DOI: http://dx.doi.org/10.15446/ing.investig.v38n2.67711

An experimental study of surface roughness in electrical discharge machining of AISI 304 stainless steel

Estudio experimental de la rugosidad superficial del acero inoxidable AISI 304 maquinado por descarga eléctrica

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ABSTRACT

The effect of the pulse current, pulse on time and pulse off time on the surface roughness of AISI 304 stainless steel workpieces produced by electric discharge machining (EDM) using grade GSP-70 graphite electrodes was studied. A factorial design was performed, considering two levels for each of the three established parameters. From the statistical analysis, it was obtained that the pulse current and pulse on time are the most significant machining parameters on the obtained surface roughness values of the stainless steel AISI 304 workpieces machined by EDM. On the other hand, the regression analysis of a second order model was done to estimate the average roughness (R_a) in terms of the pulse current, pulse on time and pulse off time. Finally, the mean absolute percentage error (MAPE) of the roughness values estimated by the second order regression model and the roughness obtained experimentally is also presented.

Keywords: AISI 304 stainless steel, electric discharge machining, factorial design, average roughness.

RESUMEN

En este artículo se presenta el estudio del efecto de la intensidad de la corriente eléctrica, tiempo de pulso y tiempo inactivo en la rugosidad superficial del acero inoxidable AISI 304 generada mediante el maquinado por descarga eléctrica (MDE), empleando electrodos de grafito grado GSP-70. Se realizó un diseño factorial, considerando dos niveles para cada uno de los tres factores establecidos. Del análisis estadístico se obtuvo que la intensidad de la corriente eléctrica y el tiempo de pulso son los parámetros de maquinado más significativos en la rugosidad superficial del acero inoxidable AISI 304 obtenida por MDE. Por otra parte, se hizo el análisis de regresión de un modelo de segundo orden para estimar la rugosidad media (R_a) en términos de la intensidad de la corriente eléctrica, tiempo de pulso y tiempo inactivo. Por último, se presenta el error porcentual absoluto medio (EPAM) de la rugosidad estimada mediante el modelo de regresión de segundo orden y la rugosidad obtenida experimentalmente.

Palabras clave: Acero inoxidable AISI 304, maquinado por descarga eléctrica, diseño factorial, rugosidad media.

Received: September 12th 2017
Accepted: May 4th 2018

Introduction

The term *nontraditional machining* refers to the group of processes that uses other mechanisms to remove material from the workpiece by various techniques involving mechanical, thermal, electrical, chemical energy or combinations of these energies. Electric discharge machining (EDM) is one of the most widely used nontraditional processes. The shape of the finished work surface is produced by a formed electrode tool (Groover, 2013), connected to a DC power supply and placed in a dielectric fluid, a transient spark discharges through the fluid, removing a very small amount of metal from the workpiece surface (Kalpakjian & Schmid, 2014). The relation between EDM machining parameters and surface finish has been investigated. Some EDM machining parameters were studied, which are shown in Table 1, as well as the materials of the workpiece and electrode.

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How to cite: Hernández-Castillo, I., Sánchez-López, O., Lancho-Romero, G. A., Castañeda-Roldán, C. H. (2018). An experimental study of surface roughness in electrical discharge machining of AISI 304 stainless steel. Ingeniería e Investigación, 38(2), 90-96.
DOI: 10.15446/ing.investig.v38n2.67711

