EFFECT OF MINIMAL QUANTITY OF LUBRICANT (MQL) IN HIGH-SPEED MILLING OF AISI H13 HARDENED STEEL WITH CARBIDE TOOL

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Abstract*. The utilization of vertical machine center has been the usual machine tool configuration in die and mould industry. However, this configuration of machine tool introduces a technical challenge to remove chips from the deep and narrow cavities. Water-based cutting fluids is an option for the removal of these chips, but the detrimental effects on tool wear caused by the tool temperature variation in milling operations hinders the use of this kind of fluid. An optional technique to remove the chips is the so called Minimal Quantity of Lubricant (MQL). However, the effects of MQL technique on high-speed milling of hardened steels are strongly influenced by several factors, and thus, different results of its application are found in literature. This work aims to compare the performance of the application of MQL technique and dry cutting in high-speed milling of AISI H13 steel (50 HR_C) on tool life, tool wear and surface roughness. Several milling experiments were carried out in semi-finish operation with coated carbide toroidal mills and workpiece with inclined surfaces. The application of MQL technique promoted the appearance and spread of the thermal cracks on cutting edge. These thermal cracks stimulated the microchippings on cutting edge and restricted the tool lifetime when compared to dry cutting.*

Keywords*: MQL, high-speed milling, tool life, tool wear, roughness*

1. INTRODUCTION

The utilization of vertical machine center has been the common machine tool configuration in die and mould industry. The main reason for this choice is related to the lower price when compared with horizontal machine center. Moreover, the secondary processing time (time for die and mould change on the machine table) is shorter with vertical machine center considering the use of conventional devices. However, the application of vertical machine center in die and mould industry introduces a challenge to remove chips from the cavities. Mainly in the cases with narrow and deep cavities, removing the chips from the cavities only with the airflow generated by the tool rotation becomes a difficult task. In the case that chips remain in the cavity, they can be compressed against the machined surface, damaging the finished surface or break the cutting edge (Fleischer *et al.*, 2006; Fallböhmer *et al.*, 2000).

The use of cutting fluid can easily remove the chips from a cavity, even when it is deep and narrow. On the other hand, the use of water-based cutting fluids, which have high cooling capacity, promote the tool life reduction because they stimulate thermal cracks on cutting edge. This problem is aggravated with high-speed milling of hardened steels. In the interrupted cutting, the thermal cracks occur when using water-based cutting fluids in function of the greater temperature gradient when compared to dry cutting. Usually, the longest tool life is reached in milling of steels with dry cutting (Vieira *et al.*, 2001).

A typical solution used to remove the chips from the cavities in high-speed milling of hardened steels is the application of compressed air. The compressed air has lower cooling capacity than water-based cutting fluids. Therefore the major purpose of its use is to minimize the effect of temperature variation on cutting edge in each tool revolution. Moreover, aiming to increase the lubrication capacity and, consequently, reduce the surface friction and temperature on tool-workpiece and tool-chip interfaces, it is possible to use the spray of a low quantity of oil, in mist form, together with the stream of compressed air. This technique is known as Minimal Quantity Lubrication - MQL (Machado and Wallbank, 1997). According to Tasdelen *et al.* (2008), MQL is a very suitable technique for short engagement time cutting as high-speed milling.

However, the effects of MQL technique on high-speed milling of hardened steels are strongly influenced by several factors. Among these factors, it can be mentioned the cutting parameters, tool material, machined material and geometry and pressure, flow and application distance of MQL. Thus, different results with the application of MQL technique on milling of steels are found in literature.

Thepsonthi *et al.* (2009) compared the application of MQL technique (pulsed–jet application with 2 ml/min and pressure of 20 MPa), dry cutting and flood cooling using a coated carbide P20 grade end-mill while milling ASSAB DF-3 steel (chemical composition similar to AISI O1) with 51 HR_C. The experiments were conducted using slot milling, in which the tool immersion was equal to the effective tool diameter and, therefore, hampers the removal of chips. They report that, at all cutting speeds tested (125, 150 and 175 m/min), the MQL technique promotes lower flank wear rates compared to dry and flood cutting during a 6 m length of cutting. Furthermore, there was a tendency to increase the difference between MQL and other methods (dry and flood cooling) in flank wear rates with increasing cutting speed. They concluded that MQL in pulsed-jet form is a feasible alternative of flood cooling and dry cutting in high-speed milling of hardened steel.

