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Research Article

INFLUENCE OF REDM PARAMETERS ON SURFACE SHAPE

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ABSTRACT

The paper presents the impact of selected machining parameters on surface's shape after machining in REDM (Rotary Electrical Discharge Machining). A mathematical model describing the influence of REDM parameters on the final shape and the relative tool-electrode wear is presented. Influence of REDM parameters on the relative tool-electrode wear and the final shape was determined in experimental practice. Results of computer simulation have been confirmed in experimental practice.

Keywords: Rotary Electrical Discharge Machining, Abrasive Electrodischarge Grinding, Rotary Electrochemical Arc/Discharge Machining – RECAM/RCDM.

INTRODUCTION

The technological improvement of manufacturing attributes can be achieved by high efficiency Rotary Electrical Discharge Machining (REDM) (Electrical Discharge Grinding-EDG or Electrical Discharge Milling), Abrasive Electrodischarge Grinding (AEDG), Rotary Electrochemical Arc/Discharge Machining – RECAM/RCDM or grinding using metallic bond diamond wheels. These machining processes use rotating tools.

In machining difficult-to-cut materials or in micro REDM using tool electrode with small diameter, the effect of tool wear on process performance is very significant.

Tool wear in EDM is characterized by the relative tool-electrode wear which is generally defined as ratio tool wear rate (TWR) to material removal rate (MRR): ν = TWR/MRR. Depending upon the operating parameters of REDM, the relative wear may be 0.01-2. Changes in radius of tool due to wear during machining is expected to reflect in the actual depth of cut and finally in the profile and dimensional accuracy of machined parts (Fig. 1).

Results of investigation of EDM with rotating electrode reported in [1, 2] show a slope curvilinear profile of bottom surface of machined groove due to the wear of disk electrode. Controlling the path of electrode can reduce shape error. In the paper [3] preliminary analysis of shape error indicates that one of the main factors leading to shape errors is wheel wear. More extended study of this problem based on mathematical modeling and experiments is reported in [4], where the general differential equation described a relationship between tool wear, initial and final shape of machined surface has been derived. The effect of wheel wear on dimensional accuracy of grinding is known from theory of tolerances. Based on the assumption of constant rate of wear, uniform probability density function (PDF) for height of machined parts has been obtained. At high the relative tool-electrode wear, this assumption is not adequate to real process and can lead to significant errors in process design [4].

MATHEMATICAL MODELING

The purpose of this mathematical modeling and computer simulation is to determine the profile of generated surface $y = F(x)$, taking into account the change in tool diameter which occurs due to the tool wear of rotary tool during machining. The final surface profile depends on input

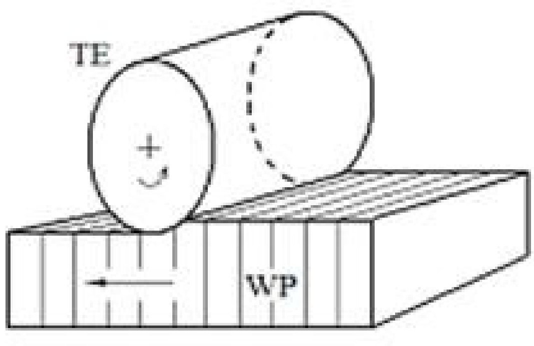

Fig. 1. Example of machining using rotating tool electrode

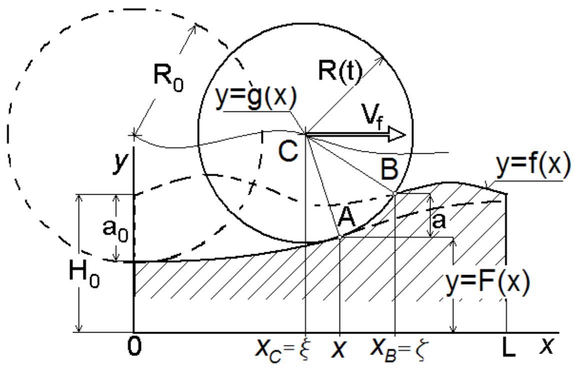

Fig. 2. Scheme of machining with curvilinear path of rotating tool

data, such as setting depth of cut a_0, initial surface profile y = f(x), diameter of tool D_0 and a curvilinear path of the center of tool y = g(x) as the result of controlling motion of tool along x and y-axis's (Fig. 2).