Table 1. Investigations on EDM process

Researchers	Parameters	Workpiece material	Electrode material
Tzeng & Cheng (2003)	Powder concentration Pulse-on time Duty cycle Pulsed peak current Open circuit voltage Regular height for electrode lift Time interval for electrode lift Server speed	Medium-carbon steel	Electrolytic copper with 99% purity
Petropoulos, Vaxevanidis & Pandazaras (2004)	Pulse current Pulse-on time	Carbon steel CK60	Electrolytic copper
Puertas, Luis & Álvarez (2004)	Intensity Pulse time Duty cycle	Ceramic material 94WC-6Co	Electrolytic copper
Ramasawmy & Blunt (2004)	Pulse current Pulse duration Area of electrode	Steel (0.38% C, 16%Cr)	Not reported
Mandal, Pal & Saha (2007)	Current Pulse on time Pulse off time	CK40 Steel	Copper (electrolytic grade)
Shabgard & Shotorbani (2009)	Work peak current Pulse-on time Voltage	FW4 welded tool steel	Graphite EC-16
Sidda Reddy, Srinivasa Rao, Suresh Kumar & Vijaya Kumar Reddy (2010)	Current Open- circuit voltage Servo Duty cycle	AISI 304 stainless steel	Copper
Mohamad, Siddiquee, Quadir, Khan & Saini (2012)	Pulse-on time Duty factor Discharge current	High Strength Low Alloy (HSLA) Steel	Pure copper rod
Zeng, Wang, Wang, Shan & He (2012)	Open voltage Servo reference voltage Discharge current Discharge duration Pulse interval time Capacitance Diameter of electrode Rotation of electrode	AISI 304 stainless steel	Tungsten rod
Aranvindan & Rajendran (2013)	Pulse on time Pulse off time Pulse current	EN 31 tool steel	Copper rod
Bhaumik & Maity (2017)	Peak current Pulse on time Gap voltage Duty cycle Powder concentration	AISI 304 stainless steel	Tungsten carbide
Buschaiah, Jagadeeswara Rao & Krishnaiah (2018)	Current Pulse on time Electrode diameter	AISI 304 stainless steel	Copper

Source: Authors

This study used the factorial design 2^3 in order to analyze the influence of the selected input parameters including, the pulse current, the pulse on time and the pulse off time on the surface finish of stainless steel AISI 304 specimens by using the EDM processes. The relation between the machining parameters and average roughness (R_a) by means of a second order regression model was estimated, which was validated by using the analysis of variance (ANOVA) and calculating the mean absolute percent error (MAPE) technique. Likewise, the level for each input parameter which produces the lowest surface roughness was determined.

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 parameters 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 parameters levels that improves the performances (Montgomery, Peck & Vining, 2006; Gutiérrez & de la Vara, 2008).

Surface roughness

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 average roughness (R_a) is the arithmetical mean of the examined roughness value in the machined zone. This is the most used parameter of roughness value due to its practicality, and it can be calculated by using the Equation (1):

$$R_a = \frac{1}{Ln}\int_0^{Ln} |Z|\, dx \tag{1}$$

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

Method and material

Equipment and material used in the experiments

The die-sinking EDM machine of type Surefirst ED-203 was used in to machining of stainless steel workpieces as shows in Figure 1.

In the study, AISI 304 stainless steel was selected as the workpiece material, the specimens were made with dimensions of 100 mm x 25 mm x 6,35 mm. This steel is frequently used for chemical and food processing equipment; brewing equipment; cryogenic vessels; gutters; downspouts; flashings (Oberg, Jones, Horton & Ryffel, 2008). Its main properties are displayed in Table 2.

Table 2. Properties of the workpiece material

Properties	Value
Condition	Annealed
Tensile Strength	85 000 psi
0,2 Per Cent Yield Strength	35 000 psi
Elongation in 2 inches	55 %
Reduction of Area	65 %
Hardness Rockwell	B80
Hardness BHN	150

Source: Oberg *et al.*, 2008

Figure 1. The used EDM machine.
Source: Authors

Graphite is one of the most used electrode material for EDM applications, because of its good thermal and electric properties (Klocke, Schwade, Klink & Veselovac, 2013). The experiments in this study were conducted using grade GSP-70 graphite electrodes, they were made with dimensions of 30 mm x 10 mm x 13 mm, and a new electrode was used in each replica of the experimental design. 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. Table 3 displays the most significant properties of the used electrodes material.

Table 3. Properties of the electrodes material

Properties	Value
Average grain size	20 µm
Hardness	83 shores
Density	1,85 g/cm³
Tensile strength	51 MPa
Flexion strength	78 MPa
Electrical resistively	1 800 µΩ/cm
Ash	0,10%

Source: Grupo Rooe, 2018

Figure 2 shows the workpiece and electrode materials used in this investigation.

