MULTIPLE REGRESSION MODELING AND PREDICTION OF THE SURFACE ROUGHNESS IN THE WEDM PROCESS

VEČKRATNO REGRESIJSKO MODELIRANJE IN NAPOVEDOVANJE HRAPAVOSTI POVRŠINE PRI POSTOPKU WEDM

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Wire electrical discharge machining (WEDM) process is a specialized thermal machining process capable of accurately cutting and machining mechanical parts with various hardnesses and intricate shapes. WEDM is also a modification of electrical discharge machining (EDM) and it has been widely used for a long time for cutting punches and dies, shaped pockets and other machine parts on conductive work materials. The surface roughness of a machined surface mainly depends on the feed rate, the current and pulse duration in the WEDM machining process. It also depends on the optimum selection of WEDM parameters. The present study focused on the multiple regression modeling and predicting the surface roughness of the Dievar hot-work tool steel during the WEDM process. Mathematical relationships between the surface roughness and WEDM cutting parameters (feed rate, current and pulse on time) have been investigated. The results show that the multiple regression analysis is a successful method for developing a mathematical model to predict the surface roughness.

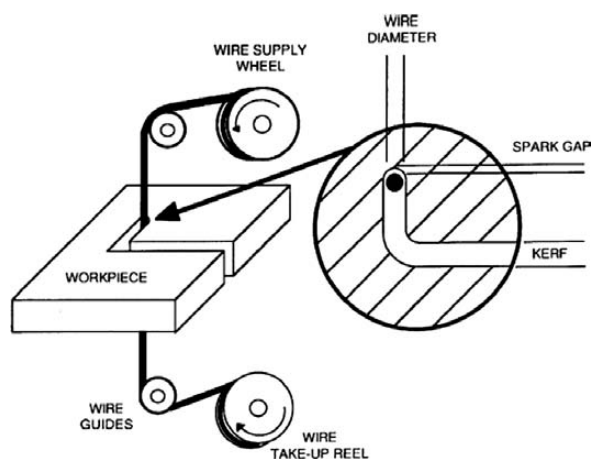Keywords: multiple regression model, WEDM, surface roughness

Obdelovanje z žično erozijo (WEDM) je poseben toplotni postopek, ki zagotavlja natančno rezanje in obdelovanje mehanskih delov z različno trdoto in zapleteno obliko. WEDM je modificirana elektroerozija (EDM) in se že dolgo uporablja za rezanje prebijal in orodij, oblikovanih žepov in drugih strojnih delov na prevodnem obdelovancu. Hrapavost površine je predvsem odvisna od hitrosti odvzema, toka in trajanja pulza pri WEDM-procesu obdelave. Odvisna je tudi od optimalne izbire parametrov pri WEDM. Ta študija je osredinjena na večkratno regresijsko modeliranje in napovedovanje hrapavosti površine orodnega jekla za delo v vročem Dievar pri obdelavi z WEDM. Preiskovana je bila matematična odvisnost med hrapavostjo površine in parametri rezanja WEDM (hitrost podajanja, tok in časovni impulzi). Rezultati kažejo, da je večkratna regresijska analiza uspešna metoda za razvoj matematičnega modela za napovedovanje hrapavosti površine.

Ključne besede: model večkratne regresije, WEDM, hrapavost površine

1 INTRODUCTION

Wire electrical discharge machining (WEDM) is a widely accepted, non-traditional material-removal process used to manufacture two- or three-dimensional components with complex shapes and profiles.[1] It is considered as a unique adaptation of the conventional electrical discharge machining (EDM) process, using an electrode to initialize the sparking process. However, WEDM utilizes a continuously travelling wire electrode, made of thin copper, brass or tungsten with a diameter of 0.05–0.3 mm, capable of achieving very small corner radii[1]. The movement of this wire is numerically controlled to achieve a desired three-dimensional shape and accuracy of a workpiece. The wire is kept in tension using a mechanical device reducing the tendency of producing inaccurate shapes. The mechanism of the material removal in the WEDM process involves a complex erosion effect by rapid, repetitive and discrete spark discharges between a wire tool and a workpiece immersed in a liquid dielectric (kerosene/deionized water) medium.[2] These electrical discharges melt and vaporize minute amounts of the work material, which are ejected and flushed away by the dielectric, leaving small craters on the workpiece.[2] **Figure 1** shows a schematic representation of the WEDM process.

