INFLUENCE OF THE CUTTING PARAMETERS ON THE WORKPIECE SURFACE TEMPERATURE OF AEROSPACE ALUMINUM ALLOY IN END MILLING OPERATION

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Abstract. *Every single design of manufacturing by conventional machining targets a finish part with ideal dimensions within acceptable tolerances. Small tolerances are commonly achieved through finishing processes. Machined workpiece accuracy is usually constrained by problems like thermal expansion phenomena and system vibration producing inevitable over cuttings. In order to reduce costs it is interesting to obtain higher accuracy and better surface finishing with only one machining process. The heat generated during machining is dissipated through the parts involved (chip, tool, workpiece and atmosphere) and its distribution depends on the cutting conditions, mainly on the cutting speed. The relationship between the heat generated and dissipated is known as energetic balance. If the heat dissipated through the workpiece is reduced, the thermal expansion will also be diminished and therefore the dimensional accuracy will be higher. This work studies the influence of some cutting parameters on the temperature of the machined surface of 7075 – T7 aerospace aluminum alloy when end milling small slots with integral cemented carbide tools. The cutting parameters varied are the cutting speed, feed rate and depth of cut. The experimental tests followed a Design of Experiment (DOE) and Variance Analysis Technique (ANOVA) with 95% of confidence was applied to the results. The temperatures of the bottom surface of the slots were measured during cutting with an infrared sensor. Surface response method and minimum square techniques were used for the optimization process. The results showed that the depth of cut was the most influencing variable on the workpiece temperature, increasing it when machining deeper slots. On the other hand, the workpiece temperature decreased when the feed velocity was increased. There has been a direct relationship between cutting time and the workpiece surface temperature.*

Keywords*: Cutting temperature, End milling process, Dimensional accuracy, Aerospace aluminum alloy*

1. INTRODUCTION

The production and machining of aluminum alloys have been increased because of their huge application in general metal working industries, mainly on aerospace, automotive and naval industries. The high mechanical resistance to weight ratio of this metal is a key factor for choosing it as structural machine parts.

On metal cutting high dimensional accuracy is obtained generally using more than one machining process and this implies in a more expensive product. Therefore if the desired accuracy could be achieved with only one machine process by selecting the correct cutting conditions it will be more economical.

This is particularly important in the aerospace industry where high material integrity and accuracy are always targeted because of the high level of security demanded by the systems where human lives are involved (Carrino et. al., 2002; Ferraz, 2002). In this area aluminum alloys have large applications because of their good properties and low density and when machining workpieces with small tolerances are not easy to be produced. They are used in the form of plates, sheets and bars and often the milling process is used to transform it in used part of an aircraft.

Milling is one of the most important machining process, allowing a very high material removal rate due to a higher number of cutting edges acting simultaneously (Marcelino. et al., 2004). End milling is used on machining of grooves, cavities and matrix principally by alloying better productivity (Drozda; Wick , 1983 and Stemmer, 1995).

An important problem with machining of aluminum is the high thermal expansion coefficient when compared whit another materials (e.g. 23 x 10^6 $1/^oC$ to carbon steel against 11 x 10^6 $1/^oC$ to aluminum). The high temperature generated during cutting causes considerable expansion of the workpiece and therefore over cutting is unavoidable.

On metal machining almost all energy consumed is transformed into heat generated by the plastic deformation and friction involved in the primary and secondary shear zones and eventually in the tool flank–workpiece interface. This heat generated during machining is dissipated through the parts involved (chip, tool, workpiece and atmosphere) and its distribution depends on the cutting conditions, mainly on the cutting speed (Trent and Wright, 2000).

To decrease the heat that goes into the workpiece it is necessary to understand the energetic balance on metal cutting based on the heat conduction laws, where the transfer of thermal energy between neighboring molecules in a material due to a temperature gradient in a time “t” always takes place from a region of higher temperature to a region of lower temperature, and acts to equalize temperature differences.

