www.czasopisma.pan.pl PAN www.journals.pan.pl
POLSKA AKADEMIA NAUK

ARCHIVE OF MECHANICAL ENGINEERING

VOL. LXV 2018 Number 4

DOI: 10.24425/ame.2018.125437

Key words: EDM, Inconel 718, surface roughness, material removal rate, response surface methodology (RSM)

RAFAŁ ŚWIERCZ[1], *DOROTA ONISZCZUK-ŚWIERCZ*[1], *LUCJAN DĄBROWSKI*[1]

ELECTRICAL DISCHARGE MACHINING OF DIFFICULT TO CUT MATERIALS

The development of industry is determined by the use of modern materials in the production of parts and equipment. In recent years, there has been a significant increase in the use of nickel-based superalloys in the aerospace, energy and space industries. Due to their properties, these alloys belong to the group of materials hard-to-machine with conventional methods. One of the non-conventional manufacturing technologies that allow the machining of geometrically complex parts from nickel-based superalloys is electrical discharge machining. The article presents the results of experimental investigations of the impact of EDM parameters on the surfaces roughness and the material removal rate. Based on the results of empirical research, mathematical models of the EDM process were developed, which allow for the selection of the most favourable processing parameters for the expected values of the surface roughness *Sa* and the material removal rate.

1. Introduction

Modern technology enhances the reliability of parts through application of nickel-based superalloys such as Inconel 718. Mechanical and chemical properties of Inconel 718, high-strength at high temperatures, good oxidation resistance and good corrosion resistance fostered a wide range application in industry. This material is widely used in aerospace and energy industry for hot section of gas turbine engines and parts such as turbine disk, blades. However, properties of Inconel 718, hardness, low thermal conductivity and work hardening effect make this material difficult to manufacture by conventional methods [1]. Therefore, non-conventional machining methods such as electrochemical machining [2, 3] and electrical discharge machining [4, 5] are used in the manufacturing process.

[1] *Warsaw University of Technology, Institute of Manufacturing Technology, Warsaw, Poland. Emails: rsw@meil.pw.edu.pl, doo@meil.pw.edu.pl, ld@meil.pw.edu.pl*

The electrical discharge machining (EDM) is one of the precision methods of manufacturing hard, conductive materials of complex shape. Removal mechanism of the material in EDM is mainly the result of the electrical discharge which results in melting and evaporation in local surface layers of both the workpiece and the tool electrode [6]. During machining, there are hundreds of electrical discharges. The main parameters and machining conditions determining the physical phenomena occurring in the EDM process are electrical parameters: pulse duration, pulse off time, discharge voltage, discharge current. The discharge voltage U is of substantial influence on the ionisation of the channel through which the current flows. For higher discharge voltage, it is possible to set a larger gap between electrodes and thereby facilitate its rinsing and draining of the dielectric products. Pulse off time t_{off} is responsible for stabilising conditions in the gap (remove erosion products, deionisation of the discharge channel) [7]. Discharge current I and pulse duration t_{on}, along with discharge voltage define the energy of the electrical discharge:

$$E = \int_0^{t_{\text{on}}} U(t)\, I(t)\, \mathrm{d}t \quad (\mathrm{mJ}). \tag{1}$$

Determination of the influence of EDM current-voltage parameters on the physical phenomena of the removal process is difficult. The EDM process with three major parameters: percent of discharge energy spent on the heating, constant governing the law of growth of the plasma channel and the equivalent temperature used to calculate the amount of the removed material is described in [8]. The proposed model of the EDM allowed prediction of the surface roughness and material removal rate based on the analysis of the superposition of multiple discharges and on determining the temperature fields inside the workpiece. Solving the thermal problem of discharge enables one to model of structural changes in surface layers and their thickness [9] in Inconel 718. Theoretical models of the EDM make valuable insight into physical phenomena. However, the application of theoretical models in the industrial applications is not always possible. The problems with identification of its influence on the surface integrity and the *MRR* can result from the observed stochastic nature of electrical discharges causes. Proper selection of machining parameters, needed to achieve specific surface layers and material removal rate require experimental investigations.

For the successful industrial applications of the EDM in manufacturing parts from Inconel, specific surface integrity should be obtained. The research that has been conducted hitherto in the field of the EDM focuses primarily on a better understanding of the physical phenomenon of the process [10, 11], improving surface layers properties [12–15] and optimization of the manufacturing process [16–19]. These studies have been carried out in various directions including the analysis of the EDM parameters. In [20] authors have analysed the influence of cryogenically treated copper electrode on the surface integrity of Inconel 825. The presented results indicate the possibility of tool electrode life improvement using cryogenically treated. The use of a cryogenically treated tool electrode allows achieving a better surface quality of the workpiece. The influence of the flushing conditions of the efficiency of debris removal during manufacturing which favourably affects the*MRR* and surface roughness have been studied in [21]. Authors of [22] have proposed using a hybrid electrical discharge with arc machining to achieve better material removal rate during processing Inconel.

