Journal of Machine Engineering, Vol. 8, No. 2, 2008

titanium alloys, wire electrode,
artificial neural networks, WEDM

Stanisław ZABORSKI[1]
Dariusz POROŚ[1]

EFFECT OF PROCESS PARAMETERS ON THE CONDITION OF THE WIRE ELECTRODE IN WEDM OF TI6AL4V

Conventional machining of titanium alloy Ti6Al4V cause high temperature and rapid wear of tool which makes him hardly suitable for machining by machine cutting. The presented experimental study was carried out on a modern wire EDM Sodick AQ327L. Three types of the wire were used. Investigated were the effects of such input parameters as the pulse width and the time between two pulses on the output parameters such as area cutting efficiency, workpiece surface roughness and wear rate of the electrode. The resulting relationships were determined using the conventional regression analysis and neural networks. The results were checked for goodness of fit.

1. INTRODUCTION

Titanium alloy Ti6Al4V commonly used for space and aircraft applications, as well as high performance automotive and marine applications, provides excellent corrosion resistance, a high strength-to-weight ratio and good high temperature properties This is where the WEDM shows its advantages by offering high machining efficiency, low cost of tooling and virtually no deformation induced into a thin-walled or slender workpiece. The available experimental data show that surface finish obtained in WEDM is strongly affected by time-related process variables: the pulse width and the time between two pulses. Investigated were the effects of these on cutting efficiency, removal rate of wire material and workpiece surface roughness. Three types of the wire were used: brass CuZn20 wire coated brass CuZn50, brass wire CuZn37 and zinc-coated CuZn37 wire. Tensile strength of the three wires was over 800 MPa.

2. WEDM OF TITANIUM ALLOYS

EDM of titanium alloys has been treated extensively in the literature, both its variations for producing cavities and for cutting with travelling wire [2,5,11]. Wire

[1] Wroclaw University of Technology Institute of Production Engineering and Automation, ul. Lukasiewicza 5, 50-371 Wroclaw, POLAND

electrical discharge machining (WEDM) has been found to be an extremely potential electro-thermal process in the field of conductive material machining. Owing to high process capability it is widely used in manufacturing of stators for stepper motors, various press tools, molds, dies and similar intricate parts. Selection of optimum machining parameter combinations for obtaining higher cutting efficiency and other dimensional accuracy characteristics is a challenging task in WEDM due to presence of large number of process variables and complicated stochastic process mechanism. Hence, there is a demand for research studies which should establish a systematic approach to find out the optimum parametric setting to achieve the maximum process criteria yield for different classes of engineering materials. An effective way to solve this state of problem is to focus on establishing the relationship between machining input parameters and machining criteria performances. A number of research works has been carried out on different materials to study the influence of different process parameters on EDM and WEDM [3, 13, 15]. In the present research study wire electrical discharge machining of Ti6Al4V has been considered. Different aspects of machining have been investigated by several researchers [7, 12, 16]. But no comprehensive research work has been reported so far in the field of wire electrical discharge machining of this alloy. No technology tables or charts are available for wire electrical discharge machining of such important and useful materials in industry. Therefore, it is imperative to develop a suitable technology guideline for optimum machining of this alloy. Further, in majority of the past research works machining speed and surface finish have been considered. Some research work has been done keeping in view of the accuracy aspects [9, 10]

The pulse times and currents should be so chosen as to prevent critical overheating of material resulting in building up residual stresses. The number of passes should be adjusted to the recast layer thickness.

3. THE INVESTIGATION METHOD

Objectives of the study required that the two investigation stages were necessary:

- the wire EDM process was modelled using an experiment design and a response surface for the central composite one as well as neural networks. Tested were the effects of pulse time parameters (ON, OFF) on area cutting efficiency (Q_p), tool material removal rate (U_m) and surface roughness (Rz)
- graphical presentation and analysis of the results

3.1. EXPERIMENT DESIGN

The rotatable design of the second order was adopted. It was assumed that the area cutting efficiency and surface roughness are significantly dependent on:

–pulse width ON [μs]

–time between two successive pulses OFF [μs].

The sought for relationship has the form:

$$\mathbf{Z = f\ (X_1,X_2)}$$

or

$$\mathbf{U_m, Rz, Q_p = z = f(ON, OFF, U)} \quad (1)$$

The second-order polynomial model was adopted:

$$Z=b_0+b_1x_1+b_2x_2+b_3x_3+b_{11}x_1^2+b_{22}x_2^2+b_{33}x_3^2+b_{12}x_1x_2+b_{13}x_1x_3 \quad (2)$$

Where: $\breve{x}_1$, $\breve{x}_2$, $\breve{x}_2$ – code values of the parameters tested,
b_k–experimental constants

In successive steps determined were: range of the factors investigated, central values, variability units and code relations. Next, the measurements were carried out. The regression coefficients were determined according to the rules relevant to rotatable planning of the second order. Next, the quality of fit of the obtained regression function was evaluated at the assumed confidence level ($\alpha = 0.05$) and individual regression coefficients were checked by the Student's *t* statistic

$$F \le F_\alpha\left(f_1, f_2\right) \quad (3)$$

Next, were worked out to perform approximation of the experimental relationships.

A neural network is a system of simple inter-connected elements (neurons) that process information. They have been used quite long now in modelling and controlling inherently random processes in many areas of science and technology including WEDM [4, 15].