If the heat that goes into the workpiece is reduced by any means, the thermal expansion will also be diminished and therefore the dimensional accuracy will increase. The energy balance equation [Eq. (1)] gives the distribution of the heat on metal cutting process.

$$Q_p = Q_z + Q_{a_1} + Q_{a_2} - Q_c - Q_{ma} - Q_f \tag{1}$$

Where,

Q_p = Heat dissipated into the workpiece

Q_z = Heat generated by the primary shear zone

Q_{a_1} = Heat generated by the secondary shear zone

Q_{a_2} = Heat generated on the flank-workpiece interface

Q_c = Heat dissipated into the chip

Q_{ma} = Heat dissipated into the environment (atmosphere or cutting fluid)

Q_f = Heat dissipated into the tool

This energy balance is largely dependant on the cutting conditions and tool and workpiece materials involved. Increasing the cutting speed, for instance, the parcels Q_z, Q_{a1} and Q_{a2} will increase and the temperature will be proportionally higher (Machado et al., 2009). However, if higher amount of this heat is dissipated, for example, into the chip, environment, and tool, consequently smaller part of this heat will flow into the workpiece. As a result the thermal expansion of it will be equally smaller and the dimensional accuracy of the machined parts higher. The use of cutting fluids is one of the options available towards producing more quality mechanical components, which can also be achieved by designing proper tools and using optimal cutting conditions.

Many techniques were proposed to measure the cutting temperature (Lenz, 1967; Abrão et al., 1997; Melo, 1998). Nevertheless almost all of them are applied to continuous cut. Knowing the emissivity of the material the infrared radiation technique was used to determinate the temperature in a non continuous cutting process (Melo et al., 2006).

This work intends to contribute for further understanding of heat produced during machining studying the influence of some cutting parameters on the temperature of the machined surface of 7075 – T7 aerospace aluminum alloy when end milling small slots with integral cemented carbide tools.

2. METHODOLOGY

2.1. Temperature Measurement

Several end milling tests were carried out in order to measure the temperature at the bottom surface of the slots being machined. An infrared sensor was used, which was connected on the bearing of the main spindle shaft in such a way that it could follow the tool during one pass. A clamp holding system was design for this purpose and Fig. 1 illustrates this. The signal of the sensor was adjust using a standard thermocouple. The calibration was made for an inclination of the sensor of 45^o and the distance between the lent of the infrared sensor until the measured surface was 76 mm with a focus of 2 mm^2. To prevent the influence of the hot chips on the temperature acquisition a brush attached to the clamp system was used to clean the surface to be measured.

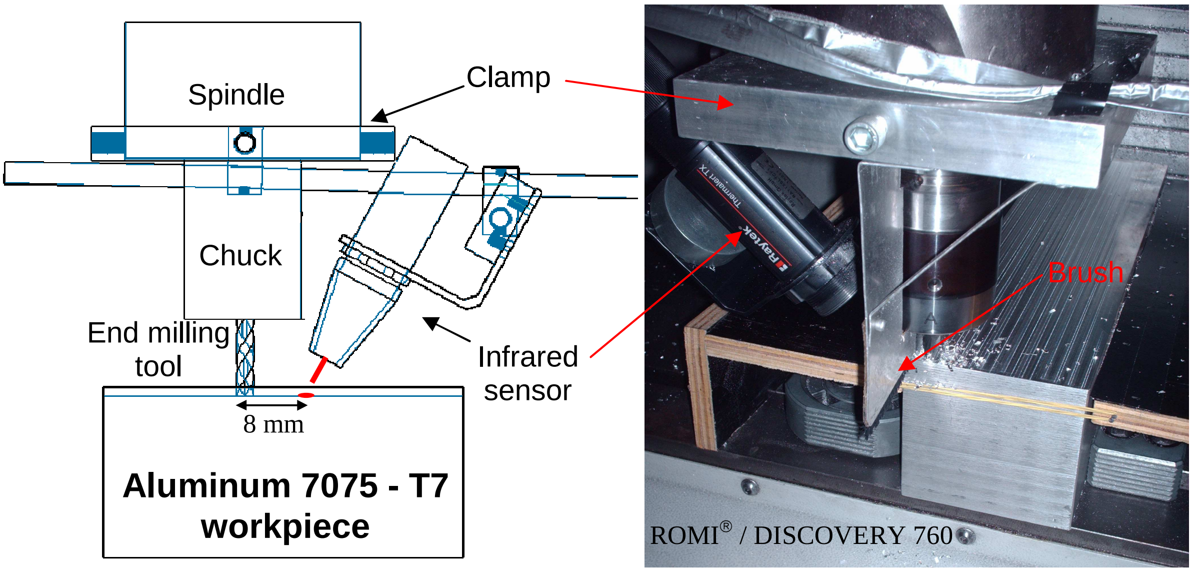

Figure 1- The temperature measurement system.

