EXPERIMENTAL ANALYSIS ON MACHINABILITY OF ALUMINUM ALLOY USING WEDM TECHNOLOGY

KATERINA MOURALOVA, JANA DVORAKOVA, JAROMIR DVORAK, JIRI KOVAR, ZDENEK KARPISEK, PETRA SLIWKOVA

Brno University of Technology,

Faculty of Mechanical Engineering, Brno, Czech Republic

DOI: 10.17973/MMSJ.2015_12_201549

e-mail: ymoura00@stud.fme.vutbr.cz

Wire electrical discharge machining (WEDM) is unconventional method commonly used for manufacturing of components with difficult shapes or profiles. It is very useful for machining very small – micro components with high dimensional accuracy and quality of surface finish. This technology allows even cutting of very hard materials, provided they are conductive. First part of this paper deals with machining aluminium alloy AlZn6Mg2Cu, setting of cutting parameters and measuring properties such as surface roughness and cutting width (kerf) of the machined samples. The second part is focused on studying of machining process using design of experiments (DOE) methods and analysis of variance (ANOVA), especially for identifying of key parameters that have influence on the WEDM process. The aim of this work is to explore the possibility, whether if by performing planned experiment and subsequent evaluation in the future allows determining exactly setting the key parameters influencing the process of WEDM.

KEYWORDS

WEDM, machining of Aluminium alloys, analysis of machinability, DOE, Analysis of variance ANOVA

1 INTRODUCTION

WEDM technology uses thermoelectric energy between the workpiece and an electrode of machine (wire) for material removing. In a small gap between the work piece and the electrode occurs a pulse discharge that removes the material from the workpiece through melting and vaporizing. This method is generally used for the production of complex shapes and for the manufacturing of materials that are difficult to machine by conventional machines. The only requirement for successful WEDM cutting process is minimal conductivity of machined material at least, but mechanical properties of the material have no influence on it. Thus this method is suitable for cutting super hard conductive materials, composites, ceramic or sandwiches with high accuracy and fine (low) surface roughness. However, despite the importance of WEDM manufacturing, it is necessary to be more economical than conventional machining to make it competitive. Overall, the electrical discharge machining is a compromise between productivity and quality machining. There are many variables that have some influence on WEDM cutting process. Each of them with different strength on production costs and final quality finish of workpiece. Therefore it should be useful to apply design of experiments. The DOE (Design of Experiments) consists of two main parts: own schedule of experiment and the statistical evaluation of designed plan. [Blecharz 2005] Evaluating of designed experiment ends with the decision, if tested factors have any influence at the monitored variables. The result of the experiment is a specific value of observed variable also called the dependent variable or response, which characterizes quality. [Bailey 2008] Many different variables operates on final quality. From the view of design of experiments they could be divided into random and explicite. The explicite variables are inputs (settings of WEDM machine) of machining process. Through analyzing all factors and their common interaction should be finally selected only those factors, that have statistically significant effect on the level of quality. [Kumar 2012] It allows to determine the optimal values of most important variables and on the other hand to determine which factors are irrelevant, so their tolerance can be reduced and thus reduce production costs also.

2 EXPERIENCES WITH CUTTING OF ALUMINIUM ALLOYS

Aluminium is a light metal with a very high electrical ($37.7\cdot10^{6}$ $S\cdot m^{-1}$) and thermal conductivity (237 $W\cdot m^{-1}\cdot K^{-1}$), sufficient tensile and compressive strength, together with excellent plasticity and a good weld ability. It is widely used in electronics. Aluminium alloys are mostly used in the automotive and aerospace industries, where the emphasis is on weight and mechanical properties. Machinability of pure aluminium is very poor in comparison with machinability of its alloys. Precipitates, soft particles and the degree of strain hardening have beneficial effect on machinability of aluminium alloys. Nonetheless despite of their mechanical properties, aluminium alloys are classified as problem-machinable materials, especially for dry machining. Problems are due to their high thermal conductivity, a low melting point (up to about 650 °C) and a strong tendency to adhere to the cutting edge of majority tool materials. During the machining process is due to the high thermal conductivity removed a considerable amount of heat from the cutting edge into the workpiece so the high thermal expansion of aluminium causes thermal deformation of the workpiece. The low melting point of aluminium alloys causes problems with chips formation and removal and with sticking of cut material onto the cutting tool. Thus it seems to be very useful to use unconventional method for machining aluminium. Because aluminium has high electrical conductivity should be suitable WEDM technology.

