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Experimental Model of the Fine Honing

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Abstract: An experimental model of the honing process oriented towards the honing operation for very fine finished is development. A two-level design of experiments has been carried out with three factors and a replica. We chose the factors that have been shown to be most significant in honing machining such as grain size and pressure. In addition, as in honing, the angle of scratching is important and depends on the relationship between the two speeds, linear velocity V_L and tangential velocity V_T, one of them has also been chosen, the linear velocity V_L, and the other velocity V_T is kept constant. By varying only V_L, the scratch angle is varied and the tangential speed V_T is kept constant, the number of factors is reduced and the number of tests is reduced. The variable with the greatest influence and which is present in a significant way in all the output parameters is the abrasive grain size G_{st}, the pressure parameters P and linear velocity V_L did not show to be particularly decisive in the finishing phase, especially for the roughness parameters. Manufacturers of hydraulic cylinders, surface finish of the inner wall of internal combustion engines and all those applications where it is machined with honing.
Keywords : Honing, regression analysis, experimental model, Surface characterization.

1. Introduction

In manufacturing process engineering, abrasive cutting methods have been an important field of study in terms of development, modelling and simulation because they define the characteristics of the final surface quality of a machined part. Honing is an abrasive machining process in which the tool, an abrasive stone, moves under pressure on a normally cylindrical surface. Figure 1.It is generally used to give a fine surface finish to elements with surfaces in contact with relative motion, as in the piston/cylinder system[1,2].

A particular feature of honing is the cross-scratching marked on the surface by the two movements of the tool, Figure 1. This cross-scratching gives it special characteristics in terms of oil retention and circulation[3].

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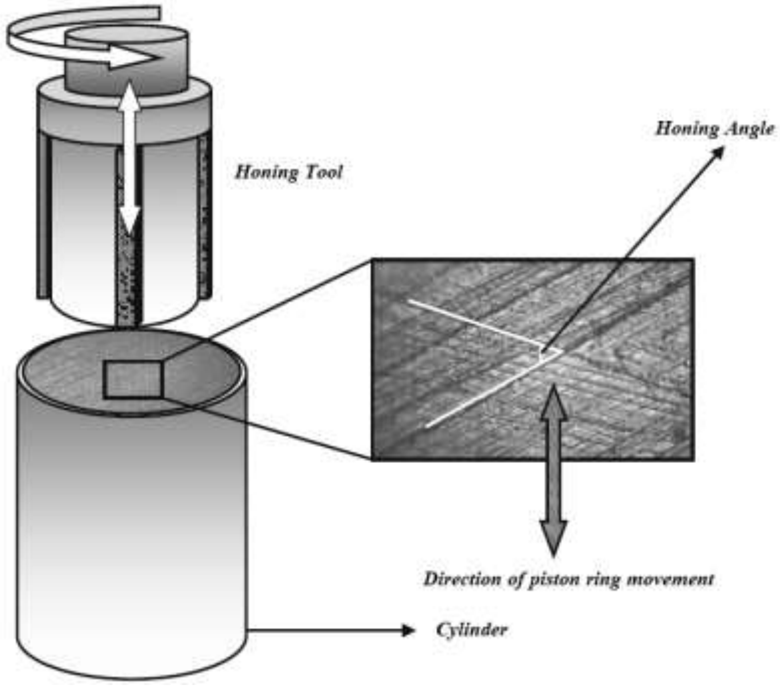
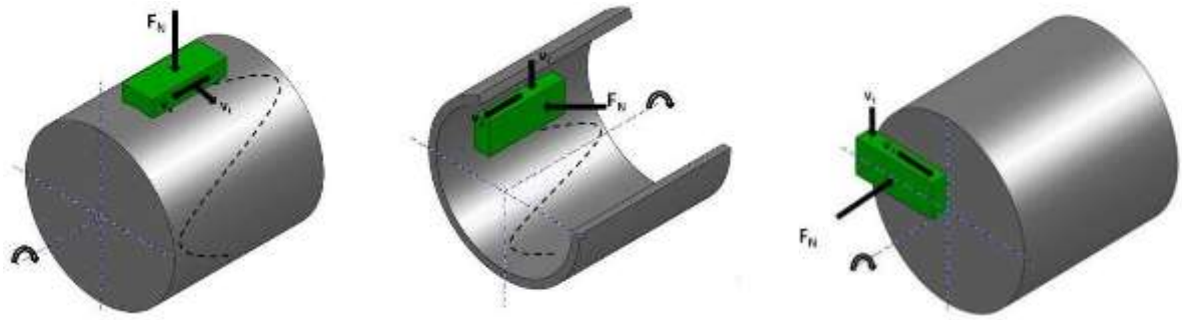


