Influence of metal turning assisted with high density current pulses on surface hardness in an AISI/SAE 1045 steel

Influencia del torneado de metales asistido por pulsos de corriente de alta densidad sobre la dureza superficial de un acero AISI/SAE 1045

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***Resumen* —Dentro de la familia de procesos de conformado asistidos eléctricamente (Electrically Assisted Forming) EAF, el proceso híbrido de torneado asistido in situ con electropulsos, viene siendo estudiado para determinar la influencia de electropulsos en la potencia de mecanizado, acabado superficial y macrodureza. Aplicando técnicas de DOE, el presente trabajo de investigación se centra en estudiar como respuesta la macrodureza en un acero AISI/SAE 1045 sometido a un proceso de torneado asistido eléctricamente, considerando diferentes factores. Los resultados obtenidos a partir del análisis de varianza ANOVA, muestran que la velocidad de avance tiene influencia sobre la dureza superficial del material. Así mismo, la interacción entre los factores frecuencia de pulsos y ancho de pulso del proceso de torneado asistido eléctricamente, evidencia un impacto en la dureza superficial del acero AISI/SAE 1045. Se aborda también la interacción tiple entre velocidad de avance, frecuencia de pulsos y ancho de pulso, y su incidencia en la característica de respuesta bajo estudio.**

***Palabras claves*— diseño de experimentos, electroplasticidad, pulsos de corriente de alta densidad, torneado de metales.**

***Abstract*— Within the family of electrically assisted forming processes EAF, the hybrid process of turning assisted in-situ with electropulses, is being studied to determine the influence of electropulses on machining power, surface finish and macro hardness. Applying DOE techniques, the present research work focuses on studying the response of macro hardness in an AISI / SAE 1045 steel under an electrically assisted turning process, considering different factors. The results obtained from the Analysis of Variance ANOVA show that the feed has an influence on the surface hardness of the material. Likewise, the interaction between the factors pulse frequency and pulse width of the electrically assisted turning process shows an impact on the surface hardness of AISI / SAE 1045 steel. The triple interaction between feed, pulse frequency and pulse width, and its incidence on the response characteristic under study is also addressed.**

***Index Terms*— design of experiments DOE, electroplasticity, electropulse, metal turning.**

I. Introduction

DESIGN of experiments (DOE) can be defined as a methodology based on mathematical and statistical tools which objective is to help the experimenter to:

- Select the optimal experimental strategy that allows to obtain the required information with the minimum cost.
- Evaluate the obtained experimental results, assuring maximum reliability in the obtained conclusions [1].

Statistical design of experiments can be applied on numerous situations whose objective is to obtain quality information, which is the base for the development of new products and processes, understanding a system and take decision to optimize and improve its quality. DOE methodology can be applied to MIMO systems (Fig. 1), in which one or more dependent variables or outputs depend on the values of one or more independent controllable variables (x) called factors. Outputs can be influenced by other variables that are not controlled by the experimenter.

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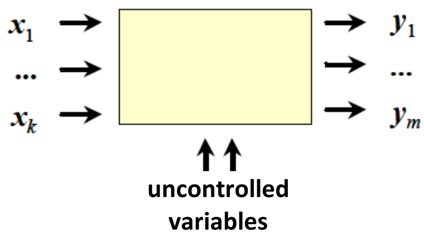

Fig. 1. Depiction of a studied system showing the factors (x) and the outputs (y) [1].

The research work hereby presented focuses in the process of electropulses assisted turning (application of electroplasticity), where the machining parameters such as cutting speed, feed, cutting depth, constitute the system inputs and the output corresponds to material hardness.

Electroplasticity is the effect produced on the plastic flow of materials due to the application of high density electrical current pulses, with magnitudes of around 15 A/mm^2 for 60 µs periods. DC high density current, when applied in short duration pulses, can significantly improve the rate of plastic deformation in metals, in addition to the Joule effect. Sprecher and others [2] and Troitskii [3, 4] have found that some of the effects of the application of high density current pulses in metal work are:

- Reduction in the required force for metal work.
- Reduction in fragility.
- Improvement of surface roughness.
- Changes in texture.

One of the beneficial effects of electroplasticity on metals is the reduction of yield strength [5], which could allow to take advantage of this kind of effect to work on certain metals or alloys that are very difficult to process with conventional machining, or in the case of common materials increase productivity, with the subsequent economic benefits.

