# Toroidal Milling of Hardened SAE H13 Steel

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*It is estimated that around 65% of the cost of a die or mould is related to the machining processes. Moreover, the literature says that 70% of the time spent in the machining processes of this kind of parts is used in finishing and semi-finishing operations. The high complexity of the machined surfaces makes mandatory the use of ball nose tools, with large overhang, what increases vibration in the process. These problems have to be minimized, since dies and moulds demand a very good surface finish and tight dimensional tolerances. A frequently used strategy to attenuate these problems is to carry out semi-finishing operations with cutters containing circular inserts, because these inserts produce smooth transitions among the passes and a smaller and more uniform stock material for the finishing operation. The main goal of this work is to evaluate the performance of rounded inserts of carbide and cermet in the semi-finishing milling (called toroidal milling) of H13 steel with hardness of 50 HRc. The influence of radial depth of cut, cutting speed and feed per tooth on tool life will also be considered. It also intends to test the feasibility of using minimum quantity of lubricant (MQL) technique instead of dry cutting in this kind of machining operation.*

***Keywords**: Milling of dies and moulds, cermet, carbide, minimum quantity of lubricant*

## Introduction

Once the manufacturing batch of a die or mould is frequently unitary, all the production costs are attributed to a single product. According to Sandvik Coromant (1999), among the costs of a die, around 20% are attributed to the raw material, 10% to the assembly, 5% to the heat treatment and 65% of the costs are attributed to the machining processes. Therefore, the optimization of machining operations is fundamental when low production costs of dies and moulds are aimed.

The most common machining operation to achieve the necessary finishing in dies and moulds is still the electro discharge machining (EDM), due to the high hardness of the material when the finishing operation is carried out. However, this is a very time consuming and expensive operation. Lately, milling has been used to replace EDM, due to the development of tool materials capable of milling hardened materials and due to the development of rigid machine tools with a high degree of accuracy, even in high spindle rotations. These new tool materials present very high hot hardness and wear resistance.

Among the total machining time of a die production process, around 70% is used in finishing and semi-finishing operations (Silva et al, 2001). The high degree of complexity of the machined surfaces demands that the finishing milling operations be carried out using ball nose tools with long overhang, which makes vibration a serious problem to the process. This problem must be minimized, since dies and moulds demand excellent surface finish and tight dimensional tolerances. An usual strategy to attenuate the problems which occur in finishing operations is to carry out the semi finishing operations with round insert cutters (called toroidal cutter), because this kind of inserts produces a surface with smooth transitions among the cutter passes, and a smaller and more uniform stock material for the final finishing operation (Sandvik Coromant, 1999).

The main goal of this work is to evaluate the performance of round inserts of carbide and cermet in the semi-finishing milling of H13 steel with 50 HRc hardness. The cutting parameters used in the experiments were placed in a range between conventional and high speed cutting (HSC) operations, producing a high volume of chip per minute and a good workpiece surface finish. According to Aspinwall et. all (2000) in a HSC operation, spindle rotation and feed velocity have to be very high and radial and axial depth of cut small. In this work, the spindle rotation was around 10000 RPM and feed velocity around 3000 mm/min. The other goals were to compare the use of dry cutting with minimum quantity of lubricant (MQL) and also to verify the influence of cutting parameters (radial depth of cut, cutting speed and feed per tooth) on tool life.

## Experimental Procedures

The experiments were carried out in semi finishing milling operations. The tool used was a toroidal end mill with 12 mm diameter and two round inserts of 7 mm diameter each (R300-0720-EPM - Sandvik Coromant). The workpiece material was the quenched and tempered SAE H13 steel with average hardness of 50 HRc, with the dimensions shown on fig. 1.

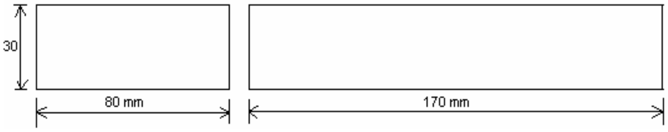

**Figure 1. Dimensions of the workpieces used in the experiments.**

In a first phase of the experiments, three tool materials were tested using the same cutting conditions: cutting speed - $v_c$= 300 m/min, feed per tooth - $f_z$ = 0,13mm, radial depth of cut - $a_e$= 1 mm and axial depth of cut - $a_p$= 1 mm.

