ANALYTICAL MODEL FOR PREDICTING SURFACE ROUGHNESS AS A FUNCTION OF AISI 1045 STEEL MACHINING PARAMETERS

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Abstract: In manufacturing process, surface roughness is an important parameter. It affects the mechanical behavior of parts obtained by turning process. The aim of our study is to get a better understanding on the effect of the machining parameters such as cutting speed, feed rate and tool nose radius on surface roughness. The methodology of experiment design was adopted and the experimentation was conducted per L27 orthogonal array with three levels for each factor.

Then a multiple regression model which expresses the roughness as a function of the machining parameters has been proposed; therefore the prediction of the surface state is possible from selected cutting parameters. The optimum cutting conditions were determined and exploited, which allowed the generation of a surface state with Ra= 0.5µm.

Key words: cutting conditions, experimental design, CNC turning process, surface roughness, prediction model.

1. INTRODUCTION

Manufacturing process of mechanical parts is often used in several sectors of activity such as aeronautics; automotive. Obviously, the parts obtained by machining have to require technical specifications according to their functionality like the dimensional and geometric precisions as well as the quality of the surface state. In order to produce parts that meet these technical specifications, several experiments based on the choice of cutting conditions are necessary before leading to satisfactory part. Through these experiments, we try to quantify and relate the various parameters that influence the surface roughness. The determination of this relationship is very necessary to carry out. In this context, several authors have studied the influence of cutting conditions on the surface roughness of pieces obtained by turning process. Cutting parameters (cutting speed, feed rate, depth of cut and lubrication), material and geometry of tool and the material of the workpiece are the most controlled factors in the experimental studies.

The machining parameters often studied are the cutting speed, the feed rate and the depth of cut [1-7]. A series of tests was carried out using experimental design, either with complete or fractional factorial designs to ensure better accuracy [1,2,8,9] or the Taguchi method to minimize the number of tests to be performed [6,10,11]. Afterward, using statistical analyzes, they determined the factors and their interactions which affect surface roughness.

The majority of this study shows that the feed rate is the most important factor in turning process in terms of surface quality, followed by the cutting speed. A high feed rate produces a poor surface quality, but it improves in the case of machining with high cutting speed. For depth of cut, they noted that it is the least influential factor, it can even be considered not influential on surface roughness [6, 7, 12, 13, 14].

As well as the cutting parameters, the cutting tool affects the quality of the machined parts. In fact, researchers are also interested to investigate the effect of the tool nose radius [8, 15]. They note that it has a little influence on surface roughness, but its interaction with other parameters, namely the feed rate and cutting speed, affect the quality of the machined surfaces. On the other hand, Ashvin et al. have shown that the tool nose radius has a strong influence on the surface state. It contributes in second order after the feed rate, for a cutting speed between 220 and 280 m/min [12].

After a good understanding of the behavior of parts against the turning process, it seems essential to correlate the roughness with the cutting conditions. The researchers proposed several prediction models that express the roughness as a function of the machining parameters by regression methods. Among them, we mention the linear model with or without interactions, the quadratic model with or without interactions or other models [1, 3, 5, 7, 12, 18].

Y.Sahin et al. and Cakir et al. have developed a polynomial model of second order without interactions, which expresses the roughness as a function of the feed rate, cutting speed and depth of cut for AISI 1050 and AISI P20 steel. Their experiment showed that the most influential parameter is the feed rate followed by the cutting speed. On the other hand the depth did not affect the surface roughness [19, 20].

In our work, the effect of the feed rate, cutting speed and the tool nose radius on surface roughness was investigated. The depth of cut was set at 0.5 mm, in fact it did not affect the surface roughness according to the literature review. The tool nose radius was varied using pads with three different levels. The studied parameters were fixed on three levels; consequently twenty-seven machining operations were performed on a CNC lathe. The results obtained from the roughness measurements were the subject of an ANOVA statistical analysis. Finally, a multiple regression model is determined for the prediction of the surface state. The model allowed us to define the optimum cutting conditions generating a surface state with Ra = 0.5 µm.

2. EXPERIMENTAL SET-UP

In order to understand the relationship between cutting conditions and surface roughness, experimental tests have been carried out. The details of experimental conditions, instrumentations and measurement and the procedure adopted for this investigation are described in this section.

2.1 Machine and material

The workpiece selected in this study was in the form of bars of 20 mm diameter and 120 mm length of AISI 1045 steel. Its chemical composition obtained by optical emission spectrometer is presented in Table 1.

