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WEDM, wire electrodes wear, dimensional analysis

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EXPERIMENTAL MODEL ON THE WIRE WEAR FOR WEDM OF HARD TO MACHINE MATERIALS

In this study, the wear of wire electrodes was investigated experimentally in wire electrical discharge machining. Naked brass wire, 0.25 mm diameter, zinc oxide coated brass wire and brass CuZn20 coated with brass CuZn50 wire were applied in the conducted research. The wire wear ratio of WEDM of titanium alloy Ti6Al4V and cemented carbide B40 was described. As important WEDM parameters, the following variables were chosen: discharge time t_{on}, average working voltage U. The following properties of machined materials, such as: melting point T_t, electrical conductivity σ, thermal conductivity K, thermal expansion coefficient k, density ρ, heat capacity c_p, were also selected to develop the semi-empirical model of the wear of wire electrodes. The variation of the wire wear with cutting different materials by applying three different wire electrodes and process parameters was modelled semi-empirically by employing dimensional analysis.

1. INTRODUCTION

Wire electrical discharge machining (Wire Electrical Discharge Machining) is an alternative shaping route for manufacturing complex component shapes of hard to machine and brittle materials. WEDM assures high machining efficiency, low cost of tooling and virtually no deformation induced into a thin-walled or slender workpiece. There are lots of models describing WEDM. Most of authors analyse surface layer state of such materials as titanium alloys which are increasingly used in aerospace, automotive industries. Titanium is also commonly applied as medical implant materials in a wide variety of applications. Authors observed that from among the currently employed wire electrodes more uniform surface characteristics in a specimen of Ti6Al4V were obtained by applying zinc-coated electrode instead of uncoated brass wire [1]. Parametric optimization is the actual subject of many WEDM research. Article authors proposed the optimization

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algorithm of WEDM parameters, for cutting titanium alloy [2]. Taguchi methods of designing an experiment and innovate variation were applied. WEDM of cemented carbides focuses on eliminating surface

layer defects. Experiments proved that the selection of the proper value of discharge time enables to reduce the depth of the heat affected zone [3]. The traditional methods of cutting cemented carbides demonstrate low efficiency and high rate of tool wear. This is where the WEDM shows its advantages by offering high machining efficiency and low cost of tooling. The great impact of time parameters on technical effects of machining was noticed in many papers [4]. This work focuses on the study of wear of the wire electrodes effects resulting from WEDM – the one of the most important abrasionless machining methods [5]. The available experimental data prove that surface finish obtained in WEDM is strongly affected by time-related process variables, such as: the pulse width and the time between two pulses.

There are models on mechanical behaviour of the electrode [6, 7]. During that time researchers [8] analyzed the effects of WEDM parameters on the state of the gap between electrodes. Duration of discharges, time between discharges, discharge voltage and dielectric pressure proved to be the most significant in establishing geometrical accuracy and surface roughness. Authors [9] analysed the effect of 13 process parameters on material removal rate, surface roughness and accuracy of WEDM. The research confirmed the significant impact of the duration of discharges and time between discharges on the effects of WEDM after the first rough cut. The relation between different machined material properties and the wire electrical discharge machinability was also analysed [10]. Thermal conductivity and specific heat were proved to be the most significant properties of the material, determining the material removal rate and the volume of the heat-affected zone. On the other hand, the results of empirical models (experimental) are usually true only for the material, the tools and the limited scope used in the experiment. The challenge facing the engineers designing tools for WEDM is to create wires, which properties will be high enough to bear the thermo-electrical and mechanical load throughout the process.

The aim of this paper was to develop the model joining advantages of both physical and empirical models The following study was to describe wire wear ratio for WEDM of titanium alloy Ti6Al4V and cemented carbide B40, using three different wire electrodes. Naked brass wire, 0.25 mm diameter, zinc oxide coated brass wire and brass CuZn20 coated with brass CuZn50 wire were applied in the conducted research. In order to realize the aim of the research, dimensional analysis was applied to design of experiment [11]. Dimensional analysis has been employed in physics, fluid mechanics and many other sciences for many years [12].