The tool materials tested in this phase were: an uncoated cermet H10 class (Sandvik CT 530 – recommended for light milling operations, where high wear resistance is necessary) and two classes of carbide: coated ISO P40 class (Sandvik GC4040 – recommended for operations where toughness is necessary) and coated H15 class (Sandvik GC1025 – recommended for light milling, where high wear resistance is needed) (Sandvik, 2001). The GC 4040 carbide is MTCVD coated with three coating layers: TiN + TiCN + $Al_2O_3$. Its grain size is, on average, 5 μm, and presents very high toughness. The coating hardness is around 2500 HV3 and the substrate hardness is 1250 HV3. The GC 1025 carbide is a PVD coated with TiCN. The coating hardness is around 3000 HV3 and the substrate hardness is 1650 HV3. Its grain size is smaller than 1 μm. The

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uncoated CT 530 Cermet presents an average hardness of 1490 HV3.

The end of tool life was considered when flank tool wear reached $VB_{máx}$= 0.3 mm. The electrical power consumed was real time monitored through the measurement of the electrical current of the main motor of the machine tool. Each time a layer of 1 mm was removed, hardness of the workpiece was measured in order to check whether it was still close to the initial hardness (50 HRc). Each experiment was carried out three times. In this phase, all the experiments were made without cutting fluid and down milling was used.

After having proved that the Cermet tool had presented the best performance among all the tools tested, a second phase of the experiments was carried out aiming to understand the influence of the cutting conditions on the tool life. In order to reach this goal, a full factorial experimental design was built ($2^3$) with three input variables each in two levels. The input variables were: cutting speed ($v_c$), feed per tooth ($f_z$) and radial depth of cut ($a_e$). Again, dry cutting and down milling were used, with the axial depth of cut ($a_p$) equal to 1 mm.

Table 1 shows the cutting conditions used in this second phase of experiments.

The third phase of experiments had the goal to verify the feasibility of using the minimum quantity of lubricant (MQL) technique instead of completely dry operation. Aiming this goal, experiments were carried out using a 15 ml/hour flow of lubricant oil in a flow of compressed air (4.5 bar). Two different oils were tested: the Macron A (from Shell) and the GSC772 (from AGELUBE). The equipment that performed the pulverization of the oil in the air was the Magi-Cut (Mist coolant equipament) from Fuso Seiko, model OS-21 AT 40. Each experiment was also carried out three times.

All the milling experiments were carried out in a MORI-SEIKI vertical machining center, model SV -40, with maximum tool rotation of 12,000 RPM and 22 kW of power in the main motor. To hold the tool in the spindle a hydraulic tool holder was used with 700 bar of pressure. The tool overhang was 70 mm.

Tool wear was frequently observed and photographed during the experiments using an optical microscope with 50 times magnification, connected to a high resolution video camera which was connected to a PC computer. All the image data collected in the computer were analyzed by an image processing software (GLOBAL LAB). After the experiment, the tool was photographed in a Scanning Electronic Microscope.

**Table 1. Cutting conditions used in the second phase experiments.**

| Experiment | $v_c$ (m/min) | $f_z$ (mm/tooth) | $a_e$ (mm) | $v_c$ | $a_e$ | $f_z$ |
|---|---|---|---|---|---|---|
| 1 | 250 | 0.13 | 1 | -1 | -1 | -1 |
| 2 | 300 | 0.13 | 1 | 1 | -1 | -1 |
| 3 | 250 | 0.16 | 1 | -1 | 1 | -1 |
| 4 | 300 | 0.16 | 1 | 1 | 1 | -1 |
| 5 | 250 | 0.13 | 2 | -1 | -1 | 1 |
| 6 | 300 | 0.13 | 2 | 1 | -1 | 1 |
| 7 | 250 | 0.16 | 2 | -1 | 1 | 1 |
| 8 | 300 | 0.16 | 2 | 1 | 1 | 1 |
| 9 | 250 | 0.13 | 1 | -1 | -1 | -1 |
| 10 | 300 | 0.13 | 1 | 1 | -1 | -1 |
| 11 | 250 | 0.16 | 1 | -1 | 1 | -1 |
| 12 | 300 | 0.16 | 1 | 1 | 1 | -1 |
| 13 | 250 | 0.13 | 2 | -1 | -1 | 1 |
| 14 | 300 | 0.13 | 2 | 1 | -1 | 1 |
| 15 | 250 | 0.16 | 2 | -1 | 1 | 1 |
| 16 | 300 | 0.16 | 2 | 1 | 1 | 1 |

