COMPARING DIFFERENT STRATEGIES TO THE MILLING PROCESS OF POCKETS IN DIES WITH INTERCHANGEABLE INSERT MILLS

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Abstract. *Manufacturing of dies is a field where machining processes are widely used, representing a major factor of the production costs. Due to the characteristics of these parts, the milling process overcome the others because of its versatility and the low times when machining surfaces. In spite of that, the production of dies has one critical point that is the rough machining of pockets. The chip removal from the pocket, the cutting parameters variations during the machining and the need of reducing times and costs, are problems that turns this operation a fundamental key. The target of this work is to find optimal cutting parameters when opening pockets. To reach this target, tests comparing different pocket machining strategies and cutting speeds were made. During these tests, the electric parameters of machine motor were monitorized to get the relationship between them and tool wear. The main conclusion is that the strategy of machining pockets has little influence over the kind of wear presented by the tool, but the dive strategy gives longer lives and lower operation time when compared to the other strategies tested. The power consumed by the spindle motor can be used as an indicative of tool wear state.*

Keywords: *pocket milling, dies, milling strategy, toroid mills, monitoring*

1. Introduction

A demand for products with higher quality and shorter delivery time, has developing production processes more efficient, but also more expensive. Among these processes, stand out the forming. The tooling manufacturing has high cost and is usually made by milling. The die and mold machining is responsible for about 60% of the total production time (Fallbohmer, 1996) and represents about 65% of the fabrication cost (Sandvik, 1999). Therefore, the rough milling process optimization of dies and molds becomes a key action in optimizing the tooling production.

The obtainment of forming tooling according to specifications in shorter times has become possible due to the possibility of working with higher velocities. These allow the industries, to reduce the time to introduce their products on the market (Neugebauer, 2000). The High Speed Machining (HSM) processes are efficient in finishing operations, while the rough ones has presented better results when done with the conventional machining (Sandvik, 1999). Recently, the demand for technologies that make possible the forming tooling production in shorter times has increasing (Christman, 2001).

At same time, the die makers face the fall of the prices and profits, these demands the control and reduction of costs with a need for shorter production times (Christman, 2001). So, the machining optimization is very important. This is more critical because the die production represents 30% of the final product cost (Lecalvez, 2001) and the machining operations are responsible to more than half of the die production cost (Sandvik, 1999).

2 Selection of Rough Milling Parameters

The efficiency of a rough milling operation depends on the right cutting tool and parameters selection. Next some considerations about this selection are done:

- Depth of cut: has little influence on the tool wear and has direct relation to the quantity of removed material, its value should be as high as possible (Diniz et al., 2001);
- Feed per tooth: in rough milling, it is interesting using high values of f_z, because in this operation, the low cutting speed and the high pitch of the cutter make the process productivity low. Besides, a high f_z produces higher mean chip thickness, reducing the specific cutting pressure and the cutting power;
- Cutting speed: has the highest influence in tool life. It must be low, in such way makes the tool life higher and the cutting power not so high;

- Pitch of the cutter: when machining ductile materials it has to be big, since this will allow that the generated chip has space to be stored until it is removed from the cutting zone. This also decreases the cutting power.

3 Cutting Forces and Power

The milling cutting force changes constantly. This is the main cause of the end of tool life. The cutting force has direction and intensity unknown (Diniz et al. 2001). It is necessary their projection in known directions to evaluate their magnitude (Diniz et al. 2001). Only the active force consumes power. In spite of this, the passive force is very important, because the tool holder strain depends on it. Besides, the passive force has more influence on tool wear than the cutting force (Micheletti, 1975).

The cutting parameters influence the machining forces. The main cutting force has the highest value and each parameter affects it in a different way. An increase in the feed rate does not increase the cutting force in the same intensity, due to the reduction of the specific cutting pressure (k_s). The depth of cut and the cutting force are proportional related. The cutting speed has little influence on the specific cutting pressure until 1.200m/min (Diniz et al., 2001, Dagiloke, 1995).

Due to the variation of the cutting force value, the chip thickness and the number of teeth in contact with the workpiece, the consumed power during the milling changes constantly. So, the computation of the milling cutting power is done using a mean value of k_s, namely k_{sm}, calculated based on a mean chip thickness (h_m).