2. WIRE ELECTRODES APPLIED IN WEDM

The challenges facing the universal wire electrodes connected with continuous development of WEDM technology are shown on Fig. 1. Brass wires were first introduced into the market in 1977, as the result from close collaboration between the major WEDM manufacturer and the wire making company. The breakthrough in cutting efficiency from

12 mm^2/min to 25 mm^2/min in 50 mm thickness of workpiece has been reached. Presently, a common type of material of wire electrodes is CuZn37. It was discovered that zinc with its' lower melting temperature (Zn≈420°C and Cu≈ 1080°C) and high vapour pressure promoted better flushability. During a cut, the zinc actually boils off, the lower number of electrically discharged particles from the wire is generated and high pressure helps to cool the cut and allows better energy transition. The higher content of zinc (>40%) is unprofitable. When the zinc content increases over 40%, the material changes from a single α phase crystalline structure into a two phase α + β structure. The brass becomes brittle and unsuitable for shaping into fine wire diameters.

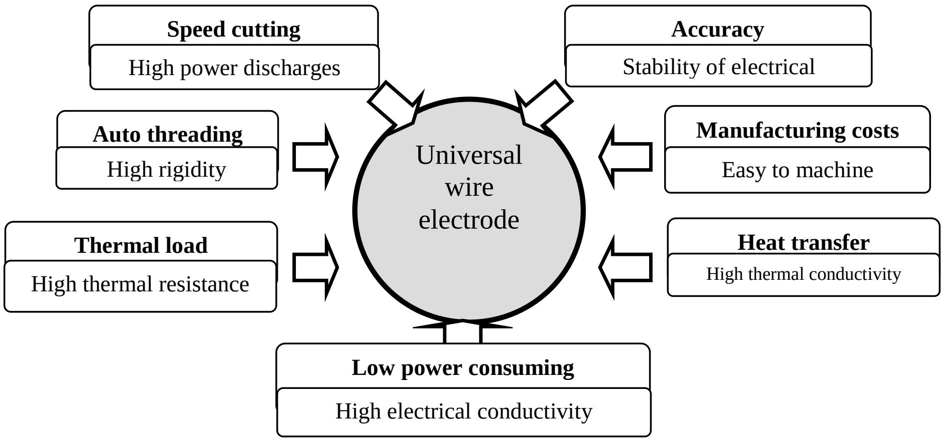

Fig. 1. Different requirements for the universal wire electrode applied in WEDM

Zinc coated brass wires were invented and patented in 1985 by engineers from the Swiss WEDM manufacturer. This was invention in order to improve accuracy. The kind of wires has higher tensile strengths (900 N/mm^2). The zinc plated wire goes through a secondary heat treatment in an oxygen environment, which produces a very thin oxide layer on the surface of the wire. Hard oxide layer helps the wire to slide through the guides without flaking of the zinc coating. The oxide layer is actually semi-conductive and small vibrations against the workpiece don't produce short circuits. The oxide layer masks the sensitivity of the machine servo system and doesn't slow down the machining process. It allows to improve the cutting speed. Roughness of the oxide layer helps to transport accumulated debris through the gap and thereby helps in the overall flushing process. Because of its' high elongation, the wire is suitable for high taper cuts. It is used to cut certain exotic composite materials and manmade materials (i.e. PCD cutting tools).

Japanese offered wire electrical discharge machines, which obtained efficiency of cutting equal to 172 mm^2/min, in 1986. At such speed, all zinc coatings completely vapoured by height equal to 25 mm. The interesting alternative appears to be diffusion coatings. Previously rejected, CuZn50 alloy seems to be in the centre of new ideas. It turns out that brass alloys with high zinc content are suitable for coatings. The core of the wires is made of brass. This new wires have porous surface which improves their "flushability". Diffusion annealed wires are appropriate for cutting high details with high efficiency without loss of accuracy.