## Results and Discussions

### Results of the First Phase of the Experiments

Figure 2 shows the volume of chip removed per tool life obtained for the three tool materials tested. It can be seen in this figure that the CT530 cermet present the longest tool life, followed by the GC 1025 carbide and, at last, by the GC 4040 carbide. The cermet tool life is 250% longer than the GC4040 carbide and 75% longer than the GC1025 carbide.

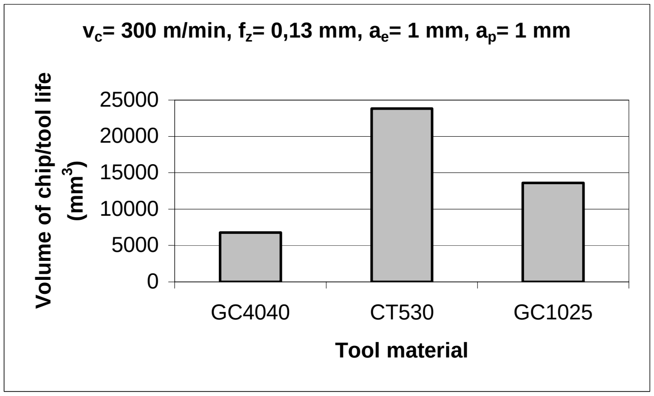
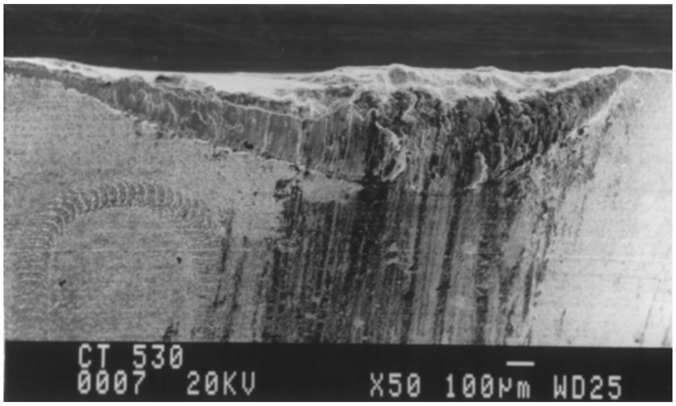


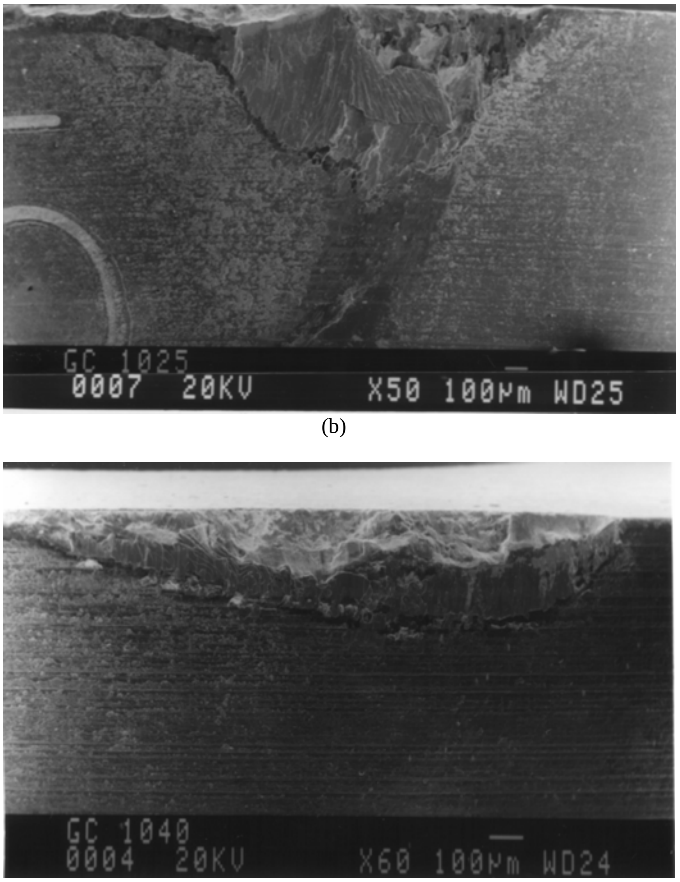
**Figure 2. Volume of chip removed per tool life for each tool material tested.**

