TURNING TOOL-HOLDER WITH INTERNAL COOLING SYSTEM BASED ON CHANGE PHASE OF FLUID

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Abstract. *The growing need of increase in productivity in machining operations emphasize the importance of the development of new cutting tools and new manufacturing methods, which have the capacity to fulfill the present demand. In this way, many efforts are directed to enable the utilization of higher cutting speeds. One great challenge is to control the temperature during the machining process, once that the temperature rises with cutting speed increase, reducing the hot hardness of cutting tool and feeding the tool wear mechanism. To minimize these effects, many cooling methods have been proposed, each one with advantages and disadvantages. The conventional cooling methods, which use cutting fluids, although have recognized efficiency, add costs to the process, besides to cause problems regarding to the environment and operators health. In this context, dry machining, associated with the employment of tools with high hot hardness, has been a good method to avoid these problems. Another option is the cryogenic machining, which utilizes carbide tools in temperatures lower than -150°C, using, for this, liquid nitrogen like cooling fluid. However, this method brings some problems, like the need of special devices with significant size around the machine-tool. In this work, it is proposed the development and the construction of a cooling tool system for turning process, with low cost and simple maintenance, composed by a tool-holder, with a cooling fluid flowing through inside its body in a loop circuit, where the fluid evaporates just under the insert location, removing heat from the insert. The cooling fluid passes through a heat exchanger were it condensates and a new cycle is started. As result the developed system provides a tool life equal or better than with the cutting fluid application, with clear economic and environmental advantages.*

Keywords*: Manufacturing Engineering; Turning; Tool life; Cooling system; Dry machining*

1. INTRODUCTION

The machining process generates, with material cut, heat that is distributed by the tool, chip, workpiece and the environment. The heat transferred to the tool causes damages mainly in two ways: reducing the mechanical strength and the wear resistance of the tool. With the wear, some unlikely problems appear, like unaccuracy of the final part dimensions and poor quality of the machined surface.

To try to diminish the heat generated in the process, two methods are commonly used: adequate cut parameters to the workpiece-tool pair, exploring the range with less heat generation, or the use of cutting fluids for cooling and lubrication of the cutting zone. The first method, used alone, limits the productivity in machining, which becomes dependent of the parameters chosen. The second method involves an entire knowledge area relating to heat transfer and tribology, and when well used allows to control the heat transferred to the cutting tool, increasing the tool life and improving the final product. However, the use of cutting fluids bring some disadvantages, like: costs added with the need of storage, pumping, filtering , recycling and cooling systems; contamination of water and soil; potential operators health problems caused by gases, fumes and bacteria formed in cutting fluids, and other. In this way, there is the need of green cooling methods, with no damages for the environment or operators health. At the same time, these methods must be efficient on removing heat from the cutting zone. They involve since dry machining until the use of environmental friendly cutting fluids. Cryogenic fluids, like liquid nitrogen, with very low temperatures have been considered like a good answer for this task, with great capacity to remove heat without damages for the environment.

There are many cooling methods in machining, however they can be divided according to the principle used. This is described as follow.

The use of liquid cutting fluids is very common in metal-mechanic industry. The traditional way is the application of fluid flooding the entire cutting zone, pointing to the desired area, eventually using high fluid pressures. The main functions of cutting fluids, in this case, are: cooling, lubrication and chip removal (Schroeter, 2002).

Cooling gains more importance for high cutting speeds, to diminish the contact temperature between tool-piece. Lubrication is important for low cutting speeds, because of the possibility of penetration in the area between chip and tool, although some authors like Merchant (1958) and Dhar (2003) report that in high speed machining conventional cutting fluids fail in this task. Chip removal is interesting for machining process in general.

Hong and Broomer (2000) report that only in United States the volume of cutting fluids discarded for the environment can be over than 155 million of liters per year. They show that coolants with additives for extreme pressure must be treated before the discharge for the environment and the treatment cost can reach US$ 5 per gallon. Dhar *et al*. (2006) show that cutting fluids are a potential factor for skin cancer (after a long exposition to the fluid).

Klocke and Einsenbläter (1997) explain over the quantity of cutting fluids used on Germany and also over the share of these fluids in the final cost of a machined part. They show that the quantity used on Germany in 1994 is of around 1,15 million of litters and that cutting fluids are responsible for 7 to 17% of the final cost of a part, while the cutting tool is responsible for 2 to 4% of this cost, i. e., cutting fluids can be more expensive than the tools themselves. This enhance the need for new methods for machining, mainly that without the use of coolants.