2.1 *Cutting of aluminium alloy AlZn6Mg2Cu*

Alloy Al-Zn-Mg-Cu is the hardest one. Alloy AlZn6Mg2Cu after thermal treatment achieves strength Rm 500-580 MPa. The shortcomings of these alloys include considerable tendency to stress corrosion, lower fracture toughness and higher notch sensitivity. For the series 7000 is the main alloying element zinc in an amount of 1-8 %. Through of Mg presence are these alloys after heat treatment the highest streng from all aluminium alloys. The main use is still in aviation and automotive industry.

3 EXPERIMENTAL ANALYSIS ON MACHINABILITY Al ALLOY AlZn6Mg2Cu BY WEDM

Samples for the experiment were prepared from aluminium alloy according to CSN 424222 AlZn6Mg2Cu having a chemical composition listed bellow see Table 1.

Labelling, norm	CSN EN 573-3	CSN	DIN 1725-1
numerical	EN AW - 7075	ČSN 424222	3.4365
chemical	EN AW – AlZn5,5MgCu	AlZn6MG2Cu	AlZn4,5MgCu1,5

Table 1. Labelling of aluminium alloys for forming, series 7000

The testing was performed on EDM wire cutting machine Makino EU64, which allows choose input parameters according to the material and height of the sample (work-piece). Tool material should be chosen from manual provided by the manufacturer. In this case was used brass wire PENTA CUT E with diameter size 0.25 mm made by company Penta Trading inc. Technical properties of wire see in Table 2.

Chemical composition		Tensile strength	colour	diameter
Cu [%]	Zn [%]	[N·mm^2]	[-]	[mm]
60	40	1000	gold	0.25

Table 2. Technical properties of used wire PENTA CUT E

The demineralised water was used as dielectric medium. The WEDM machine basic parts are a worktable, a servo controlling system, a power supply and dielectric supply system and a wire. The samples of material were clamped on the machine worktable with standard clamps. The machining parameters selection was performed in the course of preliminary tests. There were used different settings of gap voltage, pulse on time (T_{on}), pulse off time (T_{off}), wire speed of feed, discharge current. Each parameter has three levels as is shown in Table 3 and was changed every 3 mm.

parameter	Gap voltage	Pulse on time	Pulse off time	Wire speed	Discharge current
unit	[V]	[µs]	[µs]	[m/min]	[A]
Level 1	50	6	50	10	25
Level 2	60	8	40	12	30
Level 3	70	10	30	14	35

Table 3. Machining parameters used in the experiments

There were made 27 experimental cuts on 3 samples from Alloy AlZn6Mg2Cu with thickness 53 mm as is shown in picture 1.

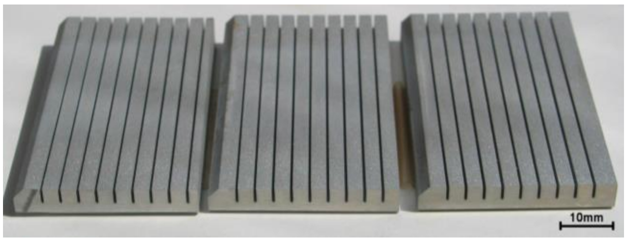

Figure 1. Alluminium alloy samples with experimental cuts

After that the cutting speed was evaluated and properties such as cutting width (kerf) and surface roughness of the machined samples were measured also.

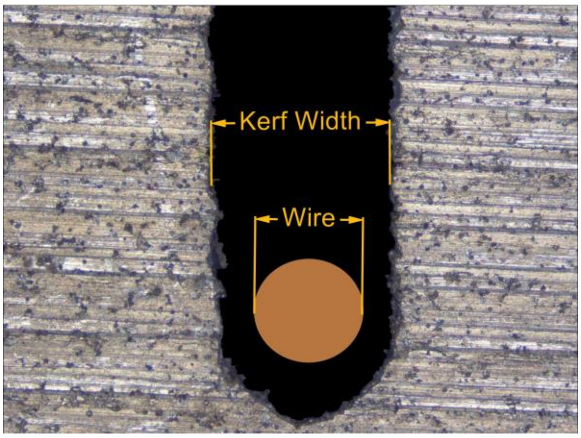

Figure 2. Width (kerf) of the machined sample measured with Alicona

The width of kerf together with material removal rate is the most important indicator of WEDM technology success. The main goal is to set machining parameters in order that is obtained maximum material removal rate together with minimum width of kerf. [Tarng 1995] In this study was obtained relative wide and not typical width of kerf about 0.5 mm so this special phenomenon should be a subject to further examination. Another important indicator of WEDM efficiency is surface roughness. A detailed analysis of the surfaces roughness in kerf after WEDM process was made with Alicona measuring instrument (see figures 3. to 7.).