4 Pocket Milling (Sandvik, 1999)

The mill capacity of feed axially is fundamental when the operation to be done is the opening of pockets. Besides, the way that this feed is done has high influence in the effectiveness and productivity of the operation. An end mill with round inserts, known as toroid mill, is strong and versatile enough to allow the opening of pockets in dies without the need of a previous hole. This reduces the number of used cutting tools and stops to change them. In rough operations, where the cutting tools must be stiffer, it is interesting the use of toroid mills. The best performance of this kind of tool comes from the possibility of generating, due the curve form of the tool nose, irregular and complex surfaces.

The axial feed can be done through two basic strategies: a diving cycle until reach the final depth, or a combination of axial and radial feeds. This feed combination can be done through linear or circular interpolation. These strategies have the advantage of directing the biggest part of the effort axially, decreasing the vibration tendency and demanding less from the machine bearings, since; it is usually more rigid in the axial direction.

The advantages and drawbacks of the three axial feed strategies are: (Sandvik, 1999):

- When using the diving strategy, with solid or interchangeable inserts ball nose tools, it is common start the pocket milling with a drilling cycle, using the mill, until reach the final depth of cut, so the first layer of the pocket is machined (figure 1A). The advantage of this method is that the end mill is used as a drill, dismissing a previous drilling, turning the process faster and cheaper. The problem is the difficulty of evacuation the swarfs.
- The ramping strategy combines radial and axial feeds, producing a ramp whose angle must respect the maximum allowable tool inclination based on its size and geometry. It reduces the chip removing problem (figure 1B).
- The helical interpolation can be used when the insert of the mill is round or when the mill allows combinations of the axial and radial feeds. It is one of the best methods to open pockets, because it makes easier the chip evacuation from the cutting zone. However, its use must consider the pocket shape. If this shape is not cylindrical the consumed time increases, since the tool path will be longer, once the tool must follow a cylindrical path and after that remove the rest of the material giving the final form to the pocket. The figure 1C shows the tool path during a helical interpolation.

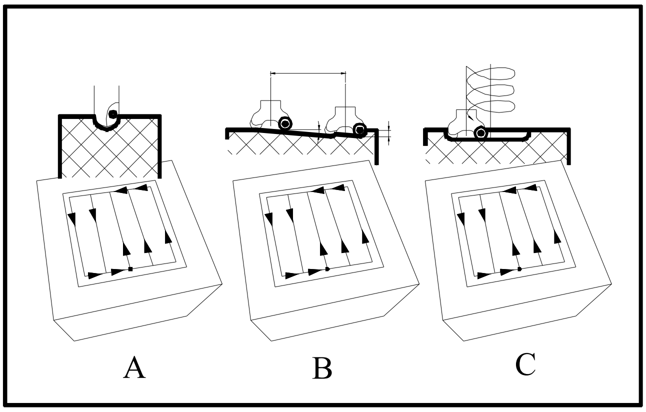


Figure 1 – Pocket milling methods: A) diving cycle, B) ramping interpolation and C) helical interpolation (Sandvik, 1999)

4.1 Corner Milling

Traditionally, the corner of the pockets machining was done with a cutting tool whose radius was the same as the corner one (figure 2). So, the tool went to the corner, stopped feeding, and then changed its movement direction. Some inconvenient arise from this application, such as the stop of the tool to change the movement direction, without changing its rotation. This generated a high friction that harmed the machined material, the surface roughness and the cutting tool (Sandvik, 1999). The tool/workpiece contact was very high, usually one quarter of the mill, what increased the systems vibrations tendency (Schuett, 1996).

