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"CLEANER PRODUCTION INITIATIVES AND CHALLENGES FOR A SUSTAINABLE WORLD"

Cleaner Machining Through a Toolholder with Internal Cooling

L. E. A. Sanchez[a], V. L. Scalon[a], G. G. C. Abreu[a]

a. Univ Estadual Paulista-Unesp, Bauru-SP, sanchez@feb.unesp.br

a. Univ Estadual Paulista-Unesp, Bauru-SP, scalon@feb.unesp.br

a.Univ Estadual Paulista-Unesp, Bauru-SP, ggcabreu@feb.unesp.br

Abstract

This work treats of a cooling system for cutting tool in turning based in a toolholder with cooling fluid flowing inside its body being that this fluid must necessarily be able to phase change due to heat generated from machining processes. In this way the fluid evaporates just under the cutting tool allowing a heat transfer more efficient than if were used a fluid without phase change once the latent heat of evaporation is beneficial for removal heat. Following, the cooling fluid evaporated passes through a condenser located out of the toolholder where it is condensated and returns to the toolholder again and a new cycle is started. In this study the R-123, a hydrochlorofluorocarbon (HCFC) fluid, was selected for the turning of a Cr-Ni-Nb-Mn-N austenitic steel of hard machinability. As result, the developed system allows a tool life equal to or better than the conventional cutting fluid method, moreover there are environmental and economics advantages once the cooling fluid is maintained in a loop circuit. .

Keywords: *Turning; Internal cooling; Dry machining; Tool life; Coolant fluid*

1 Introduction

The machining process generates heat that is distributed into the tool, chip, workpiece and environment. The heat transferred to the tool causes damages mainly in two ways: reducing the mechanical resistance and the wear resistance of the tool. With wear growth some unlikely problems appear like inaccuracy of final piece dimensions and poor quality of the machined surface. Two methods are commonly used to diminish the heat generated in the process: 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 between tool and chip. The first method used alone, limits machining productivity which becomes dependent on the parameters chosen. The second method involves an entire area of knowledge related to heat transfer and tribology, and when well makes it possible to control the heat transferred to the cutting tool, increasing its life and improving the piece's surface finish.

The most common way to apply cutting fluids is the conventional one, by flooding, working on the backside of the chip. However, of cutting fluid efficiency is reduced due to the fluid's inability to reach regions to be refrigerated and the tendency of the chip in movement to expel fluid out of the cutting region, problems that are aggravated during high-speed machining when heat generation is more intense, as it was observed by Seah et al.. (1995) and Li (1996a, 1996b) in their works. In order to increase refrigeration in machining, Pigott and Colwell (1952) and then Machado & Wallbank (1994), used cutting fluid under high pressures, of approximately 2.5 MPa, directed specifically at the chip and surface of the tool's output, resulting in longer life for the tool, less surface roughness and elimination of built-up edges. For the authors, the fluid is beneficial in minimizing the length of chip contact with the cutting tool, at the fluid's greatest reach into the cutting zone and expulsion of the chip. However, this method typically presents greater cutting fluid flows and the high pressure system is relatively expensive. Furthermore, more space is needed around the machine tool.

According to Dhar et al. (2002), the use of cutting fluids has some disadvantages, such as: added costs involving storage needs, pumping, filtering, recycling systems; water and soil contamination; potential operator health problems caused by gases, fumes and bacteria formed in cutting fluids. Besides, the authors point out that cutting fluids are a potential factor for skin cancer after long exposure to them.

Hong and Broomer (2000) report that in the USA alone the volume of cutting fluids discarded into the environment can exceed 155 million liters per year. They show that coolants with additives for extreme pressure must be treated before discharge in the environment and treatment cost can reach US$ 5 per gallon. Klocke and Einsenbläter (1997) explain about the quantity of cutting fluids used in Germany and also the share of these fluids in the final cost of a machined part. They relate that the volume used in 1994 was about 1.15 million liters and they 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. Therefore, they suggest the use of dry machining like a good green alternative, eliminating the use of cutting fluids. However, machining operations without cutting fluids will only be acceptable if they can compete with the results achieved with cutting fluids.

