The impact of high voltage electric discharge treatment on the properties of Cu – Al powder mixture

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Abstract *Studies of the impact of high voltage electric discharge (HVED) treatment on the dispersion and phase composition of 87,5 % Al + 12,5 % Cu powder system were performed. It was shown that HVED treatment in kerosene with specific treatment energy of 5 MJ/kg leads to the decrease of mean diameter of treated powder from 15 to 13 μm, and the increase of specific treatment energy leads to the decrease of mean diameter of treated powder from 15 to 6 μm. X-ray diffraction analysis shows that $CuAl_2$ and Al_4C_3 are synthesized in all considered treatment regimes.*

HVED treatment with increased specific treatment energy leads to the increase of quantity of synthesized Al_4C_3 phase. The use of "three point – plane" electrode system instead of "point – plane" during HVED treatment of 87,5 % Al + 12,5 % Cu powder system leads to the increase of quantity of synthesized Al_4C_3 and $CuAl_2$ phases, while the efficiency of powders dispersion slightly decreases. Up to 40% of particles in powder mixture, treated by HVED in kerosene with the use of "three point – plane" electrode system, have diameter close to the diameter of the initial powder mixture.

Keywords*: HIGH VOLTAGE ELECTRIC DISCHARGE, POWDER, POWDER METALLURGY, SYNTHESIS, GRINDING, ALUMINUM, CUPRUM*

1. Introduction

Currently in Ukraine there is a problem of replacing morally and physically obsolete rolling stock of urban electric transport and ensuring its high level of reliability. At the present time, Morgan Carbon, PanTrac and Hoffman companies are the leading manufacturers of electrical materials for urban electric transport in Europe. Most types of electrical contact inserts, made by thee companies, contain carbon and copper components [1]. Such current collection elements are made in an aluminum frame and are fastened with special adhesives or bolted joints, and are often placed in copper clamps. Sliding electrical contacts are the most common mobile connections in urban electric transport. The analysis of technical conditions shows that the materials of current-collecting sliding elements must provide high electrical conductivity, arc resistance, hardness, strength and wear resistance [1]. In this case, ensuring the durability of both the current collector (body) and the contact wire (counter-body), which is determined by the low coefficient of friction, is an important condition.

A number of materials, based on carbon-containing powders clad with copper, have been developed in Ukraine for the manufacture of current collector inserts. However, such materials have unsatisfactory resistivity, wear resistance and strength. Given the disadvantages of existing materials for these friction pairs, there is a need to develop new materials that would have high performance properties, especially high wear resistance. However, the available materials do not fully meet the technical and operational requirements, in particular, put forward on the criterion of durability of this system. They have unsatisfactory specific resistance (from $3 \cdot 10^{-5}$ Ohm · m to $8 \cdot 10^{-5}$ Ohm · m), wear resistance (from 0,1 to 0,4 mm of loss of diameter during 20 h), and durability (from 40 to 82 MPa). Therefore, the creation of materials that would meet the stringent requirements of operation in extreme conditions is an urgent scientific task.

The need to create new metallic materials with high physical, mechanical and operational properties that will provide the necessary reliability of products in extreme conditions, is relevant for the development of modern technology. Unfortunately, the possibilities of obtaining them using conventional metallurgical methods are largely exhausted. Therefore, scientists and engineers are facing an important task of the development of physical principles for creating new materials under conditions of high-energy action and extreme high-speed effects of temperatures and pressures, which will allow the obtainment of nanostructured materials, which do not exist in conventional conditions, from elements that do not have mutual solubility. Materials, consolidated by the methods of spark plasma sintering (SPS), self-propagating high-temperature synthesis (SHS), or selective laser sintering, have significantly (1.5–2 times) higher physical and mechanical properties than those obtained by conventional metallurgical methods due to less exposure at high temperature, which ensures the preservation of the grain heterophase structure of the powder mixture in the structure of the consolidated material [2].

