MICRO WIRE ELECTRICAL DISCHARGE MACHINING OF TITANIUM ALLOY Ti-6Al-4V

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Abstract

Micro mechanisms belong to innovative solutions used in many branches of industry, ranging from aviation and cosmonautics, through the automotive and medical industries. The manufacturing of micro and nanostructures requires the use of precision machining. An important role in manufacturing micro parts has electrical discharge machining (EDM). Micro - EDM is a nonconventional method of removing material, using the phenomenon of electric discharges occurring between two electrodes in the presence of a dielectric. Application in the process working electrode in the form of a thin wire (0.1 mm) allows cutting complex shape microelements. The paper presents the result of the micro wire electrical discharge machining of titanium alloy Ti-6Al-4V. Response surface methodology (RSM) was used to build empirical models of the influence of pulse time t_{on}, wire tension WT, wire speed WS on the roughness Ra and the cut speed V during machining titanium alloy Ti-6Al-4V.

Keywords: Micro WEDM, cut speed, surface roughness,

1. INTRODUCTION

The miniaturisation of systems and parts is one of the recent trends in many industrial applications. One of the major limitations of the developed new micro mechanism is the possibilities of the manufacturing process. Conventional technologies like milling, grinding due to the geometry of the tool and process kinematics, it is difficult to use in the processing of micro parts [1-4]. New solutions are therefore sought, including the use of nonconventional technologies like laser beam machining [5], electrochemical machining [6], electrical discharge machining [7-9], to produce micro parts. An important role in manufacturing micro parts has wire electrical discharge machining (WEDM). Wire electrical discharge machining (WEDM) is wieldy using manufacturing difficult to machining conductive materials. In micro WEDM material is removed by a series of discharges occurring in the gap between thin wire electrode (0.1 mm) and the workpiece. During the WEDM process, the electrodes are insulated from each other by the flowing dielectric (deionized water). Removal mechanism of the material in electrical discharge machining is mainly the result of the electrical discharge which causes melting and evaporation in local surface layers of both the workpiece and the working electrode [10-12]. The heat also causes evaporation of the dielectric liquid and induces high-pressure waves which wash the molten and/or vaporized metal. During discharge local temperature increase to 6000 - 7000 K which causes melting and vaporization of the material. During the machining, there are hundreds of electrical discharges which formed specific surface texture, by overlapping of craters from single discharges. Stochastic nature of electrical discharges causes that many works are focused on indicating most favorable parameters and conditions of micro WEDM depending on cutting geometry accuracy [13], surface roughness [14,15]. However, the mico WEDM of titanium alloy Ti-6Al-4V is not enough described. Therefore, this work analyses the impact of the following parameters of micro WEDM pulse time ton, wire tension WT, wire speed WS on the roughness Ra and cut speed V was conducted. Furthermore, the developed regression models of micro WEDM will allow the selection of the most favorable processing conditions.

2. MATERIALS AND METHODS

Industry applications of microwire electrical discharge machining are limited by the obtained surface roughness and cut speed. The main object of the study was the developed mathematical models of influence WEDM parameters such as: pulse time t_{on}, wire speed WS and wire tension WT on the roughness Ra and the cutting speed V during machining of titanium alloy. To achieve this goal, experimental research was carried out using a Box Behnken design of the experiment, three-level three parameters design. The choice of this type of experiment reduces the number of experimental runs required to generate sufficient information for a statistically adequate result. Experimental investigations were carried out on the WEDM machine of Charmilles Robofill 440. The cutting samples of titanium alloy Ti-6Al-4V have dimensions of 10 x 5 x 5 mm, the electrode was a brass wire with diameter 0.1 mm and deionized water was used as the dielectric. Roughness parameters were measured on the Talysurf series 2 scanning profilometer. Cut speed V was calculated by dividing the length of the cutting path by the cutting time. The results of the experimental studies are presented in **Table 1**.

Table 1 Design of the experimental matrix

No.	WEDM paramters			Observed values	
	t_{on} (µs)	WB (daN)	WS (m/min)	Ra (µm)	V (m/min)
1.	0.2	0.3	8	1.31	1.666
2.	0.4	0.3	8	1.83	5.646
3.	0.2	0.5	8	1.33	1.696
4.	0.4	0.5	8	1.98	5.392
5.	0.2	0.4	4	1.41	1.717
6.	0.4	0.4	4	1.95	5.729
7.	0.2	0.4	12	1.41	1.626
8.	0.4	0.4	12	2.02	5.222
9.	0.3	0.3	4	1.55	5.199
10.	0.3	0.5	4	1.66	5.251
11.	0.3	0.3	12	1.69	5.174
12.	0.3	0.5	12	1.73	4.898
13.	0.3	0.4	8	1.63	4.985
14.	0.3	0.4	8	1.67	4.942
15.	0.3	0.4	8	1.62	4.981

