Statistical application of the response surface methodology (RSM) with the proposition of machining strategies in 6351-T6 aluminum in the manufacture of component with complex geometry

Aplicação estatística da metodologia de superfície de resposta (MSR) com a proposição de estratégias de usinagem no alumínio 6351-T6 na fabricação de componente com geometria complexa

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ABSTRACT

In a machining process, a conventional analysis is normally used, in which each factor or cutting parameter is studied individually. However, with application of the method of planning experiments (DOE), so that the appropriate data are collected and analyzed by statistical methods, resulting in conclusions with valid and objective predictions simultaneously. In a study of the milling process in complex geometries, the response of the roughness average (R_a) of the machined surfaces, indicates the influence of several process factors, such as cutting fluid used, depth of cut (a_p), feed per tooth (f_z), cutting speed (V_c), among others. In this study, the modeling of cutting factors or parameters will be addressed: cutting speed (V_c) and feed per tooth (f_z) in the milling finishing process, varying with three advanced machining strategies of a component with complex geometry in 6351-T6 aluminum and application of a semi-synthetic cutting fluid. With the solution of the application of the response surface methodology (RSM), it will be possible to anticipate the problems that influence the variables and the objective will be the optimization, directing the best strategy with the best parameters, facilitating the machining prototyping.

RESUMO

Em um processo de usinagem, normalmente utiliza-se uma análise convencional, na qual cada fator ou parâmetro de corte é estudado individualmente. Todavia, com aplicação do método de planejamento de experimentos (DOE), afim de que os dados apropriados sejam coletados e analisados por métodos estatísticos, resultando em conclusões com previsões válidas e objetivas simultaneamente. Em um estudo do processo de fresamento em geometrias complexas, a resposta da rugosidade média (R_a) das superfícies usinadas, indica a influência dos diversos fatores de processo, como fluído de corte utilizado, profundidade de corte (a_p), avanço por dente (f_z), velocidade de corte (V_c), entre outros. Neste estudo será abordado a modelagem dos fatores ou parâmetros de corte: velocidade de corte (V_c) e avanço por dente (f_z) no processo de acabamento do fresamento variando com três estratégias avançadas de usinagem de um componente com geometria complexa em alumínio 6351-T6 e aplicação de um fluído de corte semissintético. Com a solução da aplicação da metodologia de superfície de resposta (MSR), será possível, antecipar os problemas que influenciam nas variáveis e o objetivo será a otimização, direcionando a melhor estratégia com os melhores parâmetros, facilitando a prototipagem de usinagem.

INTRODUCTION

Aluminum, the second most abundant metallic element on earth, became an economic competitor in engineering applications as recently as the late 19th century [9]. However, aluminum is not found directly in the metallic state in the earth's crust. Its attainment depends on processing steps until reaching the standardized state in which it is identified as a product. The process of obtaining primary aluminum is divided into three stages: mining, refinery and reduction [1].

One of the most striking features of aluminum is its versatility. The range of physical and chemical properties that can be developed from pure aluminum to the most complex alloys are numerous [7]. Among them, the following should be highlighted: appearance, lightness, manufacturing capacity, physical properties, mechanical properties and corrosion resistance. Also noteworthy is the wide application in the various economic sectors: transport, civil construction, electricity, packaging and consumer goods. Furthermore, aluminum has a prominent place compared to other metals, due to its recycling capacity [1]. As it is fully recyclable, the use of aluminum contributes to minimizing the amount of waste deposited in the environment, as well as lower energy consumption in its production process [14].

In addition to the base metal, aluminum alloys have many other elements, considered as alloy components or as impurities. The main ones are copper, silicon, magnesium, zinc and manganese, which determine the main characteristics of the alloy [7].

Workable aluminum alloys are classified as heat-treatable and non-heat-treatable, depending on the way in which the material is hardened. The group of non-heat-treatable alloys comprises the 1XXX, 3XXX (Al-Mn), 4XXX (Al-Si) and 5XXX (Al-Mg) series. The group of heat-treatable alloys comprises the series 2XXX (Al-Cu), 6XXX(Al-Mg-Si), 7XXX (Al-Mg-Zn-Cu) and some alloys of the 8XXX group [14].