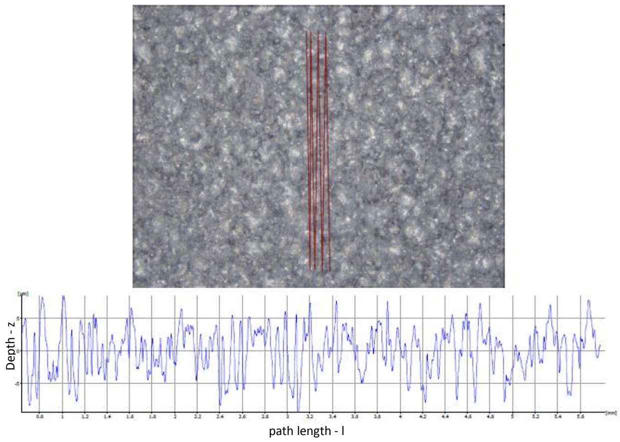

Figure 3. Profile measurement with Alicona measuring instrument

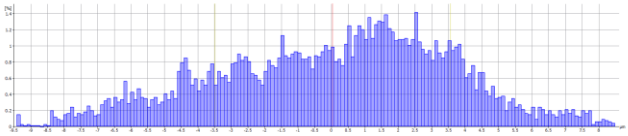

Figure 4. Histogram of roughness par. of profile measured by Alicona

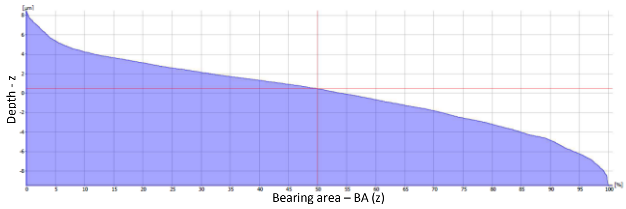

Figure 5. Profile measurement, bearing Ratio/firestone-abbott curve of roughness profile measured by Alicona

Figure 6. Measurement of profile roughness Ra by Alicona

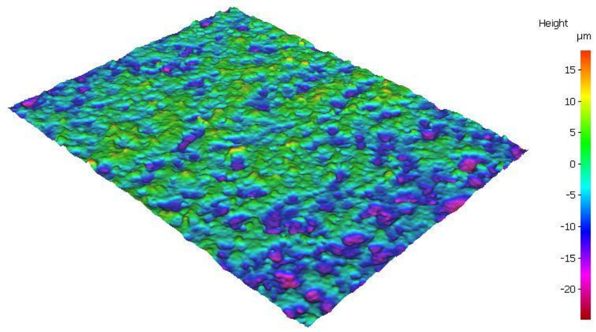

Figure 7. Filtered profile roughness Ra with Lc 800µm made by Alicona

All machining and measured parameters are listed in table 4.

Exp. n.	Gap voltage [V]	Pulse on time [µs]	Pulse off time [µs]	Wire speed [m/min]	Discharge current [A]	Cutting speed [mm/min]	Width of kerf [µm]	Ra [µm]
1	50	6	50	10	25	1.55	470.67	2.898
2	50	6	40	12	30	1.95	481.23	3.334
3	50	6	30	14	35	2.5	506.73	2.240
4	50	8	50	12	35	2	513.01	2.949
5	50	8	40	14	30	2	497.94	2.815
6	50	8	30	10	25	2.25	479.46	3.244
7	50	10	50	14	30	1.9	504.11	3.097
8	50	10	40	10	35	2.6	529.78	3.263
9	50	10	30	12	25	2.35	473.17	3.299
10	60	6	50	10	25	1.58	470.68	3.317
11	60	6	40	12	30	1.97	464.51	2.818
12	60	6	30	14	35	2.6	509.49	2.803
13	60	8	50	12	35	2.1	529.61	2.586
14	60	8	40	14	25	1.95	479.46	3.355
15	60	8	30	10	30	2.6	506.74	3.137
16	60	10	50	14	30	1.95	484.77	3.336
17	60	10	40	10	35	2.65	526.53	3.136
18	60	10	30	12	25	2.45	468.90	3.329
19	70	6	50	10	25	1.6	455.71	2.899
20	70	6	40	12	30	2	481.22	2.852
21	70	6	30	14	35	2.7	516.72	3.185
22	70	8	50	12	35	2.15	508.50	2.781
23	70	8	40	14	25	2.05	466.35	3.153
24	70	8	30	10	30	2.65	485.65	2.651
25	70	10	50	14	30	2	499.70	2.996
26	70	10	40	10	35	2.75	525.26	3.768
27	70	10	30	12	25	2.52	475.08	2.698

Table 4. Machining parameters used in the experiments

4 ANALYSIS OF VARIANCE (ANOVA)

Results of made experiments were studied by using the analysis of variance. It is useful method for verification of existence and intensity any influence of the machining parameters on the material removal process and surface quality (roughness, shape and dimensional accuracy, etc.). Due to Multiple-variable analysis should be determined which combinations of the variables determine most of the variability in data.

