INFLUENCE OF TOOL OVERHANG ON TOOL WEAR IN HARDENED STEEL MILLING

Carlos Sergio Pivetta
CDT - Centro de Desenvolvimento de Tecnologia e Recursos Humanos - Escola de Engenharia Industrial (EEI) - Avenida Barão do Rio Branco, 882 – São José dos Campos - SP
DEF/FEM/UNICAMP - Mestrando
carlos.pivetta@eei.edu.br

Anselmo Eduardo Diniz
Universidade Estadual de Campinas - UNICAMP, Faculdade de Engenharia Mecânica, Departamento de Engenharia de Fabricação - Campinas - SP
anselmo@fem.unicamp.br

Jefferson de Oliveira Gomes
Instituto Tecnológico de Aeronáutica - ITA - São José dos Campos - SP
gomes@ita.br

Davi Neves
Instituto de Estudos Avançados - Centro Técnico Aeroespacial – São José dos Campos - SP
davis@ieav.com.br

Abstract. *The milling of molds and dies cavities carried out on hardened steel using ball end mill presents limitations in terms of cavity depth, metal removal rates and tool life. Some milling operations on deep cavities are not possible due to the necessity of long tool overhang, what generates vibrations and, consequently, results in poor surface roughness and short tool life. Other point which is not totaly understood up to the present is the influence of the surface roughness obtained in the previous operation on the results of finishing operation, due to the fact that, on finishing operations, the actual depth of cut is not much larger than the height of roughness left on the surface by the previous operation. The main objective of this work is to verify the influence of the ratio tool overhang/ tool diameter, the roughness of the previous operation and cutting speed on the tool wear in finishing operations. Besides, it also intends to verify the influence of tool wear on the tool vibration, measured through the real time tool deflection. Milling experiments on AISI D2 hardened steel (58 HRC) were carried out using coated (TiNAl) carbide ball end mills with the input variables already mentioned. The main conclusions of this experiments, for the conditions used, were: nor the previous surface roughness nor the tool overhang have influence on the resulting surface roughness; when the tool overhang was the lowest one, cutting speed did not influence so much tool wear, but when the highest tool overhang was used, cutting speed presented a strong influence on tool wear.*

Keywords*: hardened steel milling, ball end milling, hardened steel machining*

1. Introduction

The production of molds and dies carried out on hardened steel has been increased lately mainly for finishing operations, replacing electrical discharge machining (EDM) (Diniz, Marcondes and Coppini, 2001). However, some kinds of mold cavity geometries are difficult to machine under conventional conditions. In several cases there are limitations due to either, they are relatively deep or they have small radius of concordance. In these cases the solution is to employ a long tool overhang and/or a small diameter tool (Fallböhmer et al, 2000). These choices can generate vibrations on the machine-fixations-tool system and so, cutting process can become unstable causing damages on the machined surface and on the tool edge.

The depth of cut has a dominant effect over the process stability. Finding the optimal cutting and rotational speed for a certain depth of cut is a common tactic to avoid vibrations (chatter) (Ning, Rahman and Wong, 2001). One possibility to avoid vibration is to change rotational speed combined with changes on feed rate, in such a way that depth of cut can be increased up to a maximum value without chattering. Also, it is possible to establish a specific rotational speed and to determine the maximum depth of cut in order to reach the highest possible metal removal rate.

Abrari et al (1998) suggested that, due to the dependence of radial and axial depth of cut on the ball end milling, cutting stability is possible using the parameters obtained in the solution of an iterative equation that combines variation of the cutting critical width and the rotational speed. The cutting stability could be pre-calculated considering the cutting characteristic variation on the cutting edge (Abrari, Elbestawi and Spence, 1998).

In many cases, the reduction of the rotational speed is immediately implemented and it does not reduce vibration because the cutting process is unstable due to other cutting parameters (Polli, 2005).