Figure 1: Schematic representation of the WEDM process[3]
Slika 1: Shematski prikaz WEDM-postopka[3]

In this process, as the material is eroded ahead of the wire and there is no relative contact between the tool and the workpiece, the work-material hardness is not a limiting factor for machining the material and there is no residual-stress generation.[2,3]

The selection of optimum machining parameters plays an important role in obtaining a higher cutting speed, a lower dimensional deviation, a better material-removal rate and a higher surface finish. Improperly selected parameters may result in serious consequences like short-circuiting of the wire and wire breakage.[2]

The degree of accuracy of workpiece dimensions obtainable and the fine surface finishes make WEDM particularly valuable for the applications involving a manufacture of stamping dies, extrusion dies and proto-type parts. Without WEDM the fabrication of precision workpieces requires many hours of manual grinding and polishing.[4–6] **Figure 2** shows some parts that were manu-factured using the WEDM process.

Tosun et al.[6] determined the effect of machining para-meters on the cutting width and material-removal rate on the basis of the Taguchi method. Tosun and Cogun[7] experimentally investigated the effect of cutting parame-ters on the wire-electrode wear. Tosun et al.[8] investi-gated, experimentally and theoretically, the effect of cutting parameters on the size of erosion craters (the diameter and the depth) on a wire electrode. Cogun and Savsar[9] investigated the random behavior of the time-lag durations of discharge pulses using a statistical model for different pulse durations, pulse-pause durations and discharge currents in EDM.

Scott et al.[10] developed the formulas for a solution of a multi-objective optimization problem to select the best parameter settings on a WEDM machine. They used a factorial design model to predict the measures of the performances as a function of the variety of machining parameters. Wang and Rajurkar[11] developed a WEDM frequency-monitoring system to detect on-line the thermal load on a wire to prevent the wire from rupture.

Figure 2: Some parts manufactured with the WEDM process[7]
Slika 2: Nekaj delov, izdelanih po WEDM-postopku[7]

Spur and Shoenbeck[12] investigated a finite-element mo-del and explained the impact of a discharge on the anode as a heat source on a semi-infinite solid whose size and intensity are time-dependent in WEDM. Tarng et al.[13] developed a neural-network system to determine the settings of pulse duration, pulse interval, peak current, open-circuit voltage, servo-reference voltage, electric capacitance and wire speed for an estimation of the cutt-ing speed and the surface finish. Spedding and Wang[14] presented a parametric combination using artificial neural networks and they also characterized the rough-ness and waviness of the workpiece surface and the cutting speed. Liao et al.[15] performed an experimental study to determine the effect of machining parameters on the material-removal rate (MRR), gap width and surface roughness. They determined the level of importance of machining parameters on the MRR. Lok and Lee[16] com-pared machining performances in terms of the MRR and surface finish by processing two advanced ceramics under different cutting conditions using WEDM. Rama-krishnan and Karunamoorthy[17] developed an artificial neural network with the Taguchi parameter design. Tsai et al.[18] studied the relationships between the heteroge-neous second phase and the machinability evaluation of the ferritic SG cast irons in the WEDM process. Sarkar et al.[19] studied the features of a trim-cutting operation of the wire electrical discharge machining of -titanium alu-minide. Caydas et al.[20] developed an adaptive neuro-fuzzy inference system (ANFIS) for modeling the surface roughness in the WEDM process. Hewidy et al.[21] developed mathematical models for correlating the inter-relationships of various WEDM process parameters such as peak current, duty factor, wire tension and water pressure on MRR, wear ratio and surface roughness. Puri and Bhattacharyya[22] considered the pulse-on time, wire tool offset and constant cutting speed to model the white-layer depth with the response surface methodology (RSM) technique in the WEDM process. Kuriakose and Shunmugam[23] used a multiple regression model to pre-sent the relationship between the input and output variables of the WEDM process, and then employed a non-dominated sorting genetic algorithm to optimize the process. Chiang and Chang[24] applied a gray relational analysis for optimizing the WEDM process while consi-dering the cutting radius of a workpiece, on-time of discharge, off-time of discharge, arc on-time of dis-charge, arc off-time of discharge, servo voltage, wire feed and water flow as the process parameters, and surface-removal rate and surface roughness as the process responses. Ramakrishnan and Karunamoorthy[25] developed artificial neural network (ANN) based models and a multi-response optimization technique to predict and select the best cutting parameters of the WEDM process.

