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Statistical analysis of surface roughness of machined graphite by means of CNC milling

Análisis estadístico de la rugosidad superficial en el fresado CNC de grafito

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ABSTRACT

The aim of this research is to analyze the influence of cutting speed, feed rate and cutting depth on the surface finish of grade GSP-70 graphite specimens for use in electrical discharge machining (EDM) for material removal by means of Computer Numerical Control (CNC) milling with low-speed machining (LSM). A two-level factorial design for each of the three established factors was used for the statistical analysis. The analysis of variance (ANOVA) indicates that cutting speed and feed rate are the two most significant factors with regard to the roughness obtained with grade GSP-70 graphite by means of CNC milling. A second order regression analysis was also conducted to estimate the roughness average (R_a) in terms of the cutting speed, feed rate and cutting depth. Finally, the comparison between predicted roughness by means of a second order regression model and the roughness obtained by machined specimens considering the combinations of low and high levels of roughness is also presented.

Keywords: Graphite, factorial design, average roughness, percentage of predictive error.

RESUMEN

El objetivo de esta investigación es analizar la influencia de la velocidad de corte, la velocidad de avance y la profundidad de corte en el acabado superficial de probetas de grafito grado GSP-70, para su uso en la remoción de material mediante descarga eléctrica (EDM), generadas mediante el proceso de fresado de control numérico computarizado (CNC) con velocidades bajas de maquinado (LSM). Para el análisis estadístico, se utilizó un diseño factorial con dos niveles en cada uno de los tres factores establecidos. Del análisis de varianza (ANOVA) calculado, se obtuvo que la velocidad de corte y la velocidad de avance son los factores más significativos en la rugosidad obtenida en el grafito grado GSP-70 usando fresado CNC. Así mismo, se realizó un análisis de regresión de un modelo de segundo orden para estimar la rugosidad media (R_a) en términos de la velocidad de corte, velocidad de avance y profundidad de corte. Por último, se presenta la comparación entre la rugosidad estimada mediante el modelo de regresión de segundo orden y la rugosidad obtenida de las probetas maquinadas considerando las combinaciones de menor y mayor rugosidad.

Palabras clave: Grafito, diseño factorial, rugosidad media, porcentaje del error predictivo.

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Introduction

Graphite is a crystalline allotrope of carbon, similar to the diamond, graphene and carbon nanotubes. It is widely used in the production of lubricants, refractory crucibles, motor brushes, electrodes for metal casting and various components for nuclear reactors (Fatimahtul, 2009; Menéndez, 2012). Graphite is a porous and fragile mineral. It does not react to chemical elements at room temperature, does not dilate at high temperatures and conducts a high amount of heat and electricity (Campubrí, 2007; Wardono, Xue Fang & Minhat, 2011). These qualities make graphite the most versatile and widely used non-metallic material in the metalworking industry, specifically in the production of electrodes used for electrical discharge machining (EDM) for material removal by means of penetration (Bertrand, Kratochvil & de Olivera, 2006; Singh & Kumar, 2012).

Electrodes manufactured with graphite are beneficial to EDM for material removal due to their high productivity, minimal tool wear and their light weight (Bertrand *et al*., 2006; Klocke, Schwade, Klink & Veselovac, 2013). Graphite

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used for EDM is classified according to mean grain size, as each type has microstructures and unique characteristics that depend on the orientation and size of the particle material. Angstrofino graphite (<1 μm) and ultrafine graphite (1 μm – 5 μm) are used in the production of cavities with fine detail and tight tolerances. Additionally, superfine graphite (6 μm – 10 μm) and fine graphite (11 μm – 20 μm) are used in the production of cavities with modest detail (Sommer & Sommer, 2005).

Graphite electrodes produced for EDM are mainly used in the manufacture of molds and dies to make electrical, electronic and automotive components (Ho & Newman, 2003; Wang, Zhou, Fu & Hu, 2007). Graphite electrodes are normally made by means of CNC milling using solid carbide cutting tools with some type of coating or polycrystalline diamond (PCD). This process facilitates the production of complex geometries with fine finishes and exact dimensions (Kratochvil, 2004; Bertrand *et al*., 2006). However, the natural abrasiveness of graphite for EDM can severely wear down cutting tools, and as such, the surface integrity and geometric accuracy of the machined parts cannot be guaranteed (Wang *et al*., 2007; Aliyev & Hentschel, 2010).

