

Silicon nano-carbide in strengthening and ceramic technologies

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Abstract. Technological advantages and conditions of new quality assurance of coatings and products, provided by silicon nano-carbide, have been ascertained in the course of composite electrodeposition of coatings, structural ceramics patterning, and surface hardening of steels via electro-explosive alloying. Silicon nano-carbide has been recommended to be used as a component of wear and corrosion resistant chromium carbide electrodeposited coatings, which can be operated at high temperatures and used for strengthening tools and equipment including those with a complex microrelief of functional surfaces. Silicon nano-carbide as a component of composite “silicon carbide – boron – carbon” can be applied to produce ceramic half products via solid phase sintering in argon under pressure of 0.1 MPa and temperature 2273 K. Application of silicon nano-carbide in technology of tool steel surface hardening via electro-explosive alloying ensures obtaining of a high micro-hard, wear and heat resistant shielding layer which is about 20 μm deep.

Introduction

Silicon carbide production is one of the most important in the structure of contemporary metallurgy. It is a combination of extraordinary thermo physical, mechanical, physical and technical properties of silicon carbide that makes it the unique material for numerous branches of engineering and pre-determines such basic applications as couplant materials, ceramics, composite materials, and coatings. World production of silicon carbide is approximately 800 thousand tons annually. The main spheres of silicon carbide application are metallurgy (about 45 % of world demand), abrasive materials production (up to 30 %), and refractory materials (up to 25 %). Product markets of silicon-carbide powder materials: micronized powder with maximum 1 μm particles (so called micronized carbide) used for ceramics and nano-powder with maximum 100 nm particles (so called nano-carbide) used for high quality structural and impact resistant ceramics and galvanics are small-scale in terms of real volume (maximum 1%) but intensively expanding, they also have high money measure. Introduction of silicon carbide in form of nano-carbide opens new horizons of its application, including surface and three-dimensional modifying metal alloys and polymers, developing special components of paints etc. [1, 2]. Manufacturers of micronized carbide are enterprises of world leader companies “Saint – Gobian” and “Exolon – ESK”. Among nano-carbide manufacturers there are research and production companies “Tokyo Tekko Co” (Japan), “Hefei Kaier Nanotechnology & Development Ltd. Co” (China), “NEOMAT Co” (Latvia) etc.

Purpose of research

The work focuses on assessment of application efficiency of silicon nano-carbide in technology of



composite electrochemical coatings (CEC), structural ceramics, and electro-explosive alloying (EEA) of steels.

Silicon nano-carbide in technology of composite electrochemical coatings

In technology of composite electrochemical coatings metal (nickel, chromium, ferrum, and copper) is crystallized from electrolytes – suspensions containing an additive which is called a strengthening agent (filler or modifying agent) and is made as a powdery substance. Its particles integrate with a metallic matrix forming on a surface of a product. Operational characteristics of the coating get improved due to particles integrated with it, so composite electrochemical coatings can facilitate solution of numerous practical problems focused on surface hardening of structural components and tool equipment, as well as on renovation of their quick-wear components. The degree of dispersibility of a hardening agent is to be increased in order to improve characteristics of composite electrochemical coatings. For the same purpose a hardening agent is to be applied with essentially smaller particles than the matrix grains. In this case, first, electrochemical coatings quality can be improved because porosity and micro-roughness of the surface are reduced, second, a matrix with a balanced sub-grain structure and proportional concentration of particles is formed, third, physical and mechanical properties of coatings are improved due to the effect of disperse hardening and reducing internal stresses, fourth, technological possibilities to produce composite electrochemical coatings are widened because of insignificant sedimentation of nano-dimensional particles in electrolytes-suspensions and increased adsorption of ions and other additives. These facts pre-determine constant attempts of experts dealing with composite electrochemical coatings technology to use materials of high dispersion, as well as nano-materials as hardening agents [3, 4].