The use of dry cutting can includes the minimal quantity of lubricant method (MQL) to reach workpiece quality and machining times similar to those obtained using cutting fluids. In this case it is called near-dry machining. The main limitation of MQL is its small effectiveness in cooling the cutting surface. Therefore, it does not work well when machining difficult-to-machine materials. However, with help of cooled air, results can be improved. Su et al. (2007) studied the effect of using cooled air in flank wear, surface finish and chip shape, in finishing turning of nickel-based super alloys (Inconel 718). In this case, specific equipment was used, developed to generate compressed cooled air that consists of applying air at -20°C, at a flow rate of 120 l/min and at a pressure of 0.6 MPa, with the addition of a very small quantity (90ml/h) of cutting oil. This technique is called CAMQL by the authors. Different cooling/lubrication conditions were investigated: dry cutting, minimal quantity lubrication, cooled air cutting and cooled air cutting with minimal quantity lubrication. The most significant results were a reduction in tool wear and surface roughness, obtaining short continuous tubular chips instead of long continuous tubular chips produced under dry cutting.

Sreejith and Ngoi (2000) suggest some methods of indirect contact of coolant with the cutting zone as an alternative to dry machining. For such, some techniques should be used such as (1) Use of an internal cooling system, where the coolant flows through channels under the insert, without direct contact with the cutting zone, (2) Internal cooling with an evaporation system, where a volatile liquid is introduced into the toolholder and evaporates in contact with the inferior surface of the insert, (3) cryogenic system, where a cryogenic fluid is conducted through a channel inside the tool and (4) thermoelectric cooling system, using a device with pairs of thermoelectric materials. When an electric current passes through these materials, one cold and one hot joint are produced in the opposite terminals of each element.

Zhao et al. (2002) studied the numerical simulation of the effect of internal cooling under flank wear using orthogonal cutting. Using an internal device for heat removal in the tool reveals that is possible to reduce cutting temperature and flank wear. According to heat intensity removed by the device and the distance between the device and the interface tool-chip, good results can be obtained. For instance, with a device that removes 25W/mm^2, flank wear can be reduced by 15% and, depending on the distance, flank wear can be reduced by more than 11%.

The needs for green cooling methods that do not harm the environment and operators health, and at the same time are efficient in removing heat from the cutting zone, have been sought incessantly. In this sense, cryogenic fluids with very low temperatures have been considered an interesting alternative for this task since they present great heat removal capacity. Cryogenic expresses the study and utilization of materials at very low temperatures (below -150°C). Gases like, nitrogen, helium and hydrogen, when in liquid state, have temperatures below -180°C. Yildz (2008) remember that liquid nitrogen has been explored as a cryogenic coolant since the 1950s. In 1965, the Grumman Aircraft Engineering Corporation reported safe and successful tool life increases using N2 as a coolant in HSS turning and milling tools. However, great expenses and operational costs involved with subzero gas production delayed the development and growth 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 closest to the cutting edge.

The most studied method for liquid nitrogen use is through jet of nitrogen applied externally to the tool, at the cutting zone, as can be seen in the experiments carried out by Paul et al., (2001, 2006) and Hong et al., (2001). There is also the use of liquid nitrogen spray utilized in the works by Kumar and Choudhury (2007). Finally, the workpiece surface and chip cooling method also was proposed by Bhattacharya et al. (1993), Hong et al. (1999) and Hong and Ding (2001). Irrespectively of the method used in all these works, the results found by the authors indicated increase of tool life and improvement in machined surface roughness.

Yildiz (2008) divides cryogenic cooling methods in groups, according to the researcher’s application, as follows: (1) cryogenic pre-cooling workpiece by enclosed bath or general flooding, (2) indirect cryogenic cooling or cryogenic tool back cooling or conductive remote cooling, (3) cryogenic spraying or jet cooling, with flood or directed approach.

