Int J Adv Manuf Technol (2010) 50:1125–1133
DOI 10.1007/s00170-010-2570-1

ORIGINAL ARTICLE

Evaluating the effect of coolant pressure and flow rate on tool wear and tool life in the steel turning operation

Anselmo Eduardo Diniz · Ricardo Micaroni · Amauri Hassui

Received: 11 September 2009 / Accepted: 4 February 2010 / Published online: 6 March 2010

Abstract High-pressure coolant (HPC) delivery is an emerging technology that delivers a high-pressure fluid to the tool and workpiece in machining processes. High fluid pressure allows for better penetration of the fluid into the cutting zone, enhancing the cooling effect, and decreasing tool wear through lubrication of the contact areas. The main objective of this work is to understand how tool wear mechanisms are influenced by fluid pressure under different cutting speeds in the finish turning of AISI 1045 steel using coated carbide tools. The main finding was that the use of a lower cutting speed (v_c=490 m/min) in dry cutting resulted in tool life close to that obtained with cutting fluid, but when the cutting speed was increased (v_c=570 m/min), the high-pressure coolant was effective in prolonging the life of the cutting tool. It was also concluded that, regardless of the cutting speed and cooling/lubrication system, the wear mechanisms were the same, namely abrasion and attrition.

Keywords Tool wear · Tool life · Cutting fluid · High-pressure fluid

Nomenclature

V_{BMAX}	maximum flank wear (mm)
V	volume of chip removed per tool life (cm^3)
a_p	depth of cut (mm)
f	feed (mm/rev)
v_c	cutting speed (m/min)
T	tool life (min)
HPC	High pressure coolant
CNC	Computerized numerical control

Abbreviations

HPHFR	High pressure high flow rate
HPLFR	High pressure low flow rate
SEM	Scanning electron microscope
EDS	Energy dispersive X-ray spectroscopy

1 Introduction

The interaction among tool, chip, and workpiece usually causes tool wear as well as other types of damage [1]. The wear/damage mechanisms discussed in this paper are abrasion and attrition. All of them are directly influenced by temperature [2, 3]. It is worthy to mention that temperature, in machining, is directly related to the cutting speed [4].

In the process of abrasion, the hard second phase in a work material can be constrained by the matrix phase, rolled along the interface or even broken into pieces while abrading the flank face of the tool [5]. Both flank and crater wear may be generated by abrasion, but flank wear is more affected by abrasion, since the tool flank face rubs against a rigid element such as the workpiece, while the contact between tool rake face and chip involves sliding and seizure/adhesion [6]. The ability of the tool to resist abrasive wear is related to its hardness. The wear land caused by abrasion generally displays scratches parallel to the cutting direction [1].

Attrition wear usually occurs at low cutting speeds, when material flow on the tool rake face is irregular and

---

A. E. Diniz · R. Micaroni · A. Hassui (✉)
Department of Manufacturing Engineering,
Faculty of Mechanical Engineering,
State University of Campinas,
CP 6122,
13083-860 Campinas, SP, Brazil
e-mail: ahassui@fem.unicamp.br

A. E. Diniz
e-mail: anselmo@fem.unicamp.br

contact with the tool is less continuous. It can be described as a cyclical adhesion and removal of workpiece/chip material from the tool, which also causes removal of tool particles. Under these conditions, microscopic particles of the tool are pulled out and dragged together with the material flow. The irregular material flow necessary for attrition wear to occur is caused by the sliding zone between chip and tool, by interrupted cutting, irregular depth of cut, and vibration. Areas worn by attrition have a rough appearance [2, 7].

Wear mechanisms are strongly influenced by the effects of temperature, especially the thermally activated ones [8]. Thus, decreasing cutting temperature usually means increasing cutting tool life.

One way to reduce cutting zone temperatures is the use of cutting fluids. However, the advantages of using cutting fluids have been questioned lately due to their impact on product cost, environment, and human health. Dry cutting has been tried as a possible alternative to the use of fluid. It is feasible in some cutting processes due to the development of tool materials that are very resistant to high temperatures. Experiments were recently carried out to identify conditions under which tool life in dry cutting could approach that achieved in cutting with abundant low-pressure fluid. Several cutting conditions and tool materials were tried in rough and finish turning of AISI 1045 steel [9, 10]. The main conclusion of these works was that, in dry cutting, it is only possible to reach a tool life similar to that obtained under abundant fluid if the depth of cut is small (1 mm or less) and the carbide grade is such that the tool material is highly wear resistant. Since the use of fluid usually provides longer tool life than dry cutting, especially in turning, attempts have been made to increase its performance, e.g., by directing the fluid flow towards the contact regions and using high-pressure fluid. The goal is to apply the fluid as closely as possible to the workpiece tool and chip-tool interfaces in order to decrease the tool temperature in these regions. Pigott and Colwell [11] were the first authors to discuss the use of high-pressure cutting fluid in steel turning with high speed steel tools. They observed a significant increase in tool life when high-pressure fluid was used in comparison with the conventional method of applying low-pressure fluid at high flow rates. According to them, the conventional method does not produce good results because chips are cooled much more than the tool and workpiece. Moreover, the low velocity of penetration does not allow the lubricant to reach the cutting edge—a situation that favors the formation of built up edge.