The previous works show that the research has focused on the effects of machining parameters, dis-charge energy, theory and experimental verification of

the crater formation on the wire electrode. The present study focuses on the modeling and prediction techniques to determine direct effects of WEDM parameters (pulse duration, current and table feed rate) on the surface roughness which is important for cutting dies and complex shapes.

2 EXPERIMENTAL SET UP AND PROCEDURE

The experimental studies were performed on a *Makino U32* WEDM machine tool. Different settings of pulse duration t (µs), current I (A) and table feed rate f (mm/min) were used in the experiments. During the experiments the voltage (40 V), the dielectric flushing pressure (5 kg/cm²), the wire speed (12 m/min) and the wire tension (9 kg) were kept constant.

A Dievar hot-work tool-steel plate was used as the workpiece material with the dimensions of 60 mm × 240 mm × 24 mm. The percent chemical composition and mechanical properties of the workpiece material is given in **Table 1**.
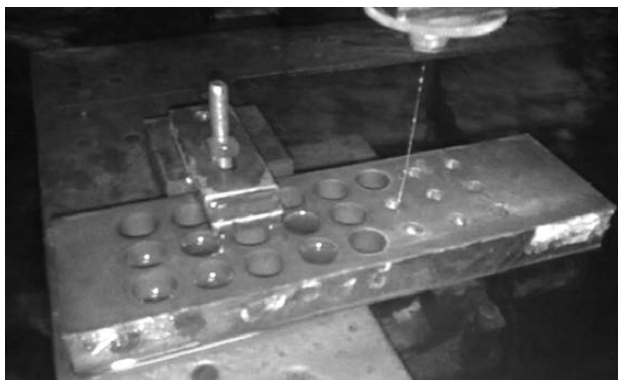
Table 1: Chemical composition and mechanical properties of the AA7075 aluminum alloy[26]
Tabela 1: Kemijska sestava in mehanske lastnosti aluminijeve zlitine AA7075[26]

Chemical composition (*w*/%)	C	Mn	Mo	Cr	V
	0.32	0.5	2.3	5.0	0.5
Mechanical properties	Tensile strength (MPa)	Yield strength (MPa)	Reduction of area (%)	Elongation (%)	Hardness (HRC)
	1640	1380	55	13	48

As shown in **Figure 3**, the workpiece was drilled to insert the cutting wire inside the holes. A total of 24 holes were opened on each sample. After the WEDM machining of the holes, the average of three measurements on three holes was established to determine the surface roughness of the machined parts.

A CuZn37 Suncut brass wire with a 0.30 mm diameter and 1000 N/mm² tensile strength was used in the

Figure 3: Experiment on the WEDM machine and the workpiece geometry
Slika 3: Preizkus na WEDM-napravi in geometrija obdelovanca

experiments. After the machining process, the measurements of the surface roughness were established using a *Mahr Perthometer M1* surface-roughness measurement device.