Neural networks are capable of independently constructing models since they learn from examples provided by a user. The user has to gather representative data for a relationship sought for but it is the network itself which is responsible for developing an appropriate data structure within its memory. Some skill is still required on the part of the user when it comes to selecting and preparing input data but the level of knowledge involved in the process of model generation is much lower than in the traditional approach employing statistical methods [14]. Neural networks are mainly used in classification tasks consisting in associating input sets with classes or associating inputs with categories. Parameters that must be determined in order to apply a neural network to solving a given task can be classified as follows:

- those concerning the neural network structure: selection of architecture, number of layers, number of neurons within a layer, type of transfer function,
- those concerning the learning process: division of the data set, quantities comprising the set, learning coefficients values, initial weight values, time of learning,

Selection of the network architecture must be preceded by the analysis of the principal problem and the available data. Regression models are usually generated using:

- linear networks,
- multi-layer perceptron networks (MLP),
- radial base function networks (RBF),
- generalized regression networks (GRNN).

3.2. EXPERIMENTAL SET-UP

The AQ327L wire electrical discharge machine is largely made up of ceramic components (Fig. 1.). 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

Fig. 1. Workstation – front view

geometry can be achieved after a smaller number of passes than in machines with conventional drives. This versatile machine is controlled by a modern 64-bit programme 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≈0.2μm.

4. EXPERIMENTAL PROCEDURE AND RESULTS

The wire used was made of brass (naked or brass CuZn50 or zinc-coated) with a diameter of 0.25 mm and $\gamma_y \approx 900$ MPa. In Sodick's wire electrical discharge machines the threading-on process requires that wire has the tensile strength of at least 750 MPa at d = 0.25 mm and this condition at present cannot be met by any grade of commercially available copper wire [8]. The tool wear was determined by a percent decrease of wire mass following the process (wire wear ratio, WWR [6]). The presence of zinc with a low melting point had a beneficial effect of increased washing out the debris from the slot. This coated variant of the wire is especially suitable for applications where the increased cutting efficiency and the slightest recast layer due to a high rate of zinc sublimation is at stake. Brass CuZn50 coating enables to cut conducting materials with higher efficiency also troublesome alloys. Cutting of cones is then limited to 7º. Available are its two grades: without and with oxide layer. Specification of the electrodes used in the present study is given in Table 1. Height of the cut workpieces was 10 mm. Surface roughness was measured using a Rank Taylor Hobson–Taly form Series 120L profilographometer.

Table 1. Application of wire electrodes.

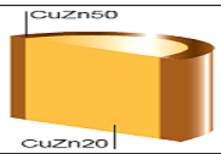
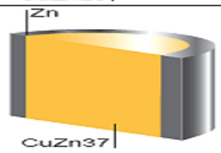
Type of wire electrode	
CuZn50 brass coated CuZn20 brass wire	
Zinc coated brass wire	
CuZn37 naked brass wire	

Table 2. Characteristic of the machined material.

Impurities content max. [%]					Structure	Phase change temp. α → β [ºC]	Density [g/cm3]
Fe	C	H	N	O			
0,17	0,01	0,0012	0,009	0,172	α + β	990	4,42

The wire wear ratio was determined using a Radwag 220/C/2 analytical scales. The R_z index was chosen as a representative measure of surface finish. Specification of the material tested is shown in Table 2. Two phase type structure α + β of titanium alloy

Ti6Al4V is shown on Fig. 2. The test pieces cut out in the process were parallelepipeds 4×10×12 mm. Three specimens were taken for each value of the process parameters. The tests were performed according to roughly estimated regressions listed in Tabel.3.

Table 3. Objest function obtained in regression analysis

Effects	**Object function**	**R-correlation**	**RMSE**
Q_v	$Q_{veM63} = 11,32 - 1,05t_{off} - 0,1t_{off}^2 + 4,79t_{on} – 0,25t_{on}^2 - 1,67U - 0,35U^2 - 0,33t_{on}t_{off} + 0,79Ut_{off}$	0,99	0,07
	$Q_{veZn} = 11,5 - 1,05\ t_{off} - 0,09\ t_{off}^2 + 4,76\ t_{on} - 0,3\ t_{on}^2 – 1,76U – 0,01U^2 - 0,33\ t_{on}\ t_{off} + 0,84U\ t_{off}$	0,99	0,06
	$Q_{veM50} = 9,26 - 0,8\ t_{off} + 0,28\ t_{off}^2 + 3,98\ t_{on} + 1,72\ t_{on}^2 + 0,02U - 3,4U^2 - 0,4\ t_{on}\ t_{off} + 0,31\ U\ t_{off}$	0,98	0,15
Rz	$Rz_{M63} = 12,1 - 0,17\ t_{off} + 0,002\ t_{off}^2 + 0.6\ t_{on} + 0,001\ t_{on}^2 + 0,7U - 0,13U^2 - 0,06\ t_{on}\ t_{off} + O,08U\ t_{off}$	0,99	0,01
	$Rz_{Zn} = 12,99 - 0,18\ t_{off} + 0,002\ t_{off}^2 + 0,61\ t_{on} + 0,001\ t_{on}^2 + 0,74U + 0,13U^2 - 0,06\ t_{on}\ t_{off} + 0,09U\ t_{off}$	0,99	0,01
	$Rz_{M50} = 14,39 - 0,52\ t_{off} - 0,01\ t_{off}^2 + 1,74\ t_{on} + 0,25\ t_{on}^2 + 0,23\ U - 0,77U^2 - 0,21\ t_{on}\ t_{off} + 0,38U\ t_{off}$	0,99	0,02
Z_v	$U_{mM63} = 9,74 – 0,65\ t_{off} – 0,006\ t_{off}^2 + 2,63\ t_{on} - 0,01\ t_{on}^2 - 0,8U - 0,17U^2 - 0,17\ t_{on}\ t_{off} + 0,4\ t_{off}\ U$	0,99	0,02
	$U_{mZn} = 10,99 – 0,65\ t_{off} - 0,09\ t_{off}^2 + 2,63\ t_{on} - 0,01\ t_{on}^2 – 0,18U - 0,8U^2 – 0,17\ t_{on}\ t_{off} + 0,4\ t_{off}\ U$	0,99	0,02
	$U_{mM50} = 13,46 - 0,8\ t_{off} - 0,15\ t_{off}^2 + 2,96\ t_{on} - 0,08\ t_{on}^2 + 0,17U - 0,61U^2 - 0,3\ t_{on}\ t_{off} + 0,53U\ t_{off}$	0,98	0,13