The workpiece material was the 7075-T7 aeronautic aluminum alloy (material used by EMBRAER for manufacturing aircraft parts) with the size of 100 X 100 X 400 mm^3 and average hardness of 150 HB. This material is the same of that used by Polli (2005) and Balkrisna e Yung (2001) in their researches in high speed machining - HSM. The alloying element is mainly Zn with additions of Cu and Mg. These elements give an excellent mechanical resistance and better machinability index to the aluminum. Tab. 1 shows the chemical composition of this alloy.

Table 1. Composition of the 7075 aluminum alloy (Weingaertner e Schroeter, 1991).

Elements		Cu	Fe	Mg	Mn	Si	Ti	Zn	Cr	others	
										Each one	total
7075 Alloy	Max	2,0		2,9	0,3	0,4	0,2	6,1	0,28	0,05	0,15
	Min	1,2	0,5	2,1				5,1	0,18		
Brinell Hardness						150					

Table. 2 shows the mechanical properties of the 7075-T7 aluminum alloy. This alloy underwent a heat treatment of annealing and age hardening (T7)

Table 2. Mechanical Properties of aluminum alloy 7075 -T7 (Weingaertner e Schroeter, 1991).

Heat treatment	Tensile strenght [MPa]	yield strength [MPa]	Elongation in 50 mm	Hardness HB	Shear strenght [MPa]
T7	570	505	11	150	330

The workpieces were face milled on its all faces and carefully fixed on the machine table using six mechanical clamps. Extra attention should be paid on the workpiece fixation because aluminum is a very soft and excessive pressure can lead to mechanical deformation of the material (Weingaertner and Schroeter, 1991). Figure 2 illustrates the workpiece, detailing the sequence of slots that will be machined, including the test numbers and their replication.

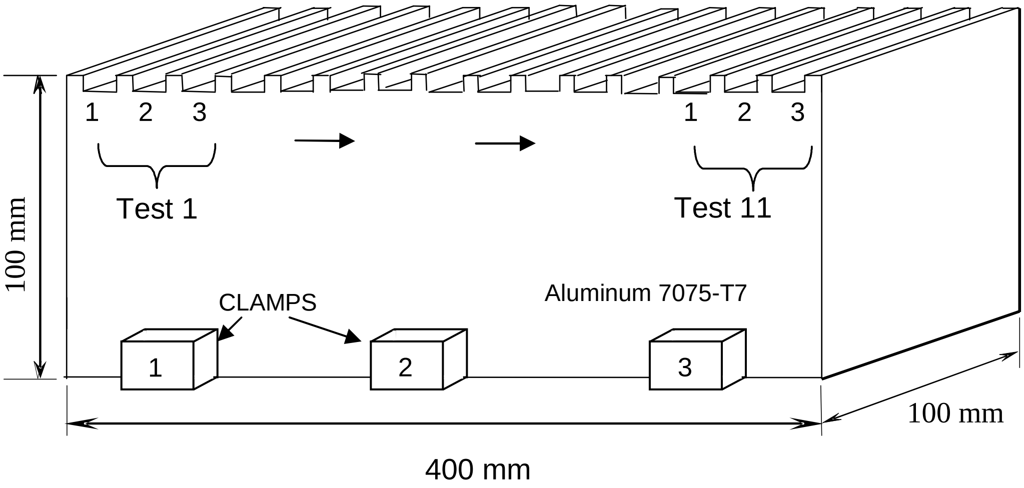

Figure 2: Workpiece details

Integral cemented carbide end milling tools of the ISO grade K10 with two teeth and edge radius of 0,5 mm, with special geometry for aluminum machining was used. They were manufactured by OSG Tungaloy. Figure. 3 shows a picture with the main dimensions of the tool used on the tests. The free length of the milling tool was maintained constant at 25 mm.