Tempering is a condition applied to metal or alloys, by means of cold plastic deformation or heat treatment, providing it with structure and characteristic mechanical properties. The standard that classifies the tempers of aluminum products and their alloys is ABNT NBR ISO 2107 [14]. According to the standard, tempers are classified according to the processes to which the products are subjected, among the existing processes, it is worth mentioning the "T", which applies to products that undergo heat treatment with or without deformation. complementary plastic, which produces stable physical properties different from those obtained with other processes. The letter “T” must be followed by one or more digits that indicate the sequence of the processes carried out: heat treatment or plastic deformation [2].

Aluminum alloys are generally considered to be easy to machine, and can normally be machined at much higher speeds than heavier metals [14]. For cutting efficiency, however, tools and machining conditions must be suitable for each specific alloy [11].

Machining this material offers several important advantages, including almost unlimited cutting speed, low cutting forces, excellent finish, good dimensional control and long tool life [2].

The use of cutting fluids, when properly chosen and applied, brings benefits such as improved surface quality of the machined part and less tool wear [7]. Aluminum, due to its low melting point, softens under heat generation during dry machining resulting in material adhered to tools [13]. In this way, aluminum is normally machined using cutting fluids, in order to reduce the chip-tool contact area, which contributes to increase the tool life and also provide chip evacuation [4]. Thus, the main function of the cutting fluid in aluminum machining is to avoid clogging in the tool during the milling operation [6].

From the above, the present study has as main objective to study the minimum roughness average evaluating its performance through the Response Surface Methodology (RSM).

This study was carried out in the milling process of aluminum material 6351-T6 and with the use of semi-synthetic based soluble cutting fluid [5]. The influence of variations in machining parameters, such as cutting speed (V_c) and feed per tooth (f_z) were monitored in order to obtain the best finish of the machined surface being verified at the roughness average (R_a).

ACTIVITIES

The Response Surface Methodology (RSM), according to [10], is a collection of mathematical and statistical tools used for the modeling and analysis of problems in which the response of interest is influenced by several variables and the objective is to optimize this response.

For most problems, it turns out that the relationships between the response and the independent variables are unknown. Thus, the first step is to find an adequate approximation to represent the response of interest as a function of the process variables. Generally, polynomial functions are used to describe such relationships [3]. Thus, if the response is well modeled by a linear function, the approximate relationship can be represented by the following model:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots \beta_k x_k + \varepsilon \quad (1)$$

where:
y – response of interest;
x_i – independent variables;
β_i – coefficients to be estimated;
k – number of independent variables; and
ε – experimental error.

If the system exhibits curvature, then a higher degree polynomial must be used, such as the second-order model described by Equation:

$$y = \beta_0 + \sum_{i=1}^{k} \beta_1 x_1 + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum\sum_{i<j} \beta_{ij} x_i x_j + \varepsilon \quad (2)$$

Almost all response surface problems use one or both of the above models. Furthermore, the polynomial model is unlikely to behave as an adequate approximation for the entire experimental space covered by the independent variables [10]. However, for a specific region, such models have been shown to be efficient.

To carry out the practical part of this research, the present work used experimentation, since the optimization of the object of study was based on objective functions determined from data collected by experiments. The strategy adopted was developed through the Response Surface Methodology.

The data collection itself is a very important activity in the execution of the work. A poorly designed database can lead to unsatisfactory or deficient results. That said, it is extremely important to plan the experiment in detail, as well as its proper execution and recording [10].

The control variables adopted for this procedure were the cutting speed (V_c) and the feed per tooth (f_z) of the tool. These variables are admittedly very important, since they strongly influence the milling process, especially the surface finish of the part.

For the specification of the parameter levels, information from the supplier's tool catalog was taken into account for calculation [8] and the performance of preliminary tests. The preliminary test was carried out with a prismatic block with inclined sides, in order to simulate the position of the cutting tool in a complex geometry. Thus, after the analysis, the three lowest average results of the roughness average measurements (R_a) are fixed for the experiment, with their respective machining parameters (Table 1).

