Investigation of Structure and Properties of Tool-electrode "Cu-Ti$_3$SiC$_2$" for EDM

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Abstract—**The aim of this paper is to study the structure formation in the composite powder material "copper- Ti$_3$SiC$_2$" and to study erosion-resistance of tool-electrode made from this material by EDM of metal alloys. The influence of Ti$_3$SiC$_2$ content on the properties (porosity, hardness, strength, electrical resistance, erosion wear) of composite materials Cu-Ti$_3$SiC$_2$ was studied. The features of the structure formation of composition of materials during sintering is deintercalation of silicon from Ti$_3$SiC$_2$, formation of a solid solution of carbon-based titanium silicide Ti$_5$Si$_3$(C), small amounts of titanium carbide, silicon, and silicide TiSi$_2$. Increasing the concentration of Ti$_3$SiC$_2$ in the composite material reduces conductive properties, increases hardness, strength and wear resistance of the electroerosion electrode composites for EDM. The new material was used as a tool-electrode for electrical discharge machining for the first time. It was determined that the relative erosion wear resistance of a tool-electrode of composite materials Cu-Ti$_3$SiC$_2$, containing 12.5 - 37.5 vol. % Ti$_3$SiC$_2$, in electrical discharge machining was 5 times higher compared to that of pure copper.**

Keywords— EDM, tool-electrode, composite material, copper, Ti$_3$SiC$_2$, erosional-resistance

I. INTRODUCTION

The current stage of development of materials science is characterized by the appearance of new materials with unique properties, which, in turn, requires new processing technology, providing high quality machined surfaces and performance. A striking example of the condition of materials has always been aviation, where new materials appeared first, and then found application not only in other industries, but in medicine. Specialists of VIAM connect a new level of aviation developments only with a fundamentally new materials and technologies, as the traditional one has already been exhausted and the most important problem is the development of strategic directions of development of materials for various industries and technologies of their processing for the long period of time [1].

So a new direction in Aero engines was the use of thermal barrier coatings based on zirconium dioxide for the details of the combustion chamber (flame tube, the outer and inner shrouds), gas turbine engine with air cooling, which can significantly reduce the surface temperature of the parts to eliminate local overheating and thus ensure the service life of the combustion chamber.

In addition, new ceramic and composite materials are developed. Carbon-carbon composite materials are a new class of structural materials, designed to create heat-loaded parts of the airframe, aerospace and hypersonic aircrafts, gas turbine engines, parts of nozzle blocks missiles, aircraft brakes, tooling for the steel industry, etc. They have the unique ability to maintain high strength and stiffness at temperatures up to 2500°C, and the application of systems, barrier and antioxidant coatings provide the using of such composites in an oxidizing environment. However, machining of such materials is problematic due to their high hardness and high stress concentrations in certain areas of the layered composite [2, 3].

The electrical discharge machining method (EDM) of metals and other conductive materials consists in the fact that under the influence of the current pulses, melting and vaporization of metal occur, liquid metal particles are ejected from the discharge zone under the influence of working hydrodynamic forces. The electrode-tool delves into the product and creates the hole, corresponding to the shape of the electrode. The inevitable result of the current pulse action is melting not only the material to be treated, but also the electrode material; therefore are required special properties, such as mechanical strength, electrical conductivity in a temperature range from room temperature to the electrode material melting temperature, erosion resistance, electrical strength.

One of the drawbacks of high-speed milling in comparison with EDM is insufficient the ratio of the depth of the machined cavity with its width. The problem grows with decreasing radius of the inner edge and the deterioration of the access cavity.

According to the data of the company "CIMdata", obtained by the results of a survey of 75 companies located in Europe,

North America and Japan, currently in the factory or in the workshop producing molds and dies, on average about 35% fall to three-axis milling machines, 4 % - to five-axis ones and 15% - to EDM. The factories of Europe, which produce the basic number of EDM machines, prefer cutting machines, which quantity is three times more than that in American factories, and the number of copying and broaching machines is about the same in all regions. Park EDM machines are expected to increase by 15% in North America and by 20% - in Europe, which confirms the attractiveness of EDM for the Europeans [4].

