On Geometrical Characteristics of WC-Co Round Cavities After ED-Machining with Different Grades of CuW Electrodes

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Cemented carbides (WC-Co) are difficult to be processed by conventional machining processes. Electrical discharge machining (EDM) appears as an efficient technology to manufacture WC-Co products with high accuracy. In EDM literature no research works investigating the influences of different grades of CuW electrodes on geometrical characteristics when ED-machining the same cemented carbide was found. This work presents an investigation on ED-Machining of cemented carbide (WC-Co) with 10% Co using two grades of coper-tungsten (CuW) electrodes with 65% and 85% of tungsten. ED-Machining experiments were carried out under rough, semifinish and finish regimes with input variables discharge current i_e, discharge duration t_e and pulse interval time t_o using analysis of variance (ANOVA) based on design of experiments with complete factorial 3^2. Output variables evaluated were WC-Co workpiece geometrical characteristics 3D surface roughness and round cavities circularity measures. Results showed that ED-Machining regime is the most significant parameter on both WC-Co workpiece circularity and surface roughness measures. Electrodes grades CuW65 and CuW85 presented similar results on workpiece circularity and 3D surface roughness.

Keywords: *ED-Machining; CuW eletrodes; WC-Co workpiece; Geometrical Characteristics.*

1. Introduction

Electrical discharge machining (EDM) is recognized as one of the most non-conventional machining processes widely used in industry, owing to its possibility of producing complex shapes with high accuracy in any electrical conductive material, regardless its mechanical properties[1]. In ED-Machining, there is no direct contact between workpiece and electrode; discrete electrical discharges are produced between them in a liquid dielectric medium. ED-Machining high temperatures of about 20,000 °C, during the spark occurrence, are responsible to melt and vaporize small amounts of material of both workpiece and electrode, with no mechanical stresses taking place[2,3].

Precision metal-mechanical industry commonly deals with hard-to-machine materials such as cemented carbides (WC-Co), which are difficult to be processed by conventional machining processes. As for that, such materials are better machined by non-conventional manufacturing processes such as ED-Machining, once its material removal principle works through thermal input into the material, which inherently is independent of material mechanical strength[4].

WC-Co composite material is composed by Cobalt as binder and WC that is a non-oxide ceramic, where hexagonal closely packed layers of W atoms are separated by closely packed layers of C filling one-half of the interstices, giving rise to a six-fold trigonal prismatic coordination for the atomic structures[5]. Effective sinking EDM electrode materials for removal of WC-Co are copper-tungsten alloys (CuW), since their thermo-physical properties such as melting point, electrical and thermal conductivities, thermal resistivity are better than those presented on common EDM electrode materials, like graphite and copper[4].

Discharge energy ($W_e \approx u_e.i_e.t_e$ [mJ], where u_e is the discharge voltage, i_e is the discharge current, t_e is the discharge duruntion) used in working gap is the main ED-machining factor responsible to process performance in terms of material removal rate V_w [mm³/min], volumetric relative wear ϑ (ϑ = electrode wear rate [mm³/min]/material removal rate [mm³/min]) , workpiece surface integrity and cavity geometrical characteristics[6]. Duszová et al.[7] evaluated EDM parameters conditions for machining WC-Co using CuW (70%W and 30%Cu) electrodes in different ED-machining regimes, searching for improved data for volumetric relative wear ϑ, material removal rate V_w and surface roughness R_a. They concluded that variation of the duty factor ($\tau = t_i / t_i + t_o$ [%], where t_i is the pulse time and t_o is the pulse interval time) slightly improves material removal rate V_w and that open circuit voltage $\hat{u}_i$ increases V_w and decreases R_a values. In a study by Qu et al.[8] when ED-machining WC-Co workpiece

using CuW with high energy density, it was observed a reduction of hardness in the region near the workpiece surface. Carlini et al.[9] investigated the ED-Machining of WC-Co with CuW electrodes using very high discharge energy and observed an increase of both surface roughness and heat-affected zone thickness.

Senthilkumar et al.[10] report that in precision metal-mechanical industries one important goal is to manufacture components with reasonable costs and according to their predefined requirements for precise dimensions and high geometrical accuracy. In this sense, geometrical tolerances such as circularity, cylindricity, perpendicularity and radial overcut must be constantly improved. They verified that circularity, surface roughness and workpiece overcut increase with the use of high discharge currents i_e, as well as the number of microvoids and craters sizes.