Figure 1.Honing process.



Exterior honingcylindrical ***Interior honingcylindrical*** ***Flat honing***

Figure 2. Types of honing.

The honing process is used in a wide variety of applications to improve geometry, surface texture and dimensional accuracy[1]. In relation to surface texture, there are many mechanical components whose performance is related to the characteristics of their surface finished[4]. Honing is normally classified according to the type of surface to be machined. In Figure 2, the main honing forms can be seen: external honing of cylindrical surfaces, internal honing of cylindrical surfaces and flat honing. In all three cases, the honing stone exerts a pressure (P) on the surface of the workpiece.

In recent years, honing has been on the rise in recent years, related to the importance in the manufacture of car engines for reducing emissions, increasing engine efficiency and improving the tribological characteristics of the cylinder-piston system. Tyagi[5], and his group of researchers studied the effects of variables on the behaviour of internal honing. They achieved the highest material removal rate for the finest surface finish, at cutting speeds close to 40 m/min, as in the case of Sasaki and Okamura[6]. With high Tyagi speeds,Tyagi found a decrease in material removal rate and a deterioration in surface quality. High start-up rates were also reported by them at high burnishing pressures. Surface finish improved at burnishing pressures of 3 to 4 kg/cm^2.

Salje and his colleagues at the Technical University of Braunschweig in Germany[7-9] developed their work for internal and external honing. They make an effort to obtain a parameter that correlates normal force, tangential force and part roughness for process optimization. A particular aspect of this work was the use of a real-time surface roughness measurement sensor for process monitoring. From this real-time measurement of surface roughness they found that roughness increases linearly with the increase in the ratio of tangential force to normal force.

Other research on honing was reported by Fischer[10-12], Haasís[13-15] and others, aimed at industrial honing applications. Fischer tried to provide a guide for the optimal selection of the honing tool. Haasis advanced works in the plateau-honing process, developed a honing process with easy tool movement, used in the finishing of drills, valves and crankshafts. Although this work provided useful information, it did not advance the fundamentals of modeling the honing process.

The development of experimental models has improved with the implementation of data collection techniques, as these present a more reliable procedure for the study of interactions between inputs and outputs of a manufacturing process. The treatment of the data obtained from an experimental process, in order to propose a model that relates the input and output signals, has been developed basically by two techniques, regression analysis and artificial neural networks, in both cases from data obtained by design of factorial experiments. Feng and Wang[16], as well as Ben Fredj[17], have carried out studies related to the advantages and disadvantages of each of these techniques, and have made comparisons between them, in which their best field of application is established and the differences between the results obtained with one or the other technique. A great deal of experimental work has been carried out on the behaviour of the honing process and the interrelation between input and output variables, in view of the difficulties presented by their analytical study. In most of these works, surface roughness has been chosen as the most important response variable, due to its importance on the tribological behavior of the system.

On the other hand, Troglio[18] presents the results of two experiments, the first one a design of complete factorial experiments at three levels, where parameters such as abrasive grain size, lubricating fluid and type of material were used to evaluate their influence on surface finished parameters such as R_a or those of the R_k family. In addition, I study the effect of the process on cylindricity and roundness. In the second experiment, he determined the wear of the tool after the honing process, for three materials. Its results include the influence on power consumption, material removal rate, and specific energy. Although it does not present regression equations for each parameter, it does show all the corresponding statistical analysis, analysis of variance (ANOVA), factor analysis, and graphs of the effects of the factors on the response variables. It is a fairly complete experimental investigation, which also studies the effects on other aspects such as cylindricity and roundness.Kanthababuet alt, develop two experimental studies on honing[19], and plateau-honing[20].

