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Influence of mechanical and electrical parameters on the energy efficiency of powder production by electro-discharge erosion of WC−Co-and WC−TiC−Co-scrap

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The electroerosive dispersion method makes it possible to obtain ultradisperse powder directly from carbide waste. In this work, the influence of the discharge energy, the composition of the alloy and liquid on the energy consumption and productivity of processing by the method of electroerosive dispersion of WC−Co and WC−TiC−Co hard alloys is studied. An empirical model is presented that describes the dependence of the discharge frequency, process productivity, and specific energy consumption on the discharge energy, vibration stand amplitude, and liquid properties. It is shown that, under certain conditions, the specific energy consumption for processing 1 kg of WC−Co or WC−TiC−Co alloy can be reduced to 3.3−4.5 kW · h kWh.

Keywords: powder, cemented carbide, ultrafine powder, energy consumption, tungsten carbide.

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Introduction

Obtaining ultrafine-grained hard alloys WC−TiC−Co and WC−Co with high hardness and wear resistance from ultrafine powders is an urgent task [1–3]. A significant part of hard alloys is produced from powders obtained as a result of their processing [4]. Electroerosive dispersion (EED) is a direct method of processing and obtaining ultrafine powders without the use of dangerous and expensive reagents [5–12]. The method is based on the formation of particles under the action of a spark discharge in a dielectric liquid. The surface of the electrodes is heated to 10^4 K during spark discharge which leads to melting and boiling of the starting material. The melt and vapors are ejected into the interelectrode gap, quickly (10^6-10^9 K/s) cooled, forming nanoscale and ultrafine-grained particles suitable for the production of an alloy of increased hardness [5]. The energy consumption of the method is high, the productivity is small due to the low discharge energy (< 1 J) and the presence of only two electrodes. The use of special plants for EED, various liquids and high-energy pulses (up to 6 J) increases productivity and reduces energy consumption.

The purpose of this work is to study the effect of discharge energy, voltage pulse frequency, fluid properties on discharge frequency, performance, energy consumption during EED of hard alloys WC−Co and WC−TiC−Co in a special plant at high discharge energy (> 1 J).

1. Procedure

Samples of medium-grained hard alloys WC−8Co, WC−16Co, WC−5TiC−10Co ($5.25 \times 6.5 \times 20$ mm) manufactured by KZTS were used as a feedstock for the EED. EED was performed in a special plant [5] in six different modes with an open-circuit voltage 80, 120, 165, 205, 250 and 300 V. Voltage and current in discharges, pulse duration, frequency of voltage pulses and current pulses were calculated on the basis of volt-ampere characteristics, which were measured using an analog-to-digital module. Distilled water and transformer oil GC-1 were used. After the EED, the electrodes were weighed on a Mettler Toledo Ml-54 scale to determine the mass of the powders obtained. The powders were dried at 600°C in a vacuum furnace. The morphology of the powder was studied using a Tescan Vega scanning electron microscope.

2. Findings and discussion

The main part of the discharge energy is consumed for heating the electrodes, dielectric liquid and its pyrolysis. All this refers to the losses of [13]. A smaller part of the energy is consumed for heating and melting the material from which the particles are formed. The surface of the craters formed in water (Fig. 1, *a*) and oil (Fig. 1, *b*) consists of crystallized carbide remaining after removal of the melt. According to the modern semi-empirical model of the electric discharge machining (EDM) [14–17], the powder production per discharge (PPD) depends on the discharge energy (E_d). We assume that the production of the powder per discharge depends on the efficiency of heat transfer from the discharge channel to the crater material, the thermophysical properties of the eroded alloys and energy losses during dielectric breakdown (E_c). Assuming that erosion at low discharge energy ($E_d \leq E_c$) is zero