Table 1. Chemical composition of AISI 1045

Steel	Chemical composition, [Wight percentage]				
AISI 1045	C	Mn	S	P	Si
	0.42	0.72	0.02	0.04	0.19

The specimens are machined in dry conditions, on a CNC lathe «Alpha 1530XS» (Figure 1(a)).

The cutting tool consists of a PDJNR2020 tool holder and a DNMG 15 06 04 insert. Three tool nose radiuses were used: 0.4, 0.8 and 1.2 mm. Figure 1(b) shows the geometry of the cutting tool inserts used.

After the machining operations, the surface roughness measurement was done using the surface roughness tester of "Mitutoyo" SJ-201M shown in Figure 2.

The inspection is carried out over a length of 12.5mm and in the direction parallel to the advance of the cutting tool. The measurements are taken on four different generatrix with a rotation between rows of approximately 90° to obtain an average value of the roughness.

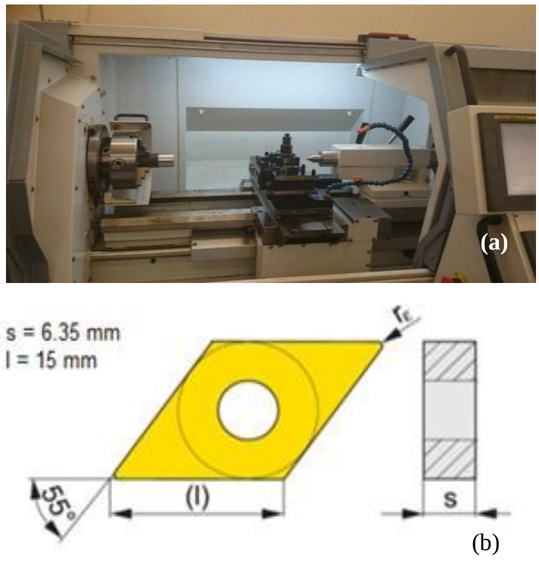


Fig. 1. (a) CNC Lathe «Alpha 1530XS»;
(b) Insert geometry.

Fig. 2. Surface roughness measurement

2.2. Experiment design

A complete 27-trial factorial design was chosen to improve the accuracy of the results. The factors studied are varied on three levels.

Table 2 summarizes the cutting conditions adopted.

Table 2. Cutting conditions

Factors		Tool nose radius, rε [mm]	Cutting speed, Vc [m/min]	Feed rate, f [mm/rev]	Depth of cut, ap [mm]
Levels	-1	0.4	75	0.045	0.5
	0	0.8	107	0.14	-
	1	1.2	150	0.24	-

3. RESULTS AND DISCUSSION

3.1. Effect of machining parameters on surface roughness

The graphs in Figure 3 show the effect of cutting conditions on surface roughness. In fact, we notice that the surface roughness is strongly influenced by the cutting speed and the feed rate. However the tool nose radius seems to have a less pronounced influence. For the tool nose radius we observe an average change of its effect of 0.5. However the variation rage effect for the cutting speed and feed rate is more important. The increase in cutting speed generates an increase in surface roughness; in contrast the decrease in feed rate produces an increase in surface roughness.

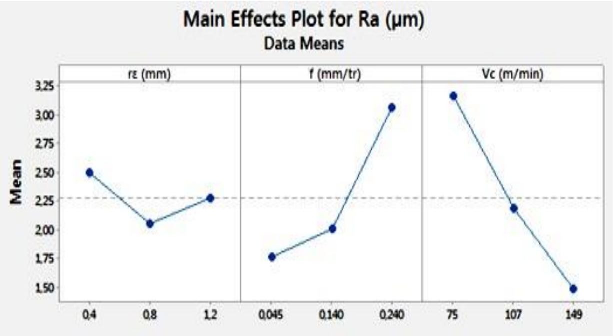


Fig. 3. Effect of machining parameters on surface roughness

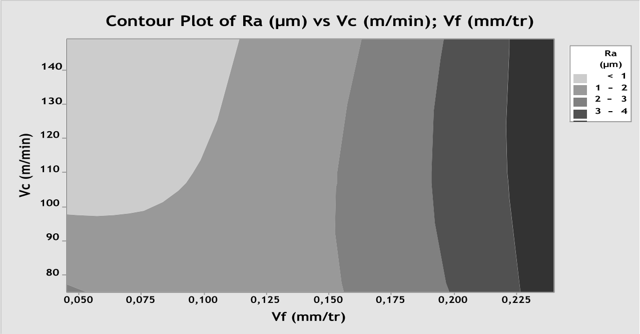
To represent the evolution of surface roughness as a function of machining parameters studied, we chose to draw a contour plot to illustrate the surface roughness according to the cutting speed Vc and feed rate f for each tool nose radius figure 4. In Figure 4 (a) that corresponds to the smallest tool nose radius rε=0.4 mm, we notice that a large part of the roughness distribution is in the form of vertical strips, especially for f ≥0.1 mm/tr. These bands indicate that for intervals of feed rate, there is a wide choice of Vc to generate a level of roughness. For example, an interval of feed rate caught between 0.1 mm/rev and 0.15 mm/rev we can choose Vc between 70 and 150 m/min to reach a roughness between Ra= 1 and 2 µm. Compared to the same graph for rε = 0.4 mm, we can also note that the field associated with the better surface roughness Ra < 1µm is wide enough for this tool nose radius. Indeed, for this tool nose radius, for a feed rate chosen between [0.05 – 0.1] and cutting speed between [100 - 150], surface roughness will be less than 1 µm.