Table 1 – Used machining parameters

Tool: R216.54-06040RAL40G 1620 (SANDVIK) - **Inclined wall = 14°** D: Ø6 [mm] / r_e : 3 [mm] / a_p : 0,12 [mm] / a_e : 0,05 [mm]		
3	**2**	**1**
V_c= 141 [m/min]	**V_c= 159 [m/min]**	**V_c= 176,5 [m/min]**
f_z= 0,195 [mm/tooth]	**f_z= 0,163 [mm/tooth]**	**f_z= 0,13 [mm/tooth]**
n= 7491 [rpm]	n= 8427 [rpm]	n= 9364 [rpm]
V_f= 5843 [mm/min]	V_f= 5478 [mm/min]	V_f= 4869 [mm/min]

The experiment sequencing was planned following three factors at three levels ($3^k = 3^3 = 27$) with 2 replicates, which resulted in 54 experiments, as shown in Table 2 [10]. The factors used are the "contour", "zigzag" and "zigzag 45°" machining strategies.

Table 2 – Presentation of the levels and factors analyzed

3 Strategies: Contour ZigZag ZigZag 45°		**Feed per tooth - f_z [mm/tooth]**		
		0.13	**0.163**	**0.195**
		R_a [µm]	R_a [µm]	R_a [µm]
Cutting speed V_c [m/min]	**176.5**	*2 replicate per strategy (3)*	*2 replicate per strategy (3)*	*2 replicate per strategy (3)*
	159	*2 replicate per strategy (3)*	*2 replicate per strategy (3)*	*2 replicate per strategy (3)*
	141.2	*2 replicate per strategy (3)*	*2 replicate per strategy (3)*	*2 replicate per strategy (3)*

The 3D modeled part used in the milling machining experiment is as shown in Figure 1.

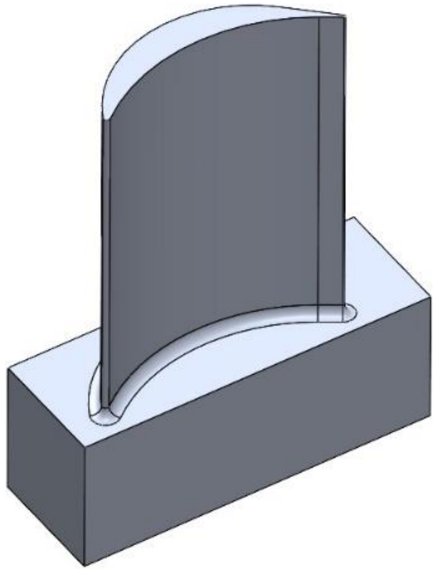

Figure 1 – Part with complex geometry to be milled in the experiment

The experiments were planned and simulated in CAM software, due to the complexity of machining and the need for more than three-axes traditional used.

The first strategy, called "contour", which consists of machining the part contouring the selected surface, obtaining constant depth control with Z-level passes in the up-cut direction, was planned as shown in Figure 2.

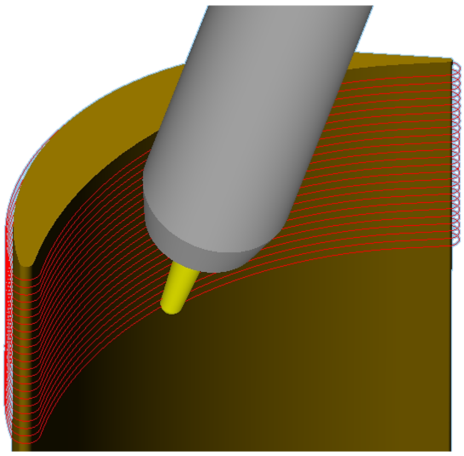

Figure 2 – "Contour" machining strategy

The second and third strategies, called "ZigZag" (Figure 3) and "ZigZag 45°" (Figure 4), are because their machining cycles are directed from one side to the other, both in the direction of concordant and discordant cutting, for each selected face, but the second strategy is at the perpendicular position of the part base and the third strategy is 45° from the perpendicular position of the part base.