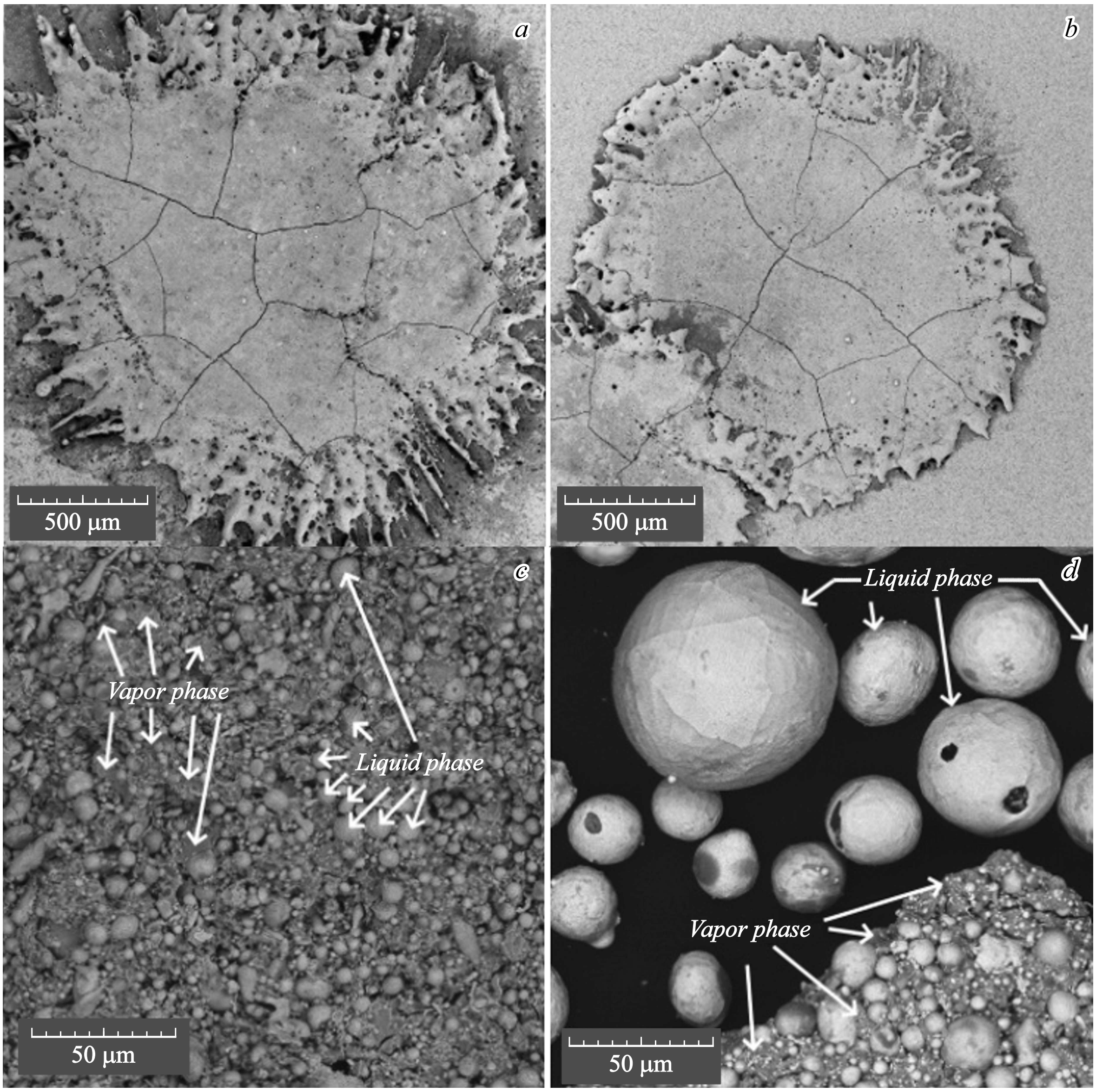

Figure 1. Crater after spark discharge in water (*a*) and oil (*b*) on the surface of the anode WC−5TiC−10Co. Morphology of powders obtained by the EED of alloy WC−5TiC−10Co in water with an average discharge energy of 0.34 (*c*), 1.52 J (*d*).

(PPD ≈ 0), PPD can be represented as a linear dependence on the discharge energy:

$$\mathrm{PPD} = \frac{\eta(E_d - E_c)}{L_v + c_p(T_m - T_0)}, \quad (1)$$

where $T_0 = 293\,\mathrm{K}$ — initial temperature. The remaining thermophysical parameters are presented in the following table. Specific energy consumption (SEC) is equal to

$$\mathrm{SEC} = \frac{E_d}{\mathrm{PPD}}. \quad (2)$$

Each voltage pulse results in the formation of a chain of discharges in case of EED in the bulk layer. Then the performance (PPR) is equal to

$$\mathrm{PPR} = F_I\, n\, \mathrm{PPD}, \quad (3)$$

where F_I — frequency of current pulses, $n = 2$ — number of digits. The discharge energy is calculated as follows:

$$E_d = \int_0^{t_I} \frac{U}{n} I dt, \quad (4)$$

where U — discharge voltage, I — current, t — time.

The produced powders consist of spherical particles and agglomerates of nanoscale particles (Fig. 1, *c, d*). Spherical particles formed by the crystallization of the liquid phase consist of ultrafine carbides with cobalt layers. Agglomerates of nanoparticles are formed by crystallization of the vapor phase [5,7].