For the tool nose radius rε=0.8mm, the corresponding plot represented in Figure 4 (b), the distribution of roughness based on cutting speed and feed rate is always in strip form, but this time they are horizontal. For a given roughness we have a large range of feed rate, but a limited range of Vc. In this plot, we can also observe that the field corresponding to Ra < 1µm is considerably reduced compared to the case of the rε=0.4 mm. Indeed, to have a surface roughness with Ra < 1 µm, f must be chosen between 0.05 and 0.075 mm/rev and Vc between 121 and 150 m/min.

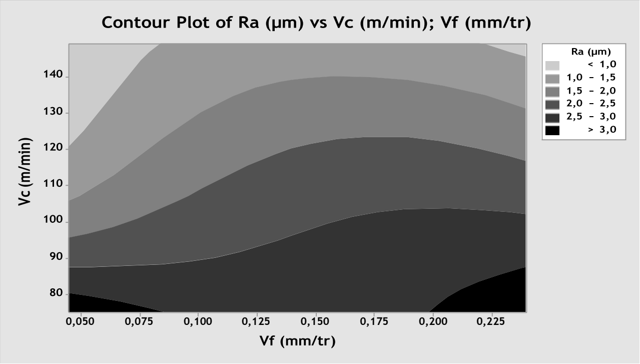
The last case of roughness distribution for rε=1.2mm is shown in Figure 4(c). This distribution is similar to that of rε=0.8 mm, but it remains far more reduced for rε = 0.4 mm.

Finally, by means of these mappings we were able to highlight the impact of the cutting speed and the feed rate on surface roughness. This impact is sensitive to the tool nose radius chosen.

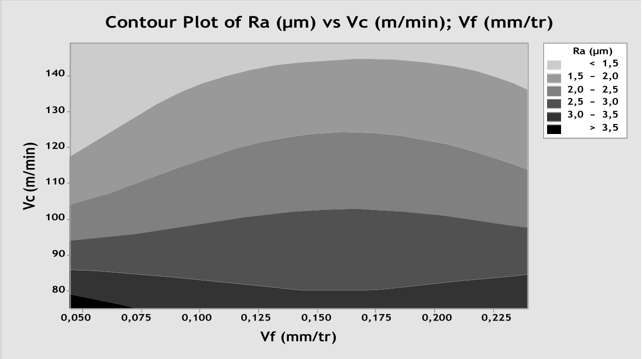
Finally, the influence of f or Vc on surface roughness depends on the choice of tool nose radius. These results allowed us to sense about the effect and the evolution of roughness as a function of the cutting conditions, but it's not sufficient to know the most influential factors on the surface state. Therefore, an analysis of variance ANOVA is performed in order to find out the factors influencing the surface state.



(a) r_ε = 0.4 mm



(b) r_ε = 0.8 mm



(c) r_ε = 1.2 mm

Fig. 4. Surface roughness as a function of cutting speed, feed rate for each tool nose radius

3.2. Analysis of variance ANOVA

Table 3 presents the results of the ANOVA analysis, with a 95% confidence interval (α = 005). The factors analyzed are the tool nose radius, feed rate, cutting speed and their interactions. In this table, we recall that ddl corresponds to the degrees of freedom and F to the ratio F = variation between sample means / variation within the samples.