In their work, Klocke and Einsenbläter (1997) suggest the use of dry machining like a good green alternative, eliminating the use of cutting fluids. Although the performance of cutting fluids is very good in tasks like cooling, chip breaking and chip transport, there are some problems involved during its utilization, which lead to the need for new strategies to fulfill these tasks. Therefore, machining operation without lubricants only will be acceptable if it can assure or even increase the results obtained with cutting fluids. Dry machining introduction ask some appropriated actions to substitute the primary functions of lubricants, which involves more detailed analysis to understand the relationship between process, tool, workpiece and machine.

The use of dry cutting can include the MQL (minimal quantity of lubricant) method to reach workpiece quality and machining times similar to that obtained using cutting fluids. In this case it is called near-dry machining.

Sreejith and Ngoi (2000) suggest like an alternative dry machining method the indirect contact of coolant with the cutting zone. For this intent, it can be used some technics, as follow:

a. Use of an internal cooling system, where the coolant flows through channels under the insert, without direct contact with the cutting zone.
b. Internal cooling with an evaporation system, where a volatile liquid is introduced into the tool-holder and evaporates in contact with the inferior surface of the insert. This is the method to be investigated in this work.
c. Cryogenic system, where a cryogenic coolant is conducted through a channel inside the tool.
d. Thermoelectric cooling system, using a device with pairs of thermoelectric materials. When an electric current pass through these materials, one cold and one hot joint are produced in the opposite terminals of each element.

Beyond these solutions, it is also necessary the development of appropriated tools for dry cutting. Some characteristics of these tools are shown as follow:

a. Use of very positive rake angle (30°) with carbide tools, which will reduce the cutting force significantly.
b. Development of refractory tool materials, which can deal with high temperatures.
c. Use of ultra-hard tool materials, like diamond and CBN.
d. Development of tool coatings which can work under high temperatures and, at same time, provide a lubricant effect to reduce the friction between tool and chip.

Another auxiliary method for dry machining was studied by Haq and Tamizharasan (2005). They used heat pipes like heat transfer device, to transfer the heat from the cutting zone. The heat pipe is a device that can transfer heat with low differences of temperature, without the application of any external energy source. Heat is transferred internally in the tool-holder, without using cutting fluids. Figure 1 shows a scheme of the heat pipe inside the tool-holder.

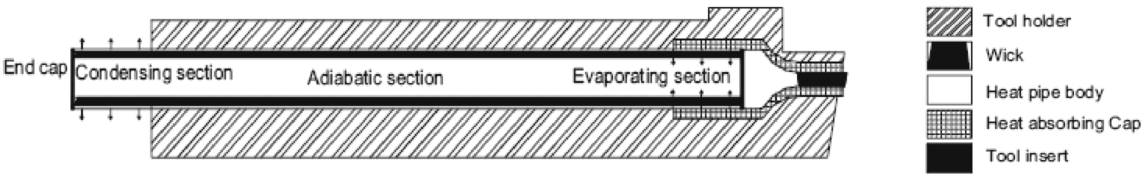


Figure 1. Scheme of heat pipe inside the tool-holder (Haq and Tamizharasan, 2005)

The authors used CBN tool during the tests, with and without the use of heat pipe. Good results were obtained with heat pipe: the temperature in the cutting zone was reduced by 5% and flank and crater wear by 6 and 9%, respectively. Figure 5 shows some results obtained in the experiments.

Chiou *et al.* (2006) also studied the use of heat pipes in dry machining, through simulations by finite elements and later by experiments. Simulations results showed a reduction on the tip temperature from 352°C (without heat pipe) to 293°C (with heat pipe), for same cutting conditions. During the turning of AISI 1020 carbon steel, the result show a reduction on the temperature from 120°C to 96°C, without and with heat pipe respectively, in the same position on the tool and with the same cutting conditions. So, the use of heat pipes is feasible for cooling tool task, without using cutting fluids. However, its application in hard turning operations may not be efficient and needs more research.