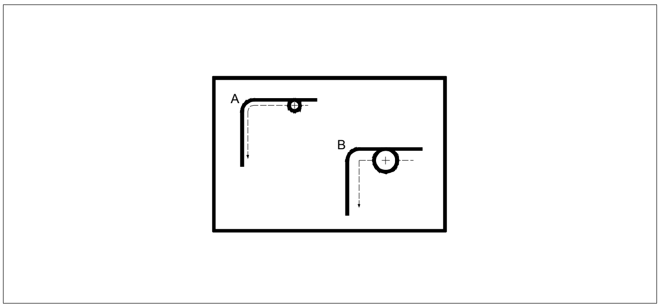


Figure 2 – Corner machining by the modern method (A) and by the conventional one (B) (Sandvik, 1999)

Nowadays the mill insert radius used is usually smaller than the radius to be produced and the corner is machined with a circular interpolation (figure 2A). This causes a feed reduction, without reaching zero. Besides, the tool/workpiece contact is reduced, decreasing the friction, generated heat and vibration possibility. When this is not possible, the advisable is creating a corner with a bigger radius.

5 Tool Materials

The material to be machined, the type and the machining conditions as well as the tool characteristics must guide the tool material selection. In pocket rough milling, it is important a higher insert toughness (Diniz et al. 2001). D'errico et al. (1999) analyzed the performance of several inserts and checked this fact. Comparing coated and uncoated, cemented carbides and cermets end mills, they concluded that the cemented carbide one is able to remove 2 to 5 times more material than the cermet considering the same tool life.

A P class cemented carbide is a good choice in this situation, but its low diffusion and oxidation resistance, demands a coating. The carbides content related to cobalt also affects the cemented carbide performance. Higher carbides quantities improve the wear resistance, but increase also the edge brittleness. Higher cobalt contents improve the toughness, improving the thermal and mechanical variations resistance, on the other hand turn the cutting edge more susceptible to plastic deformation and reduce the wear resistance (Sandvik, 1999).

Related to the carbide grains size, the smaller ones improve the wear resistance (abrasive and adhesive), while the bigger ones improve the toughness and reduce the chipping and fatigue tendency (Sandvik, 1999). The micro-grain allies high wear resistance and toughness, so it is recommended for hardened steels machining (Urbanski, 2000).

6. Experimental Procedures

6.1. Workpieces

The workpieces material was AISI P20 steel tempered and quenched (mean hardness 30 HR_C). Its chemical composition is given in table 1:

Table 1: Chemicalcomposition of AISI P20 steel quantities in %

C	*Si*	*Mn*	*P*	*S*	*Cr*	*Mo*	*Ni*	*Al*
0,011	0,380	1,510	0,015	0,001	1,810	0,160	0,720	0,011

It were opened 18 pockets per workpiece, each one 45 mm depth, in 10 passes of 4,5mm. Each pass removed 9,7 cm^3. The workpiece draft is shown in Figure 3.

It was used a flow of compressed air to evacuate the swarf from the pockets avoiding them to damage the machined surface.

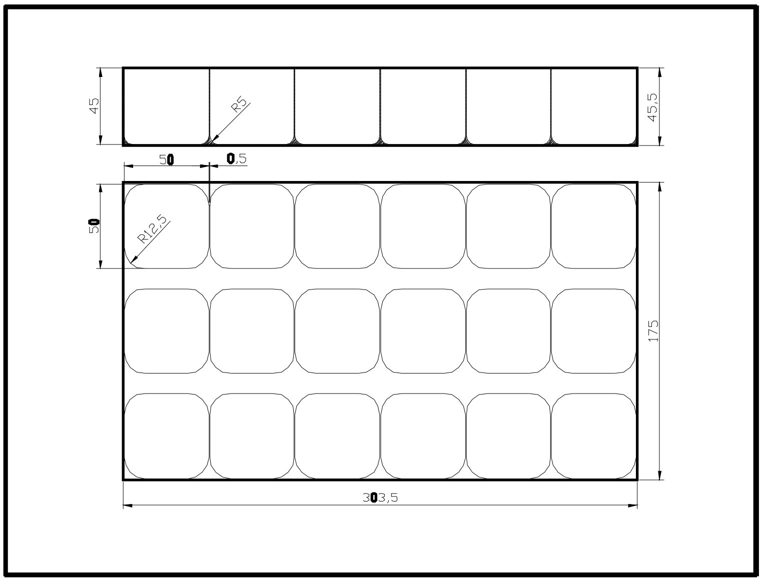


Figure 3 – Workpiece and pockets

6.2. Signal Monitoring

The electrical current was acquired by hall effect sensor, connected to the main motor of the machine. The signal was calibrated in such a way that 1A of current in the motor corresponded to 0,1V of tension that passed through the conversion board and 1V of this board corresponded to 1kW of consumed power. The sampling rate used was 200 Hz.