While selecting a hardening agent diamond and cubic boron nitride, silicon carbide, high melting point, hard, wear and scale resistant oxides, metal like carbides, borides, nitrides, silicides and their composites are the most preferable substances. However, a 25-year monitoring of academic and applied investigations in the field of composite electrochemical coatings has revealed that the requirement for such materials is met basically by micro-powders of abrasive purpose, which usually have M1...10 grain fineness, or finely-dispersed materials of chemical technology. The latter are distinguished by low concentration of main agents, typical for mechanically grinded materials fission form of particles, and a great number of admixtures. A hardening agent of this kind, average particles of which are comparable with the 5-20 μm grain of coating metallic matrix, significantly improves hardness and wear-resistance of composite electrochemical coatings, which contain ferrous metals, copper and some low-melting point alloys. However, it doesn't have a positive effect on strength characteristics of a coating, reduces its resistance to corrosive attacks, and worsens heat-resistance and high-temperature strength. The reason for it is in dissimilarity of characteristics of composite electrochemical coatings, caused by unevenly distributing particles of more than 1 μm , as well as by an increased porosity of coatings and hydrogen embrittlement. For a long period of time these factors have necessitated the development and implementation of special technologies to produce materials – efficient hardening agents in order to solve urgent problems of galvanics via composite electrodeposition.

Silicon nano-carbide was used as a hardening agent in the course of electrochemical deposition of chromium-plating electrolytes. To solve the problems of composite hardening one used nano-carbide, obtained via carbonization of silicon micro-powder by methane– SiC (1) and plasma modification of micro-powder – SiC (2) [5]. The characteristics of nano-powders (NP) of silicon carbide SiC (1) and SiC (2), their physical and chemical properties are listed in Table 1, and electron micro-photographs are shown in Figures 1 and 2.

Table 1. Basic characteristics of silicon carbide powders

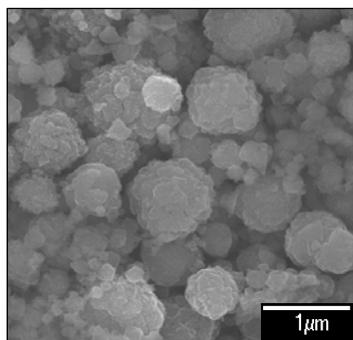
Characteristics of nano-powders	SiC (1)	SiC (2)
Phase composition	β -SiC	β -SiC
Chemical composition of the main substance	$\text{SiC}_{0.95}\text{N}_{0.05}$	$\text{SiC}_{0.95}\text{N}_{0.05}$
Concentration of the main substance, %	99.21*	99.30*
Concentration of free carbon admixture, %	0.06	0.05
Specific surface, m^2/kg	38000	37000
Dimension** of particles, nm	62	61
Form of particles	Faceted	
Corrosion resistance in solutions of electrolytes	Stable in electrolytes of different acidity	
Thermal-oxidative stability in air, K	to 913	
Notes: * After refining.		
** It is calculated according to the size of specific surface.		

For electrodeposition of composite electrochemical coatings chromium – nano-carbide chromium-plating electrolyte was used, containing NP of silicon carbide SiC (1) or SiC (2) with the following chemical composition, kg/m^3 : chromium anhydride 250, sulfuric acid 3, trivalent chromium 8. For electrolyte – suspension some pure electrolytes were added to a sample powder, the components were mixed up to complete wetting of the powder, put into electrolyzer and dissolved till a required concentration was obtained. pH was adjusted with solutions of NaOH or H_2SO_4 .

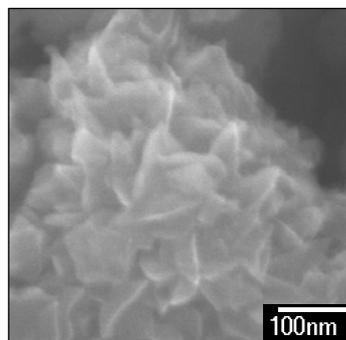
On the basis of analyzed results of experiments and industrial application of silicon nano-carbide SiC (1) and SiC (2) a possibility of parametric, concentration, structural and technological effects has been revealed. So, the following change in cathodic density of current was characteristic for the used chromium-plating electrolyte in dependence on dispersion of the filler agent (MP – micro-powder of silicon carbide with particles of maximum 5 μm):

Without a filler agent ($5 \text{ kA}/\text{m}^2$) \rightarrow MP SiC (5.5-6.0) \rightarrow NP SiC (1), SiC (2) (8-10).