The system of equations describes a relation between the profile of tool path g(x), initial shape f(x) and final profile F(x) of workpiece surface in general case of machining using a rotating tool with consideration of tool wear is as following:

$$\frac{dF}{dx}+\frac{\nu}{2\pi}\frac{F}{[g(\xi)-F]}\frac{d\xi}{dx}=\frac{\nu}{2\pi}\frac{f(\varsigma)}{[g(\xi)-F]}\frac{d\xi}{dx}+\frac{dg}{dx}-\frac{(x-\xi)}{[g(\xi)-F]}\left(1-\frac{d\xi}{dx}\right) \tag{1}$$

$$(x-\xi)^2+[F(x)-g(\xi)]^2=(\varsigma-\xi)^2+[f(\varsigma)-g(\xi)]^2 \tag{2}$$

$$[g(\xi)-F(x)]\frac{dF}{dx}=x-\xi \tag{3}$$

Derived mathematical model can be used in following processes: REDM/EDG (EDMilling), AREDM, RECAM/RCDM and grinding. Based on presented mathematical model, computer simulation of evolution of workpiece profile can be carry out by using developed software. Two tasks can be formulated:

- Direct problem - The tool path, g(x), and initial shape of surface, f(x), are known but the resulting shape of the machined surface, F(x), and needs to be predicted.
- Inverse problem or control problem - For a required shape of the machined surface, F(x), the tool path, g(x), needs to be determined.

These tasks have been solved numerically using the Finite Difference Method and iterative procedure.

More extended study of this problem based on mathematical modeling and experiments is reported in [5,6].

RESEARCH

Experimental research was carried out with a prototype electrical discharge machine EDEE40 CNC. EDEE40 CNC is machine with three axes (x, y, z) CNC-control system, and it is equipped with a head which rotates around axis z. The spindle speed was adjusted in the range of several to 6000 rpm.

During research, machining was carried out using side surface of the rotating tool and the end of tool. In the first case, tool electrode was adjusted in way its head was located below the bottom edge of the machined surface, perpendicular to its axis (Fig. 3). In the case of machining with end of tool, the width of the sample was less than the electrode diameter.

There was only one pass of the tool along the workpiece. To determine the relative tool-electrode wear ν, measurements of mass of the tool and the workpiece were performed before and after each test. Knowing the material of the tool and the workpiece and its weight loss, determined according to equation 4, the relative tool-electrode wear can be calculated.

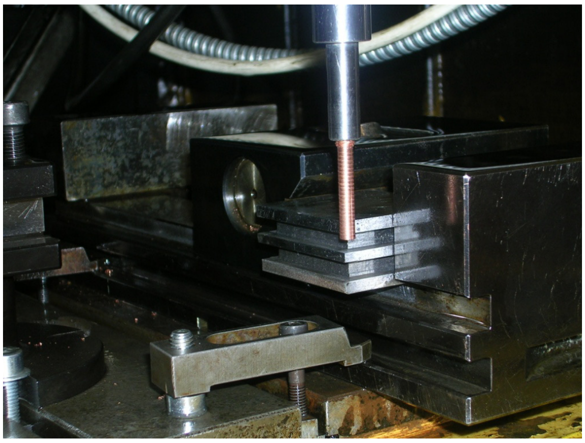

Fig. 3. Fixing of workpiece and tool

$$\nu = \frac{\Delta m_{TE}}{\Delta m_{WP}} \cdot \frac{\rho_{WP}}{\rho_{TE}} \tag{4}$$

where: Δm_{TE} - difference of the tool weight before (m_p) and after machining (m_k), m_{WP} - difference of the workpiece weight before and after machining, ρ_{WP} - the density of workpiece, ρ_{TE} - the density of tool.