The application of electroplasticity in metal work is relatively new and according to some authors who have worked on the subject [6-9], it is an efficient process in terms of energy consumption and environmentally friendly.

Fundamentally, electropulse assisted turning belongs to the family of Electrically Assisted Forming (EAF) [10], in which, while a piece is mechanically stressed, a high-density current train pulse is circulated through the piece-tool set.

Metal turning assisted with high density current pulses has been investigated since the year 2012 [11, 12], in a collaborative work between teachers of the Universidad Politécnica de Cataluña (Spain) and the Universidad Tecnológica de Pereira UTP. Results of these studies have shown benefits in its use, in terms of improvements in surface finish, material machinability and reduction in the consumed machining power [11, 12].

From the point of view of classical metal cutting theory, the necessary power to remove a layer of a material of certain mechanical properties using turning, under a certain cutting regime (angular velocity, feed, depth, lubrication, etc.), is directly proportional to ultimate strength σ_r of the material to machine. Based on the proven results of electroplasticity the value of σ_r is transiently reduced and material ductility is increased, studies [11] and [12] have confirmed that there is indeed a reduction in the required power for turning assisted with high density current pulses.

II. OBJECTIVE

It is desired to assess the change in surface hardness on an AISI/SAE 1045 steel, when turned with the assistance of electropulses. It is unknown which input variables have the greatest impact on hardness, being this the main motivation for the present study.

This research work focuses on applying DOE techniques to perform a pilot test and find the variables with the most influence via a fractional design of the experimental process in which cutting parameters (cutting speed, feed, cutting depth) and current pulses parameters (frequency and pulse width) are given. Then a full 2^3 factorial design is carried out, to which an Analysis of Variance (ANOVA) is applied. Lastly, the variables with the most influence on surface roughness of AISI/SAE 1045 steel after the machining process are evaluated.

III. METHODOLOGY

The first factorial experiment presented in this paper corresponds to a fractional factorial design with 5 factors and 2 levels. The factors and their levels are shown on table I, for the pilot test performed. The fractional design is of shape 2^{k-p} where k=5 and p=2 (fraction ¼, resolution III), therefore the number of experimental runs required with 2 generators is 16 in total; surface hardness being the output variable, measured on the different experimental specimens and with the corresponding correction factor for cylindrical surfaces.

TABLE I
FACTORS AND LEVELS OF THE PILOT TEST

Factors	Levels	
Cutting depth [mm]	0,81	1,27
Pulse frequency [Hz]	100	300
Pulse width [µs]	50	200
Cutting speed [m/min]	28,3	35,9
Feed [mm/rev]	0,138	0,174

To execute the different experimental tests according to table I, it was required to fabricate cylindrical AISI/SAE 1045 steel specimens, 150 mm long and with a 12,7 mm ($^1/_2$”) diameter. The specimens were placed between the chuck and the tailstock in a lathe, using an electrical insulating material in the moment the electropulses were applied. Table 2 shows the chemical composition of the material used in this study.

TABLE II
CHEMICAL COMPOSITION OF THE MATERIAL AISI/SAE 1045 [13]

SAE 1045	**% C**	**% Mn**	**% Si**	**% P**	**%S**	**% Cr**	**% Cu**
	0,45	0,7	0,25	0,008	0,007	0,07	0,01

The machining process was carried out in a revolver lathe model TOZ, ZPS-R5, employing a Hard Metal (HM) tool. During the different experimental tests performed in the Machine Tools laboratory of the Universidad Tecnológica de Pereira, the different cutting parameters were programed in the lathe and a current pulses generator was used where the pulse width and frequency were varied. The machining length where the pulses were applied was 80 mm. It is important to also mention that, for each test, electrical insulation had to be verified between the specimen and the chuck and between the cutting tool and the tool holder, using a multimeter to verify the no continuity. Fig. 2 shows the experimental scheme of the electrically assisted turning process.