Kaminski and Alvelid [12] stated that conventional methods of fluid application are not very effective because the low-pressure jet hinders penetration at the interfaces, increasing friction and, hence, raising the cutting zone temperature. In the turning process, higher pressure allows the amount of fluid injected to be reduced.

According to Trent [2], due to the normal high stress on the tool rake face during cutting, a seizure (or sticking) zone occurs at the chip-tool interface, where the chip velocity is zero and the actual contact area is equal to the apparent area. Because the chip velocity is zero in this region, a large amount of shearing takes place inside the chip just above this interface. Therefore, the heat generated in this region is very high. On the other hand, it is almost impossible for the fluid to penetrate between the chip and tool in this region and lubricate them, since there is no room for it because the tool and chip are in complete contact with each other. Machado and Walbank [13] said that high-pressure fluid is able to marginally decrease the size of this seizure zone, contributing somewhat to reduce the temperature in this region. Surrounding this region on the tool–chip contact area is another zone, called the sliding zone, where the contact is not so intense and penetration of the fluid is possible, mainly if it is directed towards this point under high pressure. Machado and Walbank [13] also stated that this sliding zone could be significantly reduced by the use of high-pressure fluid. When the fluid is directed towards the workpiece–tool interface in turning operations, it has to overcome the volume of air moved by the workpiece rotation. This hinders the penetration of the fluid, preventing it from reaching the interface. This problem is augmented as the cutting speed increases. Hence, when low-pressure fluid is aimed at this interface, its ability to prolong tool life decreases as cutting speed increases [9].

In a previous study, Machado and Wallbank [13] concluded that when high-pressure fluid was injected onto the rake face, the adhesion between chip and tool was strong, causing the removal of tool particles when the adhered chip material was removed from the tool by the chip flow, resulting in a greater crater wear. When fluid was not applied on the rake face, adhesion of chip material on the rake face also occurred, but it was insufficient to drag tool particles along with it as it was being removed from the rake face; hence, crater wear was minimal. That is why, in this study, high-pressure fluid was directed only towards the workpiece-tool flank face interface. Therefore, the present work aims to ascertain the behavior of coated cemented carbide cutting tools turning AISI 1045 steel using high-pressure cutting fluid directed towards the interface between workpiece and tool flank face at different cutting speeds.

2 Experimental procedures

The turning experiments were carried out on a computerized numerical control (CNC) lathe. The cutting fluid used was a vegetable oil-water emulsion with 6% oil concentration. The tests were performed on workpieces made of AISI 1045 steel

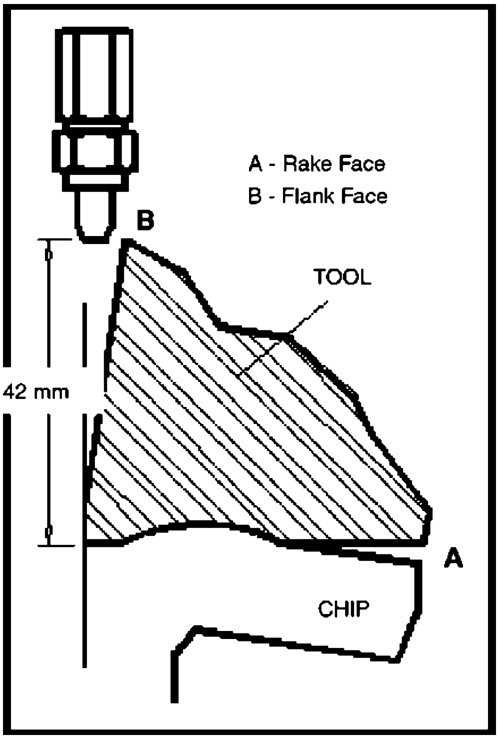


Fig. 1 Position of the cutting fluid hose

bars with an average hardness of 96 HR_B. Three types of experiments were carried out: high-pressure fluid (with high and low flow rate, herein called high pressure high flow rate (HPHFR) and high pressure low flow rate (HPLFR), respectively), dry cutting, and conventional fluid application (low pressure, high flow rate, no specific direction but with fluid falling mostly on the chip). In the latter cooling condition, fluid was applied under a pressure of 0.04 MPa and a flow rate of 9 l/min. The high-pressure fluid was directed towards the workpiece–tool interface (flank face). Figure 1 shows the position of the fluid hose when high-pressure fluid was applied.

The conventional fluid application was that usually employed in the type of CNC lathe used in the experiments.