Rahman *et al.* (2002) conducted experiments on the ASSAB 718 HH tool steel (chemical composition similar to P20) of 35 HR_C with the use of carbide tool evaluating the performance of MQL, flood cooling and dry cutting. The MQL technique used 8.5 ml/h applied with air pressure of 0.52 MPa. A wide range of cutting parameters was used during the experiments. However, an interesting result is the comparison of the performance of different forms of cooling/lubrication depending on cutting speed. When cutting speed was 75 m/min, tool wear obtained in MQL was the lowest among the three lubrication modes, while that for dry cutting was the highest. However, when cutting speed increased to 125 m/min, MQL promoted higher tool wear than flood cooling and, also, promoted similar tool wear when compared to dry cutting. The authors concluded that flank wear at low speed, low feed and low depth of cut was lower for MQL technique. But the use of heavy cutting parameters (higher cutting speed, feed per tooth and depth of cut) is detrimental to MQL from the flank wear point of view and more suitable for dry cutting.

Liao *et al.* (2007) compared the application of MQL technique (two types of oils), dry cutting and flood cooling. They performed the experiments with NAK 80 tool steel (chemical composition similar to P21) with 41 HR_C and a wide range of cutting parameters. The MQL technique used 10 ml/h applied with air pressure of 0.45 MPa. From the tool life aspect, and contrary to the results obtained by Rahman *et al.* (2002), the authors affirm that the improvement of tool life, when compared MQL technique and dry cutting, is more significant at higher cutting speed (cutting speed interval from 150 to 250 m/min). According to Liao *et al.* (2007), a possible reason for these contradictory results between these experiments may be due to the tool grade and oil of MQL used. In the prior experiment, the inferior heat resistance uncoated carbide tool and the highly viscous oil, which has poor cooling ability, were used, while in the last study, the coated carbide tool with higher heat resistance and the oil with a better cooling effect were adopted.

Two points are needed to emphasize in the previous experiments in relation to the die and mould industry. First, few mould cavities have flat surfaces as used in most prior experimental procedures. In most cases, mould cavities have inclined surfaces, which hamper the access of the fluid spray at cutting region. Second, different criteria for ended tool life were used in the previous experiments. Some criteria do not reflect the reality of die and mould industry. Therefore, this work aims to evaluate the influence of the application of MQL technique (with two types of oil - vegetal and vegetal with Teflon additive) on tool life, tool wear and workpiece roughness when compared to dry cutting. The experiments were conducted using a typical cutting parameter of high-speed milling of hardened AISI H13 steel (50 HR_C). This tool-steel is widely used in die and mould industry. Moreover, the milling testes were carried out in inclined surfaces, what difficult the access of air stream.

2. MATERIAL, EQUIPMENTS AND EXPERIMENTAL PROCEDURES

The experiments were carried out in a 3-axis CNC vertical machining center with 22 kW of power in the spindle motor and maximum tool rotation of 12,000 rpm.

The workpiece material was AISI H13 steel with 50 HR_C of hardness. Figure 1 shows the geometry of the workpieces. The machined surfaces were designed in such a way that the tool could be accelerated and decelerated while it was outside the workpiece, thereby maintaining a constant feed velocity while the tool was engaged in cutting. The tool's feed movement began 30 mm before entering the cut and ended 30 mm after leaving the cut in each pass.

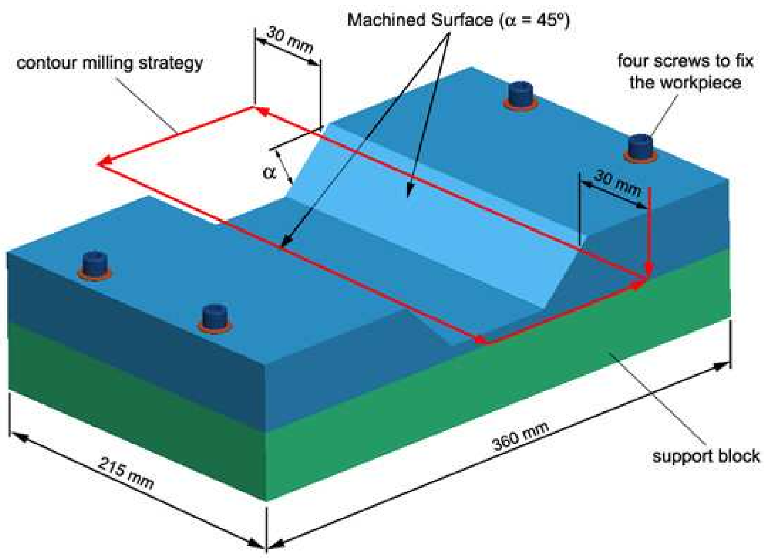


Figure 1. Geometry of the workpiece and down milling with contour cutting strategy

The tool used in the experiments had two circular inserts with diameter 7 mm (code R300-0720E-PM) set in a steel toolholder of 12 mm (code R300-012A16L-07L) both produced by Sandvik Coromant. The tool was assembled in a hydraulic chuck with overhang of 70 mm. The inserts were made of carbide (H15 grade - Sandvik code GC1025) and coated with multi layers of TiCN and TiN deposited by PVD process.