Obviously, the increase in acceptable cathodic density of current is caused by stabilization of pH in cathode layer when the second agent is added to the electrolyte. A coating is saturated with carbide nano-particles when their mass concentration is low in a coating and in electrolyte (Table 2); that is because the quantity of nano-particles rises per a unit of volume and facilitates dispersive hardening of metallic matrix. Micro-hardness of chromium containing composite coatings with nano-components is 1.80-1.90 times higher than that of chromium, and 1.10-1.20 higher than micro-hardness of composite coatings containing micro-powders (Table 2), and in all cases microhardness grows as the quantity of particles increases in a composite material. Increase in hardness is caused by high efficiency of nano-particles acting as a barrier to distribution of dislocations.



a



b

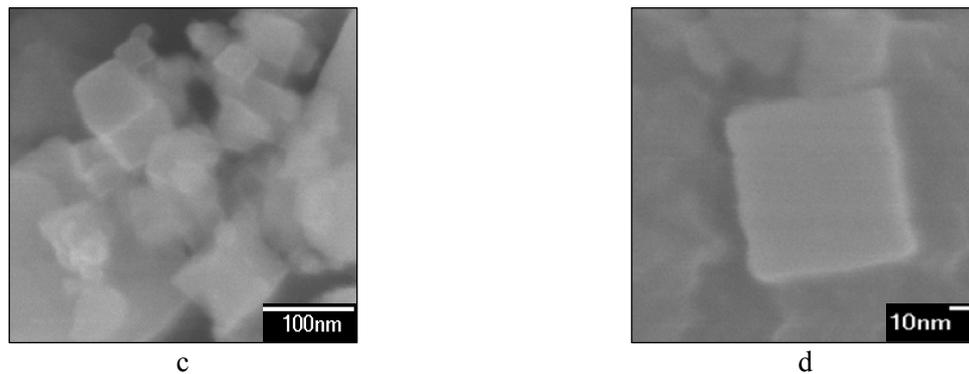


Figure 1 Micro-photographs of silicon carbide nano-powder SiC (1): a – in as received condition after refining; b – morphological picture of an aggregate; c – ensemble of nano-particles; d – a cubic nano-particle

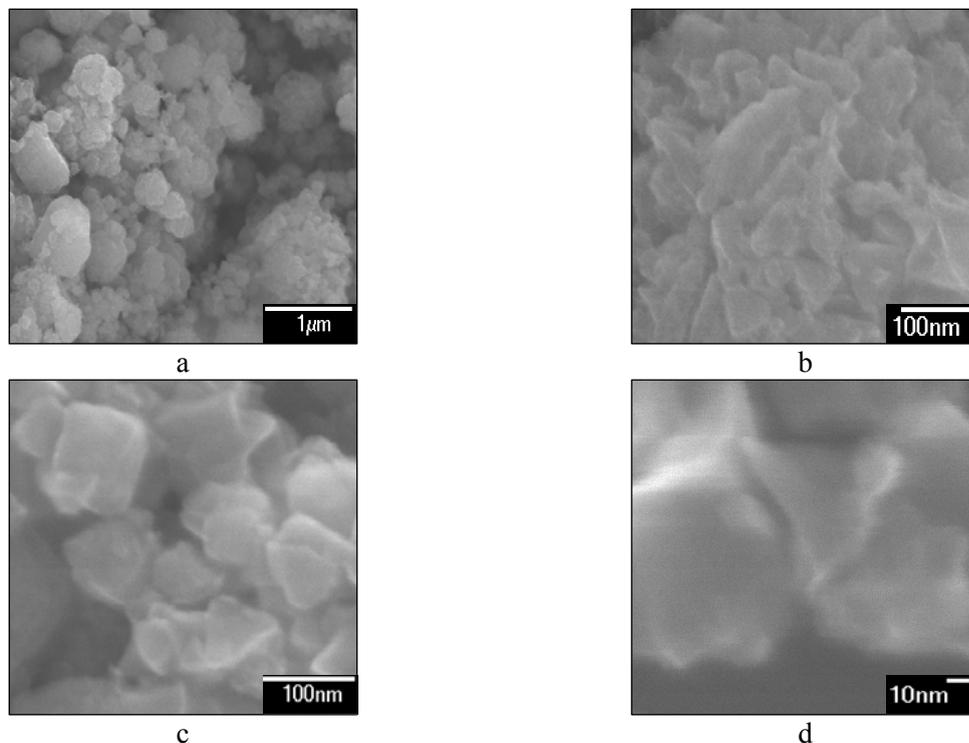


Figure 2. Micro-photographs of silicon carbide nano-powder SiC (2): a – in as received condition after refining; b – morphological picture of an aggregate; c – ensemble of nano-particles; d – octahedral nano-particle

Nano-particles in chromium matrix reduce the intensity of its wear 1.25-2.5 times when concentration of nano-powder changes from 0.15 to 0.45 %. Considerable improvement of wear resistance of Cr – NP SiC material is possible because there are no excitors of local stress concentration in the structure of the layer – micro-cracks; their number is rather significant in chromium layers. Corrosion stability of composite electrochemical coatings Cr – NP SiC, determined in a liquid medium, shows that composite electrochemical coatings excel 1.3-1.5 times conventional chromium coatings (frequency index of corrosion 0.3 %) and can be considered as stable ones.