6.3. Tests Methodology

The machining conditions used in the tests were defined based on tool manufacturer recommendations (Sandvik, 1999) and data obtained in previous tests (Costa et al. 2005). These conditions are shown in table 2.

Table 2 – Cutting conditions

Cutting speed (m/min)	***Strategy***	***Repetitions***
335	Diving	2
400	Diving	3
335	Ramp	2
335	Helical Interpolation	2
400	Ramp	3
400	Helical Interpolation	3

The flank wear adopted as an end of life criteria was 0,4 mm.

In all tests, after 5 passes the cutting edge condition was verified with a magnifying glass. When it was visualized a chipping or flank wear, after each pass the tool was checked and the result recorded.

Diving and ramp strategies were done in 3 passes in sequence, with 1,5 mm depth each one. The second pass was perpendicular to the first and the third one perpendicular to the second e parallel to the first one. After that, they were done other passes to machine the bottom of the pocket making it flat. In the helical interpolation, a 4,5 mm depth cylindrical pocket was done and after that other passes were done to machine the pockets corners, aiming making the pocket with the same shape as obtained by the other two strategies.

6.4. Equipment and Devices Used

The tests were carried out in a Mori-Seiki SV-40 machining center. The inserts model was RCHT 10 T3 M0-PL 1025 ISO P10 to medium and light applications, defined in previous tests. The tools were assembled in a tool holder model R200-015A20-10M, straight shank, and its attachment to the spindle was done by a 392.55HM-40 20 081 chuck. All of them from Sandvik Coromant.

The cutting tools were analyzed in an optical microscope connected to a high-resolution video camera. To measure the values of wear it was used the Global Lab software.

7 Results and Discussions

In all tests the chipping of the cutting edge showed up. It increased until a high value, while the tool still did not present flank wear. So, the flank wear appeared and increased very fast.

The figure 4 shows the results of tool life, in material removed volume.

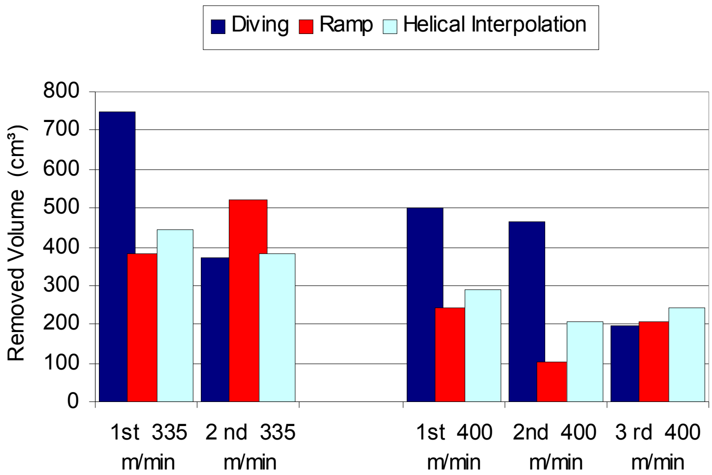


Figure 4 – Comparing the milling pocket strategies

Analyzing the figure 4 and the table 3 it is possible to note that the results dispersion is high due to the type of wear that determined the end of tool life. In other words, chipping appearing and propagation is a random phenomenon.

One can also realize that the use of diving strategy resulted in longer life than the others, contradicting the literature. It was expected that the results of this strategy were the worst due to the higher effective cutting direction angle and therefore smaller effective clearence angle, as well as the higher difficulty of evacuating the swarf.

The tool down axial movement is the moment that more demands of the tool. The most likely assumption to justify the longer tool life obtained with the diving strategy is that the amount of tool axial movement time is shorter, as shown in table 3. Probably the mill movement in this direction harms the cutting tool.