Flank wear was inspected several times during tool life, using an optical microscope. Tool life was considered ended when flank wear reached VB_B = 0.20 mm. After the end of tool life, the worn inserts were examined under a scanning electron microscope (SEM) equipped with an energy dispersive X-ray (EDS) system in an attempt to understand the wear mechanisms.

One experiment consisted of successive milling passes in two inclined surfaces of 215 mm length show in “Fig. 1”, interrupting the process at regular intervals in order to measure tool flank wear and workpiece surface roughness. The roughness profile analyses were done using a portable Mitutoyo roughness tester. The experiments continued up to the moment when the tool reached the end of its life. Each experiment was carried out threefold.

The used MQL system is the Mist Coolant Equipment model OS-21-AT-40 from Fuso Seiki. In this equipment, the pressurized air arrives to the system and is responsible for atomizing the oil near the application point. The mist application used a metallic nozzle and an approximate distance of 100 mm, according to “Fig. 2”. The MQL technique used 12 ml/h applied with air pressure of 0.45 MPa. Two types of vegetable-based integral oil were used: Vascomill 42 from Blaser Swisslube, and Fin Lube AL from Interflon. The latter oil contains teflon as an additive in its composition.

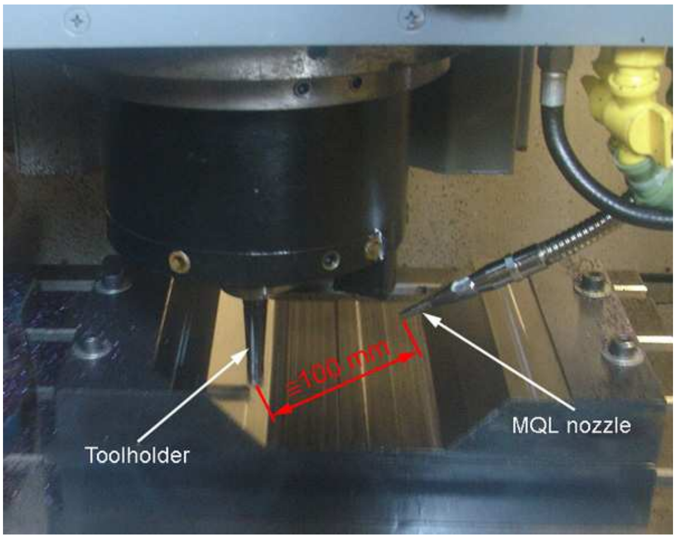


Figure 2. MQL application device with a metallic nozzle

The cutting parameters used were: Cutting speed (v_c) = 300 m/min, feed per tooth (f_z) = 0.25 mm, axial depth of cut (a_p) = 0.25 mm, radial depth of cut (a_e) = 0.40 mm and surface inclination (α) = 45º. These conditions are also suitable for semi-finishing milling operation of dies and moulds.

All experiments were carried out using down milling and contour cutting strategy.

3. RESULTS AND DISCUSSION

3.1. Tool life

Figure 3 shows the tool life results for all experiments. Based on an analysis of variance and using a 95% confidence interval, it can be stated that lubrication procedure affected tool life significantly. According to “Fig. 3”, the average tool’s lifetime with dry cutting was 61.5 minutes. On the other hand, with the application of MQL technique and vegetable-based integral oil – 12 ml/h and 4.5 MPa – average tool’s lifetime was 38.6 minutes. Furthermore, the application of vegetable-based integral oil with teflon as an additive in its composition promoted an average lifetime of 43.4 minutes. Due to the standard deviation in each condition, there is no statistical difference in tool’s lifetime, using a confidence interval of 95%, when comparing the different types of vegetable-based integral oils. Thus, the average tool’s lifetime reduction was the 37.2% and 29.4% when comparing dry cutting with integral oil and integral oil with teflon as an additive in its composition, respectively.

The MQL technique has low cooling capacity and its application aimed promoting lubrication at the cutting region. Therefore, with high lubrication and low cooling effects, the MQL is supposed to decrease both tool temperature and tool temperature variation. It is supposed that the oil, in mist form, would adsorb on the flank and rake face of the tool during the period in which there is no contact tool-workpiece in each tool revolution and, during the cutting period, would lubricate the tool-chip and tool-workpiece interfaces. So, friction would be reduced as well as the workpiece adhesions on the cutting edge would be minimized. However, the experimental results demonstrated that the MQL application did not produce the desired effect on tool's lifetime when compared to dry cutting.

