EVALUATION OF S-PARAMETERS ON THE SURFACE OF TITANIUM ALLOY TI-6AL-4V AND AL99.5 MACHINED BY WEDM

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Efficient machining using the technology of wire electrical discharge machining (WEDM) is a compromise between cutting speed and surface quality. Typical morphology of WEDM processed surface features plenty of craters caused by electro-spark discharges produced during the cutting process. The study deals with the evaluation of S-parameters enabling quantitative evaluation of the surface in all directions which are technically significant. Attention was also paid to surface morphology and its evaluation using 3D colour-filtered and unfiltered images. The experiment included 33 variants of setting machine parameters on samples made of two metallic materials: Al 99.5 and Ti-6Al-4V.

KEYWORDS

WEDM, electrical discharge machining, titanium alloy Ti-6Al-4V, aluminium Al 99.5, S-parameters

1 INTRODUCTION

Electrical discharge machining (electroerosion) is a physical process of material removal, occurring simultaneously on two electrodes during immersion in the working medium. This medium is always dielectric, a liquid with high electrical resistance. The emergence of electric discharge between the electrodes is induced by applying voltage to the electrodes. The material is flung out from the place of discharge and its microscopic particles are flushed away by the dielectric [Jameson 2001]. Morphology of thus machined surface is comprised of a plurality of craters. There are many factors that have a major impact on the quality of surface finish and can be found using different methods [Matousek 2009], [Matousek 2010], [Blecha 2011], [Blecha 2011].

In electrical discharge machining, conventional cutting forces do not occur – this allows machining of all electrically conductive materials irrespective of their hardness, toughness and mechanical properties. Workpieces can thus be machined to final dimensions after the heat treatment. This can prevent dimensional and volume changes of the components. Electroerosion can be used for machining a wide range of materials, from PCD-coated tools, through ceramics, composite materials and silicon to soft aluminum alloys used in the aerospace industry. EDM allows machining of soft materials without any deformation because the workpiece is not exposed to any mechanical load [Ghodsiyeh 2013].

[Miller 2004] presented a study for the optimization of cutting parameters which were effective for material removal rate and surface finish. The surface finish increased on with increasing the discharge current, pulse duration, and wire speed. [Hewidy 2005] modelled the machining parameters of wire electrical discharge machining of Inconel-601 using RSM. It was concluded that the volumetric metal removal rate generally increased with the increase of the peak current value and water pressure. [Mahapatra 2007] optimized the parameters using Taguchi method on D2 tool steel as work material in WEDM process. It was observed that discharge current, pulse duration, dielectric flow rate, and the interaction between discharge current and pulse duration were the most significant parameters for cutting operation. Mathematical models were developed for optimization of MRR and surface finish using nonlinear regression method. [Manna 2006] optimized the machining parameters using the Taguchi and Gauss elimination method. The test results concluded that the voltage and pulse on time were the most significant parameters for controlling the metal removal rate. [Ramakrishnan 2006] used Taguchi's robust design approach for WEDM. The three responses, namely, material removal rate, surface roughness, and wire wear ratio were considered. [Sadeghi 2011] discussed effects of process parameters on surface roughness and metal removal rate in WEDM of AISI D5 steel alloy. It was found that discharge current and pulse interval were more significant for MRR and surface roughness than open circuit voltage. [Rao 2009] proposed the mathematical models using response surface modelling (RSM) for correlating the interrelationships of various WEDM parameters such as pulse on time, pulse off time, peak current, and servo feed setting on the machining speed and surface roughness. [Yu 2011] explored the study on polycrystalline silicon material using WEDM process to optimize the groove width, surface roughness, and cutting speed. The results showed that pulse on time was the most significant factor for cutting speed, surface roughness, and groove width. [Yang 2012] analyzed the variations in metal removal rate, surface roughness average, and corner deviation (CD) of wire electrical discharge machining process in relation to the cutting of pure tungsten profiles.

2 EXPERIMENTAL SETUP AND MATERIAL

2.1 Experimental material

Samples for the experiment were made from pure aluminum Al 99.5 and titanium alloy Ti-6Al-4V.