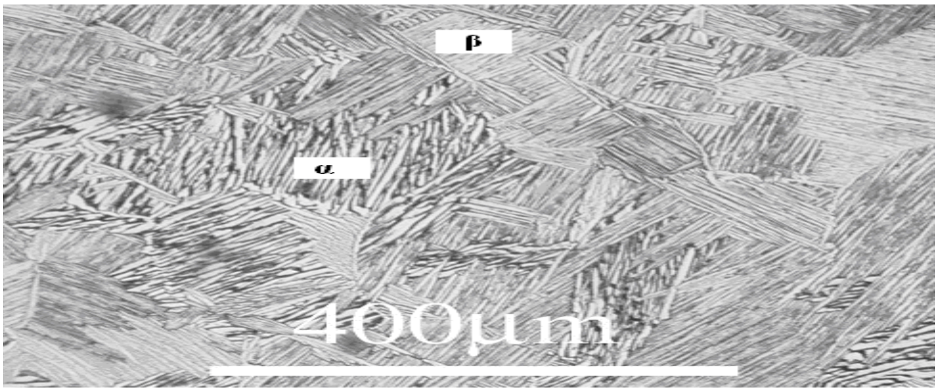
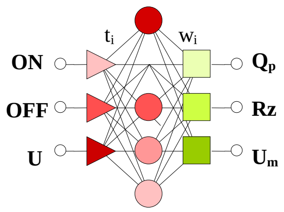
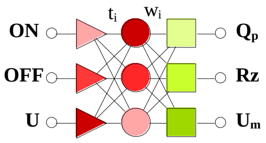
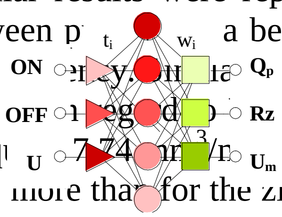


Fig. 2. Two phase type structure α + β of titanium alloy Ti6Al4V

To determine the required relationships also neural networks were used with radial base functions with 3-6-3, 3-3-3 and 3-5-3 neurons structures, i.e. with six, trhee and five neurons in the hidden layer (see Tab. 4).

Table 4. Applied neural networks characteristics

	Number of neurons	Transition function	Learning data set	Testing data set	Analysed data set	RMS	Correaltion R		
							Q_p	U_m	Rz
	3-6-3	RBF	13	12	25	0,14	0,97	0,97	0,99
	3-3-3	RBF	13	12	25	0,54	0,9	0,96	0,95
		RBF	13	12	25	0,14	0,97	0,98	0,99

4.1. EFFICIENCY OF THE PROCESS

The WEDM area efficiency was determined as a product of cutting rate and workpiece thickness. The dependence of area efficiency on time parameters obtained through regression analysis is shown in Fig. 3. Longer times of discharges and/or shorter time gaps between pulses resulted in better efficiency of cutting with a naked electrode. Similar results were reported in papers [5,11]. It was also found that longer time gaps between p[illegible] a beneficial effect on stability of the operation without compromising the [illegible]ts obtained with the RBF network are shown in Fig. 4. [illegible] of titanium alloy Ti6Al4V, the highest volumetric efficiency is eq[illegible] 7,74 [illegible] it is 16% more than for the naked brass CuZn37 electrode and 15% [illegible] than for the [illegible] coated electrode. The increase of discharge time t_{on} from 3 to 7 μs causes the increase of volumetric efficiency of cutting of titanium alloy Ti6Al4V: applying naked brass wire electrode – 190 %, and for zinc coated wire electrode - 175%, and for wire electrode coated CuZn50 - 160%. Similar results were obtained in other thesis [5,11].