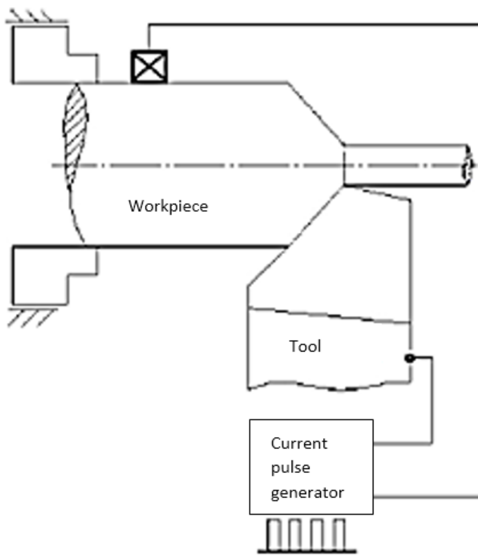

Fig. 2. Experimental scheme of the process of electrically assisted turning

Table III presents the experimental tests performed and the different combinations of levels and factors according to fractional factorial design, which are in random order. Once the specimens were machined, measures of hardness were taken, using an HP-250 hardness tester from the brand *Wekstoffprüfmaschinen* (Fig. 3).

Fig. 3. Hardness tester.

For each specimen 5 hardness measurements were recorded in the Rockwell B scale, on different zones of the machined region. To the obtained values, a correction was applied due to their cylindrical shape, according to the indications from standard ASTM E18-79 [14].

TABLE III.
FRACTIONAL FACTORIAL DESIGN FOR THE ELECTROPULSES MACHINING PROCESS

Test order	Cutting depth [mm]	Pulse width [µs]	Pulse frequency [Hz]	Cutting speed [m/min]	Feed [mm/rev]
1	1,27	200	300	28,33	0,2116
2	1,27	50	100	28,33	0,1354
3	1,27	200	100	22,34	0,2116
4	1,27	50	300	22,34	0,1354
5	0,81	200	100	28,33	0,1354
6	0,81	50	100	22,34	0,2116
7	0,81	200	300	22,34	0,1354
8	0,81	50	300	28,33	0,2116
9	1,27	200	300	28,33	0,2116
10	1,27	50	300	22,34	0,1354
11	1,27	200	100	22,34	0,2116
12	1,27	50	100	28,33	0,1354
13	0,81	50	300	28,33	0,2116
14	0,81	200	100	28,33	0,1354
15	0,81	50	100	22,34	0,2116
16	0,81	200	300	22,34	0,1354

IV. RESULTS AND DISCUSSION

The last column of table III presents the different hardness values taken on the different specimens according to the different factors and levels applied to each one. On the Minitab software [15], an Analysis of Variance ANOVA was performed for this 2^{5-2} fractional design, which is presented on table IV.

TABLE IV.
ANALYSIS OF VARIANCE FOR THE FRACTIONAL DESIGN [15]

Source	DF	Adj SS	Adj MS	F-Value
Cutting depth [mm]	1	1,2741	1,2741	1,25
WP Error	2	2,0338	1,0169	0,23
Pulse width [µs]	1	0,1287	0,1287	0,03
Pulse frequency [Hz]	1	4,3420	4,3420	0,98
Cutting speed [m/min]	1	2,3218	2,3218	0,53
Feed [mm/rev]	1	6,5472	6,5472	1,48
Cutting depth [mm]*Pulse frequency [Hz]	1	3,8661	3,8661	0,88
Pulse width [µs]*Pulse frequency [Hz]	1	25,9718	25,971	5,89
SP Error	6	26,4708	4,4118	
Total	15			

Source	P-Value
Cutting depth [mm]	0,379
WP Error	0,801
Pulse width [µs]	0,870

Pulse frequency [Hz]	0,359
Cutting speed [m/min]	0,495
Feed [mm/rev]	0,269
Cutting depth [mm]*Pulse frequency [Hz]	0,385
Pulse width [µs]*Pulse frequency [Hz]	0,051
SP Error	
Total	

According to the analysis of Variance the double interaction pulse width and pulse frequency presents a p-Value of 0,05 which indicate that these variables have influence on the studied response, which is surface hardness; besides, though it doesn't have such a significant influence, the variable that presents a p-Value closest to 0,05 is the feed, which is why these 3 variables are selected to later perform the full factorial design. Fig. 4 presents the Pareto chart where the variables with more influence can be seen more clearly.

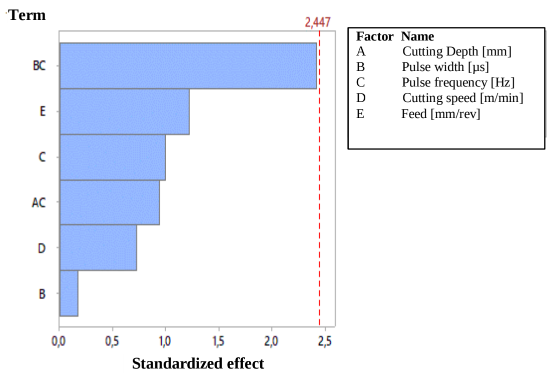

Fig. 4. Pareto chart of standardized effects [15].