Table 2. Dependence of hardening agent concentration (a) and micro-hardness (N) of composite electrochemical coatings* on concentration of NP and MP in electrolyte

Concentration of NP, MP in electrolyte, kg/m ³	a, % / N, GPa		
	Cr – NP SiC (1)	Cr – NP SiC (2)	Cr – MP SiC
1.0	0.20/9.0	0.24/9.1	0.47/8.4
3.0	0.41/9.3	0.43/9.2	0.72/8.6
10.0	0.59/9.7	0.58/9.4	0.89/8.9
20.0	0.82/10.1	0.84/10.1	1.1/9.0

Note: * Conditions of electrodeposition: CEC Cr – NP, MP SiC – cathodic density of current 8.0 kA/m², pH 2.0, T = 323 K.

To assess the possibility of replacing explosively synthesized nano-diamonds by silicon nano-carbide, we compared characteristics of chromium – carbide and chromium – diamond coatings (Table 3). As you can see, wear-resistance, microhardness, corrosion-resistance of chromium – carbide coatings are comparable with those of chromium-diamond ones, and the life time is even longer in operating conditions at temperatures above 473-573 K, that is provided by lower concentrations of carbide nano-powder in electrolyte and significant cost reduction of 1 m³ of electrolyte – suspension.

Experimental data demonstrate technological reasonability of nano-powders application with a specific surface, which doesn't exceed 40,000 m²/kg (Table 4); and has a restricted concentration (maximum 1.0 %) of free carbon (Table 5).

Table 3. Comparative characteristics of coatings containing chromium with nano-powders of silicon carbide SiC (1) and nano-diamond [6]

Conditions of electrodeposition and achieved results		Technological variants					
		1	2	3	4	5	6
Chemical composition of electrolyte, kg/m ³	Chromium anhydride	250	250	250	250	250	260
	Sulfuric acid	3	3	3	3	3	0.34
	Trivalent chromium	8	8	8	8	8	–
	Potassium fluorsilicate	–	–	–	–	–	19
	Barium sulfuric	–	–	–	–	–	7
	NP of silicon carbide – SiC (1)	4	6	7	8	10	–
	NP of diamond	–	–	–	–	–	20
Deposition mode	Temperature, K	328	328	328	328	328	331
	Density of current, A/dm ²	55	55	55	55	55	55
Results	Wear-resistance*	0.96	1.0	1.05	1.07	1.08	1.0
	Micro-hardness, GPa	8.9	9.0	9.1	9.15	9.15	9.0
	Corrosion resistance*	0.96	1.05	1.07	1.10	1.10	1.0
	Life time at temperature above 473-573 K*	1.1	1.50	1.70	2.00	2.06	1.0
	Cost of 1 m ³ of electrolyte suspension*	0.13	0.16	0.18	0.20	0.23	1.0

Note: * Wear and corrosion resistance, life time in operating conditions at temperatures above 473-573 K, cost of 1 m³ of electrolyte suspension are given according to variant 6, the values of these characteristics for it are thought of to be equal to 1.0.

Table 4. Comparative characteristics of coatings containing chromium with NP of silicon carbide SiC (1) having different specific surfaces (for conditions of technological variant 4, Table 3)

Specific surface of silicon carbide NP, m ² /kg	11000	22000	32000	38000	51000
Wear resistance	0.89	0.99	1.0	1.03	0.93
Micro-hardness, GPa	7.92	9.27	9.32	9.39	8.51
Corrosion resistance	0.82	1.0	1.0	1.0	0.91
Life time in conditions of operating at temperature above 473-573 K	0.72	1.0	1.0	1.0	0.88

Table 5. Comparative characteristics of coating containing chromium and NP of silicon carbide SiC (1) with different concentration of free carbon in it (for conditions of technological variant 4, Table 3)