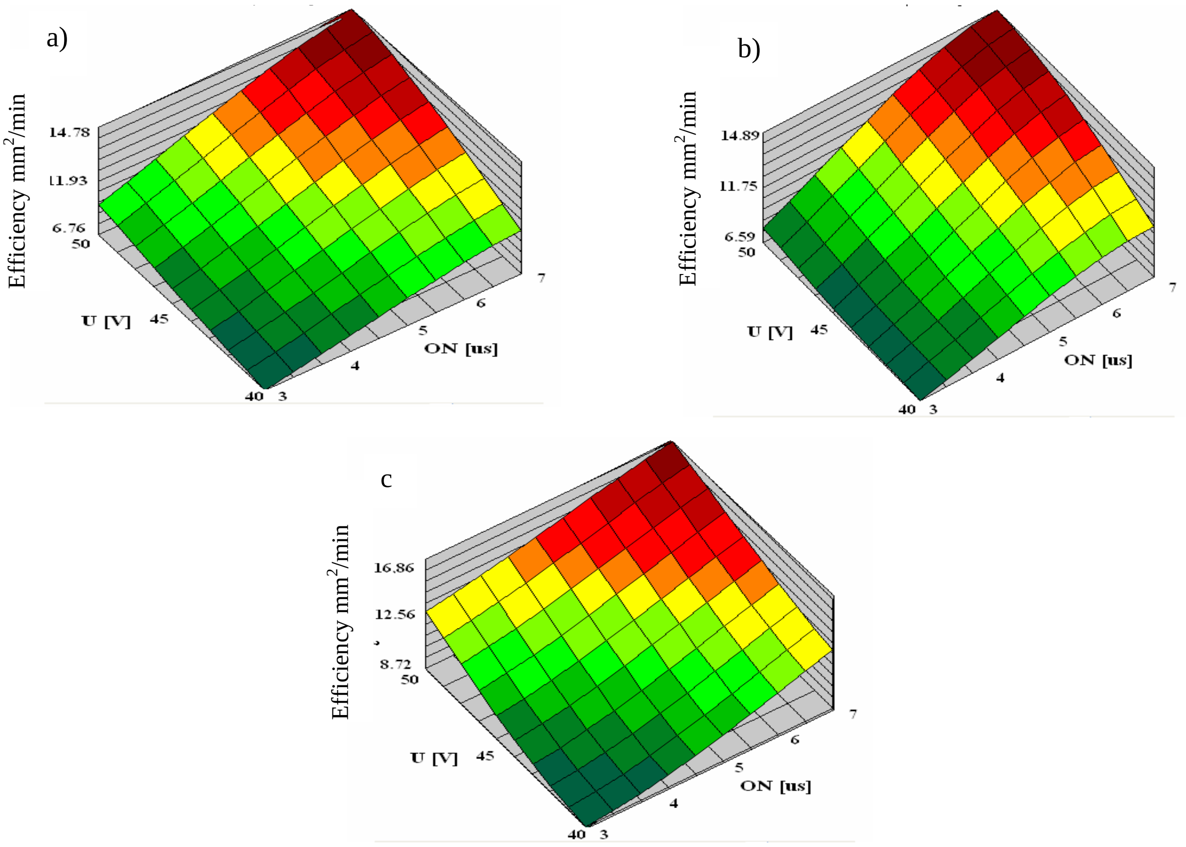


Fig. 3. Influence of time based parameters of WEDM on electrical discharge cutting efficiency of titanium alloy Ti6AL4V: a) brass wire, b) zinc coated wire, c) brass CuZn50 coated wire

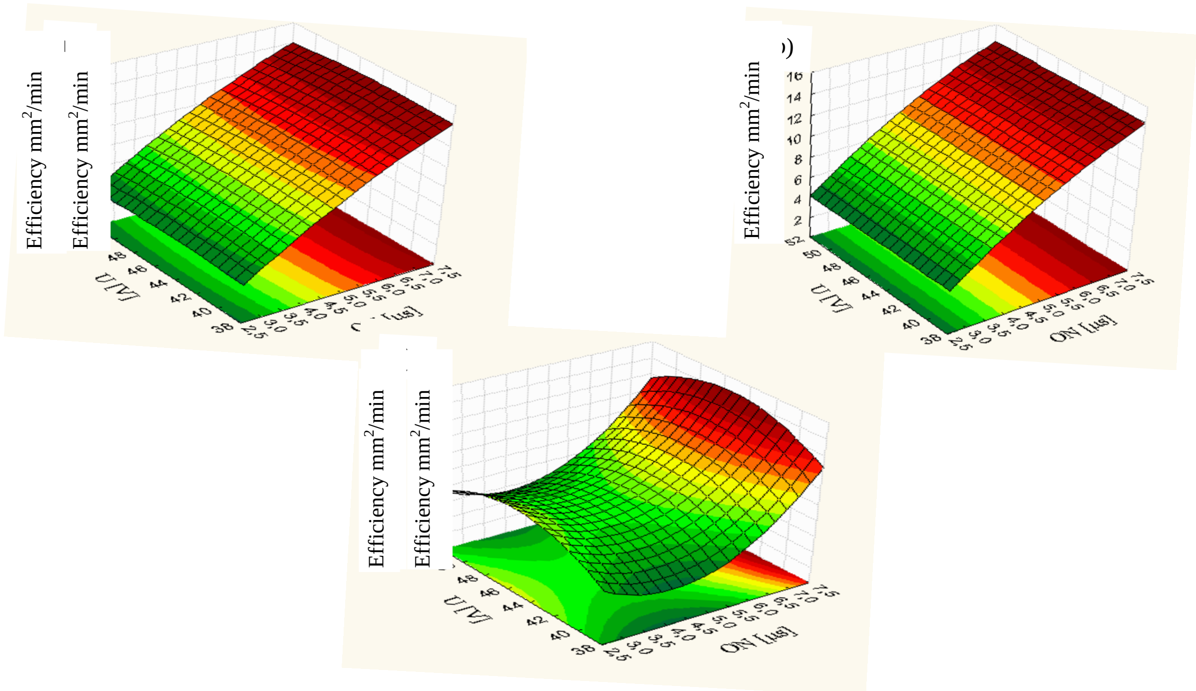


Fig. 4. Diagram of electrical discharge cutting efficiency of titanium alloy Ti6AL4V according to time based parameters of WEDM: a) brass wire, b) zinc coated wire, c) brass CuZn50 coated wire

4.2. SURFACE ROUGHNESS

Dependence of surface roughness R_z upon ON/OFF times was found to follow patterns shown in Fig. 5. Higher discharge times resulted in worse finish regardless of the tool material. Approximated results produced by a network can be seen in Fig. 6. The effect of time between two pulses on Rz is less pronounced for both electrode types, but longer OFF periods make for improved stability of the process.