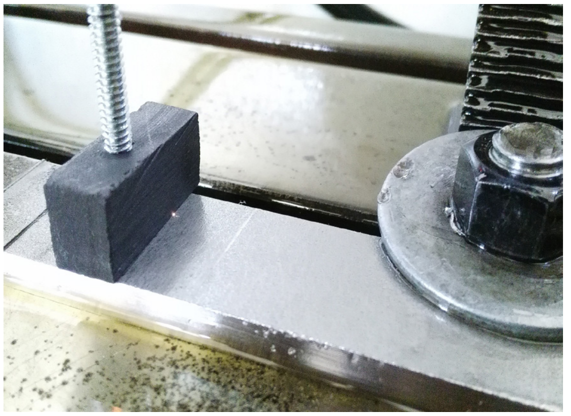


Figure 2. Workpiece and electrode materials.
Source: Authors

Design of experiments

The two-level factorial design was used in this study with the three parameters concerned: the pulse current (I_A, A), the pulse on time (T_{ON}, µs) and the pulse off time (T_{OFF}, µs). Therefore, a two-level factorial design with three factors (2^3) was selected consistent with eight combinations for the factor levels, producing two replicas for each combination. The low and high levels for each factor were codified as -1 and +1, respectively.

Table 4 displays the used factors of this work with their levels, which are established on the used electric-discharge machine.

Table 4. Factors and levels selected for the experiments

Factors	Levels	
	Low (-1)	High (+1)
Pulse current (I_A, A)	1,25	5,0
Pulse on time (T_{ON}, µs)	10	150
Pulse off time (T_{OFF}, µs)	1	3

Source: Authors

Analysis of surface roughness

The machined surfaces were produced for each combination of levels of I_A, T_{ON} and T_{OFF}, and then based on the factors values established in the factorial design. The average roughness (R_a, µm) of the machined surfaces was measured by using the Mitutoyo SJ-402 series 178 profilometer, as shown in Figure 3. The results of the experiment of design 2^3 technique mentioned in this study are displayed in Table 5.

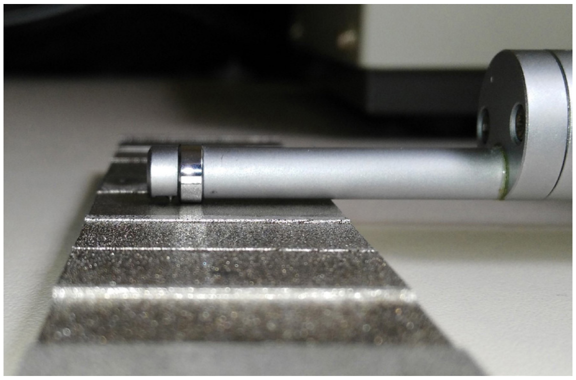


Figure 3. Machined surfaces and profilometer.
Source: Authors

Table 5. Design of experiments matrix for the second-order model

No.	I_A (A)	T_{ON} (µs)	T_{OFF} (µs)	R_a (µm)	
1	-1	-1	-1	3,10	3,90
2	+1	-1	-1	4,70	4,00
3	-1	+1	-1	2,24	2,28
4	+1	+1	-1	8,40	6,80
5	-1	-1	+1	2,54	3,42
6	+1	-1	+1	4,70	3,83
7	-1	+1	+1	3,12	2,53
8	+1	+1	+1	7,10	7,60

Source: Authors

Results and discussion

Regression model

The second order model related to the average roughness (R_a) and machining parameters (I_A, T_{ON} and T_{OFF}) generated in terms of the levels codified of the aforementioned parameters is displayed in Equation (2).

$$R_a = 4,39125 + 1,50000 * I_A + 0,61750 * T_{ON} - 0,03625 * T_{OFF} + 0,96625 * I_A * T_{ON} - 0,04750 * I_A * T_{OFF} + 0,11500 * T_{ON} * T_{OFF} \quad (2)$$

Table 6 shows the ANOVA results produced to check the adequacy of the second order. It can be noted that the P-value is less than $\alpha = 0,05$, which means that the model possesses a confidence level of 95%, that represents the relationship between average roughness (R_a) and machining parameters (I_A, T_{ON} and T_{OFF}).

