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Investigation of correlation between physical properties and microstructure geometrical parameters of Cr-Cu composite material used for vacuum arcing contacts

A new microstructure quality index is proposed, suitable for Cr-Cu system metal-matrix materials used for arc-suppressing electrical contacts of vacuum switches for high voltages (10-36 кV) and high currents (20-100 кA). Based on the example of some physical properties of the Cr-50Cu composite and its microstructure geometrical parameters it was shown that there is strong correlation between the strengthening phase distribution character, electrical conductivity and mechanical characteristics obtained under the strain test. It was ascertained that the proposed index of accordance of structure to the regular one, rationed to the size of strengthening phase particles and fractal dimension of material microstructure, were strongly related to yield strength and electric conductivity (correlation coefficient reaches 0.98 ... 0.99).

Keywords: *Cr-Cu composite material, physical properties, microstructure, fractal dimension*

1. INTRODUCTION

Materials for vacuum arcing contacts working at medium and high voltages (10 - 36 kV) and high currents (20 - 100 kA) have to meet some requirements concerning mechanical strength, electrical conductivity, ability for heat diffusion, resistance to cathode spots fusion and stationary electric arc setting while arc blowout [1]. The materials which meet these requirements are, mainly, metal-matrix composite materials having electrical conductive copper matrix and hard refracting metals, such as chromium, tungsten or molybdenum as a strengthening component. It is clear that these materials must have definite composition and microstructure that depend on the technology of obtaining them. However, there are no analytical methods of microstructure optimization, let alone its connection with a definite technology. So a necessary microstructure can be found only experimentally by means of laborious development and environmental testing of vacuum chambers.

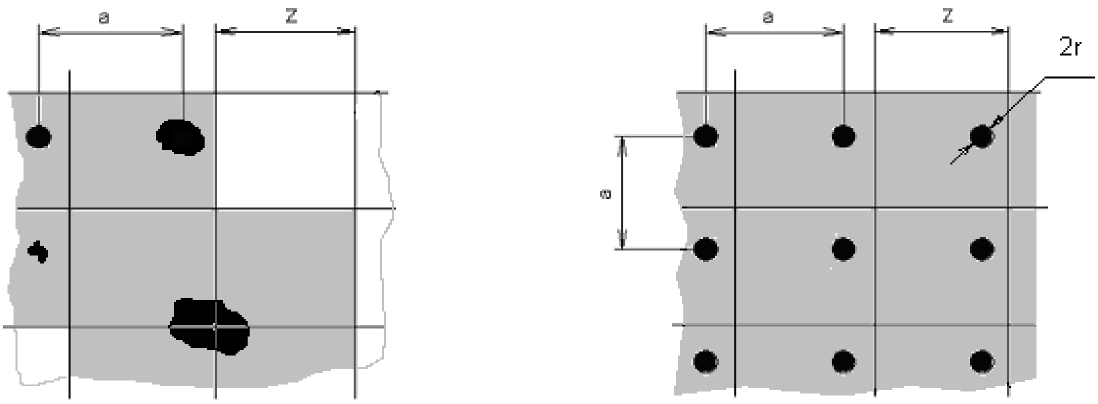
While testing one of such materials of Cr50% mass-Cu composition it was found that a material obtained by means of hot stamping has advantages, in terms of both mechanical and electrical properties, over materials obtained by means of a traditional method of preliminary pressing and final sintering in the presence of a liquid phase (liquid-phase sintering) [2]. Quantitative metallography of these materials microstructures does not give conclusive proof of such advantages. A smaller size of strengthening phase particles could provide larger mechanical strength but could not explain better electrical conductivity. Furthermore, materials obtained by means of hot stamping and having the same strengthening phase particles size (13 - 14 micrometer) had noticeable differences in physical properties depending on preliminary compaction methods. The distribution of the said size particles in all tested materials was close to a logarithmically normal one and the distribution of their forms estimated by means of Saltykov's form factor [3] showed prevalence of polyhedral and spherical particles in microstructures.

So the question arises as to more detailed estimation of microstructure quality than quantitative metallography can give.

One can assume that the physical properties of metal-matrix composites depend not only on strengthening the particles distribution but also on their ability to form a regular framework that provides both higher mechanical strength and an assured and stable way for the electrical current to flow through the conductive matrix, i.e. higher and more stable specific electrical conductivity.