95% confidence intervals	mean	Stnd. error	Lower limit	Upper limit
Cutting speed	2.19889	0.0696927	2.05563	2.34214
Width of kerf	492.999	4.28231	484.197	501.802
Ra	3.03478	0.0608585	2.90968	3.15987

Table 5. 95.0% confidence intervals for the means and standard deviations of each of the variables

	Cutting speed	Width of kerf	Ra
Cutting speed		0.5480	0,0369
		(27)	(27)
		0.0031	0.8551
Width of kerf	0.5480		-0.0367
	(27)		(27)
	0,0031		0.8560
Ra	0.0369	-0.0367	
	(27)	(27)	
	0.8551	0.8560	

3,03478

Table 6. Pearson product moment correlations between each pair of variables

These correlation coefficients listed in table 6. measure the strength of the association between the variables. P-value 0.0031 between pair of variables cutting speed and width of kerf indicates statistically significant non-zero correlation at the 95.0% confidence level.

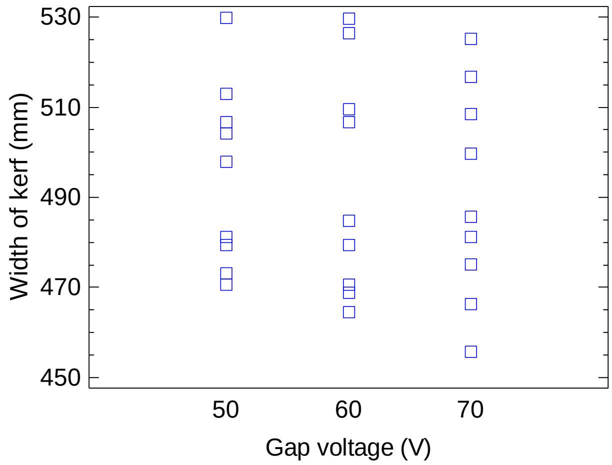

Figure 8. Scatterplot by level code

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
MAIN EFFECTS					
A:Gap voltage	99.858	2	49.929	0.72	0.5017
B:Pulse on time	1091.09	2	545.543	7.87	0.0042
C:Pulse off time	3.56337	2	1.78168	0.03	0.9747
D:Wire speed	320.442	2	160.221	2.31	0.1312
E:Discharge current	10219.6	2	5109.79	73.73	0.0000
RESIDUAL	1108.89	16	69.3059		
TOTAL (CORRECTED)	12873.4	26			

Table 7. Analysis of Variance for Width of kerf - Type III Sums of Squares

The analysis ANOVA that is shown in table 7. decomposes the variability of width of kerf into contributions due to various factors. Only variables pulse on time and discharge current have a statistically significant effect on width of kerf at the 95.0% confidence level.