In [23] has been shown that using powder suspended in dielectric gives a possibility to achieve improved surface roughness and *MRR* on the fine finishing process. Analysis of using a powder in dielectric indicates that it is possible to reduce not only value of surface roughness [24] but also reduce the micro-crack density and thickness of a recast layer [25]. The conclusion that material electrode (copper, graphite) with a combination of process parameters and polarity of the electrode has a strong influence on the surface roughness in presented in [26].

The elimination of unfavourable features of the surface layer of materials after EDM machining is carried out in a multidirectional way. In many cases, additional processing is used: electrical discharge alloying (EDA) [27, 28], surface modification with laser beam [29], coating application [30], mechanical treatments, grit blasting [31], abrasive machining [32], surface finishing [33].

The published studies of the electrical discharge machining are mainly focused on improving the surface integrity and optimisation of the process parameters. However, analyses of the surface roughness of Inconel 718 related to 3D parameters of the surface texture are not thoroughly described. Therefore, in this experimental investigation, the influence of discharge current and pulse duration on surface roughness *Sa* and material removal rate (*MRR*) was conducted.

The 3D surface roughness parameters render more information about measuring topography which is calculated across the selected area not only in section. In the EDM, the surface is formed by the electrical discharges and may demonstrate different properties in section analysis [34].

The conducted studies were aimed at determining the relationship between the investigated EDM parameters and surface roughness as well as the *MRR*. Response surface methodology was used to build models of the EDM process based on the conducted experimental investigations. The determined regression equations can be used to predict surface roughness *Sa* and the material removal rate.

2. Materials and method

The experimental studies were carried out on the EDM machine Charmilles Form 2LC ZNC. The samples of Inconel 718 with dimensions of $12 \times 12 \times 4$ mm were ground prior to the EDM machining in order to achieve the same surface roughness properties. The chemical composition and mechanical properties of Inconel 718 are presented in Table 1. The electrolytic copper with cross-section

14×14 mm was used for the tool electrode, and the commercial EDM fluid 108 MP-SE 60 used as a dielectric.

Table 1.

Typical composition of Inconel 718 with mechanical properties

Composition of Inconel 718				Mechanical properties of Inconel 718	
Element	(wt.%)	Element	(wt.%)	Element	Value
Ni	53.4	C	0.067	Density	8.19 g/cm^3
Cr	18.95	Si	0.06	Thermal conductivity	11.2 W/mK
Fe	17.01	Co	0.05	Electrical resistivity	127 µΩcm
Nb	5.48	P	0.009	Elastic modulus	200 GPa
Mo	3.2	B	0.006	Yield strength	434 MPa
Ti	1.08	S	0.005	Tensile strength	855 MPa
Al	1.00	Mg	< 0.01		
Cu	0.07	Mn	0		

The measurement circuit has been developed for analyzing and monitoring of the current-voltage waveforms during the EDM (Fig. 1) The waveforms can be described by the following parameters:

- I – pulse current, the height of the peak current during discharging,
- U – discharge voltage,
- t_{on} – pulse duration time, the time required for the current to rise and fall during discharging,
- t_{off} – interval time, i.e., the time from the end of one pulse to the beginning of the next current pulse.

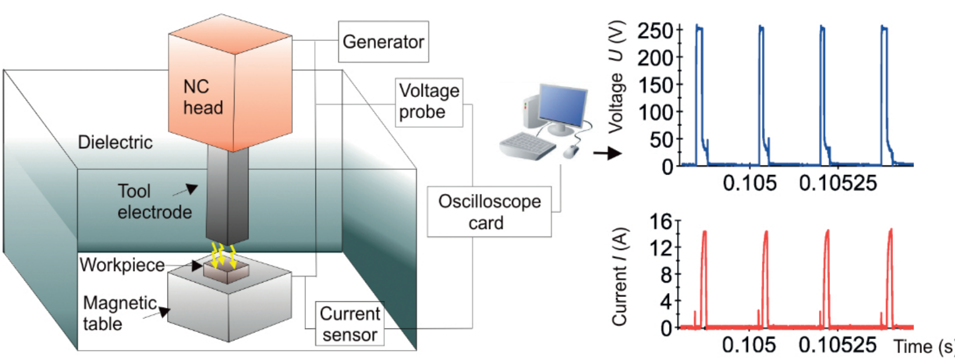


Fig. 1. Scheme of the EDM process, with the measured current-voltage waveforms for the following settings $U = 25$ V, $I = 14$ A, $t_{on} = 10$ µs, $t_{off} = 150$ µs

The application was developed in a LabView software environment that enabled the operation of the oscilloscope card. The recorded data were transferred directly to the hard disk of the computer. The processing and analysis of the measured results was carried out using National instruments DIAdem software.

The experimental investigation was performed according to the experimental design theory. The five-level central composite experimental plan was adopted for investigating the influence of pulse current, and pulse duration on surface roughness and material removal rate. This type of the experiment planning enabled reduction of the number of machining runs required to generate a statistically adequate result.

The ranges of the values for the pulse current and pulse duration in the selected design of experiment (DOE) were defined basing on the earlier preliminary test and references survey. In the preliminary test, the stability of the electrical discharges was checked by observation of current-voltage waveforms during machining with various values of the investigated EDM parameters. The range of the investigated parameters included roughing, semi-finishing and finishing EDM.