In the first[19], they conduct research to identify the parameters and their ranges for different honing operations, including plateau operation, in cylinder of internal combustion engines. They designed orthogonal experiments in which the variables to be controlled were the rotation speed, the linear forward and backward speed, the honing pressure and time, and the plateau time, for a range of three levels that they defined based on the machine used and the industrial experience. As control variables they selected the roughness parameters of the Abbott-Firestone curve (R_k, R_{pk}, R_{vk}, Mr_1, Mr_2). In their research they use three types of diamond grinding stone, D213 and D126(21) for rough honing and D54 for the plateau finished stage. They make a graphic comparison study on the effect of each experiment on the percentage curve of Abbott-Firestone material on the machined surface, where the behaviour of surface roughness with the variation of machining conditions is observed. In addition, they perform an ANOVA variance analysis study on the roughness data obtained for the different machining conditions they tested. The main conclusions found in this work are that the pressure and machining time in the honing and plateau stages influence the final surface quality. This study is in the same direction as others that have been analyzed, does not present experimental models to calculate surface roughness based on process variables, and does not analyze the effect of the abrasive stone on the process, nor does it study its productivity. In the second paper[20], however, based on the ANOVA analysis of variance data and the determination of parameters that were significant for surface roughness, they constructed and validated an algorithm that works with a decision tree to select the best machining conditions for the ranges defined by them. This research, although interesting because of the application of the algorithm, is restricted to the three types of abrasive stone they used in their experimental trials, and they did not study any aspect related to the productivity of the machining process.

Malkin[22] points out that in several studies on the modeling of abrasive processes it has been found that there are non-linear interactions between variables such as grain size, pressure and process speed, these possible non-linear interactions have not been studied in the models developed by Pawlus[23].

From the experimental studies carried out, it is concluded that a more complete and systematic experimentation methodology would be necessary, including more process parameters, especially those associated with the abrasive stone, different ranges of values of the process parameters and that it would be necessary to study the possible non-linear effects among the process variables.Since the experimental models have proven to be effective for the modelling and control of machining processes, it is proposed which experimental models will be suitable for modelling and controlling the different stages of the honing process: roughing and semi-finishing for the base honing, from which the characteristics of surface valleys are generated, and the plateau finish honing, with which the peaks in the plateau-honing are reduced. These models will make it possible to obtain quantitative relationships that allow each of the stages of the process to be controlled separately.

2. Materials and Methods

The machine used in the tests was an industrial machine model BVM 4C 130/1300 from Honingtec. The design of experiments and their execution comprises the following stages.

2.1. Input factors and response parameters of experiments

The factors that are studied in the development of this experimentation are shown in Table 1.

Table 1. Experimental design parameters

Process Variables	**Code**
Abrasive Stone (FEPA)	*Gst*
Pressure (N/cm^2)	*P*
Axial speed (m/min)	*VL*

The abrasive grain density has been set at 30 (FEPA) which is a value commonly used by process technicians for fine honing operation. The tangency speed is set at 30 m/min for all experiments. Other factors such as material of the workpiece, type of abrasive grit and cooling fluid have also remained fixed for these experiments.

The response parameters have been reduced to three roughness parameters R_a, R_t, R_q, and the material removal rate parameter Q_m. They are presented in Table 2.

Table 2. Process output parameters.

Output parameters	
ArithmeticAverage of Heights	*Ra, in µm*
Root Medium Root Roughness Square	*Rt, in µm*
Root Medium Root Roughness Square	*Rq, in µm*
Material removerate	*Qm, in cm/min*

In Table3, the work intervals for each of the factors can be seen.