3,03478 0,0608585 2,90968 3,15987

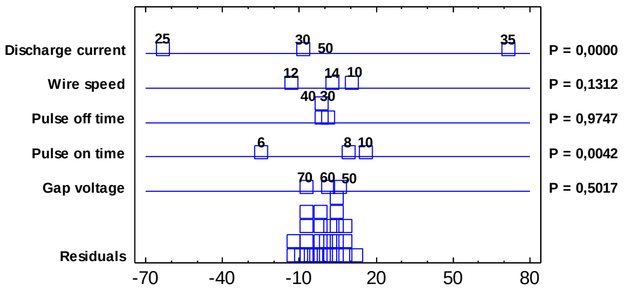

Figure 9. Graphical ANOVA for width of kerf

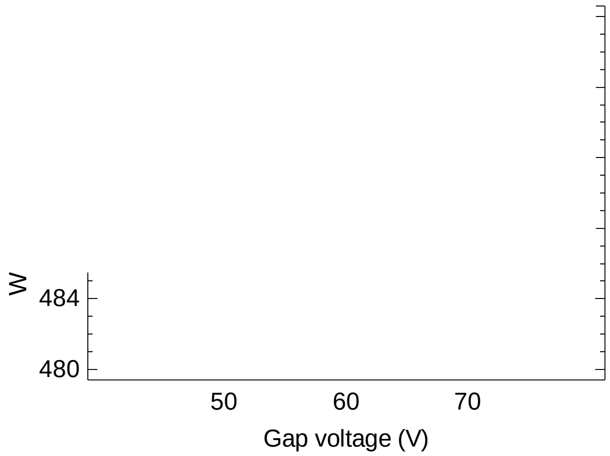

Figure 10. Means and 95.0 % LSD intervals

A multiple comparison procedure was made also to determine which means are significantly different from which others. There are no statistically significant differences between any pair of means at the 95.0% confidence level. The method currently being used to discriminate among the means is Fisher's least significant difference (LSD) procedure.

A multifactor analysis of variance for Ra was made for constructing of various tests and graphs to determine which factors have a statistically significant effect on Ra.

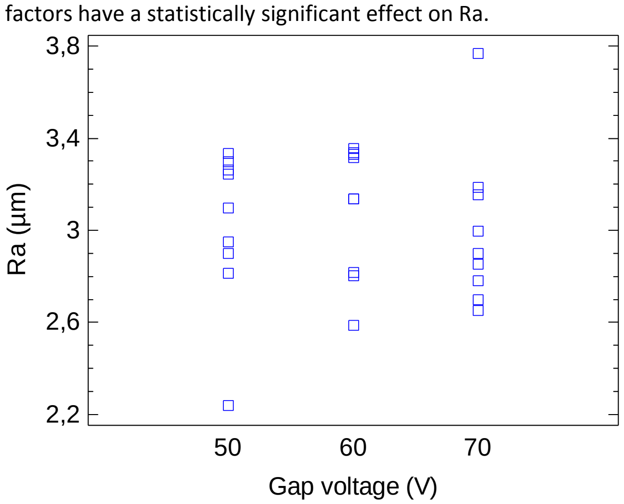

Figure 11. Scatterplot by level code

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
MAIN EFFECTS					
A:Gap voltage	0.043688	2	0.021844	0.23	0.8003
B:Pulse on time	0.437348	2	0.218674	2.26	0.1365
C:Pulse off time	0.294994	2	0.147497	1.52	0.2476
D:Wire speed	0.128565	2	0.0642825	0.66	0.5281
E:Discharge current	0.161995	2	0.0809975	0.84	0.4509
RESIDUAL	1.54754	16	0.0967212		
TOTAL (CORRECTED)	2.60003	26			

Table 8. Analysis of Variance for Ra - Type III Sums of Squares

Since no P-values are less than 0.05 as is shown in the table 8., none of the factors have a statistically significant effect on Ra at the 95.0% confidence level.

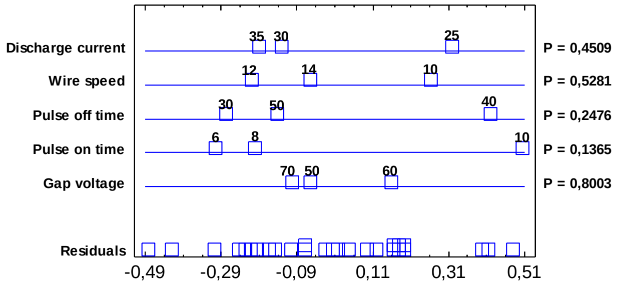

Figure 12. Graphical ANOVA for Ra

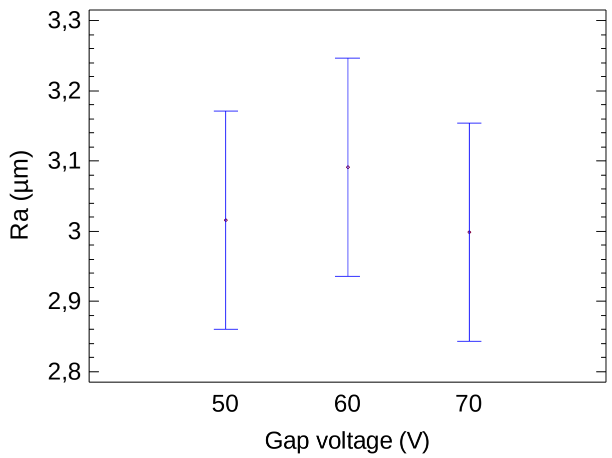

Figure 13. Means and 95.0 % LSD intervals - shows the mean Ra for each level of the factors

A multifactor analysis of variance for cutting speed constructs various tests and graphs to determine which factors have a statistically significant effect on cutting speed. It also tests for significant interactions amongst the factors, given sufficient data.