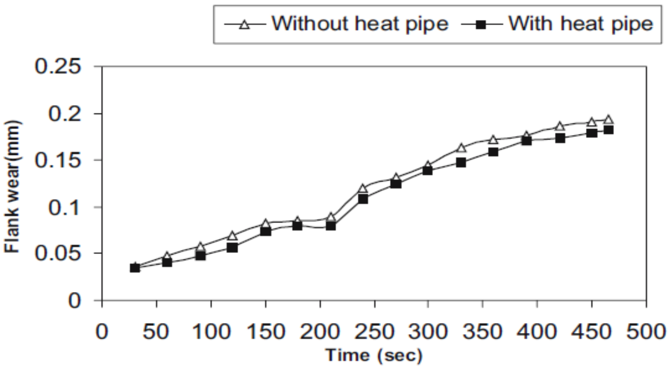


Figure 2. Flank wear for turning without and with heat pipe (Haq and Tamizharasan, 2005)

The results mentioned above agree with Zhao *et al.* (2002) study, consisting in the numerical simulation of the effect of internal cooling over flank wear in orthogonal cutting. It is demonstrated that, through an internal device for heat removal in the tool, it is possible to reduce cutting temperature and also flank wear. According to heat intensity removed by the device and the distance between the device and the interface tool-chip, it can be obtained good results. For example, with a device that removes 25W/mm^2, the flank wear can be reduced by 15% and, depending on the distance, the flank wear can be reduced by more than 11%. Figure 3 show the influence of different intensities of internal heat sinks on flank wear.

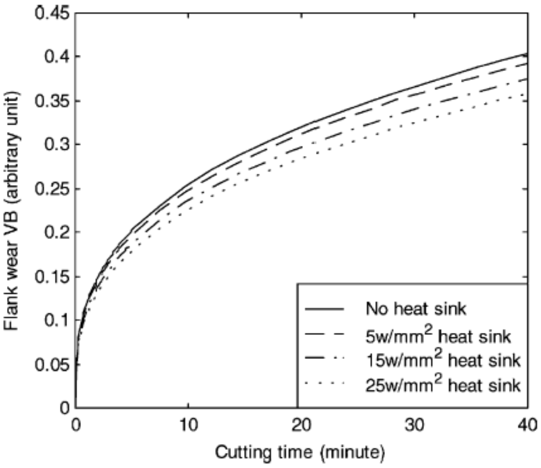


Figure 3. Effect of internal heat sink intensity on flank wear with heat sink area A_{hsink} = 2mm x 2 mm, heat sink distance D = 1 mm (Zhao *et al.*, 2002)

Su *et al.* (2006) studied the effect of using cooled air in flank wear, surface finish and chip shape, in finish turning of nickel-base super alloy Inconel 718 and in high speed milling of AISI D2 steel. In this case it was used a specific equipment developed to generate compressed cooled air. Different cooling/lubrication conditions were investigated: dry cutting, minimal quantity lubrication (MQL), cooling air cutting and cooling air cutting with minimal quantity lubrication (CAMQL). The more significant results were: the application of CAMQL showed a drastic reduction in tool wear and in superficial roughness, with great increase on chip shape in finishing operation of Inconel 718; for high speed milling of AISI D2 steel, cooling air cutting resulted in a longer tool life and slightly higher superficial roughness compared with dry cutting combined with MQL.

MQL is a technique that consists in the application of a very small quantity of cutting oil, from 6 to 100 ml/h, through a compressed air-flow, directed at the cutting edge of the tool. The main limitation of MQL is its small effectiveness in cooling the cutting surface. Because of this, MQL does not work well when machining difficult-to-machine materials. However, with help of cooled air, the results can be increased considerably.

The CAMQL technique, which offered better results in Inconel 718 turning, consists in application of air at -20°C, at a flow rate of 120 l/min and at a pressure of 0,6 MPa, and with addition of a very small quantity (90ml/h) of cutting oil UNILUB 2032. The cutting tool was a carbide insert class K with TiAlN coating, with crater type chip-breaker on the rake surface. The following graphs show the results related to the cutting tip wear and superficial roughness.

Cryogenic machining is a method described by many authors in literature. The term cryogenic express the study and utilization of materials at very low temperatures (below -150°C). Gases like helium, nitrogen and hydrogen, when in liquid state, have temperatures below -180°C.

Liquid nitrogen has been explored like cryogenic coolant since 1950's (Yildiz, 2008). In 1965, the Grumman Aircraft Engineering Corporation reported to safe and well succeeded tool life increase using N2 like coolant in HSS turning and milling tools (Machinery, 1965). However, great expenses and operational costs involved with subzero gases production delayed the development and growing of this technology until the economical cryogenic approach developed by Hong *et al*. (1999). This approach suggests the utilization of small amounts of liquid nitrogen only at the region closer to the cutting edge. Uehara and Kumagai (1969 and 1970), were pioneers in cryogenic machining. Their conclusions were significant for the performance of tools in turning processes.