These results prove that neither wear resistance, nor toughness are the most important properties to withstand this kind of operation. The coated tool materials used in this experiment, even with the high hardness of their coatings, presented a lower performance in terms of tool life than the uncoated tool (cermet CT530). The high toughness of the GC 4040 carbide did not present better tool life than the other tool materials. To try to understand the reasons for this occurrence, pictures of fig. 3 were taken.



(a)

**Figure 3. Pictures of the cutting edges in the end of tool lives – a) cermet CT530, b) carbide GC1025, c) carbide GC4040 ($v_c$ = 300 m/min, $f_z$ = 0.13 mm/tooth, $a_e$ = 1 mm, $a_p$ = 1 mm.).**



(b)

(c)

**Figure 3. (Continued).**

It can be seen in this figure that all tools presented mainly flank wear due to the high hardness of the workpiece material. Crater wear was also found very close to the cutting edge. What is interesting to note is that the carbide inserts presented some chipping at the cutting edge when flank wear was close to its maximum value and the cermet insert, which is not as tough as the GC4040 did not present any chipping. The edges of the two carbide inserts used seem to be destroyed by the junction of flank and crater wear. Another fact that has to be analyzed is the edge rounding. As the cermet tools used in this work was not coated, their edges could be sharper than the coated carbide inserts. Moreover, as the coating thickness of the GC4040 carbide is higher than the thickness of the GC1025 carbide and it is made of CVD coating, its edge radius is higher than the GC1025 insert.

In this kind of operation, chip thickness is very small, due to the small values of radial depth of cut ($a_e$) and feed per tooth ($f_z$) and the use of round inserts, which makes chip thickness close to zero when the cut is performed close to the center of the tool. Therefore, the chip is formed very close to the cutting edge. Thus, most of the chip was formed in the rounded part of the carbide coated edges and pressed the coatings of that region too much, which did not resist and collapsed, presenting the irregular wear formation shown in fig. 3. On the other hand, the cermet wear presented a more regular formation than the other materials. Therefore, it seems that the most important property of the tool for this kind of operation is the edge radius. The smaller the edge radius (or the sharper the tool), the longer the tool life, regardless of their hardness, wear resistance and toughness. The most sharpened tool presented the longest tool life and the tool which presented the greatest edge radius presented the shortest tool life, regardless their hardness and toughness.

Figure 4 shows the behavior of consumed cutting power along the tool lives in the the first phase of the experiments. It can be seen that cutting power remains almost constant along the tool lives. After the flank wear reached $VB_{max}$ = 0.3 mm, a slight increase of cutting power occurs. Therefore, small values of flank wear did not increase cutting force in a way to make the cutting power to change. The low values obtained are caused by the low values of radial and axial depth of cut and also low value of feed per tooth used in this semi finishing operation. It also can be seen in this figure that there is no influence of tool material in the cutting power. Therefore, the low friction coefficient of the coating materials like TiN and TiCN used in the GC4040 and GC1025 carbides was not able to make cutting force lower than that obtained using the uncoated CT530 cermet.

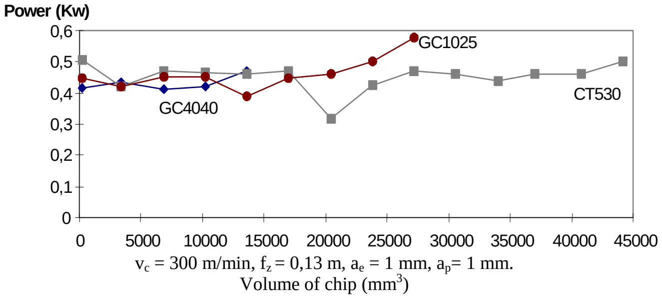


**Figure 4. Cutting power along the tool lives.**

All the chips produced with both, cermet and carbide tools presented a dark blue color, indicating the great amount of heat generated in the process and the great friction between chip and tool. Even with low values of feed per tooth and radial and axial depth of cut, the high value of cutting speed used made the heat generation very large. It is important to say that the cutting speed selected made necessary the use of a high spindle rotation (10,000 RPM) and, consequently, a high feed velocity (3,000 mm/min). These conditions can be considered close to the ones regularly called high speed cutting (HSC), which join high spindle rotation and feed velocity with low radial and axial depth of cut (Aspinwall et al, 2000).