In contrast to machining EDM, it is possible to process virtually any conducting materials. Regardless of their hardness, it is possible to carry out elements of complex shape with high machining accuracy, for example, templates, gauges, cutting tools, bending dies. Future prospects of this type of processing are associated with the implementation of cooling channels in turbine blades, pockets, transitional elements that vary seriously since the requirements for the geometry of the flow part of the blades are very high (deviations from the profile pen of 0.02-0.04 mm). And they are promising in the manufacture of small blades with a thin pen [5]. EDM is indispensable when manufacturing press tools (dies) made from difficult-to-cut tool steels, models for casting under pressure [6] due to its high accuracy. Qualitative electrical discharge machining of complex geometrical profiles, such as curved impeller blades, [7], precision shells of spherical shape, is possible. The EDM method allows obtaining thin-walled products (e.g., dental crowns), articles with a hole diameter of 0.3-1 mm and a depth of 2900 mm, for example, injectors of internal combustion engines, turbine blades [8].

Machining accuracy depends on durability of the electrode-tool. One way to reduce the electrode-tool wear is to use materials having high erosion resistance.

The main materials for the manufacture of electrode-tools for EDM are graphite [6, 9], which is currently used not only for rough, but also for sheer processing [10, 11] of copper [6, 12] and its alloys (brass, aluminum) [13]. Composite materials based on copper with the addition of chromium, molybdenum, boron nitride, tungsten carbide are also included in this group [6, 14]. Electrode materials, based on copper, constitute the bulk of the used metallic materials. The most commonly used electrolytic copper has high electrical and thermal conductivity. During processing by rectangular-shaped pulses, the use of EI copper with a porous structure (15% pores) allows increasing the removal rate of material of the part 1.5 times, compared to the EI of copper; EI vitality increases as well. Brass LS-59-1 is of limited use in case of EEE of closed cavities due to its erosion resistance, reduced to 1.5-3 times compared to copper [6].

Effective solution to improve the wear resistance of the electrodes is the use of composite materials. Using electrode-tools, made of composite materials, improves the economic

efficiency of machining of hard, refractory and titanium alloys, as well as heat-treated steels [5].

The composite materials for EDM, based on a copper with refractory dispersed particles of oxides, borides, nitrides, which improve the performance characteristics are known. Electrodes tools, made of copper and composite materials and based on copper with addition of tungsten, boron nitride, and those, made of composite materials and based on copper with chromium, molybdenum, boron nitride, tungsten carbide [15, 6, 12], etc., can be used in virtually all EDM, providing high performance. They can handle large and small areas of virtually any material.

The development of new erosion-resistant materials for tool-electrodes, intended for electrical discharge machining (EDM) with low cost and high resistance to wear, is a very important technical and economic problem, because sometimes the erosion wear of tool-electrodes can exceed the volume of removed metal from the workpiece 10-100 times, and the EDM becomes too expensive [15].

Powder metallurgy method allows varying the chemical composition, dispersion and technological parameters of manufacture of composite materials for the tool electrode. The capacities of powder metallurgy can be especially useful in the development of new EDM processes, for example, treatment of non-conductive ceramic. The manufacture of the electrode-tool by powder metallurgy is considered technologically and economically expedient if a powder particle size is less than 40 microns and an electrode-tool is manufactured on commercially available equipment. At that, specific molding pressure is not higher than 400 MPa, sintering temperature is below 1200 ° C., the holding time at sintering temperature is not more than 1 hour [5, 15].

It is well known that addition of a refractory component increases the hardness and erosion-resistance of the electrode, but it can decrease the electrical and thermal conductivity. The optimization of properties of composition material can be associated with an increase of the electrical conductivity of the refractory phase and capillaries.

When the proportion of the refractory component is increased, the performance of the electrodes increases [16], but the electrical and thermal conductivity deteriorates. Therefore, the optimization of the material composition may be related to the replacement of refractory phases with solid and conductive phases.

Ti_3SiC_2 can become the promising refractory additive [17].

The unit cell of titanium carbon silicide Ti3SiC$_2$ consists of two types of alternating and weakly bonded to each other layers of carbide [Ti_3C_2] and Si planes. Bonds "titanium - carbon" have exceptional strength, because they are mainly metallic, covalent and ionic. Bonds "titanium-silicon" are weak, resulting in the high mobility of densely packed layers of titanium, comprising carbon atoms. This allows shifting the layers relatively each other without macroscopic fracture of the material [18]. The thermal conductivity of titanium carbon

silicide hardly changes with increasing temperature, unlike titanium carbide. Ti_3SiC_2 has lower resistivity than that of titanium and much lower than that of the majority of ceramic materials. A remarkable feature of titanium is independence of its resistivity of the temperature, which is typical of the majority of carbides [19]. Since the system of titanium karbosilicide Ti_3SiC_2 has mixed conductivity n / p-type, the resistance strongly depends on the presence of even a small number of defects and small deviations from the chemical composition [17]. The interaction of carbon silicide of titanium and copper has been investigated in recent years.

