Machinability of a Martensitic Stainless Steel in End Milling Operation Using Surface Response Methodology

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Abstract. *The machinability of a martensitic stainless steel (AISI 420) was checked on an end milling operation using carbide inserts coat with TiAlN - TiN and dry cut. The tool life, surface, roughness and cutting force were statistically analised and developed in terms of cutting speed, feed per tooth and depth of cut. Those that presented higher coefficient of correlation were taken as mathematical models of responses, using factorial planning and the response surface methodology. The input variables effects in responses were investigated, crossing information contained in their bound surfaces with bound lines of material removal rate. The results obtained with this technique, allowed the choice of cutting parameters for high rate of material without great sacrifice of roughness and for a maximum tool life, besides characterizing with good precision, the influence of investigated factors over responses of interest.*

Key-words: Machinability; Milling of martensitic stainless steel, Response surface methodology, Cutting parameters.

1. INTRODUCTION

Machinability must be understood as a system of properties wich depend on complex interactions among workpiece, tool material, cutting fluid and cut conditions. Trent (1989) suggests that machinability is not only a property, but the “way” material behaves during machining. Therefore, machinability is much more than a test function, and it’s improvement is characterized by, least, one of the following factors: - increase of tool life, - higher rate of material removal, - improvement of surface finishing, - better control of the chip, - reduction of cutting forces. According to its duration, the tests of machinability are classified in to short and long duration. And the best example of long lasting test is the tool life test and their results, generally presented using Taylor’s equation.

According to Gennari Jr et al. (2000), the stainless steel is one of the main materials employed in critical parts for installation of power plants and modern chemical industries due to combination of appropriate mechanical properties and high corrosion resistance. However, the composition required allowing such properties results in poor machinability of this steel, right below to that for the carbon steel. High rate of strain hardening, high toughness and low thermal conductivity are the main factors that cooperate for this. As a consequence, the machinability of stainless steel tends to present short tool life, especially in intermittent cut operations like milling, where thermal and mechanical shocks are observed (Bhattacharya et al., 1988).

The experimentation in short scale, that certainly is analysed in statistic form, may reduce significantly unnecessary expenses and the probability of commiting expensive mistakes, when searching for the knowledge of how a given variable influences the final result of the system. Thus, a good experimental planning to make easier the definitive machinability tests is frequently beneficial. The Response Surface Methodology (RSM), is an optimization technique based on the employment of factorial planning, introduced by G.E.P. Box in the 50´s, and since then it has been used successfully in modeling of many industry processes. A complete treatment about the subject can be found in books and articles written by G.E.P. Box and his cooperators (Box and Wilson, 1951, Box and Draper, 1987).

In this work, the machinability of stainless steel ABNT420 is analysed and using a model that foresees the responses of tool life and cutting forces in terms of cutting speed, feed per tooth and depth of cut. The effects of these variables in responses were investigated crossing information contained in bound surfaces of material removal rate and surface roughness.

2. MATHEMATICAL MODEL FOR RESPONSE SURFACE METHODOLOGY

The scheme shown in figure 1, illustrates the system analysed in this work with the purpose of process optimization. The cutting speed, feed per tooth and depth of cut, of were the input data that had their values changed. The analyzed responses were: tool life, surface roughness and cutting forces indirectly obtained by measuring the relation between the electric current of the chain electrical motor and the cutting speed.

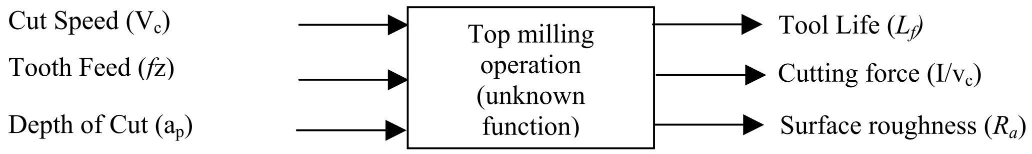

Figure 1 – Relation between the input factors and the observed output response

Using the 2nd order mathematical model of responses (Central Compounded Planning – PCC) for experiment planning, equations related to cutting force and tool life were obtained as a function of cutting speed per tooth, and depth of cut. The functional relation between the responses of this operation and the independent variables investigated can be represented by equations:

$$L_f = K.v_c^{\ k}.f_z^{\ l}.a_p^m \quad (1)$$

$$I/v_c = M.v_c^{\ k}.f_z^{\ l}.a_p^m \quad (3)$$

Where T, is the tool life given by feed, length (cm), the I/V_c term (electric current of the electrical motor by cutting speed) or cut effort (Ampers/m/min) and v_c, f_z e a_p mean cutting speed (m/min), feed per tooth (mm/tooth) and depth of cut (mm) respectively.