Concentration of free carbon in nano-powder of silicon carbide, %	0.8	1.5	2.4
Wear resistance	1.0	0.86	0.79
Micro-hardness, GPa	932	760	710
Corrosion resistance	1.0	0.89	0.79
Life time in conditions of operating at temperatures above 473-573 K	1.0	not recommended to use in these conditions	

Utilization of more dispersed nano-materials makes the technology of production and application of electrolyte-suspension more complicated. This fact has been also mentioned in other researchers' papers. For instance, authors in paper [6], who used diamond nano-powders with a specific surface 400.000-500.000 m²/kg (particles 4-5 nm) for composite chromium-plating, noted, that it is rather difficult to add nano-powders to the electrolyte, if electrolyte-suspension is made in a conventional way (it takes about 50-80 hours to stir the mixture), therefore they had to design a special multi-operational technology. Authors [7], who used nano-powder of aluminum oxide for composite chromium-plating with a specific surface 100.000-150.000 m²/kg (particles 15-18 nm), also mentioned difficulties of making electrolyte-suspension, and recommend to add nano-powder to the electrolyte in form of a concentrated suspension, processed ultrasonically with 22 kHz frequency. All the mentioned peculiarities demonstrate that there are processes of nano-particles coagulation in electrolyte, which cause coarsening of particles, and get stronger if nano-powders with specific surface 50.000-500.000 m²/kg are applied. Reasons for coagulation processes are as follows: instability of nano-systems with an excessive surface energy and an insufficient wetting of nano-powders, caused by the state of their particles surface and a surface charge available or unavailable on them. As a result, it is necessary to electrodeposite coatings from electrolytes – suspensions with higher concentration of nano-powders.

On the basis of research authors developed a method that helps to obtain composite electrochemical coatings containing chromium [8] and technological processes of composite hardening by silicon nano-carbide. CEC containing Cr – NP SiC are recommended to be used to protect components and technological tools subjected to wear (for example, threadlike sensors of twisting frames, shock strut pistons etc), simultaneous wear and corrosion (for example, die molds to press products of thermal plastic materials, components of gas and oil-field equipment etc.). However, economically and technologically they are more reasonable to be used instead of chromium-diamond CEC for surface hardening of tools, equipments, components of machines, which are operated in high temperatures (above 473-573 K): extrusion toolage for powder metallurgy, components of tool production – puncheons, stamps, matrixes, holders of puncheons etc., elements of pistons in internal combustion engines etc.

Silicon nano-carbide in technology of structural ceramics

Polycrystalline materials produced via sintering non-metallic powders of natural or artificial origin are thought of as ceramic materials. The advantages of ceramics over alternative metallic materials are as follows: availability of raw materials, low power-intensity of production processes, environmental safety, complex of good physical and chemical, mechanical properties (hardness, refractoriness, corrosion, thermal and radiation resistance etc.). Up to date types of ceramic are divided into two groups: structural and functional ones. Structural ceramics includes ceramic materials used to produce mechanically stable structural elements of devices, and functional one is ceramics with special electrical, thermal, optical and magnet functions. Structural ceramics is further subdivided into oxide and oxygen free ones (containing carbides, nitrides, borides).

Silicon carbide in form of micro-powder is used to manufacture products of wear resistant mechanical engineering ceramics – components of stop and control valves. Ceramic control and stop valves can be resistant to hydro and abrasive wear, corrosion and temperature effects, as well as to corrosive liquids influence. Therefore, it can be used in oil and chemical equipment to control technological processes. The valves consist of gates, butterfly dampers, valves, control flap balls (balls and seats), bushes of stuffing units, stuffing rings etc. Ceramic bearings are among the most promising types of ceramic products. Being hard and capable to stand temperatures up to 1000 °C, arising in friction, ceramic bearings 100 times outperform steel ones in terms of lifetime and run without being lubricated. As density of ceramics is low, application of ceramic bearings have mass advantage up to 60%, at high speeds it reduces centrifugal forces. Chemical stability, radiation resistance, good dielectric characteristics, lack of magnetism, and low density make it possible to use ceramic bearings to kit equipment in oil and chemical industries, in nuclear and power facilities. Ceramic bearings are also efficient in precision and navigation instruments, in defense industry, for example, in gyroscopes and in high-speed machines – turbines, compressors, machining centers.