Wang and Rajurkar (2000) proposed a successful method for cryogenic cooling when machining difficult-to-machine materials like PCBN, Ti alloys, Inconel® and Ta alloys. In this method, a cap coupled over the cemented carbide insert creates a chamber were liquid nitrogen circulates, through an inlet and an outlet tube, so that there is a large contact area with the insert, consequently removing more heat from the tool. Results showed a considerable increase in tool life compared with dry machining. It was also reported that this system offers a stronger and more stable cooling than using liquid nitrogen sprays, without negative effects on workpiece dimensions. Khan and Ahmed (2008) presented a study about AISI 304 stainless steel machining with a TiCN coated carbide tool, using liquid nitrogen applied externally and in a small volume on the region of contact between the workpiece and the tool tip. The liquid nitrogen goes through inside the toolholder to a chamber just beneath of the insert and then by a narrow channel pointed at the workpiece-tool. In this study the tool life increased until 5 times compared with flood cooling.

In the pursuit for an environmentally correct and efficient cooling method, without any health risk, this paper aims to develop a system based on a toolholder for turning processes with internal cooling using a coolant fluid with liquid-gas phase change, flowing in a loop circuit. The effects of this cooling system on cutting tool life are analyzed and compared with the results obtained using conventional cooling system by flood, and dry machining.

2 Materials and methods

This project was developed based on the following considerations:

(1) Need to eliminate the amount of cutting fluids in machining operations, because of environmental and health issues, besides cost reduction.
(2) Current tendency to adopt dry machining or near dry machining like "green" processes.
(3) Need to control the temperature in the cutting zone, even without cutting fluids.
(4) Need to maintain tool wear within acceptable limits.
(5) Need to use methods with low energy consumption and low costs.

Thus, study on the use of internal cryogenic cooling was the inspiration to develop the concept of a toolholder with internal cooling fluid with phase change, once fluid in evaporation allows an efficient heat exchange, consequently an improvement in the removal heat from the cutting zone. Fig. 1 illustrates the schematic of the toolholder and cooling system proposed in this work.

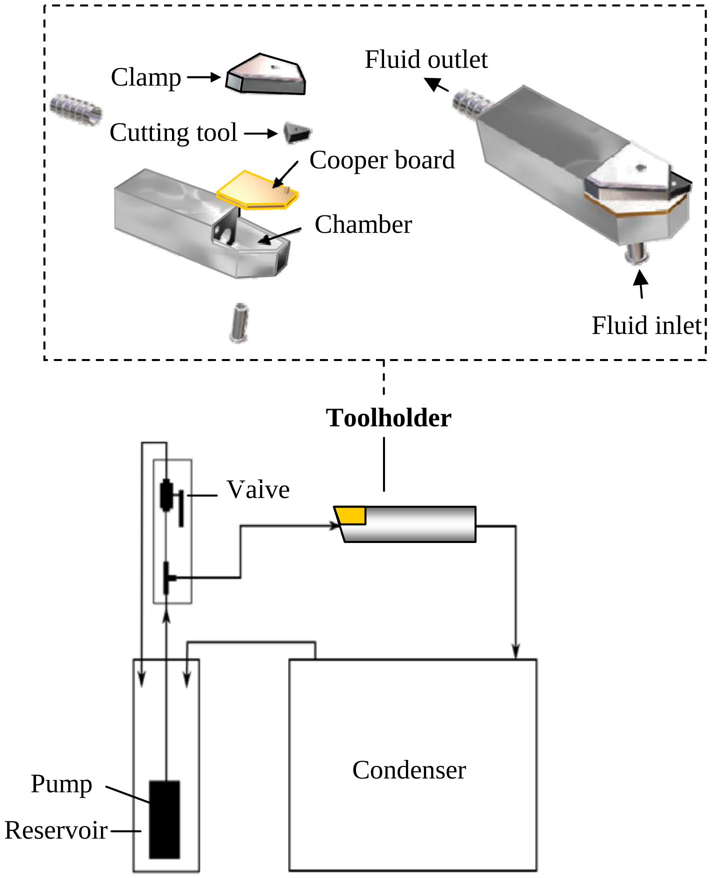

Fig. 1 Scheme of the cooling system (a) and toolholder (b).

