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Mathematical modelling of surface roughness for evaluating the effects of WEDM cutting parameters

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Abstract. Wire Electrical Discharge Machining is a cutting method used for obtaining parts with complex geometries or for cutting hard metals. In machining processes, it is necessary to obtain the desired surface quality in order to produce parts providing the required functioning. The surface quality also defines some mechanical properties of the product, such as wear resistance. Being such a considerable quality, surface quality is influenced by various parameters. It will be costly and time consuming to acquire the knowledge of appropriate cutting parameters. Unconventional technologies have not been sufficiently studied so far to provide such details. So, this paper seeks to emphasize the importance of this unconventional technology and more specifically the importance of knowing the parameters of a process before planning the production of a benchmark. Cylindrical metal carbide parts with a hardness of 1620 HV were cut during the analysis, using the minimum and maximum values of some cutting parameters. The roughness of the obtained surfaces has been measured after being cut and a comparison table that includes the parameters values set by the user and the measured roughness was drawn up. Following the regression analysis, the mathematical model that determines the value of the roughness according to the values of the parameters was established.
Keywords: *WEDM, surface roughness, cutting parameters, mathematical model.*

Introduction

The Electrical Discharge Machining process was discovered by two Russian scientists R. Lazarenko and I. Lazarenko in 1943 and in the beginning it was only used in the military industry. This subtractive machining process is used to machine especially very hard metals like pre-hardened steel or Titanium, but it can also be used for other materials which are electro conductive. Sometimes EDM is used to make objects like mold cavities because it is impossible to obtain a complex geometry using traditional cutting processes. [1]

It can be argued that only a mathematical model can serve to make better use of the process in a way that the tools can be used to the maximum, until they reach the required surface quality. The evolution of technology in the last two decades has put pressure on the development of unconventional technologies, especially micro technologies. Although the unconventional technologies like wire electrical discharge machining were extensively studied, no relevant aspects have been revealed regarding the cutting parameters influence on the workpiece. [2]

Regression analysis is a state-of-the-art modelling tool that is used to determine a model of the links between numerical data arrays. The term "regression" was introduced in statistics by Francis Galton. By researching hereditary problems based on their observations, he discovers, among other things, that in the realities of which it is more important than the collection. [3]

Basic information of EDM process

The main concept behind WEDM is about the way in which an electric arc can erode the surface of a material. These electric arcs form when the voltage difference between two closely separated objects, called electrodes, becomes high enough to overcome the resistance of the gap between them. When this occurs, a current of up to 500 A flows through a microscopically small area, vaporizing the surface of the electrodes. This vaporization separates some material from the larger workpiece, leaving a pit on the surface. As numerous arcs occur, this pitting erodes the surface over a large area, shaping it in the desired manner. [4] WEDM is based on complex, discontinuous and localized erosive effects of repetitive pulsed electric discharges between the workpiece and the electrode. As mentioned earlier, only materials that have electrical conductivity can be processed. [5]

Experimental procedures

As shown in the previous study Influence of machining parameters on surface roughness in WEDM cutting, experimental trials are performed by cutting Ø18.8 tungsten carbide bars. A metallographic analysis was performed to determine the elemental structure of the material. A Leika DM6 M LIBS metallographic microscope was used and the analysis can be seen below.

