mixture composition, including changing the percentage ratio of the main components and the amount of alloying additives. Thus, the cycle of synthesis, processing, and analysis is repeated until the optimal combination of properties is achieved. After confirming the optimal characteristics, the sample undergoes final machining to achieve its working shape (Stage 8). An electrode of the specified size for ESD coating or a finished part of a more complex configuration is produced using an electrical discharge machine.

Thus, the process shown in Figure 1 and the described techniques enable targeted control of the free SHS compression process to produce TiC–NiCr-based metal-ceramic electrodes with a modified structure and specified functional properties.

3. Discussion

An analysis of the plots of temperature and combustion rate versus relative density (see Figure 2) revealed a non-monotonic relationship: with an initial increase in density, the temperature and combustion rate rise due to improved contact between particles, but after passing the extremum, they begin to decrease due to intensified heat dissipation. Thus, optimal densities corresponding to maximum heat release were established for each composition: 0.74 for TiC–NiCrAl and 0.73 for TiC–NiCrAlY. At these densities, the synthesized materials will remain in a plastic state longer during subsequent shear deformation, which is a key factor in improving their structure and properties.

To optimize the free SHS compression process, experiments were conducted varying the holding time and pressing pressure. It was found that pressing pressure significantly affects the porosity of the resulting compacts. Thus, at a pressure of less than 10 MPa, the porosity of the resulting compacts is maximal, amounting to 10%. As this parameter increases, porosity decreases, reaching less than 2% at pressure of 30 MPa. Further increases in pressure do not lead to a significant change in porosity, and when its value exceeds 100 MPa, it leads to the destruction of the resulting compacts. The optimal delay time before applying pressure was determined to be 2–4 s after the combustion wave has passed through the entire sample. When pressure is applied immediately after the combustion wave has passed and for less than 2 s, the phase and structure formation processes in the material do not proceed fully, which affects the formation of nonequilibrium and intermediate phases. When this parameter increases beyond 4 s, the material loses its plastic properties and the ability to form compact materials.

Based on the X-ray diffraction analysis (the unit cell parameters of the samples are presented in Table 3), all electrodes are known to consist of titanium carbide and a nichrome matrix (Figure 4). When aluminum was added to the synthesized material, an intermetallic compound with the stoichiometry $\text{Al}_{1.1}\text{Ti}_{0.9}$, was detected, which can be attributed to the non-stoichiometric modification

of γ -TiAl. Deviations from stoichiometry create defects in the crystal lattice (aluminum atoms replace titanium atoms), which generate internal stresses that impede dislocation movement, leading to additional strengthening of the nichrome matrix. A slight excess of aluminum in the resulting intermetallic compound improves the wettability of TiC particles during synthesis and subsequent deformation, which reduces porosity in the resulting electrodes. The additional introduction of yttrium into the initial mixture, due to its high chemical activity, promotes the formation of complex yttrium aluminates during synthesis. The formation of inter-

metallic compounds will have a beneficial effect on subsequent ESA coating applications using the resulting electrodes, as they lower the melting point of the electrode material and improve its wettability with the steel substrate. This will increase the transfer coefficient of the electrode material and ensure increased adhesion of the resulting coating. Furthermore, during coating operation under load, excess aluminum from the non-stoichiometric phase will more readily react with oxygen from the surrounding air, forming aluminum oxide nano-layers. This will create a self-lubricating effect, thereby reducing adhesive wear of the friction pair.