3. RESULTS AND DISCUSSION

Investigation of the influence of the micro WEDM parameters on the roughness Ra and the cut speed V was carried out using response surface methodology (RSM). Regression models were built to predict the influence of investigated parameters on independent variables. Analysis of fitting different types of response function to experimental result indicates that the best fit was found for the polynomial function of the second degree:

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \beta_i i X_i^2 + \sum_{i=1, i \neq j}^{k} \beta_{i,j} i X_i X_j + \varepsilon \tag{1}$$

The analysis of variance (ANOVA) was used to check the significance of the independent brent variable in the model. The ANOVA test was conducted at a 95 % coefficient level. If probability (Prob > f) value for each factor was less than 0.05, this indicated that the model factor was significant (i.e., at a 95 % confidence level). Values of

Prob > f higher than 0.05 indicated that a model factor was non-significant and should be removed from response function. After removing not significant factor the ANOVA test was conducted again for a new function (without non-significant terms). The ANOVA results for the regression equation of roughness Ra and cut speed V, present in **Tables 2** and **3**, respectively. For each response function, the coefficient of determination, R^2 and the adjusted coefficient of determination, R^2-Adj was calculated. These coefficients represented the percentage of variance explained by the model. For R^2 and R^2-Adj approaches unity, the response function is more accurate fit to the research results. The results implied that all the developed models were significant at a 95 % confidence level.

Table 2 ANOVA table for the Ra

Source	Sum of squares	Degrees of freedom	Mean square	*F*-Value	Prob > *f*
t_{on}	0.6728	1	0.6728	444.931	0.0000
WS	0.0098	1	0.0098	6.480	0.0290
WS²	0.0105	1	0.0105	6.991	0.0245
WT	0.0128	1	0.0128	8.464	0.0155
Error	0.0151	10	0.0015		
Total SS	0.7210	14	R^2 = 0.98		R^2-Adj = 0.97

Table 3 ANOVA table for the V

Source	Sum of squares	Degrees of freedom	Mean square	*F*-Value	Prob > *f*
t_{on}	29.20008	1	29.20008	18822.57	0.000000
t_{on}^2	7.90470	1	7.90470	5095.42	0.000000
WS	0.11907	1	0.11907	76.75	0.000321
WS²	0.01674	1	0.01674	10.79	0.021835
WT	0.02509	1	0.02509	16.17	0.010106
WT²	0.03251	1	0.03251	20.96	0.005960
t_{on} *WS*	0.04326	1	0.04326	27.89	0.003242
t_{on} *WT*	0.02016	1	0.02016	13.00	0.015457
WS WT	0.02690	1	0.02690	17.34	0.008792
Error	0.00776	5	0.00155		
Total SS	37.60705	14	R^2 = 0.99		R^2-Adj = 0.99

After eliminating non significant terms in the regression equation for the roughness Ra and V, the following response function was obtained:

Ra = 0.737 + 2.9 ton + 0.044 WS + 0.0033 WS2 + 0.205 WS WT   (2)

V = -13.824 + 111.81 ton - 146.31 ton2 + 0.062 WS + 0.0042 WS2 - 4.29 WT + 9.38 WT2 -

- 0.26 ton WS - 7.1 ton WT - 0.205 WS WT   (3)

Obtained ANOVA results indicate that the values of the R^2 for the roughness Ra and the cut speed V were over 98 % and 99 %, respectively. The result shows that the regression models provided an excellent explanation of the relationship between the pulse time t_{on}, wire speed WS, wire tension WT and the response Ra and V. The difference between coefficient of determination and the adjusted coefficient of determination,