### Results of the Second Phase of the Experiments

Once proved that the cermet CT530 presented the longest tool life among the tool materials tested, the next step had the intention of evaluating the influence of the cutting parameters on the cermet tool life. A full factorial experimental design was built, having as input variables the cutting speed, the radial depth of cut and the feed per tooth. Figures 5 and 6 show the behavior of the tool lives with the cutting speed variation. As it was already expected, an increase of cutting speed increased tool wear and strongly decreased tool lives. A higher cutting speed generates a larger amount of heat and, consequently, a higher temperature on the cutting edge. Higher temperatures, besides of causing softening of the cutting edge also make the oxidation process of the cutting edge easier to occur (Nelson et al 1998). The dark blue color of the chip indicates that a high amount of heat was generated in this hardened steel milling process. It was also observed that the influence of the cutting speed on the tool life was higher when the highest radial depth of cut ($a_e$) was used. In fig. 5 it can be seen that, for a radial depth of cut $a_e$ = 1 mm, tool life decreased around 35% for a 20% increase of cutting speed. In fig. 6, for $a_e$ = 2 mm, the reduction of tool life reached 55% for the same increase of cutting speed. As radial depth of cut increases, the contact length between tool and workpiece in each tool revolution also increases. Therefore, the tool remains longer inside the workpiece in its heating process, and a shorter period outside the workpiece, in its cooling process (Deonísio et al 2001), making the use of a higher cutting speed and, consequently, a higher heat generation, more deleterious to the tool.

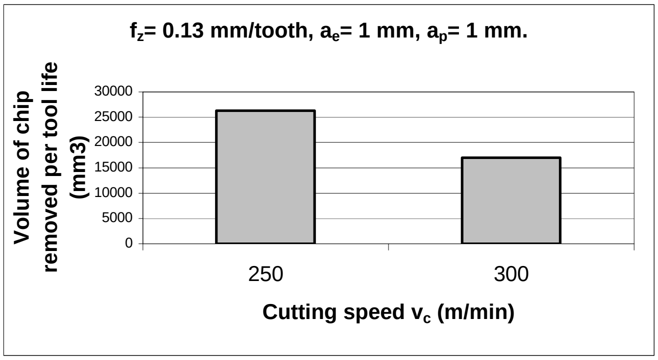


**Figure 5. Tool lives (in volume of chip removed) against cutting speed for $a_e$= 1 mm.**

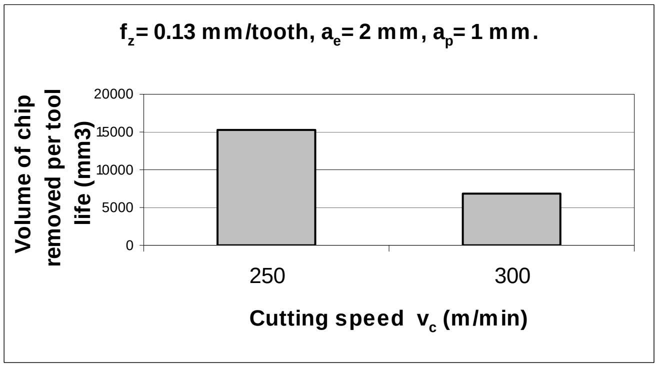


**Figure 6. Tool lives (in volume of chip removed) against cutting speed for $a_e$= 2 mm.**

Figures 7 and 8 show the influence of radial depth of cut ($a_e$) on tool lives. It can be seen that an increasing in the $a_e$ makes the tool life to decrease. When cutting speed was 250 m/min and the radial depth of cut was increased from 1 to 2 mm, tool life in volume of chip removed decreased around 40%. When cutting speed was 300 m/min, this reduction reached 60 %. As already cited, when radial depth of cut increases, the contact length between cutting edge and workpiece in each revolution also increases, making the tool temperature higher and, consequently, decreasing tool life. However, comparing figs. 5 and 6 with 7 and 8, it can be seen that the influence of the $v_c$ on tool life was much stronger than the influence of $a_e$. In figs. 5 and 6, a 20% increase of $v_c$ caused a 35 to 55% decrease in the tool life, while in figs. 7 and 8, a 100% increase of $a_e$, caused about the same decrease in the tool life. This stronger influence of cutting speed on the tool life was also found in the analysis of variance (ANOVA) carried out.