3. THE INVESTIGATION METHOD

The aim of the paper was to develop the model of wire wear by the application of dimensional analysis. The realized semi-empirical model should enable to analyse the influence of the most important process parameters and properties of machined materials on the wear of wire electrode. Thermo-physical parameters of machined materials, such as: melting point T_t, electrical conductivity σ, thermal conductivity K, thermal expansion coefficient k, density ρ, heat capacity c_p were employed.

3.1. EXPERIMENTAL SET-UP

The experiments were conducted on wire electrical discharge machine Sodick model AQ 327L, which is shown on Fig. 2. The AQ327L wire electrical discharge machine is largely made up of ceramic components. Apart from high corrosion resistance their thermal expansion is at least two times lower than that of traditional materials. A ceramic frame of the *Z* axis assures negligible sensitivity to temperature changes. Stable feed of the wire makes for reduced offset and therefore a desired finish and surface geometry can be achieved after a lesser number of passes than in electrical discharge machines with conventional drives. This versatile machine is controlled by a modern 64-bit program package with a built-in 4D CAD-CAM (Q-vic) module. As a result high accuracies of cutting can be obtained with surface roughness as fine as $Ra \approx 0.2$ μm.

Fig. 2. Front view of the workstation – electrical discharge machine Sodick AQ 327 L

3.2. EXPERIMENT

In presented research, the method based on the Buckingham **π** theorems was applied at some stage. A relationship between **n** variables (physical properties, such as: velocity, density etc.) can be expressed as a relationship between **n**–**k** non–dimensional groups of variables (called **π** groups), where **k** is the number of fundamental dimensions (such as: mass, length and time) required to express the variables. Subsequently, the important parameters were selected and their scope and dimensions were defined. The selection of important WEDM parameters was based on results of preliminary research [5] and information found in the literature. The obtained results were similar to these portrayed in papers cited in the first section. As important parameters, the following variables were chosen: discharge time t_{on}, average working voltage U. The following properties of machined materials: melting point T_t, electrical conductivity σ, thermal conductivity K, thermal expansion coefficient k, density ρ, heat capacity c_p, were also selected to develop the semi-empirical model. Parameters employed in the model and their values for machined materials are shown in Table 1.

Table 1. Thermo-physical properties of the material of applied wire electrodes

Properties: \ Materials:	CuZn37	CuZn50	Zn
Melt. point, [K]	1183	1263	692.68
Thermal conductivity, [$\frac{kg \times m}{s^3 \times K}$]	115	100	116
Electrical conductivity, [$\frac{s^3 \times A^2}{kg \times m^3}$]	16.2×10^6	16.2×10^6	16.6×10^6
Density, [$\frac{kg}{m^3}$]	8400	8700	7140
Spec. heat capacity, [$\frac{m^2}{s^2 \times K}$]	380	385	390
Dissipation coefficient	0.2	0.2	0.2
Thermal expansion coefficient [K^{-1}]	21×10^{-6}	21×10^{-6}	21×10^{-6}

Dimensions of selected variables are shown in Table 2. WEDM was realised with submerging and shower along the wire electrode. Deionised water was employed as a dielectric. The height of cut elements was constant and equal to 10 mm. Wire diameter was constant for all of the electrodes and equal to 0.25 mm.

Table 2. Dimensions of the selected variables

Dimension	Variables								
	a(Zv)	b(ton)	c(U)	d(Tt)	e(σ)	f(cp)	g(K)	h(ρ)	i(k)
M – mass	0	0	1	0	–1	0	1	1	0
L – length	3	0	2	0	–3	2	1	–3	0
T – time	–1	1	–3	0	3	–2	–3	0	0
O – temperature	0	0	0	1	0	–1	–1	0	–1
I – current	0	0	–1	0	2	0	0	0	0

Then, the independent parameters containing selected fundamental dimensions were defined. Set of n parameters, which have impact on wire wear Z_v can be written as:

$$Z_v = f(U, t_{on}, \rho, \sigma, K, k, T_t, c_p) \tag{1}$$

where: U – average working voltage, t_{on} – discharge time, T_t – melting point, k – thermal expansion coefficient, σ – electrical conduction, c – specific heat capacity, ρ – density, K – thermal conductivity, Z_v – volumetric wear of wire electrode.