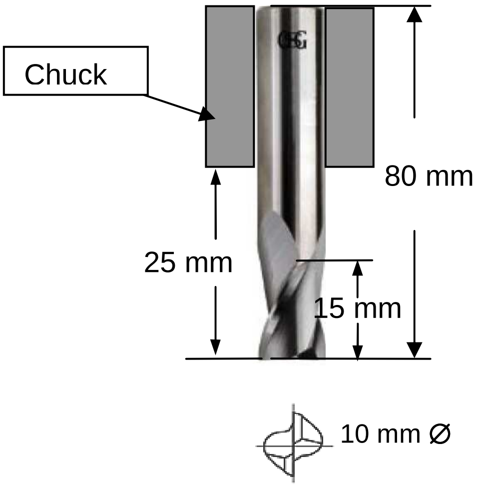

Figure 3: Cemented carbide end milling tool used in the tests

2.3 Experimental Design

Table 3 shows the cutting conditions used in the tests. The cutting speed has five levels, the feed rate four and the depth of cut on two levels. Full combination of these levels resulted on forty different cutting conditions. The number of levels was determined trying to minimize the number of tests and cover a significant interval for the cutting speed and feed rate (vc*f). The levels of the cutting parameters were determined taking into account the suggestion given by the Machining Data HandBook (1980), the book by Weingaertner and Schroeter (1991) and from the tool manufacturer OSG Tungaloy Sulamericana de Ferramentas Ltda.

Table 3. Cutting conditions used in the tests

Levels	1	2	3	4	5
Cutting speed [m/min]	10	86	165	238	314
Feed rate [mm/rev]	0.01	0.05	0.1	0.145	-------
Depth of cut [mm]	2	4	-------	-------	-------

3. RESULTS

The measurement system used in this research is based on an infrared sensor that is positioned directly at the bearing of the main spindle shaft of the machine tool which means that it travels towards the feed direction of the workpiece at the same rate of the tool. As shown in Figure 1 the sensor in pointing the bottom surface of the slot being machined in a distance of 8 mm from the milling tool centre. Therefore, the system measures the temperature of the workpiece straight after the surface is created but with a delay in time that is not constant and depends on the feed velocity used. This becomes a source of error to the system particularly in the present case where an aluminum alloy is the work material and it has a very high heat conductivity coefficient. This error, however, cannot be estimated without a complex thermodynamic model of the whole system and with a heavy experimental setup. In the present case although it will be commented in the analysis it cannot be considered in the results.

Figure. 4 shows, for each test condition, the average maximum temperature on the bottom surface of the slots versus the cutting time (which depends upon the feed velocity), for the two depth of cut used. It can be observed that the temperature initially tends to increase for high speed velocities (short cutting times), reaching a maximum and then decreases for low speed velocities (long cutting times). This behavior depends on the time available to allow dissipation of the heat into the workpiece. Under high cutting speeds the heat generated is high but smaller amount is dissipated by the workpiece (most of the heat is dissipated by the chips) and under small cutting speed the heat generated is small and with enough time for dissipation into the workpiece. It is also noticed that deeper cuts (ap = 4 mm) shows higher cutting temperatures than when cutting with the smaller depth of cut of 2 mm. Analysis of the behavior of these curves will be done later in this article.