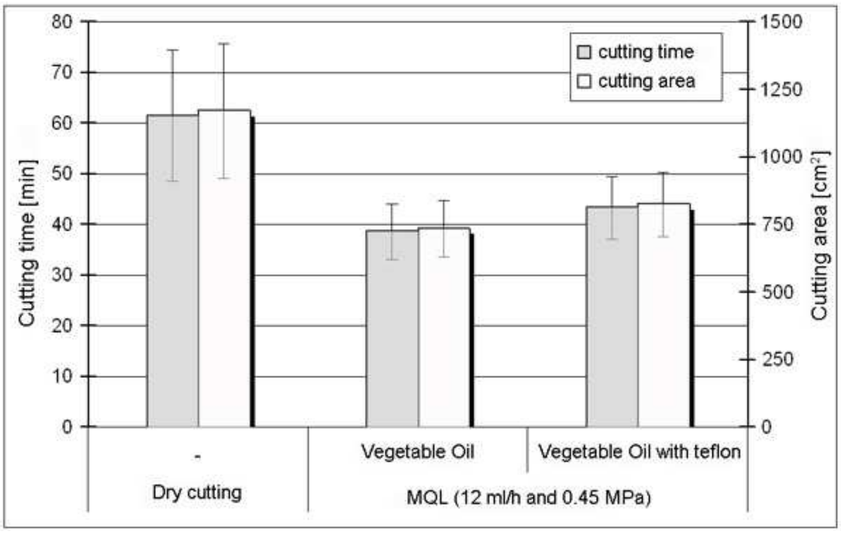


Figure 3. Tool life results in the experiments

The shorter tool's lifetime with the application of MQL technique disagree of results obtained by Rahman *et al.* (2002). The experimental conditions of Rahman *et al.* (2002) were described previously. In that experiment, they found out that, with cutting speed of 125 m/min, tool's lifetime is longer using MQL technique when compared to dry cutting. Two aspects may determine the discrepancy between the mentioned results: the cutting speed and tool diameter. In our experiments, tool rotational speed was 10,778 rpm while in the experiments described by Rahman *et al.* (2002), tool rotational speed was 1,990 rpm. The higher rotation used in the our experiments hamper the mist penetration at the cutting edge due to the air flux generated by tool rotational speeds. Thus, at higher tool rotational speeds, the lubrication efficiency with MQL technique is decreased and the ability of the fluid to reduce tool-chip friction and adhesion on cutting edge is minimized.

Liao and Lin (2007) also described that MQL application is inappropriate in the extreme high-speed cutting conditions, independently of its effect on tool's lifetime. After tested cutting speeds in the interval of 200 to 500 m/min, these authors suggest that there is an optimal cutting speed for MQL application. As a result, a cutting speed around 300 m/min led to a larger tool's lifetime extension when compared to dry cutting. The phenomena which led to these results will be discussed later in tool wear mechanism subject. However, several aspects need to be considered to extrapolate these results to other machining conditions.

Nevertheless, a difficult point for the operational viability of the MQL technique is the environment contamination. The mist formed by its application, even with a low flow rate (12 ml/h), was sufficient to difficult the tool wear and roughness inspection during the experiments. At each time of the experiment interruption for process analysis, the machine door needed to remain open for some minutes in order the mist could be dissipated from the machine environment. The MQL application in industrial environment, mainly when used in multiples machines, requires the installation of an exhaustion system. Also, at long term, the health of machine operators needs to be considered.

3.2. Tool wear

Figure 4 shows images of the worn tool at the end of tool life (taken in a SEM) used in the experiment with MQL technique and vegetable-based integral oil.