2. RESULTS AND DISCUSSION

To estimate the degree of approaching of a real microstructure to the regular one, an index is proposed based on geometrical characteristics obtained by means of quantitative metallography. To approximate the real microstructure to an idealized a following regular one is used: it contains spherical particles with diameter *2r* equal to an average Feret diameter of strengthening particles and the center-to-center distance equal to the minimum one of the real microstructure (Fig. 1). The picture of the microstructure is conventionally covered with a grid having the cell size *z* equal to the center-to-center distance of the idealized microstructure *a*. If only one pixel of the strengthening phase particle image is positioned inside the grid cell, the latter is painted over, otherwise it remains unpainted.



a *b*

Fig. 1. Index of real microstructure (a) approaching to idealized regular one (b) calculation

The quantitative value of the index is calculated as the number of painted grid cells divided by the total number of cells, i.e.

$$K_r = N_p / (N_p + N_u) \tag{1}$$

where

N_p – number of painted cells,
N_u – number of unpainted cells.

This calculation method is similar to box counting while Minkovsky's dimension calculation [4], but neither grid densening nor ratio limit calculation are performed. So the calculation of (1) is simple and fast. In a physical sense, the index of real microstructure approaching the regular one (or, in short, regularity index) is a relative frequency (probability in the limit) of a strengthening phase particle hitting the area where an idealized regular microstructure particle should be situated [5]. It is clear that covering the idealized regular microstructure with a grid having the mentioned cell size leads to at least one particle hitting each cell, i.e. regularity index is equal to 1. The closer is the regularity index to be 1, the closer is the microstructure to be regular. It is possible to consider other templates of the regular structure but the result of the index calculation is found out to be close or equal to 1.

The proposed index does not take into consideration the real structure particles size so it is desirable to normalize it, e.g., as follows

$$K_n = K_r Z / (2r) \tag{2}$$

Such a normalized index ought to be more sensitive to the physical properties of the investigated material. The inverse normalizing ratio also can be used but a model built in this way is characterized by the less wide area of usability. To verify the degree of correlation between the proposed indices, fractal dimension and physical properties of the material, the correlation coefficient is calculated according to the known relation:

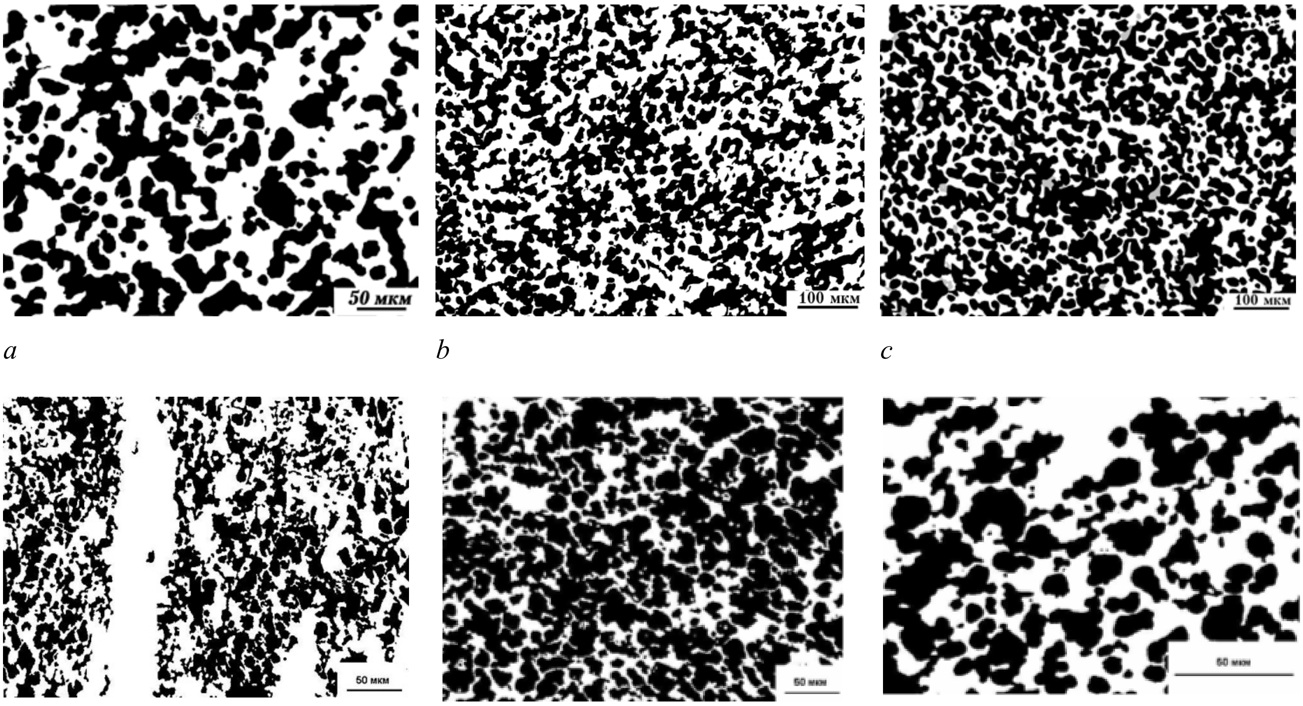
$$R = COV(X,Y) / (\sigma_x \sigma_Y) \tag{3}$$

where

X– is an array of physical values,
Y– is an array of proposed index values.