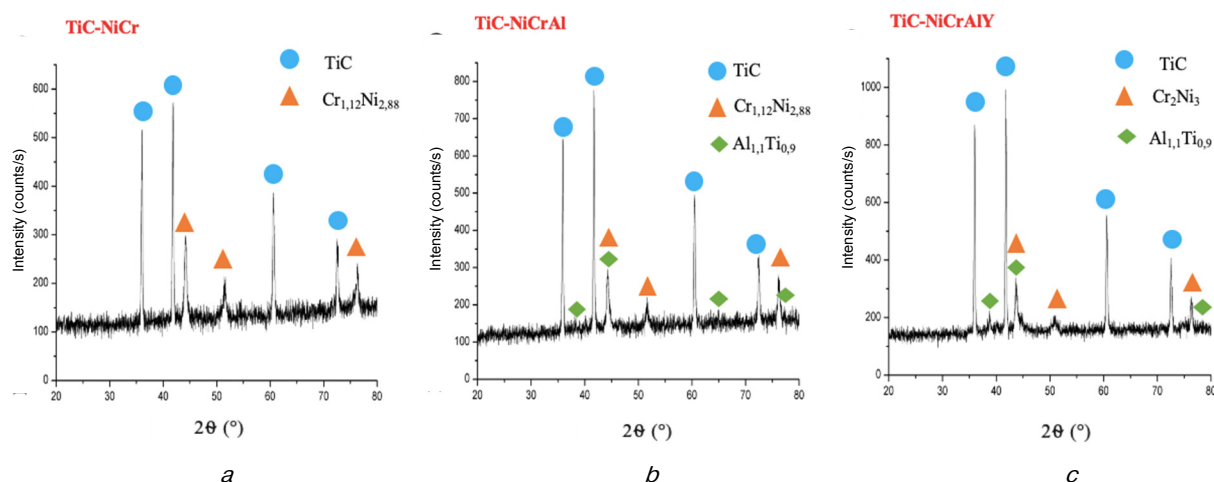


Figure 4. XRD results of the electrodes:
a — TiC–NiCr; b — TiC–NiCrAl; c — TiC–NiCrAlY
Source: by I.A. Nazarko.

Table 3. XRD Results and Unit Cell Parameters

Electrode Composition	Phase	Lattice Type	PDF-2 Card	Lattice Parameter, Å
TiC–NiCr	TiC	Cubic (Fm-3m)	10-89-3828	a = 4.3178
	Cr _{1,12} Ni _{2,88}		30-65-5559	a = 3.54
TiC–NiCrAl	TiC	Cubic (Fm-3m)	32-1383	a = 4.3274
	Cr _{1,12} Ni _{2,88}		30-65-5559	a = 3.54
	Al _{1,1} Ti _{0,9}	Tetragonal (P4/mmm)	55-0252	a = 3.9885, c = 4.0808
TiC–NiCrAlY	TiC	Cubic (Fm-3m)	30-65-8804	a = 4.322
	Cr ₂ Ni ₃		30-65-6291	a = 3.579
	Al _{1,1} Ti _{0,9}	Tetragonal (P4/mmm)	55-0252	a = 3.9885, c = 4.0808

Source: by I.A. Nazarko.

Based on the SEM analysis the obtained electrodes consist of rounded titanium carbide particles located in a matrix of a mixture of inter-

metallic compounds. Based on the obtained micrographs (Figure 5), it was found that the average particle size of TiC with the addition of aluminum

and yttrium decreases from 4.4 (TiC–NiCr) [26] to 3.4 (TiC–NiCrAl) and 3.1 (TiC–NiCrAlY) μm , respectively. In this case, the maximum particle size of TiC was 9 μm for the TiC–NiCr electrode, 6 μm for TiC–NiCrAl, and 5 μm for TiC–NiCrAlY. As a result of synthesis, the formed intermetallic compounds with aluminum are located on the surface of growing carbide grains, which creates a

barrier to the diffusion of carbon and titanium to the TiC grain. The addition of aluminum and yttrium produces a synergistic effect, resulting in even greater particle size reduction in TiC than when used separately. The resulting complex yttrium aluminates are also located at the grain boundaries of TiC, preventing the diffusion of titanium and carbon atoms toward them.