In [20], it was noted that Ti_3SiC_2 is able to replace graphite in a new class of self-lubricating materials for the electrical sliding contacts.

It is established that the formation of interphase layers contributed to the improvement of wettability of the system. The dissolution of Si from Ti_3SiC_2 into molten Cu at high temperature plays a dominant role in improving the wettability of Cu / Ti_3SiC_2 [21].

It is shown that a small amount of Ti_3SiC_2 (1.25% by mass) of the particles can increase the hardness of the composite material without a significant loss of electrical conductivity [22].

The aim of this paper is to study the structure formation in the composite powder material "copper-Ti_3SiC_2" and to study erosion-resistance of tool-electrode made of this material by EDM of metal alloys.

II. METHODS

Electrolytic copper powder ICP-1 (GOST 49-60-75) and a Ti_3SiC_2 powder, obtained by reaction sintering, were used to produce electrode composite materials. Both powders were mixed for 4 hours. The samples were pressed from the mixtures of powders at a pressure of 600 MPa. Then the pressings were annealed in a vacuum furnace at a temperature of 700 ^{0}C and repeatedly pressed at 600 MPa. The powder compacts were sintered finally in a vacuum furnace at a temperature of 1070 ± 10 ^{0} C, for 2 hours.

X-ray diffraction analysis was performed on a diffractometer «Shimadzu-XRD 6000» in the Cu-Kα-radiation. Identification of the phase composition was performed by the card file of the International Centre ща diffractometry measurements. The microstructure was studied by a scanning electron microscope «Tescan Vega3 Sem». The density of the composite materials was determined by the standard method of hydrostatic weighing (GOST 18898-89). The electrical resistance was measured on a digital programmable millimeter GOM-802 in the samples with a size of 6x6x50 mm.

The performance test of the electrodes was carried out at EDM of the tool steel sheet (12 % Cr, 1 % V) 5.5 mm thick and with a hardness of 58 HRC on a machine "Electronica Smart CNC" for processing in draft modes of E81 (pulse duration of 100 ms, 32 ms pause, 15A current) and E92 (pulse width - 150 ms, 32 ms pause, 20A current). EDM Oil - IPOL SEO 450 was used as the working fluid. The relative erosive

wear of the tool-electrode was determined by the ratio of the depth of the holes in the steel to linear wear of the electrode [15].

III. DISCUSSION AND RESULTS

Fig.1a and Table 1 show the XRD patterns of pure powder Ti_3SiC_2 where only reflexes from Ti_3SiC_2 planes are present.
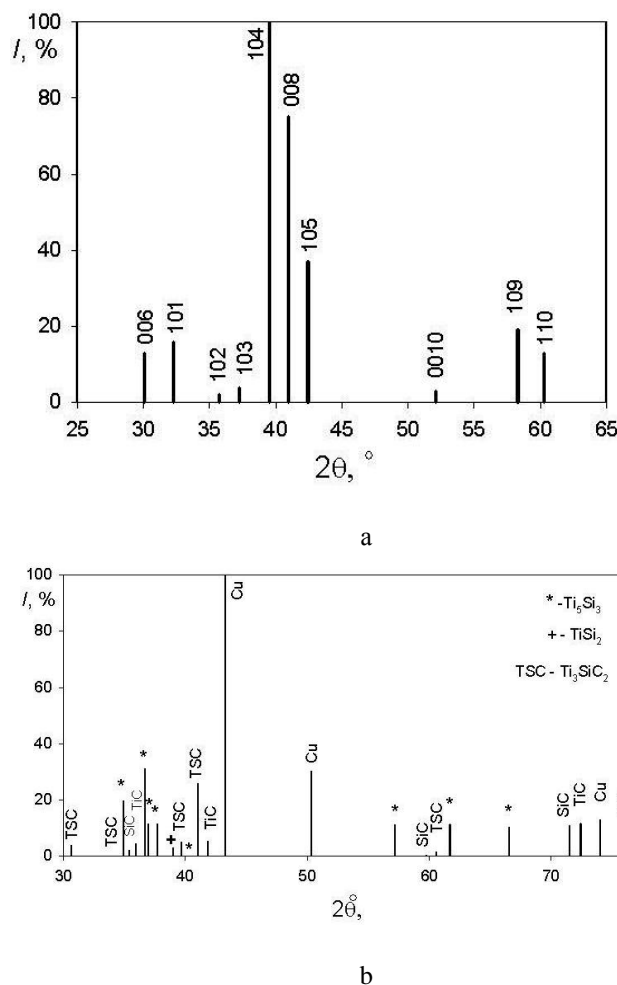