Vibration caused by the lack of stiffness of the machine-fixation-tool system can damages rapidly the surface. The wear on the machine spindle bearing and the wear on feed mechanisms also can generate vibrations and so, deteriorate surface roughness. The vibrations caused by the machine-fixation-tool system could be partly eliminated decreasing the tool overhang. Vibrations caused by a long overhang could be critic. Therefore, Brown (1998) suggests that the tool overhang/diameter ratio should not be higher than 4 (Brown, 1998). The molds and dies machined in HSM technology, generally, present cavities with short depth due to the limitations of the tools. If the depth of the cavity increase, the process will need longer tools and the cutting instability will be present, due to vibration on the system. Thus, the overhang must be as short as possible (Gomes, 2001).

In high speed milling of hardened steel it is important to have a very reliable monitoring system to accompany the cutting process, mainly on finishing operations, because the workpiece is almost finished and the rejection of the workpiece at this point would cause a great lost (Neves, 2002). The success of the monitoring system depends on the careful verification of workpiece material, tool quality, reliability of the machine-fixation-tool system and the control of the previous operations (Lee and Altintas, 1996). In the workpiece material, homogeneity of the structure and hardness must be controlled in order to maintain the finishing cutting homogenous in terms of material removal rate, cutting forces, vibrations and cutting temperatures (Dewes and Aspinwall, 1997). In terms of tool quality, the unbalancing must be checked always before its utilization (Sandvik, 1999). In terms of previous operation, the variation of stock material left to be removed by the finishing operation, geometry and roughness of the previous surface must be tightly controlled. The stock variation will generate variations on the cutting forces, on roughness and on tool life. The surface quality of the previous process modifies the finishing operations results (Abrari, Elbestawi and Spence, 1998). According to Abrari, Elbestawi and Spence (1998) the undulations left by the previous operation and by the previous tool tooth influences the undulation left behind for the current tooth and also influences the final roughness left by the current operation. Due to relative vibration between the tool and workpiece, the chip thickness will not only be affected by the instantaneous vibration of the system, but also by the amount of undulation left behind by the previous tooth.

Tool life is an important factor in dies and molds machining because the damage of the cutting edge influences the machining accuracy (Kita at al, 2001). The cutting process technology generally employed is called High Speed Machining (HSM) which involves the use of small diameter tools (< 20mm), and high rotational speed (>10000 rpm) (Koshy, Dewes and Aspinall, 2002). For machining molds and dies carried out on hardened steel it is recommended to employ the tool diameter as large as possible in order to reduce the tool deflections and, consequently, to improve surface roughness s. In the cases of limitations caused by the necessity of using a small diameter tool, the solution is to reduce the depth of cut. In this case, to compensate the loose of productivity, it is necessary to increase the feed rate and the rotational speed of the spindle (Fallböhmer et al, 2000).

The tools generally employed in HSM of hardened steel are PVD coated carbide. The main advantage of coating the tool with a very thin layer of TiNAl is to improve the cutting conditions, mainly cutting speed, since the tool is very resistant to high cutting temperatures. The carbide coated with TiNAl has higher hardness at high temperatures and higher thermal resistance, compared to TiCN coating. In addition, there is the possibility of machining without cutting fluid which produces a cleaner and more ecologic process (Sandvik, 1999).

In the rough and semi-finishing machining of hardened steel, the indexable insert ball end mill is usually employed. Its main advantage compared with solid coated carbide is the price of the tool, since this kind of tool usually has large diameter (>15 mm) (Urbanski et al, 2000). For finishing operations, solid coated carbide are more usual because it presents smaller run out errors and smaller deflection compared to the indexable insert tools due to its higher stiffness, resulting in smaller surface roughness, mainly for diameters less than 10 mm (Dewes, and Aspinwall, 1997).