Table 3. Experimental test machining parameters

	-1	1
Abrasive Stone (FEPA)	*5*	*20*
Pressure (N/cm^2)	*20*	*40*
Axial speed (m/min)	*440*	*700*

2.2. Factorial design of experiments.

The number of factors considered in this factorial design is 3. If a full 2^k factorial design is performed, at least 8 experiments are required for 3 factors. If replications are to be made, the number of experiments will grow by a multiple of 8. In this design, no central points or points centered on the faces were determined. Table 4.

Table 4. Factorial experimental design 2^3.

	Parametersprocesslevel		
Experimental test	***Gst***	***Vl***	***P***
1	-1	-1	-1
2	1	-1	-1
3	-1	1	-1
4	1	1	-1
5	-1	-1	1
6	1	-1	1
7	-1	1	1
8	1	1	1

In Figure 3, the dimensions of the specimen used in the experiments can be seen.

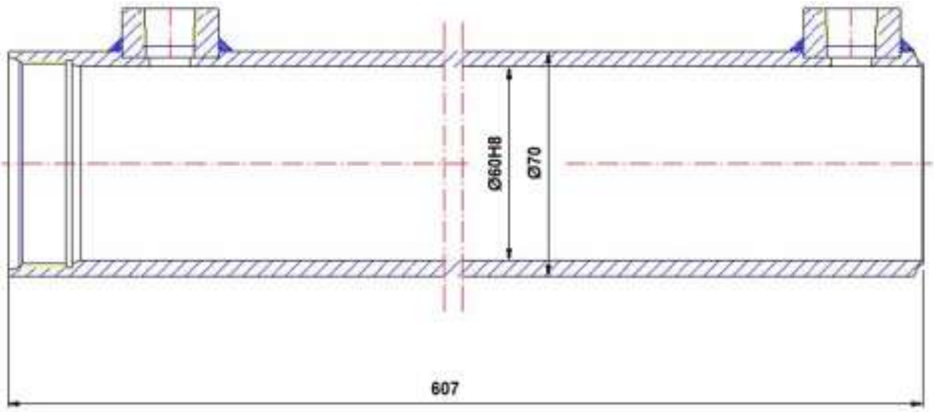


Figure 3. Test piece for study of the honing process.

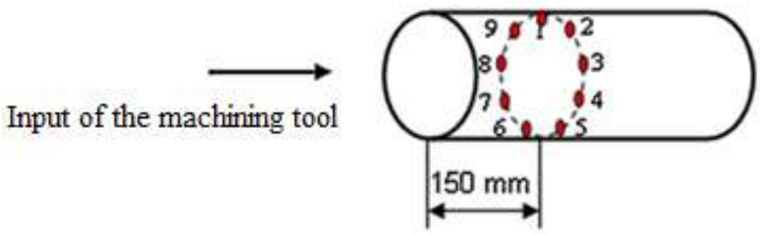


Figure 4.Methodology for measuring the tubes.

The roughness measurement methodology used is the one developed in Figure 4, which shows a diagram of the roughness measurement process of one of the test pieces.

3. Results and Analysis

Once the experiments have been carried out, Table5 shows the values obtained for the main experiment and its replication, and then carries out the analysis with the statistical program.

Table 5. Machining test results.