The most studied method for liquid nitrogen application is through jets of nitrogen, external to the tool, at the cutting zone (Paul *et al*., 2001, 2006; Dhar *et al*., 2002; Hong *et al*., 2001). There is also the utilization of liquid nitrogen spray (Zurecki *et al*., 1999, 2003; Kumar and Choudhury,2007) and the method of workpiece surface and chip cooling (Bhattacharya *et al*., 1993; Hong *et al*., 1999; Hong and Ding, 2001). Yildiz (2008) divide cryogenic cooling methods in four groups, according to researcher's application, as follow:

a. Cryogenic pre-cooling workpiece by enclosed bath or general flooding.
b. Indirect cryogenic cooling or cryogenic tool back cooling or conductive remote cooling.
c. Cryogenic spraying or jet cooling (with flood or directed approach).
d. Cryogenic treatment of cutting tool.

Wang and Rajurkar (2000) proposed a new method for cryogenic cooling when machining difficult-to-machine materials, like PCBN, Ti alloys, Inconel and Ta alloys. In this method, a cap couple over the carbide insert allows to create a chamber were liquid nitrogen circulates, through both an inlet and an outlet tube, so that there is a large contact area with the insert, and consequently removing more heat from the tool. Results show that, for example, a great increase in tool life, in some cases 10 times longer compared with dry machining. It was also reported that this system offer a more stable and strong cooling than that using sprays, without negative effects over workpiece's dimensions. Figure 4 shows the assembly for experiment.

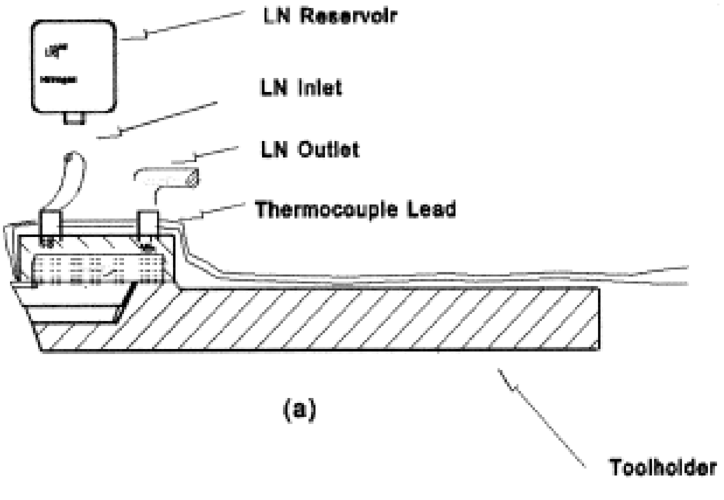


Figure 4. Assembly with tool cap for cryogenic cooling (Wang and Rajurkar, 2000)

Khan and Ahmed (2008) presented a study about AISI 304 stainless steel machining with TiCN coated carbide tool, using liquid nitrogen applied in a chamber just beneath the insert, according to Fig. 5. The tool life showed an increase of 4 to 5 times compared with flood cooling tool life.

The objective of this work is to make a tool-holder for turning process, with internal cooling, and study the use of a coolant with liquid-gas phase change, flowing in a loop circuit to minimize the operation costs. The effects of this cooling system over the cutting tool life are analyzed e compared with the results obtained by conventional cooling system (flood cooling).

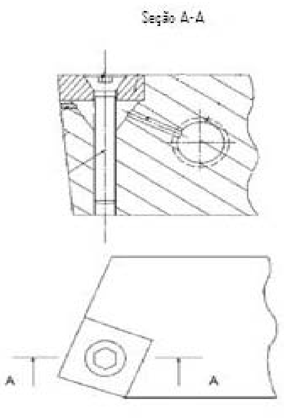


Figure 5. Modified tool-holder for cryogenic machining, with internal chamber (Khan and Ahmed, 2008)

2. THE TOOL-HOLDER CONCEPT

This project was developed based on the following considerations:

a. Need to eliminate or to diminish the amount of cutting fluids in machining operations, because of environmental and health issues, besides cost reduction.
b. Current tendency to adopt dry machining or near dry machining like "green" processes.
c. Need to control the temperature in the cutting zone, even without cutting fluids.
d. Need to maintain tool wear inside acceptable limits.
e. Need to use methods with low energy consumption and low costs.