Table 3. ANOVA for surface roughness

Sources	Sum of squares	DOF	Main square	F	Prob>F
rε	0.9113	2	0.4556	8.598	0.0102
f	8.638	2	4.319	81.5	0
Vc	12.82	2	6.408	120.9	0
rε*f	13.17	4	3.293	62.13	0
rε*Vc	2.973	4	0.7431	14.02	0.0011
f*Vc	1.708	4	0.4271	8.06	0.0066
Residus	0.4239	8	0.0529		
Total	40.64	26			

According to the results of the ANOVA analysis, we see that all of the studied factors and their interactions are considered influential on surface roughness, but with different degrees. The cutting speed is the most influential factor on roughness followed by cutting speed. For the tool nose radius, it is considered influential, but less significant in comparison with the other factors and their interactions. Then intervene the effect of the interaction between the feed rate and the tool nose radius. She is very influential on the surface roughness; so the choice of the tool nose radius is very important despite its effect. So, we can conclude that there is an indirect effect on the state of surface. For the effect of the other interactions rε * Vc and f * Vc, they are less influential on the surface state against other factors.

After studying the evolution of surface state according to machining parameters, we discerned the impact of these factors and their interactions on the surface roughness. The complexity of the phenomenon and the interdependence of the factors hindering the choice of machining parameters for manufacturers. Hence the need to develop a model that expresses the roughness based on cutting conditions.

3.3. Mathematical model for surface roughness prediction

In order to predict the surface condition of pieces obtained by turning process, the development of a mathematical model is very necessary to perform.

We chose to express the roughness as a function of the cutting conditions using a second order polynomial model with interactions (equation 1).

$$y = b_0 + \sum_{i=1}^{k} b_i . x_i + \sum_{i=1}^{k-1} \sum_{j=i+1}^{k} b_{ij} . x_i x_j + \sum_{i=1}^{k} b_{ii} . x_i^2 + \sum_{i=1}^{k-1} \sum_{j=i+1}^{k} b_{ijj} . x_i . x_j^2 + \sum_{i=1}^{k-1} \sum_{j=i+1}^{k} b_{iij} . x_i^2 . x_j + \sum_{i=1}^{k-1} \sum_{j=i+1}^{k} b_{iijj} . x_i^2 . x_j^2 \qquad (1)$$

where:

k = 3 number of factors

x_1 - tool nose radius rε;

x_2 - feed rate f;

x_3 - cutting speed Vc.

From a matrix calculation under Matlab, we have establish the coefficients bi, bii, biij , bijjet biijj

$b_0 = 14.9$
$b_1 = 8.717$ $b_2 = -275$ $b_3 = -0.2619$
$b_{11} = -2.286$ $b_{12} = 153.2$ $b_{13}=-4206.10^{-5}$
$b_{22} = 1006$ $b_{23} = 3.617$ $b_{33} = 1254.10^{-6}$
$b_{112} = -80.09$ $b_{113}=-8399.10^{-6}$ $b_{122}=-872.9$
$b_{133}=-4879.10^{-7}$ $b_{223} = -10.42$ $b_{233}=-1463.10^{-5}$
$b_{1122} = 442.4$ $b_{1133} =3806.10^{-7}$ $b_{2233}= 4214.10^{-5}$

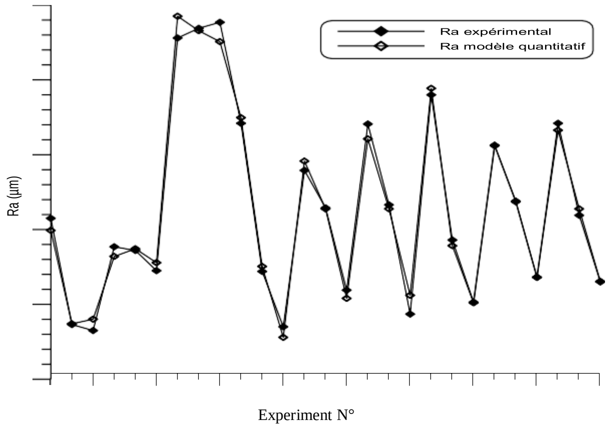


Fig. 5. Experimental *vs* predicted values of surface roughness

From these coefficients, our model has been defined and through which we have been able to plot the Ra curve according to the different combinations from our experimental design (Figure 5). This numerical curve was compared with that obtained experimentally. According to this comparison, we can see the good agreement between the model and the experience. The value of the coefficient of determination R^2 of this model is equal to 0.987. It means that 98.7% of the roughness variations are interpreted by this model, with this percentage; we can confirm the good performance of our model.

3.4. Determination of optimal cutting conditions

Using a program under Fortran 95, the constraint minimization method based on the method of Hook and Jeeves, the optimal values of the cutting speeds Vc* and feed rate f*, as well as the tool nose radius rε*, which guarantee a minimum surface roughness:

Vc* = 126.6 m/min, f* = 0.045 mm/rev and rε*=0.4mm.

The minimum value of the surface roughness is Ra_{min} = 0.54 µm.