But the properties of consolidated materials depend not only on the method of consolidation, but also on the chosen method of preparation of powders. The use of the method of preparation of starting powders of metal-matrix materials by high-voltage electric discharge (HVED) in hydrocarbon liquid, developed in IIPT of NAS of Ukraine, allows to achieve significant dispersion of particles of processed powders as well as to provide synthesis of dispersion-strengthening phases, in particular, carbides [2–9].

During the HVED treatment, metal powder particles are exposed to a combined effect of mechanical (shock wave, hydro flows, cavitation) and thermoelectric (discharge channel plasma, microplasma formations between particles, discharge current) factors, which leads to their dispersion. The use of hydrocarbon liquid prevents the oxidation of particles of the processed metal. In addition, as it is shown in [3–9], the difference between high-voltage electric discharge (HVED) in a hydrocarbon liquid is its pyrolysis (rupture of chemical bond chains) under the influence of the temperature of the plasma discharge channel and pulse pressure with the formation of active carbon nanoparticles up to C_{70} [2, 6], which creates conditions for the synthesis of dispersion-strengthening compounds, in particular, carbides [3–9].

Unfortunately, the possibility of using high-voltage discharge treatment in a hydrocarbon liquid for the preparation of starting powders of metal-matrix composites of the Al – Cu system for the manufacture of current collector inserts has not been sufficiently studied. In particular, there is no information on the patterns of changes in the dispersion and phase composition of the initial powders of the Al – Cu system under the influence of HVED treatment.

Therefore, the **goal of the work** is to investigate the influence of high-voltage discharge treatment in kerosene on the dispersion and phase composition of 87.5% Al + 12.5% Cu powder system.

2. Methodology

Elemental Al powders PA1 GOST 6058-73 (ПА1 ГОСТ 6058-73) with d_0 = 25 μm and Cu PMS-1 GOST 4960-75 (ПМС-1 ГОСТ 4960-75) with d_0 = 15 μm were selected as initial materials for the study, on the basis of which a mixture of 87.5 % Al + 12.5% Cu mass composition with an initial diameter of 22 μm was prepared. Kerosene of the TS-1 brand (GOST 10227-86) was used as a working liquid. The ratio of solid to liquid phases in the studies was 1:15 (the weight of the processed powder was 100 g, the volume of the working liquid was 1.5 l).

The scheme and detailed description of the experimental stand for high-voltage electric discharge processing and, in particular, the working chamber, are given in [3–5]. Investigations of HVED in "liquid dielectric – metal powder" disperse system were performed at a voltage U = 50 kV, the inductance of the discharge circuit L from 0.5 to 1 μH (limit technological values) and the discharge interval l_p ~ 17 mm. In the process of research, the specific energy of processing was varied by changing the number of discharges n. The capacity of the drive C was 0.8 μF, so the value of the stored energy of a single discharge W_1 was 1 kJ.

Two structural types of electrode systems (ES) were used in the research, namely "point – plane" (P – P) and "multipoint anode – plane" (MP – P) with 3 tips. These ESs were used due to the fact that according to the results of [3–6, 8–10] the change of the electric field configuration due to the use of different types of ESs allows to create conditions for changing the distribution of plasma formations in the volume of processed powder.

In turn, if the plasma formations are distributed over the entire volume of the processed powder, it will intensify the processes of erosion and hydrodynamic dispersion and synthesis of carbide and intermetallic compounds during HVED treatment [3–6, 8, 9]. When using the point–plane system, HVED develops according to the classical mechanism of spark discharge (SD) in a dispersed system, while the use of "multipoint anode – plane" type ES allows the implementation of the mode of volume-distributed multi-spark discharge (VMD).

The use of different electrode systems allowed controlling the distribution of the intensity of the influence of the main factors of HVED impact [3–6, 8–10]. Thus, if in the case of the implementation of SD most of the accumulated energy was transformed into shock waves, the implementation of VMD using multi-point anodes allows to increase the intensity of thermal and current impact factors.