Table 1 lists cutting conditions, flow rate, and fluid pressure applied in the experiments carried out under high-pressure fluid. The cutting speed, depth of cut, and feed rate listed in Table 1 were also used in the experiments involving both dry cutting and conventional application of fluid. Each experiment was carried out at least twice.

The tools used in the experiments were ISO code SNMG 120408-PF grade P15, with a triple layer coating of TiCN, Al_2O_3 and TiN. The geometry, grade, coating, and cutting conditions were suggested by the cutting tool supplier. It was also tried a cutting speed about 16% higher (570 m/min) than the recommended one to check the influence of this variable in the tests. Several times during the experiments, the tool was removed from the machine to measure its flank wear in an optical microscope. When the maximum flank wear (V_{Bmax}) reached 0.3 mm, the experiment was considered concluded and the tool was considered to have reached the end of its life. The parameter used in Fig. 2 to represent tool life was volume of chip removed per tool life, V (in cubic centimeter). This parameter, in turning, can be calculated by Eq. 1, where a_p is the depth of cut (in millimeter), f is the feed rate (in millimeter per revolution), v_c is the cutting speed (in meter/minute), and T is the tool life (in minute). The tool was then examined in a scanning electron microscope (SEM) with EDS for a detailed analysis of its wear.

$$V = a_p \cdot f \cdot v_c \cdot T \tag{1}$$

Cutting power was acquired through a signal from the CNC, which was proportional to the power consumed by the main motor (in a previous work Oliveira [14] proved the relation of this signal with cutting force). After that, this signal, which was acquired at a sampling rate of 100 Hz, was processed by an A/D Lab Pc^+ data acquisition board and analyzed using National Instruments LabView 8.0 software. In order to obtain the specific cutting energy, the value of cutting power was divided by depth of cut, feed and cutting speed.

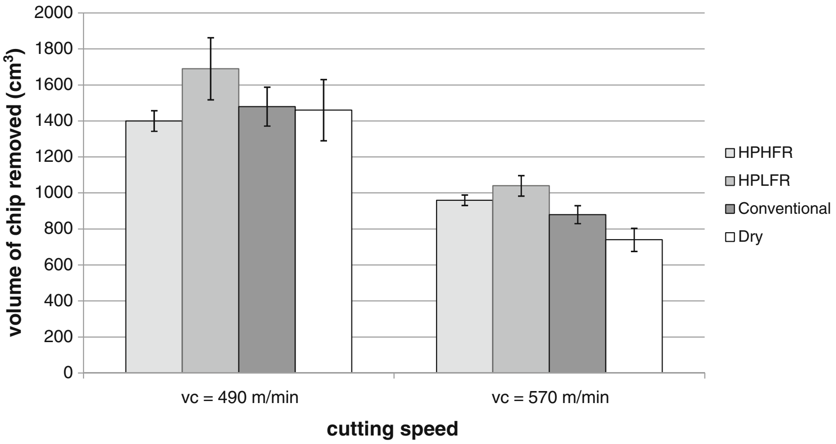
3 Results and discussion

Figure 2 shows the results of tool life, measured in volume of chip removed per tool life of all the experiments. It is worth to remain that each test condition was carried out three times. Therefore, in the figure, it is presented the

Table 1 Design of experiments with high-pressure cooling

Cutting speed (m/min)	Feed rate (mm/rev)	Depth of cut (mm)	Fluid pressure (MPa)	Flow rate (l/min)	Direction of the fluid	Diameter of the nozzle hole (mm)	Distance of fluid application (mm)
490	0.15	1	1.2	11	Flank face	2.7	42
490	0.15	1	1.2	11	Flank face	2.7	42
570	0.15	1	1.2	2.5	Flank face	1.2	42
570	0.15	1	1.2	2.5	Flank face	1.2	42

Fig. 2 Volume of material removed per tool life in all cooling conditions and cutting speeds



mean value and the dispersion of these tests. The following points can be seen in this figure:

1. For v_c=490 m/min, the cooling condition with HPLFR presented a slightly longer tool life than the other conditions. Cooling was not very effective at this cutting speed, even under high pressure. In fact, increasing the amount of high-pressure fluid even caused a slight decrease in tool life. Therefore, since the use of fluid did not significantly increase tool life, dry cutting could be used at this cutting speed.
2. For v_c=570 m/min, the use of high-pressure cutting fluid prolonged tool life more than conventional cooling and dry cutting. At this cutting speed, cooling effectively increased tool life and the use of high pressure was effective, providing longer tool life than conventional cooling. In other words, at this high cutting speed, the tool temperature was very high, so it had to be reduced using a cooling system, such as the high-pressure fluid system, that would allow the fluid to get close the workpiece-tool interface. This is better explained in the analysis of the Fig. 5 where it will be seen traces of cutting fluid in the border of the flank wear land when high pressure fluid was used.
3. Still for v_c=570 m/min, there was no significant difference between tool life attained at low and high flow rates, when high-pressure cutting fluid was applied. Therefore, the amount of fluid injected was irrelevant to tool life. What was important was that the fluid reached close to the workpiece-tool interface. Therefore, at a high cutting speed such this one, the best choice for the cutting fluid condition would be the application of high pressure and a low flow rate.