In this way, the studies about the use of heat pipes and internal cryogenic cooling were the inspiration to develop the concept of the tool-holder with internal cooling fluid, with the important approach of phase change of the fluid, once that this is the condition (evaporation) that allows best heat exchange, using the latent heat of evaporation. Figure 6 a and b show the tool-holder and the cooling system assembly.

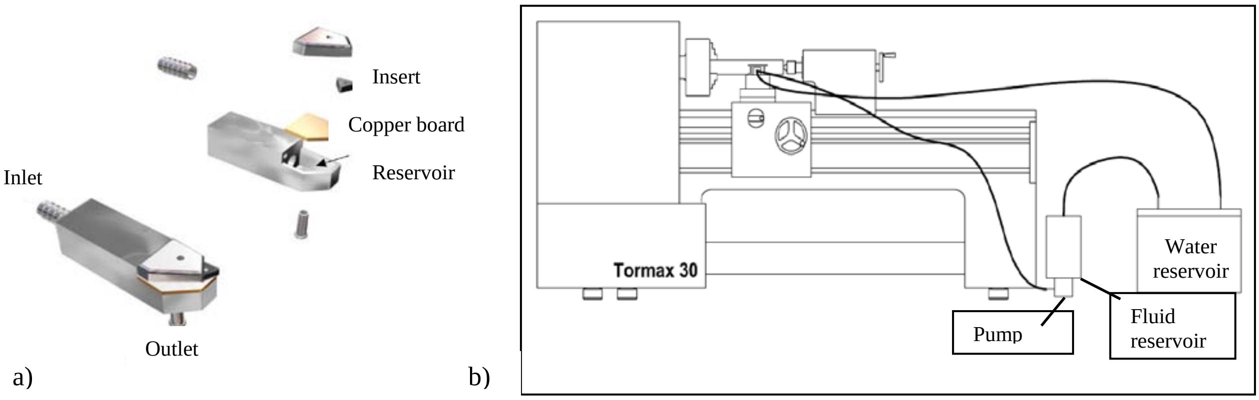


Figure 6. Tool-holder scheme and cooling system assembly.

3. MATERIALS AND METHODS

The main materials used in experiments are listed as follow:

- Carbide inserts TNMA 160408 class IC9015.
- Tool-holder with internal cooling.
- Automotive fuel pump for use with gasoline and alcohol.
- Conventional lathe with power of 7,5 kW, Tormax 30
- Portable roughness analyzer, model Surtronic 3+ Taylor Hobson
- Digital camera coupled to an optical microscope (Nikon), for flank wear measurements.
- Thermocouples type K (cromel-alumel), for temperature acquisition.
- Data acquisition system, formed by an A/D board and software LabView 10.0.

The workpiece material used is round bars with diameter = 50 mm and length = 300 mm, of SAE J775 XEV-F stainless steel, with characteristics showed in Tab. 1 and 2.

Table 1. Chemical composition of SAE J775 XEV-F stainless steel

Element	% in mass	Element	% in mass
C	0,45 / 0,55	**W**	0,80 / 1,50
Si	0,45 max	**Nb**	1,80 / 2,50
Mn	8,0 / 10,0	**P**	0,050 max
Cr	20,0 / 22,0	**S**	0,030 max
Ni	3,50 / 5,50	**Fe**	Rest
N	0,40 / 0,60		

Table 2. Mechanical properties of SAE J775 XEV-F stainless steel at 25°C

Tensile strength, yield (0,2%)	590 Mpa
Tensile strength, ultimate	980 – 1200 Mpa
Elongation ($5D_i$)	8%
Reduction of area	10%
Hardness, Brinell	350 – 400

Like cooling fluid it was chosen the R11, fluid commonly used for refrigeration circuits. This fluid has boiling temperature of 24°C, which permits its use in ambient temperature.

The methodology adopted for the experiments consists basically in comparisons among results obtained for conventional cooling (cutting fluids), internal cooling with the tool-holder developed and dry machining.

Variables to be measured and compared are the flank wear, VB, and nose wear, according to ISO 3685 standard. With this information it is possible to determine if the cooling system proposed has advantages compared to the others. The objective is to obtain results better than conventional cooling, extending the tool life and diminishing the temperature in tool-chip interface.

In addition, the roughness of surfaces obtained and samples of chips produced are analyzed, like complementary information. Also, the temperature between the back carbide insert surface and the copper board was measured, using thermocouples for data acquisition, to analyze the effect of cooling approaches on temperature during the process.