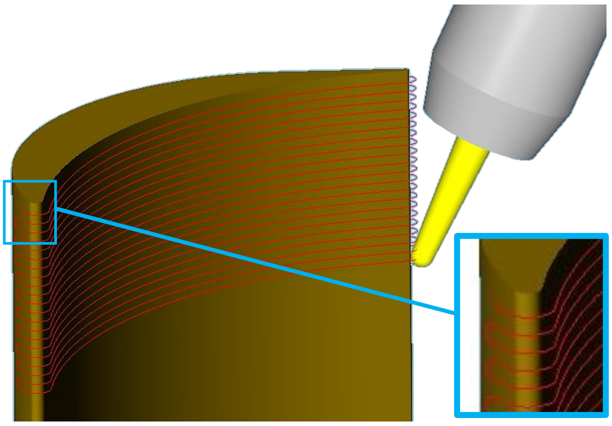

Figure 3 – “ZigZag” machining strategy

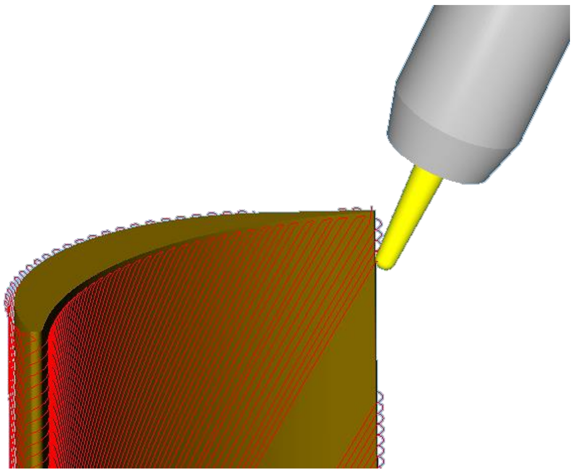

Figure 4 – “ZigZag 45°” machining strategy

RESULTS

The roughness average and service life of a cutting tool installed in a numerically controlled machine can be influenced by cutting speed and feed per tooth. With that, the average results of the measurements of the accomplishment of the factorial experiment 3^3 with 2 repetitions are shown in Table 3. The measurements were carried out in the transversal direction to the feed in the machining finishing step.

Table 3 – Result of Roughness average measurements

		Strategies: Contour			ZigZag			ZigZag 45°		
		f_z [mm/dente]								
		0,13	0,163	0,195	0,13	0,163	0,195	0,13	0,163	0,195
	V_c [m/min]	Measurements R_a [µm]								
replicate 1	176,5	0,309	0,411	0,549	0,325	0,433	0,577	0,341	0,454	0,605
replicate 1	159,0	0,339	0,453	0,604	0,357	0,476	0,635	0,375	0,502	0,667
replicate 1	141,2	0,374	0,498	0,665	0,393	0,524	0,701	0,412	0,551	0,734
replicate 2	176,5	0,315	0,419	0,561	0,331	0,441	0,589	0,347	0,463	0,618
replicate 2	159,0	0,346	0,462	0,616	0,364	0,486	0,648	0,382	0,512	0,683
replicate 2	141,2	0,381	0,508	0,679	0,401	0,535	0,713	0,421	0,561	0,748

The acceptable average roughness of this experiment should be $R_a \leq 0.5$ µm and with *p-values* meeting the significance level $\alpha \leq 0.05$.

The complex geometry part (Figure 5) was machined (finishing operation) on a Leadwell MU650 Simultaneous 5-axis Machining Center with a Ø6mm tipped solid spherical end mill and R216.54-carbide 4 knives. 06040RAL40G 1620 [8] according to Table 1.

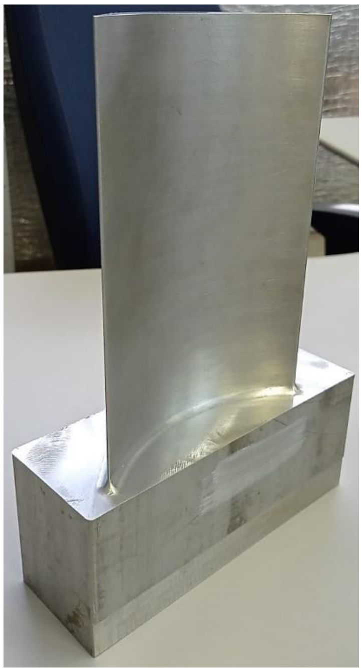

Figure 5 – Part with complex geometry machined in the “contour” strategy

To verify the variation of the observed data, follow the *boxplot* graphs as shown in Figure 6 and Figure 7.