The surface roughness is a parameter used to evaluate the quality of the mechanical parts which predominantly affects its functionality and production costs (Mata-Cabrera, Hanafi, Khamlichi, Jabbouri & Bezzazi, 2013; Schultheiss, Hägglund, Bushlya, Zhou & Ståhl, 2014). The roughness average (R_a) states the mean roughness value in the machined zone. This is the most used parameter of roughness value due to its practicality, and is calculated with the Equation (1):

$$R_a = \frac{1}{Ln}\int_0^{Ln} Z(x)\ dx \qquad (1)$$

where *Ln* is the evaluation length and *Z* is the distance between two points of the profile (ASME, 1995).

The surface roughness of the machined parts with graphite by means of CNC milling is of particular importance since surface defects generated are then transferred on to the EDM process. This has led to studies researching the cutting parameters which most affect the graphite during the CNC milling process with the aim of improving the surface finish of the electrodes. Yung-Kuang, Ming-Tsan & Show-Shyan (2009) used orthogonal matrices and ANOVA to study the influence of cutting parameters on the surface finish and tool wear from graphite grade ISO-800 (8 μm) by means of CNC milling for EDM employing solid carbide cutting tools. It was discovered that low feed rates increase the wear on the flanks of the cutting tools but produce a finer surface finish. On the other hand, Wardono *et al*. (2011) used two-level factorial designs and analysis of ANOVA to examine the effect of cutting parameters on the surface finish of graphite by means of CNC milling for EDM with shore hardness 32 and 76, using solid carbide cutting tools. It was discovered that high cutting speeds combined with low feed rates led to better surface finishes.

There are some cutting tools catalogs, technical manuals and technical sheets for EDM, which provide some approximate values for the parameters, to carry out the machined graphite by means of CNC milling, but it does not indicate the surface roughness obtained under the recommended conditions (Table 1).

Experimentation is a key element in understanding the behavior of physical phenomena, and consists of deliberately changing system variables in order to observe and identify variations. Experimentation is used in two industries: design and improvement of process and products (Montgomery, 2004; Tanco, Viles, Ilzarbe & Álvarez, 2007). The techniques of Design of Experiments (DOE) analyze the individual effects and interactions of various factors of any given process that is studied. DOE requires relatively few resources and provides information that can be used to model the process behavior and determine the combination of variable levels that improves performance (Montgomery, Peck & Vining, 2006; Gutiérrez & de la Vara, 2008).

Table 1. Parameters used in machining graphite by means of CNC milling.

Parameters	Values interval
Cutting speed (m/min)	• High speed steel 30-90, carbide 150-210 and diamond 150-600 (Poco Graphite Inc., 2006). • Roughing 100-250, finishing 50-70 (Campubrí, 2007). • Hard metal, polycrystalline diamond, coated hard metal 800-1000 (roughing), hard metal, polycrystalline diamond, coated hard metal 1000 (finishing) (Toyo Tanso Group Company, 2008). • General and finish 60-900 (SP3 Diamond Cutting Tools, 2011). • Roughing 800-1000, finishing 1000 (Mersen, 2011).
Feed rate	• Roughing 100-250 mm/min, finishing 100-300 mm/min (Campubrí, 2007). • Hard metal, polycrystalline diamond, coated hard metal 0,1-0,8 mm/tooth (roughing), hard metal, polycrystalline diamond, coated hard metal <0,08 mm/tooth (finishing) (Toyo Tanso Group Company, 2008). • General 0,025-0,130 feed per tooth in mm, finish 0,015-0,075 feed per tooth in mm (SP3 Diamond Cutting Tools, 2011). • Roughing 0,1-0,8 mm/tooth, finishing <0,09 mm/tooth (Mersen, 2011)
Cutting depth	• Up 5 times tool diameter (Campubrí, 2007).