The cutting parameters (Vc, f and ap) are the same for the three cutting approaches, to permit comparisons without other influences, Tab. 3. After each pass, the machine is stopped and variables are measured and data recorded. The passes continue until maximum nose wear is obtained. So, each pass can be compared for the three cutting approaches.

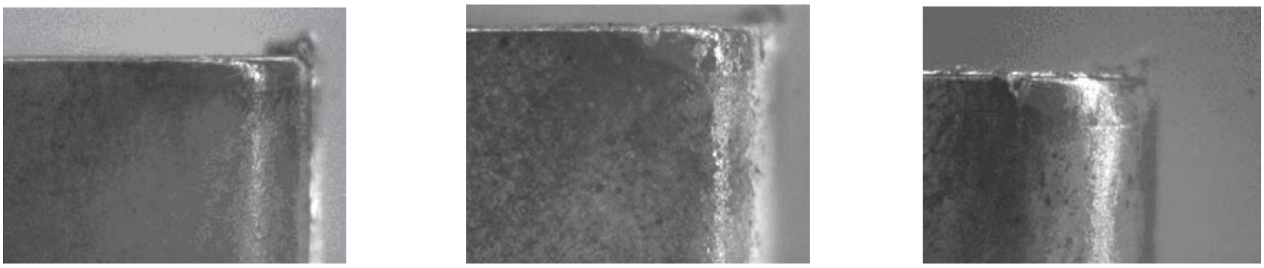
Table 3. Cutting parameters for primary experiments

Vc (m/min)	143
f (mm/rev)	0,43
ap (mm)	0,5

4. RESULTS

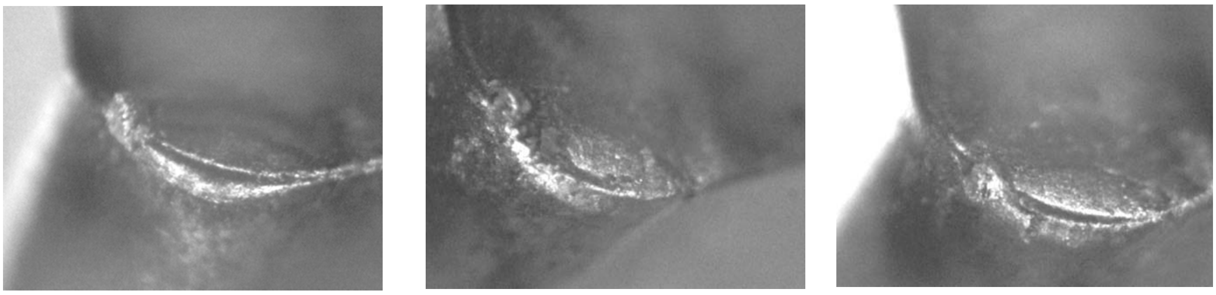
Experiments were performed, to obtain previous results about the tool-holder efficiency. However, some adjusts are needed to optimize the cooling system performance, for example, the optimum flow rate of cooling and the volume of the chamber bellow the insert must be determined. This will be made in future work.

In the following pictures sequence (Fig. 7), it can be seen that, for the same pass, the flank wear for internal and conventional cooling are very close. This behavior also occurs in nose wear, showed in Fig. 8 and 9, where is possible to see that in the first three passes the nose wear is almost the same and in the other six passes internal cooling presents a lower nose wear compared with conventional approach.



Conventional Internal cooling Dry

Figure 7. Flank wear in the same pass for the three cooling approaches (pass 8)



Conventional Internal cooling Dry

Figure 8. Nose wear for three cooling approaches (pass 8)