a

b

Fig. 1. XRD patterns of pure Ti_3SiC_2 (a) and sintered powder material «Cu-37.5 vol. % Ti_3SiC_2» (b)

Fig.1 and Table 2 show the XRD patterns of sintered composite material Cu-Ti_3SiC_2. It is noticeable that there are several phases: basic - Ti_3SiC_2 and a number of new phases - Ti_5Si_3, TiC, SiC, $TiSi_2$ (phases were identified by the card file of the International Center of Diffraction Data and [23, 24, 25]), which were formed after partial decomposition of Ti_3SiC_2 during sintering with copper. This result correlates with the data [26]. The interplanar distances in Ti_3SiC_2 decreased. This is a result of Si deintercalation from a Ti_3SiC_2 lattice [23, 20] because the silicon layers are situated between the layers of TiC, at the same time having a weak bond with TiC. The solid solutions of silicon in copper were not found,

since interplanar distances of copper do not increase and microhardness of a copper matrix grows slightly.

The interplanar distance, (nm)	Intensity, %	Phase (hkl)
0.2975	13	Ti_3SiC_2 (006)
0.2779	16	Ti_3SiC_2 (101)
0.2519	2	Ti_3SiC_2 (102)
0.242	4	Ti_3SiC_2 (103)
0.22845	100	Ti_3SiC_2 (104)
0.22093	75	Ti_3SiC_2 (008)
0.21337	37	Ti_3SiC_2 (105)
0.17581	3	Ti_3SiC_2 (0010)
0.15851	19	Ti_3SiC_2 (109)
0.15367	13	Ti_3SiC_2 (110)

TABLE II. The interplanar distance of a sintered powder material "copper- 37.5 vol. % Ti_3SiC_2» from Fig. 1b

The interplanar distance (nm)	Intensity, %	Phase (hkl)	The interplanar distance (nm)	Intensity, %	Phase (hkl)
0.2917	4.0	Ti_3SiC_2 (006)	0.20878	100	Cu (111)
0.26441	0.2	Ti_3SiC_2 (101)	0.18105	30,1	Cu (200)
0.25674	0.2	Ti_5Si_3 (002)	0,16096	0.2	Ti_5Si_3 (400)
0.25672	19.7		0.16096	11.3	
0.2521	2.0	SiC	0.15448	0.4	SiC
0.24937	4.5	TiC	0.15270	1.4	Ti_3SiC_2 (110)
0.24482	31.1	Ti_5Si_3 (210)	0.15016	11.1	Ti_5Si_3 (222)
0.24425	0.4		0.15013	0.2	
0.24285	11.5	Ti_5Si_3 (102)	0.14030	10.4	Ti_5Si_3 (213)
0.23828	0.31		0.13181	0.18	SiC
0.23823	11.5		0.13174	11.0	
0.23052	2.9	$TiSi_2$ (311)	0.13035	0.4	TiC
0.22688	5.2	Ti_3SiC_2 (104)	0.13034	11.6	
0.21973	1.2	Ti_5Si_3 (211)	0.12790	12.9	Cu (220)
0.21964	2..9	Ti_3SiC_2 (008)	0.12478	12.2	TiC
0.21571	5.5	TiC	0.12473	0.2	

The average content of elements in the particles of carbon silicide of titanium, without taking into account copper, corresponds to the stoichiometric composition with silicon content, reduced by about 14% (Fig. 2, Tab. 3).

The cards of element distribution (Fig.3) show that copper (up to 20 %) is contained in dispersed pores (diameter of less than 1 micron) of Ti_3SiC_2 of the composite material. The grains of silicide Ti_5Si_3 contains not more than 2 % of copper, which is consistent with the data on that silicide does not interact with copper (solubility is not more than 3 %) [26].

