OPTIMISATION OF WEDM SETTINGS PARAMETERS WHEN MACHINING PURE ALUMINIUM USING THE DOE

KATERINA MOURALOVA, JIRI KOVAR, TOMAS PROKES
JOSEF BEDNAR, PAVEL HRABEC
Brno University of Technology
Faculty of Mechanical Engineering, Brno, Czech Republic

DOI: 10.17973/MMSJ.2017_12_201795

e-mail: mouralova@fme.vutbr.cz

The unconventional wire electric discharge machining technology (WEDM) is widely used in many industries, which is why there is a permanent emphasis on increasing the quality of suchmachined surface. The aim of this study was to carry out a design of experiment (DoE) to reduce the surface qualit yparameter Pq. During the 33-round experiment, the input factors – machine setting parameters, such as gap voltage, pulse on time, pulse off time, wire speed, and discharge current, were changed. Subsequently, Pq – root mean square deviation of the primary profile and Pa – arithmetic average of the primary profile were evaluated on the machined surfaces of pure aluminium. By using DoE, the setting of the machine's parameters was designed in order to achieve the highest possible surface quality.

KEYWORDS
WEDM, electrical discharge machining, design of experiment, P-parameters, root mean square deviation of the primary profile Pq, pure aluminium

1. INTRODUCTION

1.1. Wireelectricdischargemachining (WEDM)

Wire electric discharge machining is one of the unconventional machining technologies and can be considered as a major technological operation in many manufacturing industries, particularly in the automotive, military, or aerospace industries, and in the manufacturing of medical instruments. Material removal takes place on two electrodesc on currently with the immersion into a working medium – dielectrics with high electrical resistance. The periodic recurrent electric shocks emanating between the wire electrode and the workpiece create a working gap, and hence a corresponding cut [Jameson 2001], [Ho 2004], [Abbas 2007].

Due to the wide use of this machining process, the demands on performance characteristics are constantly increasing. This primarily concerns dimensional accuracy, material removal rate, or topography of the machined surface. These characteristics depend on the type of the machined material and its heat treatment, the state of the machine and, above all, on the selection of the parameters of the eroding process. These parameters can be found using various methods [Blecha 2011], [Blecha 2011].

Prasad [Prasad 2015] focused on the effect of different wire electrical discharge machining (WEDM) process parameters on the damping behaviour of the aluminium alloy. The parameters such as pulse on time, pulse off time, and peak current were employed, which they consider to be most significant. The results of the experiment held revealed that the damping behaviour greatly depends on the wire EDM process parameters. Rao [Rao 2014] investigated the optimisation of Wire EDM and claim that the quality of a wire EDM surfaceisstrongly influenced by its parameter settings and material to be machined. They mainly focused on the usage of heavy metals and partly on titanium and magnesium alloys in the light metals, though an attempt has been made to study the effect of wire EDM parameters on aluminium alloy because of its growing applications in various industries. Reddy [Reddy 2015] performed an experiment to study the multiple response optimisation of Wire EDM on aluminium. They claim that complicated cuts can be made through difficult-to-machine electrically conductive components. Bobbili [Bobbili 2015] investigated a multi response optimisation technique for wire-EDM operations on ballistic grade aluminium alloy for armour applications. Four machining variables were used for the experiment: pulse-on time, pulse-off time, peak current, and spark voltage, which proved to be significant to Grey relational grade. Cheng [Cheng 2017] employed the high-speed wire electrical discharge machining (WEDM-HS) for processing of the pure aluminium (Al) oxide film to research its performance influenced by the WEDM technology. This method proved to greatly improve the outputs of the research by reducing the abrasive wear and adhesive wear, and increasing the anti-erosion ability.

1.2. Design of Experiment (DoE)

The design of experiment (DoEis a test or a sequence of tests in which a change in input factors has been systematically performed to identify the corresponding changes in the output variable – a so-called response. The response is modelled by linear regression analysis, where the individual factors, their quadrates, and interactions act as predictors. This statistical method provides important information about the significance of the predictors and their settings in order to achieve an optimal response [Montgomery 2017].

1.3. Root mean square deviation of the primary profile (Pq)

Rootmean square deviation of the primary profile Pqis a basic profile parameter, whichisverysimilar to parameter Pa but is more sensitive to the occurrence of protrusions and depressionsbecause the amplitude height values are amplified to the second power, whichisbased on the formula (1):

$$Pq = \sqrt{\frac{1}{l}\int_{0}^{l} Z^{2}(x)dx}, \qquad (1)$$

where *l* is the sampling length and *Z(x)* are the ordinate values. The use of the Pq parameter is relatively wide spread especially in the automotive industry and isused to evaluate very finely machine surfaces [Jiang 2012].