Parameters **π** are determined by equating the powers of the fundamental units on both sides of Eq. (2). Set of simultaneous equations are solved. The equation of dimensional analysis is given as:

$$\begin{aligned} &C\cdot[L^3T^{-1}]^a\cdot[T]^b\cdot[ML^2T^{-3}I^{-1}]^c\cdot[O]^d\cdot[M^{-1}L^{-3}T^3I^2]^e\cdot \\ &[L^2T^{-2}O^{-1}]^f\cdot[MLT^{-3}O^{-1}]^g\cdot[ML^{-3}]^h\cdot[O^{-1}]^i=[M^0L^0T^0O^0I^0] \end{aligned} \tag{2}$$

The set of simultaneous equation is given:

$$\begin{aligned} &c-e+h+g=0 \\ &3a+2c-3e+2f-3h+g=0 \\ &-a-3c+b+3e-2f-3g=0 \\ &d-f-g-i=0 \\ &-c+2e=0 \end{aligned} \tag{3}$$

Presented simultaneous equation can be written in matrix form: AX = C_1

$$A=\begin{vmatrix} -1 & 0 & 1 & 1 & 0 \\ -3 & 2 & 1 & -3 & 0 \\ 3 & -2 & -3 & 0 & 0 \\ 0 & -1 & -1 & 0 & -1 \\ 2 & 0 & 0 & 0 & 0 \end{vmatrix} \quad X=\begin{vmatrix} e \\ f \\ g \\ h \\ i \end{vmatrix} \tag{4}$$

Assigning a = 1 and b, c, d, = 0 gives equation:

$$\begin{aligned} &C=[0\ \ -3\ \ 1\ \ 0\ \ 0]^T \\ &TX=[0\ \ -2.5\ \ 2\ \ 2\ \ -0.5]^T \end{aligned} \tag{5}$$

then

$$\pi_1 = \sqrt{\frac{Z_v^{\ 2}\cdot Cp^5\cdot\rho^4}{K^4\cdot k}} \tag{6}$$

If it is noted that thermal diffusivity α is given as:

$$\alpha = \frac{K}{\rho\cdot Cp} \tag{7}$$

then finally:

$$\pi_1 = \sqrt{\frac{Z_v^{\ 2}\cdot Cp}{\alpha^4\cdot k}} \tag{8}$$

Proceeding similarly, b = 1, c = 1 … were assigned and π_2, π_3, π_4 were determined. The results, in form of determined unknown powers of dimensional analysis, are shown in Table. 3.

Table 3. Results of dimensional analysis for the developed model

	π_1	π_2	π_3	π_4
a	1	0	0	0
b	0	1	0	0
c	0	0	1	0
d	0	0	0	1
e	0	0	0.5	0
f	2.5	2	0	0
g	-2	-1	-0.5	0
h	2	1	0	0
i	-0.5	-1	0.5	1

Determined dimensionless products π can be written as:

$$\pi_2 = \left(\frac{t_{on} \cdot Cp}{k \cdot \alpha} \right) \tag{9}$$

$$\pi_3 = \left(\frac{U^2 \cdot \sigma \cdot k}{K} \right) \tag{10}$$

$$\pi_4 = \left(T_t \cdot k \right) \tag{11}$$

If relation between dimensionless products is expressed as: $\pi_1 = f(\pi_2, \pi_3, \pi_4)$, the final form of model can be written as:

$$Z_v = A \cdot P \cdot \sqrt{\frac{\alpha^4 \cdot k}{Cp}} \cdot \left(\frac{Cp \cdot t_{on}}{k \cdot \alpha} \right)^b \cdot \left(\sqrt{\frac{U^2 \cdot \sigma \cdot k}{K}} \right)^c \cdot \left(T_t \cdot k \right)^d \tag{12}$$