Two types of 4 and 10 mm diameter electrode made of electrolytic copper M1E were used in research. In order to reduce the non-coaxial position of the electrode in the rotating head, larger diameter rods were attached, from which the electrodes were turned to the appropriate dimensions with the aid tool placed on the machine table.

The experimental research was carried out with samples made of steel C45. The most important dimensions of samples are length (samples lenght is 100 mm) and thickness of protrusions: 7 mm and 4 mm.

Research was conducted in two steps. At first, preliminary research was conducted in order to determine REDM characteristics for EDEE40 CNC machine tool and select main machining parameters: t_c - machining time, t_p – pulse on-time, t_{off} - pulse off-time, U_r – operating voltage, I_r – operating current, n_e – rotation speed of tool.

In the second step, designed experiment based on the result from the first step was used.

For this purpose, three-level two factor plan was selected to research.

Research was carried with machining parameters shown in Table 3.

The research was carried out at constant generator settings. During tests, depth of cut a_0 and rotation speed of tool n_e were changed. It allowed to determine the general REDM characteristics

Table 1. Machining setting for first step

Sample no.	Machining parameters						
	t_c [min]	a_0 [mm]	I_r [A]	U_r [V]	t_p μs	t_{off} μs	n_e [rpm]
1.1	47	3	24	40	250	16	200
1.2	29	2	16	35	160	10	200
1.3	75	4	7	30	160	10	200
1.4	53	4	26	35	250	16	200
1.5	45	1.5			160	10	600
1.6	44	2	12	35	160	10	600

Table 2. Values of coded factor

Coded factor		-1	0	1
$a_0 \rightarrow X_1$	[mm]	0.5	1	1.5
$n_e \rightarrow X_2$	[rpm]	600	2700	6000

Table 3. Machining setting for designed experiment

Sample no.	Machining parameters						
	t_c [min]	a_0 [mm]	t_p μs	t_{off} μs	I_r [A]	U_r [V]	n_e [rpm]
2.1	21	1.5	160	10	9	60	6000
2.2	34	0.5	160	10	6	95	600
2.3	19	1.5	160	10	10	50	2700
2.4	22	1	160	10	10	50	2700
2.5	25	1	160	10	6	90	600
2.6	18	0.5	160	10	5	100	6000
2.7	21	0.5	160	10	10	50	2700
2.8	70	1	160	10	7	35	600
2.9	17	1.5	100	10	5	40	600

which is independent from the type of generator. The results were submitted for statistic analysis in order to find the factors significantly affecting the final shape of workpiece.

In this case significant factor was the relative tool-electrode wear . Least squares was used in order to determine the parameters that have a statistically significant effect on the relative tool-electrode wear ν.

The measurement results of experimental studies are presented in Table 4 and Table 5. Results for second step are shown in Table 5. As shown in Tables 4-5, the relative tool-electrode wear ν is in range from 0,35 to 57.58%. Regression model was calculated for variables coded values [7].

Characteristic of the relative tool-electrode wear ν is described by the equation:

Table 4. Measurement results of the electrode mass, and calculated the relative tool-electrode wear ν for first stage of research

	Tool				Workpiece					
Sample no.	2R	m_p	m_k	Δm	m_p	m_k	Δm	TWR	MRR	ν
	[mm]	[g]	[g]	[g]	[g]	[g]	[g]	[mm³/min]	[mm³/min]	[%]
1.1	10	37.646	37.46	0.186	1292.62	1275.38	17.24	0.466	47.027	0.95
1.2	10	31.34	31.268	0.072	1275.36	1263.38	11.98	0.292	52.962	0.53
1.3	10	31.268	31.211	0.057	1263.38	1251.22	12.16	0.089	20.786	0.41
1.4	10,1	35.116	34.749	0.367	1251.22	1229.68	21.54	0.815	52.104	1.50
1.5	4	2.993	2.897	0.096	804.778	802.042	2.736	0.251	7.795	3.09
1.6	10	30.609	30.46	0.149	1251.22	1214.01	37.21	0.398	108.421	0.35