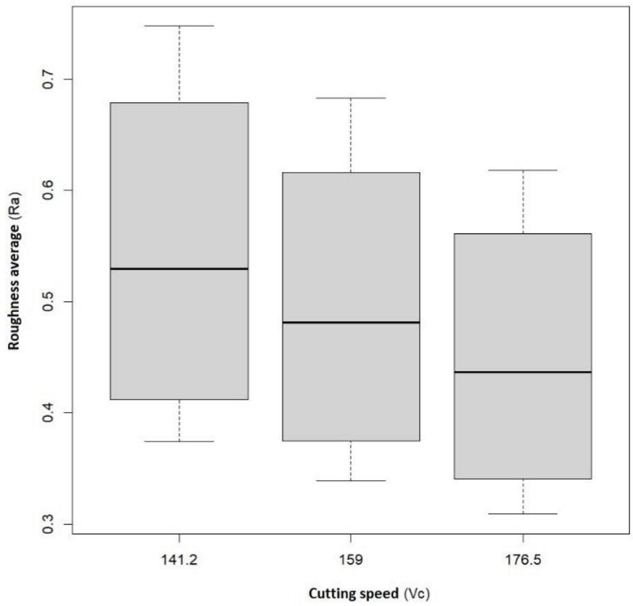

Figure 6 - Cut Speed *BoxPlot* Chart

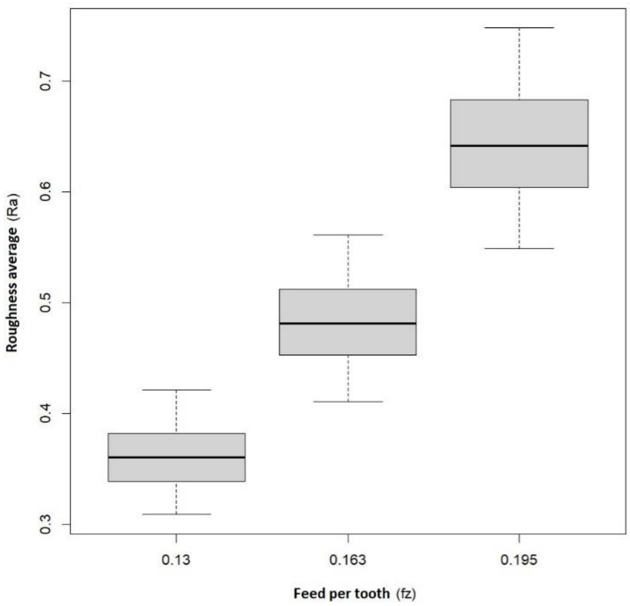

Figure 7 - Feed Per Tooth *BoxPlot* Chart

The relationship between the factors “cutting speed” and “feed per tooth” were generated in the interaction graphs as shown in Figure 8, in order to display the averages for the levels.

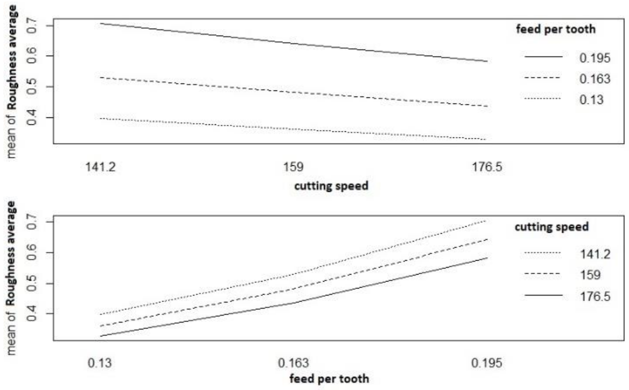

Figure 8 - Interaction Graphs - Cutting Speed and Feed per Tooth

Note that there is no interaction between the experiment factors, “Cutting Speed” and “Feed per Tooth”, as they do not intersect. To verify significance, a second-order model is required, as follows:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{12} x_1 x_2 + \beta_{11} x_1^2 + \beta_{12} x_2^2 + \varepsilon \quad (3)$$

where x_1 = cutting speed and x_2 = feed per tooth, and can also be adjusted to the data.

