International Journal of Modern Manufacturing Technologies
ISSN 2067–3604, Special Issue, Vol. XII, No. 3 / 2020

INFLUENCE OF SELECTED HYDROMECHANICAL PARAMETERS OF WEDM MACHINE ON QUALITY AND CUTTING PERFORMANCE

Łukasz Łomozik[1], Henryk Bąkowski[2], Andrzej Sokołowski[3]

[1]Sm Hydro, 10B Karolinki Street, 40-467 Katowice, Poland
[2]Silesian University of Technology, Faculty of Transport, 8 Krasinskiego Street, 40-019 Katowice, Poland
[3]Silesian University of Technology, Faculty of Mechanical Engineering, 18A Konarskiego Street, 44-100 Gliwice, Poland

Corresponding author: Andrzej Sokołowski, andrzej.sokolowski@polsl.pl

Abstract: The article presents the impact of selected hydromechanical parameters of Wire Electrical Discharge Machining (WEDM) on the quality and efficiency of cutting, i.e. the surface roughness and the material removal rate. Based on the literature analysis and own experience, the following parameters of the WEDM operation were considered: the wire feeding speed, the pressure of the dielectric fluid and the speed of the working head. Using the parameter values recommended by the machine manufacturer, preliminary tests were carried out. The cut out element was the satellite of the satellite mechanism being part of a low-power hydraulic motor. Observations of the tested surface determined the presence of numerous erosive craters on this surface. Based on the results obtained, three-dimensional charts were developed showing the impact of selected input parameters on the considered output factor. The conducted research may constitute the basis for optimization of the electro-erosion cutting process.
Key words: Wire Electrical Discharge Machining (WEDM), hydromechanical parameters, surface roughness, material removal rate.

1. INTRODUCTION

The electro-discharge cutting process is well known for its high economic benefits and degree of machining accuracy. Since its introduction in 1969, enormous progress has been made in terms of cutting speed, which is now 4-6 higher and 3-4 times more accurate. Due to the increasing importance of electro-discharge cutting in the industry along with the increasing demands on accuracy and economy of technological processes, there is a need for careful research over the impact exerted by the electro-discharge machining on the quality and effectiveness of the cutting. Unfortunately, due to the complexity of physical phenomena occurring during machining, despite numerous years of research in this field, no fully accurate picture of phenomena occurring during the shaping of workpieces has been obtained so far.
The paper [1] presents the effect of discharge pulse time and current intensity in the pulse on the efficiency of the material removal process and selected parameters of the roughness profile. It has been proven that the increase in current and pulse time corresponds to an increase in the amount of material removed in a single pulse, generating craters that create surface roughness. However, this relationship is not directly proportional. Similar results were obtained by the authors of the paper [2].
Paper [3] describes the influence of wire tension and wire rewinding speed (wire feeding speed) on machining rate. It has been shown that stable machining (cutting) can be achieved with a minimum wire rewinding speed of 4 m/min. [4]. The quoted papers also present some evidence that as the wire speed increases, the surface roughness first increases and afterward decreases. An increase in wire tension, on the other hand, reduces roughness.
In work [5] author presented influence of the nickelising parameters on the structure and tribological properties of composite coatings AHC+Ni, including nickel nanowires. To solve this problem, it was applied A polyselectional, partial, D optimum experiment to determine the influence of parameters of the nickelising process on the properties of coatings. This plan assumes three levels of standardized parameters: lower, average and upper.
This paper aimed at analyzing the influence of hydromechanical parameters, i.e. feed rate of the working head, wire rewinding speed and dielectric fluid pressure on the surface roughness of cut parts. Based on the results obtained, three-dimensional charts were developed, determined from the second-degree polynomial function, showing the impact of selected input parameters on the considered output factor.

2. MATERIALS AND METHODS

To shorten the test time, an experimental plan based on Hartley's special polyselective test plan [6] on a

hypercube with three repetitions was used.
The plan provides for conducting experiments only at three equally equidistant levels of input factors variability, thanks to which the number of experiments necessary to complete the entire study is significantly reduced. The plan is therefore much more effective than other plans of this type.
The use of the three-level plan allowed to obtain mathematical models of the studied process in the form of the second-degree polynomial equation (1)[6].

$$y = b_0 + \sum b_k x_k + \sum b_{kk} x_{kk}^2 + \sum b_{jk} x_k x_j \quad (1)$$

In the planned experiment, the input factors (assumed independent variables) were coded on three levels (Table 1). Input factor levels in the relevant cutting trials were set according to the matrix of the selected experiment plan (Table 2).