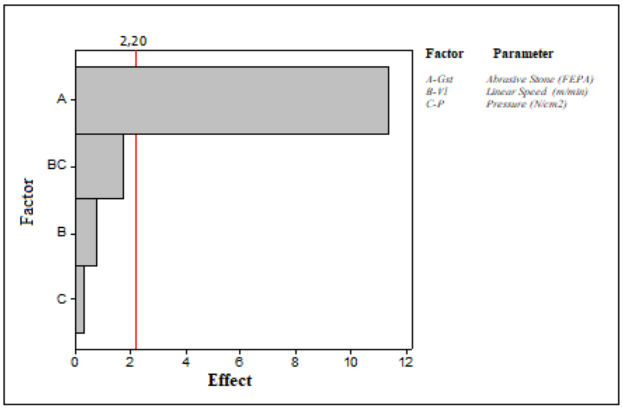
test	*Ra (μm)*	*Rt (μm)*	*Rq (μm)*	*Qm (cm/min)*
1	0,036	0,383	0,039	0,0050
2	0,091	1,958	0,148	0,0490
3	0,037	0,408	0,041	0,0020
4	0,063	1,152	0,092	0,0570
5	0,030	0,223	0,028	0,0120
6	0,081	1,677	0,129	0,0660
7	0,032	0,282	0,032	0,0110
8	0,106	2,402	0,179	0,0700
9	0,035	0,352	0,037	0,0070
10	0,092	2,003	0,151	0,0410
11	0,030	0,223	0,028	0,0010
12	0,079	1,615	0,124	0,0530
13	0,030	0,216	0,027	0,0160
14	0,086	1,827	0,139	0,0480
15	0,031	0,239	0,029	0,0040
16	0,077	1,554	0,120	0,0820

The results of the statistical analysis reduced to the most significant effects, obtained with MINITAB, are presented below, thus giving rise to the reduced model.

3.1. Factorial analysis of response parameters

After making the factorial analysis for the variables, according to the values obtained in Table 5, the analysis was reduced to the variables and the interactions observed were the most significant for this study. The interactions that were not considered important p-value>0.05 have been removed, and the Pareto diagram in Figure 5a, and the factor analysis and interactions that have been shown to be significant in Table 6 are shown below.

As can be seen from the Pareto diagram, the variable that clearly has the greatest influence on finish honing is the abrasive grain size. It was found that the change in pressure level has not been shown to be decisive for the finished.



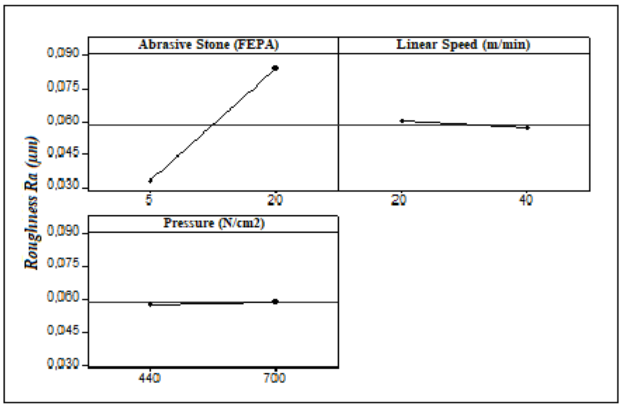


Figure 5.Effects of process variables on roughness *Ra*.

In Figure 5b, the influence of the variation of the process parameters on the resulting values of *Ra* can be seen.

From the above figure it can be concluded that for the finished operation, only the change in the grain size parameter has a significant effect on the change in surface roughness *Ra*. The decrease in the value of the parameter, which in the case of grain size means using a smaller grain size stone, decreases the resulting roughness value *Ra*.

In Table 6, the values of the coefficients for the model of the roughness parameter *Ra* are shown.

Table 6. Estimate of significant effects and coefficients for *Ra*.

Parameters	*p*	Coefficients
	0,000	0,0699789
Gst	0,000	0,00343966
VL	0,497	-0,00191337
P	0,763	-0,000865798
*VL*P*	0,106	0,00000306572

For the current analysis, the value of the adjusted determination coefficient $R^2(adj)$ indicates that the model can explain up to 89.62% of the data studied. The proposed equation that predicts the behavior of the *Ra* parameter according to the process parameters is:

$$Ra = 0{,}0699789 + 0{,}00343966*Gst - 0{,}00191337*VL - 0{,}000865798*P + 0{,}00000306572*VL*P$$

For the *Rt* parameter, the Pareto diagram is shown in Figure 6.

In Figure 6, the influence of the variation of the process parameters on the resulting *Rt* values can be seen. The coefficients of the parameters that have been shown to be most significant are shown in Table 7.