Table 4 – Analysis of Variance (ANOVA)

```
          Df Sum Sq Mean Sq  F value   Pr(>F)
fz         1 0.7155  0.7155 1166.960  < 2e-16 ***
Vc         1 0.0813  0.0813  132.668 1.12e-15 ***
fz:Vc      1 0.0044  0.0044    7.258  0.00959 **
Residuals 50 0.0307  0.0006
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Table 5 – Linear Model (Model Fitted)

```
Call:
lm(formula = Ra ~ fz + Vc + fzVc)

Residuals:
      Min        1Q    Median        3Q       Max
-0.047438 -0.016646  0.003008  0.015148  0.050318

Coefficients:
             Estimate Std. Error t value Pr(>|t|)
(Intercept) -0.394972   0.231692  -1.705  0.09445 .
fz           8.109118   1.405755   5.769    5e-07 ***
Vc           0.001168   0.001452   0.804  0.42503
fzVc        -0.023736   0.008811  -2.694  0.00959 **
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.02476 on 50 degrees of freedom
Multiple R-squared:  0.9632,    Adjusted R-squared:  0.9609
F-statistic: 435.6 on 3 and 50 DF,  p-value: < 2.2e-16
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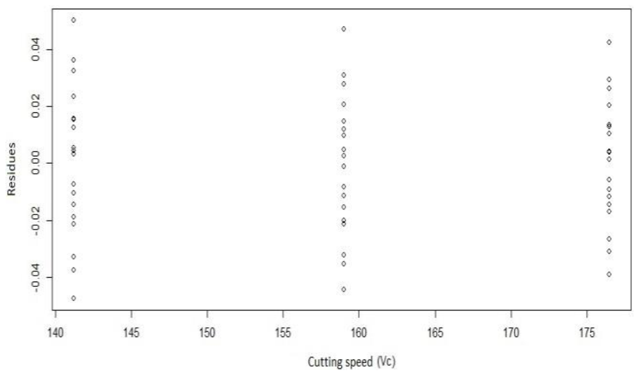

