Physical and mechanical properties and structure of copper-based composite materials for diamond tools binder

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Abstract. The article describes the structure and physical and mechanical properties of dispersion-strengthened composite materials of Cu-Al-Ti-Sn-C-O system developed as a binder for making diamond tools for grinding composite materials and, in particular, hard alloys. It is shown that the materials under analysis have high thermal conductivity and recrystallization temperature values and are not inferior by mechanical properties to Cu-Sn system binders and, in particular, Cu-20 Sn binder widely used in the industry.

1. Introduction

Organic-, metal- and ceramic-bonded abrasive diamond tools are widely used at final stages of mechanical treatment of hard alloys and steels. However, organic- and ceramic-bonded tools cannot be efficiently used for grinding composite materials in intense treatment conditions due to low wear resistance.

Metal-bonded diamond wheels are more wear-resistant, however in case of high-rate grinding of composite materials, in particular, hard alloys, they clog and lose their cutting properties [1]. The fastest tool clogging takes place during grinding without use of lubricating and cooling process fluids. Further use of such tools requires their dressing, which leads to additional expenses.

The main cause of fouling of metal-bonded grinding wheels, according to authors of [2, 3], is processes of adhesion between the wheel surface and treated surface accompanied with seizing and sticking of grinding products on the wheel surface. Comprehensive studies of the fouled layer of diamond grinding wheels enable the authors [4] to suggest that the fouling process of diamond grinding wheels depends not only on the material treated but on the structure and composition of wheel binders.

Analysis of patent and scientific information in the field of metal binders for diamond grinding wheels showed that for these purposes of greatest interest are dispersion-strengthened copper-based composite materials made by the reactionary mechanical alloying method [5,6], namely, by milling a mixture of copper powder, aluminum and graphite powder in ball mills - attritors. Finely-dispersed aluminum oxides that form in the copper matrix of granules as well as graphite particles can provide the binder material with a combination of high strength at high temperatures ($0.8...0.9 T_m$) and high tribotechnical properties [7]. Indeed, the results of the latest studies [8] conducted by us show good prospects of use of composite materials developed by powder metallurgy methods out of a mixture of mechanically alloyed granules of Cu-Al-C-O system, tin powder and copper powder as a binding material for diamond grinding points. According to the results of laboratory tests of diamond grinding
points during grinding of a hard alloy without cooling [8], such a binder provides a higher service life of diamond tools comparing to M2-01 bonded diamond tools (standard metal binder, old designation M1) that represents Cu-20%Sn powder alloy [9]. However, by mechanical properties, namely, by compressive strength characteristics, a tin bronze-based binder with dispersion-strengthened granules Cu(Al,Sn)-Al2O3-C(graphite) [8] is inferior to M2-01 binder material. Therefore, the main purpose of the present work is analyzing possibilities of improving strength characteristics of a copper-based dispersion-strengthened binder. In connection therewith we suggested additional introduction of titanium, which is a carbide-forming element and is capable of enabling improvement of diamond grain fixation strength as well as increasing of intergranular bond strength during sintering, into the composition of analyzed mechanically alloyed granules [10].

2. Experimental materials and methods
Mechanically alloyed granules of copper-based Cu-Al-Ti-C-O system were produced with the use of the reactionary mechanical alloying method – by milling in air in high-energy ball mills (attritors) with capacity of 15 l of a powder charge that contains 1.0 wt % PTM-1 titanium powder, 0.3 wt % PP-1 aluminum powder, 0.3 wt % GK-3 graphite powder and PMS-1 copper powder as the rest.

The treatment consisted of two stages: at the first stage the ratio of masses of charge and steel balls was 1:15...1:20, treatment time was 60 min; at the second stage the ratio of masses of charge and steel balls was from 1:10 to 1:15, treatment time was 30 min. The produced mechanically alloyed granules were conventionally designated as C10T03A03G. This composition of granules was selected through optimization by two criteria: hardness and ultimate compressive strength of sintered material made of these granules.

To make samples of the composite materials (binders) under analysis mechanically alloyed granules with sizes under 100 μm were used the quantity of which was at least 90% of the total quantity of produced granules. To increase the strength and to reduce the sintering temperature of the binder materials under analysis, C10T03A03G granules were mixed with POE tin powder. The composition of the charge of the analyzed binder materials is given in Table 1.