Table 6. Analysis of Variance for the regression model

Source	Degrees of Freedom	Sum of Squares	Mean Square	F_0	P-Value
Regression	6	57,3078	9,5513	26,039	0,001
Residual Error	9	3,3011	0,3668		
Total	15	60,6089			

Source: Authors

In Table 7, the ANOVA analysis for the individual model coefficients is displayed. It can be noted that there are three parameters with P-value inferior to $\alpha = 0,05$, meaning that these are indications of a confidence level of 95%. These significant parameters are: the pulse current (I_A), the pulse on time (T_{ON}) and the interaction between them.

Table 7. Analysis of variance of R_a (µm)

Source of variation	Degrees of freedom	Sum of squares	Mean square	F-ratio	P-value
I_A	1	36,0000	36,0000	98,15	0,000
T_{ON}	1	6,1009	6,1009	16,63	0,003
T_{OFF}	1	0,0210	0,0210	0,06	0,816
I_A*T_{ON}	1	14,9382	14,9382	40,73	0,000
I_A*T_{OFF}	1	0,0361	0,0361	0,10	0,761
$T_{ON}*T_{OFF}$	1	0,2116	0,2116	0,58	0,467
Error	9	3,3011	0,3668		
Total	15	60,6089			

Source: Authors

In addition to this, the coefficient of determination R^2 = 94,55% obtained through the ANOVA technique explains the amount of reduction in the R_a variability obtained by using the machining parameters (I_A, T_{ON} and T_{OFF}) in the model.

On the other hand, it can be observed in Figure 4 that the residues from average roughness are in line with normal distribution and the second order regression model has extracted all the information available from the experiment data.

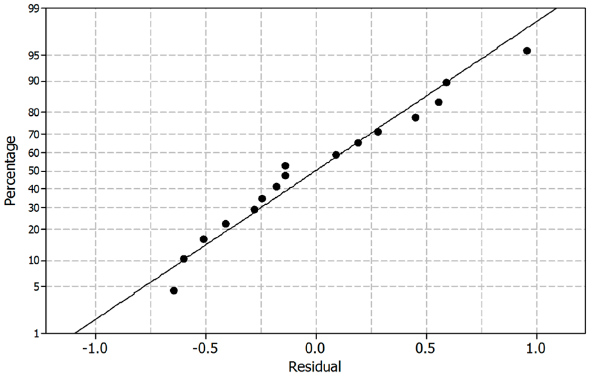
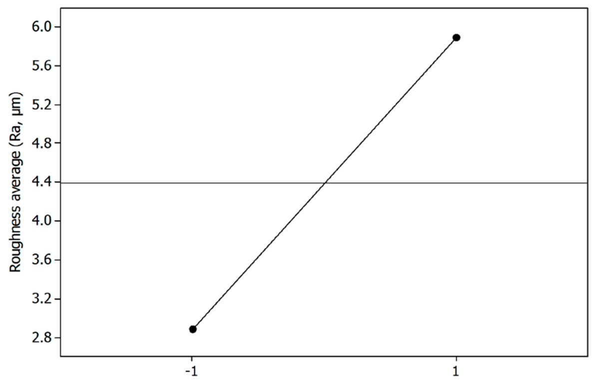


Figure 4. Normal probability plot of the residuals.
Source: Authors

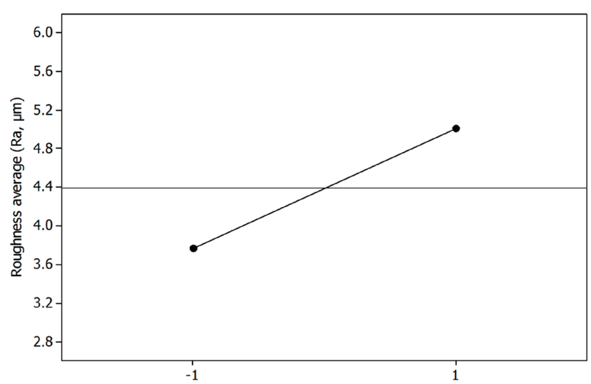
Main effects

Figure 5 displays the graphical representations of the main effects of the resulting average roughness (R_a) and the parameters of the experimental design (I_A, T_{ON} and T_{OFF}). Figure 5a shows that the levels of pulse current (I_A) significantly influence the obtained average roughness (R_a) values, and as increased the pulse current, the average roughness increased. In Figure 5b, it can be observed that the average roughness increases as the pulse on time (T_{ON})

