



## Correlation analysis of the roughness as function of cutting speed and feed rate (the roughness as function of machining parameters)

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**ABSTRACT.** Experimental evaluations based on statistical and scientific criteria play fundamental role in identification of optimal performance parameters in manufacturing engineering. Based on this premise, the Doehlert's experimental planning method was applied to external cylindrical turning process of ABNT 1045 steel, with the purpose of determining the roughness correlation as a function of the cutting speed ( $V_c$ ) and feed rate ( $f$ ). The Doehlert's matrix was defined with five levels for feed rate and three levels for cutting speed, according to coded variables. From these experiments the correlation between input and output variables was determined. The best model is in agreement with the analysis of variance and Fischer's test. Graphs were obtained for both response and contour surfaces. In addition, the optimal point for the best model was determined by the Lagrange criterion, which corresponds to a feed rate ( $f$ ) of 0.0880 mm rev<sup>-1</sup> and the cutting speed ( $V_c$ ) of 155 mm min.<sup>-1</sup>, resulting in a minimum roughness average value ( $R_a$ ) equals to 0.8916  $\mu$ m.

**Keywords:** Doehlert's experimental planning; roughness; external cylindrical turning.

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### Introduction

The quality of machined products is directly linked to the roughness. Depending on the implementation of certain components and characteristics of assembly will be needed to apply subsequent finishing processes such as grinding and polishing (Ratnam, 2016). In the process of turning the roughness is directly influenced by the characteristics of the machine, machining tools parameters, tool wear, cutting speed and feeds, among others. Slamani, Gauthier, and Chatelain (2016) examined the surface roughness as function of the cutting speed in turning operations and concluded that there is a trend to increase the roughness with respect to tool wear, being therefore considered surface roughness as quantitative parameter for tool's evaluation.

In general, the experimental determination of the various correlational parameters for machine/material is fundamental for optimal performance in manufacture engineering. For such reason, the idea of experimental design is established, which is a set of tests with scientific and statistical criteria in order to determine the influence of several variables on a given system or process results (Montgomery, 2009). The main difference between the various types of plans -such as factorial design, central composite design, Taguchi and Doehlert- are their planning matrices. For this study, as an alternative rather useful and attractive to the second order, was used the Doehlert's planning.

The Doehlert matrix was presented by David H. Doehlert in 1970, where the matrix points correspond to the vertices of a regular simplex. In general, the total number of experimental points in the planning equals to  $k^2+k+pc$  where  $k$  is the number of factors and  $pc$  is the number of experiments at the midpoint. An important property of the planning is related to the number of levels that each variable possesses, which allows to evaluate the variables considered more important, that is, exhibit more pronounced effects at most number of points on studied region (Hammami, Ouejhani, Bellakhal, & Dachraoui, 2009). Doehlert's Design describes a circular area for two variables and its matrix consists of a central point and six additional points forming a regular simplex. The Doehlert matrices are pre-established and their constructions require

smaller number of experiments when compared to other plans (Araujo & Janagap, 2012; Ennaciri, Baçaoui, Sergent, & Yaacoubi, 2014).

The objective of this work is to identify through Doehlert's planning matrix the correlation of roughness average (Ra) as function of cutting speed (Vc) and feed rate (f) in turning process of ABNT 1045 steel.

## Material and methods

Firstly, all experiments were performed according to Doehlert's matrix shown in Table 1 and obtained the corresponding roughness (Ra) in which the numbers in parentheses indicate the coded levels. After that, were proposed models with and without interaction between cutting speed and feed rate (input variables). Quadratic models also were proposed as shown in Equation 1 to 3 and then were used the least squares method to obtain the models (response functions). The analyses to determine the best model were performed through coefficient adjustment, variance analysis and F-test, generating the most representative model (Montgomery, 2009). Finally, defined the best model, was carried out the optimal point using the Lagrange criterion, i.e., to determine cutting speed and feed rate that generate the smallest roughness.