Since spherical particles are formed during the melting of the carbide skeleton, the melting temperature of the

Thermophysical properties of the alloys used and process parameters EED

Parameter		Alloy		
		WC−8Co	WC−15Co	WC−5TiC−10Co
Specific heat capacity (c_p), J/(g·K)		201	218	239
Melting point (T_m), K		3143	3143	3373
Latent heat of melting (L_v), J/g		430	418	424
Energy for heating and melting ($L_v + c_p(T_m - T_0)$), J/g		1009	1094	1166
Parameter a in equation (7)	Water	0.009	0.007	0.010
	Oil	0.014	0.016	0.0035
Efficiency (η), %	Water	7.4	7.3	8.7
	Oil	7.4	6.8	9.7
Dielectric strength (DS), kV/mm	Water	0.4		
	Oil	2.2		
Minimum specific energy consumption SEC, kW·h	Water	3.9	4.1	3.7
	Oil	3.4	4.5	3.3

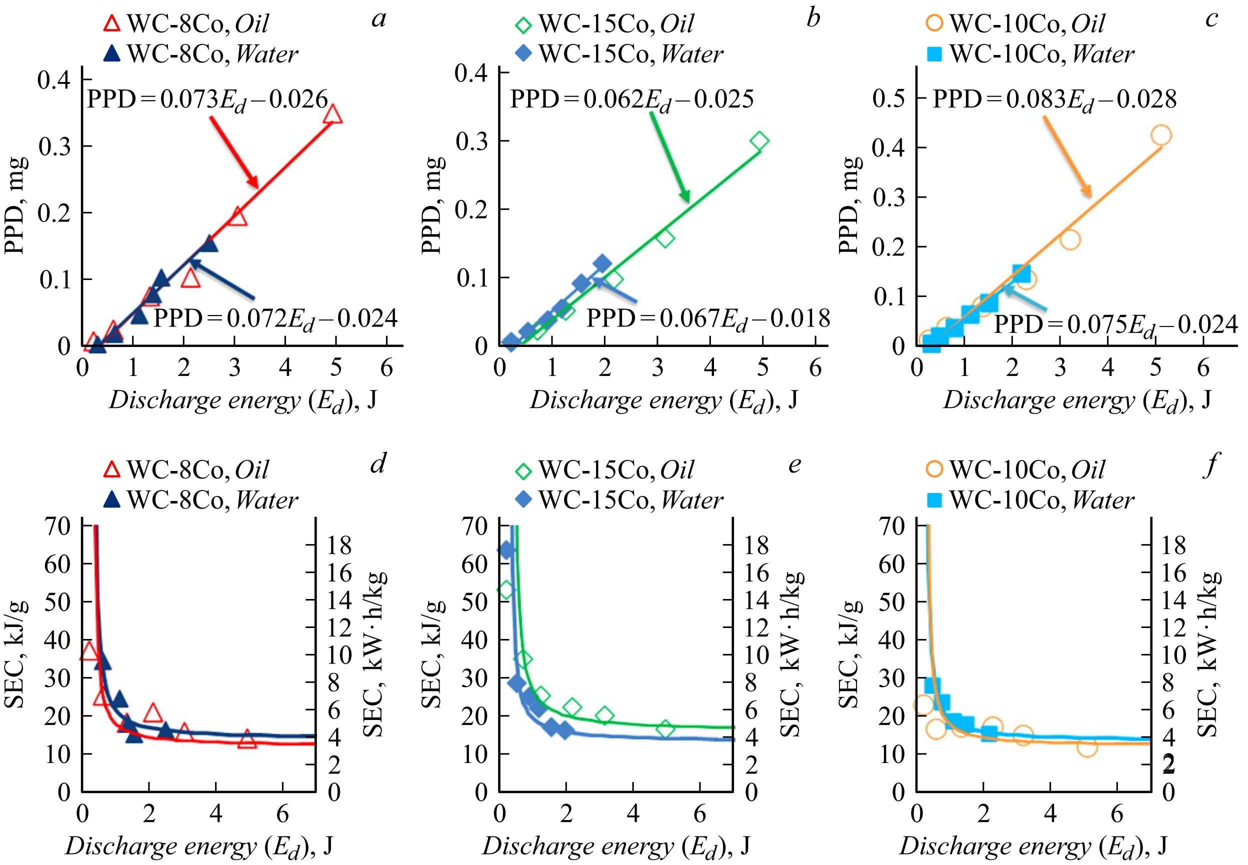

Figure 2. Dependences of powder production per discharge (PPD) (a–c) and specific energy consumption (d–f) on the discharge energy of alloys WC−8Co (a, d), WC−15Co (b, e) and WC−5TiC−Co (c, f).