Table 1. Levels of factors on a standardized scale

-1	Standardized scale factor level, corresponding to the minimum value of the parameter concerned
0	Standardized scale factor level, corresponding to the average value of the parameter concerned
1	Standardized scale factor level, corresponding to the maximum value of the parameter concerned

Table 2. Hartley's plan matrix [5, 6]

Test No	Input factors on a standardized scale		
	X_1	X_2	X_3
1	-1	-1	1
2	1	-1	-1
3	-1	1	-1
4	1	1	1
5	-1	0	0
6	1	0	0
7	0	-1	0
8	0	1	0
9	0	0	-1
10	0	0	1
11	0	0	0

2.1 Materials and equipment used in the tests

The tests were carried out on chromium-nickel-molybdenum alloy steel 40CrMnNiMo8-6-4. The chemical composition of this steel is presented in Table 3 and selected mechanical and physical properties are listed in Table 4. The material was delivered as 280x150x10 mm plates.
The material was used to cut out the satellites (Figure 1) of the satellite mechanism, which is a part of the hydraulic engine (Figure 2) produced by of SM Hydro company.

Table 3. Chemical composition of the alloy steel used in the tests [%] [7]

C	Si	Mn	Cr	Ni	Mo	S
0.37	0.3	1.4	2.0	1.0	0.2	<0.01

Table 4. Selected mechanical properties of alloy steel [7]

Trade name of steel	Density [g/cm^3]	Hardness [HB]	Tensile strength; Rm, [MPa]	Yield point; Re, [MPa]
IMPAX	7.8	330	1020	900

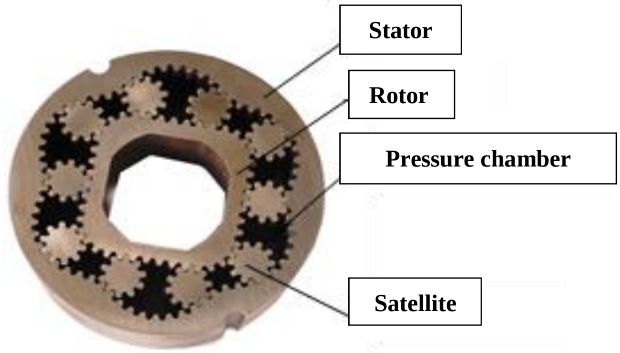

Fig. 1. Satellite mechanism

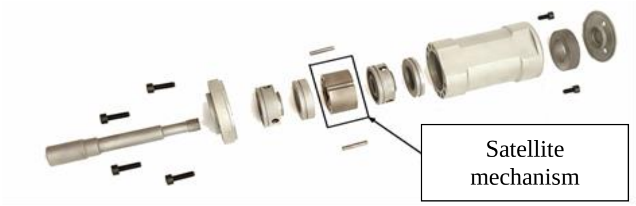

Fig. 2. View of the disassembled hydraulic motor [8]

Experimental tests were carried out on a Sodic AG 600L EDM electrical discharge machine. The working electrode was CuZn37 brass wire of 0.2 mm diameter and 900 MPa strength. The electric medium was distilled and deionized water with a resistance of $R = 5 \cdot 10^4\ \Omega cm$.
The surface roughness of cut parts was measured on the SRT-6210 needle profile meter (Figure 3).

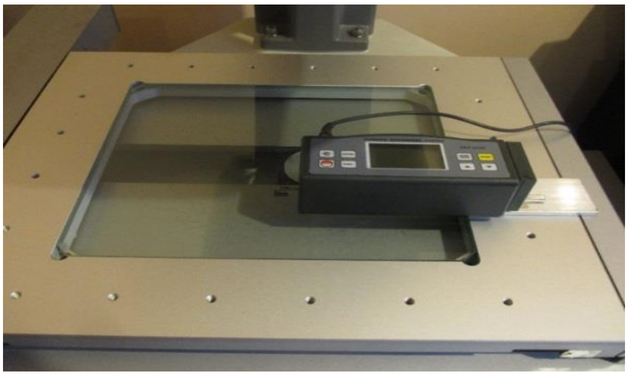
Fig. 3. Needle profile meter SRT-6200

2.2 Selection of the parameters under consideration

The basis for determining the appropriate input parameters for experimental tests was the literature analysis [4, 10]. This analysis has been done in order to determine from among the hydromechanical parameters factors that can affect the surface roughness of the details to be cut. Input factors X_1, X_2, and X_3 are respectively the wire feed rate, the pressure of the flushing fluid and the feed rate of the working head. Using the recommended values of parameters (the values recommended by the machine manufacturer [9]) and the literature review, tests were carried out to check machining stability for the maximum, average and minimum levels of the considered parameters. The roughness of the surface after machining was taken as the criterion value for assessing the influence of machining parameters on this value (Table 5).