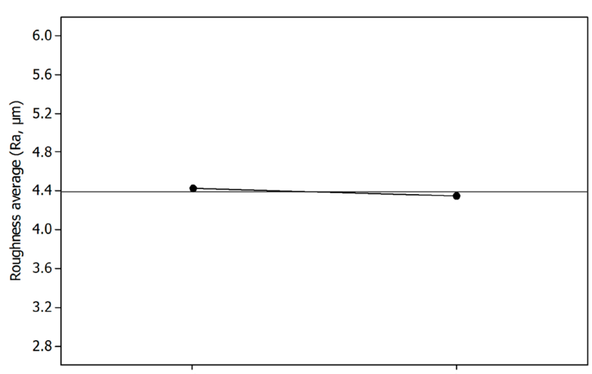
increases, meaning that the pulse current can significantly affect average roughness values. Figure 5c shows that the pulse off time does not affect the average roughness (R_a), as there is no significant variation between the mean data for each parameter level.



(a) Pulse current (I_A, A)



(b) Pulse on time (T_{ON}, µs)



(c) Pulse off time (T_{OFF}, µs)

Figure 5. Main effects for the R_a (µm) and the experimental parameters of the design (a) I_A, (b) T_{ON} and (c) T_{OFF}.
Source: Authors

Cube plot

The cube plot in Figure 6 shows that the lowest average figure for average roughness is 2,260 µm between the eight combinations of levels for the experiment parameters, obtained with levels -1(1,25 A), +1 (10 µs) and -1 (1 µs) for I_A, T_{ON} and T_{OFF}, respectively. The highest R_a value is 7,600 µm, obtained through a combination of 1, 1 and -1, which corresponds to I_A of 5,0 A, T_{ON} of 150 µs and T_{OFF} of 1 µs.

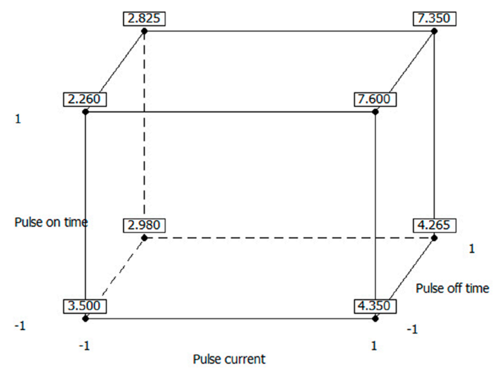
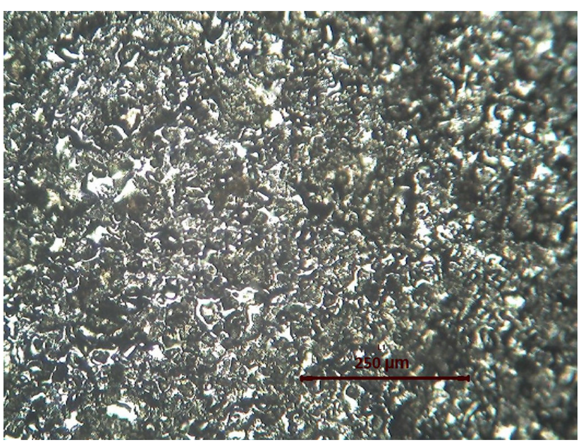
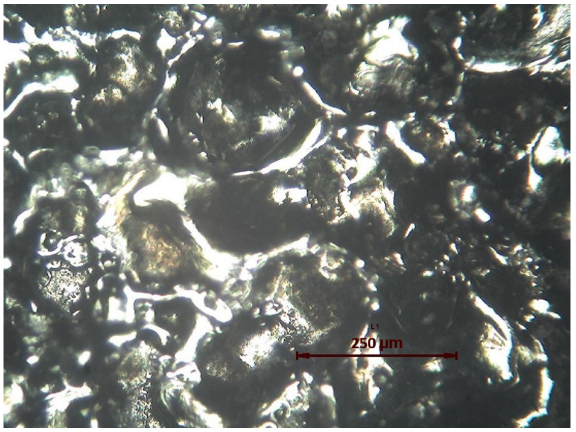