2. EXPERIMENTAL SETUP AND MATERIAL

Experimental samples (Figure 1) were made of pure Al 99.5 aluminium, which is a low density material. Its undisputed advantages include excellent corrosion resistance, good weldability, and anodising properties. The hardness of this material varies depending on the type of product, the grain size ranges from 20 to 42 HBW and the tensile strength between 65-160 MPa (depending on the direction of loading relative to the axis of the semi-product). It isused in almost all areas of industry for structural elements and junctions mechanically less stressed, requiring a material that is highly ductile, highly corrosion resistant, very well thermally and electrically conductive. It is weldable in virtually all ways. For the experiment, a default semi-productfrom bars of 20 mm diameter was used, from which a prism was made by electric discharge machining.

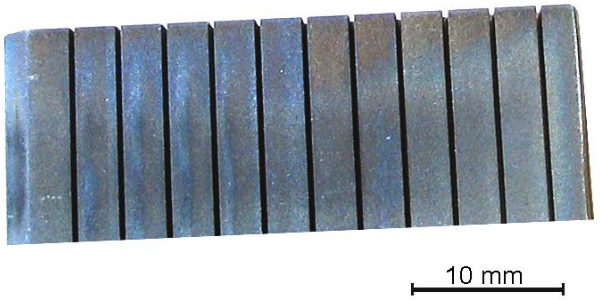

Figure 1. Samples for the experiment for which the machining parameter settings were changed every 3 mm

The WEDM machine used in this study was high precision five axis CNC machine MAKINO EU64. As electrode, pure copper wire with a diameter of 0.25 mm was used. Samples were immersed in deionised water, which served as dielectric media and also removed debris in the gap between the wire electrode and workpiece during the process.

3. TYPOGRAPHY AND MORPHOLOGY OF WEDM MACHINED SURFACE

Using a non-contact 3D Alicona profile-meterbased on the principle of coherent correlation interferometry, the root-mean square deviation of the primary profile Pq was evaluated on the electric discharge machined surface of the samples. The evaluation of this parameter was performed on each sample on a curve of 15 mm curve in accordance with standard ISO 4287 [ISO 4287]and a 10x magnification lens was used. The evaluated values of parameter Pq were compiled into the graph in Fig. 3. The lowest value of parameter Pq was evaluated for sample number 33, being only 3.97 µm.

The morphology of the electric discharge machined surface using 3D emboss mentis shown in Fig. 2.

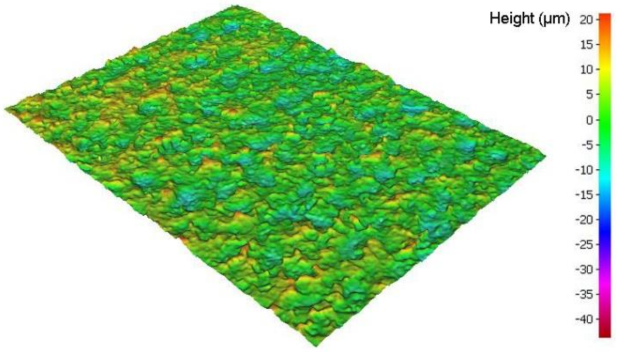

Figure 2. 3D colour-filtered embossment of the surface of a sample made of pure aluminium

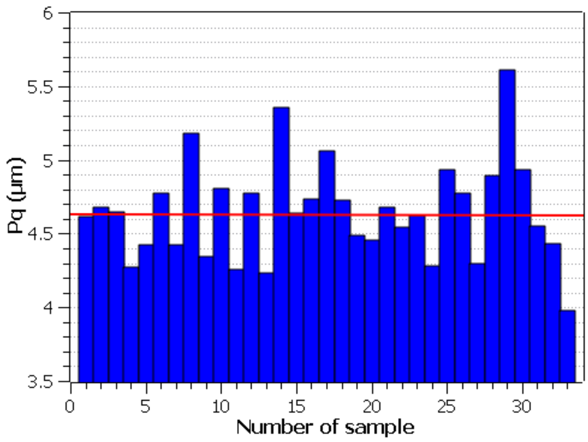

Figure 3. Evaluation of parameter Pq for individual samples, the red line represents the average value

4. DESIGN OF EXPERIMENT AND REGRESSION MODELS

The purpose of the experiment, the results of which were evaluated in the MiniTabstatistical program, was to obtain the relationship between the root-mean square deviation of the primary profile Pqdepending on the following settings of the machine – gap voltage (U), pulse on time (T_{on}), pulse off time (T_{off}), wire speed (v), and dischargecurrent (I). The design of experiment was based on 5 factors and theirlimit values (Table 1). The limit values of the settings of each parameter were used on the basis of previous extensive tests [Mouralová 2015].