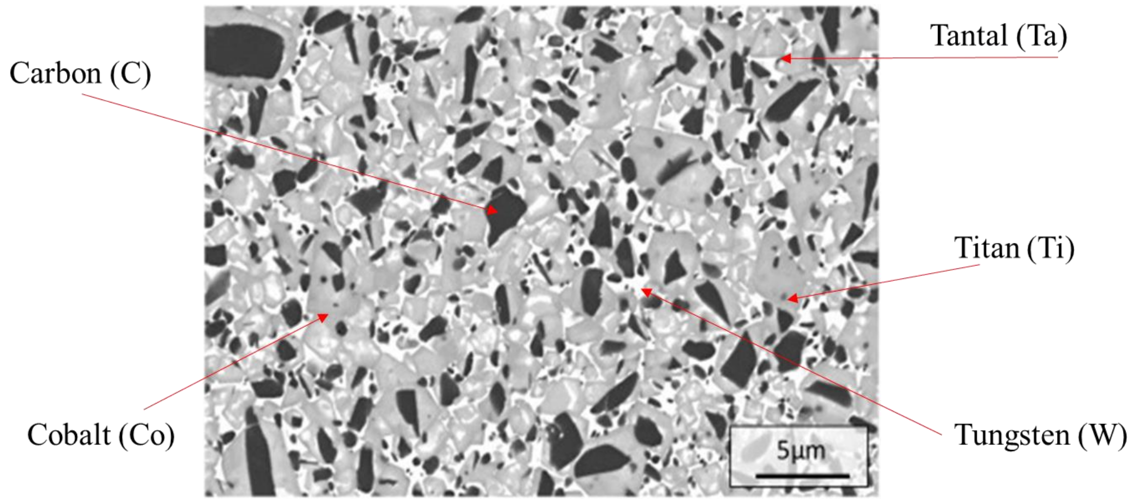

Figure 1. Metallographic analysys for carbide bar

Metal carbide contains 10% Cobalt (Co) and the size of the Tungsten (W) grains reaches a maximum of 0.5 µm. There is also Carbon (C) with black, Titanium (Ti) and Tantalum (Ta). After analyzing the elemental structure, the hardness of the carbide bars was analyzed. For this, the Vickers method was used on a Struers Duramin 40 durimeter. The square-shaped frame with a square base and a diamond tip was applied for 18 seconds, according to ISO6507. The hardness of the outer cylindrical surface was measured. In Table 1. the values obtained from the hardness test analysis can be found.

Table 1. Hardness test results

Sample nr.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Hardness [HV]	1620	1618	1618	1620	1620	1620	1619	1620	1620	1620

Metal carbide bars were machined on the AgieCharmilles AC Progress V4. The cutting was made with CobraCut A wire of size Ø0.25 mm, made of CuZn36 material (brass). During machining, the maximum spark size was 0.06 [mm]. The tensile strength the wire was 900"N/mm2" . The main proprieties of CobraCut A can be found in Figure 2 in the below. As show in this Figure, this wire is used especially for finishing – 85% performante, with a very high cutting precision – 80%.

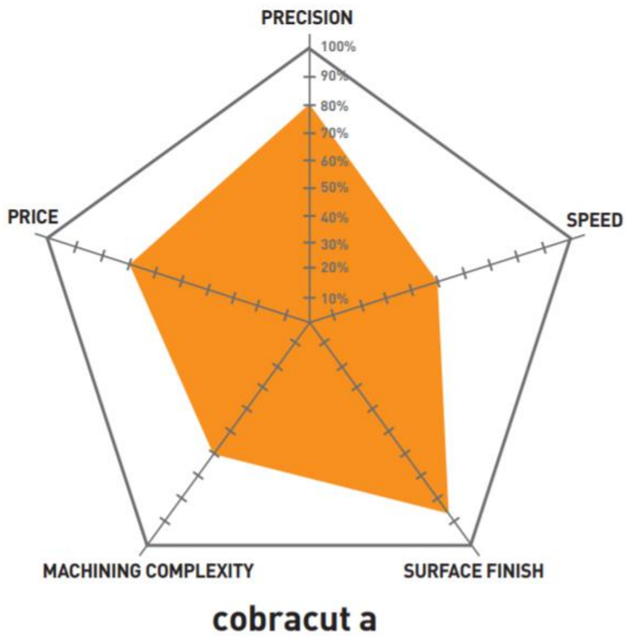

Figure 2. CobraCut A wire performance

The next step of the study was to determine the parameters that can be changed on the machine mentioned above. In the table below one can find the parameters that could be modified by the user in correlation with their minimum and maximum values.