Such equation can be written:

$$\hat{y} = y - \varepsilon = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_{11}x_1^2 + b_{22}x_2^2 + b_{33}x_3^2 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3 \quad (4)$$

This is a model where ŷ e y are the estimated response and the output response in logarithm scale, and ε, the experimental error and b_i the values of the estimated parameters by the least-square method, using equation (5).

$$b = (X^T X)^{-1} X^T y \quad (5)$$

Where b is the matrix of estimated parameters, X is the matrix of the independent variables levels, X^T is the transposed of X, and y is the output response observed [ln$T$, ln (I/v_c)].

3. EXPERIMENTAL PLANNING

Input Variables According to figure 1, in this work, the system representing the milling operation is composed of three input factors (v_c, f_z e a_p), each of them with five values or levels (see Table 1), encoded according to the following equation:

$$x = \frac{\ln x_n - \ln x_{n0}}{\ln x_{n1} - \ln x_{n0}} \quad (6)$$

Where, according to Choudhury et al. (1999), x is the level value (code) for each factor corresponding to its value x_n, that is: x_{n1} is the value of the level +1 and x_{n0} corresponds to the zero level value. Numeric input factors were obtained (cut conditions) encoded by levels ($\pm\sqrt{2}$, 0, ±1), as shown in Table 1:

Table 1- Levels of the independent variables and identification by code.

Independent variables	Levels in code form				
	$-\sqrt{2}$ (Too low)	-1(low)	0 (central)	+1 (high)	$+\sqrt{2}$ (Too high)
v_c, m/min (x_1)	87.07	94.46	115	140	151.88
Fz, mm/tooth (x_2)	0.077	0.083	0.10	0.12	0.129
a_p, mm (x_3)	0.56	0.67	1	1.5	1.77

To obtain these conditions, it was first chosen the values for zero "central" and +1 "high" levels, from pre-tests considering cut limitations (milling machine capability, inserts manufacture is recommendations, etc). Then, values related to other levels were calculated, according to the equations below:

$$x_1 = \frac{\ln v_c - \ln 115}{\ln 140 - \ln 115} \tag{7}$$

$$x_2 = \frac{\ln f_z - \ln 0.10}{\ln 0.12 - \ln 0.10} \tag{8}$$

$$x_3 = \frac{\ln a_p - \ln 1}{\ln 1.5 - \ln 1} \tag{9}$$

Therefore, x_1 is the encoded value of cutting speed for v_c, x_2 is the encoded value for the corresponding value f_z, and x_3 for the a_p value.

Output Values. According to figure 1, three response systems were analysed in the present work, and these are: tool life, cutting force and surface roughness. The cutting force (I/v_c) may be obtained by equation (10) (Diniz and Noritomi, 1998):

$$\frac{I}{v_c} = \frac{F_c}{\eta . u} \tag{10}$$

Where, F_c is the main cutting force, η is the machine-tool efficiency and u is the electric tension in the main electrical motor terminals. But, during cut procedure, it can be considered that tension remains constant for a given rotation of the electrical motor, varying the current only. Considering also, that the machine efficiency remains constant with cutting conditions variation, it can be said that cutting force is directly proportional to the relation I/v_c.

4. EXPERIMENTAL PROCEDURE

The process used for the tests was the slot milling (channels), with dry cut in a ROMI INTERACT IV CNC, milling machine with 22cv of power. The machinability tests were carried out over a rectangular bar (fig 2) of stainless steel ABNT 420, in agreement with the ISO/R 683-3, made by Villares Metals S/A, which has its composition described on Table 2.