Aluminium Al 99.5 is a material with low density. Its undeniable advantages include excellent corrosion resistance, good weldability and suitability for anodizing with a hardness of 20 to 42 HBS, tensile strength of 65-160 MPa and chemical composition according to Tab. 1. It is used in almost all sectors of industry for structural elements and nodes subjected to low mechanical stress, requiring high formable material, highly corrosion resistant, very well thermally and electrically conductive. It is weldable in almost all ways. The experiment used a semi-finished steel rod with diameter of 20 mm, from which a prism was made by electrical discharge machining.

Contents	Si	Fe	Cu	Zn	Ti
Max (wt.%)	0.3	0.4	0.05	0.07	0.05

Table 1. Chemical composition of aluminium Al 99.5 prescribed by the norm

Titanium alloy Ti-6Al-4V with a chemical composition according to Tab. 2 was used in two sets. The first set – material without subsequent heat treatment, the second set – heat treatment, see Tab. 3. This alloy has a high tensile strength (900 MPa) and excellent resistance to corrosion. It has the highest strength-density ratio of all metallic materials. It features high biocompatibility and ability to withstand thermal loads up to the temperature of 315 °C. The alloy is used for manufacturing structural components of weapons and aircrafts, turbine blades, fasteners, medical and dental implants, and sports equipment. The experiment used a semi-finished prism with a thickness of 18 mm.

Contents	Al	Fe	O	V
Min (wt.%)	5.5			3.5
Max (wt.%)	6.75	0.25	0.2	4.5
Type of HT	Heat treatment (HT)			
1	Quenched and tempered 940 °C / 45' / water 500 °C / two hours / air			

Table 2. Chemical composition of titanium alloy Ti-6Al-4V prescribed by the norm and one type of heat treatment

2.2 Wire EDM machine setup

The WEDM machine used in this study was high precision five axis CNC machine MAKINO EU64. As electrode, brass wire (60 % Cu and 40 % Zn) PENTA CUT E with a diameter of 0.25 mm was used. Samples were immersed in the deionized water which served as dielectric media and also removed debris in the gap between the wire electrode and workpiece during the process. For each of the 33 samples made from different materials, different settings of the parameters (gap voltage, pulse on (T_{on}) and off time (T_{off}), wire feed and discharge current) were used to determine their effects on the machined surface (Tab. 3). Values of individual parameters were determined on the basis of previous tests [Mouralova 2015].

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 3. Machining parameters used in the experiments

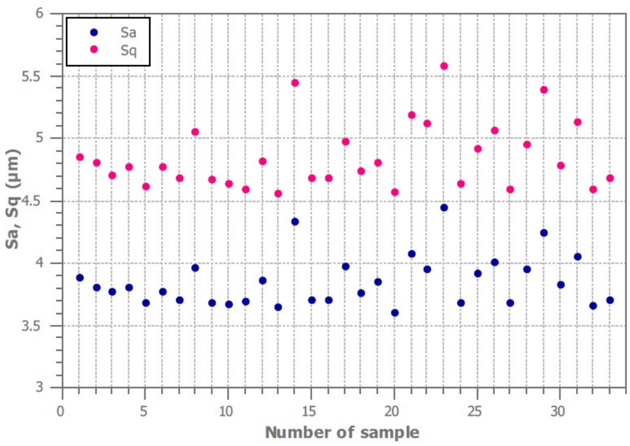
3 RESULTS OF EXPERIMENT

Surface morphology, surface and profile parameters of the machined surface were studied using IFM G4 contactless measuring apparatus from Alicona. The measured data were analyzed using IF-Laboratory Measurement software supplied by the manufacturer Alicona.

Surface method was used to evaluate the following parameters: arithmetical mean height (Sa), root mean square height (Sq), maximum peak height (Sp), maximum pit height (Sv), maximum surface height (Sz), kurtosis (Sku), root mean square gradient (Sdq) and developed interfacial area ratio (Sdr). All the parameters were measured along a curve 10 mm long when using a 10x objective. Surface parameters enable quantitative evaluation of the surface in all directions which are technically significant. The surface quality evaluation allows us to draw up the overall shape of the surface, the general texture, and thus better predict the functional properties of surfaces during operation. For example, the profile evaluation uses three parameters (Ra, Pa, Wa) for arithmetical mean deviation while surface evaluation uses only parameter Sa [Jiang 2012].