This study used a factorial design 2^3 in order to analyze the influence of cutting speed, feed rate and cutting depth on the surface finish of grade GSP-70 (20 μm) graphite specimens for use in EDM by means of CNC milling with low-speed machining (LSM). The link between the cutting variables and roughness average (R_a) by means of a second order regression model was estimated, which was validated using ANOVA and calculating the percentage prediction error (PE %). Likewise, the level for each factor which produces the lowest surface roughness was determined.

Method and material

Design of experiments

A two-level factorial design was used with three factors concerned: cutting speed (CS, m/min), feed rate (FR, mm/min) and cutting depth (CD, mm). Therefore, a two-level factorial design with three factors (2^3) was selected consistent with 8 combinations for the factor levels, producing two replicas for each combination. The low and high levels for each factor were codified as −1 y +1 respectively. Based on the values established in the factorial design, the alphanumeric codes programs were developed for CNC milling.

Table 2 displays the factors with levels used in the studio; the selection of the feed rate and the cutting depth is based on the recommendation from the manufacturer of the end cutter shown in Table 1, and the cutting speed is based on the machining center specification.

Table 2. Factors and levels used.

Factors	Levels	
	Low (-1)	High (1)
Cutting speed (CS, m/min)	40	120
Feed rate (FR, mm/min)	150	250
Cutting depth (CD, mm)	0,50	2,50

Machine tool used

The experiments were conducted without coolant in a CNC Modern Tool Ltd. vertical machining center, the Challenger MM-430 model with a 15 KW motor, a maximum cutting speed of 8000 rpm, a 16 tool magazine and an operating system with FAGOR® control. Figure 1 displays the schematic of the machine tool used in this study.

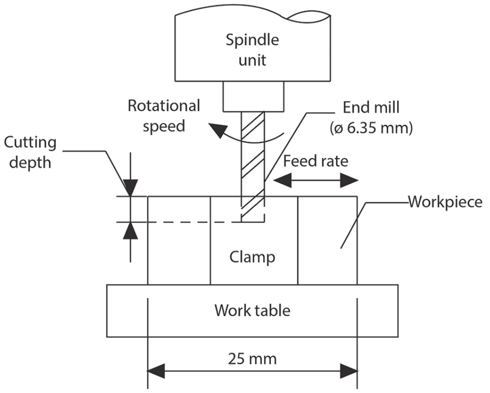


Figure 1. Schematic of machining.

Cutting tool used

A T&O® solid carbide vertical cutting tool was used with X-FACTOR® coating, four flutes with a 6,35 mm diameter.

Workpiece material

The grade GSP-70 graphite is an isotropic fine grain material with high purity and density levels, and as such is an ideal element to use with tasks involving EDM and other applications. Its most significant properties are displayed in Table 3. Grade GSP-70 graphite specimens were made for EDM with dimensions of 170 mm × 25 mm × 10 mm.

Table 3. Physical properties of the test material.

Properties	Value
Average grain size	20 µm
Hardness	80 shores
Density	1,85 g/cm³
Tensile strength	78 MPa
Compressive strength	189 MPa
Electrical resistively	1800 µΩ/cm
Ash	0,10 %

Results and discussion

Based on the values established in the factorial design, machined surfaces were produced for each combination of levels of CS, FR and CD. The roughness average (R_a, µm) of the machined surfaces was measured with a Mitutoyo SJ-402 series 178 profilometer. The results of the experiment of design 2^3 mentioned in this study are displayed in Table 4.

Regression model

The second order model related to the roughness average (R_a) and machining variables (CS, FR y CD) generated in terms of the levels codified of the aforementioned variables is displayed in Equation (2).

$$\begin{aligned} R_a = {} & 1{,}36938 - 0{,}255625 * VC + 0{,}150625 * VA \\ & + 0{,}078125 * PC - 0{,}146875 * VC * VA \\ & + 0{,}030625 * VC * PC - 0{,}000625 * VA * PC \end{aligned} \tag{2}$$

Table 4. Results of experiments.