In the present study, the pulse duration, current and table feed rate were selected as the input parameters and the surface roughness was selected as the output parameter. A two-level factorial design method was carried out to mathematically model the output parameters. The levels of the factorial design used in the present study are shown in **Table 2**. The two levels of the factors are referred to as the low (–1) and the high (+1) levels.

Table 2: Factors and levels for factorial design
Tabela 2: Dejavniki in stopnje faktorske zasnove

WEDM parameters	Low level (–1)	Base level (0)	High level (+1)
Feed rate, *f*/(mm/min)	13.77	14.53	15.30
Current, *I*/A	35.10	37.05	39.00
Pulse duration, *t*/µs	4.95	5.22	5.50

3 DESIGN OF EXPERIMENTS (DOE)

A scientific approach to planning the experiments must be incorporated in order to perform an experiment most effectively. Statistical design of experiments (DOE) is a process of planning the experiments so that appropriate data can be collected and analyzed with statistical methods resulting in valid and objective conclusions.[4,26,27]

Factorial design is widely used in the experiments involving several factors where it is necessary to investigate the joint effects of the factors on a response variable. A very important special case of a factorial design is the one, where each of the k factors of interest has only two levels. A full factorial design is often used to fit a first-order response-surface model and to generate factor-effect estimates[4,27]. In the present study a full factorial design was employed to determine the minimum number of experiments for obtaining an adequate model of responses. Thus, in the present study, using three parameters, 8 (2^k) number of experiments was carried out to construct a regression model.

If the surface roughness is represented by R_a, the linear regression equation for these experiments can be written as:

$$R_a = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_5 x_5 + \beta_6 x_6 \quad (1)$$

where β_0 is the response variable of the surface roughness at the base level; β_1, β_2, β_3 are the coefficients associated with each variable, β_4, β_5, β_6 are the interaction coefficients in the coded forms, x_1 is the feed rate, x_2 is the current and x_3 is the pulse duration at two levels used to arrive at a full two-level factorial experiment.

4 RESULTS AND DISCUSSIONS

The experiments were carried out under different process conditions. **Table 3** shows the full factorial-design matrix used in this study.

Table 3: Full factorial-design matrix
Tabela 3: Zasnova polne faktorske matrike

	Process parameters			Response
Run	f/(mm/min)	I/A	t/μs	R_a/μm
1	4.95	39.0	15.30	2.94
2	4.95	39.0	13.77	2.78
3	5.50	35.1	13.77	2.98
4	4.95	35.1	15.30	2.84
5	5.50	35.1	15.30	3.01
6	4.95	35.1	13.77	2.62
7	5.50	39.0	15.30	3.01
8	5.50	39.0	13.77	2.58

The regression equation obtained from the regression analysis based on the experiment set is expressed as equation (2). After calculating each of the coefficients of equation (1) and substituting the coded values of the variables for any experimental condition, the linear regression equation for the surface roughness can be obtained in actual factor forms as given in equation (2):

$$R_a = -10.9281 + 5.2722f + 0.3914I - 1.1785t - 0.1564fI + 0.04812ft + 0.0287It \qquad (2)$$

These equations indicate that the feed rate that has the biggest coefficient has the most significant effect on the surface roughness. The coefficients of the current and the pulse duration are smaller[4]. Therefore, the contribution order of the parameters obtained is as follows: the feed rate, the current and the pulse duration.

It is evident from **Table 4** that our set of data, predicted with a full factorial design, is close to experimental values. In the prediction of the surface-roughness values the average error is found to be 1.17 %.

According to the analysis of variances (ANOVA), given in **Table 5**, the contribution order of the WEDM parameters for the surface roughness is as follows – the feed rate: 48.98 %, the current: 10.46 % and the pulse duration: 1.05 %.