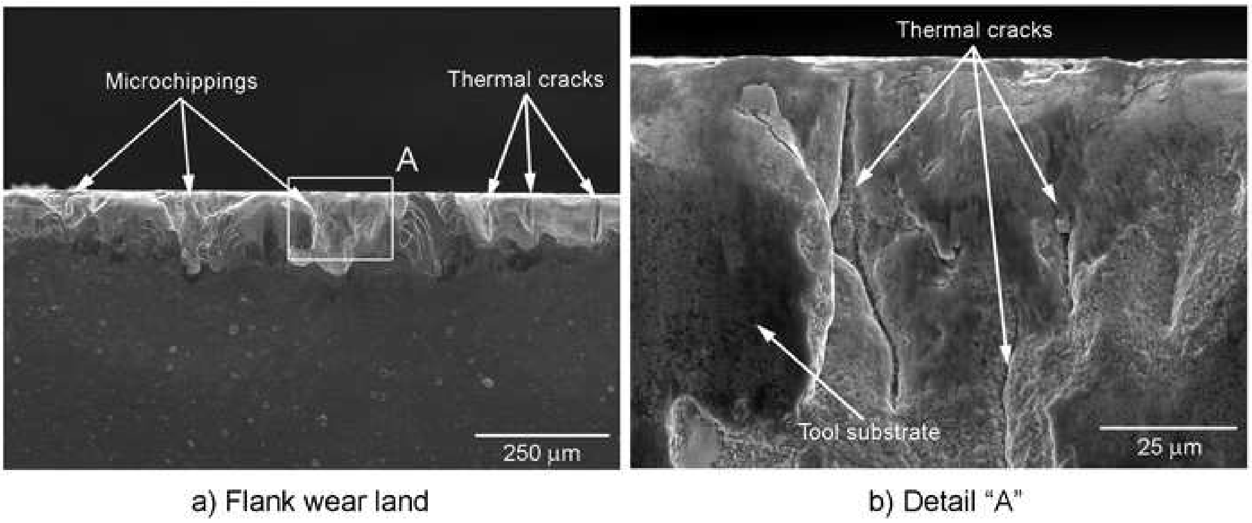


Figure 4. Flank wear land at the end of tool life (MQL technique and vegetable-based integral oil)

"Figure 4a" indicates that the main wear mechanisms in this tool was microchipping of the cutting edge (chipping size smaller than the maximum flank wear) and, also, the presence of cracks perpendicular to cutting edge. "Figure 4b" is the magnified detail "A" (microchipping region) shown in "Fig. 4a". As can be seen in "Fig. 4b", the tool substrate is exposed and several cracks took place at the bottom of the microchipping.

Cracks perpendicular to cutting edge and that spread both on rake and flank face of the tool are described as thermal cracks. In milling operations, thermal cracks are caused by alternating thermal expansion and contraction of the surface layers of the tool, which are heated during the cutting, and cooled by conduction into the body of the tool during the intervals between cuts in each tool revolution. The cracks are usually initiated at the hottest position on the rake face, some distance from the cutting edge, and then, spread across the edge and down the flank. If cracks become very numerous, they may join and cause small fragments of the tool edge to break away (Trent and Wright, 2000). The loss of small fragments (microchippings) on cutting edge together with the presence of thermal cracks on the cutting edge suggested the occurrence of the described phenomenon.

Figure 5 shows images of the worn tool at the end of tool life used with MQL technique and vegetable-based integral oil with teflon as an additive in its composition.