Table 2. The minimum and maximum values of the parameters on the WEDM machine

Parameter	Values	
	min.	**max.**
Wire feed rate [mm/min] - $\mathbf{V_a}$	0,50	4
Wire rotation speed [mm/min] - $\mathbf{V_r}$	90	325
Dielectric pressure [mmHg] - $\mathbf{P_d}$	0,30	18
Wire tension [N] - $\mathbf{T_f}$	10	40
Electrical current [A] - **I**	1	40
Electrical potential [V] - **U**	12	82

The cutting parameters in the table above are: $\mathbf{V_a}$ - wire feed rate, $\mathbf{V_r}$ - wire rotation speed, $\mathbf{T_f}$ - wire tension, $\mathbf{P_d}$ - dielectric pressure, **I** - electrical current(A) and **U** - electrical potential (V). Considering that the user can change a number of six parameters, with two values (minimum and maximum), the total number of parts that must be made to have a complete study is to be determined:

$$2^6 = 64 \text{ – number of cutting parts} \quad (1)$$

Thus, 64 pieces were cut to determine the mathematical model. But first, the roughness measurement plan on the workpiece surface was established. The roughness of the cut parts was measured using a Mitutoyo Surftest SJ-301 roughness meter. A linear surface was measured at mid-height, more precisely at half the diameter, as it can be seen in Figure 3.

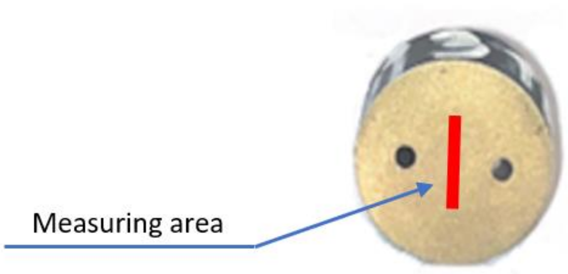

Figure 3. Roughness measuring area

Regarding the roughness measurement, the arithmetical mean deviation of the assessed profile Ra, the maximum height of the profile Rz and maximum peak height Rp were measured. [6]

Table 3. The values of the test parameters and the resulting roughness

Nr.	Wire feed rate [mm/min]	Wire rotation speed [mm/min]	Dielectric pressure [bar]	Wire tension [N]	Electrical current [A]	Electrical potential [V]	R_a [µm]
1	4	325	18	40	40	82	2,86
2	4	325	18	40	40	12	2,88
3	4	325	18	40	1	82	0,52
4	4	325	18	10	40	82	2,87
5	4	325	0,3	40	40	82	2,87
6	4	90	18	40	40	82	2,87
7	4	325	0,3	10	40	82	2,88
8	4	325	18	10	1	82	0,53
9	4	325	18	40	1	12	0,54
10	4	90	18	10	40	82	2,87
11	4	90	18	40	1	82	0,53
12	4	90	18	40	40	12	2,88
13	4	325	0,3	40	1	82	0,53
14	4	90	0,3	40	40	82	2,87
15	4	325	18	10	40	12	2,89
16	4	90	0,3	10	40	82	2,88
17	4	90	18	40	1	12	0,54
18	4	90	0,3	40	1	82	0,53
19	4	90	0,3	40	40	12	2,89
20	4	90	18	10	1	82	0,53
21	4	325	0,3	10	1	82	0,54
22	4	325	0,3	10	40	12	2,89
23	4	325	0,3	40	1	12	0,55
24	4	325	18	10	1	12	0,55
25	4	90	0,3	10	1	82	0,54
26	4	325	0,3	10	1	12	0,55