In order to evaluate the degree of influence of HVED in kerosene on the morphology and particle size of powders, the following hardware and software was used –BIOLAM-I (БІОЛАМ-І) optical microscope with a maximum magnification of × 1350, REMMA-102 (РЕММА-102) raster electron microscope with a magnification range from 10 to × 250000 (IPM NASU), Canon digital camera. Powder samples for optical microscopy were taken in accordance with GOST 23402-78 (ГОСТ 23402-78). After obtaining a sharp image, magnification was recorded and photographs were taken, which were processed for further analysis.

Since the average diameter of particles and their shape factor are the most informative in materials science in terms of describing the morphology of the powder, the diagnosis of morphological characteristics was performed before and after HVED treatment by average diameter (d_m) and shape factor (F) in accordance with GOST 25849-83 (ГОСТ 25849-83). The number of particles that came into the field of view of the microscope eyepiece was not less than 2000 pieces, and at least five samples were considered for each studied mode. As a result of processing, the values of the above characteristics were obtained for each particle that came into view. This allowed to present data in the form of graphs and histograms with a confidence interval of 0.96.

The study of the phase composition of the powders was performed by X-ray phase analysis. The diffraction patterns were recorded using a DRON-4-07 (ДРОН-4-07) diffractometer under CuKα radiation. A Ni β-filter was used to reduce the background on the diffractograms as well as to reduce the probability of β-lines. Phase identification on diffraction patterns was performed using POW_COD databases [11]. A standard made of quartz was used to determine the instrumental function.

3. Results and discussion

The study of the effect of HVED treatment on the change in the properties of 87.5% Al + 12.5% Cu powder system was performed in the modes shown in table 1. After processing, the features of the high-voltage electric discharge process in the modes with different types of used ES were compared. The initial mixture of 87.5% Al + 12.5% Cu powders had an average diameter of 22 μm and was characterized by a monomodal size distribution, the main peak of which was at the point of 20 μm (~ 55%) (see Fig. 1, curve 1).

HVED treatment of this powder mixture in kerosene with single-point EC at W_s = 5 MJ / kg leads to a change in dispersion (see Fig. 1, curve 2) – the particle size distribution retains a monomodal appearance and shifts to the area of smaller diameters, and the average diameter decreases to ~ 12 μm. Increasing the specific processing energy to 10 MJ / kg leads to an increase in the dispersion efficiency (see Fig. 1, curve 2) – the particle size distribution undergoes a significant shift to the area of smaller diameters, and the average particle diameter of the mixture decreases to 7 μm. Increasing specific processing energy to 20 MJ / kg leads to the further decrease of the average particle diameter of the mixture to 6 μm.

Table 1: *Modes of HVED treatment of 87.5% Al + 12.5% Cu powder system in kerosene.*

No. of mode	Number of points of the electrode system	W_s, MJ/kg
1	1	20
2	1	10
3	1	5
4	3	20
5	3	10
6	3	5

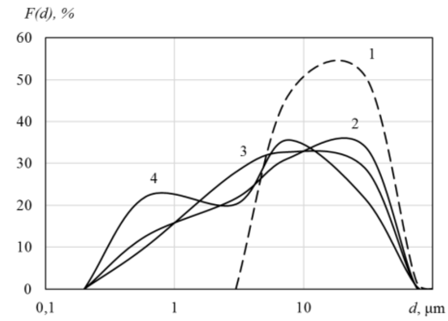

Fig. 1 *Particles size distribution of initial 87.5% Al + 12.5% Cu powder (1) and after HVED treatment in kerosene in SD mode with different values W_s = 5 MJ/kg (2), W_s = 10 MJ/kg (3) and W_s = 20 MJ/kg (4)*

Changing the type of used ES from one-point to three-point did not affect the dispersion efficiency (see Fig. 2). Treatment with W_s = 5 MJ / kg allowed reducing the average particle diameter to 13 μm (see Fig. 3). Treatment with W_s = 10 MJ / kg reduced the average diameter of the mixture after treatment to ~ 9 μm, and with W_s = 20 MJ / kg to 7 μm.