Table 2 – Chemical Composition of the steel used in the tests

Villares	Similars		Content (% in weight)				Hardness
	AISI	DIN WNi	C	Si	Cr	V	
VP420	420	1.2083	0.40	0.50	13.5	0.25	48-54 HRc

It was used a toroidal tool with 32 mm of diameter, with three interchangeable inserts and screw fixation [reference R390-032A32-11M, Sandvik, 1999]. Inserts for the milling operation with corner facing of 90 degree in stainless steels with ramp angle α=3,6°, Vickers hardness of HV3=1500HV, has the following chemical composition: 10,5 wt-% Co (cobalt) and the remaining of WC (tungsten carbide). This carbide is coated with a TiAlN and TiN layer of 2 - 6 micrometer of thickness by physical deposition vapor technique (PVD). [reference R390-11T308M-MM 2030, Sandvik, 1999].

The electric current sensoring of the three-axis engine was done by a Hall effect current sensor of Newtronic, with board ampere band of 0 to 50 A, and output signal from 0 to 5 VDC. The signal is sent to an analogical-digital managed by a computer using the LabView 5.1 software, from National Instruments. The acquisition of the signal was done with a sample rate of 5000 points/sec during 20s of each pass. Each value of current, having a relation of 0.0968V/A, that is, the real value of current consumed by the motor found multiplying the output signal by this convertion factor.

The end of tool life criterion is recommended by ISO8688-1 standard, 1989, for tools life test in end milling. Therefore, the uniform flank wear of the tool (V_B=0,35 mm) was taken as the end of tool criterion life. The measures of wear (V_B) and roughness (Ra) were taken at regular intervals of each channel produced (350mm) or at two channels in case of less severe conditions of cut. Each measure of roughness (Ra), was obtained by the average of three measurements at different pre-determined points on the same channel. The apparatus used for this purpose, was the Mitutoyo portable device for roughness measurement, surftest 211 models. The selected cut-off value, due to roughness amplitude, was of 0,8. The wear was measured by appropriated microscope for tools with two micrometric screws, hundredth of millimeter precise, 5µm resolution, and 40X magnification.

Figure 2, shows the basic components of the slot milling (channels).

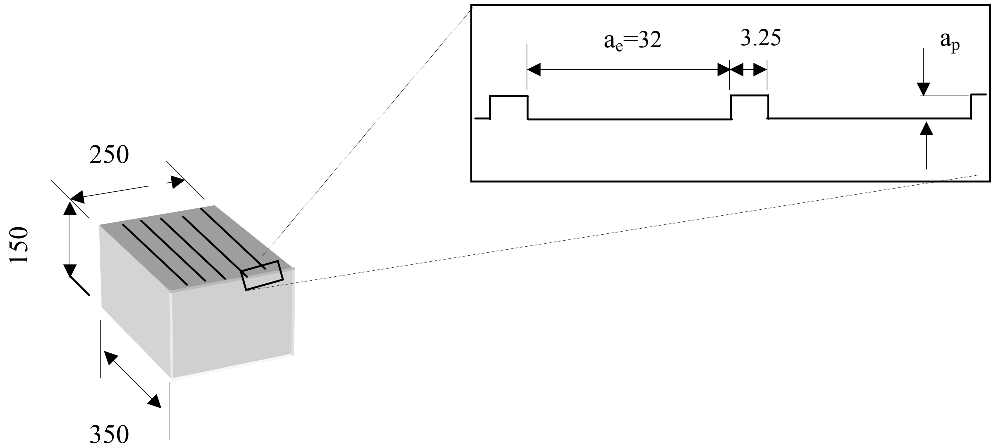

Figure 2. Basic geometry of the test block and the slot milling process

5. RESULTS

A Table 3 shows the cutting conditions obtained by experimental planning and the results obtained for tool life, cutting force and surface roughness.