Data pertaining to circularity, cylindricity and perpendicularity of round cavities are scarce in EDM literature[11]. Circularity is defined as a condition of a surface of revolution (sphere, cone, and cylinder) where all points of the surface intersected by any plane perpendicular to a common axis (cone, cylinder) or passing through a common center (sphere) are equidistant from the axis of the center[12]. This indicates that circularity can be altered in two ways: by changes in area and by changes in the perimeter of a particle. To consider this, an ideal perfect circle (true circle) is assumed. If the area and perimeter do not change, then circularity is constant. Consequently, it should be possible to determine roundness if circularity can be corrected using aspect ratio. In other words, if it is possible to combine the difference in circularity value due to aspect ratio with the circularity itself, then the aspect ratio-corrected circularity can be used to represent roundness[13]. Adamczak et al.[14] presented the principle of reference method and the importance of cylindricity measurement and also the method for comparing the cylindrical profile.

Selvarajan et al.[12] optimized ED-Machining parameters for enhancing circularity, cylindricity and perpendicularity of Si 3N4-TiN Composite holes by employing grey relational analysis technique. Dhanabalan et al.[15] analyzed ED-Machining process on form tolerances of inconel 718 and 625. Results showed that increasing discharge duration t_e, the circularity, cylindricity and perpendicularity values decreased up to discharge duration t_e=350 μs, and when applying higher t_e their values increased.

Recently, Popli and Gupta[16] Investigated the circularity and conicity of a super alloy during rotary ultrasonic machining with the variation on tool rotation, feed rate, ultrasonic power abrasive, mesh size and variable electrode design. They observed that variation in abrasive size and tool shapes has significant effect on the performance of machining.

Tiwary et al.[17] studied the effect of dielectrics on circularity during micro-electro-discharge machining of Ti-6Al-4V using hydrocarbon oil, pure deionized water and deionized water mixed with Cu powder. They concluded that hydrocarbon oil obtained the lowest circularity in all discharge currents i_e used, with the best result for current i_e=2 A. D'Urso and Merla[18] investigated the influence of electrode materials on geometrical characteristics of micro-EDM holes in terms of conicity and diametral overcut. Copper, brass and tungsten

carbide (WC-Co) electrodes were used for three different discharge energies. From 0.05 mm to 0.09 mm diametrical overcuts were produced and the best result was achieved for cooper electrode at low discharge current i_e.

Physical and electrical characteristics of ED-Machining debris were studied by Murray et al.[19] and it was verified debris with particle sizes as small as 1 nm and as large as 10 μm. They concluded that debris particles were present in all regions around workpiece samples, adding evidence that debris plays a key role in electrical conditions in working gap, and also that debris sizes showed no clear dependence on discharge current i_e. However, they did not investigate geometrical aspects such as workpiece overcut and form error.

Muttamara et al.[20] studied the effects of graphite and copper electrodes, under the same ED-Machining parameter settings, over the WC-Co workpiece surface characteristics. It was observed that surface roughness produced with graphite electrode was higher than that of copper electrode. According to them, it is probably due to the graphite particles from graphite electrode that produces pores on the workpiece surface layer, which does not occur when ED-machining with copper electrodes. Shabgard et al.[21] and Kunieda et al.[22] reported on the influence of ED-Machining on surface integrity of WC-Co workpiece. They found that the surface roughness achieved through ultrasonic assisted EDM is marginally higher than the roughness achieved by conventional EDM process. Also, in sinking EDM hydrocarbon dielectrics are normally used because surface roughness is better and tool electrode wear is lower when compared to deionized water as dielectric fluid.

Research works were found regarding ED-Machining performance applied to different grades of WC-Co on aspects related to technological performance measures, workpiece morphology and surface integrity, when using one single grade of CuW electrode[23-25]. However, so far in EDM literature no research works investigating the influences of different grades of CuW electrodes on surface roughness and circularity when ED-machining the same cemented carbide was found.

In this regard, the objective of present work is to evaluate the effects of two different grades of copper-tungsten electrodes (CuW85% and CuW65%) when ED-machining cemented carbide (WC-Co10%) concerning workpiece 3D surface roughness (Sa) and circularity for three levels of discharge energy ($W_e \approx u_e.i_e.t_e$ [mJ]).