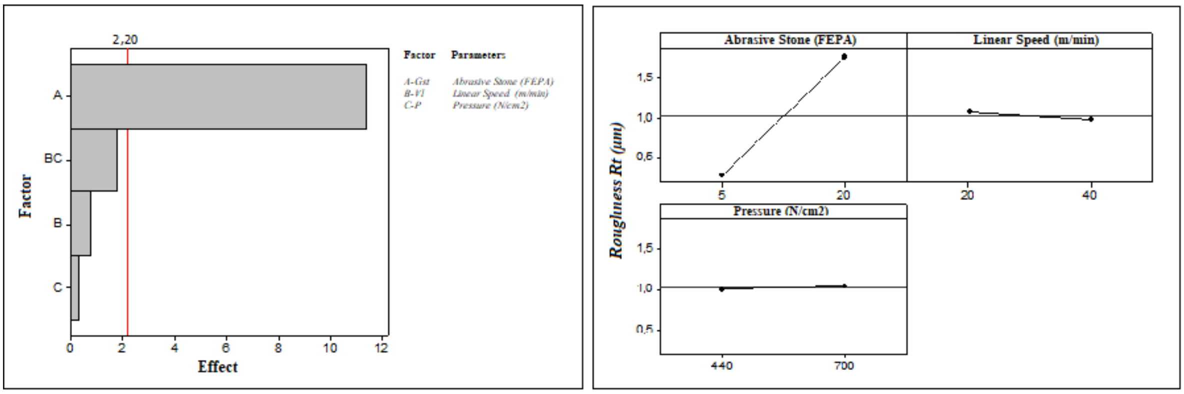


Figure 6.Effects of process variables on roughness *Rt*.

Table 7. Estimate of significant effects and coefficients for *Rt*.

Parameters	*p*	Coefficients
	0,000	1,35685
Gst	0,000	0,0988508
VL	0,479	- 0,0550006
P	0,759	- 0,00248642
*VL*P*	0,106	0,0000881269

For the current analysis, the value of the adjusted determination coefficient $R^2(adj)$ indicates that the model can explain up to 89.64%. The proposed equation that predicts the behavior of the *Rt* parameter according to the process parameters is:

$$Rt = 1{,}35685 + 0{,}0988508*Gst - 0{,}0550006*VL - 0{,}00248642*P + 0{,}0000881269*VL*P$$

For the *Rq* parameter the Pareto diagram is shown in the Figure 7, the influence of the variation of the process parameters on the resulting *Rq* values can be seen.

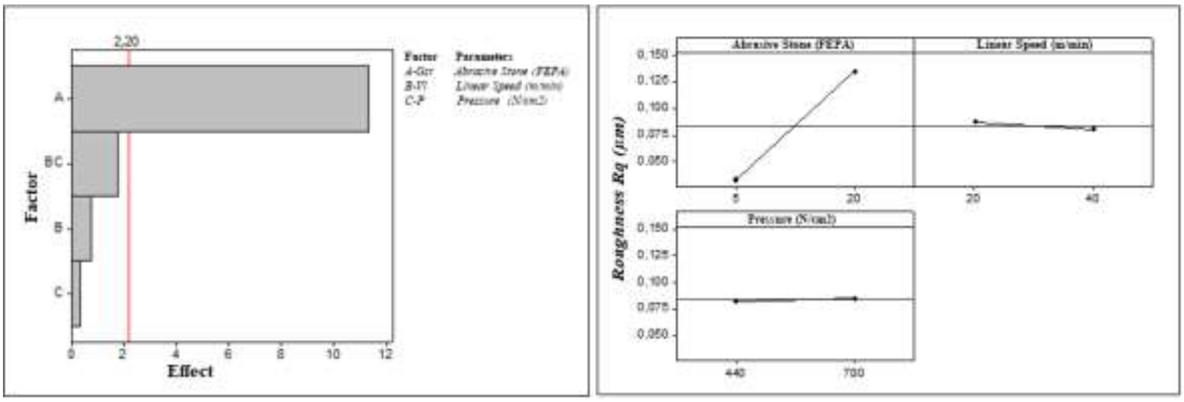


Figure 7.Effects of process variables on roughness *Rq*.