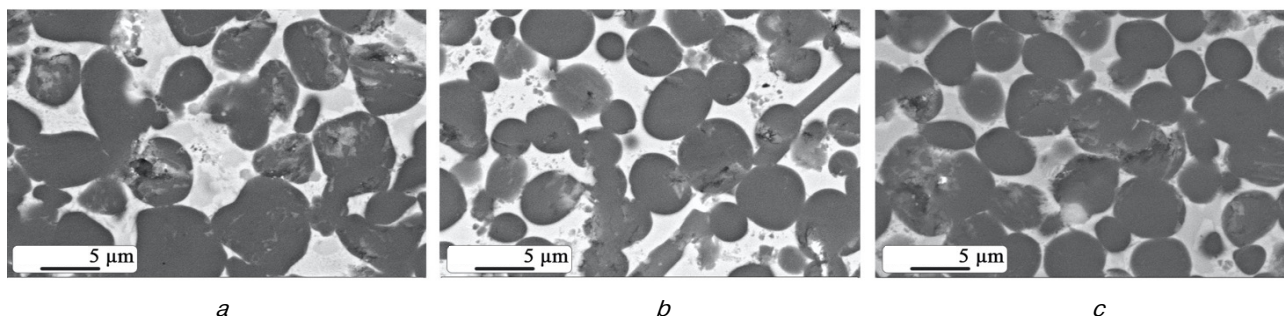


Figure 5. SEM images of the electrode microstructures:
a — TiC–NiCr; *b* — TiC–NiCrAl; *c* — TiC–NiCrAlY
 Source: by P.M. Bazhin.

Figure 6 shows the characteristic indentation curves for the electrodes of the three studied compositions. These curves resemble those for elastic-plastic bodies, but with a clear shift toward elasticity as aluminum and yttrium are alloyed. The TiC–NiCr electrode exhibits the largest area between the loading and unloading curves, corresponding to the greatest plastic deformation work of 181.4 nJ (Table 4). For the TiC–NiCrAl electrode, the loading curve becomes noticeably steeper due to an increase in hardness to 15.4 GPa, while the unloading curve is more vertical (shifts to the right), indicating an increase in the elastic modulus. The TiC–NiCrAlY electrode exhibits the steepest loading curve, indicating the material's maximum resistance to indentation. The obtained loading curves are smooth, without pronounced jumps, which emphasizes the absence of microcracking or the presence of pores in the studied electrodes.

The mechanical properties of the obtained electrodes were measured using experimental indentation dependences. It was found that additional alloying with aluminum and yttrium alters these properties due to the formation of additional phases and changes in the size of carbide grains (Table 3).

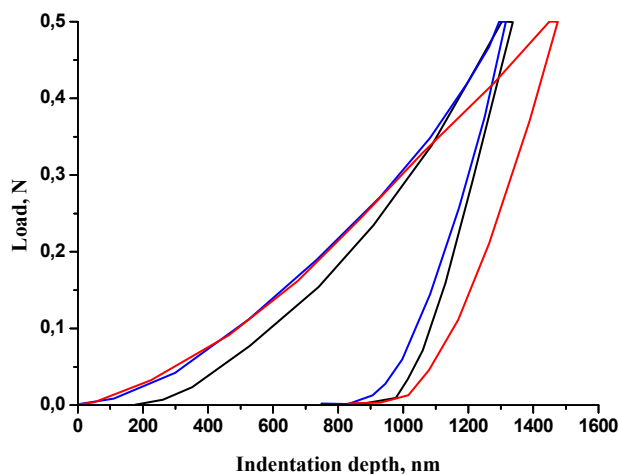


Figure 6. Loading/unloading dependencies for the electrodes:
 — TiC–NiCr; — TiC–NiCrAl; — TiC–NiCrAlY
 Source: by A.P. Chizhikov.

As can be seen from Table 4, additional alloying with aluminum and yttrium increases the hardness and elastic modulus of the obtained materials, but also reduces the work of elastic and plastic deformation. Elastic recovery remains virtually unchanged for all the electrodes studied, remaining at a level of 34–35%. During structure

formation, yttrium atoms form dispersed phases with yttrium, which are localized at the boundaries of TiC grains, preventing their migration. This will ensure the preservation of a fine-grained structure even under thermal exposure during electric spark discharges. Based on the Hall-Petch law, it can be argued that an increase in hardness and elastic

modulus indicates a refinement of the structural components in the electrodes. At the same time, the high density of grain boundaries and the presence of brittle intermetallic phases limit the free path of dislocations, which naturally leads to a decrease in the work of plastic deformation and the overall energy capacity of material failure.