2. Experimental Procedures

The experiments were conducted with three different input levels of discharge energy ($W_e \approx u_e.i_e.t_e$ [mJ]) for rough, semi-finish and finish regimes (Table 1) and three fold replicated for each regime. As output performance variables the WC-Co workpiece circularity and surface roughness Sa (average height of selected area) were evaluated. A negative polarity was used to the electrode (cathode) and the WC-Co workpiece as the anode, due to the high percentage of WC ceramic phase in the WC-Co alloy, which would inhibit the emission of primary electrons that are responsible to start the ionization process and to accelerate the dielectric voltage breakdown, and then faster create the plasma channel[6]. The values of duty factor τ (t_i / t_i + t_o) was progressively

reduced from the rough to finish regime (0.64 to 0.11), providing adequate flushing condition of debris away from the working gap, by setting a longer value for interval time t_o.

An EDM machine-tool +GF+ AgieCharmilles© CNC, model SP1, was used to carry out the experiments. A hydrocarbon dielectric fluid with 3.12 cSt viscosity at 40°C, flash point of 134°C and 0.01wt% of aromatic contents was used and 0.1 MPa pressure flushing was provided by applying 6.35 mm diameter rigid hoses positioned at 180° of each other and placed near the workpieces. 10 mm diameter cylindrical bars of two grades of CuW electrodes (CuW65% and CuW85%) were mounted axially in line with round submicron grain size WC-Co workpiece samples with chemical composition shown in Table 2. The chemical composition analysis was performed by a scanning electron microscope (SEM) of Tescan® manufacturer; model VEGA3 LMU, equipped with an energy dispersive spectroscopy (EDS) probe manufactured by Oxford Instruments. An especial assembly device was designed and manufactured, providing adequate clamping of the WC-Co samples, as shown in Figure 1.

As shown in Figure 2, WC-Co workpieces circularity measurements were carried out in a Mitutoyo® roundness equipment, model RA 1600. A preset filter cut off at 50 ripples per revolution (UPR), as recommended in the instruction manual observing the dimensional fields of the samples, was used. All measurements were performed with a 1 mm diameter ruby probe. For the computational interface, the Roundpak® software was applied, which allows the plotting of graphs for enhanced understanding the measurements.

Topographical analysis of the WC-Co workpiece surfaces were made with an optical stereoscopic microscope Discovery V12, Carl Zeiss®. The workpiece surface morphology was taken by a Leica® DCM 3D digital microscope with dimensions area of 1.27 x 0.95 mm². Confocal Z scan 200 μm with lateral resolution of 0.1 μm and vertical resolution of 2.0 μm was used, totalizing 384 x 288 data points. Workpiece surface roughness was measured using Leica Scan topography in accordance with I SO 4287: 2002 and ISO 25178-2: 2012. 3D roughness measurement differs from two-dimensional measurement by assessing roughness in a given volume, providing distribution and regularity data in the third dimension. Surface roughness Sa (average height of selected area) was used for the characterization of each sample topography after ED-machining for the three tested regimes. Only the WC-Co cavity bottom was used for 3D superficial roughness measurement.

3. Results and Discussions

For enhanced understanding of the graphics, Figure 3 presents the WC-Co workpiece circularity variation results for ED-Machining under rough ($i_e = 37$ A, $t_e = 180$ μs), semi-finish ($i_e = 11$ A, $t_e = 56$ μs) and finish regimes ($i_e = 4$ A, $t_e = 13$ μs), using the two CuW electrodes grades (CuW65% and CuW85%). It can be seen that from finish to rough regimes, independently of CuW electrode grade, the circularity variation increases substantially.

It is probably explained by the increase of discharge energy ($W_e = u_e . i_e . t_e$ [mJ]), from finish to rough machining,

Table 1. Electrical input parameters of energy for ED-Machining experiments.

| Regime	Electrode Polarity	u_i [V]	t_e [μs]	t_o [μs]	i_e [A]	τ [%]
Rough	negative	80	180	100	37.0	0.64
Semi-finish	negative	80	56	24	11.0	0.70
Finish	negative	80	13	100	4.0	0.11

Table 2. Chemical composition of cemented carbide and electrodes.