Considering the above assumptions, the experimental research was conducted for the following machining conditions: pulse current within the range I=1.7−14 A, pulse duration within the range t_{on} = 5−150 µs, with constant open-circuit voltage U_0 = 225 V, discharge voltage U = 25 V and pulse off time t_{off} = 0.3 µs. Pulse polarity was positive in each experiment. The selected experimental plan is of central composite orthogonal design with five levels and two dependent variables. In this experimental plan, ten machining runs were executed, including three level factorials designs points, four axial points and two central points. In Table 2, the ranges of machining parameters applied in the experimental design are presented.

Table 2.

Design of experiment

Levels	EDM parameters	
	discharge current I (A)	pulse duration t_{on} (µs)
−1.078	1.7	5
−1	2	10
0	8	78
1	13.5	145
+1.078	14	150

The measurement of the surface topography after the EDM was carried out on a Taylor–Hobson FORM TALYSURF Series 2 scan profilometer. For each sample, the area 2 × 2 mm was measured. The discretisation step for the X-axis and the Y-axis was 10 µm. The following 3D parameter was selected for describing the surface roughness after the EDM:

Sa is the arithmetic mean of the deviations from the mean *Sa* – average value of the absolute heights over the entire surface. *Sa* parameter responds to the 2D roughness profile parameters *Ra*. It may be obtained by adding individual height values without regard to the sign and dividing the sum by the number of the data matrix, where M is a number of points per profile, N the number of profiles and $z_{x,y}$ the height of the profile at a specific point,

$$Sa = \frac{1}{NM} \sum_{x=0}^{N=1} \sum_{y=0}^{M=1} \left| z_{x,y} \right| . \tag{2}$$

Material removal rate (MRR) was calculated based on the volume of material removed from the workpiece divided by machining time:

$$MRR = \frac{m_1 - m_2}{\rho\,\Delta t} \quad \left[\frac{\mathrm{mm}^3}{\mathrm{min}}\right], \tag{3}$$

where: m_1 – sample weight before processing, m_2 – sample weight after processing, ρ – specific density, Δt – time of manufacturing.

Each sample was weighed before manufacturing on a precision electronic digital balance (scale has a 0.0001 gram precision). The samples after the EDM process were cleansed with the compressed air and weighed again. The results of the DOE are presented in Table 3.

Table 3.

Experimental design and results

Exp. no.	Parameters		Observed values	
	Discharge current I (A)	Pulse duration t_{on} (µs)	Roughness Sa (µm)	MRR (mm^3/min)
1.	2	10	2.34	0.92
2.	13.5	10	6.32	31.47
3.	2	145	1.41	0.25
4.	13.5	145	12.5	35.04
5.	8	5	3.71	8.71
6.	8	150	7.66	12.58
7.	1.7	78	1.53	0.23
8.	14	78	10.3	38.04
9.	8	78	7.82	17.03
10.	8	78	7.63	16.26

Response surface methodology was used to build an empirical models of the effect of the investigated EDM parameters: pulse current and pulse duration on surface roughness Sa and MRR. In RSM, relations between the desired response and the independent input parameters can be represented by:

$$Y = f(X_1,\ X_2,\ \ldots,\ X_N) \pm \varepsilon, \tag{4}$$

where: Y is the response, f is the response function, ε is the experimental error (fitting error – residuals), $X_1, X_2, X_3, \ldots, X_n$ are independent parameters.

In this study, the second-order polynomial regression model was chosen to fit the response function to experimental results (Eq. (5)). This function allows locating the region of interest where the response reaches its optimum or near optimum value.

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \beta_i i X_i^2 + \sum_{i=1,\ i\neq j}^{k} \beta_{ij} i X_i X_j + \varepsilon, \tag{5}$$

where: β_0 is a constant, β_i, β_{ii}, β_{ij} represent the coefficients of linear, quadratic, and cross terms, X_i corresponds to the independent variable.

Analysis of variance (ANOVA) was used to test the significance of the established quadratic model. Statistical analyses in the first stage were checked for the following assumption: residuals have a normal distribution, constant variance and are independent of an order of data. The assumption of constant variance was checked by plotting residuals versus predicted values. Normality assumption and independence residuals were checked by plotting the expected normal value vs residuals and residuals vs. order of data, respectively [35]. The procedure of developing the model with the Response Surface Methodology is presented in Fig. 2.

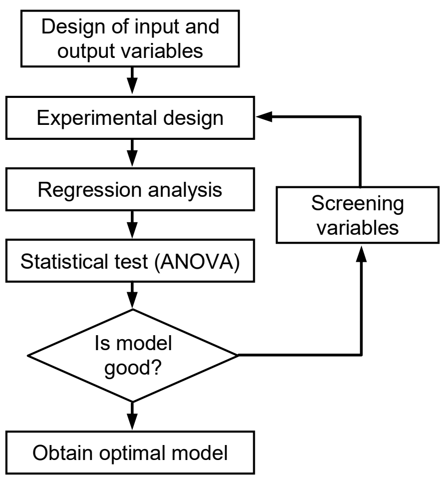


Fig. 2. The procedure of the model development with the Response Surface Methodology