Parameter	Pulse on time (µs)	Pulse on time (µs)	Gap voltage (V)	Wire speed (m/min)	Discharge current (A)
Maximum	70	10	40	14	35
Minimum	50	6	30	10	25

Table 1. Parameters of machining using WEDM

The design of experiment was chosen with respect to a lower number of samples of type 'Halfresponse surface design', which contains 33 rounds (Table 2) divided into two blocks for the five input parameters. Seven central points were used to analyse the experimental noise, and the entire design of experiment was randomised in order to reduce the impact of external influence. This data collection plan is described in detail, for example, in the Montgomery [Montgomery 2017]. The evaluation of the experiment was carried out at the level of significance of 95% (α=0.05).

The analysis of statistically significant parameters was performed using the ANOVA method shown in Fig.5 , along with a normal residual distribution test using the Anderson-Darling test (Fig. 4), where the P-value was 0.812, therefore, the zero hypothesis of normality cannot be rejected.

Statistically insignificant parameters (P value>0.05) were removed from the model to maximise the mathematical record of the obtained model between the variable and the process parameter *Pq*.

Number of sample	Gap voltage (V)	Pulse on time (µs)	Pulse off time (µs)	Wire feed (m/min)	Discharge current (A)
1	70	8	40	12	30
2	60	8	30	12	30
3	60	8	40	12	25
4	60	10	40	12	30
5	50	8	40	12	30
6	60	8	50	12	30
7	60	6	40	12	30
8	60	8	40	12	35
9	60	8	40	10	30
10	60	8	40	14	30
11	60	8	40	12	30
12	50	6	30	10	35
13	70	10	50	10	25
14	70	10	30	10	35
15	60	8	40	12	30
16	70	6	50	10	35
17	70	10	50	14	35
18	60	8	40	12	30
19	60	8	40	12	30
20	70	6	50	14	25
21	50	6	30	14	25
22	60	8	40	12	30
23	70	10	30	14	25
24	50	6	50	10	25
25	60	8	40	12	30
26	50	10	50	14	25
27	50	10	30	10	25
28	50	6	50	14	35
29	50	10	50	10	35
30	70	6	30	14	35
31	50	10	30	14	35
32	60	8	40	12	30
33	70	6	30	10	25

Table 2. Machining parameters used in the experiments

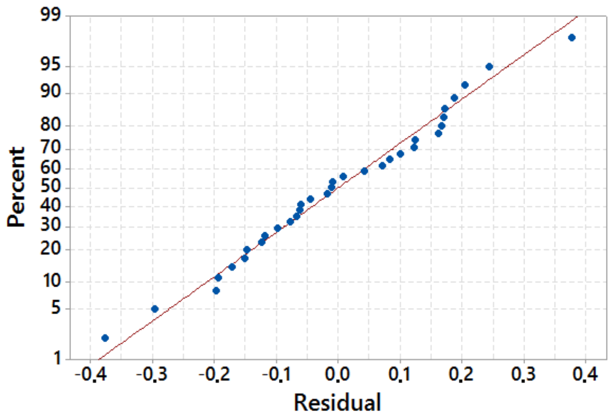

Figure 4. Normal residual distribution test

Source	P-Value
Model	0.000
Linear	0.000
Gap voltage (V)	0.725
Pulse on time (µs)	0.065
Pulse off time (µs)	0.265
Wire speed (m/min)	0.173
Discharge current (A)	0.000
Square	0.022
Discharge current (A)·Discharge current (A)	0.022
2-Way Interaction	0.001
Gap voltage (V) ·Pulse off time (µs)	0.044
Pulse on time (µs) ·Wire speed (m/min)	0.043
Wire speed (m/min) ·Discharge current (A)	0.002
Lack-of-Fit	0.703

Figure 5. Anova for parameter Pq

In order to maintain the hierarchical mode, linear parameters were retained in the model, even such with P-value greater than 0.05 except for the discharge current, which even without the combination with other parameters has a statistically significant influence on the monitored parameter.