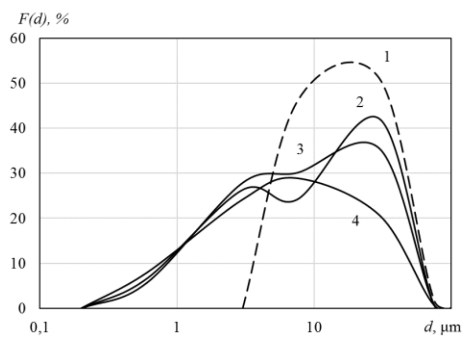

Fig. 2 *Particles size distribution of initial 87.5% Al + 12.5% Cu powder (1) and after HVED treatment in kerosene in VMD mode with different values W_s = 5 MJ/kg (2), W_s = 10 MJ/kg (3) and W_s = 20 MJ/kg (4)*

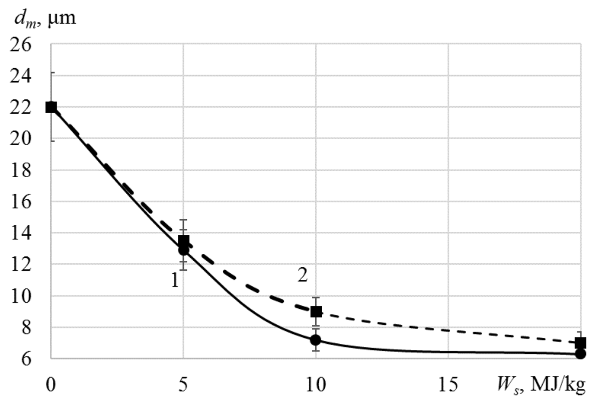

***Fig. 3** Dependence of the average particle diameter of 87.5% Al + 12.5% Cu powder on the specific processing energy when using SD mode (1) and VMD mode (2) in kerosene*

X-ray phase analysis of the initial mixture of 87.5% Al + 12.5% Cu powders confirmed that only aluminum and copper are present in the composition of the initial mixture (see Fig. 4), no significant impurity content was detected.

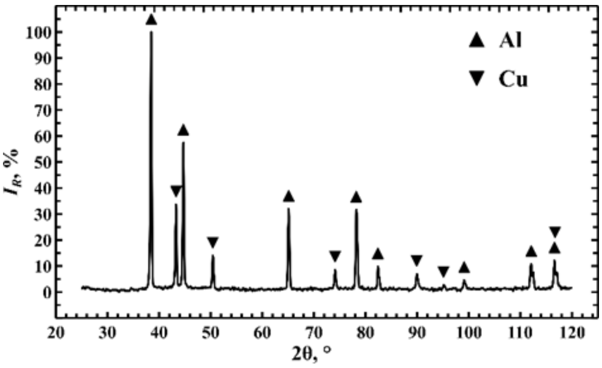

***Fig. 4** X-ray diffraction patterns of 87.5% Al + 12.5% Cu initial powder mixture*

HVED treatment of 87.5% Al + 12.5% Cu powder mixture in kerosene with SD leads to a change in its phase composition (see Fig. 5, a, c, e). In the composition of the powder, in addition to the initial Al and Cu, as a result of HVED treatment with a specific energy of 5 MJ/kg, reflexes appear, corresponding primarily to $CuAl_2$ intermetallic phase and aluminum carbide Al_4C_3 (see Fig. 5, a). Increasing the specific energy to values of 10 and 20 MJ/kg increases the quantity of synthesized phases, as evidenced by some increase in the corresponding peaks on X-ray diffraction patterns (see Fig. 5, c, e).