Enterprises in Russia produce wear resistant silicon carbide ceramics oriented towards ceramic raw materials – micronized carbide, and imported technological equipment characterized by high thermal power parameters of compaction. Here, it is an important scientific and technical issue, relevant to various branches as well, to develop an industrial technology to produce silicon carbide with properties providing its efficient application in manufacturing structural ceramics for mechanical engineering (so called structural carbide). Structural carbide, containing additives, which activate sintering process, can be used to develop more promising manufacture of ceramics – by solid-phase sintering, implemented by means of relatively affordable Russian equipment.

One made use of silicon nano-carbide in technology of structural ceramics, which was produced via carbonation of silicon micro-powder with methane – SiC (1) and modification of carbide micro-powder in plasma flow of nitrogen – SiC (2) with further refining.

Silicon nano-carbide is similar to structural silicon-carbide powders produced by overseas companies (Table 6) in basic characteristics (dispersion degree, phase and chemical composition). Technological advantage of the introduced material is its possibility to deliver it as a composition with pre-set components, containing additives, which activate the sintering process (reactive boron and carbon).

Table 6. Chemical and phase compositions, modes of solid-phase sintering and physical and mechanical properties of silicon-carbide ceramic materials

Characteristics of silicon carbide powders, conditions of preparing and modes of solid-phase sintering	Trade mark, manufacturer			
	SiC (1)	SiC (2)	A-10 “Hermann Starck Co.”	B-10 “Hermann Starck Co.”
Phase composition	β -SiC	β -SiC	α -SiC	β -SiC
Chemical composition, %				
SiC	90.16	90.00	97.0	95.0
C _{free}	2.70	2.69	1.0	1.9

Characteristics of silicon carbide powders, conditions of preparing and modes of solid-phase sintering	Trade mark, manufacturer			
	SiC (1)	SiC (2)	A-10 "Hermann Starck Co."	B-10 "Hermann Starck Co."
B _{free}	2.52	2.63	–	–
Si _{free}	0.03	0.02	0.01	0.02
SiO ₂	4.51	4.60	1.88	3.02
Al	0.04	0.03	0.1	0.04
Fe	0.04	0.04	0.01	0.02
Correlation SiO ₂ : C in mixture, mole/mole (stoichiometric "for carbide" 1 : 3)	1 : 3.01	1 : 2.98	1 : 2.69	1 : 3.17
Specific surface, m ² /kg	38000	37000	11000	15000
Dimension* of particles, nm	67	66	700	600
Heat treatment of mixture T = 1073 K, P = 100 Pa, τ = 1 h	+	+	+	+
Plasticizing of mixture with 5 % solution of plasticizing substance	+	+	+	+
Cold press of half products in steel collapsible press form P = 50 MPa	+	+	+	+
Relative hardness before sintering	0.63	0.62	0.64	0.61
Solid-phase sintering in argon T = 2273 K, P = 0.1 MPa, τ = 2 h	+	+	+	+
Relative density of sintered samples	0.95	0.96	0.86	0.87
σ _{u32. 20° C} , MPa	340	380	310	320
Note: * Calculated according to specific surface.				

Silicon nano-carbide was proofed and applied in solid-phase sintering of half products needed to manufacture ceramic sealing rings of grades 156.017 and 156.073 from 16 to 30 mm in outer diameter and 18 to 30 mm high intended for pumps and submersible electrical engines, dispensing oil and oil products, and condensed carbonic gases in order to substitute imported non-grinded A-10 and B-10 grades silicon carbide synthesized in furnace by companies "Hermann Starck Co.". Here, technological advantages of silicon nano-carbide were confirmed and following results were obtained (Table 6). Silicon nano-carbide makes it possible to avoid adding organic substances to the mixture and their carbonation to provide evenly distributed reactive carbon and restoration of silica film on carbide nano-particles, and mixing on rolls. It simplifies and reduces the cost of the technology and facilitates its implementation according to the following acceptable variant: heat treatment of powder in vacuum at 1073 K, adding a plasticizer, mixing and pressing under the pressure of 50 MPa, annealing for 2 hours in argon under the pressure of 0.1 MPa and at temperature 2273 K. If one follows the technology, relative density after forming 0.62-0.63, after sintering 0.95-0.96 and stable shrinkage 26-29% are provided.

Silicon nano-carbide in technology of steel surface hardening via electro-explosive alloying

Changing operational standards of materials constantly necessitate research into the field of surface modification. That is why, an urgent issue these days is development of environmentally safe new technologies to modify materials in order to change their structure and phase state, physical and mechanical properties with number of advantages over both conventional technological processes of thermomechanical, chemical and thermal treatment; and methods of impact based on such types of concentrated flows of energy that include laser irradiance, high-current electron and ion beams etc.