Table 5: ANOVA results for the circularity-surface-roughness measurements
Tabela 5: ANOVA-rezultati meritev površinske hrapavosti krožnih površin

Parameter	Degree of freedom	Sum of square	Mean square	F	Contribution (%)
f	1	0.0890	0.0890	3.34	48.98
I	1	0.0190	0.0190	0.71	10.46
t	1	0.0019	0.0019	0.07	1.05
fxI	1	0.0560	0.0560	2.12	30.82
fxt	1	0.0008	0.0008	0.03	0.44
Ixt	1	0.0150	0.0150	0.55	8.26
Total	6	0.1817			100

It is clear from the response surface plots shown in **Figures 4** to **6** that the increasing feed rate, current and pulse duration increased the surface roughness. As shown in the related graphs, the feed rate has the biggest effect on these responses. A small increase in the feed rate caused a big increment in the surface-roughness value. The current also has an effect on the responses but not more than the feed rate. It is clear that the pulse duration has a small effect on the responses. The maximum surface roughness of 3.01 μm was obtained

Figure 4: Response surface graph of the effects of the current and feed rate on the surface roughness
Slika 4: Ploskovni diagram vpliva toka in hitrosti podajanja na hrapavost površine

Table 4: Test and comparison sets used for the regression analysis
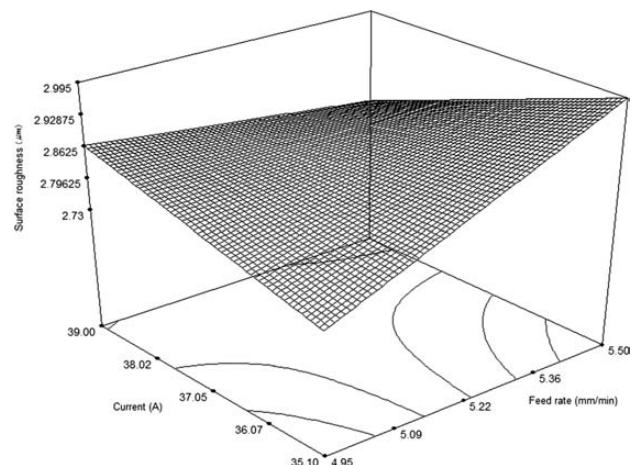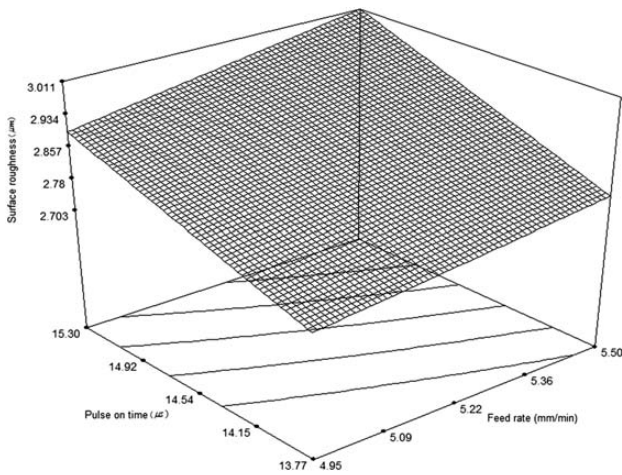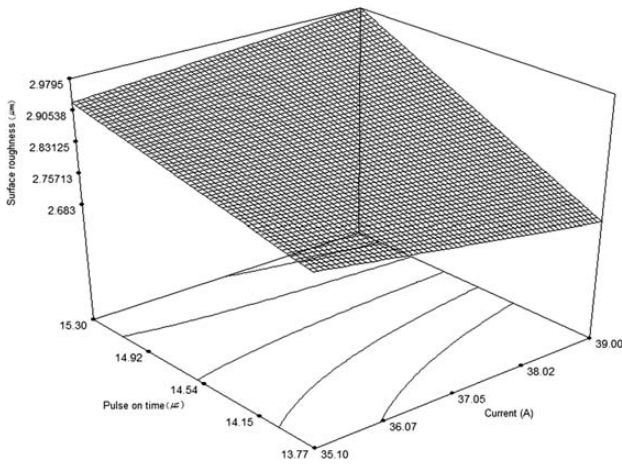**Tabela 4:** Preizkusni in primerjalni podatki, uporabljeni pri regresijski analizi