Nr.	Wire feed rate [mm/min]	Wire rotation speed [mm/min]	Dielectric pressure [bar]	Wire tension [N]	Electrical current [A]	Electrical potential [V]	R_a [µm]
27	4	90	18	10	1	12	0,55
28	4	90	0,3	40	1	12	0,55
29	**4**	**90**	**0,3**	**10**	**40**	**12**	**2,90**
30	4	90	0,3	10	1	12	0,56
31	4	90	18	10	40	12	2,89
32	4	325	0,3	40	40	12	2,89
33	0,5	325	18	40	40	82	2,42
34	0,5	325	18	40	40	12	2,44
35	**0,5**	**325**	**18**	**40**	**1**	**82**	**0,08**
36	0,5	325	18	10	40	82	2,43
37	0,5	325	0,3	40	40	82	2,43
38	0,5	90	18	40	40	82	2,43
39	0,5	325	0,3	10	40	82	2,44
40	0,5	325	18	10	1	82	0,09
41	0,5	325	18	40	1	12	0,10
42	0,5	90	18	10	40	82	2,43
43	0,5	90	18	40	1	82	0,09
44	0,5	90	18	40	40	12	2,44
45	0,5	325	0,3	40	1	82	0,09
46	0,5	90	0,3	40	40	82	2,44
47	0,5	325	18	10	40	12	2,45
48	0,5	90	0,3	10	40	82	2,44
49	0,5	90	18	40	1	12	0,10
50	0,5	90	0,3	40	1	82	0,10
51	0,5	90	0,3	40	40	12	2,45
52	0,5	90	18	10	1	82	0,09
53	0,5	325	0,3	10	1	82	0,10
54	0,5	325	0,3	10	40	12	2,45
55	0,5	325	0,3	40	1	12	0,11
56	0,5	325	18	10	1	12	0,11
57	0,5	90	0,3	10	1	82	0,10
58	0,5	325	0,3	10	1	12	0,11
59	0,5	90	18	10	1	12	0,11
60	0,5	90	0,3	40	1	12	0,11
61	0,5	90	0,3	10	40	12	2,46
62	0,5	90	0,3	10	1	12	0,12
63	0,5	90	18	10	40	12	2,45
64	0,5	325	0,3	40	40	12	2,45

From the data in the table above some main conclusions can be drawn. First of all, we must highlight the lowest value of the roughness that was obtained - 0.08µm and the highest value - 2.90µm. The roughness values are low due to the machine, the wire and the dielectric on which the cutting process was made.

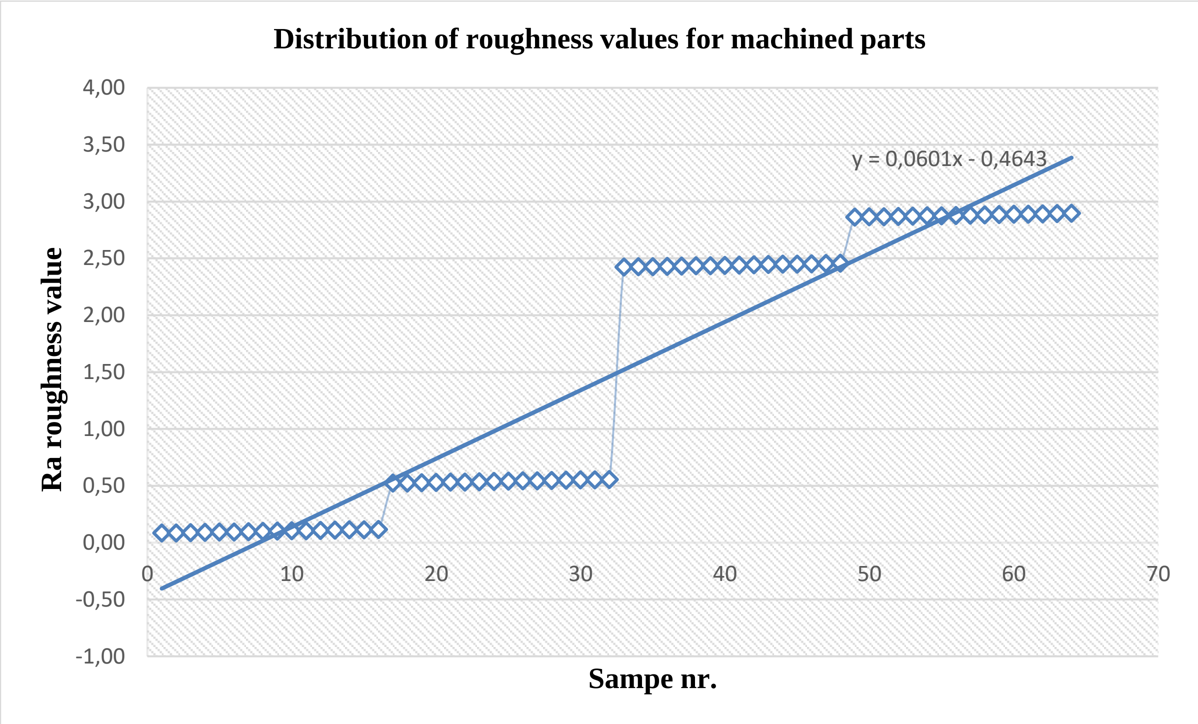

Figure 4. Distribution of roughness graph

As shown in the previous Figure, 16 roughnesses were obtained in the interval [0.08; 0.12], 16 roughnesses in the interval [0.52; 0.56], 16 roughnesses in the interval [2.42; 2.46], and other 16 roughnesses in the interval [2.86; 2.90].