Here, it is worth mentioning that silicon carbide has always attracted attention of the authors of innovative technologies in the field of modification, including the following ones: alloying surface layer of steel cast products to improve their wear resistance via treatment of cast forms from inside by mixtures, containing silicon carbide; electrical discharge alloying by electrodes made of various materials of treated surfaces, preliminary coated by mixtures, containing silicon carbide; electro-explosive alloying along with adding silicon carbide to explosion zone.

The essence of electro-explosive alloying is that the surface is influenced by heterogeneous plasma beams forming in the course of electric explosion of conductors [9 – 11]. Here, the following processes take place: melting, saturation of thin surface layers of metals with products of electric explosion and self-annealing of alloying zone. The main advantage of electro-explosion alloying over other similar pulse plasma methods of surface processing is that any electricity-conductive material can be used to produce plasma. Technological possibilities of the method can be considerably widened, if powder additives of various substances are added to the zone of conductor explosion. In recent years electro-explosion alloying has been developed as an independent research domain mainly; its technological implementation is a multivariate one. Layer by layer tests of the structure, phase composition and characteristics of alloying zone demonstrate that, at least, a near surface layer has a nano-composite structure. There are intermediate and border layers below the near surface layer; constantly reducing degree of alloying and growing dimensions of structural components are their distinctive features. Nano-dimensional phases are typical to all layers. Therefore, one can insist that nano-composite bounded with the base layers are obtained via electro-explosion. As the consequence of structural changes we can consider the increased several fold microhardness, wear resistance, stability to high temperature oxidation, and corrosion resistance of processed surfaces. The main structural component of equipment, which is used for electro-explosive alloying, is a plasma generator consisting of coaxial electrodes and compression chamber with the nozzle, directing the products of explosion; the latter is located in a technological chamber connected to a vacuum pump. When a conductor explodes an ultrasonic beam of explosion products is formed, and while reacting with the surface it provides necessary conditions for pulse liquid-alloying (for approximately 100 microseconds). The mode of processing usually depends on charge voltage of storage condenser, and the surface to be processed is oriented perpendicularly to the axis of plasma beam. Technological information available nowadays, relies on results of research and implementation of electro-explosive carburizing, boriding, aluminizing, carbon-boriding, but no data are practically at disposal of researchers concerning high-melting carbides, borides, nitrides, silicides, applied traditionally in strengthening technologies due to good physical and chemical properties and complex nature of modifying effect [12 – 13].

Silicon nano-carbide SiC (1) (Table 1), containing 99.21 % β -SiC with specific surface 38000 m²/kg was first applied as a powdery additive in the technology of surface hardening of steels via electro-explosive alloying. Forming composite surface layers were tested on the samples of tool steel X12 in conditions of electro-explosion of aluminum foil and adding silicon nano-carbide to the zone of explosion. This steel was selected because of its wide application in production of tools aimed to form materials (stamps, punches etc.), so high resistance to tear is relevant for this steel. It is worth paying attention to silicon nano-carbide. Phase composition of surface layers of steel after processing was tested, as well as their properties – micro-hardness, wear and heat resistance.

30 mg of aluminum foil were used as an exploded conductor; a sample of 7.5 mg silicon nano-carbide was placed on the foil. 25 x 20 x 5 mm samples of steel were tested. The surface was impacted within 100 microseconds, efficient accepted power density was 6.0 GWatt/m², and dynamic pressure of jet on the surface was 14.2 MPa. In these conditions a zone of alloying was approximately 20 μ m deep.

Electro-explosion alloying in high-intensive conditions of plasma impact on a surface caused melting and saturation of steel surface layer both with products of aluminum foil explosion and nanoparticles of silicon carbide, then it was self-annealed and austenite structure was formed. Microhardness of the surface of non-processed samples was 2513 \pm 205 MPa, and after processing it increased 2.8 times in average. Mass loss of steel samples in as received condition was 27.4 \pm 7.3 mg while wear

resistance was tested, and after electro-explosive processing – 3.3 ± 2.5 mg, i.d. wear resistant increased 8 times. Tests on heat resistance demonstrated that mass corrosion of samples in initial state was 2.7; 5.2 and 10.6 g/(m²·h) at temperatures 800, 850 and 900 °C, respectively. After shielding processing the following values were obtained 0.3; 1.5 and 5.3 g/(m²·h). Heat resistance increased 9; 3.5 and 2 times at given temperatures, that is approximately two times higher than corresponding values of heat resistance of this steel after two-component electro-explosion alloying, for example, by boron or gadolinium.