Regression analysis with the backward elimination process has been performed to achieve the model prediction for the *MRR* and surface roughness *Sa* accurately, with a 95% confidence. The developed models of the surface roughness *Sa* and *MRR* were checked with ANOVA test. The degree of fit of the regression equation to the results of the experimental studies is described by the coefficient of determination R-squared (R^2). R-squared $\in \langle 0, 1\rangle$ and it reflects the variability of the investigated relationship. If the value of the R-squared approaches unity, more accurate fit of the regression equation to the research results will be obtained. The Fisher test (F) was used to verify the significance of the factor in each regression equation. F-value corresponds to a continuous probability distribution. If this probability (Prob $> f$) value for each factor is less than 0.05 (i.e., at 95% confidence level), then the factor in the model has a significant effect on the response surface. Values of Prob $> f$ higher than 0.05 indicate the non-significance of a model factor. For each equation, the calculated coefficient R-squared and R-Adj indicate that the model explains all the variability of the response data around its mean. Verification of the adequacy of the developed model was determined by statistical tests (for $f = 0.05$) F-Snedecor [35, 36].

3. Results and discussion

3.1. Surface roughness

The surface topography after the EDM is formed by the overlap of individual electric discharges and is of random nature. Depending on the investigated EDM process parameters, there were significant differences in surface texture properties. The influence of the two significant EDM parameters was investigated: pulse current $I = 1.7-14$ A, and pulse duration $t_{on} = 5-150$ µs. These two parameters determine the amount of energy of the discharge pulse (with constant voltage). The 3D analysis (Figs. 3, 4) of the surface obtained after the EDM for roughing and finishing operations show that the shape of the roughness is a direct result of the applied parameters.

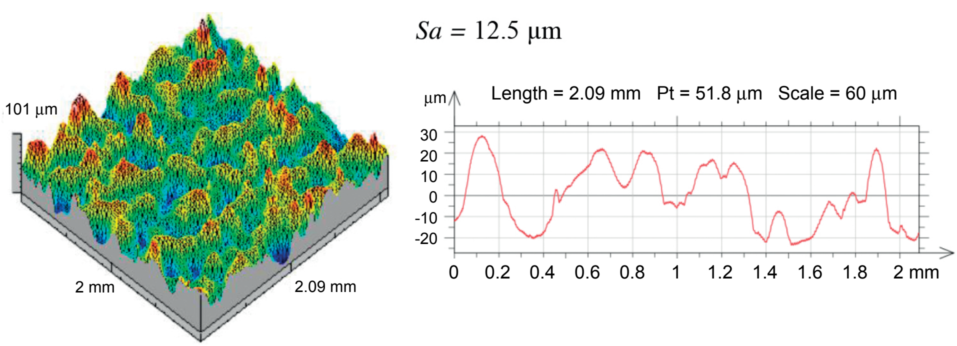


Fig. 3. Surface texture of Inconel 718 after the EDM ($I = 13.5$ A, $t_{on} = 145$ µs)

Based on the results from the experimental studies, an empirical model of influence discharge current I and pulse duration t_{on} on the surface roughness parameters was built. The results for the ANOVA test after elimination of non-significant terms are presented in Table 4.

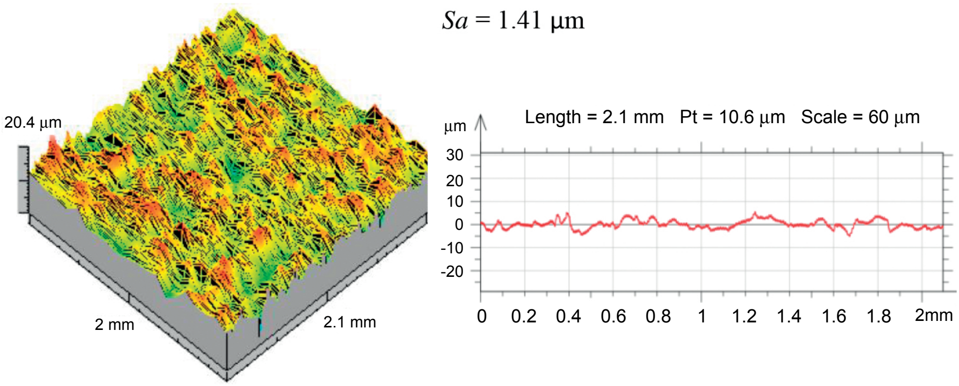


Fig. 4. Surface texture of Inconel 718 after EDM (I = 1.7 A, t_{on} = 78 μs)

Table 4.