Exp. No.	CS (m/min)	FR (mm/min)	CD (mm)	R_a (µm)	
1	−1	−1	−1	1,42	1,17
2	1	−1	−1	0,97	1,00
3	−1	1	−1	1,92	1,80
4	1	1	−1	0,90	1,15
5	−1	−1	1	1,32	1,40
6	1	−1	1	1,40	1,07
7	−1	1	1	1,90	2,07
8	1	1	1	1,07	1,35

Table 5 shows the ANOVA produced to check the adequacy of the second order. It can be noted that the P value is less than a = 0,05, which means that the model possesses a confidence level of 95 % that represents the relationship between roughness average (R_a) and machining variables (CS, FR and CD).

Table 5. ANOVA for the regression model.

Source	Degrees of Freedom	Sum of Squares	Mean Square	F_0	P-Value
Regression	6	1,86636	0,31106	15,10	0,000307
Residual Error	9	0,18536	0,02059	–	–
Total	15	2,0517	–	–	–

In Table 6, the ANOVA for the individual model coefficients is displayed. It can be noted that there are three effects with P-Value inferior to a = 0,05, meaning that these are indications of a confidence level of 95 %. These significant effects are: cutting speed (CS), feed rate (FR) and the interaction between cutting speed and feed rate (CS*FR).

Table 6. ANOVA for the R_a (µm).

Source	Degrees of Freedom	Sum of Squares	Mean Square	F_0	P-Value
CS	1	1,04551	1,04551	50,77	0,000055
FR	1	0,36301	0,36301	17,63	0,002312
CD	1	0,09766	0,09766	4,74	0,057403
CS*FR	1	0,34516	0,34516	16,76	0,002702
CS*DC	1	0,01501	0,01501	0,72	0,415468
FR*DC	1	0,00001	0,00001	0,00	0,986481
Error	9	0,18536	0,02059	–	–
Total	15	2,05172	–	–	–

In addition to this, the coefficient of determination $R^2 = 90,97\%$ obtained through the ANOVA explains the amount of reduction in the Ra variability obtained using the machining variables (CS, FR and CD) in the model.

On the other hand, it can be observed in Figure 2 that the residues from roughness average are in line with normal distribution and the second order regression model has extracted all the information available from the experiment data.

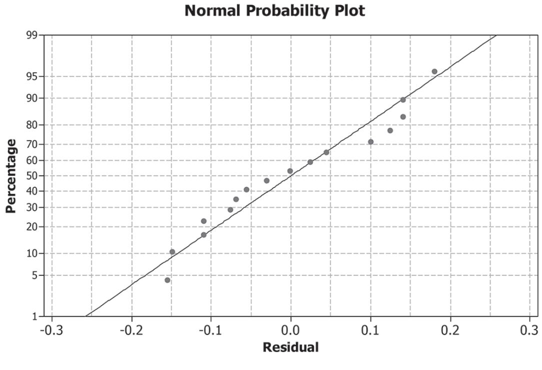


Figure 2. Normal probability plot of the residuals.

Main effects

Figure 3 displays graphical representations of the main effects of roughness average (R_a) and the variables of the experimental design (CS, FR and CD). Figure 3a shows that the levels of cutting speed (CS) significantly influence the roughness average (R_a), as increased cutting speed reduces roughness average. In Figure 3b one can observe that roughness average increases as the feed rate (FR) increases, meaning that feed rate can significantly affect roughness average. Figure 3c shows that cutting depth does not affect roughness average (R_a) as there is no significant variation between the mean data for each variable level.

Cube plot

The cube plot in Figure 4 shows that the lowest average figure for roughness average is 0.985 µm between the 8 combinations of levels for the experiment variables, obtained with levels 1(120 m/min), -1 (150 mm/min) and -1 (0,5 mm) for CS, FR and CD respectively. The highest R_a value is 1,985 µm, obtained through a combination of -1, 1 y 1, which corresponds to CS of 40 m/min, FR of 250 mm/min and CD of 2,50 mm.