Table 1. Charge composition and conventional designation of materials of the analyzed binders based on mechanically alloyed granules C10T03A03G.

| Conventional designation of materials | Charge composition, wt. % |
|-------------------------------------|--------------------------|
|                                     | Mechanically alloyed granules | POE tin powder |
| C10T03A03G - 0                      | 100                       | -              |
| C10T03A03G - 3                      | 97                        | 3              |
| C10T03A03G - 5                      | 95                        | 5              |
| C10T03A03G - 10                     | 90                        | 10             |
| C10T03A03G - 20                     | 80                        | 20             |

The technology of making cylinder-shaped samples with 13 mm diameter and 12...14 mm height based on C10T03A03G mechanically alloyed granules included the following operations:

1. Mixing of working charge components in a tumbler.
2. Cold pressing of the working charge in a container with 12 mm inner diameter at pressure of 300 MPa.
3. Removal of produced cylinder samples out of the container.
4. Sintering of the samples under a layer of a solid carburizing agent at 700°C or 750°C during 60 min.
5. Hot pressing (additional compaction) of the samples in a container with 13 mm inner diameter pre-heated up to 550 °C, with holding at the pressure of 300 MPa during 3 min.

For comparison, samples of the standard binder M2-01 (Cu-20 wt % Sn) were made using the same technology, but sintering was conducted at the temperature of 700 °C. Increasing the sintering temperature up to 750 °C caused deterioration of properties of M2-01 binder material.
The produced samples were used to determine hardness and density. The hardness was measured using the Rockwell machine by Scale B. Density was determined by weighing the samples on VLR-200 scales with precision of ±0.001 g. The volume was determined by measuring the diameter with precision of ±0.01 mm and the sample height with precision of ±0.05. The heat conductivity coefficient of the analyzed samples was determined by the comparison method. Copper of M1 grade was used as a reference.

The compression test of the samples was conducted on the vertical hydraulic press 2PG-50 until appearance of first cracks or destruction. The phase composition of dispersoids in the matrix of material was determined by electrolytic separation and further X-ray phase analysis of anode deposit on the X-ray diffractometer DRON-3M. The water solution containing 3 wt % CuSO₄, 3 wt % H₃PO₄, 3 wt % ammonium citrate was used as the electrolyte. The microstructure of the samples was analyzed on the metallographic microscope AltamiMet and scanning-electron microscope Hitachi TM4000Plus. The microspecimen were pickled with the saturated ammonia solution.

3. Results and their discussion

According to the results of the studies (Table 2), C10T03A03G-0 material made of mechanically alloyed granules without tin addition has the hardness of 91…90 HRB and ultimate compressive strength of 790…800 MPa. The sintering temperature, according to Table 2, has almost no influence on hardness and compressive strength of C10T03A03G material.

| Conventional material designation | Density, kg/m³ | Hardness, HRB | Ultimate compressive strength, MPa |
|----------------------------------|----------------|---------------|----------------------------------|
| C10T03A03G - 0                   | 8420/8430      | 91/90         | 790/800                          |
| C10T03A03G - 3                   | 8450/8460      | 92/91         | 940/1130                         |
| C10T03A03G - 5                   | 8510/8500      | 94/94         | 1150/1450                        |
| C10T03A03G - 10                  | 8470/8510      | 96/95         | 1090/1150                        |
| C10T03A03G - 20                  | 8530/8540      | 102/104       | 650/740                          |
| M2-01                            | 8580/-         | 92/-          | 1280/-                           |

Note: properties of samples sintered at 700 °C as the numerator, those at 750 °C as the denominator.

The hardness of samples made of a mixture of mechanically alloyed granules and tin powder increases with tin content increase. A slight increase of hardness of the samples under analysis after tin addition up to 10 wt % is explained by formation of α- solid tin solution in copper. A sharp increase of material hardness in case of introduction of tin up to 20 wt %, according to the analysis of C10T03A03G -20 material sample microstructure, is explained by presence of a hard eutectoid {α+δ}, where δ - solid phase (compound Cu₃₁Sn₈). Increasing the sintering temperature up to 750 °C has little influence on hardness of the analyzed materials with tin addition (see Table 2).