| Materials	Element - Chemical composition [%]				
	W	C	Co	Cu	Others
Samples WC-Co	80,57	8,57	10,43	-	0,43
Electrode CuW65	65,00	-	-	35,00	n / D
Electrode CuW85	85,00	-	-	15,00	n / D
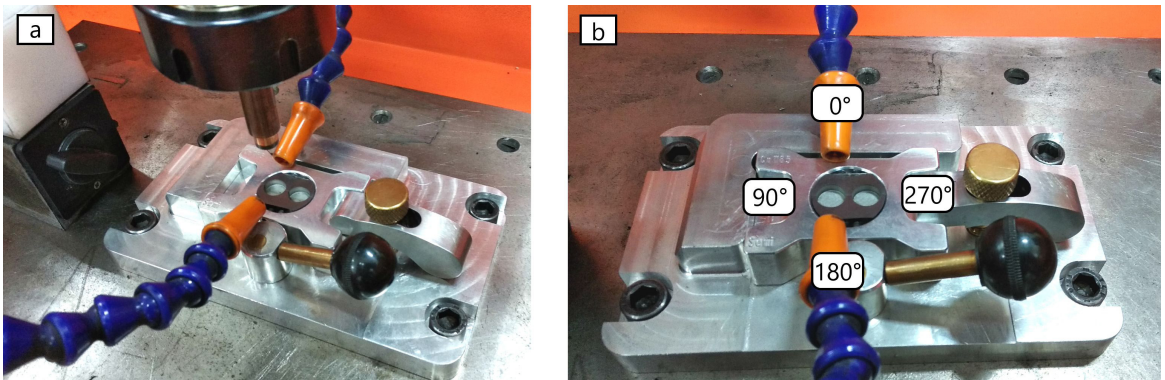
Figure 1. (a) Assembly device for samples and electrodes clamping and (b) positions for circularity measurements.
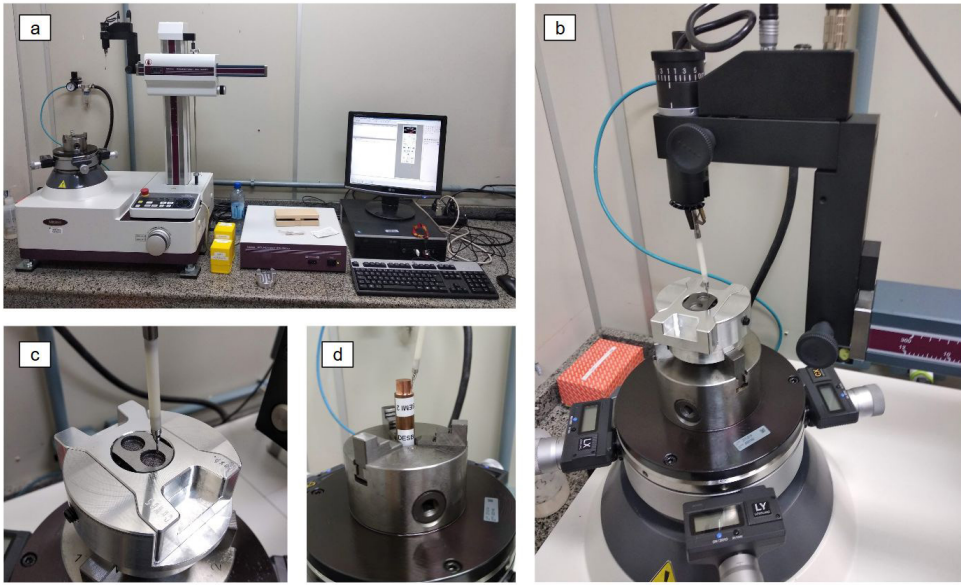
Figure 2. (a) Roundness equipment overview, (b) workpiece clamping detail, (c) workpiece measurement and (d) electrode measurement.
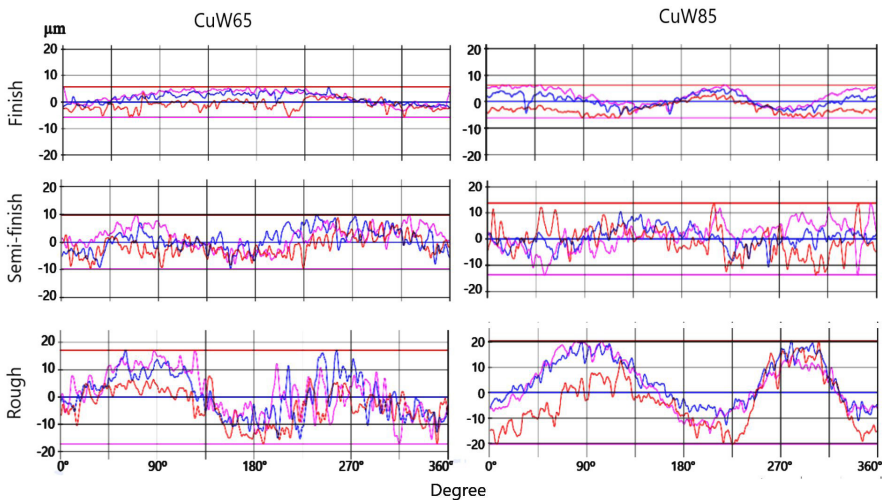
Figure 3. Circularity deviations for rough, semifinish and finish ED-Machining with both CuW electrode grades.