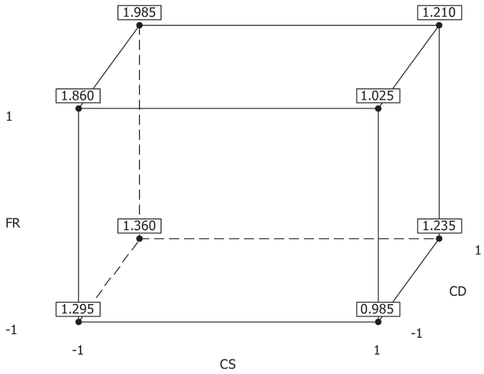
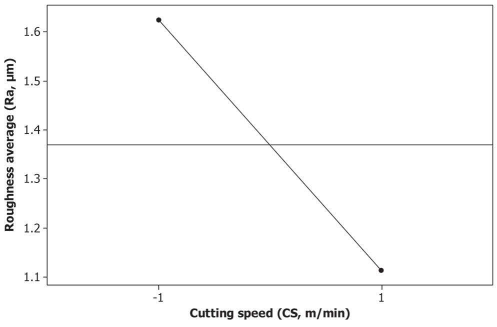


Figure 4. Cube plot (data means) for R_a.

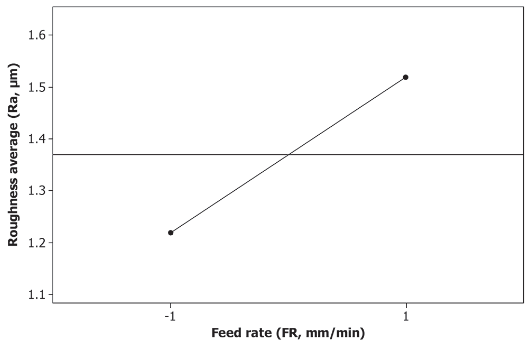
Tests to check the regression model

To check the second order regression model which measures roughness average, four further tests were conducted to compare roughness recorded from experiments with estimated roughness by means of percentage prediction error (PE%). The Equation (3) was used:

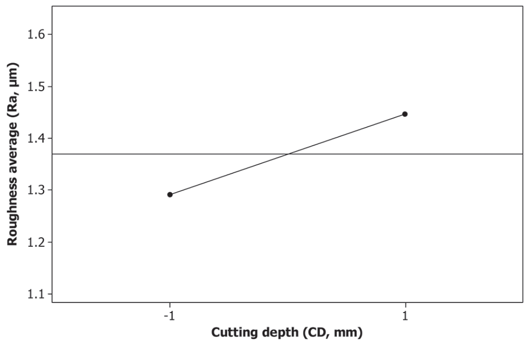
$$PE\% = \left|\frac{R_a \text{ experimental} - R_a \text{ predicted}}{R_a \text{ experimental}}\right| * 100 \qquad (3)$$



(a) Cutting speed (CS)



(b) Feed rate (FR)



(c) Cutting depth (CD)

Figure 3. Main effects for the R_a (µm) and the variables of the experimental design (a) CS, (b) FR and (c) CD.

In Table 7, the results from four machined tests are displayed taking into account cutting variable levels with the lowest values of surface roughness in the factorial design. According to Table 6, the second order regression model for R_a gives acceptable results with a percentage prediction error of 2,05% between the estimated values and experiment data.

Table 7. Machined tests with the lowest values of predicted R_a.