Table 5. Output quantity

No.	Variable	Measurement	Unit
1	y	Surface roughness (Ra)	μm

Table 6. A list of test results

Test No	Input factors on a standardized scale			Input factors on a real scale			Measurement results				
							Ra [μm]				
No	X_1	X_2	X_3	WS (wire rewinding speed) [mm/min]	WP (flushing fluid pressure) [MPa]	SF (head feed rate) [mm/min]	y_1	y_2	y_3	$\hat{y}$	σ
1	-1	-1	1	40	30	5.5	133.73	227.30	147.21	169.41	50.58
2	1	-1	-1	80	30	4.5	55.88	108.66	76.81	80.45	26.57
3	-1	1	-1	40	60	4.5	15.88	27.00	22.39	21.75	5.58
4	1	1	1	80	60	5.5	59.63	58.29	60.12	59.34	0.94
5	-1	0	0	40	45	5	120.69	179.90	154.56	151.71	29.71
6	1	0	0	80	45	5	30.25	80.92	59.73	56.96	25.44
7	0	-1	0	60	30	5	48.67	103.36	71.18	74.40	27.48
8	0	1	0	60	60	5	42.97	64.68	48.17	51.94	11.33
9	0	0	-1	60	45	4.5	4.68	4.76	5.14	4.86	0.24
10	0	0	1	60	45	5.5	32.15	74.70	61.79	56.21	21.81
11	0	0	0	60	45	5	80.94	145.10	129.13	118.39	33.40

where:
y_1 - the result of measurement in test 1
y_2 - the result of measurement in test 2
y_3 - the result of measurement in test 3
$\hat{y}$ - average value
σ - standard deviation

3. RESULTS AND DISCUSSION

As a result of the application of the experimental plan, it was possible to determine the main directions of generated surface roughness curves taking into account hydromechanical parameters. The tests were repeated three times.
After conducting the technological, metrological and statistical assessment, the results can be presented as in Table 6.

3.1 Statistical model analysis

The research was carried out with the assumed level of significance $\alpha=0.05$. To confirm the repeatability of the experimental results, standard deviation of repeatability σ_{rel} = 24.874 was calculated. Based on the calculated value, the conditions of the experiment should be considered as reproducible. Statistica Software has been used for the determination the regression equation and for conducting the statistical tests.
The resulting coefficients of the standardized equation and their significance are presented in Table 7. For the best possible adjustment of the regression function to actual results of the experiment, the directional regression coefficients were analyzed using the Student's t-test.

Table 7. Regression coefficients

Coefficient	Value	Significance
b_0	76.208	significant
b_1	-24.353	significant
b_2	-31.87	significant
b_3	28.337	significant
b_{11}	54.320	significant
b_{22}	1.873	insignificant
b_{33}	-36.100	significant
b_{12}	33.941	significant
b_{13}	-41.952	significant
b_{23}	42.821	significant

Based on the general form of the second-degree polynomial, for the experiment according to Hartley and the obtained data shown in Table 7, an equation expressing the dependence of the examined output factor on the considered independent variables was determined (2).

$$Ra = 31.473 - 24.353\ WS - 31.87\ WP + 28.337\ SF + 54.32\ WS^2 - 36.1\ SF^2 + 33.941\ WS\ WP - 41.952\ WS\ SF \quad (2)$$

The Fisher-Snedecor test was used to assess the adequacy of the designated regression equation. Value of F = 7.403 was calculated. Since $F < F_{kr} = F_{(0.95)} = 19.3$, therefore, the regression equation is to be considered adequate.

In Table 8, the mean values of actual measurements (x) and the corresponding values obtained from the designated regression function (z) together with the square differences of these values are shown. Square differences determine the error of the mathematical model developed. For additional assessment of the model, determination factor R^2=0.755 was calculated. Based on the calculated indicators, i.e. Fisher's F-factor and determination factor, it can be concluded that the developed mathematical model sufficiently reproduces the real data and can be used for the defined range of input factors.