ANOVA table for Sa (after elimination)

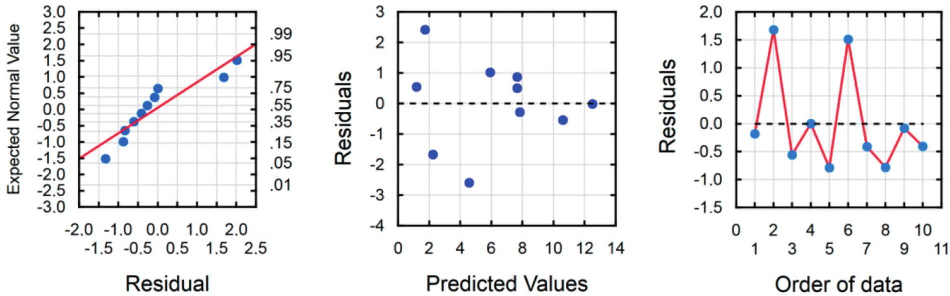
Source	Sum of squares	Degrees of freedom	Mean square	F-Value	Prob > f
t_{on}	14.35	1	14.35	12.26	0.0127
I	94.94	1	94.94	81.12	0.0001
$t_{on}I$	12.70	1	12.70	10.85	0.0165
Error	7.02	6	1.17		
Total SS	129.03	9			
R-sqr	0.95				
R-Adj	0.93				

Final response equations for the surface roughness parameters Sa were described by the polynomial function of the second degree:

$$Sa = 1.8767 - 0.0141 t_{on} + 0.3191 I + 0.0046 t_{on} I. \tag{6}$$

The developed model of the surface roughnessSa was checked by a residual normal probability plot, the residuals versus the predicted values, and the residuals versus the order of data (Fig. 5a, 5b, 5c).

The obtained normal probability plot (Fig. 5a) shows that the residuals are normally distributed. The dependence between the expected normal value and residuals are approximately linear. An analysis of the relations between residuals versus the predicted values (Fig. 5b) indicates that residuals are of stochastic nature. Errors are of random pattern around the centre line and are not correlated with another variable or with each other. The analysis of plot residuals versus the order of data (Fig. 5c) indicates that the error terms were independent one from another.



(a) (b) (c)

Fig. 5. Plots for the check model of the arithmetic mean of the deviations from the mean *Sa*: (a) the normal plot of residuals, (b) the residuals versus the predicted values, and (c) theresiduals versus the order of the data

The value of R-squared coefficient of determination are 0.95 (Table 4), which shows that that adopted model will explain the variation of surface roughness *Sa* up to 95%. High value of R-squared with the good agreement of adjusted R^2 coefficient R^2-Adj (0.93) indicates that the established model is adequate in representing the process. Fig. 6 shows the estimated response surface for the surface roughness parameters *Sa* in relation to the discharge current I and pulse duration t_{on}.

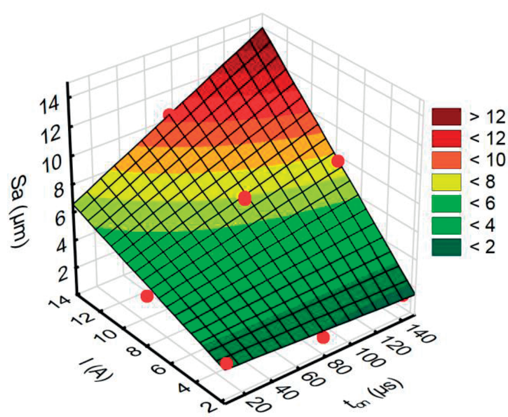


Fig. 6. Estimated response surface for the arithmetic mean of the deviations from the mean *Sa*

The parameter of surface roughness *Sa* (Fig. 6) is mainly dependent on the discharge current. The increased current and pulse duration cause an increase in the amount of eroded material in a single discharge. However, these relations are not directly proportional. At low currents (about 1.7 A) increasing the pulse time (and therefore energy) does not lead to a significant increase in the *Sa* parameter. With the same current and increasing pulse time t_{on}, only the diameter of craters change and the outcome is that the value of S a does not change. With the increasing pulse duration and current, the diameter and the depth of the craters increase. The heat generated in the discharge is delivered to the workpiece and causes melting and evaporation of more material volume.

3.2. Material removal rate

The Electrical Discharge Machining is a process in which material is removed from the surface by a series of discharges occurring in the gap between the tool electrode and the workpiece. The volume of material which melted and evaporated from the base during the discharges depends predominantly on the discharge energy. However, for proper preparation of the EDM technology in manufacturing parts from Inconel 718, knowledge is required as to the influence of discharge current and pulse duration on material removal rate considering the allowance distribution into several stages, starting from roughing, semi finishing and finishing. This knowledge will be useful for appropriate selection of machining allowances to achieve the best material removal rate for each step of manufacturing. An empirical model for estimating the effect of the discharge current and pulse duration on *MRR* was build according to the above-presented response surface methodology. The ANOVA test was conducted to obtain a significant term of the regression equation for the polynomial functions of second degree (Table 5).

Table 5.

ANOVA table for the *MRR* (after elimination)

Source	Sum of squares	Degrees of freedom	Mean square	F-Value	Prob > f
t_{on}	7.89	1	7.89	7.32	0.0403
t_{on}^2	30.51	1	33.51	9.77	0.0353
I	1781.01	1	1781.01	424.1	0.00002
I^2	38.62	4	38.62	11.26	0.0284
Error	18.26	5	3.652		
Total SS	1879.29	9			
R-squared	0.99				
$R2$-Adj	0.98				

The performed research showed that the relationship between the expected normal value and residuals was approximately linear, which indicated that the residuals are normally distributed (Fig. 7a). Residuals versus the predicted values (Fig. 7b) are of stochastic nature. The study of residuals versus the order of data (Fig. 7c) showed that the error terms were independent one from another.