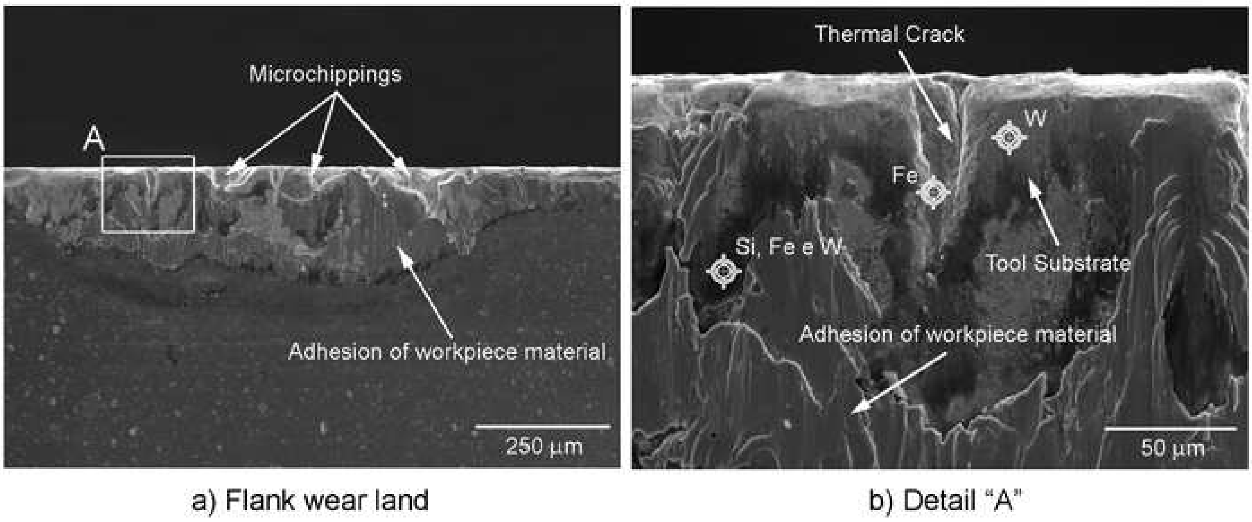
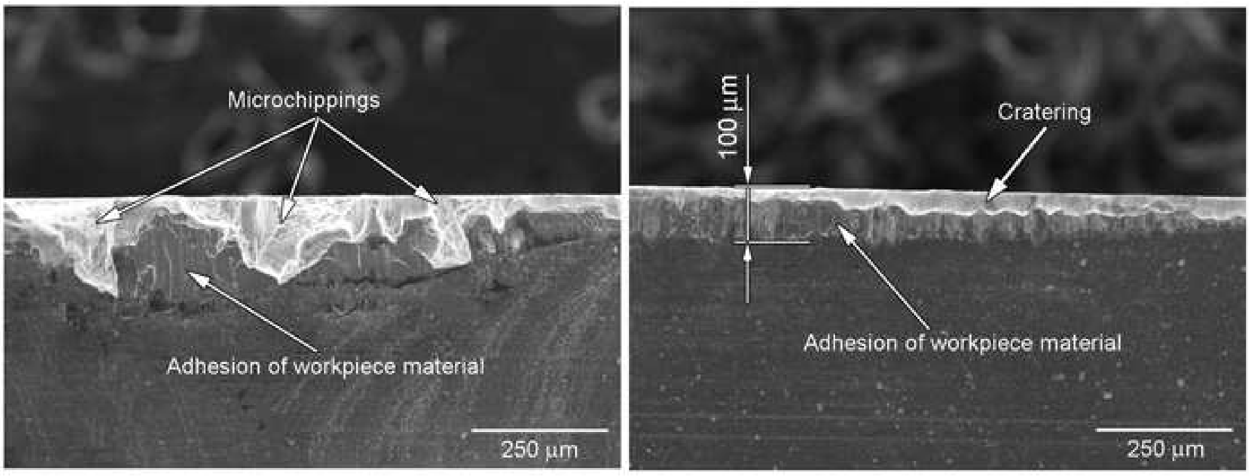


Figure 5. Flank wear land at the end of tool life (MQL technique and vegetable-based integral oil with teflon additive)

According to "Fig. 5a", the flank face is again characterized by microchipping and adhesion of workpiece material in the wear land. "Figure 5b" is magnified the detail "A" (notch wear) shown in "Fig. 5a". In "Fig. 5b", with support of EDS analysis, it can be identified high content of tungsten (W) and iron (Fe), which demonstrated that the coating was removed and tool substrate is exposed. Tool substrate (WC-Co) has a strong chemical affinity with the elements of the workpiece material (mainly, Si and Fe), which can be evidenced by others EDS analysis. However, an interesting point in "Fig. 5b" is that, in the bottom of the notch, there is a crack. Again, it is suggested the occurrence of thermal cracks. Moreover, the main hypothesis to explain the microchippings in "Fig. 5a" is the interaction of thermal and mechanical cracks, which promote the detachment of superficial material of cutting edge. This phenomenon is known as a "spalling" (Machado and Silva, 2004).

There is no significant difference between tool wear mechanisms using MQL technique with vegetable-based integral oil and integral oil with teflon as an additive. Furthermore, the tool wear mechanism using MQL technique promoted the appearance of thermal cracks on the cutting edge, which together mechanical cracks, caused microchippings on cutting edge. As mentioned earlier, Liao and Lin (2007) found out that MQL can provide extra oxygen to promote the formation of a protective oxide layer between chip and tool on the rake face. This layer is basically quaternary compound oxides of Fe, Mn, Si, and Al, and it is proved it acts as diffusion barriers effectively. Hence, the strength and wear resistance of a cutting tool can be retained which leads to a significant improvement of tool life. These authors stated that there is an optimal cutting speed at which a stable protective oxide layer can be formed. When cutting speed is lower than this speed, there is less oxide layer and the improvement of tool life is less apparent. As the cutting speed is far beyond the optimal value, the protective layer is absent and the thermal cracks are apt to occur at the cutting edge due to large fluctuation of temperature. Resultantly, application of MQL is inappropriate in the extreme high-speed cutting condition irrespective of its little increase in tool life. The tool wear mechanisms, identified in "Fig. 4 and 5", lead to an inference that cutting speed in these experiments was at a level above an optimal cutting speed at which a stable protective oxide layer on cutting edge could be formed.