With regard to WEDM of titanium alloy Ti6Al4V with lowest volume of analyzed parameters, the lowest surface roughness is equal 11,12 mm^3/min and it is 7% less than for the the zinc coated electrode and 7% less than for the brass CuZn50 coated electrode. Similarly for highest cutting parameters, the lowest surface roughness is equal 13,33 mm^3/min and it is 7% less than for the zinc coated electrode and 29% less than for the brass CuZn50 coated electrode. The increase of discharge time t_{on} from 3 to 7 μs causes the increase of surface roughness of titanium alloy Ti6Al4V: applying naked brass wire electrode – 20 %, and for zinc coated wire electrode - 20%, and for wire electrode coated CuZn50 - 44%. Similar results were obtained in other thesis [5, 11].

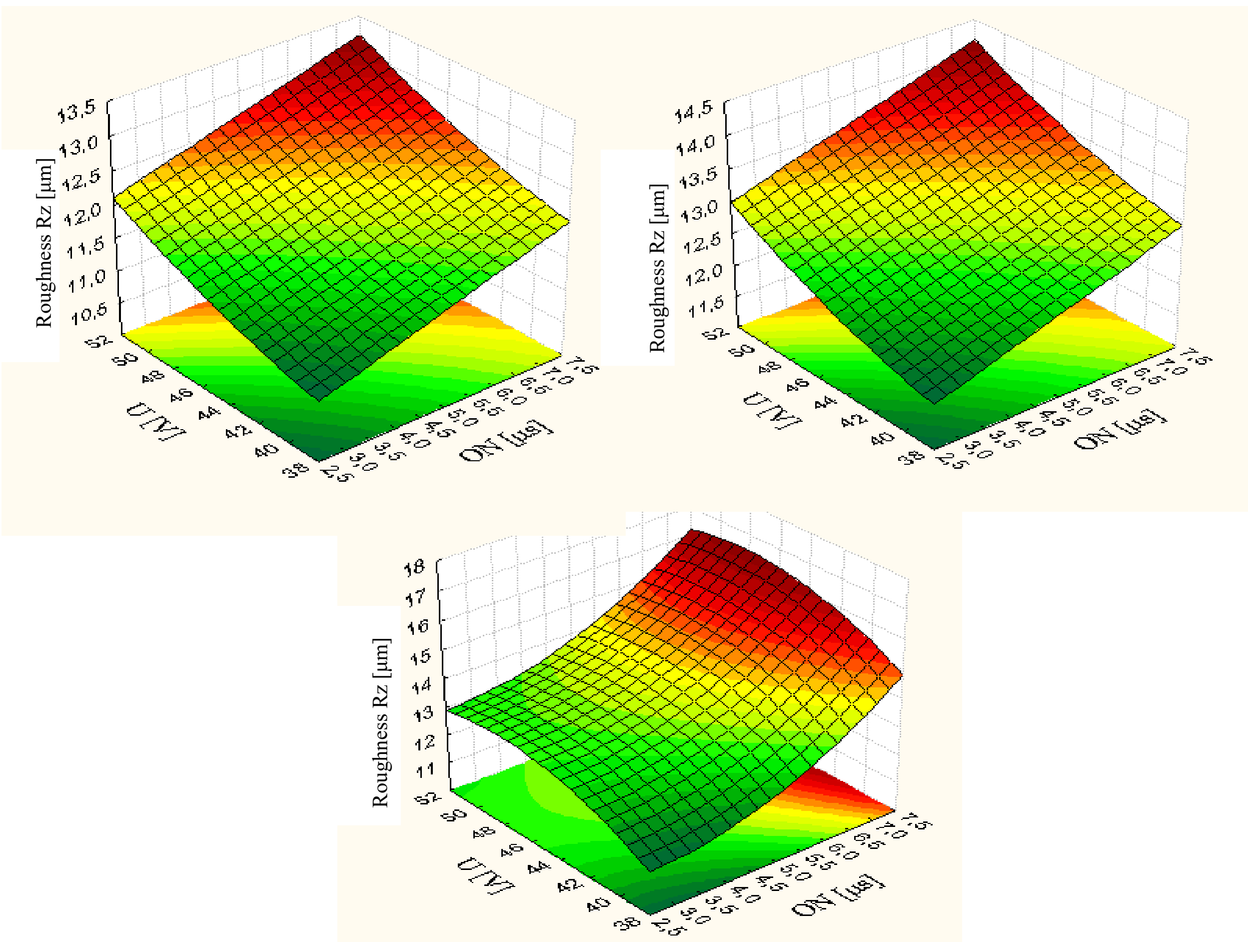


Fig. 5. The object function of surface roughness of machined surface of titanium alloy Ti6AL4V: a) brass wire, b) zinc coated wire, c) brass CuZn50 coated wire