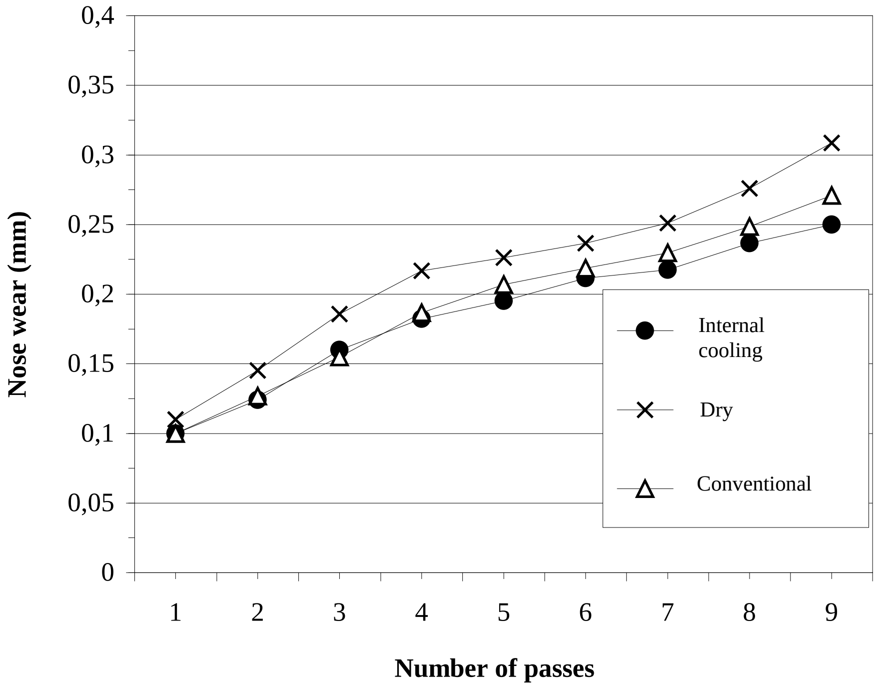


Figure 9. Nose wear per pass for the three cooling approaches

When analyzing the surface finish, again the results of internal and conventional cooling are very close, as seen in Fig. 10. Both approaches give better results when compared to dry machining. For the first three passes the conventional cooling provide better results, but for the final passes internal cooling appears like the best approach. These variation into the results may be explained by some phenomena, like built-in edge, that appears in some passes, like can be seen in Fig. 7. The important conclusion is that internal cooling provided good results, equal or even better than the other cooling approaches and, so, can be a good alternative for dry machining.

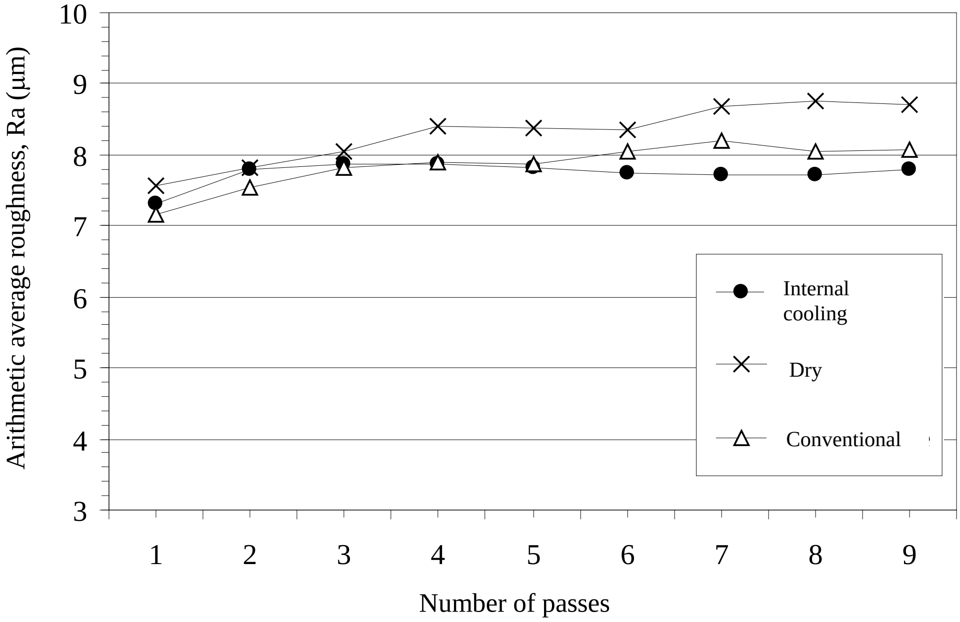


Figure 10. Arithmetic average roughness, Ra, per number of passes for three cooling approaches

Figure 11 show the deformation rate (ε_0) for chips obtained during the first pass for each cooling approach. This parameter can be used like an indicator of the energy consumed during the cutting process. In this way, for greater deformation rates more energy is necessary to cut the workpiece material. The results obtained show that internal cooling provides an intermediate value for deformation rate. If well adjusted, it is probable that this cooling method can provide lower values for $\boldsymbol{\varepsilon_0}$, which indicates that less energy is transmitted like heat into the tool.