Figure 6 shows images of the worn tool used in dry cutting at the end of tool life (60 min of cutting) and 40 minutes of cutting time.



a) Flank wear land at the end of tool life b) Flank wear land at 40 min of cutting time

Figure 6. Flank wear land at the: a) end of tool life and b) 40 min of cutting time (both with dry cutting)

According to "Fig. 6a", the presence of microchippings and adhesion of workpiece material on the cutting edge also took place in tools used with dry cutting. However, there were no identifications of thermal cracks (cracks perpendicular to cutting edge) with dry cutting as in case of MQL application. Moreover, a major difference of microchipping with dry cutting when compared to those occurred with MQL application is that, with dry cutting, the entire cutting edge is damaged. As can be seen in "Fig. 4a and 5a", with MQL application, just restrict microchippings are found out on cutting edges of the tools.

Based on this evidence and to gain a better understanding of tool wear progression throughout the tool's lifetime, one experiment with dry cutting were interrupted at 40-min of lifetime and the cutting edge was examined also by SEM. This analysis is showed in "Fig. 6b". According to "Fig. 3", 40 minutes of cutting time is the average lifetime for tools used with MQL application, and with dry cutting in that moment (see "Fig. 6b"), flank wear (VB_B) was only 0.10 mm. But the most important aspect in "Fig. 6b" is cratering wear. The occurrence of diffusion phenomenon in an operation where the tool/workpiece contact in each engagement was so short (the angle of contact between cutting edge and workpiece in each revolution was 22º43' and the contact time 0.351 ms) is not expected for a high-speed milling operation. But in opposition to the initial expectation, at 40 minutes of cutting time with dry cutting, crater was formed on the cutting edge. Therefore, an explanation for the microchipping when used dry cutting is different of the spalling phenomenon when MQL technique was used. Here, the growth of crater size weakened the cutting edge, and together with impact frequency of high-speed cutting, promoted the microchippings on cutting edge. The different phenomena that determined the end of tool life is the reason why the average lifetime with dry cutting is superior to MQL technique in the experimental conditions used.

3.3. Roughness of the workpiece

Figure 7 shows the average workpiece roughness values (Ra) obtained in the experiments perpendicularly and parallel to the feed direction. One point of this graphic is an average of all roughness values measured throughout tool life in that cutting condition. The dispersion showed at each point indicates the variation of roughness along tool life.

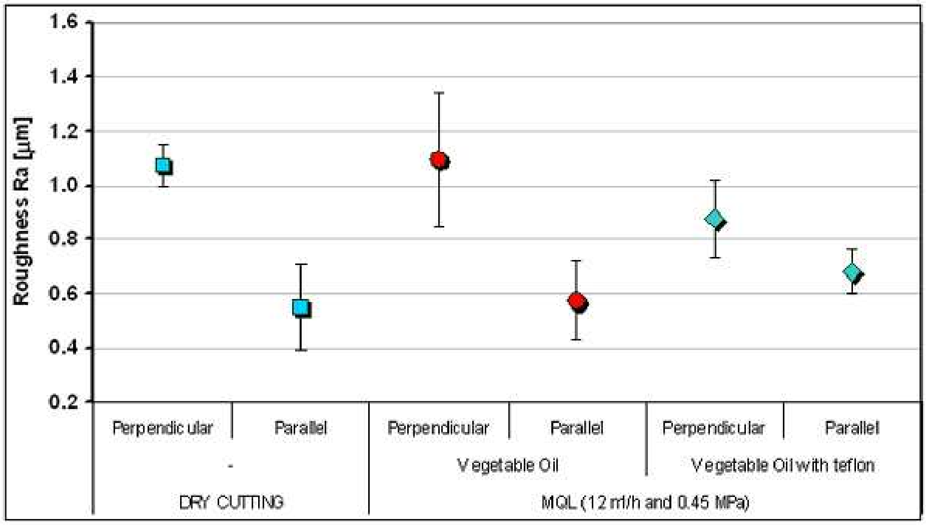


Figure 7. Workpiece roughness values (Ra) obtained in the experiments

Vivancos *et al.* (2004) affirm that models to predict theoretical surface roughness in high-speed machining are limited because the real values of the roughness present great differences in relation to the theoretical ones. This fact occurs as a consequence of the movement errors, edge building-ups and changes in the tool profile due to wear. In the same way, there are also some other influential factors such as: chattering, deflections in the tool, machining strategies, CNC parameters, the CAM system used, being difficult to model all these effects. According to “Fig. 7”, there was no significant variation between the roughness values considering tool life in each cooling/lubrication condition. Therefore, the MQL technique application did not cause a qualitative difference in roughness results when compared to dry cutting.