Figure 3 shows SEM micrographs of the wear lands on both rake and flank face of the tool used at v_c=490 m/min and HPHFR cooling, while Table 2 depicts the EDS results of the points shown in this figure. As can be seen, points EDS1 (rake face) and EDS4 (flank face) were filled with adhering workpiece/chip material. These adhesions were thick, preventing the material underneath them from being detected. Point EDS2, which was in the chip-tool rake face contact area close to the cutting edge, presented only material from the tool coating (titanium), indicating that the layer of coating under the adhesion on the rake face was preserved. In other words, the adhesion on the rake face did not cause tool wear.

The presence of workpiece/chip material on the flank wear land proves that the deformation of the material in the primary/secondary shear zone was such that caused the material to extrude between workpiece and cutting edge and stick to the flank face. The images taken by optical

Fig. 3 Tool rake and flank faces: v_c=490 m/min and HPHFR

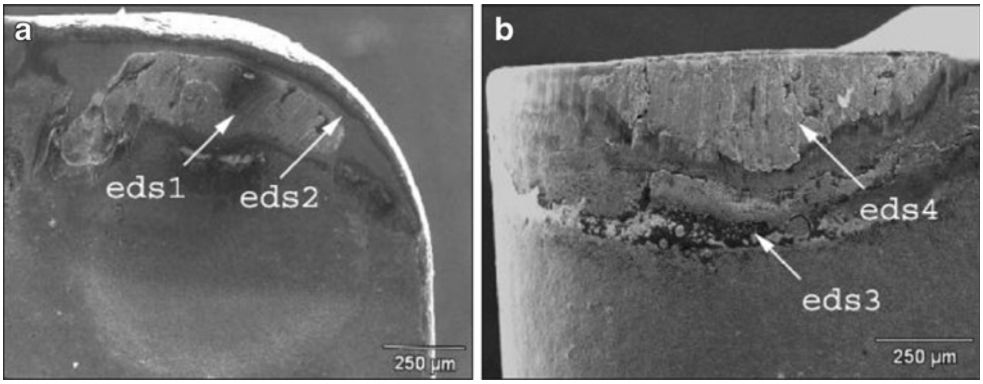


Table 2 EDS results of the points shown in Fig. 3

	Mg	Si	P	S	Zn	Al	Ti	Mn	Fe	W
EDS 1	-	-	-	-	-	-	-	1.29	98.71	-
EDS 2	-	-	-	-	-	-	95.43	-	4.56	-
EDS 3	0.82	4.01	20.01	18.56	52.81	-	2.01	1.13	0.65	-
EDS 4	-	-	-	-	-	-	-	-	100	-

microscopy during the experiments (not shown here for lack of space) indicated that the adhesion of workpiece material on the flank face increased as a function of cutting time, pushing the wear border away and increasing flank wear. Moreover, this adhesion intensified as the tool reached the end of its life. It was impossible to identify the material under the adhered layer (either tool coating or tool substrate material), but it is safe to assume that adhesion was facilitated as the tool coating was being removed by abrasion against the workpiece. The phenomenon of attrition may began as adhesion occurred, further increasing flank wear. One evidence of the presence of attrition wear is the rough appearance of the wear land [2].

Point EDS3, at the edge of the flank wear land, was filled with elements from the cutting fluid (P and Zn), indicating that the fluid reached close to the wear land but did not penetrate the workpiece-tool interface.

SEM images were also taken of the tool employed to cut with HPLFR and v_c=490 m/min, but are not shown here to save space. However, both the rake face and flank face wear lands were very similar to the wear lands produced with the tool used to cut with HPHFR. Part of the rake face was full of adhered chip material and another part, also in the chip-tool contact area, showed exposed coating layer material (Ti), indicating that this adhesion did not cause wear. The flank face wear land was filled with workpiece/chip material and its edge was full of elements from the cutting fluid. In other words, in this cooling condition, the flank wear mechanism was the same, i.e., the coating layer was very likely removed by abrasion, allowing adhesion to occur; hence, attrition was also responsible for the increase in wear. Moreover, once again, the fluid failed to reach the contact area between workpiece and tool, reaching only its border. Consequently, lubrication did not occur and the only effect of the fluid was to cool the region close to the wear land, thereby decreasing the cutting edge temperature through heat conduction.

Figure 4 shows SEM micrographs of the tool used to cut in the conventional cooling condition and v_c=490 m/min, while Table 3 provides an EDS analysis of the points shown in the images of Fig. 4.