is smaller than 0.1, which indicated that the established models were adequate and representing the process. Performed residual analyses indicate that the fit of the response model of the roughness *Ra* and the cut speed *V* to experimental results is very good. The normal probability plots of residuals (**Figures 1a, 2a**) shows that the correlation between predicted and experimental data is good (experimental data is distributed approximately along a straight line). The plots of residuals versus the predicted values (**Figures 1b, 2b**) and the residuals versus the case number values (**Figures 1c, 2c**) indicate that the residuals did not follow any trend and they have a stochastic nature. The plotted residuals versus the case number show that the error terms were independent of one another. The analysis of the residuals plots indicates that the developed models were adequate from a statistical point of view.
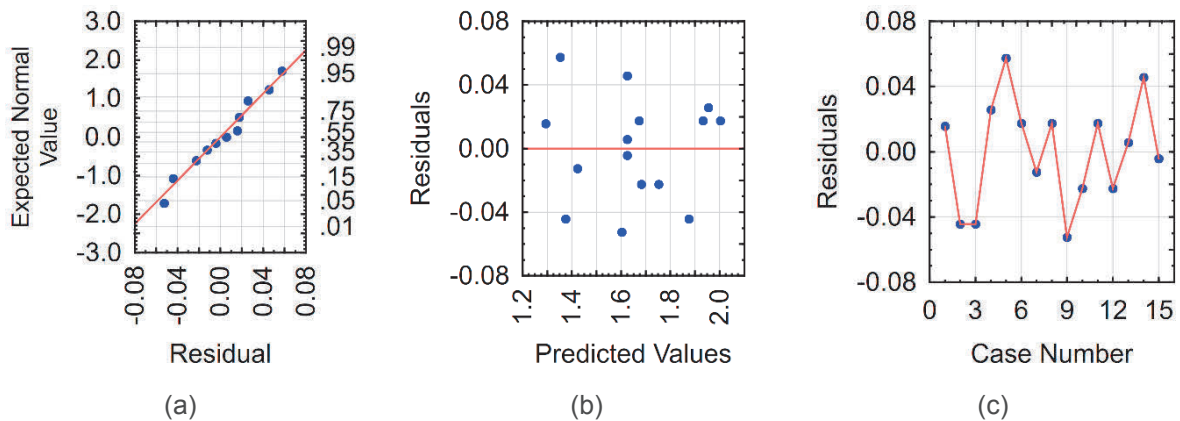

Figure 1 Plots of residuals for roughness *Ra* model: (a) the normal plot of residuals, (b) the residuals versus the predicted values and (c) the residuals versus case number
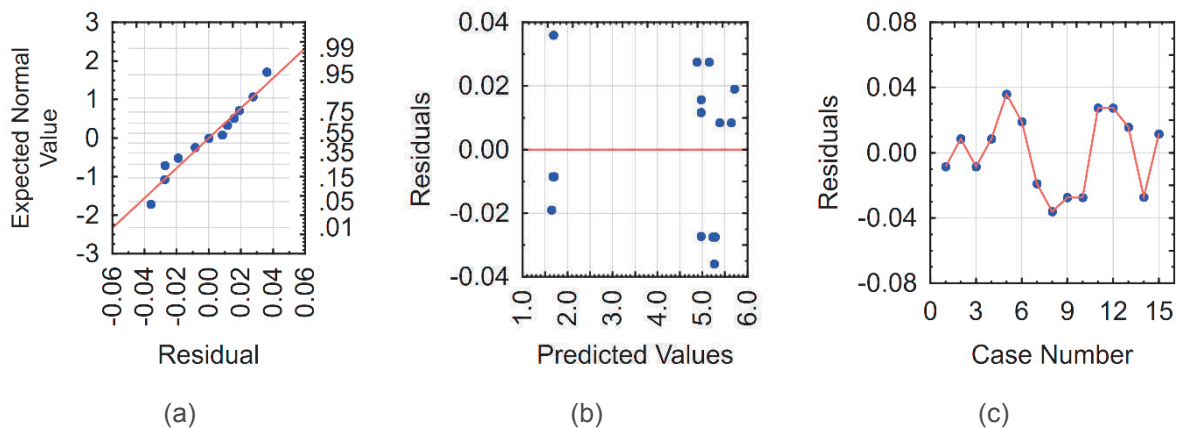

Figure 2 Plots of residuals for cut speed *V* model: (a) the normal plot of residuals, (b) the residuals versus the predicted values and (c) the residuals versus case number

To better understanding the influence of the micro WEDM parameters on the roughness *Ra* and the cut speed *V*, the response surface plots were estimated. Based on the regression models (**equations 2 - 3**), the influence of the pulse time t_{on}, wire speed *WS* and wire tension *WT* on the *Ra* and the V is shown in **Figures 3,** 4 respectively. The conducted experimental studies indicated that the main parameters that influenced roughness *Ra* and cut speed *V* was the pulse time (**Figures 3, 4**). The roughness *Ra* and the speed cut *V* increase with the growth of the pulse time. With the increase of the pulse time, the amount of energy delivered to the workpiece causes the melting and evaporation of a higher volume of material, which generates a crater with a larger depth. This leads to obtain a higher value of roughness height parameter *Ra*. The presented dependence also has effects on the speed cut. The increased pulse time corresponded to an increase in the