3.1 Results of measuring S-parameters in aluminium Al 99.5

Surface parameters Sa and Sq measured on the surface of samples made of aluminum Al 99.5 are processed in Graph 1. In this set of samples, the average Sa and Sq values were 3.85 µm and 4.85 µm, respectively. The highest value of Sa (4.45 µm) and Sq (5.58 µm) was found in sample 23 machined with the following parameters: voltage=70 V, T_{on}=10 µs, T_{off}=30 µs, current=25 A; its surface morphology is shown in Fig. 1.



Graph 1. Surface parameters of samples made of Al 99.5

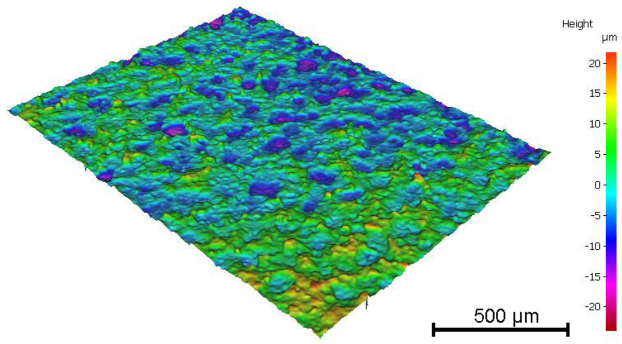
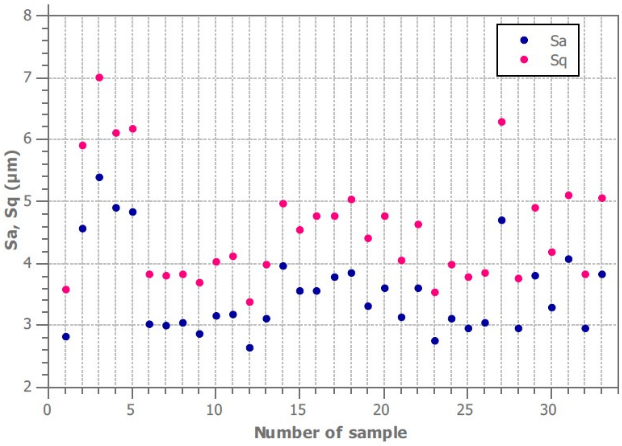


Figure 1. Colour-filtered image of the surface of sample 23 made of Al 99.5, magnified 10x, voltage =70 V, T_{on}=10 µs, T_{off}=30 µs, wire feed=14 m/min, current=25 A

3.2 Results of measuring S-parameters in titanium alloy Ti-6Al-4V

Values of surface parameters Sa and Sq measured on the surface of the set of samples made of titanium alloy Ti-6Al-4V are processed in Graph 2.



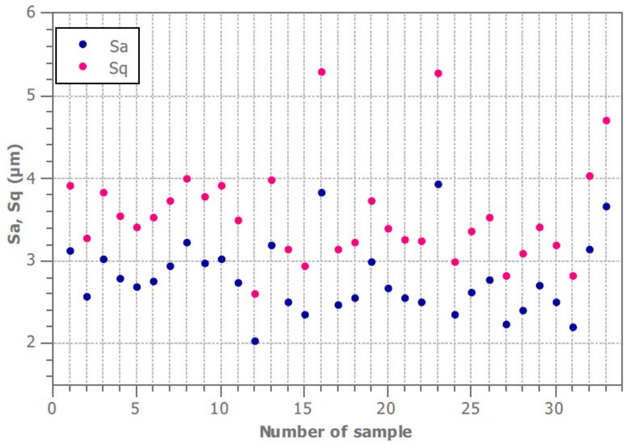
Graph 2. Surface parameters of samples made of Ti-6Al-4V

Interval of values for parameter Sa ranged from 2.64 µm to 5.4 µm measured on sample 3. Average value of Sa and Sq was 3.53 µm and 4.54 µm, respectively. The lowest Sa (2.64 µm) as well as Sq (3.39 µm) value was found in sample 12; its colour-unfiltered image is shown in Fig. 2.