Again, the rake face was full of adhered chip material (EDS1), but showed no detectable crater wear. Elements from the fluid were now visible at the edge of the chip-tool contact area (Zn, S, and P in EDS2), since the fluid was poured onto the chip. The flank wear land was full of adhered workpiece/chip material, and a point now appeared without this adhered layer (EDS 4). This point presented mostly material from the tool substrate, proving that there was no longer any tool coating material under this type of adhered material on the flank wear. This region (EDS4) offers another clue suggesting that the wear was caused by attrition. According to Trent [2], as already cited, attrition can be described as the cyclic adhesion and removal of workpiece/chip material from the tool, which also causes removal of tool particles. Under these conditions, microscopic particles of the tool are pulled out and dragged away together with the material flow. Therefore, at the moment the flank wear land image was recorded, particles from the tool in the EDS4 area had already been removed, exposing the tool substrate. Another aspect of this flank wear land was that scratches parallel to the cutting direction appeared in the region of the tool nose radius, indicating that abrasion also occurred in this wear land.

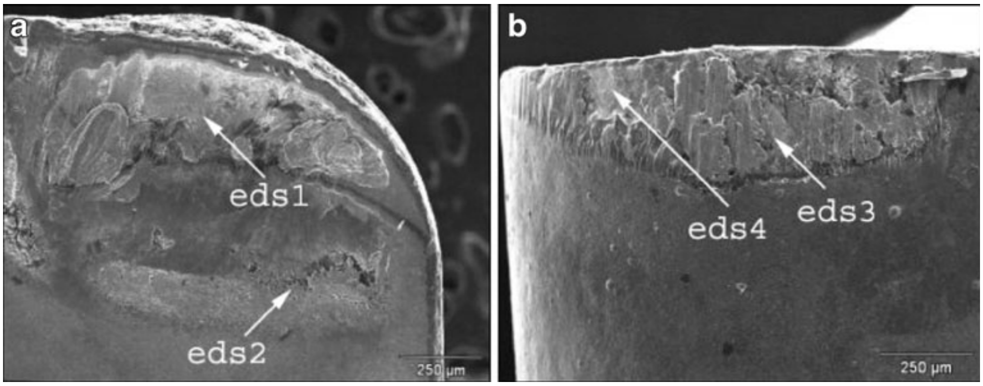


Fig. 4 Tool rake and flank faces: v_c=490 m/min and conventional cooling

Table 3 EDS results of the points shown in Fig. 4

	Ca	Si	P	S	Zn	Al	Ti	Mn	Fe	W
EDS 1	-	-	-	-	-	-	-	0.93	99.07	-
EDS 2	10.07	1.25	28.69	2.06	47.47	-	1.82	1.79	6.86	-
EDS 3	-	-	-	-	-	-	-	1.28	98.72	-
EDS 4	-	-	-	-	-	-	1.45	-	3.23	95.31

There was no trace of cutting fluid elements on the flank face, since the fluid was poured onto the chip in the direction of the rake face.

Again, the SEM images of the tool used in dry cutting and v_c=490 m/min is not shown here, but it can be stated that, as in the case of conventional cooling, the rake face was full of adhered workpiece material, the flank face wear land was full of adhered chip/workpiece material, and this land also showed a region devoid of adhesion, with exposed tool substrate. The region of the tool nose radius presented scratches typical of abrasive wear.

Concluding the analysis of the tool wear mechanisms using v_c=490 m/min, it can be stated that crater wear was absent and that flank wear was caused by abrasion and attrition, regardless the cooling condition employed. At this point, it is important to discuss why the dry and conventional cooling conditions, which surely caused the increase in cutting edge temperature when compared to the high-pressure fluid conditions, did not significantly reduce the tool life. Abrasion is stimulated by temperature since it decreases tool hardness, making it easier for the workpiece flow to remove particles from the tool during workpiece/tool friction [2]. This leads to the conclusion that the tool used here presented a sufficiently high level of hot hardness to withstand abrasion quite well, even at the high temperatures caused by conventional cooling and by dry cutting at this cutting speed.

But what about attrition—is it stimulated by temperature? According to Trent [2], the conditions for attrition to occur are relatively low cutting speed, and less laminar, more intermittent workpiece material flow passing the cutting edge, which may be caused by any vibration in the process. Moreover, they assert that the rate of wear by attrition is not directly related to tool hardness but to tool grain size (the kind of tool was not a variable in the experiments, so all tools had the same grain size), and that fine-grained alloys are much more resistant than coarse-grained alloys. Thus, if attrition occurs at low cutting speeds, a high tool temperature is not mandatory for its occurrence. Therefore, the higher tool temperatures attained in dry cutting and conventional cooling did not increase the attrition-related wear; hence, tool life in these conditions could be similar to that achieved with high-pressure fluid injection.

Figure 5 shows the SEM images of the tool used to cut with HPHFR and v_c=570 m/min, while Table 4 shows the EDS results of the points depicted in Fig. 5.

As can be seen in the figure, the rake face is full of adhered workpiece material (EDS1 and EDS2). No tool substrate material was found in the chip-workpiece contact area, although point EDS2 showed a minor amount of titanium from the coating layer. Again, there was no crater wear on this face.