Table 3 – Mean values and standard deviation of tool life measured in the tests

	v_c=335m/min	v_c=400m/min	
Diving strategy	560,8cm³	386,3cm³	mean
	268,8	166,9	standard deviation
Ramp strategy	449,6cm³	182,3cm³	mean
	98,3	72,0	standard deviation
Helical strategy	412,5cm³	244,1cm³	mean
	45,9	41,8	standard deviation

The table 4 presents the times and cutting lengths for each strategy and cutting speed used during the tests.

Table 4 - Times and cutting lengths

strategy	Cutting time (s)	Cutting length (mm)	Cutting time (s)	Cutting length (mm)
diving	9,65	154,5	8,09	154,5
ramp	10,24	175,1	8,58	175,1
helical interp.	15,04	257,2	12,60	257,2
	v_c = 335m/min		v_c = 400m/min	

Besides, in the ramp strategy, as the corners machining is done in a higher number of passes, it wears more the tool and in the helical interpolation strategy the higher time necessary to remove the same quantity of material, also decreased the tool life.

Comparing the helical and ramp strategies, the first one got longer mean tool life when the v_c was 335m/min and shorter when the v_c was increased to 400m/min, but these results presented low means differences and high dispersion. If there is some advantage of helical strategy when the v_c was 400m/min, it can be due to the lesser number of tool passes in the corners (1 against 7). In this pass, the friction between tool and workpiece and, therefore, the system vibration, increased due to the higher contact length between them. This increase of friction and vibration was more meaningful when the cutting speed had its value increased to 400m/min.

The increase of cutting speed caused a reduction of tool life in all tested conditions. This can be explained by the increase in thermal and mechanical shocks intensity stood by the tool, responsible for the cutting edge chipping in the tested conditions. Milling is an interrupted cutting operation, so an increase of heat generated and cutting edge temperature increased the thermal shocks stood by the cutting tool in each revolution. The effect of the higher cutting speed on the entrance shock stood by the tool was reduced, since during the tests the chip thickness in this phase was about zero. But, the fatigue caused by efforts variations damaged the cutting edge. Considering that the thermal shocks are responsible by cracks and comb wear, and that the chipping is caused mainly by mechanical shocks, one can assume that the presented wear were caused by a combined effect of these phenomena.

Analyzing the figure 5 one can conclude that the diving strategy was the one that spent less time to remove 46cm^3 of material, what mean five passes of the tool. This shows that, more than result in longer life; this strategy also reduced the cutting time. The time necessary to one pass, when the helical interpolation diving strategy was used, was the highest among the three tested strategies, due to the trajectory described by the tool. Therefore, despite presenting higher tool life than the ramp strategy when the cutting speed was 400m/min, the helical interpolation strategy presented cutting times 47% longer than the ramp strategy ones, what make its use disadvantageous.

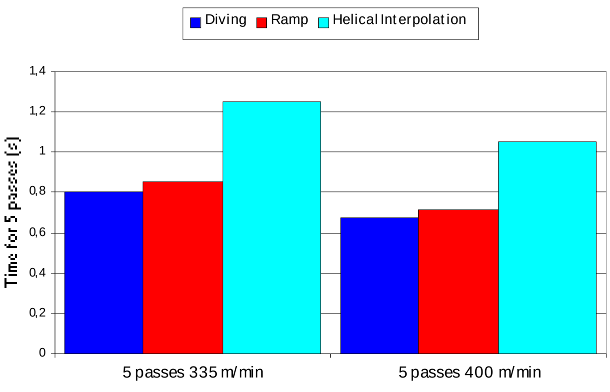
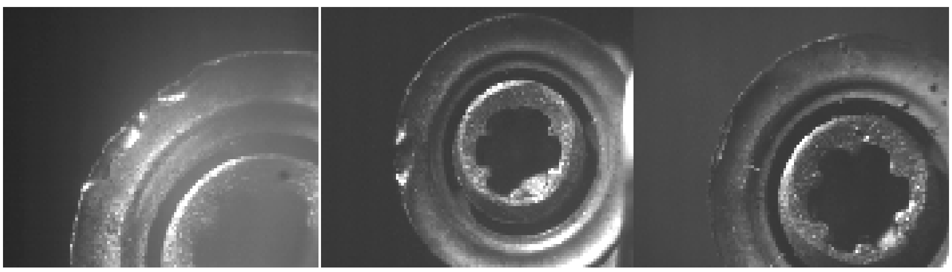