Table 8. Results of the regression function

No	x	z	$(x-z)^2$
1	169.41	252.5	6905.3
2	80.45	55.5	620.6
3	21.75	-18.2	1595.5
4	59.34	30.0	861.4
5	151.71	139.3	153.0
6	56.96	90.6	1133.8
7	74.40	108.1	1134.0
8	51.94	44.3	57.8
9	4.86	11.5	44.5
10	56.21	70.8	213.7
11	118.39	76.2	1779.3

Based on Table 8, the data obtained with measurements and data calculated with regression function is shown in Figure 4 in the form of the spreading diagram.

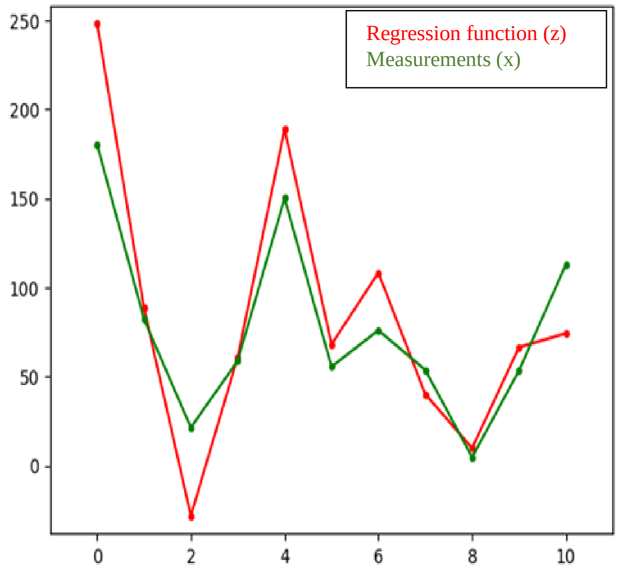

Fig. 4. Spreading diagram (see Table 9)

3.2 Results presentation and discussion

Based on the tests carried out, three-dimensional graphs determined from the second-degree polynomial function were developed, as shown in Figures 5-7.

In Figure 5 we can see that the highest surface roughness was obtained in the case of the minimum flushing fluid pressure (WP) and wire rewinding speed (WS). The effect of wire wear and poor flushing of the working gap are considered in this case.

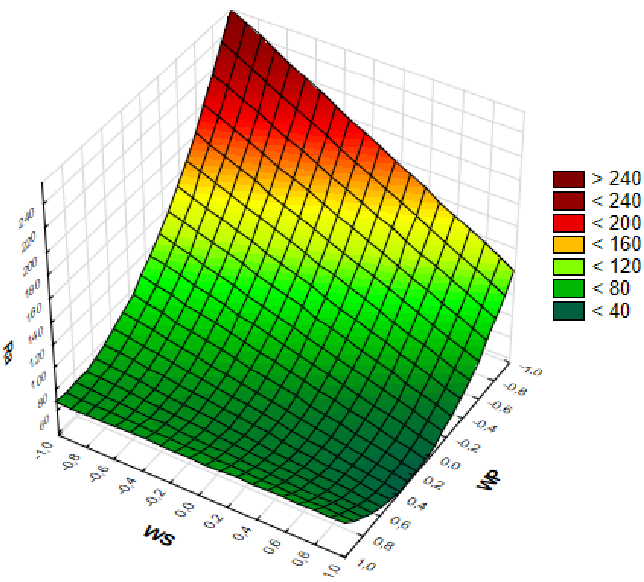

Fig. 5. Influence of wire rewinding speed WS and flushing fluid pressure WP on surface roughness Ra at an average head feed rate

The chart also shows that in this case the high flushing fluid pressure (WP) significantly reduces the effect of wire rewinding on surface roughness. Figure 6 shows that the high head feed rate and the minimum wire feed rate reduce cutting quality. This is due to the shortened time of the electrode's presence in the workspace and its wear as a result of the low wire feed rate [10]. It can be concluded from Figure 7 that an increase in the working head feed rate (SF) and a decrease in dielectric fluid pressure increase the surface roughness. This graph confirms the hydromechanical effects shown in Figures 5 and 6.