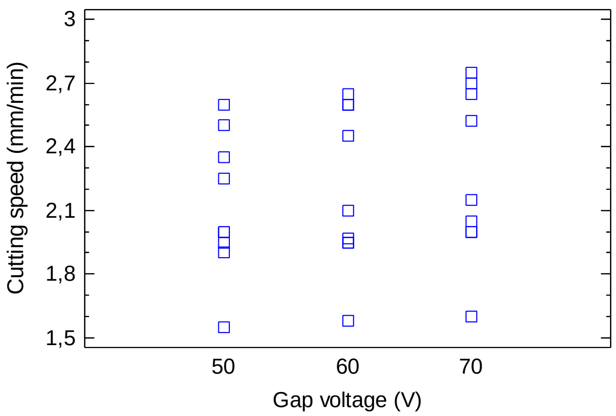

Figure 14. Scatterplot by level code

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
MAIN EFFECTS					
A:Gap voltage	0.0974	2	0.0487	2.02	0.1948
B:Pulse on time	0.411289	2	0.205644	8.53	0.0104
C:Discharge current	0.880067	2	0.440033	18.26	0.0010
INTERACTIONS					

AB	0.00924444	4	0.00231111	0.10	0.9809
AC	0.0744	4	0.0186	0.77	0.5729
BC	1.74451	4	0.436128	18.10	0.0005
RESIDUAL	0.192756	8	0.0240944		
TOTAL (CORRECTED)	3.40967	26			

Table 9. Analysis of Variance for Cutting speed - Type I Sums of Squares

This table 9. decomposes the variability of Cutting speed into contributions due to various factors. Since Type I sums of squares have been chosen, the contribution of each factor is measured having removed the effects of factors above it in the table. Since 3 P-values are less than 0.05, these factors have a statistically significant effect on Cutting speed at the 95.0% confidence level.

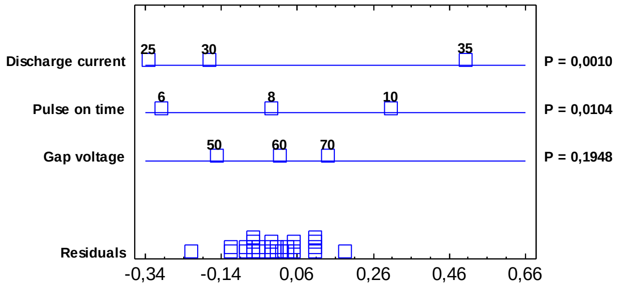

Figure 15. Graphical ANOVA for cutting speed

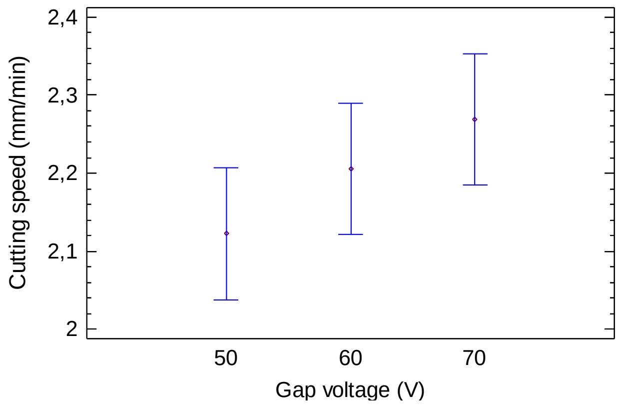

Figure 16. Means and 95.0 % LSD intervals shows the mean cutting speed for each level of the factors

Gap voltage	Count	LS Mean	LS Sigma	Homogeneous Groups
50	9	2.12222	0.0517413	X
60	9	2.20556	0.0517413	X
70	9	2.26889	0.0517413	X