The main materials used in the experiments are listed as follow:

- Cemented carbide inserts, class IC9015 and code TNMA 160408, without chip-breaker and with a triple layer coating of TiN, Al_2O_3 and TiCN.
- Toolholder with internal cooling made for this purpose, with rake angle of 6° and clearance of 5°.
- R-123 cooling fluid, used inside the toolholder for extracting heat of cutting tool.
- Automotive fuel pump, for gasoline and ethanol, employed for cooling fluid circulation.
- Semi-synthetic 4% soluble emulsion for use as the conventional cutting fluid.
- Conventional lathe machine with 7.5 kW of power.
- Taylor Hobson surface roughness tester, model Surtronic 3+.
- Digital camera coupled to a Nikon stereomicroscope, for flank wear measurements and aspect of chips produced in different cooling approaches.
- Type K thermocouples, composed of chromel-alumel, for measuring machining temperatures.
- Data acquisition system, comprised of an A/D board and LabView 10.0 software.

The workpiece materials used are round bars, 50 mm in diameter and 300 mm in length, made of SAE J775 XEV-F steel. This material treats of a Cr-Ni-Nb-Mn-N austenitic steel, made by the cold rolling process. Its machining is difficult because of low thermal conductivity, of 38.2 W/m.K, that concentrates heat at the tool tip, besides this material precipitates chromium carbides pretty deleterious to the cutting tool wear.

Fig. 2 presents a general view of experiment setting where can be observed the lathe with the toolholder (above), which is indicated the cooling fluid flow direction, and others important components of the cooling system as condenser and reservoir with pump inside it.

The cooling fluid chosen (R-123), a hydrochlorofluorocarbon (HCFC), is a fluid little aggressive to the environment in case of a leak of the cooling system, commonly used in refrigeration circuits with a boiling temperature of 28°C what permits its use at ambient temperature

The methodology adopted for the experiments basically consists of comparing results obtained for conventional cooling with cutting fluid, internal cooling with the toolholder developed in this work and dry machining. The variables to be measured and compared are average flank wear (VB_B) and nose wear, according to ISO 3685 (1993) standard. With this information it is possible to determine if the proposed cooling system has some advantage compared to the other two conditions.

In addition, surface roughness and samples of chips produced are analyzed as complementary information. The selected cut-off was 2.5 mm and chip deformation ratio was evaluated. Also, the temperature between the carbide insert beneath the surface and the copper board was measured using thermocouples for data acquisition in order to analyze the effect of cooling approaches on temperature during the process. Temperature values in each machining condition were recorded in the second pass of the cutting tool on the specimen, when it was observed the stabilization of the temperature.

Cutting parameters are the same for the three cutting approaches to permit comparisons without other influence. They were selected in preliminary tests so the values chosen were sufficient to ensure tool life of at least three passes, and thus measure tool wear gradually. These parameters are cutting speed (Vc) of 143 m/min, feed (f) of 0.43 mm/rev and depth of cut (ap) of 0.5 mm. After each pass, the tool machine was stopped and tool wear and surface roughness measured. The passes continued until average flank wear (VB_B) of 0.3 mm was reached, when nose wear was also evaluated.