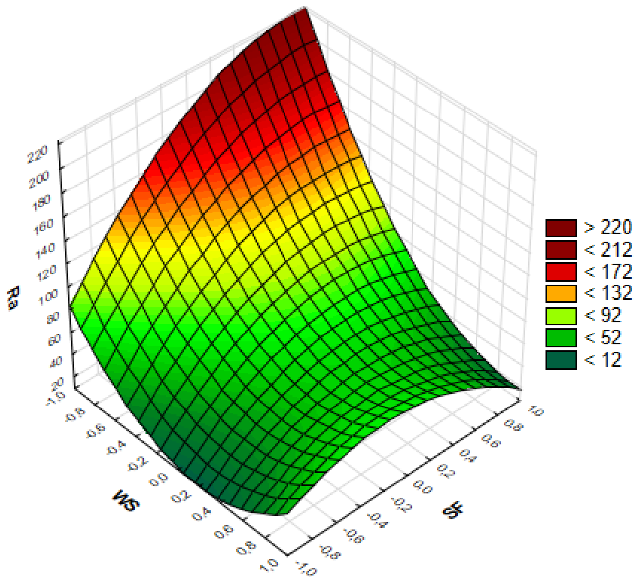

Fig. 6. Influence of wire rewinding speed WS and head feed rate SF on surface roughness Ra at an average flushing fluid pressure

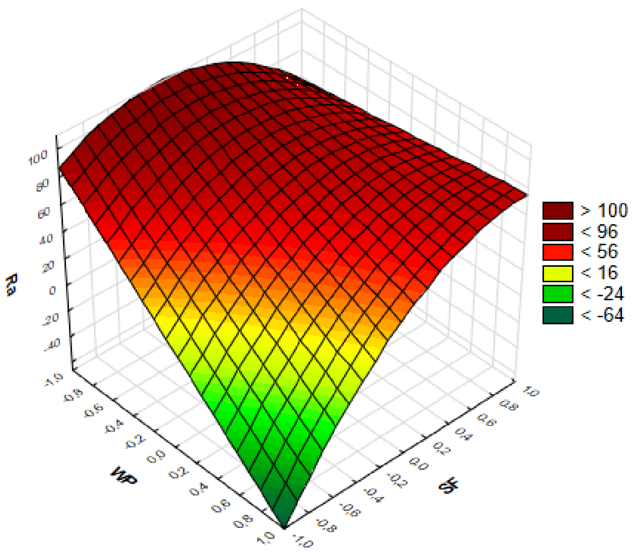

Fig. 7. Influence of flushing fluid pressure WP and head feed rate SF on surface roughness Ra at average wire rewinding speed

Figures 8-10 present the impact of individual parameters with the assumed average values of other factors. The impact of individual parameters with the assumed average values of other factors is significant. The influence of the head feed rate on the surface roughness of the workpiece at the average wire feed rate and average dielectric flushing fluid pressure is shown in Figure 8. The lowest surface roughness was obtained with the minimum feed rate of the working head. When the feed rate is increased, the surface roughness increases. This results from the weakening of the erosion products removal efficiency from the erosion gap and uneven amount of energy supplied to the machining [11]. This effect can be significantly reduced by increasing the speed of wire rewinding, as shown in Figures 5 and 6. The influence of dielectric flushing fluid pressure on the surface roughness of the cut sample for average values of wire rewinding speed (WS) and head feed rate (SF) is shown in Figure 9. The tests show that the influence of flushing fluid pressure (WP) on the quality of the machined surface is relatively low. The lowest roughness was obtained for the highest pressure. This is due to the more efficient removal of hollow products from the erosion gap. The pressure effect can be significantly reduced by reducing the head feed rate or increasing the wire rewinding speed as shown in Figures 6.

The influence of wire feeding speed on the surface roughness of the workpiece for average values of flushing fluid pressure (WP) and head feed rate (SF) is unequivocal (Figure 10). In this case, there is a linear relationship, i.e. the higher the wire feeding speed, the lower the roughness of the surfaces of the cut parts. This is due to the improvement of the erosion products removal efficiency and the reduction of the working electrode wear effect, which directly affects the quality of the machined surface.

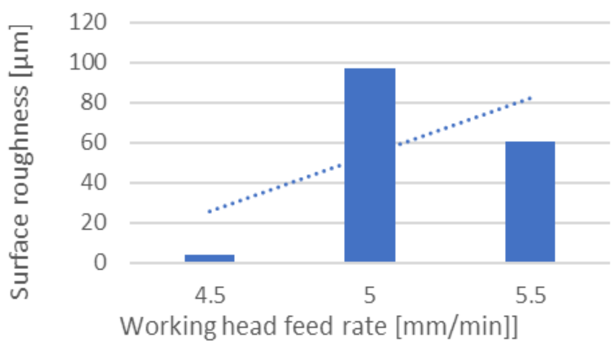

Fig. 8. Influence of the working head feed rate on the surface roughness of the workpiece