After elimination of non-significant terms, the final equations for the influence of the investigated EDM parameters on the *MRR* are:

$$MRR = -5.7141 + 0.1322 t_{on} - 0.0007 t_{on}^2 + 1.0459 I + 0.1207 I^2. \qquad (7)$$

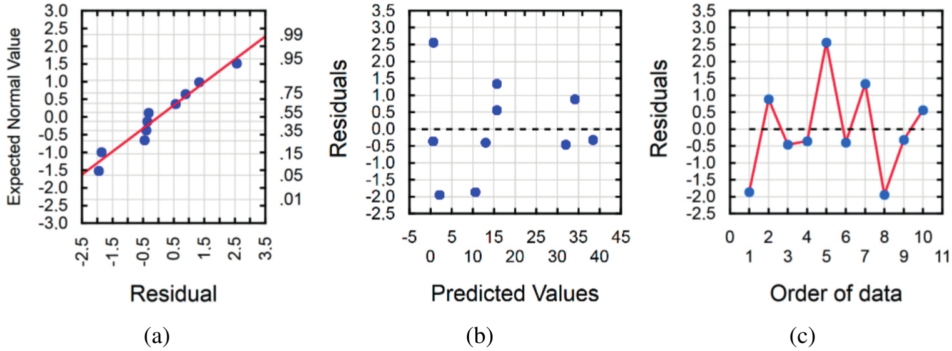


Fig. 7. Plots for the check model of the *MRR* (a) the normal plot of residuals, (b) the residuals versus the predicted values and (c) the residuals versus the order of the data

The value of the *R*-squared coefficient of determination is 0.99 (Table 5) which shows that that adopted model explains the variation of the *MRR* up to 99%. High value of *R*-squared with the good agreement of R^2-Adj (0.98) indicate that the established model is adequate in representing the process.

The material removal rate depends on the discharge energy. With the increase of discharge current and pulse duration, more volume of material is removed from the workpiece in a single discharge. However, for the lowest value of the current, the change in the pulse duration does significantly affect the *MRR*. The observed fact results from the Gaussian shape of the heat flux of the electrical discharge. At a minimal value of current, the increase in pulse duration results in heating more volume of the workpiece, but current density is not high enough to melt and evaporate a larger volume of material. The estimated response surface for the *MRR* related to the discharge current and pulse duration is shown in Fig. 8.

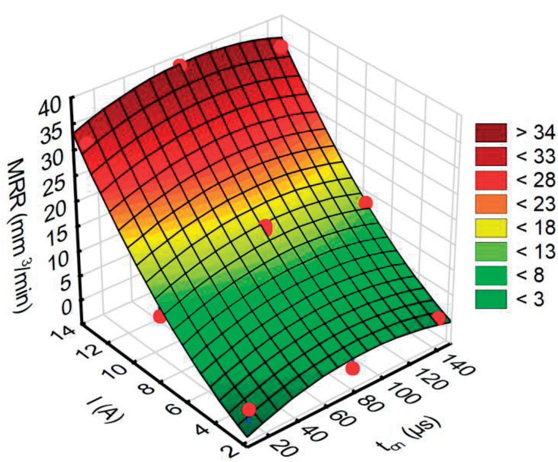


Fig. 8. Estimated response surface for material removal rate

4. Conclusions

The experimental investigations and their statistical analysis show that the discharge energy is the main factor influencing on the surface roughness *Sa* and material removal rate after the EDM. The increase in current and pulse time results in the increase of the diameter and power of the discharge channel. It is leading to the generation of the roughness of much greater height and the distance between the individual vertices. The surface texture after the EDM is isotropic.

Let us summarize the results of the experimental investigation:

- The roughness parameter *Sa* is within the range of 1.4–12.5 µm and it suits the EDM finishing and roughing treatment.
- Surface roughness *Sa* is mainly dependent on the discharge current. The increase of discharge current increased the amount of eroded material in a single pulse, thus leading to higher roughness.
- The material removal rate is within the range of 0.25–35 mm^3/min and it corresponds to the finishing and roughing machining. Due to the economic aspects of the treatment, it is necessary to divide the electrical discharge machining into several stages. EDM technology Inconel 718 should be starting from roughing (maximum energy parameters) through semi-finishing and finishing, so that the share of the treatment with the lowest energy values is limited to the necessary minimum.
- The models developed are considered reliable representatives of the experimental results with prediction errors less than ±5%. They can be used in the technology of manufacturing parts of Inconel 718 for achieving the desired surface roughness and *MRR*.

Acknowledgements

This work was supported by a grant from the Fundamental Research Funds of the Faculty of Production Engineering, Warsaw University of Technology.

The authors would like to express gratitude to the organisers of scientific conference Industry 4.0, Technical Institute of the State Higher Vocational School in Nowy Sącz, Faculty IV of Technical Sciences of the Polish Academy of Sciences and Machine Construction Committee Technology Section for the possibility of presenting partial results published in this paper.

Manuscript received by Editorial Board, April 18, 2018;
final version, September 09, 2018.