Table 5. Measurement results of the electrode mass, and calculated the relative tool-electrode wear ν for designed experiment

	Tool				Workpiece					
Sample no.	2R	m_p	m_k	Δm	m_p	m_k	Δm	TWR	MRR	ν
	[mm]	[g]	[g]	[g]	[g]	[g]	[g]	[mm³/min]	[mm³/min]	[%]
2.1	10	206.201	205.622	0.579	391.803	390.829	0.974	3.244	5.946	52.43
2.2	10	205.124	205.101	0.023	390.829	388.173	2.656	0.080	10.015	0.76
2.3	10	203.94	203.899	0.041	388.173	386.68	1.493	0.254	10.074	2.42
2.4	10	202.919	202.869	0.05	386.68	384.8	1.88	0.267	10.956	2.35
2.5	10	206.215	206.208	0.007	800.429	798.659	1.77	0.033	9.077	0.35
2.6	10	205.148	204.849	0.299	798.659	798.201	0.458	1.954	3.262	57.58
2.7	10	203.99	203.94	0.05	798.201	796.819	1.382	0.280	8.437	3.19
2.8	4,1	3.023	2.98	0.043	809.5	804.778	4.722	0.072	8.648	0.80
2.9	4	3.266	2.795	0.471	802.042	799.736	2.306	3.260	17.391	18.02

$$\hat{y} = \exp(3{,}418 - 0{,}253 \cdot X_1 + 1{,}427 \cdot X_2) \quad (5)$$

After decoding variables and transforming, it was as below:

$$\nu = 1{,}33 \cdot 10^{-4} \cdot a_0^{-0.253} \cdot n_e^{1.427} \quad (6)$$

The calculated correlation coefficients are shown below.

$r_{(\nu,\ a0)} = -0.09923$

$r_{(\nu,\ ne)} = 0.70543$

In order to determine whether the proposed equation describing the relationship ν is adequate, at a given level of significance, condition $F / F_{kr} \geq 1$ must be fulfilled. F is statistic in the Fisher test and it is equal to 6.934.

For a confidence level of $1 - \alpha = 0.95$, F_{kr} value is 5.1433, which proves that the model is well matched.

Student's t-test assesses the significance of the variables in the equation describing the relative tool-electrode wear ν. The condition that the parameter is important for expected value α, is $|t| > t_{kr}$. The t value for depth of cut a_0 is -0.205, and for the rotation speed of tool n_e is 2.431.

At a expected value $\alpha = 0.05$, value $t_{kr(6,0,005)}) = 1.94$ proved that important factor is value of electrode rotation n_e. The influence of depth of cut a_0 was many times smaller.

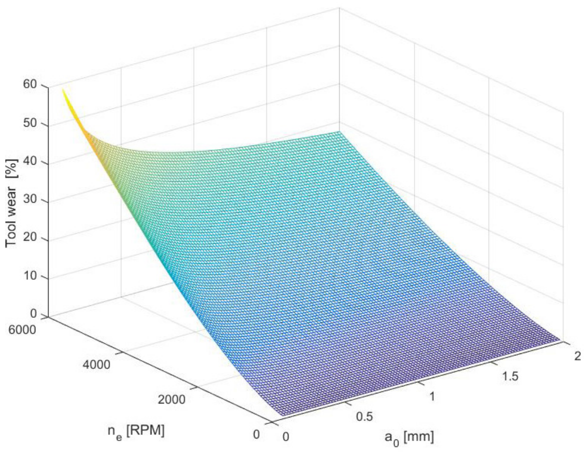

Fig. 4. Diagram of the relative tool-electrode wear ν vs depth of cut a_0 and rotatiation speed n_e