Figure 5 – Relation among the pocket milling strategies and the cutting time



Diving Ramping Helical interpolation

Figure 6 – Relation among pocket milling strategy and the type of tool wear

Observing the figure 6 it is possible to note that the kind of tool wear was not influenced by the strategy adopted. All of them caused chipping that resulted in the end of the tool life. The difference occurred in the moment of the damage appearing and the growing rate of them. This fact occurred despite the cutting speed used. This is partly caused because, in all strategies tested, from the pocket 25 mm depth, the swarfs got in the cutting zone. A more efficient swarf evacuation system could represent a gain in tool life postponing the chipping arising and/or decreasing its growing rate.

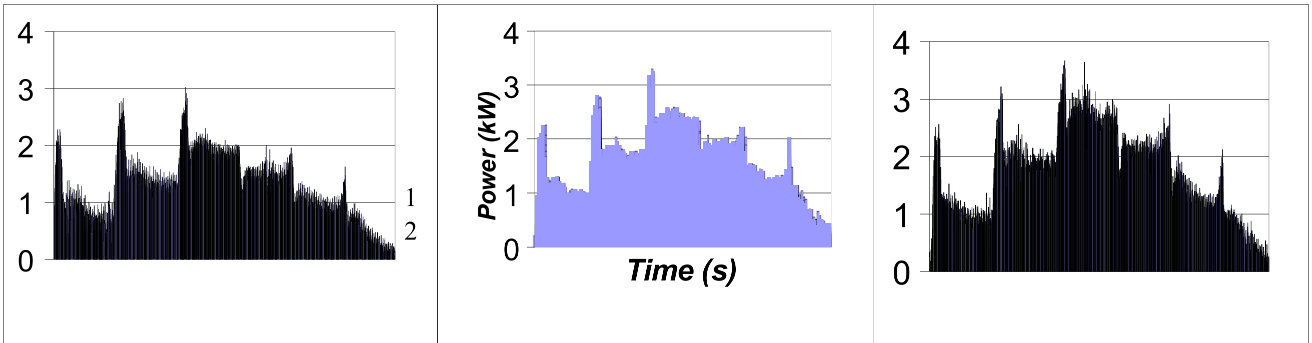
7.1. Power Monitoring

The pocket milling power monitoring make it possible to identify the cutting phases, that are related to different cutting parameters used in specific instants of the tests.

Analyzing the figures 7 it is possible to realize that the consumed power was proportional to the cutting depth, but it was also influenced by the tool positions inside the pocket. There was an increase in cutting power when machining the corners due to the increase of the friction and contact length between tool and workpiece. It is also possible to notice that the tool axial movement influenced the consumed power. Comparing cuts with the same cutting depth, when the feed is axially the consumed power is higher than when it is radial.