The analysis of residuals (fig. 5) is important to analyze the behavior of the data. The normal probability plot indicates that some of the data are centered around zero and follow the fit line.

The frequency histogram shows that, although most of the data are not centered around zero, they tend to show the behavior of a normal distribution. On the other hand, the plot of standardized residuals versus the order of observation of the data follows an irregular curve, which indicates that there is randomness in the data collection.

According to the previously obtained results, a full factorial design is performed for the variables that have more influence on the response; in this analysis pulse frequency, pulse width and feed are included. The selected variables concur with studies done by Sánchez et al. [12], in which the material surface hardness is influenced by the rate of plastic deformation, which in turn is related to the feed.

According to Sánchez et al. [11, 12], the greatest reductions in hardness on AISI/SAE 1045 carbon steel and AISI/SAE 4140 steel were observed for frequencies from 100 Hz to 300 Hz, feeds of 0,046 mm/rev and pulse durations of 200 µs. Table V shows the variables pulse width, pulse frequency and feed, the combinations of their different levels and the new hardness results from the new turned specimens.

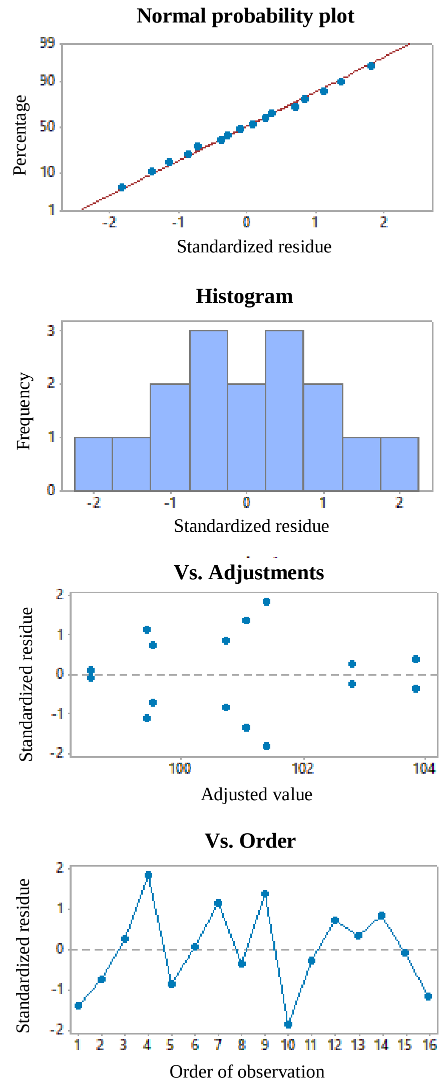

Fig. 5. Residuals plots for hardness HRB [15].

TABLE V.
COMBINATIONS OF LEVELS FOR THE 2^3 FACTORIAL DESIGN WITH THEIR RESPECTIVE HARDNESS VALUES

Pulse width [µs]	Pulse frequency [Hz]	Feed [mm/rev]	Hardness HRB	Correction factor	Corrected hardness
50	300	0,138	100,75	2,50	103,25
50	300	0,174	100,85	2,50	103,35
50	100	0,138	98,40	2,58	100,98
200	100	0,174	100,15	2,50	102,65
50	100	0,174	96,35	2,68	99,03
50	100	0,138	95,40	2,73	98,13
50	300	0,174	102,10	2,50	104,60
200	300	0,174	96,10	2,69	98,79

50	100	0,138	98,95	2,55	101,50
200	100	0,138	97,40	2,63	100,03
50	300	0,138	96,80	2,66	99,46
200	100	0,138	95,85	2,70	98,55
50	300	0,174	101,30	2,50	103,80
50	100	0,174	97,75	2,61	100,36
200	100	0,138	99,60	2,52	102,12
200	300	0,138	95,50	2,72	98,22
50	100	0,174	96,00	2,70	98,70
200	100	0,174	100,45	2,50	102,95
200	300	0,174	100,85	2,50	103,35
50	300	0,138	96,90	2,65	99,55
200	300	0,138	99,80	2,51	102,31
200	300	0,174	100,85	2,50	103,35
200	300	0,138	98,75	2,56	101,31
200	100	0,174	101,35	2,50	103,85

An Analysis of Variance ANOVA was performed on the data from table V, and the p-Values shown on fig. 6 were obtained. The resulting p-Value of 0,037 indicates that feed has influence on the material surface hardness.