Table 3- Experimental conditions and results

N° test	*v* m/min	f_v mm/tooth	a_p mm	Code (levels) X1	X2	X3	Tool life - L_f (cm)	Cutting force I/v_c (A/m/min). * 10^{-2}	Roughness Average R_a (µm)
1.	94.46	0.083	0.67	-1	-1	-1	2562.3	4.013	0.57
2.	140.00	0.083	0.67	1	-1	-1	403.7	2.658	0.77
3.	94.46	0.120	0.67	-1	1	-1	2562.3	4.088	0.51
4.	140.00	0.120	0.67	1	1	-1	298.4	3.024	2.00
5.	94.46	0.083	0.82	-1	-1	1	1316.3	5.188	0.90
6.	140.00	0.083	1.50	1	-1	1	280.8	3.804	0.58
7.	94.46	0.120	1.50	-1	1	1	965.3	6.252	0.88
8.	140.00	0.120	1.50	1	1	1	140.4	4.320	0.71
9.	115.00	0.100	1.00	0	0	0	368.6	3.751	0.69
10.	115.00	0.100	1.00	0	0	0	351.0	3.745	0.99
11.	115.00	0.100	1.00	0	0	0	386.1	4.051	0.59
12.	115.00	0.100	1.00	0	0	0	386.1	3.958	0.50
13.	87.07	0.100	1.00	-1.41	0	0	1895.4	4.629	0.56
14.	151.88	0.100	1.00	1.41	0	0	140.4	3.021	0.49
15.	115.00	0.083	1.00	0	-1.41	0	403.7	3.815	1.01
16.	115.00	0.129	1.00	0	1.41	0	245.7	4.103	0.42
17.	115.00	0.100	0.56	0	0	-1.41	1614.6	2.934	0.86
18.	115.00	0.100	1.77	0	0	1.41	228.2	5.537	0.63

6. DEVELOPMENT OF THE ESTIMATED MODEL AND RESULT ANALISYS

Using a central composed planning (PCC) and Table 3 data, the parameters of the model was estimated. The coefficients (b_0, b_1, b_2, etc) were estimated using equation (4). The estimated equations of tool life and cutting force, considering the parameters connected to the significant terms (see Table 4), are respectively expressed as:

$$\hat{y}_1 = Ln(L_f) = 6.874 - 0.929x_1 - 0.167x_2 - 0.461x_3 + 0.250x_1^2 + 0.331x_3^2 \tag{12}$$

$$\hat{y}_2 = Ln(I / v_c) = -3.257 - 0.166x_1 + 0.047x_2 + 0.191x_3 \tag{13}$$

Table 4, presents the analysis of regression variance for adjustment of the models to Table 3 data.

Table 4. Analysis of regression variance for adjustment of models to Table 3 data.

	Estimated value			Standard siding			t of Student			Significance Level		
	L_f	I/v_c	R_a	L_f	I/v_c	R_a	L_f	I/v_c	R_a	L_f	I/v_c	R_a
b_0	5.874	-3.257	-0.454	0.112	0.024	0.172	52.53	-136.61	-2.65	0.000000	0.000000	0.029279
x_1	-0.929	-0.167	0.069	0.068	0.015	0.105	-13.57	-11.40	0.65	0.000001	0.000003	0.531450
x_2	-0.167	0.047	-0.018	0.068	0.015	0.105	-2.44	3.22	-0.17	0.040367	0.012278	0.867195
x_3	-0.461	0.191	-0.063	0.068	0.015	0.105	-6.73	13.10	-0.60	0.000149	0.000001	0.564878
x_1x_2	-0.086	0.006	0.161	0.084	0.018	0.129	-1.02	0.36	1.25	0.336985	0.730350	0.245333
x_1x_3	0.066	0.004	-0.290	0.084	0.018	0.129	0.78	0.24	-2.26	0.455885	0.818839	0.054123
x_2x_3	-0.088	0.021	-0.083	0.084	0.018	0.129	-1.04	1.17	-0.64	0.326652	0.278745	0.537198
x_1x_1	0.250	-0.008	-0.040	0.084	0.018	0.129	2.98	-0.47	-0.31	0.017693	0.654514	0.762233
x_2x_2	0.003	0.020	0.069	0.084	0.018	0.129	0.03	1.11	0.53	0.973611	0.298463	0.608209
x_3x_3	0.331	0.030	0.130	0.084	0.018	0.129	3.95	1.63	1.01	0.004260	0.141161	0.342525

The analysis of regressions variance (Table 4), for the complete predicted models, has presented coefficients of regression (R^2) equal to 0.97, 0.98 and 0.54 for tool life, cutting force and surface roughness, respectively. It means that 97 and 98% of the total variation surrounding the average data of tool life and cutting force, respectively, are explained by regression. The parameters with level of significance lower than 5% ($p<0,05$) are considered significant and were included in equations (12) and (13), The others have no significant influence on the response. From the values observed for surface roughness, 46% are the residuals, without showing significant terms, indicating that the models is not the most appropriated to represent them.