References

[1] C.P. Mohanty, S.S. Mahapatra, and M.R. Singh. An experimental investigation of machinability of Inconel 718 in electrical discharge machining. *Procedia Materials Science*, 6:605–611, 2014. doi: 10.1016/j.mspro.2014.07.075.

[2] S. Skoczypiec. Discussion of ultrashort voltage pulses electrochemical micromachining: a review. *The International Journal of Advanced Manufacturing Technology*, 87(1-4):177–187, 2016. doi: 10.1007/s00170-016-8392-z.

[3] A. Ruszaj, J. Gawlik, and S. Skoczypiec. Electrochemical machining – special equipment and applications in aircraft industry. *Management and Production Engineering Review*, 7(2):34–41, 2016. doi: 10.1515/mper-2016-0015.

[4] B.K. Sahu, S. Datta, and S.S. Mahapatra. On electro-discharge machining of Inconel 718 super alloys: an experimental investigation. *Materials Today: Proceedings*, 5(2):4861–4869, 2018. doi: 10.1016/j.matpr.2017.12.062.

[5] L. Li, Z.Y. Li, X.T. Wei, and X. Cheng. Machining characteristics of Inconel 718 by sinking-DM and wire-EDM. *Materials and Manufacturing Processes*, 30(8):968–973, 2015 doi: 10.1080/10426914.2014.973579.

[6] R. Świercz and D. Oniszczuk-Świercz. Influence of electrical discharge pulse energy on the surface integrity of tool steel 1.2713. *Proceedings of the 26th International Conference on Metallurgy and Materials*, pages 1450–1455, Brno, Czech Republic, 24–26 May 2017. WOS:000434346900234.

[7] M. Kunieda, B. Lauwers, K.P. Rajurkar, and B.M. Schumacher. Advancing EDM through fundamental insight into the process. *CIRP Annals – Manufacturing Technology*, 54(2):64–87, 2005. doi: 10.1016/S0007-8506(07)60020-1.

[8] B. Izquierdo, J.A. Sánchez, S. Plaza, I. Pombo, and N. Ortega. A numerical model of the EDM process considering the effect of multiple discharges. *International Journal of Machine Tools and Manufacture*, 49(3-4):220–229, 2009. doi: 10.1016/j.ijmachtools.2008.11.003.

[9] B. Izquierdo, S. Plaza, J.A. Sánchez, I. Pombo, and N. Ortega. Numerical prediction of heat affected layer in the EDM of aeronautical alloys. *Applied Surface Science*, 259:780–790, 2012. doi: 10.1016/j.apsusc.2012.07.124.

[10] G. Puthumana. An influence of parameters of micro-electrical discharge machining on wear of tool electrode. *Archive of Mechanical Engineering*, 64(2):149–163, 2017. doi: 10.1515/meceng-2017-0009.

[11] A. Żyra, R. Bogucki, and S. Skoczypiec. Austenitic steel surface integrity after EDM in different dielectric liquids. *Technical Transactions*, 12:231–242, 2017. doi: 10.4467/2353737XCT.17.222.7765.

[12] J. Holmberg, A. Wretland, J. Berglund, and T. Beno. Surface integrity after post processing of EDM processed Inconel 718 shaft. *The International Journal of Advanced Manufacturing Technology*, 95(5-8):2325–2337, 2018. doi: 10.1007/s00170-017-1342-6.

[13] Z. Chen, J. Moverare, R.L. Peng, and S. Johansson. Surface integrity and fatigue performance of Inconel 718 in wire electrical discharge machining. *Procedia CIRP*, 45:307–310, 2016. doi: 10.1016/j.procir.2016.02.053.

[14] C. Upadhyay, S. Datta, M. Masanta, and S.S. Mahapatra. An experimental investigation emphasizing surface characteristics of electro-discharge-machined Inconel 601. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, 39(8):3051–3066, 2017. doi: 10.1007/s40430-016-0643-2.

[15] D. Oniszczuk-Świercz and R. Świercz. Surface texture after wire electrical discharge machining. *Proceedings of the 26th International Conference on Metallurgy and Materials*, pages 1400–1406, Brno, Czech Republic, 24–26 May 2017. WOS:000434346900226.

[16] L. Straka, I. Corný, J. Pitel', and S. Hašová. Statistical approach to optimize the process parameters of HAZ of tool steel EN X32CrMoV12-28 after die-sinking EDM with SF-Cu electrode. *Metals*, 7(2):35, 2017. doi: 10.3390/met7020035.

[17] P. Vishnu, N. Santhosh Kumar, and M. Manohar. Performance prediction of electric discharge machining of Inconel-718 using artificial neural network. *Materials Today: Proceedings*, 5(2):3770–3780, 2018. doi: 10.1016/j.matpr.2017.11.630.

[18] V. Aggarwal, S.S. Khangura, and R.K. Garg. Parametric modeling and optimization for wire electrical discharge machining of Inconel 718 using response surface methodology. *The International Journal of Advanced Manufacturing Technology*, 79(1-4):31–47, 2015. doi: 10.1007/s00170-015-6797-8.

[19] S. Prabhu and B.K. Vinayagam. Multiresponse optimization of EDM process with nanofluids using TOPSIS method and genetic algorithm. *Archive of Mechanical Engineering*, 63(1):45–71, 2016. doi: 10.1515/meceng-2016-0003.