The ultimate compressive strength of the samples of the analyzed materials, depending on tin content, is maximum with tin content of 5 wt %. With further increase in tin content in the materials under analysis one can observe reduction of compressive strength characteristics, which is probably related to formation of δ - phase in their structure. The material under analysis, C10T03A03G – 5, made based on the above mentioned technology at the sintering temperature of 750 °C has its maximum compressive strength value of 1,450 MPa. At that, the hardness of this sample is 94 HRB. The calculated hardness and ultimate compressive strength values of C10T03A03G – 5 material are not inferior to, but exceed the hardness and strength of M2-01 binder material.

Thus, addition of tin powder in the amount of 5 wt % to the charge composition protects the surface of granules against oxidizing because tin, a soft ductile metal, fills in most pores during cold pressing of the samples. Formation of the liquid phase of tin during heating provides wetting of the
surface of copper granules and accelerates the sintering process, which ensures quite a strong bond between the granules.

The microstructure of the analyzed C10T03A03G - 5 material sample, according to Figure 1a, indeed, consists of separate granules between which there can be chains of small inclusions. At times, there are also inclusions with sizes of 10...15 μm at the boundary of granules that are probably particles of aluminum powder and especially titanium not completely exhausted by reaction. This is testified by distribution maps of these alloying elements on the grinding surface (Figure 1d and Figure 1e). As these elements are very active in relation to oxygen, oxides form on their surface, which is proven by the oxygen distribution map (Figure 1c). The other alloying elements - carbon and tin - are quite evenly distributed over the whole volume of material (Figure 1b and Figure 1g). During sintering tin completely dissolves in copper granules, while carbon can be found in the form of dispersed particles of titanium carbide and graphite.

According to the results of the X-ray phase analysis of anode deposits obtained by electrolytic dissolving of copper matrix of C10T03A03G - 5 material under analysis, the major disperse phases in the granules are aluminum oxide γ-Al₂O₃ and titanium carbide TiC. The X-ray phase analysis also confirms the possibility of presence of a small quantity of graphite and α-titanium particles in the analyzed materials. At times, there are small pores between the granules in the samples. The porosity of the samples, as demonstrated by sample density measurements (see Table 2), is under 5%.

Figure 1. The images of the structure of the composite materials C10T03A03G - 5 (a) and maps of distribution of chemical elements: carbon (graphite) (b), oxygen (c), aluminum (d), titanium (e), copper (f) and tin (g). REM (Hitachi TM4000Plus).
Formation of dispersed particles $\gamma$-Al$_2$O$_3$, TiC in C10T03A03G - 5 composite material provides the given material with a high recrystallization temperature, which is supported by the results presented in Figure 2. Hardness of these samples after heating up to 850 °C and holding during 1 h decreases only slightly and makes up 85±1 HRB. Hardness of Cu-20 wt %Sn samples after annealing at 700 °C/1 h decreases to 60 HRB.

![Figure 2](image-url)  
**Figure 2.** Hardness of C10T03A03G-5 and M2-01 materials/annealing temperature curves.

It should also be noted that presence of inclusions of dispersed graphite particles in C10T03A03G – 5 material can provide the material with high tribotechnical properties [9].

The foregoing makes it possible to classify the analyzed materials as dispersion-strengthened composite materials [11] of Cu-Al-Ti-Sn-C-O system.

An important property for binder materials of diamond tools is high heat conductivity. According to the measurement results, the highest heat conductivity coefficient at 20…30 °C equal to 195 W/(m·°K) is characteristic of C10T03A03G – 0 material samples, i.e. without tin addition. Samples made of a mixture of C10T03A03G granules and 5 wt % tin powder have the heat conductivity coefficient of 80±5 W/(m·°K), which is several times as high as the heat conductivity coefficient of M2-01 binder samples, that equals 24±5 W/(m·°K) [9].

Thus, the analyzed composite materials and, in particular, C10T03A03G – 5 made of mechanically alloyed granules of Cu-Al-Ti-C-O system have, comparing to the standard binder material M2-01 (Cu-20 wt %Sn), physical and mechanical properties of a higher level.

4. Conclusions
The results of the conducted studies make it possible to recommend the developed copper composite material of Cu-Al-Ti-Sn-C-O system with C10T03A03G – 5 conventional designation, which contains 95 wt % of mechanically alloyed granules of Cu-Al-Ti-C-O system and 5 wt % tin, for its further test as binders for making diamond tools designed for high-rate grinding of composite materials and, in particular, hard alloys.

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