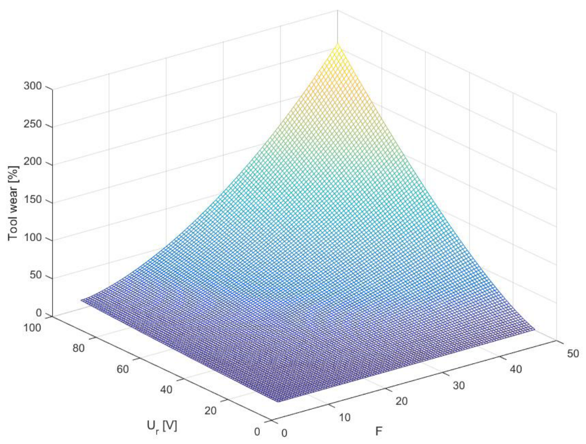

Fig. 5. Diagram of the relative tool-electrode wear ν vs operating voltage U_r and F factor characterizing work of the machine's controller

Influence of input parameters on output parameters is shown in Fig. 4.

Figure 3 shows that the depth of cut a_0 has an insignificant influence on the relative tool-electrode wear in range of low and medium rotations of tool.

As stated in research, the relative tool-electrode wear ν increases significantly for high rotations. Authors [8] report that the circumferential speed starts to significantly affect the relative tool-electrode wear ν for high linear velocity of heat source (above 3 m/s) and for long discharge time.

Taking into account also voltage and F factor conditioning the operation of the EDEE40 CNC control system, regression model is:

$$\nu = 7.315 \cdot 10^{-10} \cdot a_0^{-0.253} \cdot n_e^{1.427} \cdot U^{1.472} \cdot F^{2.412} \quad (7)$$

The calculated correlation coefficients for U_r and F are shown below.

$r_{(\nu, F)} = 0.27237$

$r_{(\nu, Ur)} = -0.07009$

In order to determine whether the proposed equation describing ν is adequate at a given level of significance, condition $F / F_{kr} \geq 1$ must be fulfilled. F is statistic in the Fisher test and is equal to 2.524.

For a confidence level of $1 - \alpha = 0.75$, F_{kr} value is 2.0642, which proves that the model is well matched.

Student's t-test assesses the significance of the variables in the equation describing the ratio tool wear rate ν. The condition that the parameter is important for expected value , is $|t| > t_{kr}$. The t value for depth of cut a_0 is –1.279, for the F factor is 2.431 and for voltage is 0.548.

At an expected value $\alpha = 0.05$, value $t_{kr(4,0,005)}$ = 2.13 proved that important factor is the value of electrode rotatiation n_e. At an expected value $\alpha = 0.1$, the value $t_{kr(4,0,005)} = 1.53$, important factor is F factor value. The influence of other machining parameters (machining depth and voltage) was many times smaller.

The relative tool-electrode wear ν vs U_r and F is showed in Figure 5.

As it was metioned aboved, the first stage of research was carried in order to overall assessment of machining characteristic. Therefore machining parameters (generator settings, rotation speed of tool, depth of cut, workpiece length) were changed in wide range at this stage of research.

Analyzing results obtained in the first stage of research, it can be stated that generator settings have the biggest impact on tool wear. Impact of generator type and CNC control system on the relative tool-electrode wear was widely reported in the literature. In this paper author focused on impact of rotating electrode.

EXPERIMENTAL VERIFICATION

In order to verify mathematical model, selected machining surface profiles were compared with computer simulation results.

Comparison of the experimental profile for sample 2.3 with the profiles obtained from the simulation is shown in Figure 6. For the case shown in Figure 6a, change of the relative tool-electrode wear ν was not taken into account. The error of simulation is 5.5%. Profile error is defined as the ratio between the experimental and the simulation profile to the machining depth $\Delta = (Y - Y_S) / a_0$.

Taking into account changes of the relative tool-electrode wear ν depending on depth of cut, profiles obtained in research and simulation are almost similar (Fig. 6b) and error of simulation is low and it is 4.4%.