Figure 2. Colour-unfiltered image of the surface of sample 12 made of Ti-6Al-4V, magnified 10x, voltage=50 V, T_{on}=6 µs, T_{off}=30 µs, wire feed=10 m/min, current=35 A

Surface parameters Sa and Sq measured on the surface of the set of 33 samples made of titanium alloy Ti-6Al-4V with subsequent heat treatment (quenched and tempered) were processed in Graph 3.

In this set of samples, the average Sa and Sq value was 2.75 µm and 3.56 µm, respectively. These average values were best achieved in sample 5; a colour-filtered image of its surface is shown in Fig. 3.



Graph 3. Surface parameters of samples made of Ti-6Al-4V with heat treatment

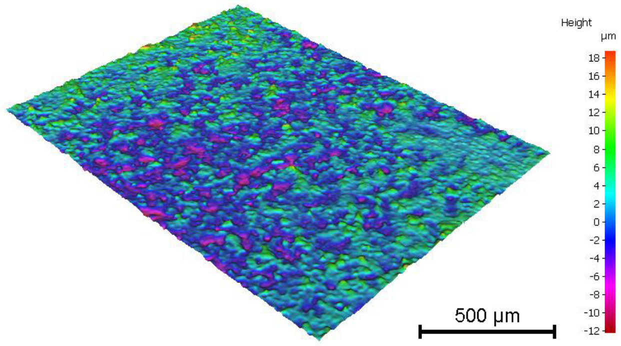
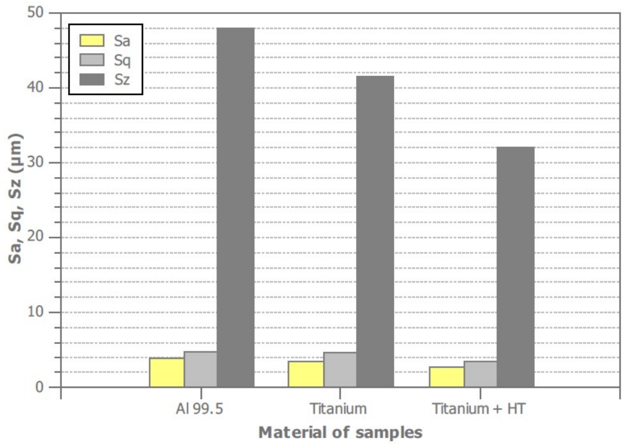


Figure 3. Colour-filtered image of the surface of sample 5 made of Ti-6Al-4V with heat treatment, magnified 10x, voltage=50 V, T_{on}=8 µs, T_{off}=40 µs, wire feed=12 m/min, current=30 A

4 CONCLUSIONS AND DISCUSSION

EDM-machined surface morphology is made up of a large amount of craters [Han 2007], [Tosun 2003]. Dimensions of thus formed craters are decisive for evaluating surface quality parameters. The values of surface parameters are dependent not only on the machine setting parameters [Kumar 2013] but also on the mechanical and physical properties of the machined material. For all samples, the measured average Sa, Sq and Sz values are shown in Graph 4. These results are consistent with the literature [Tian 2015], [Ramasawmy 2004].



Graph 4. Average value of surface parameters Sa, Sq and Sz

The highest average value of Sz parameters, 49 µm, was observed in samples made of aluminium Al 99.5. High Sz values are clearly associated with a low melting point of the material, low strength and relatively large grain size of the Al workpiece. Graph 4 shows that the titanium alloy, after subsequent heat treatment (quenched and tempered), exhibits by 10 µm lower average Sz value than samples from the same material without the heat treatment. This fact is entirely consistent with a coarser microstructure of the titanium sample after heat treatment. Average value of Sa and Sq parameters was highest for samples made of Al 99.5, and lowest in samples from titanium alloy Ti-6Al-4V with subsequent heat treatment.

The above experiments show that the surface quality parameters Sa, Sq and Sz very strongly depend not only on the chemical composition of the machined material and machine setting parameters but also on the mechanical parameters of the machined material affected by heat treatment.

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REFERENCES

[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.

[Ghodsiyeh 2013] Ghodsiyeh, D., Golshan, A., & Shirvanehdeh, J. A. (2013). Review on current research trends in wire electrical discharge machining (WEDM). Indian journal of science and technology, 6(2), pp. 4128-4140.