The obtained model after the removal of insignificant interactions (1) describes 66.6% of the experimentally determined data. The statistically significant interactions in the model are shown in Figs. 7 and 8.

$$\begin{aligned}\mathrm{Pq}\,(\mu\mathrm{m}) &= -3.24 + 0.0401\mathrm{U} + 0.360\ \mathrm{T_{on}} + \\ &+ 0.0679\ \mathrm{T_{off}} + 0.763\ \mathrm{v} - 0.139\ \mathrm{I} + 0.00673\ \mathrm{I}\cdot\mathrm{I} - \\ &- 0.001044\mathrm{U}\ \cdot\mathrm{T_{off}} - 0.0263\ \mathrm{T_{on}}\cdot\mathrm{v} - 0.01735\ \mathrm{v}\cdot\mathrm{I},\end{aligned} \qquad (1)$$

where: U (V) is gap voltage, T_{on} (µs) is pulse on time, T_{off}(µs) is pulse off time, v (m/min) is wire speed, and I (A) is the discharge current.

The regressionanalysis (Fig. 6) found a dependence between the parameters *Pa* (µm) and *Pq* (µm) recorded using the equation (2), which represents 95.2% of the experimentally measured data.

$$\mathrm{Pa}\,(\mu\mathrm{m}) = 1.005 + 0.4621\ \mathrm{Pq} \qquad (2)$$

Where *Pq*(µm) is the rootmean square deviation of the primary profile and *Pa* (µm) is the arithmetic average of the primary profile.

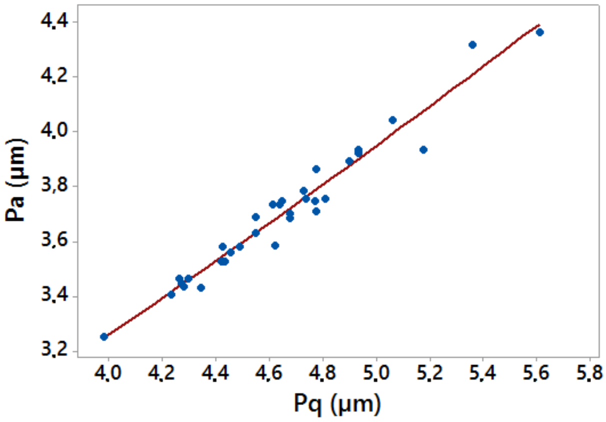

Figure 6. Regression between Pa and Pq parameters

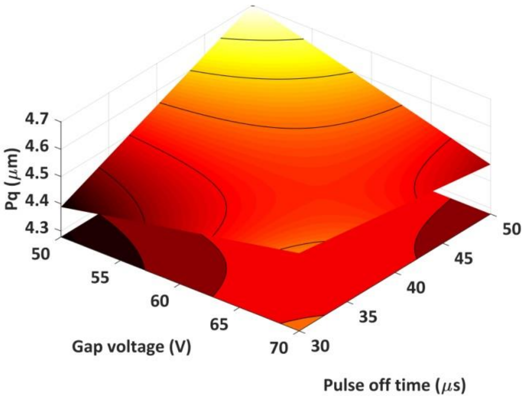

Figure 7. Surface plot between Gap Voltage and Pulse off time.

Fig. 7 shows the influence of the combination of gap voltage and pulse off time parameters on the *Pq* surface quality parameter. To analyse the interaction, it was necessary to freeze the pulse on time 6 µs, wire speed 10 m/min, and discharge current 25 A parameters, while based on optimisation, the gap voltage 50 V and pulse off time 30 µs combinationis the mostsuitable to achieve the predicted minimum value of Pq = 3.86 µm.

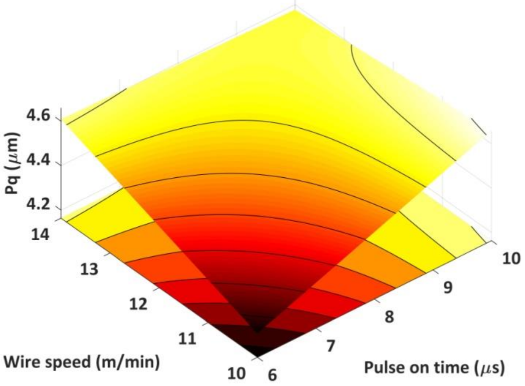

Figure 8. Contour plot for Ton and v parameters for Pq response

Using the contour plot (Fig. 8) when setting the values of gap voltage 60 V, pulse off time 40 µs, and discharge current 30 A, the ideal setting of pulse on time 6 µs and wire speed 10 m/min was found.