For case shown in Fig. 7, the relative tool-electrode wear ν is small and it is ν = 0.45 %. For this reason change of machining depth is small. The error of simulation for constant value of ν is small and it is 1.07 %.

Change of machining depth for sample 2.4 (Fig. 8), similarly as for sample 2.3, was small. Therefore, constant value of ν (18.02%) was taken into account in the computer simulation. Simulation error for this case is 2.6%.

Based on the analysis of workpiece profiles obtained in experimental and computer simulation, it can be concluded that the relative er-

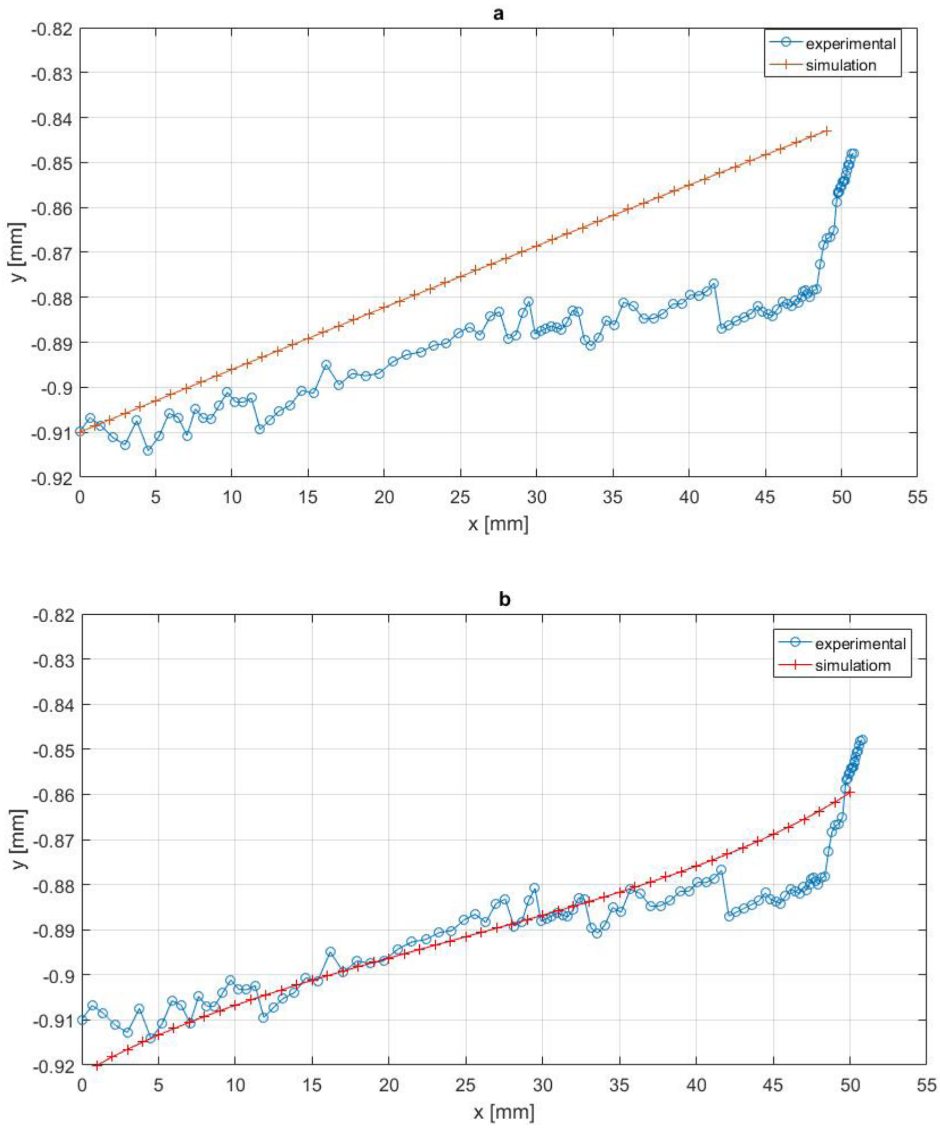

Fig. 6. Comparison of experimental and computer simulations results for sample 2.3