[20] Rahul, K. Abhishek, S. Datta, B.B. Biswal, and S.S. Mahapatra. Machining performance optimization for electro-discharge machining of Inconel 601, 625, 718 and 825: an integrated optimization route combining satisfaction function, fuzzy inference system and Taguchi approach. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, 39(9):3499–3527, 2017. doi: 10.1007/s40430-016-0659-7.

[21] M. Tanjilul, A. Ahmed, A.S. Kumar, and M. Rahman. A study on EDM debris particle size and flushing mechanism for efficient debris removal in EDM-drilling of Inconel 718. *Journal of Materials Processing Technology*, 255:263–274, 2018. doi: 10.1016/j.jmatprotec.2017.12.016.

[22] A. Ahmed, A. Fardin, M. Tanjilul, Y.S. Wong, M. Rahman, and A.S. Kumar. A comparative study on the modelling of EDM and hybrid electrical discharge and arc machining considering latent heat and temperature-dependent properties of Inconel 718. *The International Journal of Advanced Manufacturing Technology*, 94(5-8):2729–2737, 2018. doi: 10.1007/s00170-017-1100-9.

[23] S. Kumar, A.K. Dhingra, and S. Kumar. Parametric optimization of powder mixed electrical discharge machining for nickel-based superalloy inconel-800 using response surface ethodology. *Mechanics of Advanced Materials and Modern Processes*, 3:7, 2017. doi: 10.1186/s40759-017-0022-4.

[24] G.S. Prihandana, T. Sriani, M. Mahardika, M. Hamdi, N. Miki, Y.S. Wong, and K. Mitsui. Application of powder suspended in dielectric fluid for fine finish micro-EDM of Inconel 718. *The International Journal of Advanced Manufacturing Technology*, 75(1-4):599–613, 2014. doi: 10.1007/s00170-014-6145-4.

[25] G. Talla, S. Gangopadhyay, and C.K. Biswas. Effect of powder-suspended dielectric on the EDM characteristics of Inconel 625. *Journal of Materials Engineering and Performance*, 25(2):704–717, 2016. doi: 10.1007/s11665-015-1835-0.

[26] A. Torres, I. Puertas, and C.J. Luis. EDM machinability and surface roughness analysis of INCONEL 600 using graphite electrodes. *The International Journal of Advanced Manufacturing Technology*, 84(9-12):2671–2688, 2016. doi: 10.1007/s00170-015-7880-x.

[27] S. Spadło, P. Młynarczyk, and K. Łakomiec. Influence of the of electrical discharge alloying methods on the surface quality of carbon steel. *The International Journal of Advanced Manufacturing Technology*, 89(5-8):1529–1534, 2017. doi: 10.1007/s00170-016-9168-1.

[28] S. Spadło, J. Kozak, and P. Młynarczyk. Mathematical modelling of the electrical discharge mechanical alloying process. *Procedia CIRP*, 6:422–426, 2013. doi: 10.1016/j.procir.2013.03.031.

[29] I. Pliszka, N. Radek, and A. Gądek-Moszczak. Properties of WC-Cu electro spark coatings subjected to laser modification. *Tribologia*, 5:73–79, 2017.

[30] T. Chmielewski, D. Golański, and W. Włosiński. Metallization of ceramic materials based on the kinetic energy of detonation waves. *Bulletin of the Polish Academy of Sciences Technical Sciences*, 63(2):449–456, 2015. doi: 10.1515/bpasts-2015-0051.

[31] J. Holmberg, A. Wretland, and J. Berglund. Grit blasting for removal of recast layer from EDM process on Inconel 718 shaft: an evaluation of surface integrity. *Journal of Materials Engineering and Performance*, 25(12):5540–5550, 2016. doi: 10.1007/s11665-016-2406-8.

[32] A. Ruszaj, S. Skoczypiec, and D. Wyszyński. Recent developments in abrasive hybrid manufacturing processes. *Management and Production Engineering Review*, 8(2):81–90, 2017. doi: 10.1515/mper-2017-0020.

[33] T. Sałaciński, M. Winiarski, T. Chmielewski, and R. Świercz. Surface finishing using ceramic fiber brush tools. *Proceedings of the 26th International Conference on Metallurgy and Material*, pages 1220–1226, Brno, Czech Republic, 24–26 May 2017. WOS:000434346900195.
[34] R. Świercz and D. Oniszczuk-Świercz. Experimental investigation of surface layer properties of high thermal conductivity tool steel after electrical discharge machining. *Metals*, 7(12):550, 2017. doi: 10.3390/met7120550.
[35] Douglas C. Montgomery. Design and Analysis of Experiments. 9th edition. *Wiley*. 2017.
[36] I. Ayesta, B. Izquierdo, J.A. Sánchez, J.M. Ramos, S. Plaza, I. Pombo, N. Ortega, H. Bravo, R. Fradejas, and I. Zamakona. Influence of EDM Parameters on slot machining in C1023 aeronautical alloy. *Procedia CIRP*, 6:129–134, 2013. doi: 10.1016/j.procir.2013.03.059.