Exp. no	f/(mm/min)	I/A	t/μs	Experimental R_a/μm	Regression R_a/μm	Error %
1	4.95	36.1	13.77	2.78	2.67	3.97
2	5.50	35.1	15.00	2.99	3.02	−0.91
3	4.95	39.0	14.77	2.86	2.88	−0.86
4	5.50	39.0	14.77	2.83	2.82	0.34
5	4.95	35.1	14.77	2.71	2.72	−0.53
6	5.50	39.0	15.00	2.88	2.87	0.43
			$\%\text{Error} = \dfrac{(R_{a\,\text{experimental}} - R_{a\,\text{predicted}})}{R_{a\,\text{experimental}}} \cdot 100$			Average error: 1.17 %

Figure 5: Response surface graph of the effects of the pulse on time and feed rate on the surface roughness
Slika 5: Ploskovni diagram vpliva trajanja pulza in hitrosti podajanja na hrapavost površine

Figure 7: Comparison of experimental and predicted surface-roughness values
Slika 7: Primerjava eksperimentalnih in napovedanih vrednosti za hrapavost površine

5 CONCLUSIONS

The prediction of WEDM parameters for a quality product and dimensional accuracy plays a very important role in the planning of the WEDM process. The following conclusions can be drawn from this study:

- A full factorial regression analysis is a powerful tool for mathematical modeling and predicting the responses using a small number of experiments;
- Mathematical modeling of the response variables (surface roughness) was made using a full factorial design and the experimental results were compared with the predicted values of the response variables to decide about the closeness of the predictions to the experimental values;
- The priority order of WEDM parameters for the surface roughness was found to be as follows: the feed rate, the current and the pulse duration;
- The increasing feed rate caused a big increment in the surface-roughness value;
- Within the range of the input variables for the present case, the results showed that the predicted values calculated with a regression analysis are very close to the experimental values, with $R^2 = 0.87$.
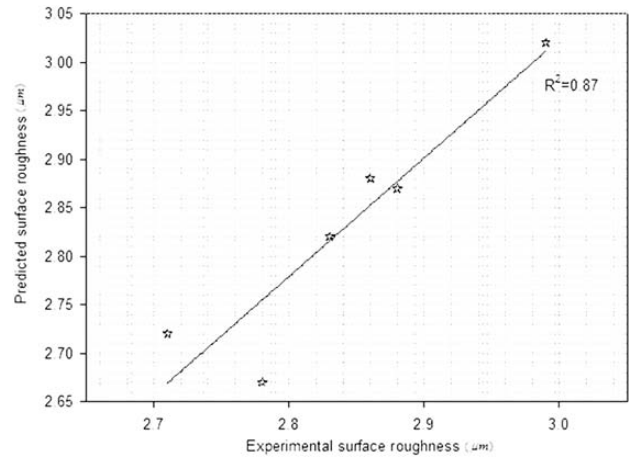

Figure 6: Response surface graph of the effects of the pulse on time and current on the surface roughness
Slika 6: Ploskovni diagram vpliva trajanja pulza in toka na hrapavost površine

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with experiments #5 and #7, whereas the minimum surface roughness of 2.58 μm was obtained with experiment #8.

The analysis results for the responses have shown that the value of multiple correlation coefficient R^2 is 0.87 (which means that the explanatory variables explain 87 % of the variability in the response variable) for the surface roughness response. With the adjusted R-square (Adj R^2), the value closer to 1 indicates a better fit. It is generally the best indicator of the fit quality and it was found to be 0.90. The statistical analysis also proved that a full factorial regression analysis fits well with the experimental observations. **Figure 7** presents a comparison of the predicted and actual results for the surface roughness.

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