Equations (12) and (13) may be transformed using equations (7-9) to supply the existent functional relations between the responses and the factors, considering only the parameters connected to the isolated variables:

$$L_f = K.v^k.f_z^l.a_p^m \qquad \hat{L} = 2.34.10^{11}.v_c^{-4.73}.f_z^{-0.894}a_p^{-0.851} \tag{15}$$

$$I / v_c = M.v^k.f_z^l.a_p^m \qquad \hat{L} = 3.867.v_c^{-0.846}.f_z^{0.258}a_p^{0.472} \tag{16}$$

Where $\hat{L}$ and $\widehat{I / v_c}$ are the tool life and the estimated cutting force, respectively. These equations are valid for slot milling of steel ABNT 420 using carbide inserts under dry conditions and in the following bands of cut speed (v_c), feed per tooth (f_z) and depth of cut (a_p): $94.46 \le v_c \le 140$ m/min; $0.08 \le f_z \le 0.12$ mm/tooth; and $0.67 \le a_p \le 1.5$ mm.

Figure 3 was built from equation (15) and shows the tool life bounds predicted in a plane containing the cutting speed v and feed per tooth f_z. In this case, the selected plane was for the depth of cut equal to 1,0mm. These bounds were obtained using an applicative program "matlab".

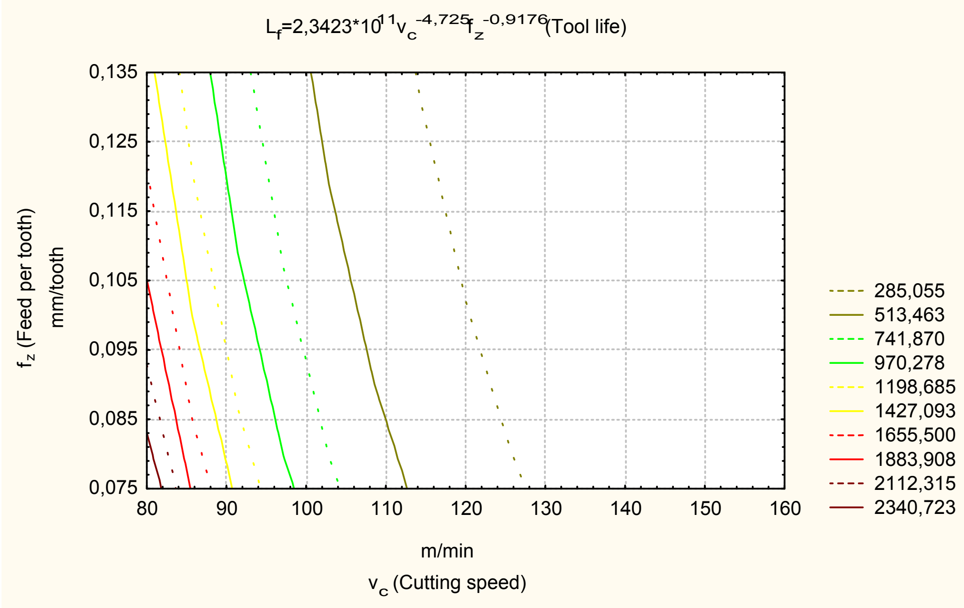

Figure 3. Bound of tool life in cutting speed-feed per tooth plane for depth of cut of 1.00mm.

It can be observed from figure 3, that tool life reduces when there is an increase of the per tooth, depth of cut and cut speed.

To reduce the time of machinability, however, (to reach high rates of production), the cutting speed and feed per tooth must be as big as possible. From the bounds showed on fig. 3, it is possible to select a combination these parameters that reduce the time of machinability but not the tool life, since exist a great number of combinations of cut and feed velocities that results on the same tool life. This may be illustrated by using a 3rd. model, that may include the rate of material removal (MRR), given by equation (17):

$$MRR = \frac{f_z \times z \times N_s \times a_a \times a_p}{100} \tag{17}$$

Where z is the number of teeth in cut, N_s is the angular velocity (rpm), a_a is the radial depth of cut (mm). The equation (17) may be written as:

$$\ln MRR = \ln f_z + \ln z + \ln N_s + \ln a_a + \ln a_r - \ln 100 \tag{18}$$

For a specific depth of cut of 1,00 mm on a slot milling (channel) operation, using a milling cutter of D=32mm (i.e. a_r=32 mm) and number of teeth in the mill, z =3 with transform equations (7-9), equation (18) becomes:

$$\ln MRR = 0.2325 + 0.1530 x_1 + 0.5978 x_2 \tag{19}$$

For a constant rate of material removal, equation (19) may be represented by lines, as illustrated in figure 4. This figure was obtained by superposition of MRR lines in the tool life bounds, in cutting speed-feed per tooth plane for 1,00 mm of depth of cut. Figure 4, shows that the rate of material removal may be increased without reducing tool life of L_f=1427 cm. This shows that, the selection of cut conditions represented by point "B" is better than those represented by point "A". In this case, almost 50% of increase in the material removal rate is obtained without reducing tool life and without sacrifice in roughness, pointing out that, in this work, such factor had an independent behaviour from input variables. Therefore when tracing lines of material removal rate with tool life curves, as in figure 4, it is possible to find the right conditions of cutting speed and feed per tooth for a given depth of cut.

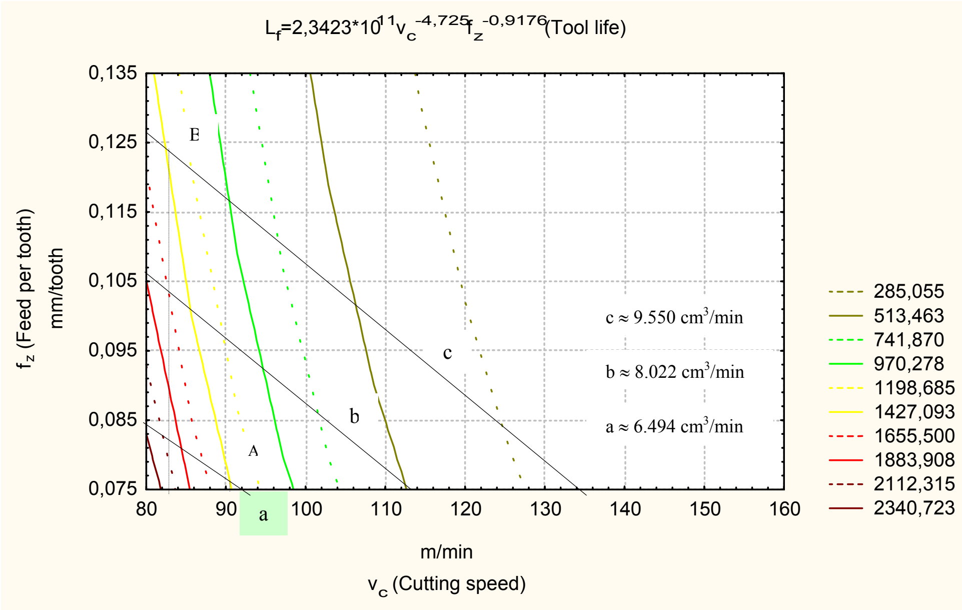

Figure 4. Tool life bound and MRR (cm^3/min) in cutting speed-feed per tooth plane for cut depth of 1.00 mm

Figure 5 was built from equation (16) and shows the bounds of cutting forces estimated in a plane containing the cutting speed v_c and the depth of cut a_p. In this case, the plane selected was for the feed per tooth constant and equal to 0.1mm/tooth. We may observe by figure 4 and equation (16), that the cutting force is inversely related to cutting speed and directly related to depth of cut and feed per tooth.