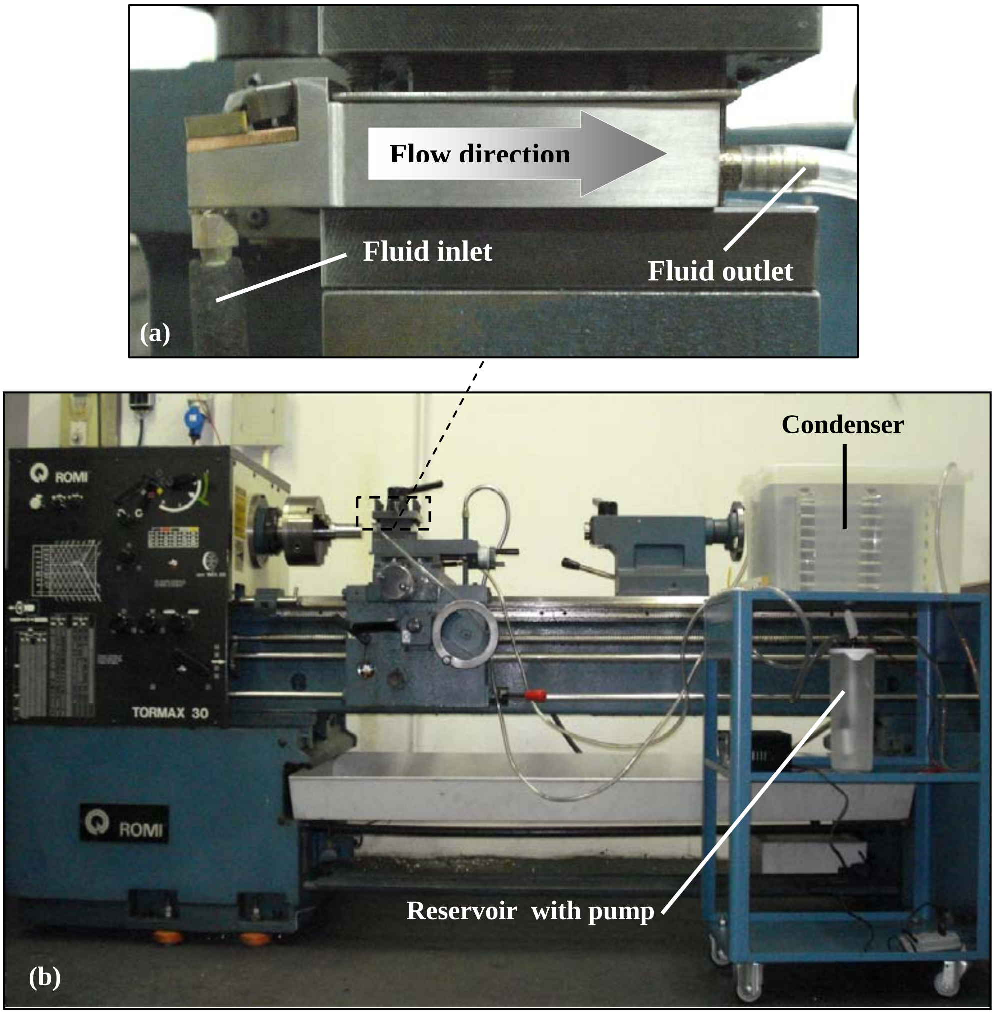

Fig. 2 View of experiment set up with toolholder (a), lathe and remaining of cooling system (b).

Results and discussion

The most important result of this study deals with tool wear in machining with coolant fluid in the phase change in the toolholder. The graph in Fig. 3 presents average flank wear in this condition compared to dry machining and to conventional machining, in which abundant cutting fluid is used on the backs of chips.

As can be observed, average flank wear for the three conditions is very similar until half way through the tests, approximately. After the fifth pass, tool wear rate in dry machining increases a little more than in the other two conditions, although without any major difference between them. The contained flank wear in the turning of material used in these tests recalls the difficult to machine nickel-based alloys, like Inconel ® and Waspalloy ®, in which they have hard carbides in their microstructure and low thermal conductivity, which makes tool heat dissipation difficult. In the tests carried out, both depth of cut and feed are little concentrating efforts and heat on a small chip contact area with the tip of the tool. In this situation, specific visualization of the tool flank is not the most indicated for evaluating cutting tool wear and life.