4. EXPERIMENT RESULTS AND DISCUSSION

The results of goodness of fit for the developed semi-empirical model were presented on graphs. The dependence of volumetric wear of the wire electrode on discharge time t_{on} obtained by application of the semi-empirical model is shown on Figs. 4, 5 and 6. The results were obtained for constant brake time t_{off} = 13 μs and average working voltage U = 45 V. Scope of the selected parameters of the analyzed process is shown in Table 4. The unknown coefficient and power indexes were calculated for each pair of machined material and wire electrode. For the mentioned aim, the non - linear estimation was applied. As far as this study is concerned, it appeared that the most adequate method was Hooke-Jeeves pattern moves function**.** In a sense this is the simplest of all algorithms. At each iteration, this method firstly defines a pattern of points by moving each parameter one by one, so as to optimize the current loss function. The entire pattern of points is then shifted or moved to a new location – this new location is determined by extrapolating the line from the old base point in the *m* dimensional parameter space to the new base point. The step sizes in this process are constantly adjusted to "zero in" on the respective optimum. Statistical software STATISTICA 6.0 was applied for the estimation, and results are shown in Table 5. The analysis of correlation, mean error (ME), root mean square error (RMSE), average error of prediction Δ_{av}, were determined from equations:

$$ME = 1/n \cdot \sum_{i=1}^{n} (Z_i - \hat{Z}) \tag{13}$$

$$RMSE = \sqrt{1/n \sum_{i=1}^{n} (Z_i - \hat{Z}\ )^2} \tag{14}$$

$$\Delta sr\% = 1/n \cdot \sum_{i=1}^{n} \frac{Z_i \cdot 100\%}{Z_i - \hat{Z}} \tag{15}$$

where: Z_i – result from a model, $\hat{Z}$ – result from an experiment.

Table 4. Scope of the selected WEDM parameters

Parameters	Dimension	x_k	Δx_k	$-\alpha$	–1	0	1	α
t_{on}	µs	$x1$	1.65	3	3.35	5	6.65	7
U	V	$x3$	4.11	40	40.89	45	49.11	50

Table 5. Results of non-linear estimation by Hook-Jeeves's pattern moves function

Wire electrode-machined material	Results of non–linear estimation H–J function				R	ME	RMSE	$\Delta_{sr}\%$
	A	b	c	d				
CuZn37-Ti6Al4V	7.80	0.09	0.53	–8.18	0.79	0.01	0.52	1.05
CuZn37-B40	7.52	–0.12	1.03	–7.38	0.86	0.03	1.33	2.05
Zn(CuZn37)-Ti6Al4V	401.75	0.18	0.08	–6.80	0.99	0.01	0.47	0.72
Zn(CuZn37)-B40	4.88	–0.08	0.80	–6.84	0.90	0.02	1.34	1.56
CuZn50-Ti6Al4V	5.12	0.37	0.92	–8.62	0.98	0.03	1.48	2.55
CuZn50-B40	1.31	0.21	0.84	–8.90	0.98	0.01	1.44	1.97

The obtained results of conducted experiments characterize high co-efficiency of correlation. The comparison of results for wire electrical discharge machining of cemented carbides B40 and titanium alloy Ti6Al4V with application of naked brass wire electrode are shown on Fig. 3.