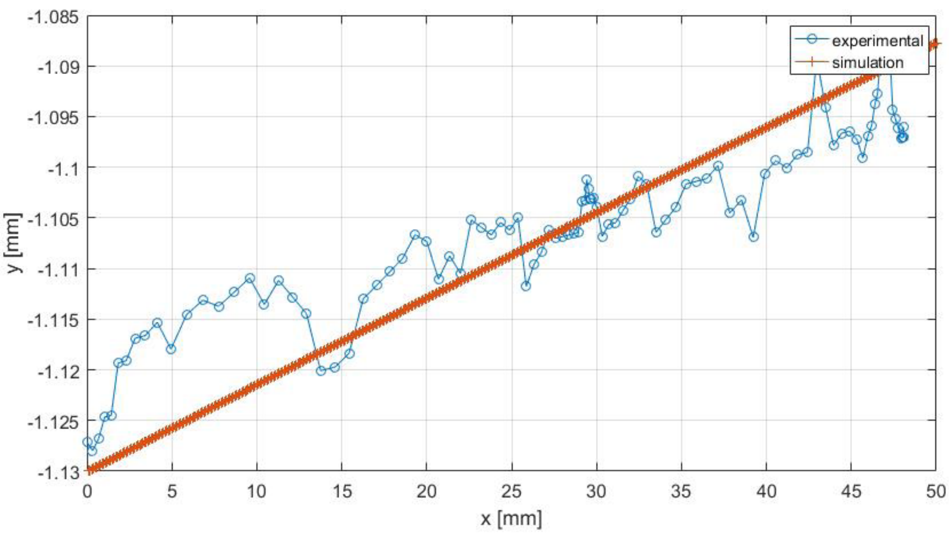

Fig. 7. Comparison of experimental and computer simulations results for sample 2.5