Another point is the comparison between the values in directions parallel and perpendicular to the feed direction. Also it can be seen in “Fig. 7”, that in all cases, roughness in direction perpendicular to the feed direction has higher values than in parallel direction during tool’s lifetime. As described before, roughness is influenced by several factors and a comparison of cutting parameters (in perpendicular and parallel direction) does not provide a conclusive analysis. But, this set of values promote substantive information to the users define cutting parameters (for example, f_z, a_e and a_p) and estimate roughness values. The reason for these higher values is related to the fact that the roughness is measured on a surface with an inclination of 45º to the parameter a_p (which is the main parameter responsible for the roughness perpendicular to the feed direction). As the parameter a_p was 0.25 mm, the pick distance on an inclined surface was 0.35 mm, while the parameter f_z (responsible for the roughness in the feed direction) was 0.25 mm.

An example of how the sources of variability may affect roughness profile in direction parallel to the feed is demonstrated in “Fig. 8”. This roughness profile was obtained with dry cutting and 5-min of cutting time.

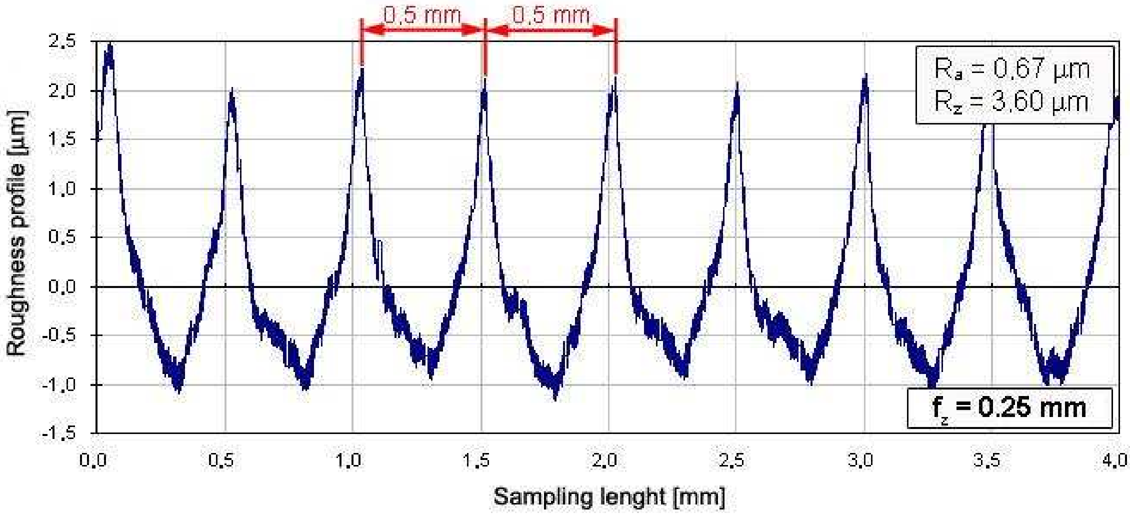


Figure 8 – Roughness profile in direction parallel to feed direction (dry cutting and 5-min of cutting time).

The analysis was realized with 5-min of cutting time because the tool wear is short and has small effect in roughness profile. The pick feed distance in parallel direction to the feed should be equal to the feed per tooth (0.25 mm). However, as can be seen in “Fig. 8”, the pick feed distance is twice this value (0.50 mm). This fact suggests that, mainly in the beginning of tool life, roughness profile was formed only by a cutting edge in each tool rotation. This is evidence that factors as tool runout, chatter and deflections in the tool strongly affect roughness values. According to Schmitz *et al.* (2006), these sources of variability in roughness profile are a common difficulty when using multiple cutting edges tools in milling. The main effects are premature failure in a cutting edge because of higher cutting force variation and increase of roughness values of machined surface. Therefore, in the case of dry cutting, the microchippings also may have been motive by higher cutting force variation and reduced tool’s lifetime.

4. CONCLUSIONS

Based on the results for application of MQL technique in high-speed milling of AISI H13 hardened steel with coated carbide inserts obtained in this work, it can be concluded that:

1- Dry cutting promoted longer tool’s lifetime when compared to MQL technique;

2- The application of MQL technique promoted the appearance and spread of the thermal cracks on cutting edge. These thermal cracks promoted a fast microchippings appearance on cutting edge when compared to dry cutting;

3- There is no substantive difference of roughness values using dry cutting and MQL technique;

4- A wide quantity of sources of variability affects roughness profile and hampers the development of theoretical models.

5. ACKNOWLEDGEMENTS

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