Table 8. Estimate of significant effects and coefficients for *Rq*.

Parameters	*p*	Coefficients
	0,000	0,106460
Gst	0,000	0,00684167
VL	0,480	- 0,00381154
P	0,757	- 0,000172115
*VL*P*	0,107	0,00000610577

The coefficients of the parameters that have been shown to be most significant are shown in Table 8.

For the current analysis, the value of the adjusted determination coefficient $R^2(adj)$ indicates that the model can explain up to 89.52%. The proposed equation that predicts the behavior of the *Rq* parameter according to the process parameters is:

$$Rq = 0{,}106460 + 0{,}00684167*Gst - 0{,}00381154*VL - 0{,}000172115*P + 0{,}00000610577*VL*P$$

The Pareto diagram for the *Qm* parameter is shown in the Figure 8, the influence of the variation of the process parameters on the resulting *Qm* values can be seen. It should be noted that for the material removal rate, the pressure has been shown to be a significant parameter, contrary to what the results showed for the roughness parameters.

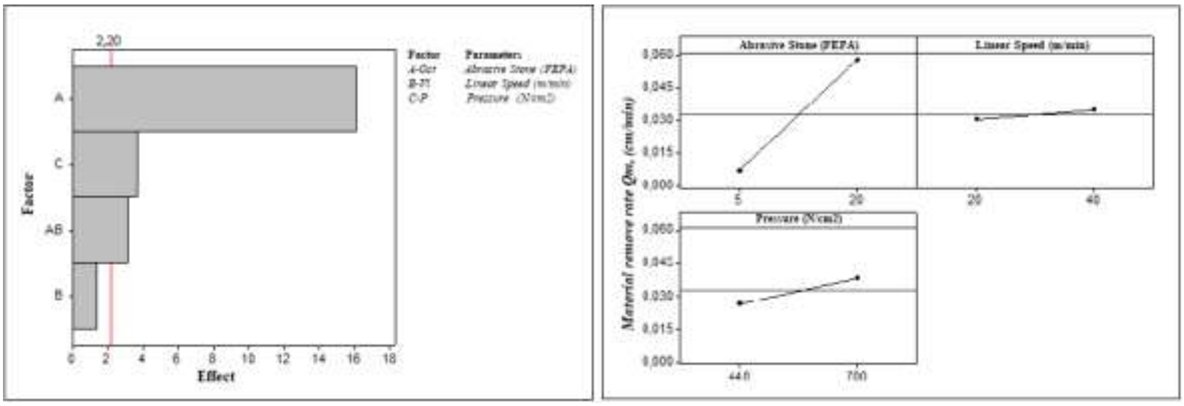


Figure 8. Effects of process variables on the material remove rate*Qm*.

Table 9. Estimate of significant effects and coefficients on the material remove rate*Qm*.

Parameters	*p*	Coefficients
	0,000	-0,0172596
Gst	0,000	0,0014000
VL	0,183	-0,000608333
P	0,003	0,0000451923
*Gst*VL*	0,009	0,0000066666

The coefficients of the parameters that have been shown to be most significant are shown in Table 9.

For the analysis, the value of the adjusted determination coefficient $R^2(adj)$ indicates that the model can explain up to 94.93%, the proposed equation that predicts the behavior of the *Qm* parameter depending on the process parameters is:

$$Qm = - 0{,}0172596 + 0{,}0014*Gst - 0{,}000608333*VL + 0{,}0000451923*P + 0{,}000006666*Gst*VL$$

4. Validation of the Models

With the results obtained, graphs have been made to compare the values obtained with the different models and the real data of each of the experimental tests Figure 9.