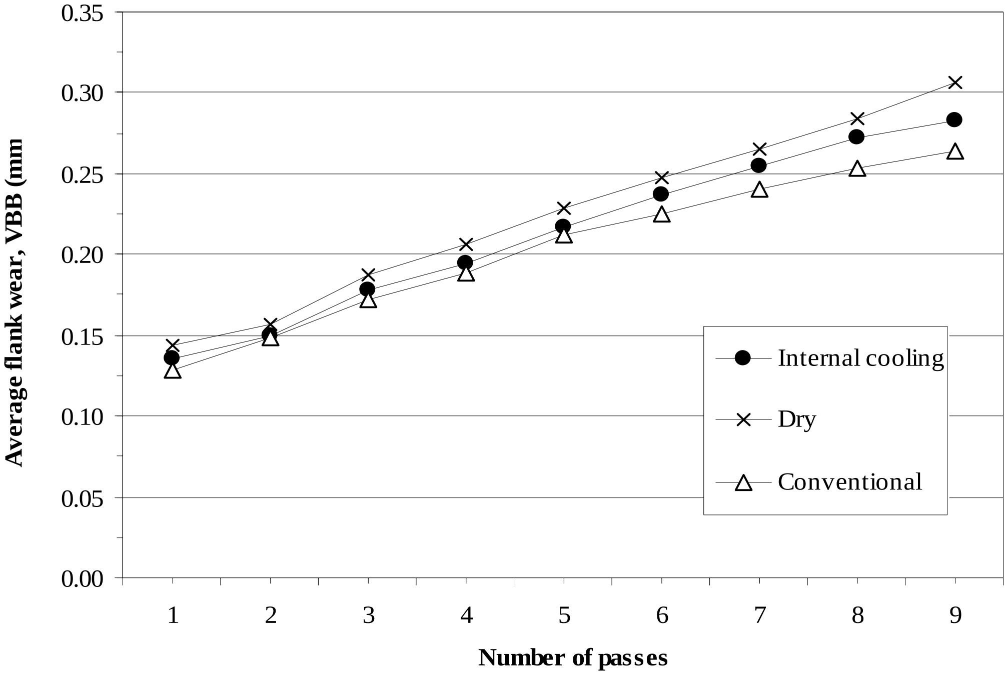

Fig. 3 Average flank wear for the tool at the end of each pass.

Another factor that points to the inadequate measuring of flank wear is its dissonant behavior with surface roughness, since improved finishing is normally expected with less flank wear. However, the best finishing was obtained in machining with the coolant fluid inside the toolholder, as seen in the graph in Fig. 4, which was not the condition that produced the least flank wear. Continuing with the information gathered in the tests, photographs of the tool flanks show little wear, and although with different values, the three conditions are similar. However, analysis of the tool tip is more conclusive since it shows more significant wear in this region that ends up converging with surface roughness results.