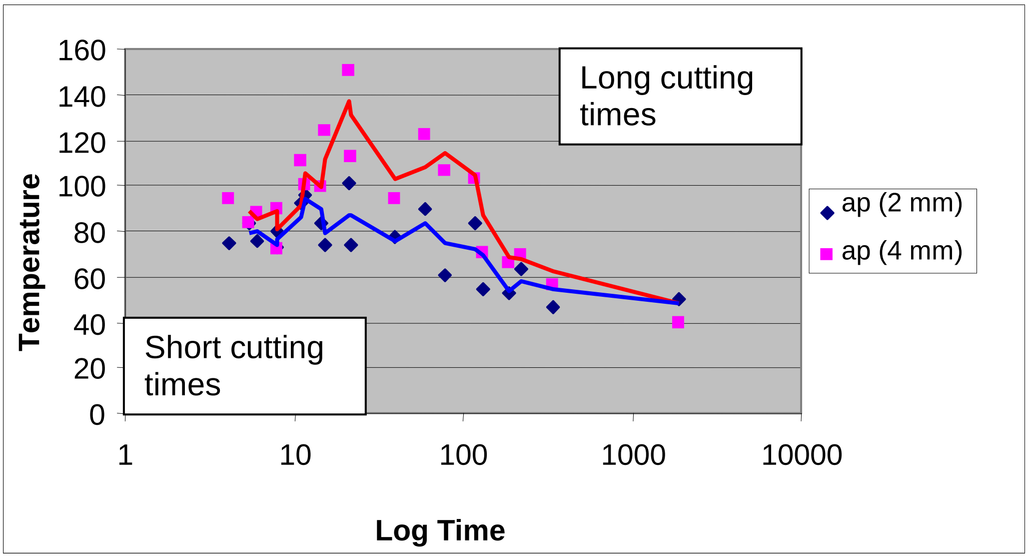

Figure 4: Maximum surface temperature versus time of cut for 2 and 4 mm of depth of cut

Figure. 5 shows the graphic of tendencies of the maximum surfaces temperatures on the bottom surface of the slots machined when varying the depth of cut from the lower (2 mm) to the upper level (4 mm), generated by the Statistics®.Although the high standard deviations do not allow differences be taken for sure statistically, the expected tendency of increase of the temperature when increasing the depth of cut is depicted in this figure. Deeper cuts generate more heat because higher volume of material is involved in the plastic deformation process and therefore higher cutting temperature is obtained on the bottom surfaces of the slots.

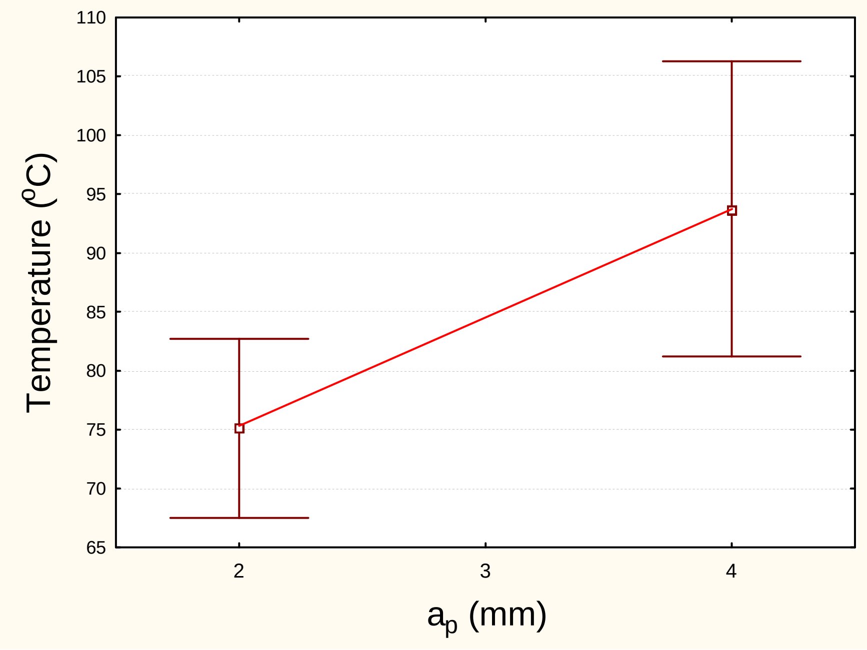

Figure 5: Influence of the depth of cut on the maximum temperature on the bottom surface of the slots machined

3.1 Surface Response

Considering that the influence of the depth of cut on the maximum temperature is statistically negligible and after feeding the whole data results into the Statistics®, a Surface Response (SR) graphic is generated and showed in Fig. 6. In this 3D graphic the maximum temperature on the bottom surface of the slots is plotted against the feed rate on the 'x' axis and the cutting speed on the 'y'. This SR graphic was produced using the distance weighted least squares method (Calado; Montgomery, 2003).