Also, the double interaction of pulse width and pulse frequency causes an impact on the response, since its p-Value is less than 0,05; therefore, the null hypothesis is rejected, and the alternative hypothesis is accepted, which indicates that these factors influence the response. The triple interaction pulse width, pulse frequency and feed has a p-Value of 0,062, which is close to the limit thus allowing to state that the joint effect of these three factors has influence in the material surface hardness.

Source	P-Value
Model	0,064
Linear	0,093
Pulse width [μs]	0,584
Pulse frequency [Hz]	0,162
Feed [mm/rev]	0,037
2-Way Interactions	0,177
Pulse width [μs]*Pulse frequency [Hz]	0,049
Pulse width [μs]*Feed [mm/rev]	0,533
Pulse frequency [Hz]*Feed [mm/rev]	0,430
3-Way interactions	0,062
Pulse width [μs]*Pulse frequency [Hz]*Feed [mm/rev]	0,062
Error	
Total	

Fig. 6. p-Values for the full 2^3 factorial design [15].

Fig. 7 shows the residual plots for hardness HRB from the full factorial design. In the normal probability plot an approximation of the data to follow the fitting line is evidenced; while the histogram shows that the data are not totally centered around zero, however they show a distribution that tends to be normal. Once again it can be seen that there are no patterns in the order of the data collection and therefore there is randomness in them.

An Analysis of Variance ANOVA is shown on table VI for the full 2^3 factorial design. It can be seen how we have 7 effects, out of which 3 are main effects, 3 are double interactions and one triple interaction. For each of them the degrees of freedom, the sum of squares, mean squares and test statistics have been determined.

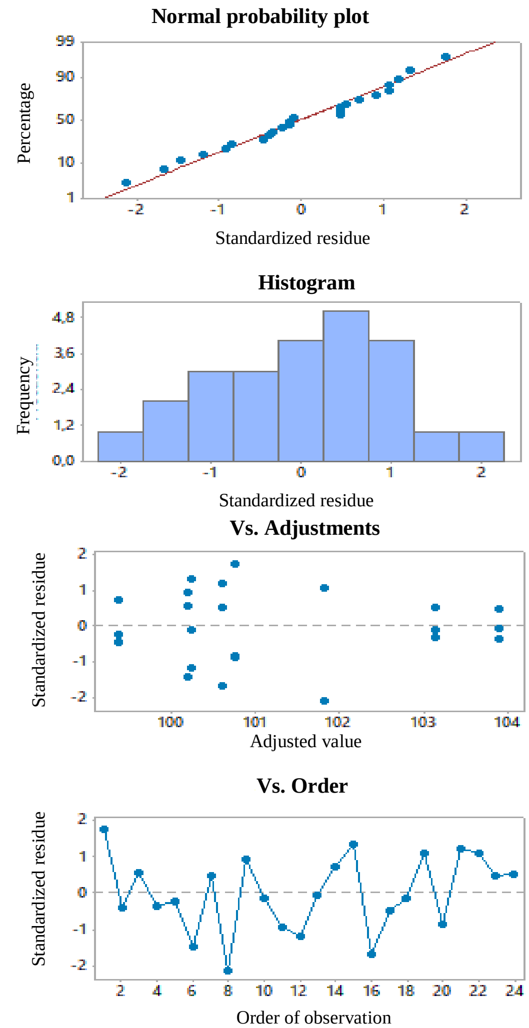

Fig. 7. Residual plots for hardness HRB in full factorial design [15].

Test statistics (F Value) allow us to also determine what variables have influence on the response, being an alternate method to comparing p-Values with the significance of 0,05. On this method, yet again, feed and the double interaction pulse width with pulse frequency are the ones that have a greater effect on the response.