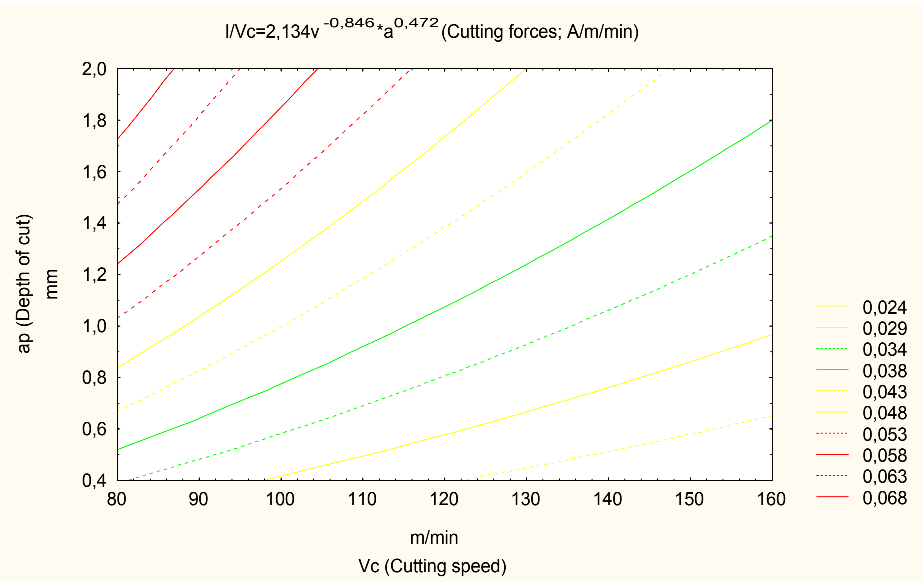

Figure 5. Cutting force bound in cutting speed plane for a feed per tooth of 0.1mm/tooth.

Figure 6, shows the response surface for tool life (feed length), built from equation (15) considering only the parameters connected to isolated variables. This surface is related to a depth of cut of 1.00mm.

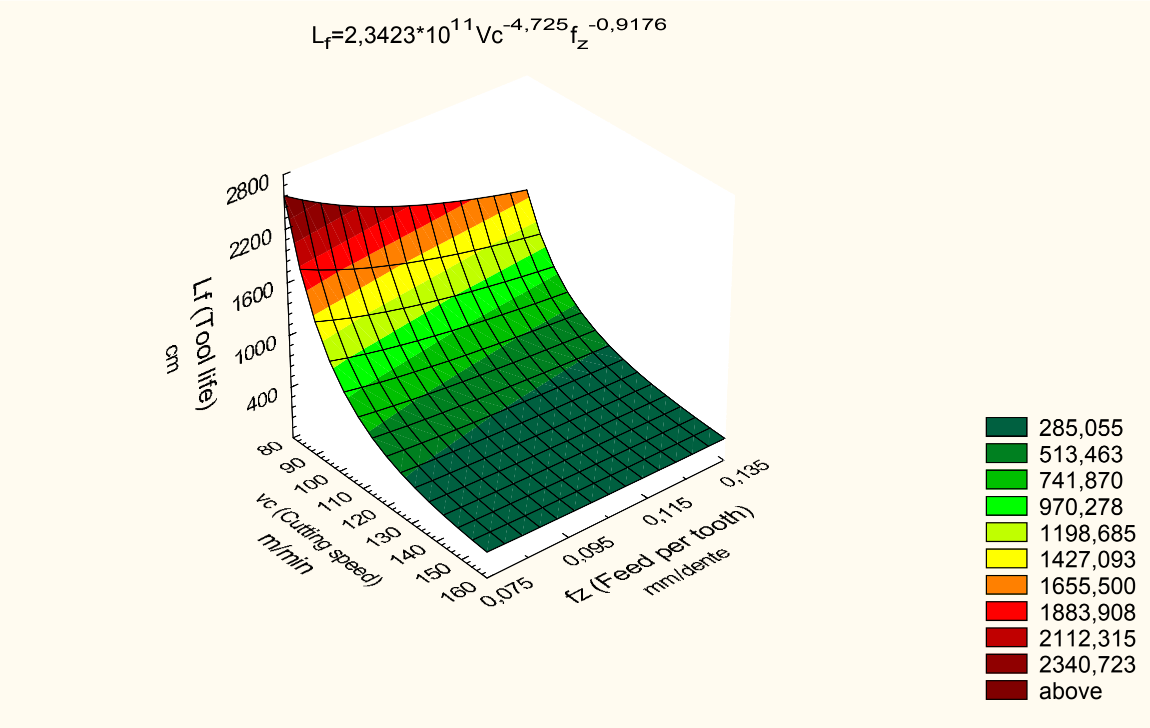

Figure 6. Response surface adjusted to tool life, related to the depth of cut of 1.00 mm.

It can be observed in figure 6, that the highest values of tool life were obtained for lowest values cutting speed and feed per tooth.

Figure 7, shows the response surface for cutting force and was built from equation (16) considering only the parameters connected to isolated variables, related to a feed per tooth of 0.10 mm/tooth.