Figure 6. Cube plot (data means) for R_a.
Source: Authors

Figure 7 displays the differences between the surface finishes values obtained under different machining conditions. Figure 7a shows a surface roughness micrograph of 2,54 µm value machined using a pulse current (I_A) of 1,25 A, a pulse on time (T_{ON}) of 10 µs and a pulse off time (T_{OFF}) of 3 µs. Likewise, Figure 7b displays a surface finish micrograph with a value of 8,40 µm obtained using a pulse current (I_A) of 5,00 µs, a pulse on time (T_{ON}) of 150 µs and a pulse off time (T_{OFF}) of 1 µs.



(a) R_a = 2,54 µm



(b) R_a = 8,40 µm

Figure 7. Surfaces roughness micrograph (a) R_a = 2,54 µm and (b) R_a = 8,40 µm.
Source: Authors

Mean absolute percent error

The mean absolute percent error (MAPE) is the average of the absolute differences between the adjusted and experimental R_a values, expressed as a percent of experimental values (Heizer & Render, 2011) and is computed with using the Equation (3):

$$MAPE = \frac{\sum_{i=1}^{n} \frac{100 * \left| R_{\text{a experimental } i} - R_{\text{a adjusted } i} \right|}{R_{\text{a experimental } i}}}{n} \tag{3}$$

Table 8 shows the absolute percent errors computed. The sum of percent errors is 152,131%, therefore, the value of MAPE is 9,508%. MAPE expresses the error as a percent of the experimental values, undistorted by a single large value.

Table 8. Absolute percent errors

No.	I_A(A)	T_{ON}(µs)	T_{OFF} (µs)	$R_{a\ experimental}$	$R_{a\ adjusted}$	Absolute percent error
1	-1	-1	-1	3,10	3,34	7,863
2	-1	-1	+1	2,54	3,14	23,474
3	-1	+1	-1	2,24	2,42	7,868
4	-1	+1	+1	3,12	2,67	14,463
5	+1	-1	-1	4,70	4,51	4,122
6	+1	-1	+1	4,70	4,11	12,580
7	+1	+1	-1	8,40	7,44	11,384
8	+1	+1	+1	7,10	7,51	5,722
9	-1	-1	-1	3,90	3,34	14,263
10	-1	-1	+1	3,42	3,14	8,297
11	-1	+1	-1	2,28	2,42	5,976
12	-1	+1	+1	2,53	2,67	5,484
13	+1	-1	-1	4,00	4,51	12,656
14	+1	-1	+1	3,83	4,11	7,278
15	+1	+1	-1	6,80	7,44	9,467
16	+1	+1	+1	7,60	7,51	1,234

Source: Authors

Conclusions

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

- The factorial design 2^3 used in this study is an effective tool to study the influence of machining parameters on the surface roughness of AISI 304 stainless steel, produced by using of electrical discharge machining.

- The pulse current (I_A) and pulse on time (T_{ON}) are the most significant parameters, obtained with a confidence level of 95% on EDM machining of AISI 304 stainless steel.

- The surface roughness of the AISI 304 stainless steel workpieces decreased with a using of low pulse current (I_A) and a low pulse on time (T_{ON}). It is recommended that the electrical discharge machining of AISI 304 stainless steel be performed with a pulse current (I_A) of 1,25 A, a pulse on time (T_{ON}) of 10 µs and a pulse off time (T_{OFF}) of 3 µs, in order to obtain lower levels of surface roughness values.

- 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.

- The value of MAPE obtained is 9,508%, which is perhaps the easiest measure to interpret, because expresses a percent of experimental values.

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