The figures showing the feed per tooth influence on tool life will not be shown because this influence was very small. When feed per tooth increases, the volume of chip removed per unit of time also increases and, consequently, the heat generation grows. But the area on the tool to receive this heat increases in the same proportion and, so the tool temperature does not increase too much. This fact explains the small influence of feed per tooth on the tool life.

Therefore, the sequence of influence of the input variables experimented in this work on tool life is: first, the variable which influenced the most tool life is cutting speed, followed by the radial depth of cut and, lastly the feed per tooth.

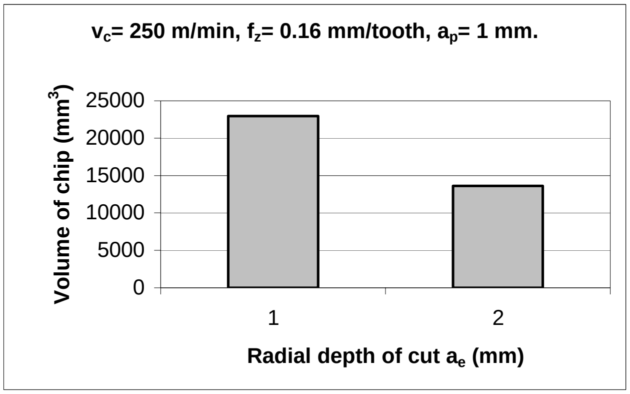


**Figure 7. Volume of chip removed per tool life against radial depth of cut for $v_c$= 250 m/min.**

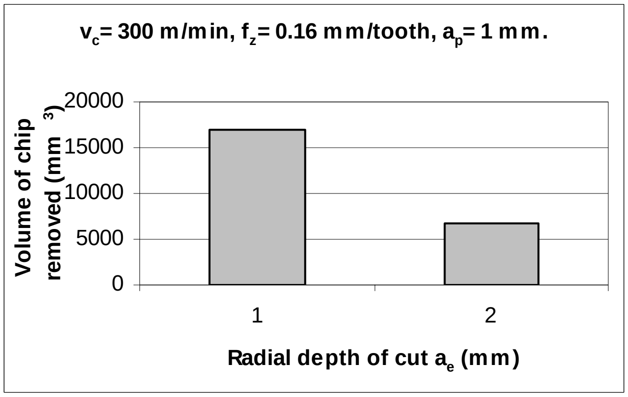


**Figure 8. Volume of chip removed per tool life against radial depth of cut for $v_c$= 300 m/min.**

## Results of the Third Phase – Experiments With Minimum Quantity of Lubricant (MQL)

During the process of metal cutting, due to the relative movement between tool and workpiece and the consequent chip formation, severe friction conditions between tool – workpiece – chip show up, which make the heat generation in the cutting zone very strong. The main purpouses of using a cutting fluid are to remove the excessive heat from the cutting zone and to decrease the friction between tool and workpiece and between tool and chip, aiming to increase tool life and to improve workpiece surface finish. However, the use of a large amount of cutting fluid brings inconvenientes to the process, such as problems with the recycling of the fluid and with the health of the machine tool operators. The use of minimum quantity of lubricant (MQL) technique, where a very small amount of oil is pulverized in a flow of compressed air, is one attempt to minimize these problems without harming tool life and workpiece surface roughness (Rahman, et al, 2000).

Besides, on milling operations, the use of cutting fluid is not recommended because it increases the temperature variation already present in the process, which generates thermal cracks on the cutting edge and, consequently, decreases tool life (De Melo et al, 2000). Therefore, most of the milling process are dry operations.