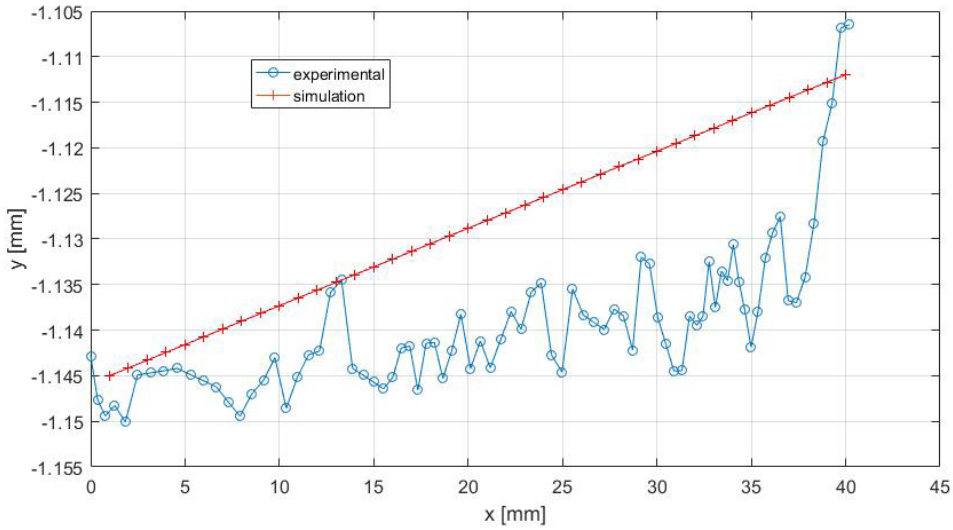

Fig. 8. Comparision of experimental and theoretical results for sample 2.4

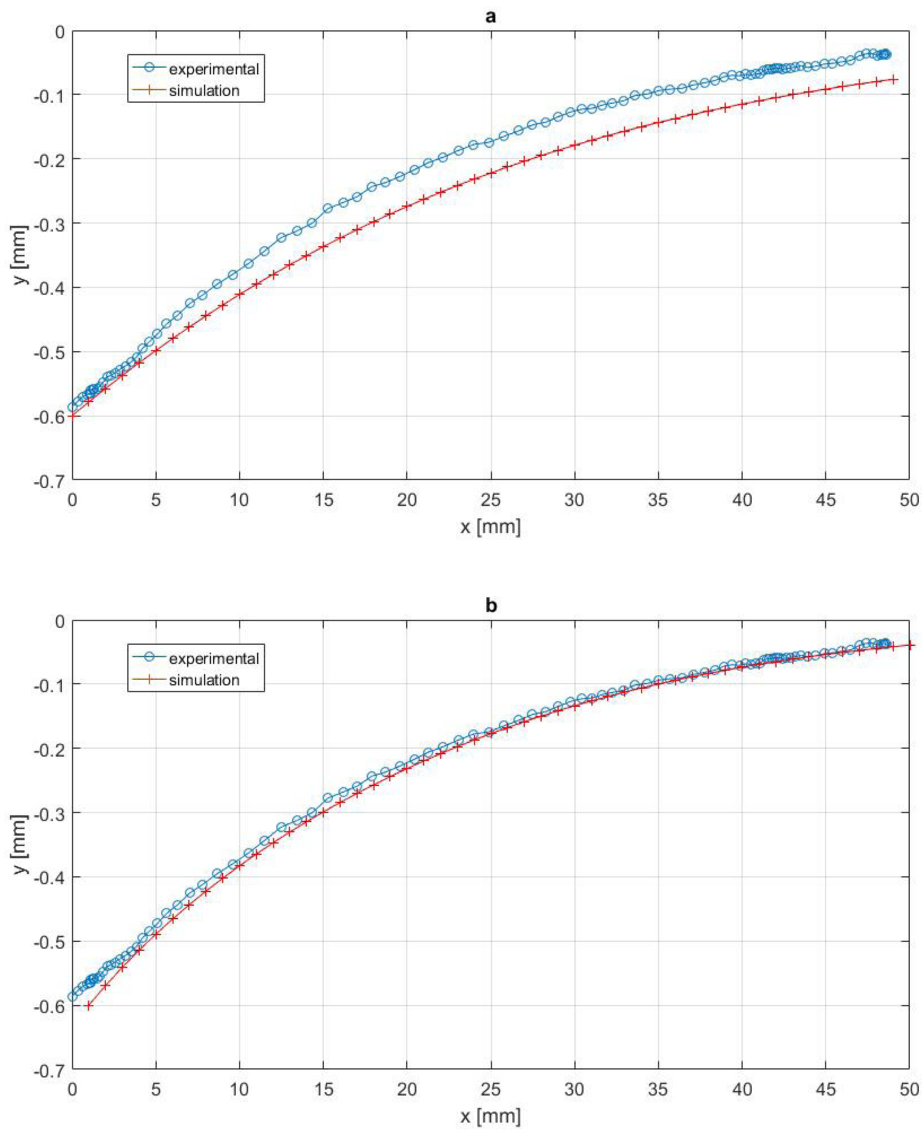

Fig. 9. Comparision of experimental and theoretical results for sample 2.6

ror for majority of simulation cases does not exceed 3%.

Profiles for sample 2.6 are shown in Figure 9. The relative tool-electrode wear ν shown in Fig. 9a was defined in experimental study and it is 57.58 and simulation error is 7.5%. For case shown in Fig. 9b, the result obtained in research is $\nu = 3.2y^2 - 2.3y + 1.89$. As it can be seen, profiles obtained in experiments and in simulation are similar and simulation error is below 1%.

CONCLUSIONS

Tool wear significantly effects workpiece profile after REDM. The influence of machining parameters on the relative tool-electrode wear was determined in research. The relative tool-electrode wear increases significantly for high rotation speed. The study showed a good agreement of theoretical and experimental results of modeling of REDM process.

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