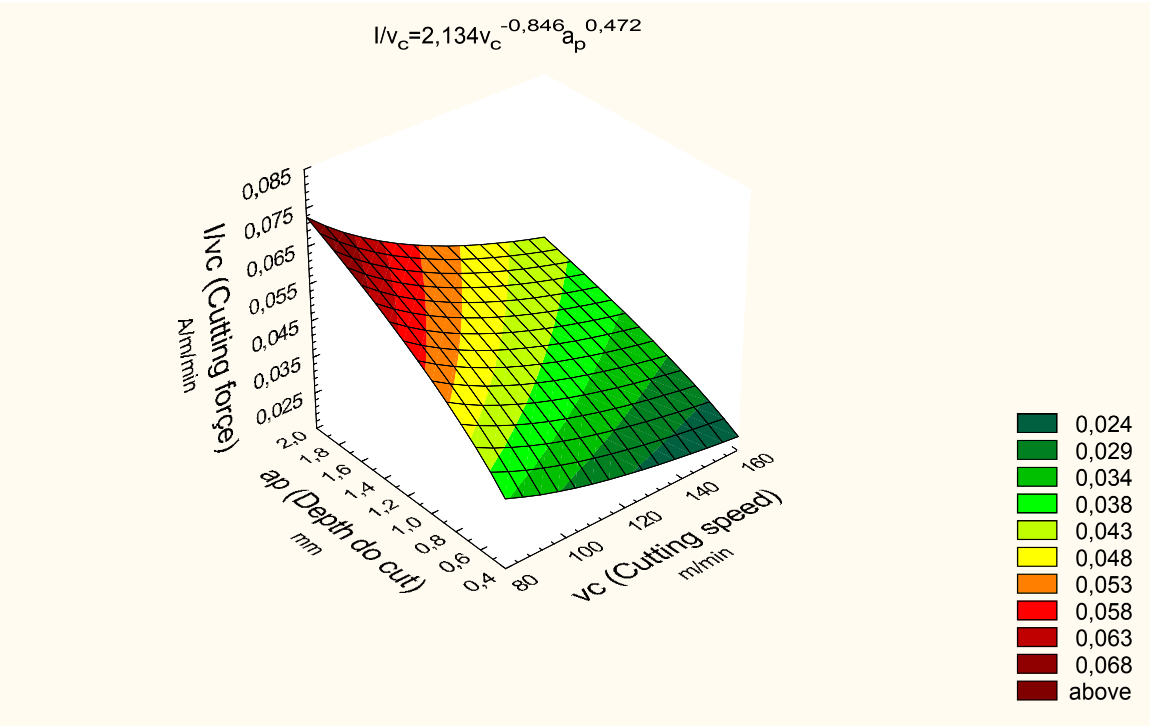

Figure 7. Response surface adjusted to cutting force, related to the feed per tooth of 0.10 mm/tooth.

7 CONCLUSIONS

1. Mathematical models of responses for tool life and cutting force in the machining of stain less steel with carbide insert were found using an experimental planning and response surface methodology. These models are valid inside the cutting speed band of 87-152 m/min, feed per tooth band of 0.077-0.129 mm/tooth and depth of cut of 0.56-1.77mm.

2. The correlation coefficient was 0.97 for tool life and 0.98 for cutting force, indicating that 97% and 0.98% of the variabilities from respective data were explained by these equations. However, the roughness data has presented a great dispersion with correlation of only 54% and no significant terms, showing lack of consistence in responses prevision, using the central compounded planning.

3. The input factors effects (cut speed feed per tooth, and depth of cut), are significant in tool life and cutting force models. The effect of cutting speed is dominant for both responses. Once this factor has an inverse relation with the two responses analysed, the other factors (feed per tooth and depth of cut) have direct relation with the cut effort and inverse with tool life.

4. The study presented has resulted in characterization, with good precision, of the influence of investigated factors over responses.

5. Graphics of bounds lines and response surfaces for cutting force and tool life, were built in function of two more significant independent variables.

6. The factorial planning methodology gives a great sum of information's from a small number of experiments.

8. ACKNOWLEDGMENTS

The authors wishes to thank prof. J. C. Mendes Carvalho for helps his technical assistance, to Villares Metals S/A for the supplying the workpice, to CAPES & FAPEMIG & IFM for financial support.

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