In order to validate our model, a cutting operation with these optimal cutting conditions was carried out and the average surface roughness was measured. In Table 5, we have the optimal values of the cut parameters as well as the theoretical and experimental values of Ra. According to these values of Ra, we can conclude that our model is validated.

Table 5. Optimal cutting conditions

rε [mm]	f [mm/rev]	Vc [m/min]	ap [mm]	Ra model [µm]	Ra experimental [µm]
0.4	0.045	127	0.5	0.54	0.50

3.5. Discussion

According to previous studies on different steels, a number of authors have shown that feed rate is the most important factor in roughness [13, 14, 17]. On the other hand, according to our study, we have obtained that the cutting speed is the most influential factor. A part of this difference may be due to the range chosen for each parameter as well as the microstructure of the material. To understand the origin of this difference, we will study the effect of cutting speed and feed rate for the different tool nose radius considered. We performed an ANOVA statistical analysis for each tool nose radius. Tables 6, 7 and 8 below present the results with a confidence interval of 95% ($\alpha = 0.05$).

Table 6. ANOVA analysis for rε = 0.4mm

Sources	Sum of squares	DOF	Variances	F	p	Influ-ence
f	21.61	2	10.80	42	0.002	yes
Vc	0.49	2	0.25	1	0.45	no
Residus	1.0	4	0.25			
Total	23.11	8				

Table 7. ANOVA analysis for rε = 0.8mm

Sources	Sum of squares	DOF	Variances	F	p	Influ-ence
f	0.09	2	0.004	0.04	0.959	no
Vc	7.45	2	3.723	35.15	0.002	yes
Residus	0.42	4	0.106			
Total	7.88	8				

Table 8. ANOVA analysis for rε = 1.2mm

Sources	Sum of squares	DOF	Variances	F	p	Influ-ence
f	0.19	2	0.096	0.55	0.616	no
Vc	7.85	2	3.924	22.47	0.006	yes
Residus	0.70	4	0.175			
Total	7.84	8				

Depending on the statistical analysis, we have found that for the tool nose radius rε = 0.4 mm, it is the feed rate which is the most influential parameter as confirmed by several works [3, 4, 12]. For the two other cases where rε = 0.8 mm and rε = 1.2 mm, it is the cutting speed which is the most influential parameter on the quality of the surface state.

Therefore the effect of the feed rate and the cutting speed on the roughness varies as a function of the tool nose radius. This variation is illustrated through the graph of figure 6.

According to this graph, we observe that the increase of the tool nose radius generates a decreasing of the effect of feed rate and the increase of the effect of cutting speed.

The area I corresponds to the portion where the feed rate is the most influential factor and the area II presents the part where the cuttings speed is most influential. The tool nose radius does not have a direct influence on the roughness, but it affects the way other parameters affect the quality of the surface state: the cutting speed and the feed rate.

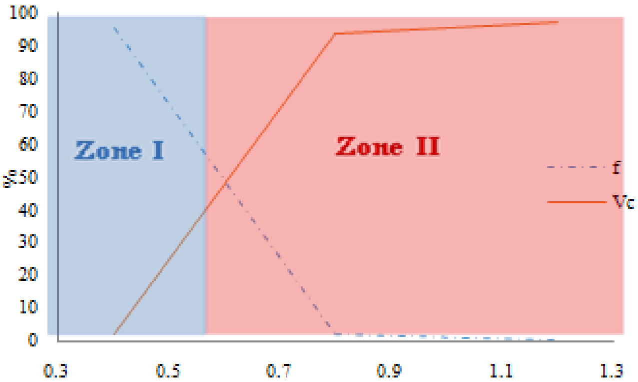


Fig. 6. Effect of the cutting speed and feed rate on surface roughness as a function of the tool nose radius

4. CONCLUSIONS

Through our study we were able to analyze the effect of the cutting conditions, namely the cutting speed, the feed rate and the tool nose radius on the surface state of parts obtained by turning process.

According to the results obtained, we found that the roughness improves with the increase of cutting speed and decrease of feed rate. For the tool nose radius, it seems to have a little influence on the surface state, but it has a strong influence on how the feed rate and the cutting speed affect the surface roughness.

Given the complexity of the choice of machining parameters to obtain a better surface roughness, we have developed a mathematical model. After validating our model by experiment, we determined the optimal cutting parameters: Vc* = 126.6m/min, f*= 0.045mm/rev and rε* = 0.4mm to generate a surface roughness with Ra = 0.5µm.

Our model expresses roughness based on cutting speed, feed rate and tool nose radius, will allow manufacturers to predict surface roughness for given cutting conditions of AISI 1045 steel.

This relevant result will allow us through a study in progress, to predict the fatigue life of the pieces obtained by turning process.

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