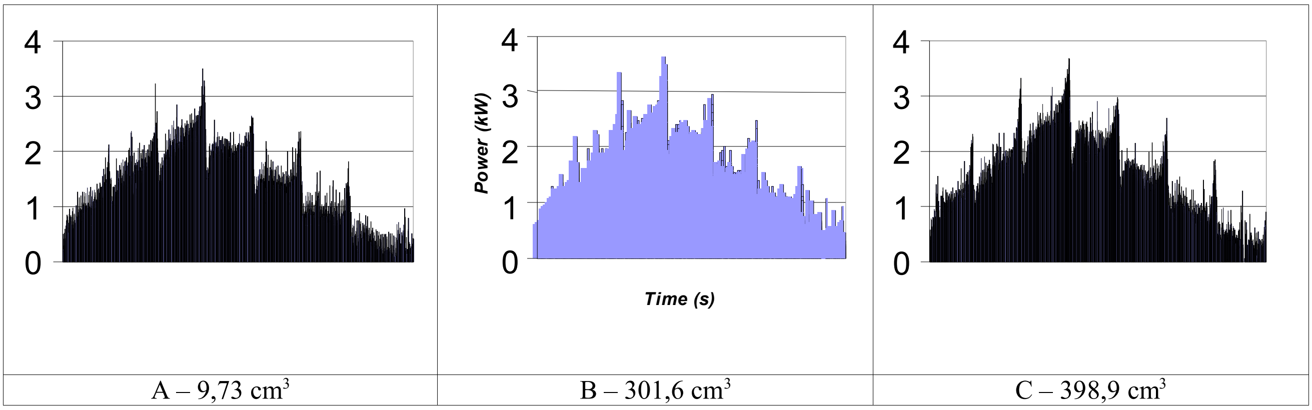
The diving presented the lower mean power consumption among the tested strategies. This is another factor that explains the best performance of this strategy, since lower power consumption means less heat generation and, therefore, less intense thermal shocks on the cutting edge. The mean cutting force during the use of helical interpolation strategy was higher than the other strategies through the tool life. This can be explained because, using this strategy, when the tool cuts the corners, the cutting depth was always 4,5mm. This was a critical moment of the operation, since the friction and the contact length were high.

So, the diving strategy presented a longer tool life, lower cutting times and power consumption, what makes its use advantageous in relation to the others tested strategies in all aspects analyzed in this work. The cutting speed of 335m/min showed more efficient because it presented a better relation between cutting time and tool life, but this is valid only when the volume of material to be removed is high, since in this situation, if the v_c of 400m/min is used the tool changing time and cost will make the process too expensive.



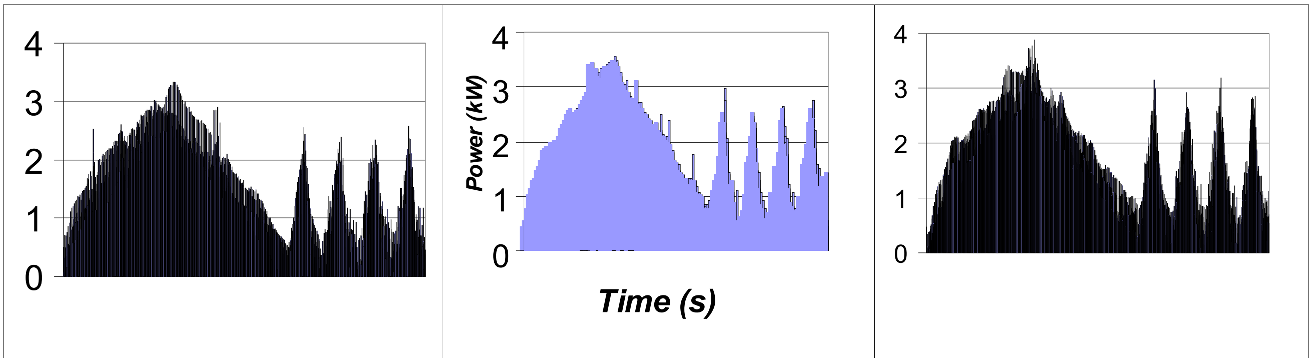
A – 9,73 cm³	B – 593,5 cm³	C – 788,1 cm³

Figure 7 A – Power monitoring for the diving strategy



A – 9,73 cm³	B – 301,6 cm³	C – 398,9 cm³

Figura 7 B – Power monitoring for the ramp strategy



A – 9,73 cm ^{3}	B – 301,6 cm^3	C – 418,4 cm^3

Figura 7 C – Power monitoramento for the helical interpolation strategy

8. Conclusions

The tool axial feed is the main cause of its end of life, since, the longest the movement the highest the tool wear;

The diving strategy presents the shorter time to remove a determined amount of material when compared to the others tested strategies. Because, with this strategy, the actual cutting length is shorter;

The cutting time is a disadvantageous of the helical interpolation strategy, when it is used to open non circular pockets, due to the longer cutting trajectory;

The milling strategy dos not influences the type of tool wear, but it is important in the moment of wear appearance and its growing rate.

9. Acknowledgements

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10. References

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