Table 4. Average Values of the Mechanical Characteristics of the Electrodes

Electrode	Hardness (H), GPa	Elastic modulus (E), GPa	Elastic recovery (η), %	Elastic deformation work, nJ	Plastic deformation work, nJ	H/E	H^3/E^2
TiC–NiCr	13.0	305	34.8	94.8	181.4	0.042	0.023
TiC–NiCrAl	15.4	365	33.8	87.8	162.5	0.042	0.028
TiC–NiCrAlY	16.9	395	34.7	84.7	156.5	0.043	0.031

Source: by A.P. Chizhikov.

For the resulting electrodes, the H/E ratio characterizes the elasticity and the material's ability to resist wear without damaging the structure. This parameter is slightly higher for the TiC–NiCrAlY electrode, which may indicate the efficiency of material transfer during ESA and the improved quality of the resulting diffusion layer. Due to the increased H/E ratio of 0.043, the TiC–NiCrAlY electrode material exhibits increased elasticity, resulting in smaller microdroplets formed during spark discharges. This will result in a smoother and denser coating on the steel surface, which is critical for protecting the steel from corrosion and wear. At lower H/E ratios, the electrode will be more prone to brittle spalling of entire macro-particles, which will increase the thickness of the applied coating but also reduce its continuity.

The H^3/E^2 ratio determines the maximum load an electrode can withstand before irreversible failure. As can be seen from Table 4, this ratio increases from 0.023 to 0.031 with additional alloying with aluminum and yttrium. As this ratio increases, the material becomes more resistant to microcrater formation, even under extreme point pressures. The TiC–NiCrAlY electrode has the highest H^3/E^2 ratio, indicating that the resulting coating performs well when used in an elastic mode. Therefore, the TiC–NiCrAlY electrode is recommended for applying coatings in precision

friction pairs where minimal wear is critical and a low friction coefficient is required. This electrode requires low discharge energy during ESA to avoid the development of internal stresses and cracking of the coating during crystallization on the steel substrate. For the TiC–NiCrAl electrode, the H^3/E^2 ratio is 0.028, indicating that the coating formed during ESA is more rigid than that formed with the TiC–NiCr electrode ($H^3/E^2 = 0.023$), but is less brittle than the coating formed with the yttrium electrode. The TiC–NiCr electrode can be recommended for coating steel components subject to high impact or bending conditions, due to the formation of a metal-ceramic layer whose mechanical behavior is as close as possible to that of steel.

Conclusion

The object of this study was metal-ceramic electrodes based on TiC–NiCrAl and TiC–NiCrAlY, intended for the application of wear-resistant coatings by the electrospark alloying method. In this work, a comprehensive process flowsheet was developed and implemented, including the preparation of powder charge blanks, cold pressing of blanks, synthesis and consolidation of materials by the free SHS compression method, as well as certification of the structure and properties of the obtained samples using X-ray diffraction analysis,

scanning electron microscopy and nanoindentation. Optimum process parameters were determined experimentally: the relative density of the charge blanks (0.74 for TiC–NiCrAl and 0.73 for TiC–NiCrAlY), pressure (30 MPa) and delay time before applying the load (2–4 s), ensuring the formation of pore-free compacts with a uniform fine-grained structure. The obtained results allow us to formulate the following conclusions.

1. A technological process for producing TiC–NiCr-based electrodes with additional alloying of the initial powder mixture with aluminum and yttrium was developed and optimized. It was found that the introduction of aluminum and yttrium into the initial powder mixture allows for the control of phase and structural transformations directly during the formation and consolidation of the material.

2. It was shown that additional alloying with aluminum and yttrium leads to the formation of new intermetallic phases ($\text{Al}_{11}\text{Ti}_{0.9}$ and complex yttrium aluminates), which contribute to the improvement of the mechanical properties of the obtained electrodes: hardness up to 16.9 GPa, elastic modulus up to 395 GPa, and ratios $H/E = 0.043$ and $H^3/E^2 = 0.031$. The formation of these phases, as well as a reduction in the melting temperature of the electrode material and improved wettability with respect to the steel substrate, will increase the material transfer coefficient and adhesion of the coating applied by spark etching.

3. Practical recommendations are provided for the use of the resulting electrodes, depending on their composition, for applying protective coatings to metal surfaces.

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