that provides both higher plasma channel pressure and higher temperature over the melted eletrode/workpiece pools. Thus, when the higher energy plasma channel is interrupted, by setting the interval time t_o, more material is violently expelled away from the melted pools of the electrode/workpiece for rough regime. As consequence, more amount of debris concentrates in a non-uniform way in the working gap. It then provides the increase in circularity deviation, due to the occurance of more sparks where the debris concentration are higher, exactly because in such places the dielectric breakdown easier occurs.

The circularity geometry shape for WC-Co workpiece, under ED-Machining with rough regime ($i_e = 37\,A$, $t_e = 180\,\mu s$), can be also observed three-dimensionally in Figure 4. The depth of erosion was 3.5 mm; however, the measuring probe reached 2.0 mm due to its mechanical construction.

It is possible to observe that at the input positions of clean dielectric fluid the circularity error is smaller than at the output places of the contaminated dielectric. It corroborates the previous explanation, i.e. where debris presence is higher more material is removed from the workpiece, causing an increase in circularity deviation.

Figure 5 shows a comparison of WC-Co workpiece circularity distribution for the rough, semi-finish and finish regimes with CuW65 and CuW85 electrodes. It is possible to observe the existence of circularity deviations within the same regime. Such deviations are more prominent for the roughing and semi-finishing regimes. These deviations within the same regime, for semi-finish ($i_e = 11\,A$, $t_e = 56\,\mu s$) and rough ($i_e = 37\,A$, $t_e = 180\,\mu s$) regimes, are related to the higher surface roughness obtained as the discharge energy ($W_e \approx u_e.i_e.t_e\,[mJ]$) applied is increased. In these regimes, with higher values

of W_e, the dielectric fluid is more contaminated with EDM byproducts and flows in the working gap in a turbulent way. This fact then provides non-uniform material removal around the cavity, causing such circularity deviation. On the other hand, in finish regime ($i_e = 4$ A, $t_e = 13$ μs), where low discharge current is used, less material is removed from the workpiece. So, lower surface roughness is achieved along with both a more uniform flow and less contaminated dielectric fluid. This fact is responsible for the lower circularity deviation in this ED-machining regime. The aforesaid performance occurred in the same way for both electrode grades (CuW65 and CuW85), as presented in Table 3.

Table 4 presents an ANOVA for WC-Co workpiece circularity when ED-Machining under rough, semifinish and finish ED-Machining with CuW65% and CuW85% electrodes, in order to identify the most significant parameters. The input data selection was defined in ED-Machining system variables: CuW electrodes grades, general error of electrodes circularity and selected ED-Machining regimes. The ANOVA results show an error of 8.4%, which means that the relational analysis results have an accuracy of 91.6% in significant level of 95%. From the ANOVA table, it is evidently seen that ED-Machining regimes (88.99%) plays a

major role in determining the WC-Co workpiece circularity. The influence of the two CuW electrode grades on WC-Co circularity was not significant.

In order to validate the ANOVA results a standardized residual analysis was carried out to verify that there is no distribution of occurrences with respect to the reference line in Figure 6a. A second test, shown in Figure 6b, was done to check if there is a trend among the factors. It is observed that the greater the dispersion the lower the trend on the variables. So, it means that the ANOVA treatment can be considered as valid.
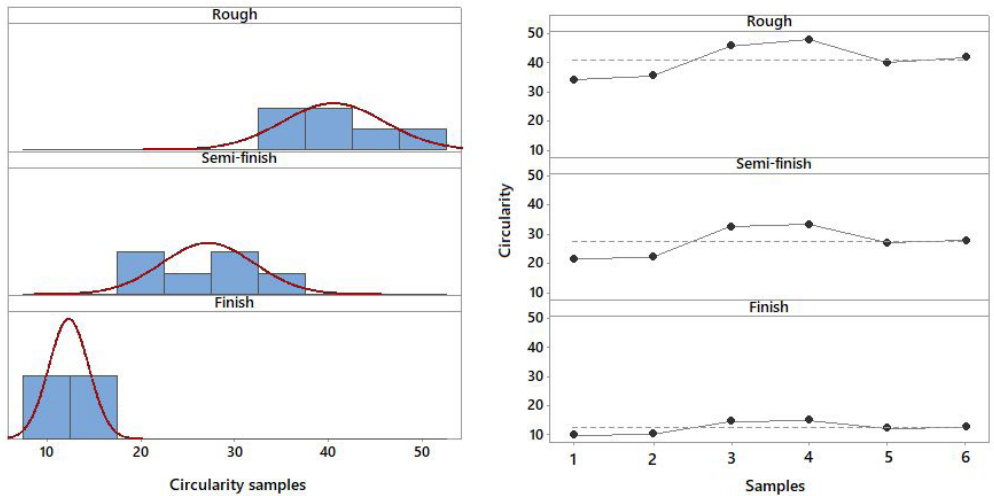
Figure 7 shows the 3D topography and WC-Co workpiece surface roughness results for ED-machining under rough