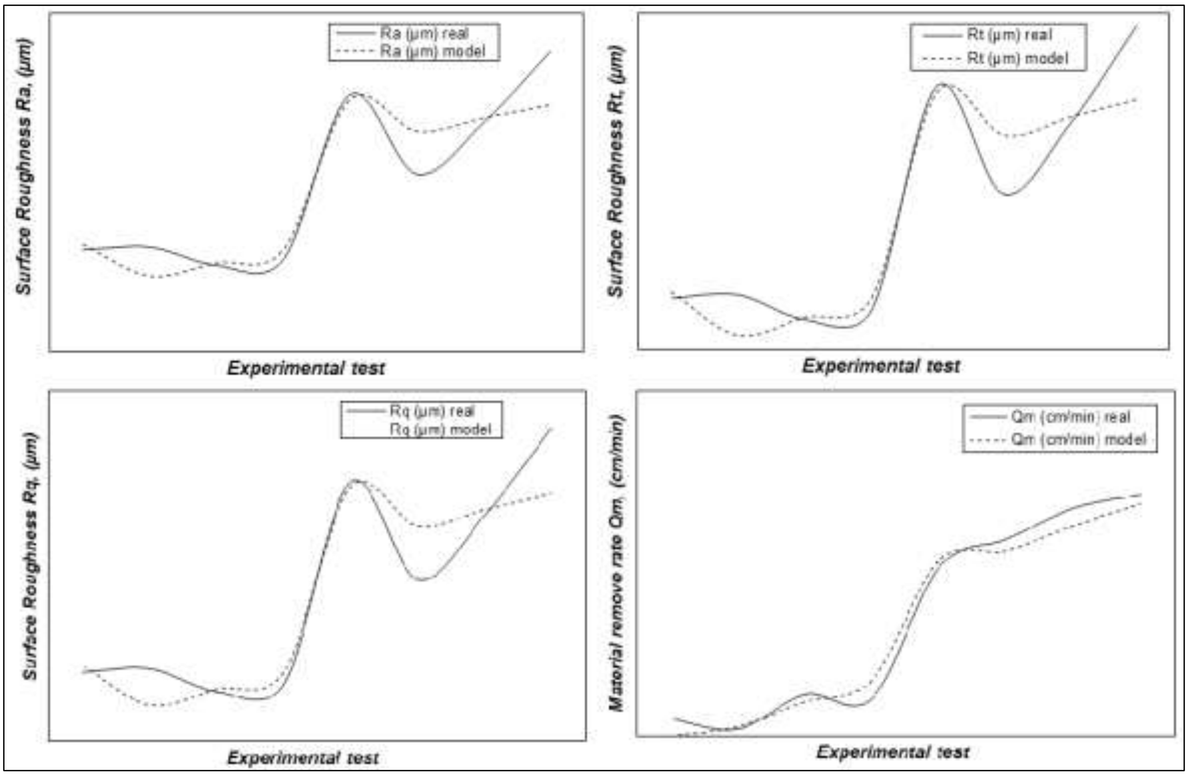


Figure 9. Comparison of measured values vs. values obtained with the model.

These models allow predicting the influence of the values of process variables, pressure, grain size and linear velocity on surface roughness and material removal rate.

5. Conclusions

Once all the variables had been studied, a series of considerations have been drawn as conclusions, important for analysing the results obtained.Taking as a reference the experimental values of the roughness parameters (*Ra*, *Rt*, *Rq* and *Qm*), these can be predicted with linear equations using only main effects and some interactions. The adjustment obtained with these equations is in most cases close to 90%. The variable with the greatest influence and which is present in a significant way in all the output parameters is the abrasive grain size *Gst*, the parameters pressure *P* and linear velocity *Vl* did not show to be particularly decisive in the finishing phase, especially for the roughness parameters.The *Gst* grain size parameter has a direct influence on surface roughness and the rate of material removal, when changing from a high grain size to a low grain size the surface roughness decreases.For the *Qm* material removal rate parameter, a reduced model with significant interactions provides an adjustment of about 90%. The grain size parameter *Gst* and pressure show to be the most influential.

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