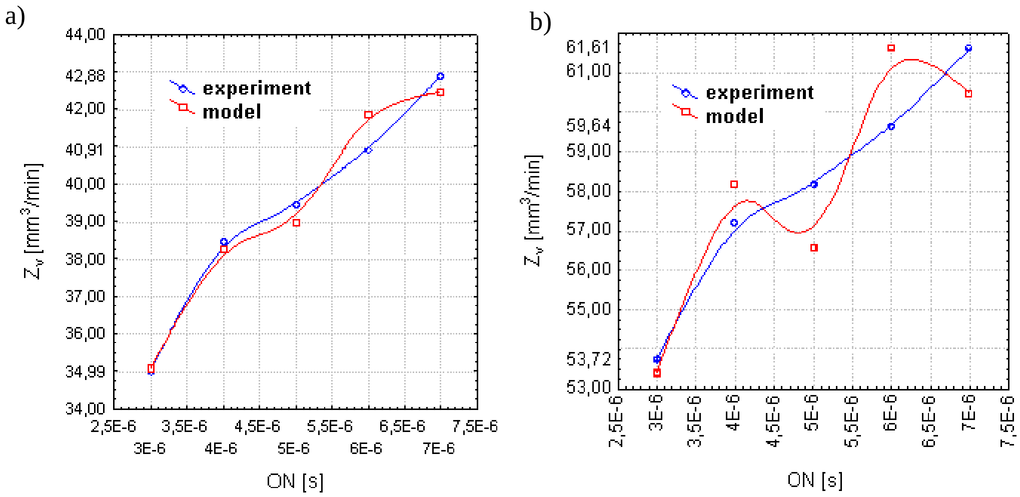

Fig. 3. Verification of the results of volumetric wear for the semi-empirical model and the results obtained in experiments for WEDM with naked brass wire: a) – Ti6Al4V, b) – B40

The wear of electrode was calculated basing on speed of wire travelling and measurement of difference of volume of the new wire and the wire after WEDM. The highest wear of electrode was received for cutting cemented carbides with electrode coated with brass CuZn50 (Fig. 5.). The situation was similar for titanium alloy Ti6Al4V. The reason of this state can be that brass CuZn50 has lower thermal conductivity $\left(100\ \left[\frac{kg \times m}{s^3 \times K}\right]\right)$ than the other materials of the applied wire electrodes (115 for brass CuZn37). The highest volumetric wear, concerning WEDM of cemented carbides B40 with electrode coated with brass CuZn50, is equal to 83.6 mm^3/min. It is 36% more than for naked brass CuZn37 electrode (Fig. 3.) and 5% more than for zinc coated electrode (Fig. 4.).

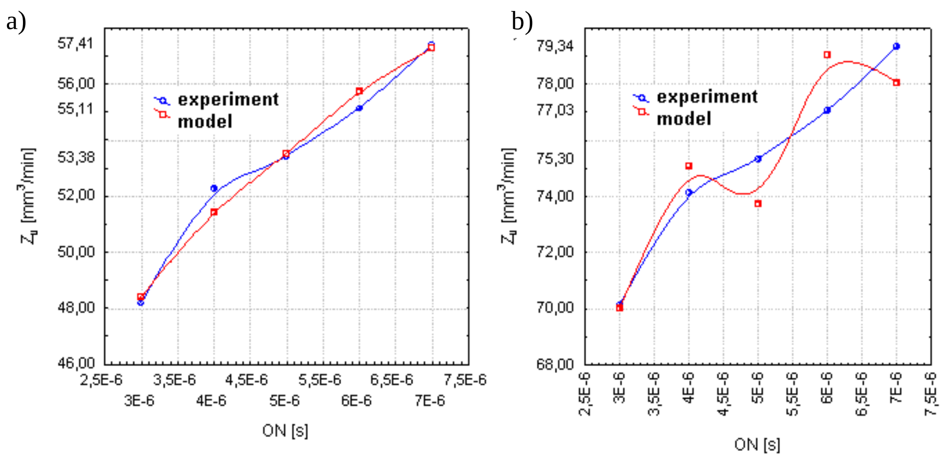

Fig. 4. Verification of the results of volumetric wear for the semi-empirical model and the results obtained in experiments for WEDM with zinc coated brass wire: a) – Ti6Al4V, b) – B40