Therefore, the zone of alloying is characterized by high micro-hardness and is stable to abrasive wear and high temperature oxidation in the air.

Conclusions

High efficiency of silicon nano-carbide has been confirmed in the technology of composite chromium-plating, structural ceramics, surface modifying of steels via electro-explosion alloying. Chromium-carbide coatings are distinguished by wear resistance, micro-hardness, corrosion resistance comparable with chromium-diamond coatings, and a prolonged lifetime. Sintered silicon-carbide ceramic half products have high density and stable shrinkage. Zone of alloying containing silicon nano-carbide is characterized by high micro-hardness, abrasive wear and thermal-oxidative resistance.

The work is performed in Siberian State Industrial University as a project of the State Order of Ministry of Education and Science of Russia № 11.1531/2014/K.

References

- [1] Galevsky G V Rudneva V V Yurkova E K Nano-materials and nanotechnologies: assessment, tendencies, and forecasts *Russian Journal of Non-Ferrous Metals* 2007 V. 48 No 2 p 157 - 160
- [2] Brodov A A Kazakova T I Molotilov B V Economic analysis of the industrial use of nano-materials *Steel in Translation* 2006 V. 36 No 5 p 67 – 71
- [3] Nozdrin I V Terenteva M A Galevsky G V Rudneva V V Features of Electrodepositing of «Nickel – Chromium Diboride Nanopowder» Composite Coatings *Russian Journal of Non-Ferrous Metals* 2013 V. 54 No 5 p 383 – 387
- [4] Skachkov O A Firstov M N Zmii V I Pozharov S V Ezhov A Yu Astakhov S I Chuikova V B High-temperature protective coatings on refractory metals *Steel in Translation* 2006 V. 36. No 4 p 75 – 80
- [5] Polyakh O A Rudneva V V Yakushevich N F Galevsky G V Anikin A E Silicon carbide production from steel plant wastes *Steel in Translation* 2014 Vol. 44 No 8 p 565 – 572
- [6] Pat. 2156838 RF, MPK C25D15/00. Way of receiving composite metal-diamond coverings, E.V. Nikitin, L.A. Polyakov, N.A. Kalugin; combine «Elektrokhimpribor». No. 99108896/02; declar. 21.04.99; publ. 27.09.2000.
- [7] Pat. 2148109 RF, MPK C25D3/04. Way of receiving heat-resistant chromic coverings, I.G. Idrisov, V.V. Kovalyov. BTI AGTU. No. 99102009/02; declar. 01.02.99; publ. 27.04.2000.
- [8] Pat. 2318083 RF, MPK C25D 15/00. Way of receiving composite electrochemical coverings on the basis of chrome, G. V. Galevsky, V. V. Rudneva, O. A. Polyakh. No. 2006129821/02; declar. 17.08.2006; publ. 27.02.2008. Bull. 6. 5 p.
- [9] Ivanov Y F Denisova Y A Teresov A D Petrikova E A Gromov V E Soskova N A Budovskikh E A Electron-beam surface treatment of alloys based on titanium, modified by plasma from an electrical explosion of conducting material *Bulletin Of The Russian Academy Of Sciences Physics* 2012 Vol. 76 No 11 p 1246 – 1252
- [10] Ivanov Y F Budovskikh E A Gromov V E Bashchenko L P Soskova N A Raikov S V Formation of nano-composite layers at the surface of vt1-0 titanium in electro-explosive carburization and electron-beam treatment *Steel In Translation* 2012 Vol. 42 # 6 p 499- 501
- [11] Karpil S V Morozov M M Ivanov Y F Budovskikh E A Gromov V E Formation of nano-phases

- in electro-explosive alloying with aluminum and boron and electron- beam treatment of titanium surfaces *Steel in Translation* 2010 Vol. 40 # 8 p 723-728
- [12] Oskolkova T N Budovskikh E A Pulse plasma treatment of surface of alloy VK10KS *Metal Science and Heat Treatment* 2012 Vol. 53 #11-12 p 608 - 610
- [13] Oskolkova T N Budovskikh E A Electric explosion alloying of the surface of hard alloy VK10KS with titanium and silicon carbide *Metal Science and Heat Treatment* 2013 Vol. 55 # 1 p 96 - 99