Table 3. WC-Co workpiece circularity deviations for rough, semifinish and finish ED-Machining using CuW65% and CuW85% electrodes.

Regime	Average Circularity [μm]	
	CuW65	CuW85
Rough	39.712 ± 5.829	41.430 ± 6.174
Semi-finish	26.858 ± 5.527	27.572 ± 5.557
Finish	12.193 ± 2.383	12.599 ± 2.340
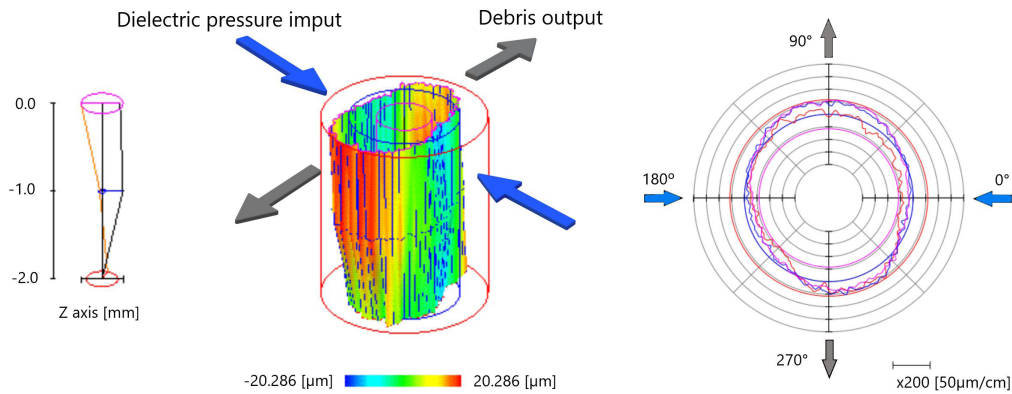
Figure 4. 3D circularity representation for rough EDM regime ($i_e = 37$ A, $t_e = 180$ μs).

Figure 5. Distribution of circularity [μm] for rough ($i_e = 37$ A, $t_e = 180$ μs), semi-finish ($i_e = 11$ A, $t_e = 56$ μs) and finish regimes ($i_e = 4$ A, $t_e = 13$ μs).

Table 4. ANOVA table for ED-Machining effects on WC-Co circularity.

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	13	4907,04	91,60%	4907,04	377,46	18,46	0,000
Blocks	2	128,90	2,41%	128,90	64,45	3,15	0,063
Linear	4	4775,32	89,14%	4775,32	1193,83	58,39	0,000
CuW Eletrode Alloy	1	0,00	0,00%	0,00	0,00	0,00	1,000
Electrode Error	1	8,05	0,15%	8,05	8,05	0,39	0,537
EDM Regime	**2**	**4767,26**	**88,99%**	**4767,26**	**2383,63**	**116,58**	**0,000**
2-Way Interactions	5	2,82	0,05%	2,82	0,56	0,03	1,000
Alloy*Electrode Error	1	0,00	0,00%	0,00	0,00	0,00	1,000
Alloy*Regime	2	0,00	0,00%	0,00	0,00	0,00	1,000
Electrode Error*Regime	2	2,82	0,05%	2,82	1,41	0,07	0,933
3-Way Interactions	2	0,00	0,00%	0,00	0,00	0,00	1,000
Alloy*Electrode Error*Regime	2	0,00	0,00%	0,00	0,00	0,00	1,000
Error	22	449,81	8,40%	449,81	20,45		
Total	35	5356,85	100,00%				