[Han 2007] Han, F., Jiang, J., & Yu, D. (2007). Influence of machining parameters on surface roughness in finish cut of WEDM. The International Journal of Advanced Manufacturing Technology, 34(5-6), pp. 538-546.

[Hewidy 2005] Hewidy, M. S., El-Taweel, T. A., & El-Safty, M. F. (2005). Modelling the machining parameters of wire electrical discharge machining of Inconel 601 using RSM. Journal of Materials Processing Technology, 169(2), pp. 328-336.

[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-Manufacturing Technology, 61(2), pp. 815-836.

[Kumar 2013] Kumar, A., Kumar, V., & Kumar, J. (2013). Multi-response optimization of process parameters based on response surface methodology for pure titanium using WEDM process. The International Journal of Advanced Manufacturing Technology, 68(9-12), pp. 2645-2668.

[Mahapatra 2007] Mahapatra, S. S., & Patnaik, A. (2007). Optimization of wire electrical discharge machining (WEDM) process parameters using Taguchi method. The International Journal of Advanced Manufacturing Technology, 34(9-10), pp. 911-925.

[Manna 2006] Manna, A., & Bhattacharyya, B. (2006). Taguchi and Gauss elimination method: a dual response approach for parametric optimization of CNC wire cut EDM of PRAlSiCMMC. The International Journal of Advanced Manufacturing Technology, 28(1-2), pp. 67-75.

[Matousek 2009] Matousek, R., Bednar, J. (2009) Grammatical Evolution: Epsilon Tube in Symbolic Regression Task. In MENDEL 2009, Mendel Journal series. MENDEL. Brno, BUT. pp. 9 - 15. ISBN 978-80-214-3884-2, ISSN 1803-3814.

[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.

[Miller 2004] Miller, S. F., Shih, A. J., & Qu, J. (2004). Investigation of the spark cycle on material removal rate in wire electrical discharge machining of advanced materials. International Journal of Machine Tools and Manufacture, 44(4), pp. 391-400.

[Mouralova 2015] Mouralova, K. (2015). MODERN TECHNOLOGIES IN WIRE ELECTRICAL DISCHARGE MACHINING THE METAL ALLOYS (in Czech) Disseratation work. BUT, Brno, 98p.

[Ramakrishnan 2006] Ramakrishnan, R., & Karunamoorthy, L. (2006). Multi response optimization of wire EDM operations using robust design of experiments. The International Journal of Advanced Manufacturing Technology, 29(1-2), pp. 105-112.

[Ramasawmy 2004] Ramasawmy, H., & Blunt, L. (2004). Effect of EDM process parameters on 3D surface topography. Journal of Materials Processing Technology, 148(2), pp. 155-164.

[Rao 2009] Rao, R. V., & Pawar, P. J. (2009). Modelling and optimization of process parameters of wire electrical discharge machining. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 223(11), pp. 1431-1440.

[Sadeghi 2011] Sadeghi, M., Razavi, H., Esmaeilzadeh, A., & Kolahan, F. (2011). Optimization of cutting conditions in WEDM process using regression modelling and Tabu-search algorithm. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 225(10), pp. 1825-1834.

[Tian 2015] Tian, Y., Liu, X., & Qi, H. (2015). Generation of stainless steel superhydrophobic surfaces using WEDM technique. In International Symposium on Precision Engineering Measurement and Instrumentation, International Society for Optics and Photonics.

[Tosun 2003] Tosun, N., & Pihtili, H. (2003). The effect of cutting parameters on wire crater sizes in wire EDM. The International Journal of advanced manufacturing technology, 21(10-11), pp. 857-865.

[Yang 2012] Yang, R. T., Tzeng, C. J., Yang, Y. K., & Hsieh, M. H. (2012). Optimization of wire electrical discharge machining process parameters for cutting tungsten. The International Journal of Advanced Manufacturing Technology, 60(1-4), pp. 135-147.

[Yu 2011] Yu, P. H., Lee, H. K., Lin, Y. X., Qin, S. J., Yan, B. H., & Huang, F. Y. (2011). Machining characteristics of polycrystalline silicon by wire electrical discharge machining. Materials and Manufacturing Processes, 26(12), pp. 1443-1450.

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