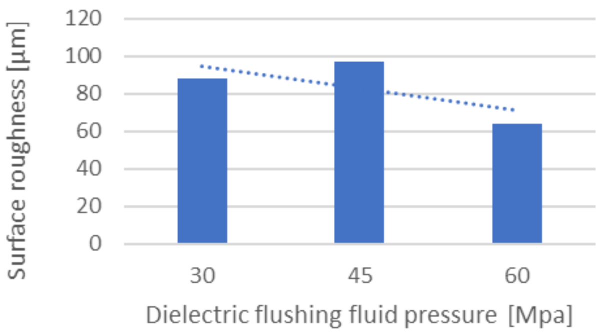

Fig. 9. Influence of dielectric flushing fluid pressure on the surface roughness of the workpiece

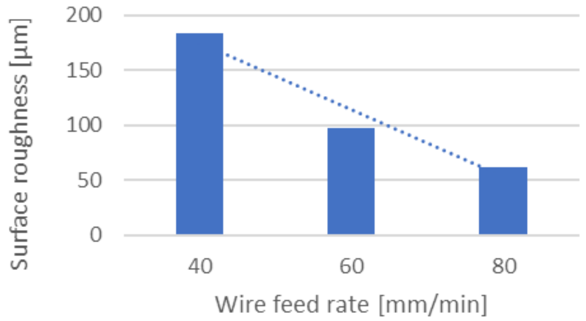

Fig. 10. Influence of the wire feeding speed on the surface roughness of the workpiece

4. CONCLUSIONS

Based on the analysis of the results obtained from the conducted tests, the following conclusions were formulated:
-The conducted tests have shown that among the analyzed parameters of the electro-discharge machine, the significant influence on the surface roughness of the cut parts have the wire feeding speed and the head feed rate.
-The effect of dielectric flushing fluid pressure on the resultant factor is relatively small. It only gains in importance in the case of a low working head feed rate. In this situation a reduction in flushing fluid pressure causes a significant increase in roughness. This is due to poor drainage of machining products from the erosion gap.
-It is advisable to conduct future studies on the influence of other operating parameters of WEDM machines, such as electric current and the duration of the electric discharge pulse on selected quantities and economic characteristics.
-The conducted research may constitute the basis for optimization of the electro-erosion cutting process, which can significantly improve the quality and economic conditions of machining, applicable in many industries.

5. REFERENCES

1. Scott D., Boyina S., (1990). *Analysis and optimization of parameter combinations in wire electrical discharge machining*. International Journal of Production Research, **29**(11), 2189-2207
2. Świercz R., Oniszczuk-Świercz D., (2014). *Wpływ parametrów obróbki elektroerozyjnej na właściwości użytkowe stali o wysokiej przewodności cieplnej*. Mechanik 2015, **88**(1), 29-34.
3. K. L. Meena, A. Manna,S. S. Banwait, Jaswanti., (2013). *Effect of wire feed rate and wire tension during machining of pr-al-sic-mmc,s by wedm*. European Journal of Engineering and Technology, **1**(1), 7-13.
4. Rozenek M, Dąbrowski, L., (2011). *Aspekty ekonomiczne i dokładnościowe wycinania elektroerozyjnego*. Archives of Mechanical Technology and Materials, **31**(2), 87-95.
5. Posmyk A., (2013). *Composite coating with ceramic matrix including nickel nanowires*. Surface Engineering, **29**(3), 171-176.
6. Korzyński M., (2017). *Methodology of the experiment*, Copyright PWN.
7. https://www.uddeholm.pl/polish/files/Imaax_Supreme.pl.pdf, Accessed on: 08.11.2018.
8. Bąkowski H., (2018). *Estimation of the wear mechanism in sliding contact of satelite gears of a hydraulic motor*, Tribology 2/2018, pp 5-12.
9. Sodick Corporation (2005), *User manual. Wire cutter control system LN1W*, Nakamachidai, Tsuzuki-ku, Yokohama: Sodick Corporation.
10. Siwczyk M., (2001). *Obróbka Elektroerozyjna*. Podstawy Technologiczne, **II**, Kraków: Firma Naukowo-Techniczna "Mieczysław Siwczyk".
11. K. E. Trezise., (1981). *A Physicists's View of Wire E.D.M*. Twenty *Second International Machine Tool Design and Research Conference*, Department of Mechanical Engineering University of Manchester Institute of Science and Technology 1981, pp 413-419.

Received: April 23, 2020 / Accepted: December 20, 2020 / Paper available online: December 25, 2020 © International Journal of Modern Manufacturing Technologies