The main characteristics of a carbide tool are: macro-geometry, micro-geometry of the cutting edge, carbide grade and coating. The macro-geometry refers to the angles of the tool like rake and clearance angle. A rough operation requires a more robust geometry. The inserts for hardened steel cutting must have robust edges and rake angles either negative or null mainly for cutting materials with hardness higher than 54 HRC removing the amount of material usually programmed for roughing. The micro-geometry refers to the cutting edge geometry, like edge radius and chamfer. The carbide grade for molds and dies milling on hardened steel must have high hardness in order to cope the high temperatures generated by the high cutting speed (HSM) (Sandvik, 1999).

The tool geometry must simultaneously permit the tool access to the desired areas of the deep cavities without loosing stiffness. In several cases it is necessary to tilt the tool to the wall being cut in order to avoid the contact with the center of the tool, where the cutting speed is zero.

Several studies were carried out related to hardened steel milling. Neves (2002) concluded, for end milling of AISI H13 (52 HRC) hardened steel using solid submicron carbide tool coated with TiNAl, that down milling orientation was better than up milling orientation, the cutting speed is much more important to the increase of tool wear than tool overhang and as tool wear increases the cutting forces also increase. Kim at al (2001) concluded that, when workpiece hardness overcome 60 HRC, its machining becomes much more difficult. These authors also showed that the use of compressed air to cool the tool is much better, in terms of tool life than liquid fluid. Koshy, Dewes and Aspinwall (2002) concluded, based on milling experiments of the AISI D2 hardened (58HRC) steel using carbide ISO P05-P20 with TiCN coating (3 μm thickness) and TiN superior layer, that low values of feed per tooth, around 0,05 mm/tooth, resulted in high tool wear due to inefficient material removal caused by the friction mainly the in the center of the tool.

Thus, they suggested that the best feed “fz” range is between 0,05 to 0,1 mm/tooth. Toh (2004) when milling AISI H13 (52 HRC) verified that the roughness for up milling were better than down milling. Chen, Huang and Chen (2005) verified that the increase of tool inclination in relation to the machined surface generates longer tool life, up to a certain value which is dependent on the tool diameter.

2. Experimental Procedure

The effect of employing different cutting conditions and tool overhang when finish milling hardened AISI D2 (58 ± HRC) was investigated in terms of tool wear and tool displacement (deflections). The workpieces utilized were bocks with dimensions of 10 mm x 15 mm x 106 mm and one block with dimensions 100 mm x 206 x 210 mm. All the milling experiments were carried out in a vertical 5-axis C600V HERMLE CNC machine center with 15 kW in the main motor and 16,000 rpm in the spindle The workpiece was machined at horizontal milling at an inclined position, 15º with tool center line (figure 1A). The axial and radial depth cutting used are illustrated in fig. 2 (Gomes, 2001).