The flank wear land was also full of adhered chip/workpiece material (EDS3), and in some areas this adhesion was removed by the material flow, exposing the tool substrate (EDS4—full of W from the substrate). Border elements from the fluid were visible in the flank wear land (P and Zn—EDS5), indicating that even under high pressure the fluid only approached the interface between workpiece and tool flank face, but failed to penetrate in it. However, as it was stated before, the high pressure fluid system was able to make the fluid to get close to the workpiece-tool interface and, therefore, to provide a better cooling of this region than when both conventional cooling and dry cutting were used. The tool nose radius showed scratches parallel to the cutting direction, indicating the presence of abrasive wear.

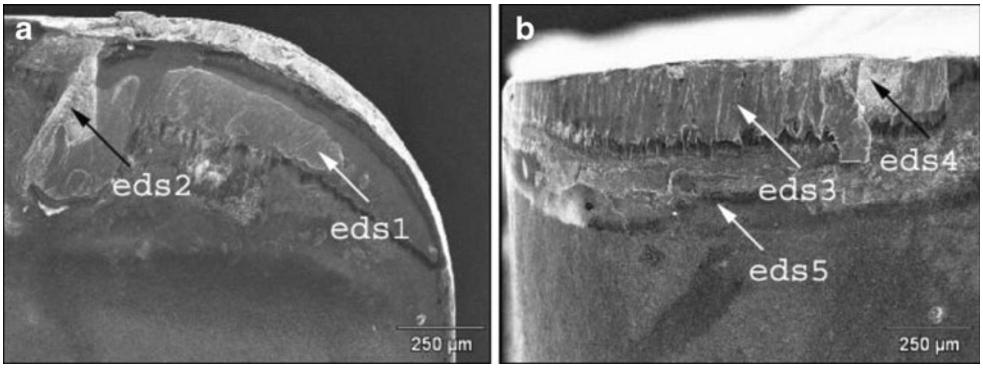


Fig. 5 Tool rake and flank faces: v_c=570 m/min-HPHFR

Table 4 EDS results of the points shown in Fig. 5

	Ca	Si	P	S	Zn	Al	Ti	Mn	Fe	W	Mo
EDS 1	-	-	-	-	-	-	-	1.27	98.73	-	-
EDS 2	-	-	-	-	-	-	0.40	0.77	98.83	-	-
EDS 3	-	-	-	-	-	-	-	1.15	98.85	-	-
EDS 4	-	-	-	-	-	-	1.87	-	1.61	96.52	-
EDS 5	2.64	1.69	18.49	-	29.66	-	35.90	-	10.25	-	1.36

Based on these results, it can be stated that the wear mechanisms did not change, i.e., abrasion and attrition were present, causing the tool wear.

The images of the wear lands for the HPLFR with v_c=570 m/min were very similar to those of HPHFR at the same cutting speed. They are therefore not shown here.

Figure 6 shows the SEM micrographs of the tool employed to cut with conventional cooling and v_c= 570 m/min, while Table 5 lists the EDS results of the points depicted in Fig. 6.

In this condition, some differences were found compared to the tools used to cut under other cooling conditions. The rake face was still full of adhered chip material (EDS1), but for the first time it was possible to see tool substrate elements (W) together with tool coating elements (Ti—see point EDS2). This indicates that crater wear occurred, since elements of tool substrate were visible (W), but the wear was still very shallow, since elements from the coating (Ti) were also visible. Such minor crater wear may be caused by attrition, since it is very reasonable to assume that this region would be covered by chip material again if the cutting continued a little longer, like its neighboring region (EDS1 region). Attrition is a cyclic phenomenon, alternating moments when the tool region is full of chip material and moments when this material is removed by the chip flow, dragging with it material from the tool coating and substrate and exposing them. However, it should be noted that this crater wear was not the responsible for the end of tool life. Again, it was possible to find fluid elements at the edge of the rake face wear land.

Like in the images of the tools used in other cooling conditions, the flank wear land was full of adhered chip/workpiece material (EDS4), and also contained regions with exposed tool substrate (EDS5) and scratches parallel to the cutting direction in the tool nose radius. Therefore, the wear mechanisms that generated flank wear and caused the end of tool life were the same, i.e., abrasion and attrition. However, unlike the other cooling conditions, the cutting edge was already damaged presenting a shape different from the original one. It seems that close to the end of tool life, due to the very aggressive conditions (high cutting speed, not very effective cooling, and high flank wear), the wear rate accelerated and began to remove large particles of the cutting edge. This finding was confirmed by the optical microscope analysis performed during the experiments. Flank wear was around 0.17 mm when the experiment reached 90% of tool life. In the last 10% of tool life, flank wear increased by another 0.13 mm, reaching the criterion of the end of tool life (flank wear of 0.3 mm).

The appearance of the wear lands of the tool used in dry cutting are not shown here, but it was very similar to the images of the tool used in conventional cooling. The only significant difference was that the areas in the flank wear land where the tool substrate was exposed were larger than in the tool used in conventional cooling.