TABLE VI.
COMBINATIONS OF LEVELS FOR THE 2^3 FACTORIAL DESIGN WITH THEIR RESPECTIVE HARDNESS VALUES [15]

Source	Degrees of freedom	Sum of squares	Mean squares	F Value	P Value
Model	7	52,193	7,456	2,46	0,064
Lineal	3	23,081	7,694	2,54	0,093
Pulse width [μs]	1	0,948	0,948	0,31	0,584
Pulse frequency [Hz]	1	6,500	6,500	2,15	0,162
Feed [mm/rev]	1	15,633	15,633	5,16	0,037

Double interactions	3	16,914	5,638	1,86	0,177
Pulse width*Pulse frequency	1	13,696	13,696	4,52	0,049
Pulse width*Feed	1	1,229	1,228	0,41	0,533
Pulse frequency*Feed	1	1,990	1,989	0,66	0,430
Triple Interactions	1	12,198	12,198	4,03	0,062
Pulse width*Pulse frequency*Feed	1	12,198	12,198	4,03	0,062
Error	16	48,452	3,028		
Total	23	100,645			

In fig. 8 it can be appreciated that feed corresponds to the straight line with the greatest slope, which matches with the obtained p-Value of 0,037; in comparison with the values of pulse width and pulse frequency, with p-Values of 0,584 and 0,162 respectively, therefore, it is the feed the one that has influence on the obtained surface hardness.

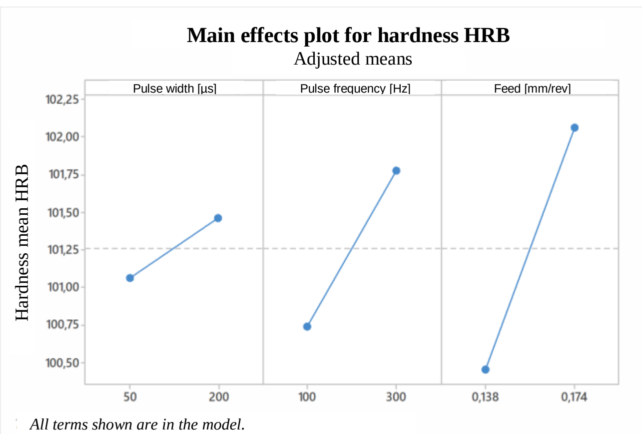

Fig. 8. Main effects plot [15].

Table VII shows the values of the lineal regression presenting the standard deviation and the coefficient of determination (R^2).

TABLE VII.
STANDARD DEVIATION AND COEFFICIENT OF DETERMINATION [15].

Model summary

Standard deviation S	**R^2**	**R^2 adjusted**	**R^2 predicted**
1,9693	22,33%	11,37%	0%

It is important to note that, considering the three variables feed, pulse width and pulse frequency with hardness as the response, they present a low coefficient of determination with a value of 22,33% therefore it doesn't fit well to a linear model where all three variables are considered. The experimental process may require a different model and an experimental volume bigger than the one proposed, something that is beyond the reach of the study here performed.

In the case of hardness HRB and feed, they don't have a linear relationship. This is confirmed in the study performed by Sánchez et al. [11], that shows the relative hardness of AISI/SAE 1020, 1045 and 4140 steels under an assisted turning process with electropulses at 100 Hz and pulse duration of 200 µs and 50 µs, and the relative hardness of the same materials when assisted with electropulses at 300 Hz and a pulse duration of 200 µs and 50 µs. It can be seen how for AISI/SAE 1045 steel hardness doesn't increase as feed is increased.

V. CONCLUSIONS

A study has been performed to determine the variation on macrohardness of an AISI/SAE 1045 steel on a turning process assisted with electropulses. Based on DOE techniques a 2^{5-2} fractional factorial design was performed as a pilot test including the factors cutting depth, cutting speed, feed, pulse width and pulse frequency. The results allowed to discard the factors cutting speed and cutting depth, since statistically they didn't have significant influence on the response.

A full 2^3 factorial design was carried out involving the factors feed, pulse frequency and pulse width, for which an Analysis of Variance, main effects plot and residual plot were performed.

The feed was the factor that, independently, had the most influence on the material surface hardness, with a p-Value of 0,037; which is below the level of significance used of 0,05.

The interaction between the factors pulse frequency and pulse width of the electrically assisted turning process show an impact on surface hardness for AISI/SAE 1045 steel. However, it isn't possible to make a conclusive statement regarding this subject without performing additional tests and research involving pulse frequencies and widths with different levels, since the obtained p-Value for the interaction of these two factors is very close to the significance value of 0,05.

The triple interaction of pulse frequency, pulse width and feed doesn't produce a significant effect in the variation of surface hardness, since its p-Value is 0,062; besides, it corroborates the results of studies performed previously for 1045 steel, where there isn't a significant variation in hardness for feeds between 0,046 mm/rev and 0,356 mm/rev, pulse width of 200 µs and frequency of 300 Hz.

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