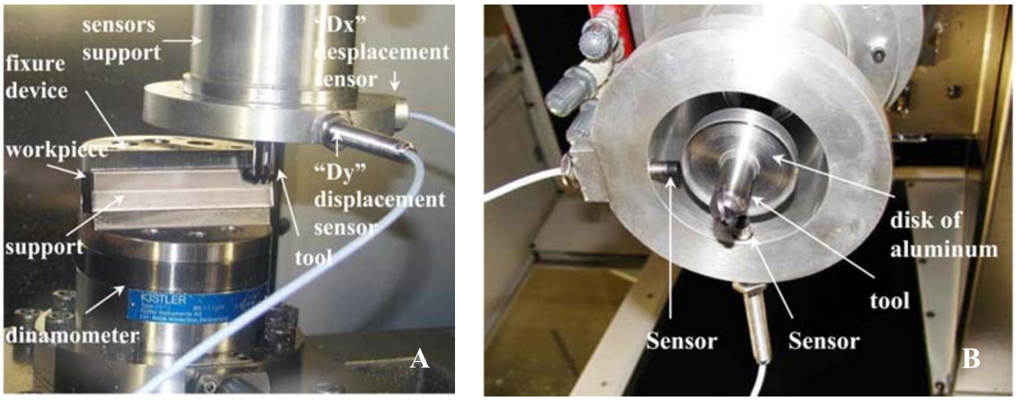


Figure 1 – Set up of experiments A) workpiece; B) sensors

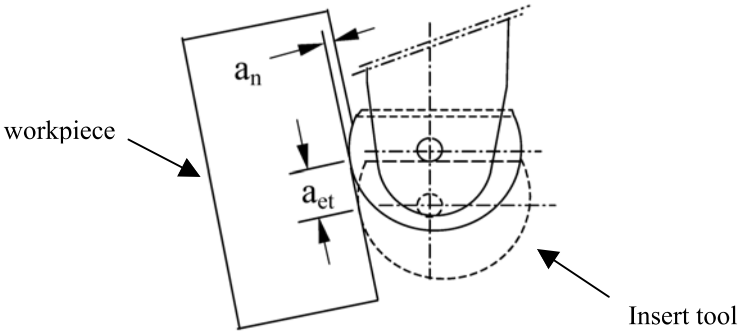


Figure 2 – tool engagement

The milling experiments were carried out using indexable insert tools with micro grain carbide ball end mills with 16 mm diameter, coated with TiNAl and two edges. The tool was mounted in the tool holder using thermal interference. Tool wear was measured using a 40 X magnification microscope connected to a digital camera and a computer. The tool wear was measured and the worn tool photographed several times during one experiment. The tool life criterion was a flank wear value of V_{Bmax} = 0.2 mm. If the milling time overcame 30 minutes and this value of flank wear had not yet been reached, the experiment was finished.