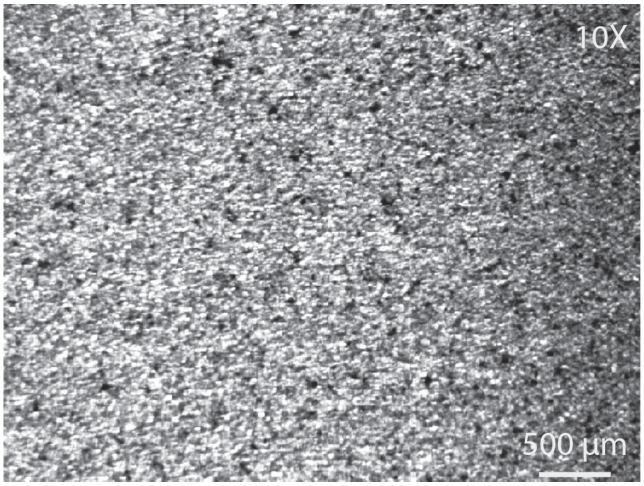
Exp. No.	CS (m/min)	FR (mm/min)	CD (mm)	Predicted R_a (µm)	Experimental R_a (µm)	PE%
1	1	-1	-1	0,985	0,97	1,55
2	1	-1	-1	0,985	1,00	1,50
3	1	-1	-1	0,985	0,95	3,68
4	1	-1	-1	0,985	1,00	1,50

Table 8 shows the estimated roughness and roughness recorded from experiments in which the levels of machining variables produced the greatest amount of surface roughness. With an average percentage prediction error of 2,14 % between estimated values and those from experiments, it can be observed that the predictions of the second order regression model are reasonable.

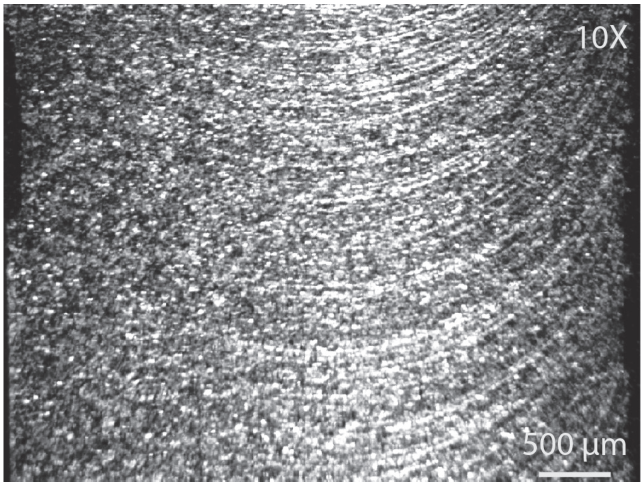
Figure 5 displays the differences between the surface finishes obtained under different cutting conditions. Figure 5a shows a surface roughness micrograph of 0,95 µm machined at a cutting speed (CS) of 120 m/min, a feed rate (FR) of 150 mm/min and a cutting depth (CD) of 0,50 mm. Likewise, Figure 5b displays a surface finish micrograph with a value of 2,05 µm obtained with a cutting speed (CS) of 40 m/min, a feed rate (FR) of 250 mm/min and a cutting depth (CD) of 2,50 mm.

Table 8. Machined tests with the highest values of predicted R_a.

Exp. No.	CS (m/min)	FR (mm/min)	CD (mm)	Predicted R_a (µm)	Experimental R_a (µm)	PE%
1	-1	1	1	1,985	1,95	1,80
2	-1	1	1	1,985	1,95	1,80
3	-1	1	1	1,985	2,05	3,17
4	-1	1	1	1,985	1,95	1,80



(a) $R_a = 0,95$ µm



(b) $R_a = 2,05$ µm

Figure 5. Surfaces roughness micrograph.

Conclusion

The following conclusions are based on the experiment results, the ANOVA, the second order regression model and tests conducted for the present work.

- The factorial design 2^3 used in this study is an effective tool to study the influence of cutting parameters on the surface roughness of grade GSP-70 graphite, generated by means of CNC milling with low-speed machining (LSM).

- The cutting speed (CS) and feed rate (FR) are the most significant factors with a confidence level of 95 % on CNC milling of grade GSP-70 graphite.

- The surface roughness of the grade GSP-70 graphite decreased with a high cutting speed (CS) and a low feed rate (FR). It is recommended that the CNC milling of grade GSP-70 graphite is carried out with a low-speed machining (CS) of 120 m/min, a feed rate (FR) of 150 mm/min and a cutting depth (CD) of 0,50 mm in order to obtain low surface roughness.

- The normal probability plot shows that the residuals follow a straight line, which implies that the residuals are distributed normally, therefore the adequacy of the regression model is validated.

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