Thus, because the effect of MQL on the process is mainly lubrication and it presents a very small cooling ability to the tool (Braga et al., 2003), it will not cause thermal cracks generation and will not have the bad influences of cutting fluid on the environment and on to the human health. Therefore, in this work, besides the dry cutting experiments, MQL was also tried in order to verify its influence on the tool life and on the workpiece surface finish. Figure 9 shows that the use of MQL did not influence tool life. The same volume of chip per tool life was reached in both, dry cutting and MQL experiments. Moreover, there was no difference of tool life between the use of GSC 792 AGELUBE (oil 1) and MACRO A SHELL (oil 2) oils. The failure of the MQL to increase tool life might be caused by the high spindle revolution and the great amount of heat generated in the process, which may have hindered the air-oil mist to enter into the cutting area. According to Rahman et al (2000), it is difficult for the fluid to reach the tool-workpiece and tool-chip contact areas because both the heat generated is strong enough to evaporate the oil before it reaches them and part of the fluid is removed by the chip generated. In addition, the high spindle revolution creates an air turbulence surrounding the tool that deviates the air-oil flow from the cutting zone.

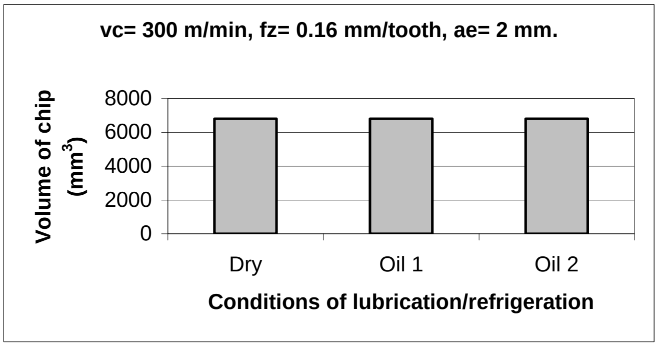


Figure 9. Volume of chip removed per tool life for MQL and dry cuts.

Figure 10 presents the average surface roughness (Ra) behavior as the volume of chip removed increased for dry and MQL cutting. The Ra values remained around 0.8 μm, what can be considered a good level for a semi finishing operation. This Ra value shows that the radial depth of cut, feed per tooth and tool overhang used in this work are suitable for reaching surface roughness values good enough to obtain a kind of surface that could be easily improved in the finishing operations. It can also be seen in this figure that there was no significant variation between roughness values of dry and MQL cutting. In addition, in all conditions experimented a slight decrease of surface roughness occurred along tool life. According to Fallbohmer el al (1996), the cutting with a tool with a certain wear sometimes generates a better workpiece roughness than a fresh tool, because roughness is a reproduction of the tool nose profile on the workpiece surface. Sometimes, due to the changing of the cutting edge radius, tools with a given level of wear ($VB_{max}$<0,3 mm) can have a smoother topography than fresh tools.

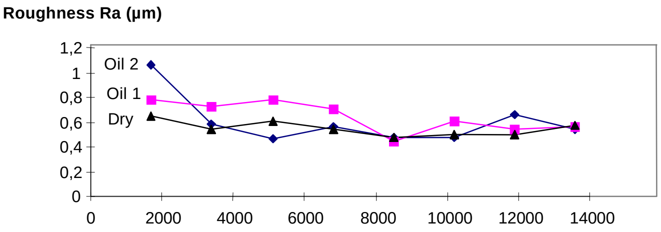


Figure 10. Surface Roughness against volume of chip removed for the three lubrication/refrigeration conditions tested.

No chip changing of thickness, color and shape was observed when MQL was used. The chip remained with a dark blue color what is another proof that the MQL was not able to lubricate the cutting zone and, therefore, it failed to decrease heat generation. The kind of tool wear also did not present any substantial alteration when MQL was used.

## Conclusions

Based on the results obtained in this work, the following conclusions can be taken:

- Cermet generated the longest tool life among all the tools tested. It presented a regular flank wear, while the carbide tools presented chippings and flank wear on the cutting edge.
- The most important aspect of the tool for this kind of operation is the edge radius. The smaller the edge radius (or the sharper the tool) the longer the tool life, regardless their hardness, wear resistance and toughness.
- Cutting power remained in relatively low values, once the experiments were carried out with cutting parameters typical for semi finishing operations.
- Among the cutting parameters experimented, cutting speed was the one which mostly influenced tool life, followed by radial depth of cut and, finally, by feed per tooth.
- The values of average surface roughness obtained were around 0.8 μm, what can be considered a good level for a semi finishing operation.
- Minimum quantity of lubricant did not present better results than dry cutting neither in terms of tool life nor in terms of workpiece surface roughness.

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