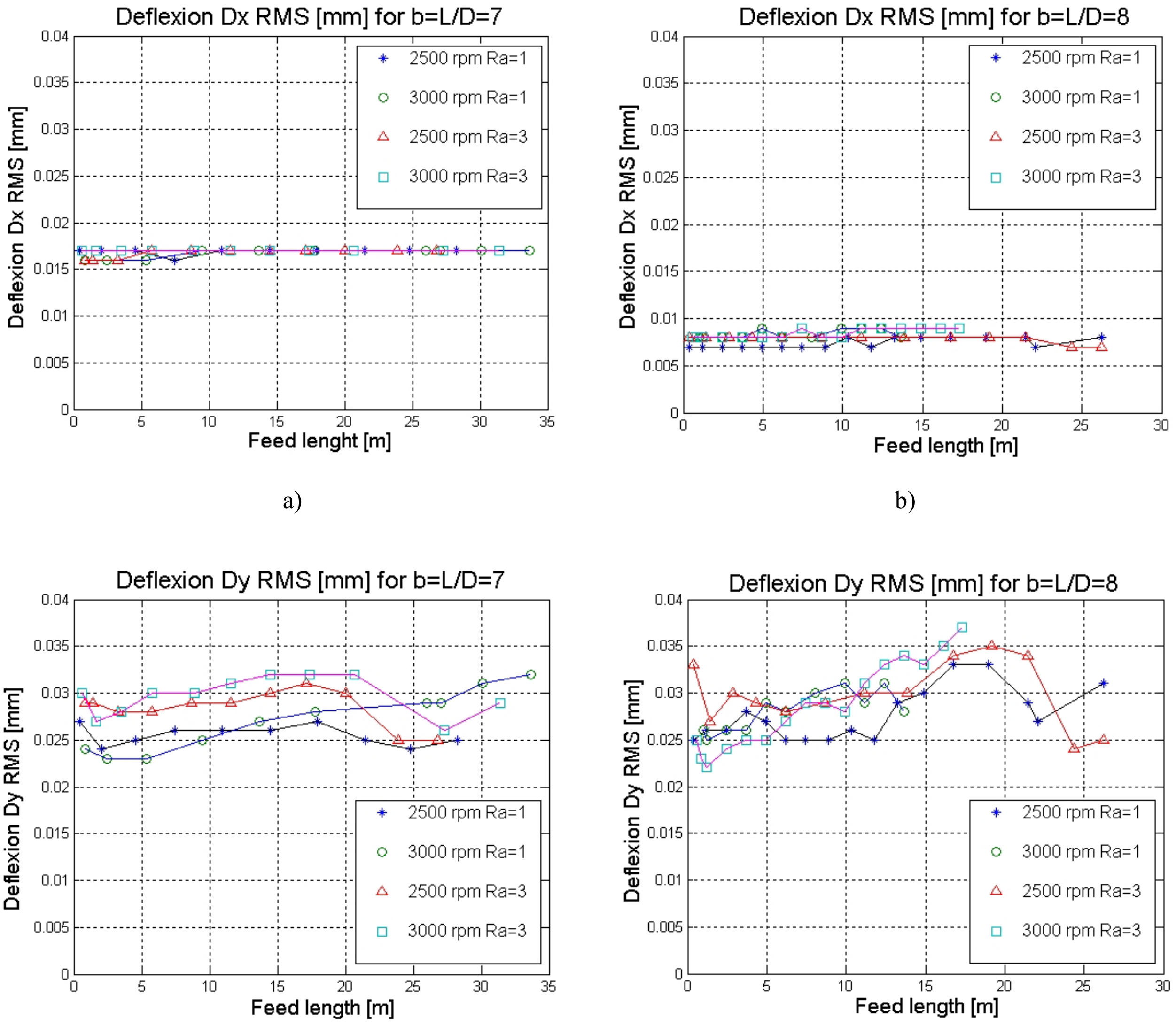
Tool vibration values were obtained during the milling experiments using two capacitive displacement sensors which measured real time displacement without contact. They are able to detect tool oscillations as small as 1 µm. Because of this kind of measurement, tool vibration was called in this work by either, tool deflection of tool displacement. These two sensors were placed at 37,7 mm far from the tool tip, one in the feed direction (*Dx*) and the other in the perpendicular direction (*Dy*), according to fig. 1B. The signals of these sensors, after passing through a couple/amplifier, were acquired by an A/D board at frequency of 10 kHz and stored in a computer memory. In order to capture these signals, a disk of aluminum was mounted on the tool at 37,7 mm from the tip and sensors were fixed to a cylinder. The displacement signals were acquired using the LABView software. Besides, an application program was made for acquire and convert the signals from volts to micro meter (displacement unit).

The input variables were always in two levels and were: cutting speed (provided by the rotational speeds 2,500 RPM and 3,000 RPM), tool overhang (b = 7 and 8) and the roughness left by the semi finishing operation (*Ra* = 1 μm and *Ra* = 3 μm). The axial and radial depth (a_n and a_{et} on figure 1C) and the feed per tooth were maintained constants and were, respectively, a_n = 0,1 mm, a_{et} = 0,2 mm and f_z = 0,1 mm. The cutting fluid used was compressed air which had just the purpose of expelling the chips far from the cutting zone.

3. Results and discussions

Figure 3 presents the tool displacement values against machined feed length for all the experiments carried out. It can be seen in this figure that the tool deflections in the "x" direction (feed direction) are much smaller than in the "y" direction (perpendicular to the feed – called passive direction). Due to the large radius of the tool, the projection of the chip area in the passive direction (proportional to the force in this direction) is very large, much larger than the average chip thickness (proportional to the force in the feed direction), what made the deflections in the feed direction to be low. Another interesting point shown in figure 2 is that the "Dx" deflections when the "b" ratio was 7 were larger than when "b" was 8.