Table 10. Multiple Range Tests for Cutting speed by Gap voltage

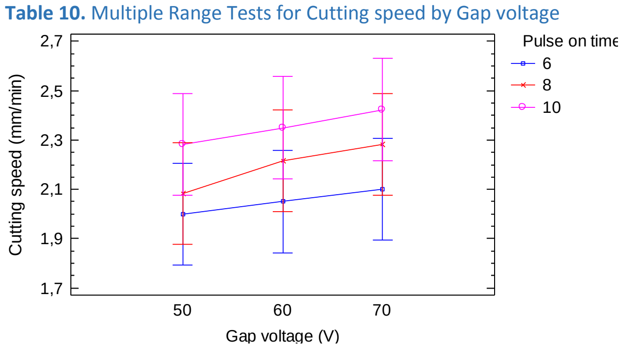

Figure 17. Interactions and 95.0 % confidence intervals

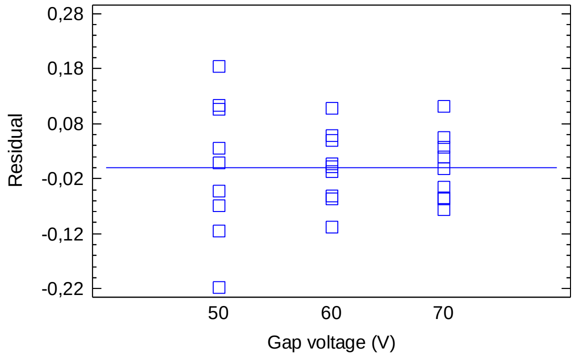

Figure 18. Residual plot for cutting speed

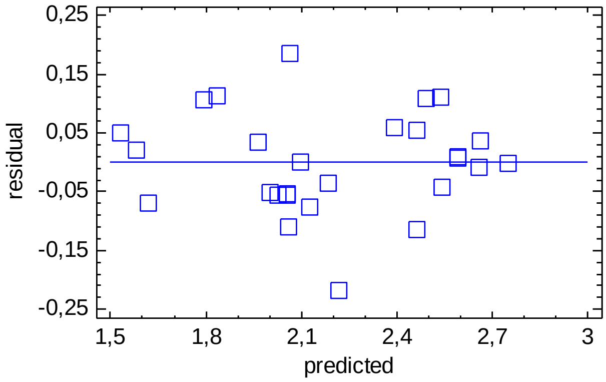

Figure 19. Residual plot for cutting speed

Simple regression was used to describe the relationship between cutting speed and width of kerf also. The dependent variable was cutting speed and the independent one was width of kerf. The equation of the fitted model is:

$$\text{Cutting speed} = -2.19807 + 0.00891879 \cdot \text{Width of kerf} \quad (1)$$

	Least Squares	Standard	T	
Parameter	**Estimate**	**Error**	**Statistic**	**P-Value**
Intercept	-2.19807	1.34357	-1.636	0.1144
Slope	0.00891879	0.00272262	3.27581	0.0031

Table 11. Coefficients of simple regression

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Model	1.02401	1	1.02401	10.73	0.0031
Residual	2.38565	25	0.0954262		
Total (Corr.)	3.40967	26			

Table 12. Analysis of variance

Results of fitting a linear model:
Correlation Coefficient = 0.54802
R-squared = 30.0326 %
R-squared (adjusted for d.f.) = 27.2339 %
Standard Error of Est. = 0.308911
Mean absolute error = 0.264205
Durbin-Watson statistic = 2.24928 (P=0.7388)
Lag 1 residual autocorrelation = -0.215507

Since the P-value in the ANOVA table is less than 0.05, there is a statistically significant relationship between Cutting speed and Width of kerf at the 95.0% confidence level. The R-Squared statistic indicates that the model as fitted explains 30.0326 % of the variability in Cutting speed. The correlation coefficient equals 0.54802, indicating a moderately strong relationship between the variables. The standard error of the estimate shows the standard deviation of the residuals to be 0.308911.

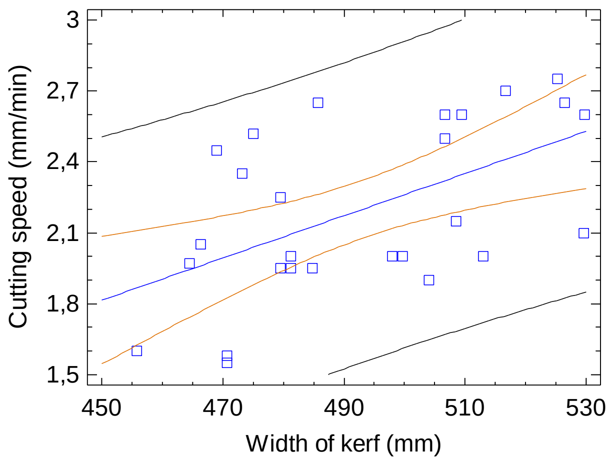

Figure 20. Plot of fitted linear model

5 CONCLUSIONS

The application of statistical analysis methods [Matousek 2010] together with design of experiments is simple, effective and efficient in developing a robust and variously used WEDM process. From the experimental results, simple regression and ANOVA analysis of machining parameters, the following conclusions were made:

- Parameter with the most important influence on cutting process and especially on the width of kerf is cutting speed.
- The pulse on time together with discharge current and gap voltage are parameters which significantly affects the width of kerf and surface roughness also.