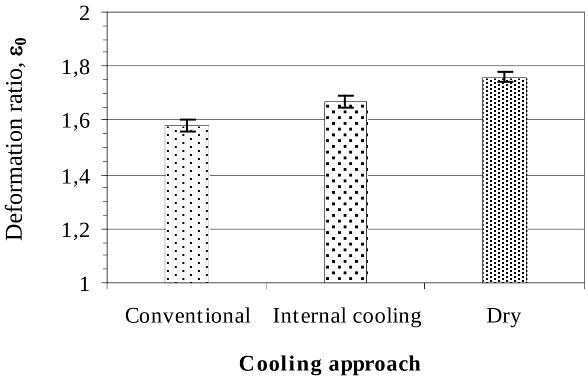


Figure 11. Deformation ratio (ε_0) according to cooling approach

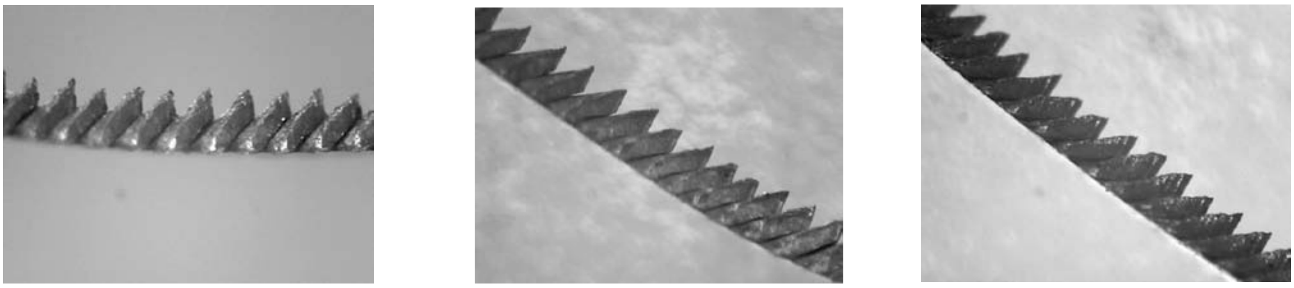

Conventional Internal cooling Dry

Figure 12. Chip samples for three cooling approaches.

Figure 13 show the temperatures obtained during the second pass for each cooling approach. It is clear that, like a primary observation, the cooling system proposed can be a good alternative for conventional cooling methods. The temperature obtained with internal cooling is close to the conventional approach. With the adjustments mentioned before, the expectative is to get results closer and even better than conventional ones. An important notice is that the temperature measurement was made with the thermocouple placed just between the insert and the copper board. In this location, cutting fluid has contact with the thermocouple in conventional cutting, what could have influenced in the temperature result obtained. This reinforces the expected results for the present study.

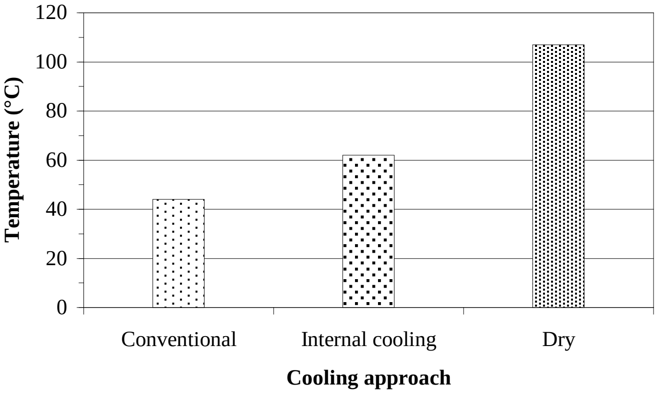


Figure 13. Temperatures obtained during the second pass according to cooling approach

6. CONCLUSION

Environmental and health legislation are becoming more and more severe with respect to the use of cutting fluids in machining operations. Dry machining is being adopted like "machining of the future" after some authors. Therefore, it is possible to use dry machining with also a cooling system to enhance greater tool life, without using cutting fluids. This project tries to develop a cooling method that is environmentally friendly, with low costs and easy maintenance.

The results showed good outcomes comparing internal cooling and conventional cooling systems. Internal cooling provided slightly lower nose wear (increased tool life) and roughness values than conventional and dry machining. Considering the costs involved with the use of cutting fluids (storage, filtering, cooling, and others), which can be responsible for until 20% of the final cost of a part, internal cooling appears like a very good alternative like machining tool cooling system.

The system proposed is of easy assembly and maintenance; it does not need a great area to be installed; the cooling fluid is not lost because it flows in a closed circuit and it is not dangerous for environment or operator's health. These characteristics, allied with the good results obtained in the study, justify its use in industry floor, in substitution of conventional cooling methods.

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