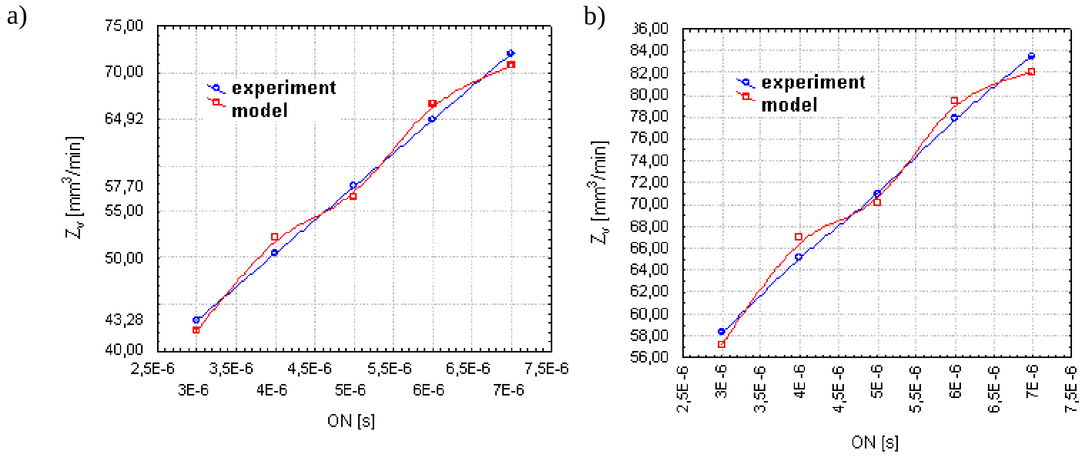

Fig. 5. Verification of the results of volumetric wear for the semi-empirical model and the results obtained in experiments for WEDM with brass CuZn50 coated brass wire: a) – Ti6Al4V, b) – B40

Analogically, for WEDM of titanium alloy Ti6Al4V the highest volumetric wear of the electrode coated with brass CuZn50 is equal to 72.1 mm^3/min - it is 68% more than for naked brass CuZn37 electrode (Fig. 3) and 26% more than for zinc coated electrode (Fig. 4). The volumetric wear of wire electrodes was much higher for machining of cemented carbides B40 than for titanium alloy Ti6Al4V, regardless of the type of employed electrode and in the same scope of WEDM parameters. Such significant difference confirms that the values of properties of materials applied in manufacturing of wire electrodes have important impact on the received effects of the WEDM process. Owing to the thermal nature of WEDM, the wear of electrodes is higher for cutting materials, which characterize higher melting point. With regard to the process parameters, the application of longer times of discharges and higher average working voltages results in the increase of volumetric wear of electrodes during the cut of all types of machined materials. Morphology of wear in wire due to melting and sublimation is presented on Figs 6 and 7.

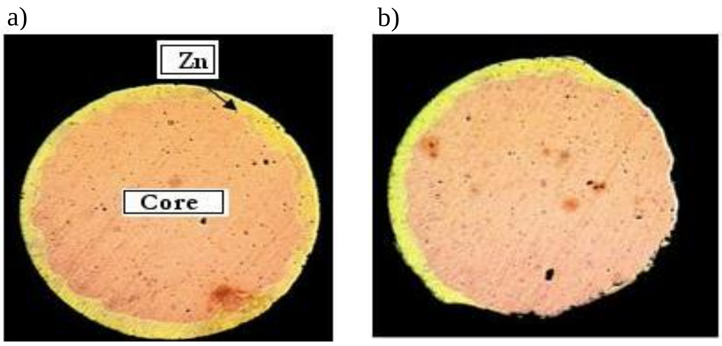

Fig. 6. Zinc coated wire BEDRA (CuZn37)Zn: a) new, b) after machining – scope ×25

Cross-sectional and longitudinal views show clearly numerous craters and microcracks. In comparison with models which appeared previously in the literature, the developed semi-empirical model is different, on account of the fact that it is mainly based on electrical and thermal properties of materials of wire electrodes and the most important WEDM parameters.