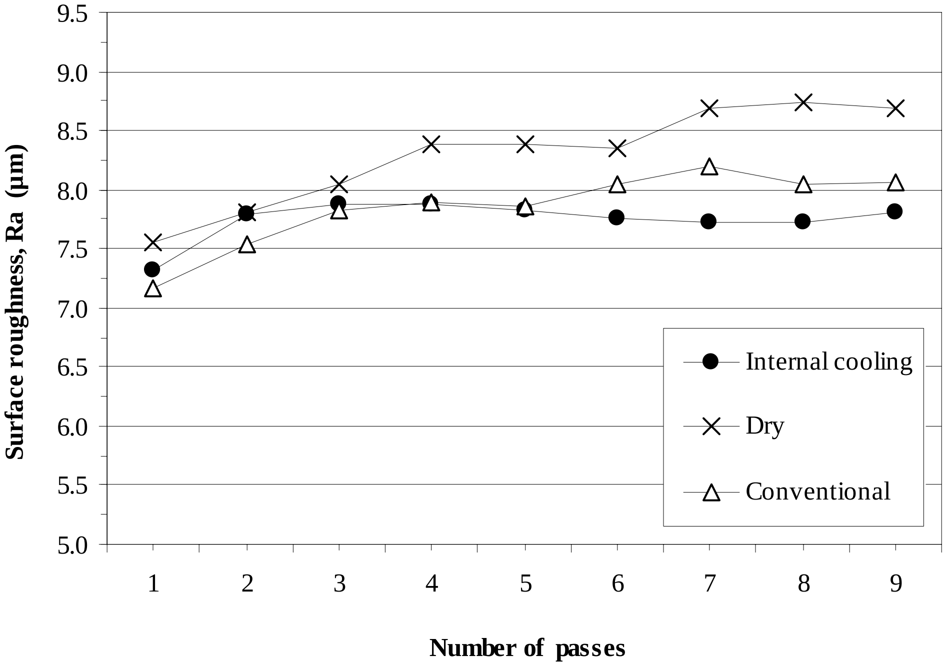

Fig. 4 Specimen surface roughness at the end of each pass in different conditions.

Due to greater representativeness of nose wear for analyzing the behavior of machining steel used in the tests, the graph in Fig. 5 was built, which it is possible to observe more moderate nose wear in the condition that uses the toolholder with internal fluid with phase change in relation to machining with the conventional application of cutting fluid, and notably less than occurred in dry machining.

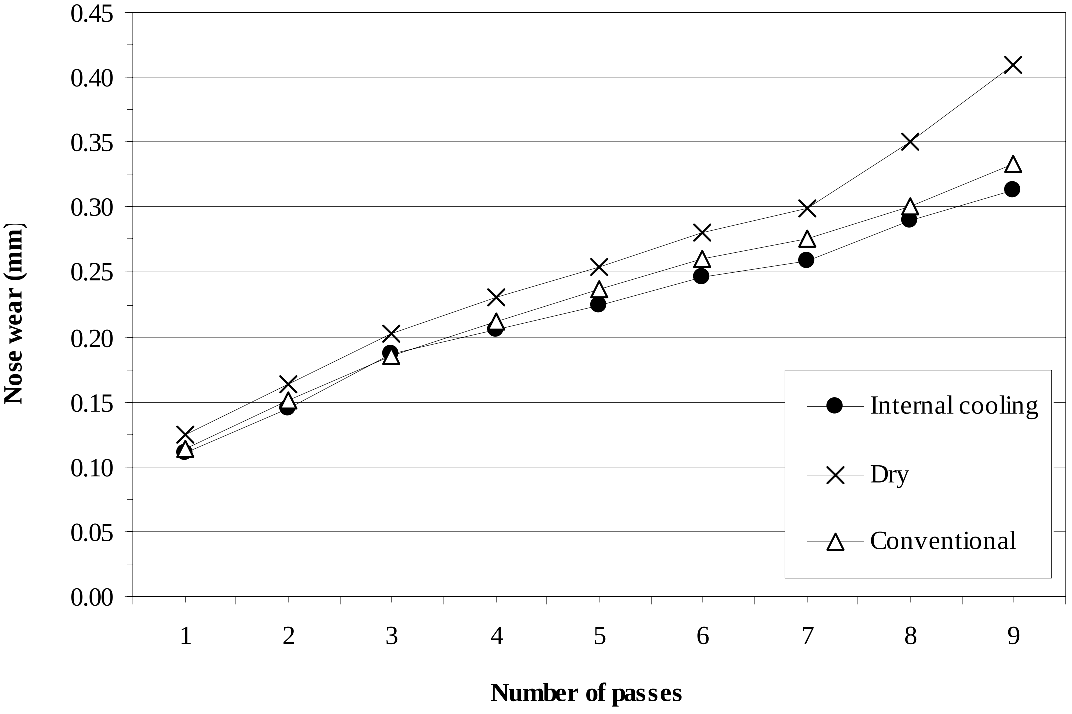

Fig. 5 Nose wear for the three machining conditions.