It can also be seen in this figure that "Dx" is not influenced by tool wear, since it did not vary as feed length increased. Therefore, it can be concluded that the tool is rigid enough to withstand a supposed increase of force in this



a)

b)

c)

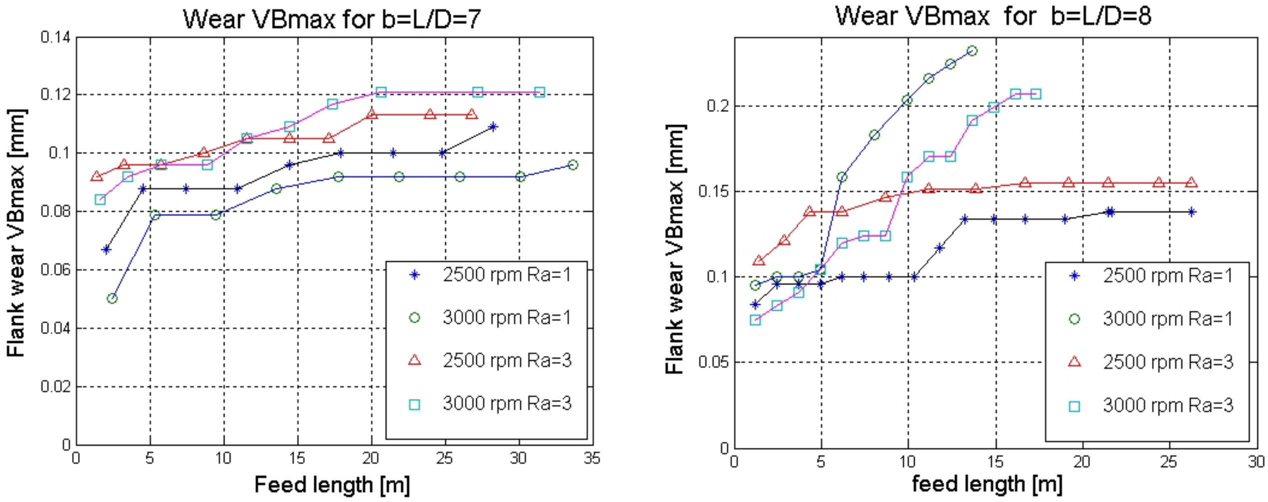
d)

Figure 3 – RMS of tool displacements (deflections) against machined feed length

direction caused by the tool wear. It is also important to note that, as already said, forces in the “x” direction are lower than in the “y” direction. But, the behavior of the displacement in the “y” direction was very different. In some conditions, like for the experiments with b = 7, Ra_{prev} = 1.0 µm and n = 3,000 RPM, with b = 8, Ra_{prev} = 3.0 µm and n = 3,000 RPM and with b = 8, Ra_{prev} = 1.0 µm and n = 3,000 RPM, there was a continuous increase of “Dy” with feed length. In the other experiments, an initial growth occurred, followed by a drop of “Dy” in the end of the tool lives. In order to explain these results, it is necessary to examine figures 4a and 4b which show tool flank wear against feed length for all the experiments. In the two conditions in which a large tool wear occurred (b = 8, Ra_{prev} = 3.0 µm and n = 3,000 RPM and with b = 8, Ra_{prev} = 1.0 µm and n = 3,000 RPM), it also occurred a continuous increase of tool displacement. Therefore, it can be said that a large tool wear caused an increase of the “Dy” displacement which also caused an increase in tool wear. However, this is not the only cause of “Dy” growth, since in the experiment with b = 7, Ra_{prev} = 1.0 µm and n = 3,000 RPM, displacement increased continuously with feed length, but tool wear did not reach a large value. In the other hand, in this experiment, despite the fact that displacement grew continuously, the slope of the curve is low, much lower than in the other two experiments in which “Dy” increased continuously.

When tool flank wear values remained low (below 0.15 mm), the “Dy” displacement oscillated between high and low values. Very likely the same behavior occurred with force in this direction (cutting forces were not measured in these experiments). Depending on the kind of tool wear, either an increase or a decrease of cutting force may happen. For example, crater wear uses to decrease cutting forces, due to the fact it increases the effective tool rake angle. In the other hand, flank wear, due to the fact it causes an increase of the tool-workpiece contact area, it tends to increase cutting forces. Therefore, the force in the “y” direction may have had oscillations in its values due to the variations in the wear forms, as feed length grew. Just when flank wear was very large, force may have increased steeply, causing the growth of “Dy” displacement.