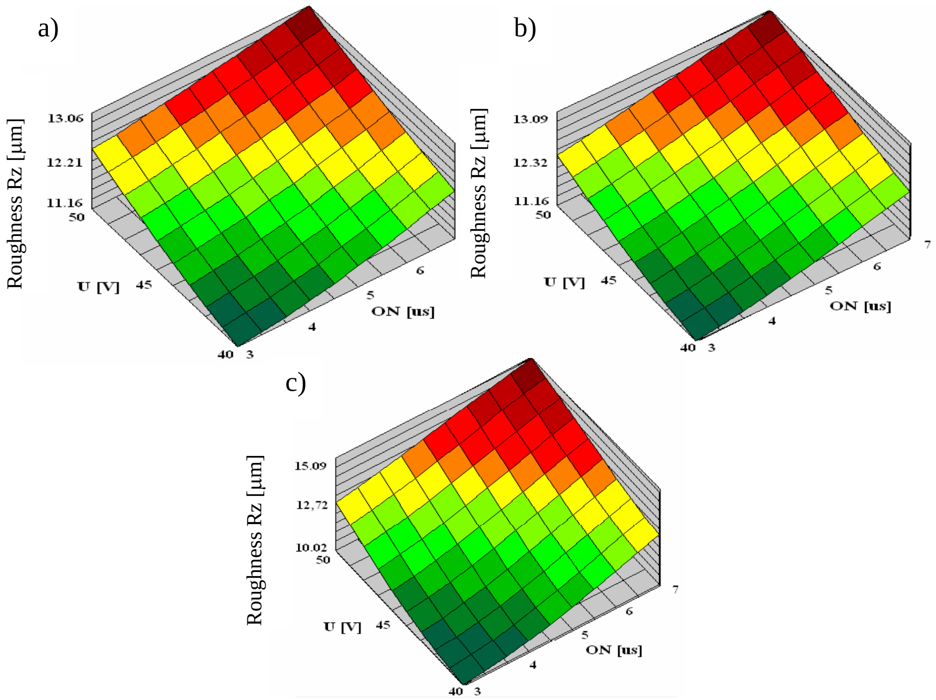


Fig. 6. Influence of time based parameters of WEDM on surface roughness of titanium alloy Ti6AL4V: a) brass wire, b) zinc coated wire, c) brass CuZn50 coated wire

4.3. WEAR OF THE ELECTRODE

Breaking of the wire due to thermal overload is the chief factor hampering efforts to increase cutting efficiency in the WEDM process. Phenomena occurring at the surface of the wire electrode have been investigated extensively [6, 8, 9]. Figs 7 and 9 show percent

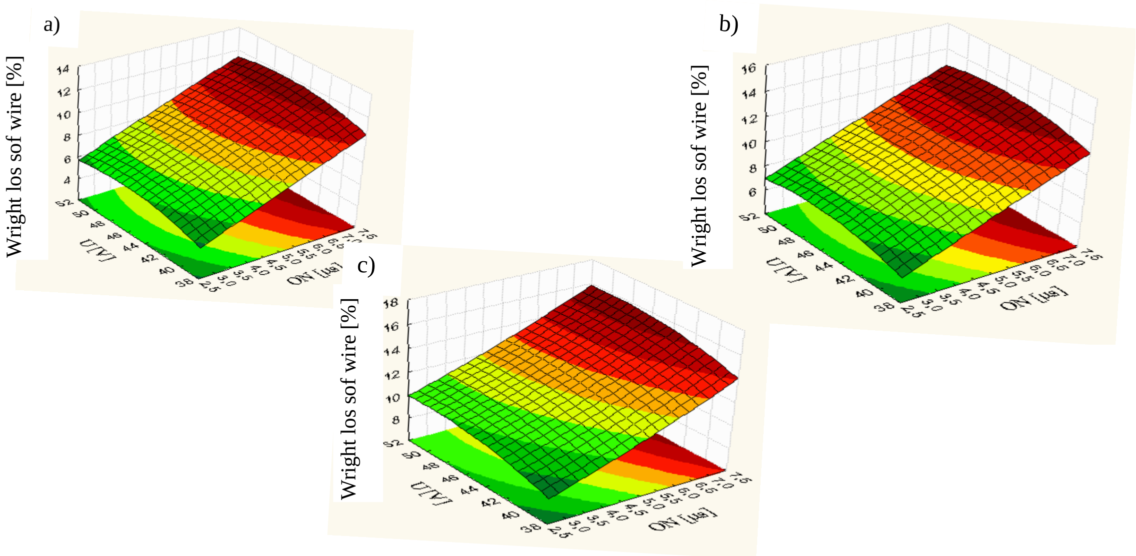
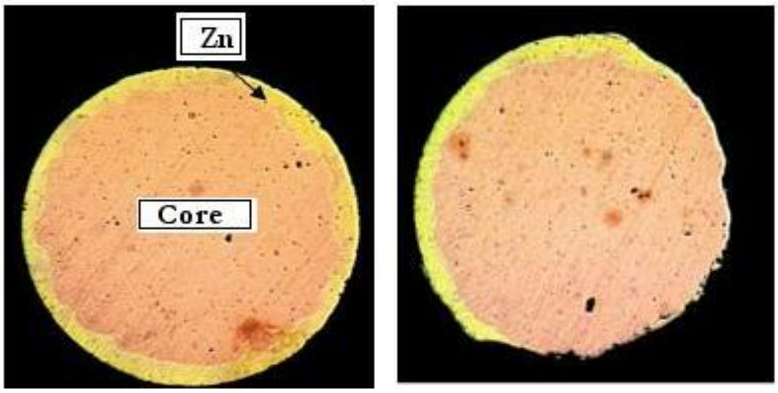


Fig. 7. The object function of weight loss of wire during machining of titanium alloy Ti6AL4V:a) brass wire, b) zinc coated wire, c) brass CuZn50 coated wire



a) b)

Fig. 8. Cross section of zinc coated wire BEDRA (CuZn37)Zn: new – a) and used- b) [1]

Weight loss of wire in this study. The highest volumetric wear, concerning WEDM of titanium alloy Ti6Al4V with electrode coated with brass CuZn50, is equal to 9,5 - 17,5%. Lower volume of wear was noticed for naked brass CuZn37 electrode equal to 5,8 – 12,5 and for zinc coated electrode equal to 7-14%(Fig. 7.).