Energy dispersive analysis showed that the part of grains Ti_3SiC_2 was transformed to titanium carbide, silicon carbide, titanium silicide $TiSi_2$ and a solid solution of carbon in titanium silicide Ti_5Si_3(C) after the interaction of Ti_3SiC_2 with copper during the solid-phase sintering of "copper-Ti_3SiC_2". The microstructure of the sintered composite material is shown in Fig. 4; the grain of Ti_3SiC_2 has a characteristic shape of lamella; the grain of Ti_5Si_3(C) has uneven color, which depends on the carbon concentration. Energy dispersive analysis showed that the silicon content in Ti_3SiC_2 grains is below stoichiometric approximately by 14 % due to deintercalation of silicon (Table 4).
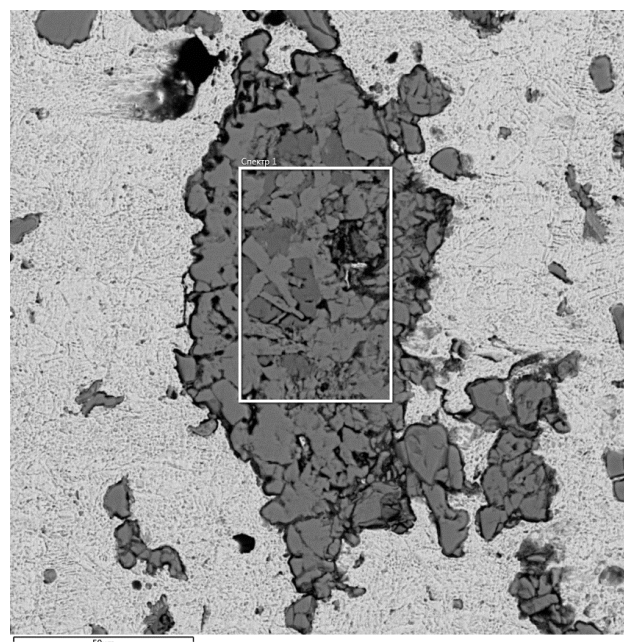

Fig. 2. The microstructure of particles of titanium carbon silicide with a plot for determining the elemental composition

TABLE III. Elemental composition (wt. %) in the particle titanium carbon silicide from Fig. 2

Element	Cont., Wt. %	The average deviation, wt.%
Ti	67.28	0.32
Cu	18.81	0.22
Si	10.99	0.11

The structure formation of the material "copper-Ti_3SiC_2" during sintering has the following features. First, the formation of silicide Ti_5Si_3 along with $TiSi_2$ is observed. Second, XRD reflections of most of the Ti_5Si_3(C) planes are bifurcated and interplanar distances differ from pure compound Ti_5Si_3(C) insignificantly because solid solutions of Ti_5Si_3(C) carbon contain different quantity of carbon in

different grains, which was noted earlier in [9] during Ti_3SiC_2 sintering.

The porosity of materials of the sintered composition increases slightly when increasing the Ti_3SiC_2 concentration in copper
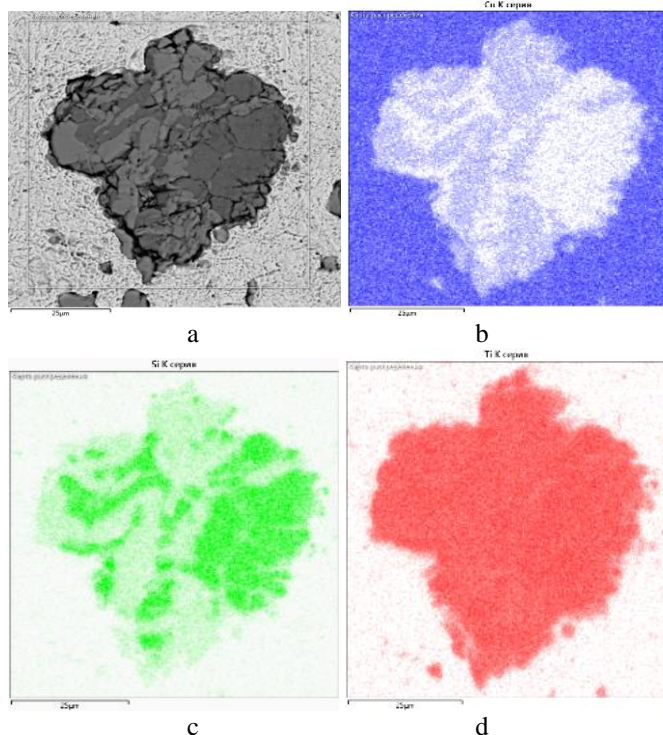