5. CONCLUSIONS AND DISCUSSION

Based on the design of experiment, 33 samples of pure aluminium 99.5 were produced, on which the surface quality parameters Pq and Pq were evaluated. The quality of the primary profile has not yet been dealt with in WEDM machining, so it is possible to compare the quality of the machined surface (aluminium alloys) only with profile parameters in studies such as Prasad [Prasad 2015], Rao [Rao 2014], Reddy [Reddy 2015], or Cheng [Cheng 2017], which also dealt with the machining of pure aluminium. The lowest value of Pq was reached at sample no. 33, being 3.97 µm. Using the regression analysis, a relationship was compiled to calculate this value based on the machine parameter settings. Furthermore, an optimisation was performed, during which a possible decrease of parameter PQ to 3.86 µm was achieved.

ACKNOWLEDGEMENTS

This research work was supported by the BUT, Faculty of Mechanical Engineering, Brno, Specific research 2016, with the grant 'Research of modern production technologies for specific applications', FSI-S-16-3717 and technical support of Intemac Solutions, Ltd., Kurim.

This work is an output of research and scientific activities of NETME Centre, supported through project NETME CENTRE PLUS (LO1202) by financial means from the Ministry of Education, Youth and Sports under the „National Sustainability Programme I“.

REFERENCES

[Abbas 2007] Abbas, N. M., Solomon, D. G., & Bahari, M. F. (2007). A review on current research trends in electrical discharge machining (EDM). International Journal of machine tools and Manufacture, 47(7), pp. 1214-1228.

[Blecha 2011a] Blecha, P.,Blecha,R.,Bradac,F.(2011). Integration of Risk Management into the Machinery Design Process.In Mechatronics Springer Berlin Heidelberg, pp. 473-482.

[Blecha 2011b] Blecha,P.,& Prostrednik, D.(2011).Influence on the failure probability. Annals of DAAAM&Proceedings, pp.11-13.

[Bobbili 2015] Bobbili, R., Madhu, V., & Gogia, A. K. (2015). Multi response optimisation of wire-EDM processparametersof ballistic grade aluminium alloy. Engineering Science and Technology, an International Journal, 18(4), pp. 720-726.

[Cheng 2017] Cheng, D., Shi, G., Shi, G., Xu, Z., & Zhu, K. (2017). Performance of the oxide film of pure aluminium processed by WEDM-HS. Micro & Nano Letters, 12(4), pp. 209-213.

[Ho 2004] Ho, K. H., Newman, S. T., Rahimifard, S., & Allen, R. D. (2004). State of the art in wire electrical discharge machining (WEDM). International Journal of Machine Tools and Manufacture, 44(12), pp. 1247-1259.

[ISO 4287] Geometrical Product Specifications (GPS) -Surface texture: Profile method -Terms, definitions and surface texture parameters. ISO 4287 (1997). Geneva: International Organisation for Standardisation.

[Jameson 2001] Jameson, E.C.(2001).Electrical discharge machining.Society of Manufacturing Engineers.ISBN 0-87263-521-X.

[Jiang 2012] Jiang, X. J., & Whitehouse, D. J. (2012). Technological shifts in surface metrology. CIRP Annals-ManufacturingTechnology, 61(2), pp. 815-836.

[Montgomery 2017] Montgomery, D. C. (2017).Design and analysis of experiments. John Wiley & Sons, Ninth edition, ISBN 9781119113478

[Mouralova 2015] Mouralova, K. (2015). MODERN TECHNOLOGIES IN WIRE ELECTRICAL DISCHARGE MACHINING THE METAL ALLOYS (in Czech: Moderni technologie dratoveho elektroerozivniho rezani kovovych slitin) Disseratation work. BUT, Brno, 98s.

[Prasad 2015] Prasad, D. S., Shoba, C., Varma, K. R., & Khurshid, A. (2015). Influence of wire EDM parameters on the damping behaviour of A356. 2 aluminium alloy. Journal of Alloys and Compounds, 646, pp. 257-263.

[Rao 2014] Rao, P. S., Ramji, K.,& Satyanarayana, B. (2014). Experimental investigation and optimisation of wire EDM parameters for surface roughness, MRR and white layer in machining of aluminium alloy. Procedia Materials Science, 5, pp. 2197-2206.

[Reddy 2015] Reddy, V. C., Deepthi, N., & Jayakrishna, N. (2015). Multiple Response Optimisation of Wire EDM on Aluminium HE30 by using Grey RelationalAnalysis. MaterialsToday: Proceedings, 2(4-5), pp. 2548-2554.

CONTACT:

Ing. Katerina Mouralova, Ph.D.
Brno University of Technology, Faculty of Mechanical Engineering
Technicka 2896/2, 616 69 Brno, Czech Republic
e-mail:mouralova@fme.vutbr.cz