The use of VMD for HVED treatment of 87.5% Al + 12.5% Cu powder mixture in kerosene does not fundamentally change the dynamics of the synthesis of new phases in comparison with SD (see Fig. 5, b, d, f). First of all, we can point to the appearance of $CuAl_2$ intermetallic compound, as well as Al_4C_3 carbide when exposed to a specific energy of 5 MJ/kg (see Fig. 5, b), the number of which increases with increasing specific energy to 10 and 20 MJ/kg (see Fig. 5, d, f).

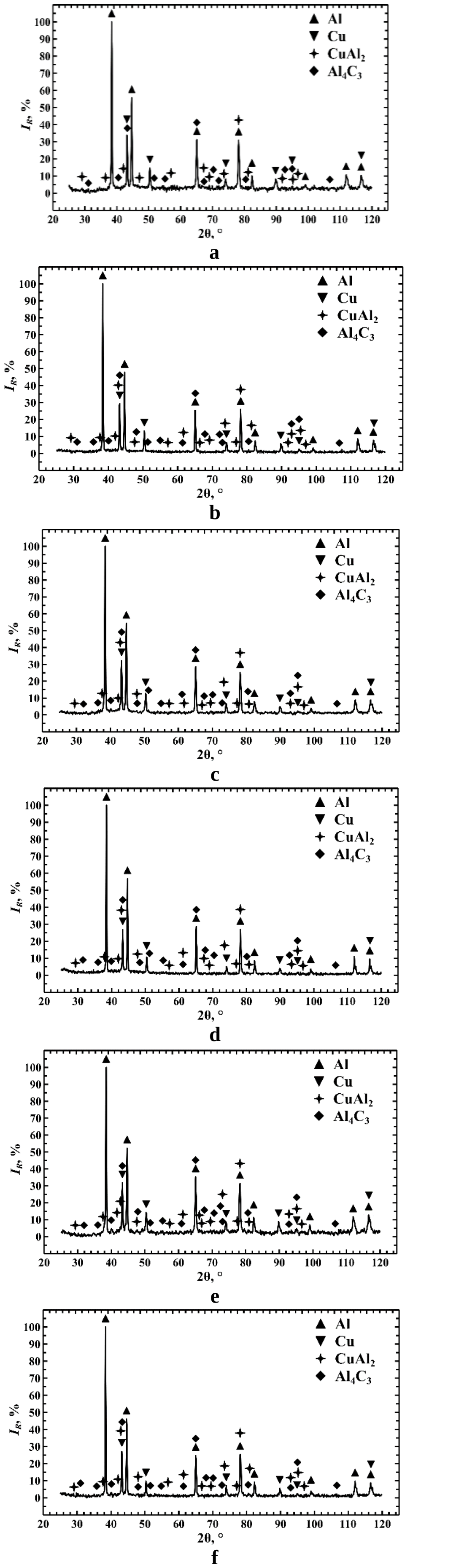

***Fig. 5** X-ray diffraction patterns of 87.5% Al + 12.5% Cu powder mixture after HVED treatment in kerosene in the modes of SD (a, c, e) and VMD (b, d, f) with a specific energy of 5 MJ/kg (a, b), 10 MJ/kg (c, d) and 20 MJ/kg (e, f)*

4. Conclusions

1. The possibility of using HVED treatment in a hydrocarbon liquid for the preparation of the initial mixture of powders for metal-matrix composites of Al – Cu – C system is shown.

2. The regularities of high-voltage electric discharge treatment of 87.5% Al + 12.5% Cu powder mixture in kerosene were studied and it was shown that HVED treatment with W_s = 5 MJ/kg leads to a decrease in the average particle diameter of the treated mixture from 15 μm to 13 μm, and increasing the specific processing energy to W_s = 20 MJ / kg allows to reduce the average particle diameter of the treated mixture to 6 μm.

3. It is found out that regardless of HVED mode, treatment of 87.5% Al + 12.5% Cu powder mixture leads to the synthesis of $CuAl_2$ intermetallic compound and Al_4C_3 carbide, the amount of which increases with increasing specific processing energy.

5. References

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