This equal distribution of 4 times 16, provides truthfulness of the mathematical model of roughness. In addition, a well-simmetry distribution can be observed, in each interval of measurement of the difference between the minimum and maximum points of 0.04 µm in all 4 intervals. Another symmetry highlighted in the graph Distribution of roughness values for machined parts refers to the difference between the minimum and maximum between the values of the first set of 16 roughnesses in relation to the next.

Consequently, as can be seen in the graph below, the roughness distribution does not have a linear distribution. This is due to the uneven distribution of the processing parameters, respectively to the sudden touching of the minimum and maximum points.

Reductio ad absurdum is applied to develop the mathematical model. It is understood that the functions Ra=f(Va,Vr,Pd,Tf,I,U) are described by subtracting the processing parameters with a given coefficient:

$$Ra= x*Va+y*Vr+z*Pd+a*Tf+b*I+c*U \quad (2)$$

All the values in Table 3 are entered in an analysis program for the implementation of the regression analysis and the following information is exported:

SUMMARY OUTPUT

Regression Statistics	
Multiple R	1
R Square	1
Adjusted R Square	1
Standard Error	3,73286E-16
Observations	64

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	6	90,70311887	15,11719	1,08E+32	0
Residual	57	7,94254E-30	1,39E-31		
Total	63	90,70311887			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0,000000	1,65148E-16	1,985267	0,051934	-2,8403E-18	6,59E-16
Va	0,125500	2,66633E-17	4,71E+15	0	0,1255	0,1255
Vr	-0,000011	3,97113E-19	-2,7E+13	0	-1,054E-05	-1,1E-05
Pd	-0,000478	5,27241E-18	-9,1E+13	0	-0,0004785	-0,00048
Tf	-0,000150	3,11072E-18	-4,8E+13	0	-0,00015	-0,00015
I	0,060000	2,39286E-18	2,51E+16	0	0,06	0,06
U	-0,000250	1,33317E-18	-1,9E+14	0	-0,00025	-0,00025

In conclusion, the mathematical model for the determination of roughness as a function of measurement is as follows:

$$R_a=0{,}1255\times V_a-0{,}00001054\times V_r-0{,}0004785\times P_d-0{,}00015\times T_f+0{,}06\times I-0{,}00025\times U \qquad (2)$$

$$R_a=\frac{V_a}{8}+\frac{527V_r}{5\times10^7}+\frac{957P_d}{2\times10^6}+\frac{3T_f}{2\times10^4}+\frac{3I}{5\times10}+\frac{U}{4\times10^3} \qquad (3)$$

Conclusions

In conclusion, it can be stated that this mathematical model is accurate. The author considers it imperative that the industry prepare a library with all the information regarding the processing of materials according to hardness and electrical conductivity.

In this way, the development of mathematical models such as the one discovered in this study will help the unconventional technology industry. This is the only way that unconventional technologies will become much more powerful than they are at the moment. [7]

Using this mathematical model it will be possible to calculate the processing parameters taking into account the two essential principles: the principle of high productivity and the principle of quality. Also, it will be possible to reduce costs because the intermediate control operation of the processing surface will be necessary only rarely.

This mathematical roughness calculation model refers only to tungsten carbide whose hardness and metallography are known. However, this mathematical model can be improved by adding correction coefficients to the formula for relative or other errors. The results of this study can also be improved.

In this case, we analyzed the surfaces of 64 machined parts with a minimum parameter and a maximum parameter. If we had analyzed with a median parameter, ie with the average value of the parameters, the results would have been closer to the truth. But in this case, we should have analyzed 729 pieces – $3^6 = 729$.

The third stage of this study will have to integrate through a software application all the values obtained and the determined mathematical mode. Then, this application will have to serve engineers, technologies and operators in order to be able to process materials better and faster.

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