Figure 9 - Cutting Speed Residuals Graph

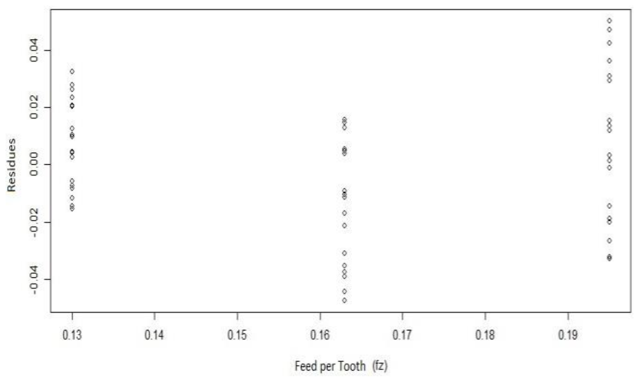

Figure 10 – Feed per Tooth Residuals Graph

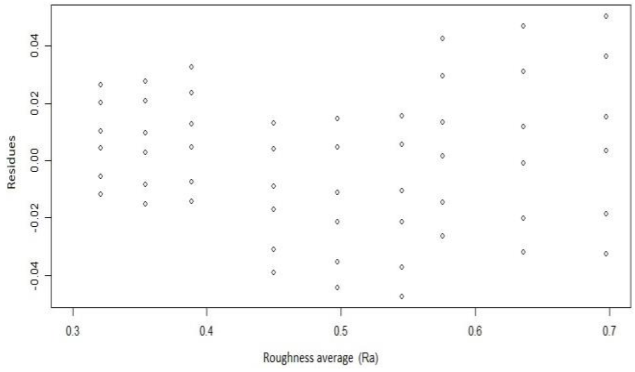

Figure 11 – Roughness average Residuals Chart

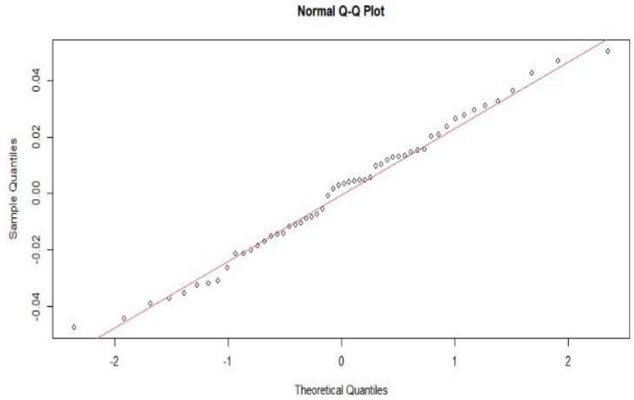

Figure 12 - Quantile-Quantile Normal Graph

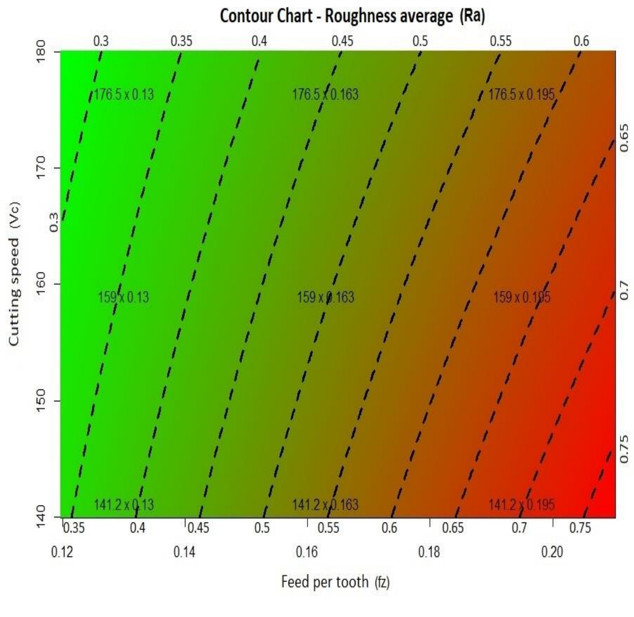

Figure 13 - Roughness average Contour Chart (2D)

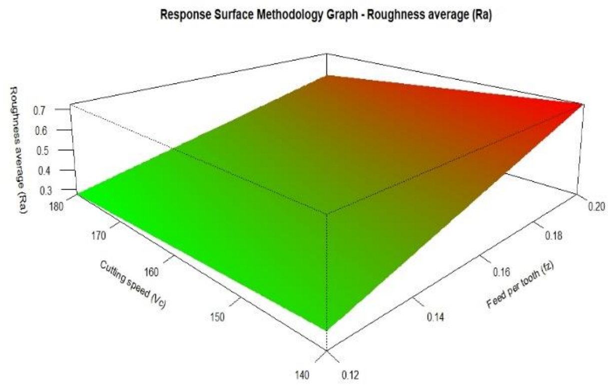

Figure 14 - Response Surface Methodology Graph - RSM (3D)

DISCUSSION

Note in Table 4 that all V_c and f_z terms are significant and that the mean square of the error in the fit of the second order model is 0.0006. In Table 5, the forecasts form the adjusted model and it can be verified that the value of R^2 is 0.9632 and the adjusted one that already includes the errors is R^2_{aj} = 0.9609, which shows great confidence, as they are 96.09 % reliable. Also, the most significant factor value is the linear term is the "feed per tooth (f_z)" with the *p-value* is 5e-07. The prediction profile, on the other hand, shows the response variable as a function of each experiment factor, "f_z" and "f_zV_c", but the prediction profile is very useful for optimization. Thus, this adjustment results in the minimum predicted average roughness.

The second-order model with the additional higher-order terms is shown in the Fitted Linear Model (Table 5). Although there are some large *p-values*, all the terms in the model were kept only to ensure hierarchy. The forecast profile results in the minimum roughness average (R_a), which is reached around a cutting speed (V_c) of 176.5 m/min and feed per tooth (f_z) of 0.13 mm/tooth and also meeting the adopted significance level. The graphs in Figure 13 and Figure 14 respectively, confirm the estimate of the optimal operating conditions found in the forecast profile, thus verifying how the adjusted response values relate. As shown in Figure 5, we see the finished machined part.

CONCLUSION

From the results obtained in the milling process in complex geometry in 6351-T6 aluminum and with the use of soluble semi-synthetic cutting fluid applying the DOE tool, it is concluded that:

- The RSM technique applied was efficient, as it exposed each of the selected parameters in the machining process, as expected;

- Of the factors: cutting speed (V_c) and feed per tooth (f_z), the second has greater influence on the roughness average (R_a), that is, on the final finish of the machined part. And the first has a direct influence on the useful life of the inserts, as they did not wear out in this experiment.

The models presented, through the DOE methodology, of minimum roughness average (R_a) that results in the surface finish of the machined part, are close to reality and with a very low error margin for both cases, acceptable. Therefore, the feasibility of modeling complex surface machining processes by this Analysis of Variance (ANOVA) by Response Surface Methodology (RSM) technique is concluded.

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