amount of eroded material in a single impulse. The result of experimental studies shows that wire speed *WS* and wire tension *WT* do not have a significant influence on the roughness high and speed cut.
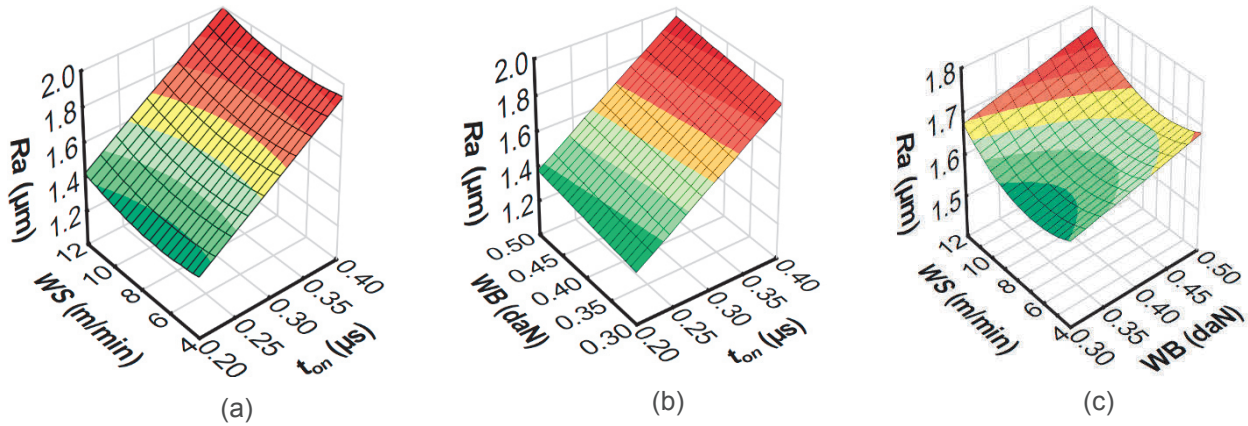

(a)　　　　(b)　　　　(c)

Figure 3 Estimated response surface plot for the roughness *Ra*: (a) constant *WB* = 0.4 daN, (b) constant *WS* = 8 mm/min and (c) constant t_{on} = 0.3 µs
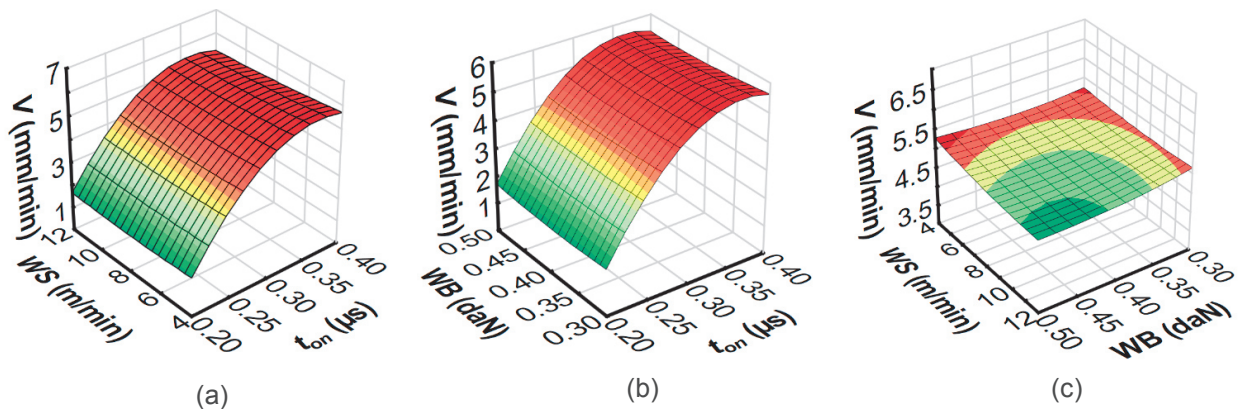

(a)　　　　(b)　　　　(c)

Figure 4 Estimated response surface plot for the cut speed *V*: (a) constant *WB* = 0.4 daN; (b) constant *WS* = 8 mm/min and (c) constant t_{on} = 0.3 µs

4.　CONCLUSIONS

Conducted experimental studies were focused on the analyses of influence micro WEDM parameters on the roughness *Ra* and speed cut *V* during machining of titanium alloy Ti-6Al-4V. Based on the theoretical analyses and experimental research, the following conclusions were obtained:

- The roughness parameter *Ra* was the range of 1.31 - 2.02 µm and corresponded to finishing and semi finishing machining. *Ra* was mainly dependent on the pulse time. Furthermore, the increase of pulse time increased the amount of eroded material in a single pulse, thus leading to higher roughness. The presented dependence also has effects on the speed cut.
- The developed regression equations could be used in micro wire electrical discharge machining of titanium alloy Ti-6Al-4V as a guideline for the selection of WEDM parameters.

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