For external cylindrical turning was used Nardini ND325 lathe (Figure 1), with main motor consisting of 8-5Hp (6/3.7 kW) of power. The selected machining tool was a MD Tool P20 class. Surface roughness measurements were carried out with a portable rugosimeter Digimess with 0.08 mm cutoff length and 0.001  $\mu\text{m}$  Roughness Average resolution. The ABNT 1045 steel sample pieces were obtained from cylindrical rods with diameter of 97 and 500 mm length, divided into 16 samples.

$$y = b_0 + b_1x_1 + b_2x_2 \quad (1)$$

$$y = b_0 + b_1x_1 + b_2x_2 + b_3x_1x_2 \quad (2)$$

$$y = b_0 + b_1x_1 + b_2x_2 + b_3x_1^2 + b_4x_2^2 \quad (3)$$

## Results and discussion

Table 2 shows the models that were proposed at variables codified respectively, with estimated parameters and the adjustment coefficients determination ( $r_{adj}^2$ ).

The analysis of variance (ANOVA) is shown in Table 3, in which *finv* mean the inverse function of Fischer's distribution, F-test, calculated for a confidence interval of 0.95,  $p-1$  degrees of freedom to regression (MQR) and  $n-p$  degrees of freedom to error (MQE), in which  $p$  is number of the parameter of model and  $n$  is total number of observations.

According the Table 2 the best model was model\_3, in which in this model the adjustment determination coefficient ( $r_{adj}^2$ ) was the highest, 0.9898, this result is also corroborated with F-test test, shown in Table 3. All models were statistically validated, once the relation MQR/MQE were higher than *finv* to all models, in accordance with the statistic of F-test. However, the model\_3 showed the highest MQR/MQE ration among the models, which means this model has the lowest residual, being identified as the best model. Its natural variables are given by Equation 4. The response surface and its contour's plot are shown in Figure 2 and 3, respectively.

Table 1. Doehlert's Matrix.

Experiments	Input Variables		Output Variable	
	$x_1$ (feed rate f) mm rev <sup>-1</sup>	$x_2$ (cutting speed) m min. <sup>-1</sup>	$y$ $R_a$ ( $\mu\text{m}$ )	
1	0.151 (0)	243.8 (0)	1.622667	1.572333
2	0.199 (1)	243.8 (0)	3.021	2.752333
3	0.176 (0.5)	304.73 (0.866)	2.363	2.338333
4	0.091 (-1)	243.8 (0)	0.796	1.120667
5	0.125 (-0.5)	192 (-0.866)	1.228333	1.115667
6	0.176 (0.5)	192 (-0.866)	2.074667	2.005667
7	0.125 (-0.5)	304.73 (0.866)	1.333667	1.230333

Table 2. Models proposal.

Models	$r_{adj}^2$	
$y = 1.7329 + 0.9656x_1 + 0.1214x_2$	0.9461	Model_1
$y = 1.7329 + 0.9656x_1 + 0.1214x_2 + 0.1158x_1x_2$	0.9350	Model_2
$y = 1.5867 + 0.9656x_1 + 0.1214x_2 + 0.3358x_1^2 + 0.0542x_2^2$	0.9898	Model_3

Table 3. ANOVA Table.

	SQ	nGL	MQ	MQR/MQE	finv
Regression	2.8415	2	1.4207	53.66	6.94
Model_1 error	0.1059	4	0.0265		
Total	2.9474	6			
Regression	2.9474	3	0.9505	29.75	9.27
Model_2 error	0.0958	3	0.0319		
Total	2.9683	6			
Regression	2.9373	4	0.7343	145.96	19.25
Model_3 error	0.0101	2	0.0050		
Total	2.9474	6			

$$Ra = 2.3347 - 27.3234 * f - 0.0031 * V_c + 155.1702 * f^2 + 0.00001 V_c^2 \quad (4)$$