All results obtained in this study were in agreement with findings in literature where width of kerf depends on gap voltage, pulse on time, pulse off time, wire feed and cutting speed [Parashar 2010, Prakash 2013, Rao 2010, Selvakumar 2014, Tosun 2003,].

ACKNOWLEDGEMENTS

This research work was supported by the BUT, Faculty of Mechanical Engineering, Brno, Specific research 2013, with the grant "Reseach of advanced technologies for competitive machinery", FSI-S-13-2138, ID 2138 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".

The paper is a part of research project of the ACADEMY STING named IGA_AS_03 "Support of Business Management".

REFERENCES

[Bailey 2008] Bailey, R. A. Design of Comparative Experiments. Cambridge University Press (2008). ISBN 978-0-521-68357-9.

[Blecharz 2005] Blecharz, P. Basic methods of DOE (Taguchi´s wiew). 1.edition. Ostrava: Repronis pro P. Q. M., Czech-Swiss i.n.c., 2005. 124 p. ISBN 80-7329-106-1 (original in Czech language).

[Kumar 2012] Kumar, K., Agarwal, S., Multi-objective parametric optimization on machining with wire electric discharge machining, International Journal of Advance Manufacturing Technology (2012) 62:617–633.

[Manna 2006] Manna, A., Bhattacharyya, B., (2006) Tagucha and Gauss elimination method : a dual response approach for parametric of CNC wire cut EDM of PRAISiCMMC. Int. J Adv Manuf Tehcnol 28(1-2) :67-75. ISSN :0268-3768.

[Matousek 2010] Matousek, R., Bednar, J., (2010) Grammatical evolution and STE criterion: Statistical properties of STE objective function, Lecture Notes in Electrical Engineering, vol 68, pp 131–142, doi: 10.1007/978-90-481-9419-3_11.

[Parashar 2010] Parashar, V., Rehman, A., Bhagoria, J.L., Puri, Y.M., Kerfs width analysis for wire cut electro discharge machining of SS 304L using design of experiments, ISSN 0974-5645, Indian Journal of Science and Technology, Vol. 3 No. 4, Apr. 2010, pp. 369-373.

[Prakash 2013] Prakash, J.Udaya, T.V. Moorthy a J. Milton Peter. Experimental Investigations on Machinability of Aluminium Alloy (A413)/Flyash/B4C Hybrid Composites Using Wire EDM. Procedia Engineering. 2013, vol. 64, s. 1344-1353.

[Rao 2010] Rao, P. S., Ramji, K., Satyanarayan, B., A Prediction of Material removal rate for Aluminum BIS-24345 Alloy in wire-cut EDM, International Journal of Engineering Science and Technology, 2 (12) (2010), pp. 7729–7739.

[Selvakumar 2014] Selvakumar, G., Sornalatha, G. S., Sarkar, S., Mitra, S., Experimental investigation and multi-objective optimization of wire electrical discharge machining (WEDM) of 5083 aluminum alloy. ISSN: 1003-6326 Transactions of Nonferrous Metals Society of China, Elsevier, Vol. 24, pp. 373-379. (DOI: 10.1016/S1003-6326(14)63071-5)

[Sharma 2014] Sharma, A., Pal Garg, M., Kapil Kumar Goyal K. K., Prediction of optimal conditions for WEDM of Al 6063/ ZrSiO4 (p) MMC, Procedia Materials Science 6 (2014) 1024 – 1033.

[Tarng 1995] Tarng, Y.S., Ma, S.C., Chung, L.K. (1995) Determination of optimal cutting parameters in wire electrical discharge machining. Int J Mach Tools Manuf 35(129):1693–1700.

[Timings 2000] Timings, R. L., Wilkinson, S. P., 2000. Manufacturing Technology, Volume 2. Pearson Education.

[Tosun 2003] Tosun, N., Cogun, C., Pihtili, H., (2003) The effect of cutting parameters on wire crater sizes in wire EDM. Int. Journal of Advanced Manufactoring Technology 21:857–865.

CONTACTS

Ing. Katerina Mouralova, Ph.D.
Brno University of Technology, Faculty of Mechanical Engineering
Technicka 2896/2, 616 69 Brno, Czech Republic
e-mail: ymoura00@stud.fme.vutbr.cz

Corresponding author:
Ing. Jana Dvorakova, Ph.D.
Brno University of Technology, Faculty of Mechanical Engineering
Technicka 2896/2, 616 69 Brno, Czech Republic
Phone: +420 54114 2556, e-mail: dvorakova.j@fme.vutbr.cz