Therefore, it can be concluded that, when v_c=570 m/min was used, the wear mechanisms were the same as those that occurred for v_c=490 m/min, i.e., there was no crater wear (or if it occurred, it was very shallow) and that the flank wear was caused by abrasion and attrition, regardless of the cooling condition used. Tool life was shorter with v_c=

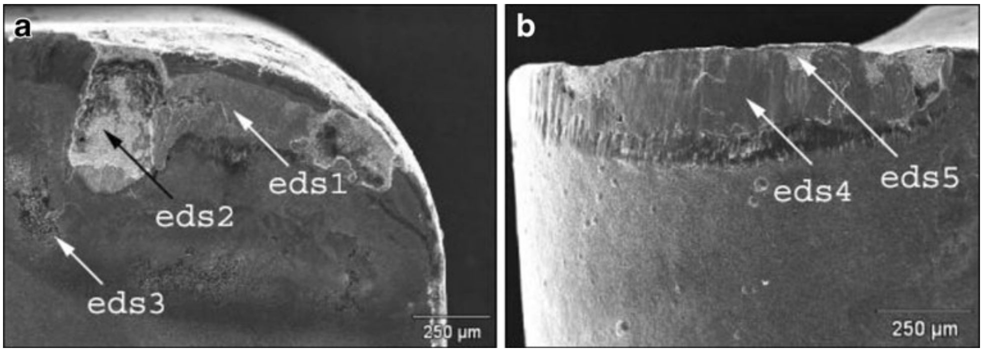


Fig. 6 Tool rake and flank faces: v_c=570 m/min with conventional cooling

Table 5 EDS results of the points shown in Fig. 5

	Ca	Ta	Nb	Si	P	S	Zn	Ti	Mn	Fe	W
EDS 1	-	-	-	-	-	-	-	-	1.29	98.71	-
EDS 2	-	22.71	18.27	-	-	-	-	10.82	-	−5.14	43.05
EDS 3	7.07	-	-	2.31	17.03	14.42	44.56	2.87	2.16	−8.70	-
EDS 4	-	-	-	-	-	-	-	-	0.92	99.08	-
EDS 5	-	18.24	17.02	-	-	-	-	6.04	-	4.57	54.13

570 m/min than with v_c=490 m/min, because at a higher cutting speed the tool temperature was also higher. This higher temperature increased abrasive wear, since it caused tool hardness to decrease during cutting. As Trent [2] asserted, tool hardness does not influence attrition. But it is very likely that attrition was also stimulated by the increase in temperature, not because tool hardness was lower, but because the workpiece/chip ductility increased, facilitating workpiece/chip deformation in the primary shear zone, and hence, facilitating adhesion. Another aspect pointed out by Trent [2] is that relatively low cutting speeds are necessary for attrition to occur. The wear mechanisms found on the tool for v_c=570 m/min indicated that attrition could also be important at a relatively high cutting speed (this cutting speed is 16% higher than that recommended by the tool manufacturer).

At this cutting speed, the difference in tool life under the various cooling conditions used here were greater than with v_c=490 m/min, particularly for dry cutting. The tool used in this condition presented a tool life roughly 30% lower than the tools used in the conditions with fluid injected under high pressure. Therefore, it can be concluded that with dry cutting, the tool temperature was such that the tool could no longer withstand the abrasion and attrition that began early in the tool life. Again, it is very likely that attrition was also stimulated by the increase in temperature (of course, the tool temperature was higher in dry cutting), because the workpiece/chip ductility increased, facilitating workpiece/chip deformation in the primary shear zone, and hence, facilitating adhesion. In other words, at high cutting speeds, the use of cutting fluid under high pressure directed correctly towards the wear zone is crucial to obtain a long tool life.

Figure 7 shows the specific cutting energy (cutting force per undeformed chip area or cutting power per volume of chip removed per minute) at the beginning and end of tool life in all the cutting conditions employed here.

An analysis of Fig. 7 reveals several points: (a) the cooling conditions did not affect the specific cutting energy at either the beginning or the end of tool life. At the end of tool life, the differences in specific cutting energy in all the cooling conditions were a little greater, but not sufficient to state that the specific energy values were different. This fact also suggests that, even when injected under high pressure, the fluid did not reach the interfaces, which would have lubricated the contacts, thus decreasing the cutting power and, consequently, the specific cutting energy; (b) the specific cutting energy decreased slightly as the cutting speed increased; c) the increase in specific cutting energy from the beginning to the end of tool life was, on average, 22% at the cutting speeds and cooling conditions used, as expected, since tool wear damages the shape of the cutting edge, making cutting more difficult.