So the purpose of this paper is to verify the degree of the real structure approaching the idealized regular one due the physical properties critical for materials of electrical arcing contacts.

We took two groups of materials having Cr50% mass-Cu composition, one obtained by means of traditional powder pressing and sistering in the presence of the liquid phase (so called liquid-phase sistering) [2], the other obtained by means of hot stamping. The materials samples were obtained as follows: chromium powder made by reduction and electrolytic copper powder were mixed in the attritor and then pressed under 300 – 400 MPa and sintered under the temperature of 1150-1200°C in a hydrogen atmosphere. Then the second group of materials samples was additionally compacted by means of hot stamping under the temperature of 850°C until the samples reached relative density of 0.97-0.99 with respect to the theoretical density, followed by annealing under the temperature of 650°C in an argon atmosphere to eliminate mechanical stresses. Each group of materials was subdivided in three batches: the first one depending on the strengthening phase particles size and the second one depending on porosity. The samples of the third batch in the second group were additionally compacted under the pressure of 500-700 MPa and under room temperature. Each batch contained up to 15 samples. Then thin sections on each sample were photographed by means of a digital camera and microstructure images were processed by means of the AMIS software [6] (see Fig. 2) to obtain quantitative metallography data and to calculate both the proposed indices and fractal dimensions for each microstructure.



a *b* *c*

d *e* *f*

Fig. 2. Materials microstructures after processing by means of AMIS software: first group, first batch (a), first group, second batch (b), first group, third batch (c), second group, first batch (d), second group, second batch (e), second group, third batch (f). Strengthening phase particles are painted black

The tensile strength, tensile yield point and relative elongation were determined by means of a mechanical test, while specific resistance was measured by means of electrical testing. The mentioned physical properties and calculated microstructure indices were placed in Table 1.

Then correlation coefficients were calculated separately for the first and second group of materials. They are placed in Table 2.

One can see that both proposed indices and fractal dimension are noticeably correlated to the physical properties. It is interesting that there is strong correlation between the normalized regularity index and tensile yield point, and the known Hall-Petch relation [7-9] describes the yield point dependence on the material grains size. Whether the proposed indices of the microstructure quality are reliable enough for other classes of materials is the matter of further research.

Table 1.

Physical properties and microstructure indices of materials

Group	Batch	Material properties and microstructure indices							
		Relative density	Specific conductivity (MSm/m)	Yield point (MPa)	Break point (MPa)	Relative elongation (%)	Regularity index	Normalized regularity index	Fractal dimension index
1	1	0.985	11.11±0.55	186±9	190±10	1.2±0.06	0.960	0.980	1.87
	2	0.982	9.91±0.49	121±6	133±7	0.27±0.01	0.999	0.940	1.89
	3	0.981	9.52±0.48	120±6	130±7	0.2±0.01	0.990	0.847	1.93
2	1	0.983	13.89±0.35	305±17	478±23	7±1	0.875	0.911	1.87
	2	0.986	22.22±0.67	346±15	485±24	9.8±1	0.998	0.970	1.95
	3	0.970	12.82±0.38	314±16	448±22	3.2±1	0.88	0.870	1.87

Table 2.

Correlation between microstructure geometrical indices and physical properties

Group	Index	Physical properties			
		Specific electrical conductivity	Yield point	Break point	Relative elongation
1	Regularity index	-0.904	-0.975	-0.967	-0.963
	Normalized regularity index	0.868	0.741	0.761	0.773
	Fractal dimension	-0.885	-0.765	-0.784	-0.795
2	Regularity index	0.990	0.985	0.618	0.798
	Normalized regularity index	0.950	0.808	0.901	0.982
	Fractal dimension index	0.999	0.966	0.685	0.848

3. CONCLUSIONS

It was found out that the proposed regularity index, normalized regularity index and fractal dimension were noticeably correlated with mechanical strength and specific electrical conductivity, at least for two groups of materials having Cr50% mass-Cu composition, and could be used as a microstructure quality quantitative index, meanwhile the proposed indices are easier and faster to calculate. The use of both proposed indices and fractal dimension for other classes of materials requires further research.

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