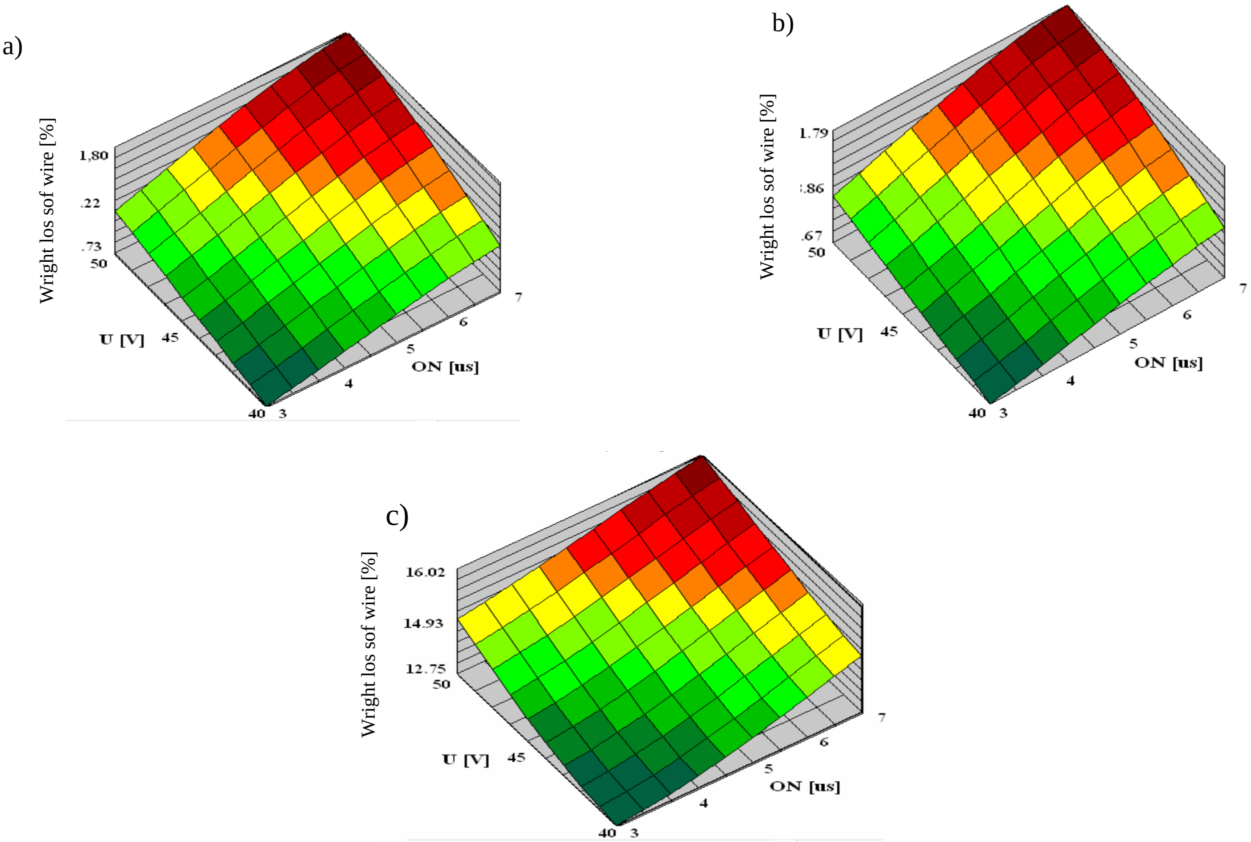


Fig. 9. Influence of time based parameters of WEDM on weight loss of wire during WEDM of titanium alloy Ti6AL4V: a) brass wire, b) zinc coated wire, c) brass CuZn50 coated wire

The WWR values were determined at successive stages of the process with both parameters ON and OFF being gradually decreased. Morphology of wear in wire due to melting and sublimation is presented in Fig 8. Cross-sectional view shows clearly numerous craters and microcracks. Photograph of cross section of Ti6Al4V before and after WEDM is shown on fig.10. Throughout the WEDM thick oxide layer appeared on the material's machined surface. The experimental relationships obtained both from regression functions and response surfaces and from neural networks are marked by high correlation. Evaluation accuracies of the investigated quantities are presented in the tables below. Table 3 gives the measured values and those approximated as well as approximation error values in the WEDM using the monometallic brass electrode. The same for the coated one can be seen in Table 4. Slightly better goodness of fit seen in the results produced by networks confirms their usability in modelling complex nonlinear relationships. Regression analysis results are also satisfactory, but it must be kept in mind that the corresponding relationships were relatively simple. Introduction of additional parameters other than the used time ones would require higher polynomials in regression functions and as a consequence a higher number of necessary tests. Larger numbers of inputs and effects tested would result inevitably in lower correlations. Neural networks would show then their superiority.