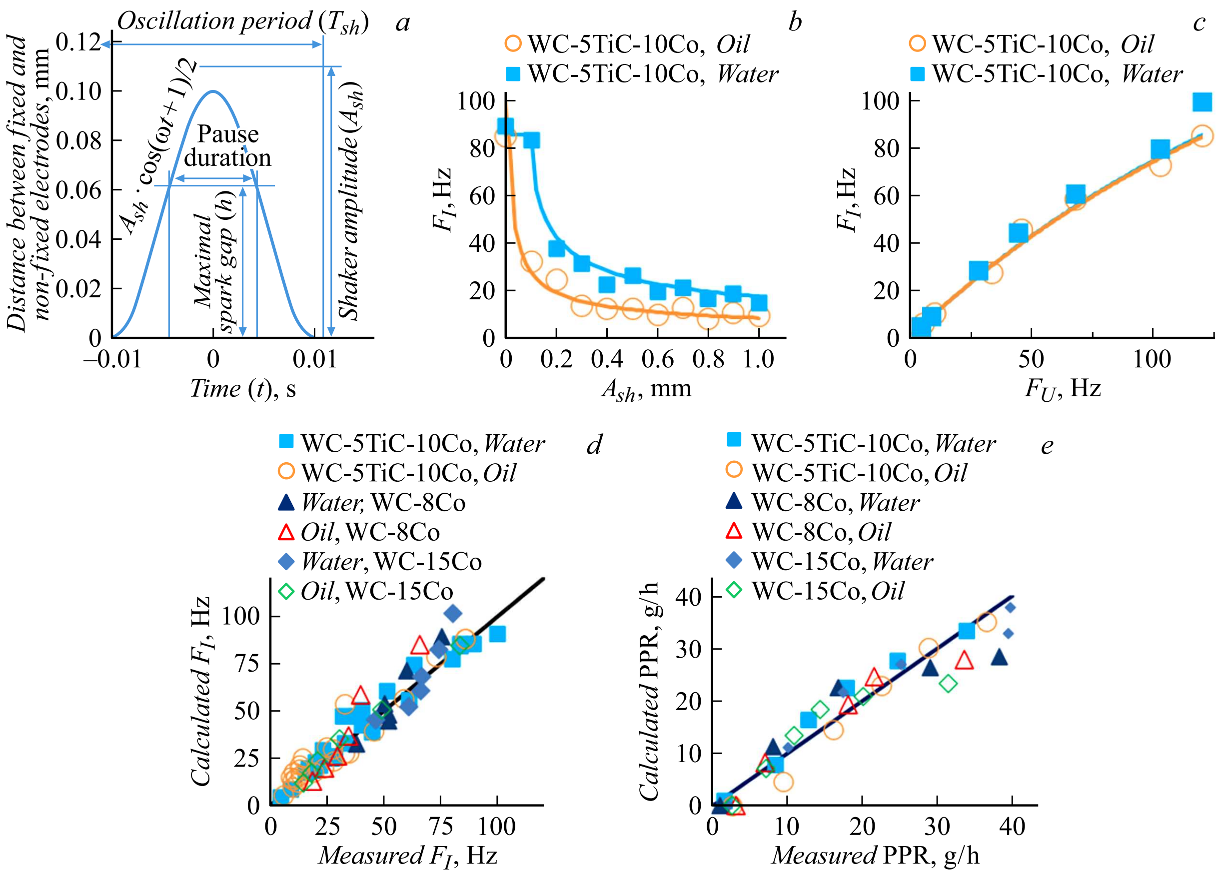

Figure 3. The distance between the stationary and loose electrodes from time (*a*), the dependence of the frequency of current pulses on the amplitude of the shaker (*b*) and on the frequency of voltage pulses (*c*), the dependence of the calculated pulse frequency (*d*) and performance (PPR) (*e*) on the experimental values.

raw alloy is considered equal to the melting temperature WC for the alloys WC–Co and (Ti, W)C for the alloy WC–TiC–Co.

The performance of the powder per discharge during EED of the studied alloys increases linearly with an increase of the discharge energy to 5 J (Fig. 2, *a–c*) according to the model (1). The increase of the production of the powder per discharge continues after the increase of the discharge energy above 2 J in contrast to EDM, due to the discharge power (15–40 kW), several times higher than the discharge power in case of EDM [14–17]. The process efficiency (7–10%) (see table) is higher than in case of EDM due to the high power. The dependence of specific energy consumption on the discharge energy based on the equations (1) and (2) is changed to a hyperbola (Fig. 2, *d–f*). Specific energy consumption decreases with a decrease of discharge energy due to a decrease of relative energy losses at the initial stage of discharge.