a   b

c   d

Fig. 3. Structure (a) and maps of Cu (b), Si (c), Ti (d)
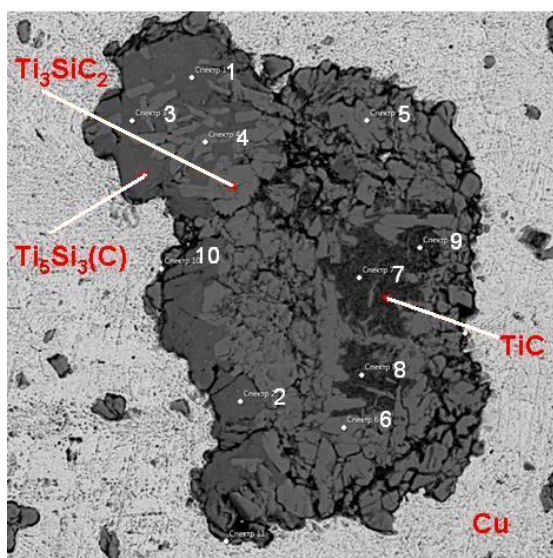

Fig. 4.   The microstructure of the material "copper-Ti_3SiC_2"

TABLE IV.   Elemental composition of the sintered material "copper - Ti_3SiC_2" from Fig. 3

№ spectrum in a point	Phase	Concentration, %		
		Si	*Ti*	*Cu*
1	$Ti_5Si_3(C)$	25.84	70.77	2.66
2	$Ti_5Si_3(C)$	25.45	70.34	3.53
3	$Ti_5Si_3(C)$	25.51	71.53	2.23
4	Ti_3SiC_2+Cu	8.88	68.79	22.33
5	Ti_3SiC_2+Cu	8.79	68.83	22.38
6	Ti_3SiC_2+Cu	8.45	69.05	22.50
7	TiC	0.41	92.82	6.14
8	TiC	0.78	90.11	8.62
9	TiC	2.66	86.46	10.64
10	TiC	6.63	68.51	24.12
11	Cu	6.19	20.87	68.45
12	Cu	4.11	26.45	64.79

since copper and Ti_3SiC_2 have physical and chemical interaction, favourable for sintering; the bending strength and the hardness decrease significantly, (Tab. 5).

TABLE V. The properties of the sintered powder material "copper-Ti_3SiC_2"

The concentration of Ti_3SiC_2, vol, %	Porosity, %	Hardness, HB, (MPa)	Flexural strength, (MPa)	Electrical resistivity, (Ohm· m)	Relative erosional wear, %	
					W=75 MJ	*W=100 MJ*
0	0	400	500	0.021	5,6	6,9
12.5	2	650	280	0.06	3.2	5.2
25.0	6	770	300	0.010	-	-
37.5	7	800	340	0.014	1.0	4.0

The electrical resistivity of the composite material (Tab. 5) increases along with the growth of Ti_3SiC_2 concentration because about half of Ti_3SiC_2 turns into non-conductive titanium silicide during sintering.

The erosive wear of tool-electrodes "copper-Ti_3SiC_2" was less, compared to the wear of electrodes made of pure copper with EDM on both tested modes (Tab. 5).

Good performance characteristics are achieved due to low porosity, the structure with nano-sized capillaries, which hold the molten copper, and to constancy of the electrical resistance of Ti_3SiC_2 at EDM temperature.

IV. CONCLUSION

Ti_3SiC_2 is decomposed partially into solid solution $Ti_5Si_3(C)$ and small amounts of TiC, SiC, $TiSi_2$ during the sintering of the composite material "copper-Ti_3SiC_2"; up to 20 % of copper is contained in the pores of Ti_3SiC_2. The porosity of compositions was low.

The electrical resistance strongly depended on concentration of Ti_3SiC_2 because the products of Ti_3SiC_2 decomposition are not electrically conductive. Ti_3SiC_2 was used to manufacture tool-electrodes for electrical discharge machining for the first time, and this material demonstrated promising properties.

The relative erosive wear of the composite electrode "copper-Ti_3SiC_2" was 5-6 times less than the wear of a pure copper electrode during machining the tool steel in a draft mode.

Performance characteristics can be further improved by increasing the conductivity by preventing Ti_3SiC_2 decomposition.

Acknowledgment

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