This result can be credited to greater heat removal from cutting tool in the two conditions in which it is refrigerated. Between these two conditions, the application of cutting fluid has a slight disadvantage due to the fluid's difficulty in reaching the region of intense heat generation located at the chip-tool interface

The relative temperature between the different machining conditions, measured by a thermocouple positioned between the bottom surface of the insert and the tool holder's copper plate is shown in Fig. 6. In the two machining conditions without application of cutting fluids, the temperature on the bottom face of the insert can be considered to be directly proportional to the cutting region in the chip-tool interface. In these two conditions, lost heat flows for the chip, piece and tool are similar and the results prove that the use of internal cooling is capable of substantially reducing cutting region temperature compared with dry cutting. Also, when cutting fluid is employed, a significant parcel of the energy generated in the cutting region is transferred to the fluid and contact of the fluid with the insert body cools its faces, contributing towards a reduction in heat flow to the toolholder where the thermocouple is positioned. As a result of this different form of dissipation of energy, the temperature inside the insert is not directly proportional to the temperature in the cutting region, as in the other two machining conditions. Thus, the lowest temperature measured with the application of external fluid may not imply in a greater reduction of the temperature in the cutting region. This hypothesis is still taken into consideration due to the encouraging results obtained for tool wear and surface roughness.

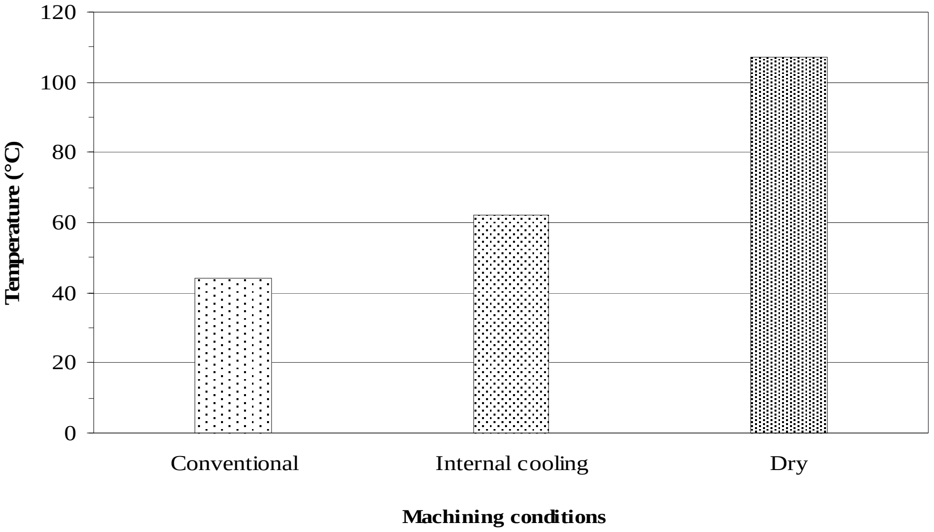

Fig. 6 Temperature in the different machining conditions.

Conclusions

With regard to the development and results of this study, some points considered important can be objectively underscored, such as:

The proposal of the toolholder system with internal refrigeration using a fluid with phase change is promising since the results obtained demonstrate that the heat was removed from the cutting tool.

In relation to dry machining, the proposed system offers clear economic gains mainly in the increase of tool life. When considering the machining with cutting fluid, the system is competitive once the costs involved with cutting fluids ends up being a significant part of the piece's total cost.

The proposed refrigeration system is simple, cheap and does not harm the environment since it is a closed system that does not consume coolant fluid.

Due to longer maintenance of tool tip geometry, the machining with the proposed system produces surface roughness values noticeably lower than with dry machining and even lower than with machining with cutting fluid.

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