Figure 1. External cylindrical turning process.

$$SR \text{ Model}_3 \text{ } yb = b_0 + b_1 * N_1 + b_2 * N_2 + b_3 * N_1 * N_1 + b_4 * N_2 * N_2$$

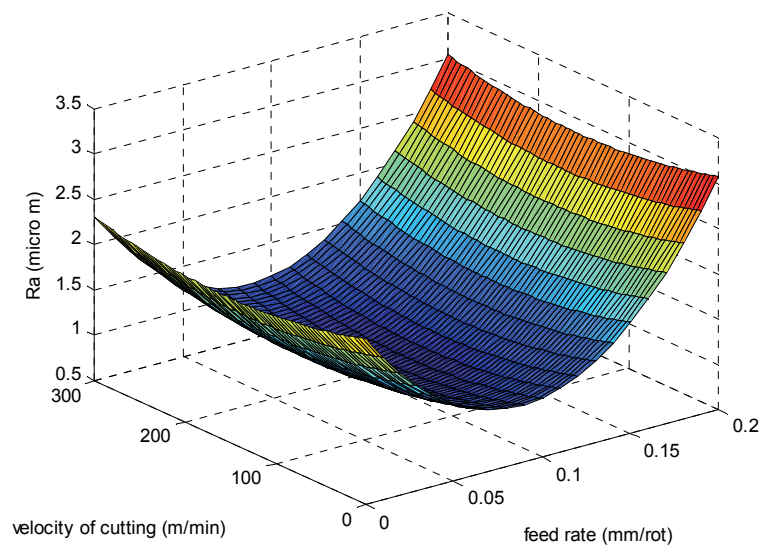
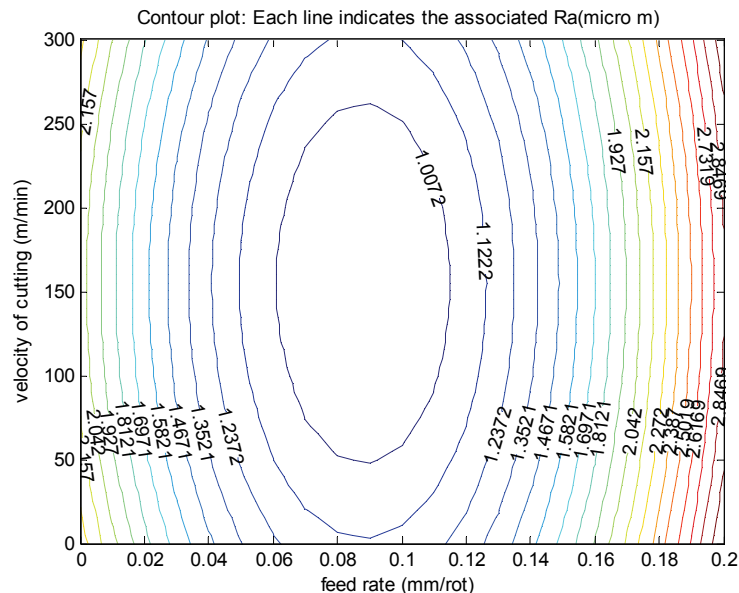


Figure 2. Response surface from the best model (Model\_3).

By Lagrange criterion, that shows the critical point is a minimum, is identified a feed rate ( $f$ ) equal to  $0.0880 \text{ mm rev}^{-1}$  and cutting speed ( $V_c$ ) equal to  $155 \text{ m min}^{-1}$ , which means that using these parameters in the process of external cylindrical turning the roughness will be smaller and equal to  $0.8916 \mu\text{m}$ .

The Table 4 shows the effects of the feed rate ( $f$ ) and cutting speed ( $V_c$ ) in the roughness ( $R_a$ ) related to the best model, in which is noticed that the variable that influences the most for surface finishing of the workpiece is the feed rate.



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