It can be seen on figure 4a that, for b = 7, neither the surface roughness left by the previous operation, nor cutting speed substantially influenced tool wear. After 30 m of cutting, all flank wear values were in the range of 0,09 to 0,13 mm, still very far from the point that is considered end of tool life. Just when b = 8 was used (figure 4b) it can be said that cutting speed strongly influenced tool flank wear (surface roughness left by the previous operation did not influence tool wear at all). This result is opposite to the literature, which affirms that cutting speed strongly influences tool wear and tool life, regardless other factors like tool overhang. We believe that cutting speed did not influence tool wear when b = 7 was used, because the experiments were interrupted before it reached a larger value which would allows a differentiation between them. Very likely, if the four experiments were extended up to the point where V_B values were larger, the cutting speed influence on tool wear would be demonstrated. This fact can be proved by the results shown on figure 3b in which the resulting of two factors of influence on tool wear, like high cutting speed and high tool overhang, made tool wear to increase fast and, so, the influence of cutting speed could be noted.



a) b)

Figure 4 – Flank wear influenced by cutting speed and tool overhang

The same discussion can be made in a different way. When figures 4a and 4b are compared, it can be seen that tool overhang influenced tool wear mainly when cutting speed was high. For the lowest cutting speed (obtained with 2,500 RPM), after 30 m of cutting, the flank wear values were between 0.11 and 0.12 mm for b = 7 and between 0.13 and 0.16 mm for b = 8. When the rotational speed was 3,000 RPM, for the same 30 m of cutting, the flank wear values for b = 7 were in the range of 0.09 mm to 0.13 mm and for b = 8 they were bigger than 0.2 mm. Again it can be concluded that both factors together (cutting speed and tool overhang) in high values are very harmful to the tool.

Based on these discussions, two conclusions can be extracted: a) with a low value of “b” (in this case b = 7) higher cutting speeds can be used and, even though, the tool life still will be long (in situations similar to those used in the experiments, longer than 30 m); b) a large value of “b” (like b = 8) can be used when deeper cavities have to be machined, but lower cutting speeds have to be used, in order not to have very short tool lives.

The fact that the surface roughness left by the previous operations did not influence tool wear shows that the increase of this parameter caused a negligible increase of the actual volume of material removed per tool revolution.

Figures 5 to 7 show the cutting edges in the end of some experiments. It can be seen on these figures that, in the experiment in which flank wear overcame V_{Bmax} = 0.2 mm (figure 6), the cutting edge was very damaged and crater wear had already met flank wear. Very likely, if the cutting had continued a little more, the complete breakage of the