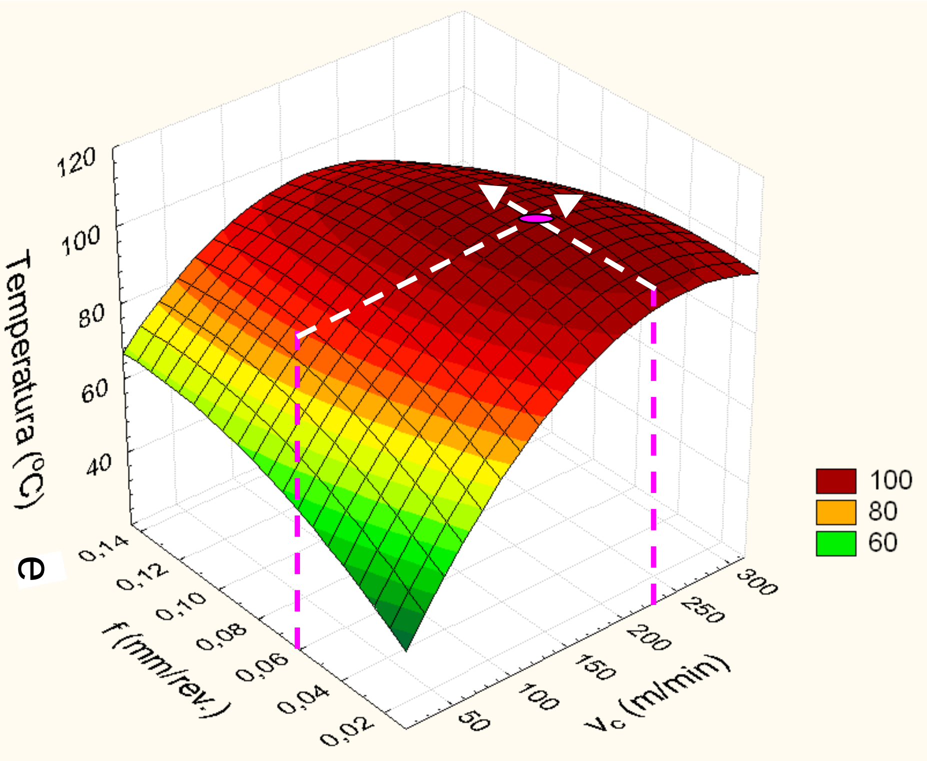

Figure 6: Surface response for the average temperature on the bottom surface of the slots as a function of the cutting speed and feed rate

This graphic shows a region of high surface temperatures in the range of cutting speed between 150 and 250 m/min and feed rate between 0.06 and 0.11 mm/rev. Considering that high temperature on the workpiece should be avoided when tight tolerances are targeted, this cutting condition regions must not be used. When using low cutting speeds and feed rates the workpiece temperature will be low. This is linked to the low amount of heat being generated. On the other hand, when using high cutting speeds and feed rates the workpiece temperatures are also low and here the heat generated is pretty high. However, here the heat balance (or the heat dissipation) is favorable to the workpiece temperature, meaning that less time for heat dissipation into the workpiece. In fact the test with the top cutting speed of 314 m/min and higher feed rate of 0.145 mm/rev, the cutting time for machining a slot was only 4 seconds which is really short for heat conduction.

Within the high temperature range only one stationary or inflection point on the surface is observed and this is a point of maximum. This point represents the top maximum temperature (104 ^{o}C) on the bottom surface of the slot, which indicates the worst cutting condition for obtaining tight tolerances. Figure 7 shows the coordinates of this point: cutting speed of 225 m/min and feed rate of 0.06 mm/rev.

When the cutting speed is increased on one hand it increases the amount of heat generated and tends to increase the cutting temperature, on the other hand the amount of heat dissipated into the workpiece is reduced (less time for heat conduction) and tends to decrease the workpiece temperature. This point of maximum temperature represents a balance of the effect of these two factors.