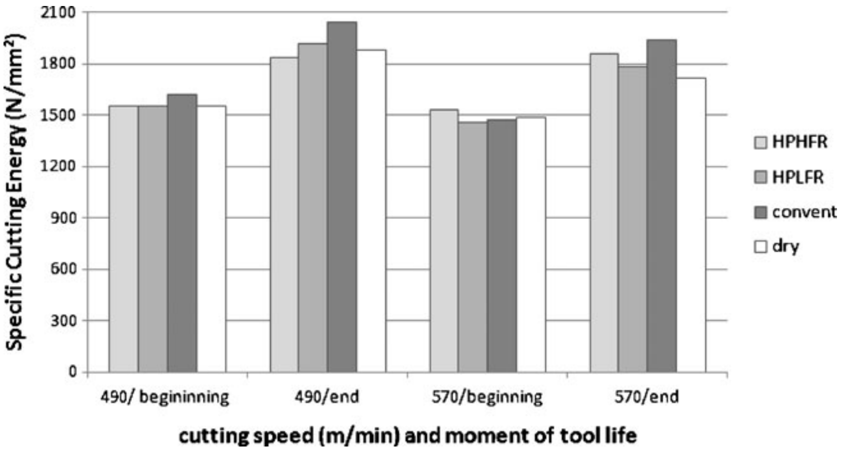


Fig. 7 Specific cutting energy in the different cutting conditions tested

4 Conclusions

Based on the above results and on the scope of the tested conditions, several conclusions can be drawn for steel turning with coated carbide tools:

- For v_c=490 m/min, the cooling condition with HPLFR presented a longer tool life than with HPHFR and slightly longer than in the conventional condition and dry cutting. Cooling was less effective at this cutting speed, even under high pressure. Dry cutting can be used at this cutting speed without affecting tool life excessively.
- For v_c=570 m/min, the use of high-pressure cutting fluid led to longer tool life than conventional cooling and dry cutting. At this cutting speed, cooling effectively increased tool life. In this situation, the use of high-pressure cutting fluid is beneficial for tool life. On the other hand, the flow rate was not significant, so the best choice for the cutting fluid condition would be HPLFR. Therefore, in bottleneck operations where the cutting time must be shortened and, consequently, cutting speed must be high (like v_c=570 m/min), it is important to use HPLFR to have the longest tool life in such cutting speed.
- No crater wear occurred at either of these cutting speeds (or if it did, it was very shallow) and flank wear was caused by abrasion and attrition, regardless of the cooling condition employed.
- The high-pressure fluid approached the wear land, but did not reach the workpiece-tool interface and therefore did not provide lubrication.
- When v_c=570 m/min was used, tool life was shorter because the tool temperature was higher.
- The cooling conditions did not affect the specific cutting energy at the beginning of tool life. This is further evidence that lubrication, which would have reduced the specific cutting energy, did not occur even under high fluid pressure.

References

1. Sandvik Coromant (1994) Modern metal cutting, 1st edn. Sandvik Coromant Technical Editorial Department, Tofters Tryckeri, Sweden
2. Trent EM (1991) Metal cutting. Butterworths-Heinemann, Oxford
3. Usui E, Shirakashi T, Kitagawa T (1978) Analytical prediction of three-dimensional cutting process. Trans ASME 100:236–243
4. Trigger KJ, Chao T (1951) Cutting temperatures and metal-cutting phenomena. Trans ASME 777-793
5. Wong T, Kim W, Kwon P (2004) Experimental support for a model-based prediction of tool wear. WEAR 257:790–798. doi:10.1016/j.wear.2004.03.010
6. Diniz AE, Marcondes FC, Coppini NL (2006) Tecnologia da usinagem dos materiais. Artliber Editora, São Paulo (in Portuguese)
7. Machado AR, Silva MB (2003) Usinagem dos metais. Editora da UFU, Uberlândia (in Portuguese)
8. Mari D, Gonseth DR (1993) A new look at carbide tool life. WEAR 165:9–17. doi:10.1016/0043-1648(93)90366-T
9. Diniz AE, Micaroni R (2002) Cutting conditions for finish turning process aiming the use of dry cutting. Int J Mach Tools Manuf 42:899–904. doi:10.1016/S0890-6955(02)00028-7
10. Diniz AE, Oliveira AJ (2004) Optimizing the use of dry cutting in rough turning steel operations. Int J Mach Tools Manuf 44:1061–1067. doi:10.1016/j.ijmachtools.2004.03.001
11. Pigott RJS, Colwell AT (1952) Hi-jet system for increasing tool life. SAE Quarterly Trans 6(2):547–558
12. Kaminski J, Alvelid B (2000) Temperature reduction in the cutting zone in water jet-assisted turning. J Mater Proc Tech 106:68–73. doi:10.1016/S0924-0136(00)00640-3
13. Machado AR, Wallbank J (1994) The effects of a high pressure coolant jet on machining. Proc Inst Mech Eng Part B: J Eng Manuf 208:29–38
14. Oliveira A J (2003) The optimization of cutting parameters aiming the dry turning of AISI 1045 steel in rough operations. Master Thesis (in Portuguese)