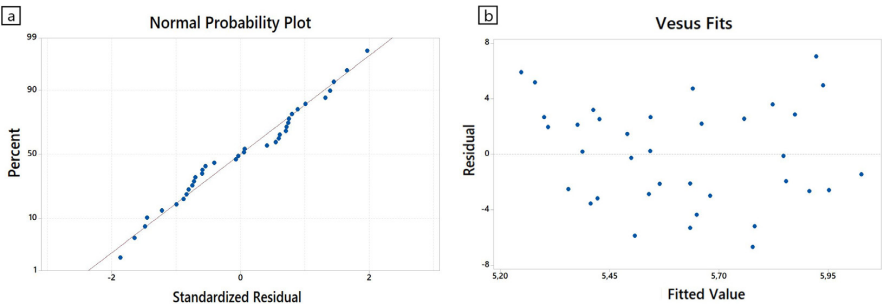| S	R-sq	R-sq(adj)	R-sq(pred)
4,52172	91,60%	86,64%	77,52%

Figure 6. Residual plots analysis for ANOVA treatment validation.

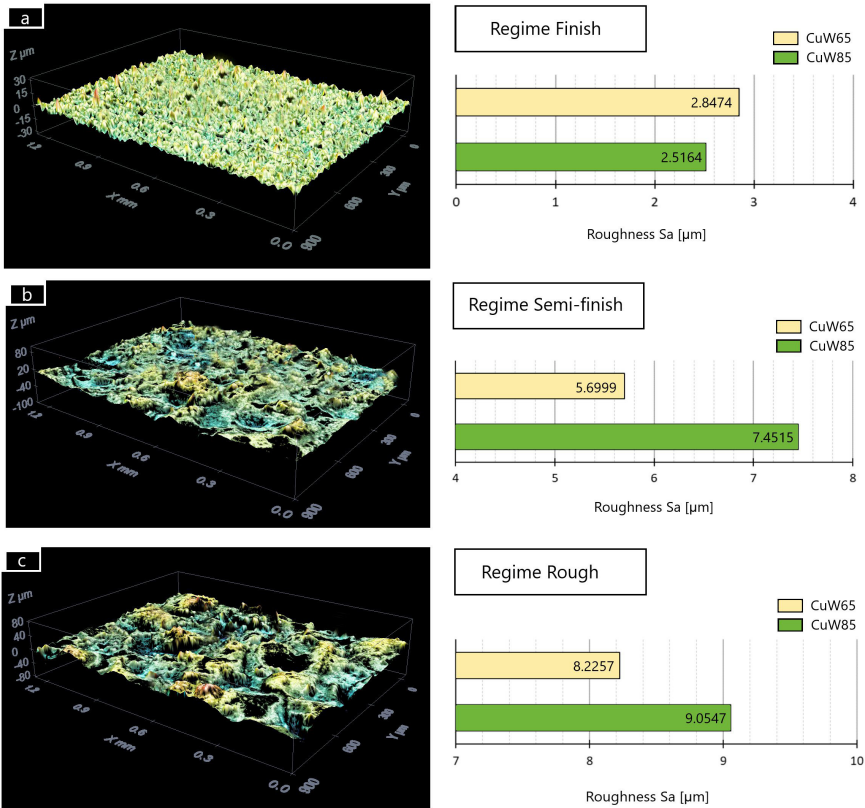**Figure 7.** 3D topography and WC-Co surface roughness Sa results for ED-Machining under (a) finish (i_e = 4 A, t_e = 13 µs), (b) semi-finish (i_e = 11 A, t_e = 56 µs) and (c) rough (i_e = 37 A, t_e = 180 µs) regimes using the two CuW electrodes grades (CuW65% and CuW85%).

Table 5. ANOVA table for ED-Machining effects on WC-Co workpiece surface roughness.

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	13	231,3	99,98%	231,3	17,792	9734,8	0,000
Blocks	2	0,003	0,00%	0,003	0,001	0,73	0,493
Linear	4	224,76	97,16%	224,76	56,19	30744	0,000
CuW Eletrode Alloy	1	0	0,00%	0	0	0	1,000
Electrode Error	1	5,061	2,19%	5,061	5,061	2768,9	0,000
EDM Regime	2	219,7	94,77%	219,7	109,85	60103	0,000
2-Way Interactions	5	6,534	2,82%	6,534	1,307	715	0,000
Alloy*Electrode Error	1	0	0,00%	0	0	0	1,000
Alloy*Regime	2	0	0,00%	0	0	0	1,000
Electrode Error*Regime	2	6,534	2,82%	6,534	3,267	1787,5	0,000
3-Way Interactions	2	0	0,00%	0	0	0	1,000
Alloy*Electrode Error*Regime	2	0	0,00%	0	0	0	1,000
Error	22	0,04	0,21%	0,04	0,002		
Total	35	231,34	100,00%				