a) b)

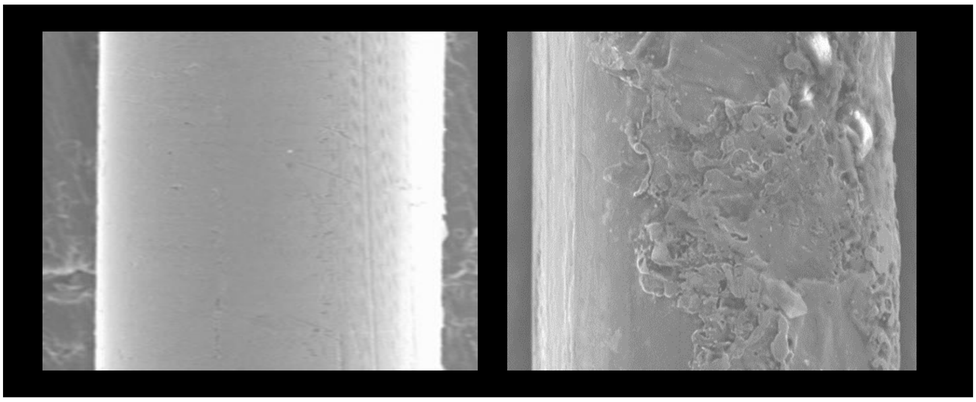

Fig. 7. Naked brass wire BEDRA CuZn37: new – a) and after machining, b) – scope x 250

Although power indexes and coefficients are different for employed materials and wire electrodes, the results of the model should be reliable for the prediction of changes of parameters, in the scope analyzed in the research. The model is not universal, nevertheless the presented methodology of employing statistical software and dimensional analysis might be potentially the good direction for exploring phenomena occurring throughout WEDM.

5. CONCLUSION

In the experiment three various wire electrodes: 0.25 mm diameter naked brass wire, zinc oxide coated brass wire and brass CuZn20 coated brass CuZn50 wire, were applied. The materials such as: titanium alloy Ti6Al4V and cemented carbides B40, were machined. In the conducted research, the volumetric wear of the electrodes throughout machining two materials: B40 cemented carbides and Ti6Al4V titanium alloy, was studied in this paper. The aim of the study was to develop the model of wire electrodes wear by employing dimensional analysis. The received semi-empirical model enables to analyze the influence of the properties of materials of wire electrodes on their volumetric wear. The semi-empirical model takes into consideration the chosen properties of applied materials, such as: electrical conductivity, thermal conductivity, density and melting point. The aim of the development of the models of WEDM is usually to avoid the wire breaking while realizing the cutting with high efficiency. The wire breaking is the most important problem which limits the increase of the efficiency of WEDM. The wire wear is mostly caused by overheating. Finally, the marks on the machined surface occur and presupposed accuracy is lost. Additionally, the machining time is longer.

The conducted researches enable to draw the following conclusions:

– Higher value of thermal conduction and specific heat capacity of machined material cause the decrease of efficiency of WEDM.
– Owing to the thermal nature of WEDM, the efficiency of cutting is lower for materials, which characterize higher melting point.

– As far as the WEDM of cemented carbides B40 is concerned, the highest wear for cutting with brass coated electrode is equal to 83.6 mm^3/min and it is 36% more than for the naked brass CuZn37 electrode and 5% more than for the zinc coated electrode.
– With regard to WEDM of titanium alloy Ti6Al4V, the highest volumetric wear for cutting with brass coated electrode is equal to 72.1 mm^3/min and it is 68% more than for the naked brass CuZn37 electrode and 26% more than for the zinc coated electrode.
– In the future research, it would be interesting to analyze the influence of modified shape of generated discharge pulses on the WEDM results.
– In the future research, it would also be profitable to employ a wire electrode with larger active surface (not flat).

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