The production of the powder per discharge in oil and water is comparable. The minimum productivity and efficiency of the process are observed in case of EED of the alloy WC–15Co, maximum values are observed in case of the erosion of the alloy WC–5TiC–10Co (see table). The productivity and process efficiency increase and specific energy consumption decreases with an increase of the concentration of WC or (Ti,W)C, which prevent heat removal from the surface of the electrodes due to lower thermal conductivity.

The frequency of the current pulses is less than the frequency of the voltage pulses supplied by the generator, since part of the time the free electrode is located at a distance from the fixed electrodes. The electrodes are displaced as a result of the operation of the shaker, which is necessary to clear the gap from the formed particles, prevent any short circuit and weld the electrodes to each other. The vibrating screen performs harmonic oscillations described by a cosine (Fig. 3, *a*). Discharges occur only when the distance between the fixed and free electrodes is less than the breakdown gap (h):

$$A_{sh}\frac{\cos(\omega t+1)}{2} < h. \tag{5}$$

The size of the breakdown gap depends on the voltage between the electrodes (U_0/n) and the dielectric strength (DS) of the liquid:

$$h=\frac{U_0}{\mathrm{DS}\,n}. \tag{6}$$

The frequency of the current pulses is reduced due to the discarding of the loose electrode from the fixed ones by the shock wave generated by the spark discharge. It needs time T_r for returning that depends on the distance of displacement of the electrode. The distance depends on the kinetic energy of the impact wave, for the formation of which a certain part of the energy of the discharge was consumed. The return time is proportional to the discharge energy in first approximation:

$$T_r = aE_d, \tag{7}$$

where a is a constant depending on the fraction of the discharge energy spent on the formation of the shock wave, rheological properties of the liquid, mass, density and geometric parameters of the pieces. Summing up the equations (5)–(7), we obtain the dependence of the frequency of current pulses on the frequency of voltage pulses:

$$F_I = \begin{cases} \frac{1}{\frac{1}{F_U} + T_r}\left(1 - \frac{\arccos\left(\frac{2h}{A_{sh}} - 1\right)}{\pi}\right), & A_{sh} > h, \\ \frac{1}{\frac{1}{F_U} + T_r}, & A_{sh} \le h. \end{cases} \tag{8}$$

Derived equations (5) and (7) describe in detail the dependence of the pulse frequency on the amplitude of the shaker (Fig. 3, *b*) and the frequency of the supplied pulses (Fig. 3, *c*). The values of dielectric strength for all liquids obtained by fitting turned out to be an order of magnitude lower than the reference ones. This is probably due to contamination of the liquid by the formed particles and pyrolysis products. As expected, transformer oil has a high dielectric strength, and water has a low dielectric strength. An increase of the pulse energy leads to a decrease of the frequency of current pulses in all liquids. The resulting model (8) correctly details the frequency of current pulses in a plant with different discharge energies, liquids and amplitudes (Fig. 3, *d*). EED performance values calculated using the proposed model (1), (3), (8), correlate with experimental values obtained at different discharge energies for oil and water (Fig. 3, *e*). Maximum performance under experimental conditions is achieved in oil due to high efficiency and increased pulse frequency of the current.

Conclusion

The paper establishes the main dependences of productivity and specific energy consumption for the production of powder by electroerosive dispersion of hard alloys WC–8Co, WC–15–Co and WC–5TiC–10Co in a special plant. The produced powders consist of spherical particles obtained by crystallization of the liquid phase and agglomerates of nanoscale particles produced by crystallization of the vapor phase. The performance of the process depends on the mass of the powder obtained in one discharge and on the frequency of discharges. Productivity per discharge increases linearly with the increase of the discharge energy, and specific energy consumption decreases and tends to a constant value (3.3–4.5 (kW · h)/kg), equal to the ratio of the energy required for heating and melting the eroded material to heat transfer. The heat transfer efficiency (6.8–9.7%) depends on the carbide content and the properties of the liquid. An increase of the amplitude of the shaker reduces the discharge frequency by increasing the time the electrode is located at a distance when a breakdown is impossible. With an increase of the discharge energy, the discharge frequency decreases due to the ejection of the electrodes by shock waves that occur during the passage of the discharges. The return time depends on the rheological properties of the liquid used and the discharge energy.

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Conflict of interest

The authors declare that they have no conflict of interest.

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