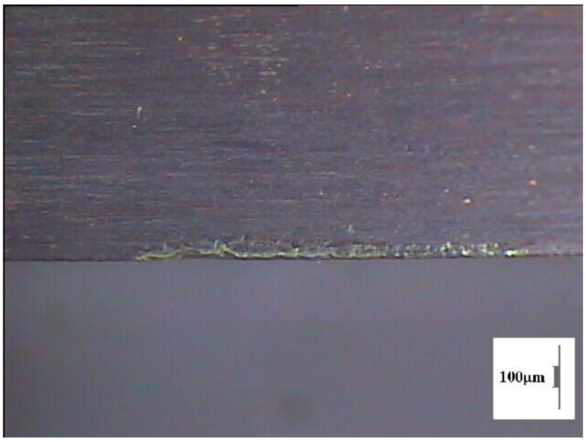


Figure 5 – Cutting edge in the end of the experiment with b = 7, n = 2,500 RPM

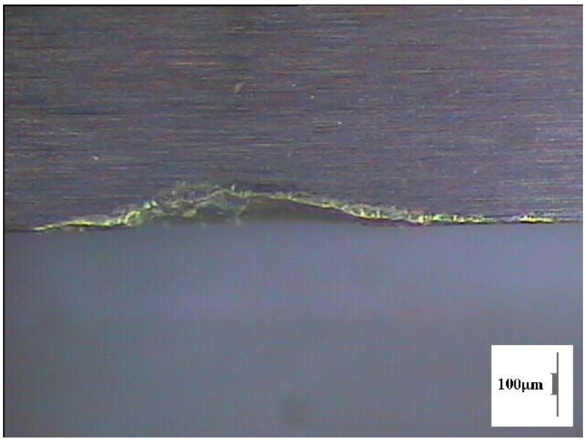


Figure 6 – Cutting edge in the end of the experiment with b = 8, n = 3,000 RPM

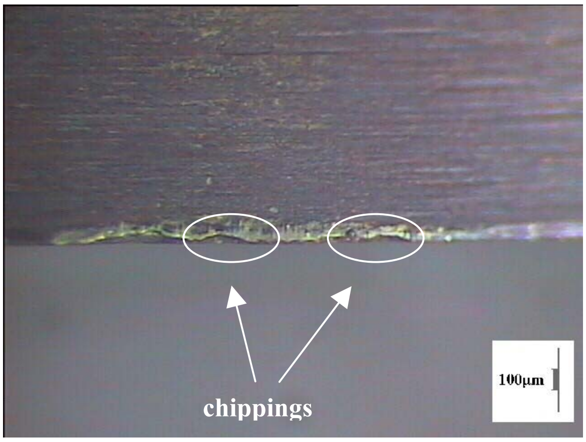


Figure 7 – Cutting edge in the end of the experiment with b = 8, n = 2,500 RPM

edge would occur. Therefore, $V_{Bmax} = 0.2$ mm is a good criteria of tool life. Figure 5 shows one of the tool cutting edges for the experiment made with b = 7 and n = 2,500 RPM, in which flank wear was around $V_{Bmax} = 0.1$ mm at the end of the experiment. It can be seen in this figure that flank wear was still homogeneous, without large chippings. Figure 7 shows one of the tool cutting edges for the experiment made with b = 8 and n = 2,500 RPM. In this experiment, V_{Bmax} was around 0.15 mm when the experiment was finished. It can be seen in this figure the presence of some chippings on the cutting edge. Based on these figures, a hypothesis can be created to explain the wear behavior of these tools. Up to a flank wear value of 0.1mm, flank wear is homogeneous. When it gets close to 0.15 mm, some chippings start to occur due to the successive impacts of the edge against the workpiece, already weakened by the wear. These chippings continue to grow up to a complete breakage of the edge, when V_B will be bigger than 0.2 mm. If this behavior is true, a tougher tool carbide grade would provide longer tool life.

4. Conclusions

Based on the results of the experiments carried out in this work, some conclusions can be drawn for the milling of AISI D2 steel with micro grain carbide ball end mills coated with TiNAl:

a) The tool overhang "*b*" influences significantly on the tool wear when a high value is associated with a high rotational speed of the spindle and, consequently, with a high cutting speed. So, if a high value of tool overhang have to be used in order to cut deep cavities, a low cutting speed must be chosen;
b) The workpiece roughness obtained in the previous operation does not influence flank wear;
c) As tool flank wear increases, the number and size of the chippings on the cutting edge also increase. When flank wear is around $V_{Bmax} = 0.2$ mm the cutting edge is close to a complete breakage.
d) Tool deflection in the feed direction does not vary with tool wear but, in the direction perpendicular to the feed, this kind of deflections varies strongly. When flank wear increase quickly up to a value bigger than 0.2 mm, deflection in the feed direction also increases steeply. In other cases, this deflection varies according to the sizes and forms of the tool wear.

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