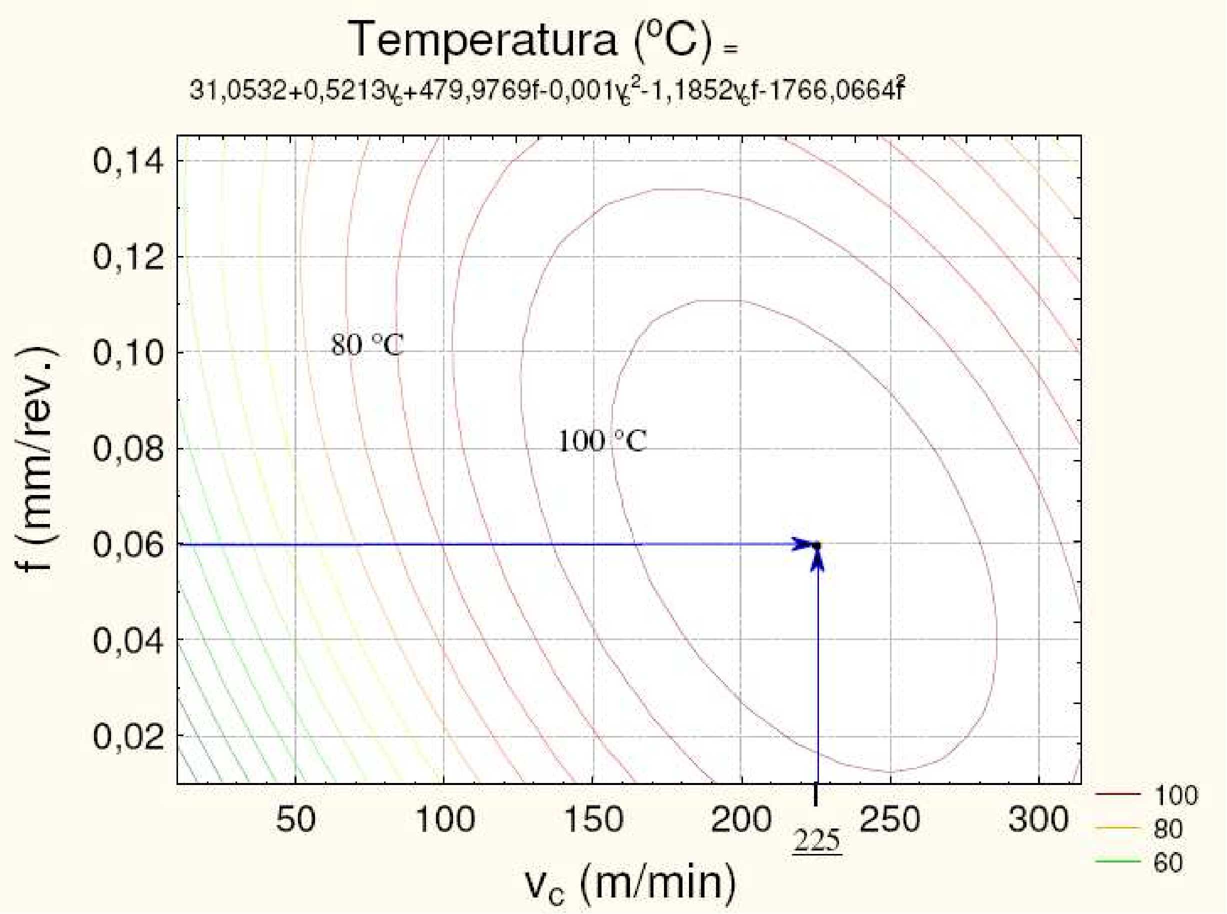

Figure 7 – Maximum temperature point

4. CONCLUSIONS

The results presented allow the following conclusions to be drawn.

- The variables of influence on the workpiece temperature can be ranked as follow: cutting speed, depth of cut and feed rate.
- Changing the depth of cut from 2 mm to 4 mm tends to increase the workpiece temperature due to the higher amount of work necessary to form the chip and consequently higher heat generation and cutting temperature.

- The range of cutting speed between 160 and 285 m/min and feed rate between 0,01 and 0,011 mm/rev represents the region of high temperature on the bottom surface of the slots machined.
- Top temperature was reached when using a cutting speed of 225 m/min and feed rate of 0.06 mm/rev. Greater cutting conditions will implies in lower workpiece surface temperatures. Here the time available is short enough for heat conduction, although more heat is generated.
- Beyond the maximum temperature the higher the cutting conditions (cutting speed and feed rate) the lower is the workpiece surface temperature.

5. REFERENCES

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5. RESPONSIBILITY NOTICE