S	R-sq	R-sq(adj)	R-sq(pred)
0,0428	99,78%	99,77%	99,75%
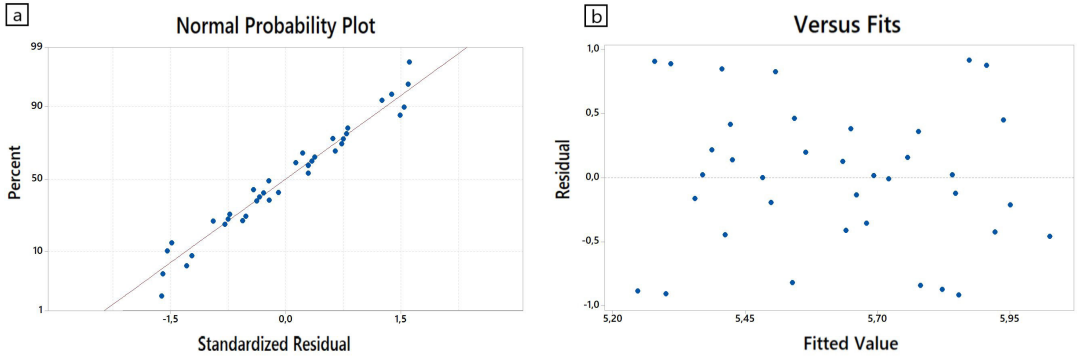
Figure 8. Residual plots analysis for ANOVA treatment validation.

(i_e = 37 A, t_e = 180 μs), semi-finish (i_e = 11 A, t_e = 56 μs) and finish regimes (i_e = 4 A, t_e = 13 μs), using the two CuW electrodes grades (CuW65% and CuW85%). An area of 1.200 mm^2 was scanned and the 3D surface roughness Sa (average height of selected area) was measured. Regardless the CuW electrode grade is possible to observe that from rough to finish regimes the workpiece surface roughness is improved as the discharge energy ($W_e \approx u_e.i_e.t_e$ [mJ]) decreases. In this work for roughing, semi-finish and finish ED-machining regimes the WC-Co workpiece surface roughness Sa of about 9.0-8.2 μm, 7.4-5.7 μm and 2.5-2.8 μm, respectively for electrodes CuW85 and CuW65, was obtained. Is possible to verify that for both CuW electrode grades the roughness Sa becomes higher as the discharge current i_e increases, which is due to the formation of larger and deeper craters on the workpiece surface.

An analysis of variance (ANOVA) is given in Table 5 for WC-Co workpiece surface roughness. The ANOVA results show an error of 0,2%, which means that the relational analysis results have an accuracy of 99.7% in significant level of 95%. The output ANOVA results clearly show that ED-Machining regime (94.7%) plays a major role in determining the WC-Co workpiece surface roughness. The two CuW electrode grades (CuW65 and CuW85) do not have significant influences on surfaced roughness.

In order to validate the ANOVA results a standardized residual analysis was carried out to verify that there is no distribution of occurrences with respect to the reference line in Figure 8a. A second test, shown in Figure 8b, was done to check if there is a trend among the factors. It is observed that the greater the dispersion the lower the trend on the variables. So, it means that the ANOVA treatment can be considered as valid.

4. Conclusions

This work investigated the electrical discharge machining (EDM) of cemented carbide (WC-Co) with 10% Co using two grades of coper-tungsten (CuW) electrodes with 65% and 85% of tungsten. The output variables analyzed were the WC-Co workpiece geometrical characteristics 3D surface roughness and round cavities circularity measures under rough, semifinish and finish ED-machining. From the results the following conclusions can be presented: (i) CuW electrode grades (CuW65% and CuW85%) has slightly influences on WC-Co workpiece roughness, (ii) ED-Machining regimes plays a major role in determining the WC-Co workpiece circularity and surface roughness measures, (iii) from finish to rough regimes, independently of CuW electrode grade, the circularity variation increases substantially, (iv) existence of circularity deviations within the same regime was observed, and such deviations are more prominent for the roughing

and semi-finishing regimes (v) regardless the CuW electrode grade is observed that from rough to finish regimes the workpiece surface roughness is improved as the discharge energy decreases and (vi) increased surface roughness contributes to increase circularity error.

5. Acknowledgements

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