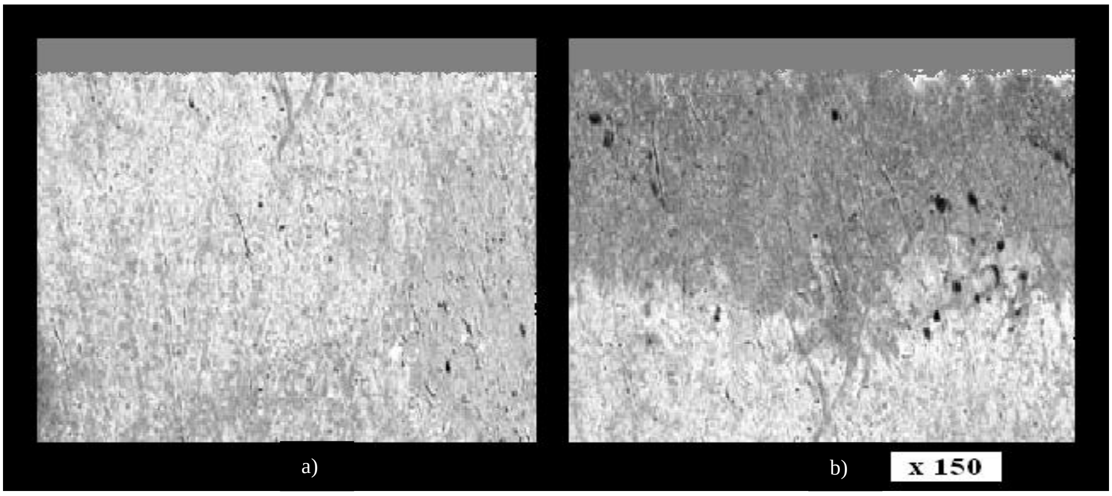


Fig. 10. Photograph of cross section of Ti6Al4V, a) before machining and b) after machining

5. CONCLUSIONS

The presented investigation on WEDM of sintered carbides proved that time parameters of the WEDM process have a significant effect on manufacturing outcome characteristics. The regression analysis and neural networks can be effectively utilized in quantitatively assessing the effect. All the effects tested were determined with correlations equal to 0.93 or higher.

Applying of brass wire coated with brass CuZn50 thanks to increased energy conduction of outlayer resulted in higher speed of cutting. Zinc coating on brass wire results in better cooling and flushing of wire. Using zinc coated wire better accuracy and lower surface roughness were obtained. For all types of electrodes higher times between discharges were found to make for improved stability of the operation without markedly compromising efficiency. Higher discharge times did increase efficiency, but were accompanied by higher wear rates of electrodes and worsened surface roughness indexes. The results so far obtained will be a basis for working out a fully customizable semi - empirical model of the process.

ACKNOWLEDGEMENTS

The support of the Committee of Science Research, Poland, (Grant No. N503 033 32/4181 is gratefully acknowledged

REFERENCES

[1] BALLEYS F., *Electrical Discharge Generator Breaks New Ground*, Mold Making Technology Online, 2007.
[2] CHEN S.L., YAN B.H., HUANG F.Y., *Influence of kerosene and distilled water as dielectrics on the electric discharge machining characteristics of Ti–6A1–4V*, J. Mat. Proc. Technol., 87, 1999, 107–111.
[3] HUANG J.T., LIAO Y.S., HSUE W.J., *Determination of finish- cutting operation number and machining parameters setting in wire electrical discharge machining*, J. Mater. Process. Technol. 87 (1999), 69–81.
[4] INDURKHYA G., RAJURKAR K.P., *Artificial neural network approach in modelling of EDM process*, in: Proc. Artificial Neural Networks in Engineering (ANNIE' 92) Conf., St. Louis, Missouri, U.S.A., 15-18 November, 1992, 845-980.
[5] KURIAKOSE S., SHUNMUGAM M.S., *Characteristics of wire-electro discharge machined Ti6Al4V surface*, Materials Letters, 58, 2004, 2231-2237.
[6] KINOSHITA N., FUKUI M. and GAMO G. *Control of wire EDM preventing from breaking*. Ann. CIRP, 31,1982.
[7] PAN B., KIM D J., KIM B.M., DEAN T.A., *Incremental deformation and the forgeability of γ-titanium aluminide*, Int. J. Mach. Tools Manuf. 41, 2001, 749–759.
[8] PROHASZKA J., MAMALIS A., G., VAXEVANIDIS N., M., *The effect of electrode material on machinability in wire electro-discharge machining*. J. Mat. Proc. Technol., 69, 1997, 233-237.
[9] PURI A.B., BHATTACHARYYA B., *Modeling and analysis of the wire tool vibration in wire-cut EDM*, Int. J. Mater. Process. Technol. 141/3, 2003, 295–301.
[10] PURI A.B., BHATTACHARYYA B., *An analysis and optimization of the geometrical inaccuracy due to wire lag phenomenon in WEDM*, Int.J. Mach. Tools Manuf. 43/2, 2003, 151–159.
[11] SARKAR S., MITRA S., BHATTACHARYYA B., *Parametric analysis and optimization of wire electrical discharge machining of γ -titanium aluminide alloy*, J. Mat. Proc. Technol., 159, 2005, 286–294.
[12] SHARMAN A.R.C., ASPINWALL D.K., DEWES R.C., CLIFTON D., BOWEN P., *The effects of machined workpiece surface integrity on the fatigue life of-titanium aluminide*, Int. J. Mach. Tools Manuf. 41, 2001,1681–1685.
[13] SPEDDING T.A, WANG Z.Q., *Study on modelling of wire edm process*, J. Mat. Proc. Technol., 69, 1997,18-28.
[14] TADEUSIEWICZ R., Sieci neuronowe, Akademicka Oficyna Wydawnicza RM, Warszawa,1993.
[15] TSAI K.M., WANG P.J., *Predictions on surface finish in electrical discharge machining based upon neural network models*, Int. J. Mach. Tools Manuf. 41, 2001, 1385–1403.
[16] ZALTIN N., FIELD M., *Procedures and precautions in machining titanium alloys*, Titanium Sci. Technol. 1 (1973), 489–504.