NUMERICAL ANALYSIS OF THE TEMPERATURE FIELD IN A MODIFIED TOOLHOLDER DURING TURNING

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Abstract. *The machining process is, nowadays, an important process that is present in most of production lines of products and equipment. Therefore, an optimization that allows increase the rate of material removal from the workpiece represents an important component to reducing the cost of manufacturing. The temperature reduction on the workpiece-tool interface helps to increase tool life and provides greater robustness to the severe conditions of cutting. One of the methods that have been studied is the use of a tool holder with internal cooling, however to make it more efficient and economically viable, it is necessary to study the behavior of thermal energy in its interior to optimize the layout of pipes by where circulate the refrigerant fluid, thereby bringing better efficiency in heat removal and so reduce the temperature of the cutting region. This study proposes to develop a model of three-dimensional transient heat conduction, discretized by a non-uniform mesh, to evaluate the temperature and heat flux at any point of the set of tool and toolholder. The calibration of the virtual model of the set was made by using the finite element method, correlate with an experimental procedure of turning by using thermocouples to mensore the temperatures of one point in the body of the tool holder along the time. The results show that it is possible to obtain a good correlation of the model with the experimental results. The simulation shows itself as a great tool for improving the method of heat removal from the tool holder as it is a low cost method and can provide important information for the optimization of the dimensional characteristics of the equipment.*

Keywords: *Turning, Heat transfer, Numerical simulation*

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 by 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 surface finishing.

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 periods of exposure.

Hong and Broomer (2000) reported that, only in the USA, the volume of cutting fluids discarded into the environment can exceed 155 million liters per year. 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) discussed about the quantity of cutting fluids used in Germany and also the contribution 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 by 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 it can compete with the results achieved with cutting fluids.

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 and (3) cryogenic system, where a cryogenic fluid is conducted through a channel inside the tool.

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/mm2, flank wear can be reduced by 11% and, depending on the distance, flank wear can be reduced by more than 15%.

The needs for green cooling methods that do not harm the environment and operators health, and at the same time are efficient in heat removal 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 and Nalbant (2008) remember that liquid nitrogen has been explored as a cryogenic coolant since the 1950s. 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.

Yildiz and Nalbant (2008) divide 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 Ti 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.

Due to the high energy generation in machining process is proposed a toolholder with internal cooling to allow the dry cutting instead of conventional cooling, which uses flood external fluid. The method for evaluating the running of the device will employ parameters determined in experimental analysis of equivalent way to the technique of inverse problems. As reference parameter it will be used the temperature progress in a cutting determined tool point. By the use of this reference parameter it will be possible evaluate the heat quantity taken out by the cooling fluid. With this procedure it is possible verify its efficiency in the heat removal in relation to total heat flow that is introduced into the system and, with this, compare it with the efficiency obtained in the dry cutting without presence of any fluid.

2. MATERIALS AND METHODS

Understanding the process of machining and all the parameters involved is of crucial importance to this work. Therefore will be presented some considerations that determined the fundamentals applied on this methodology. An important zone at the machining process to be studied is the cutting region, where there is a contact between the tool and the workpiece material. The mechanical energy used for material removal from the workpiece is almost entirely transformed into heat in a small region near the edge, and many of the problems of machining are caused directly or indirectly by the action of high temperature that occurs there (Trent, 2000).

In the cutting region there are three main areas, represented schematically in Fig. 1, which are the main contributors to the generation of heat, the primary shear plane (region A of figure) where occurs the plastic deformation of the material; the secondary shear plane (region B) where occurs the chip deformation and friction at chip-tool interface; the friction between the tool and workpiece (region "C"). According to Trent (2000), at most of the cutting conditions is the "C" region that shows less warming. In general, the tool temperature is mainly affected by the secondary source of heat, however the primary heat source also contributes to its heating and indirectly affects the temperature distribution on the chip output surface.

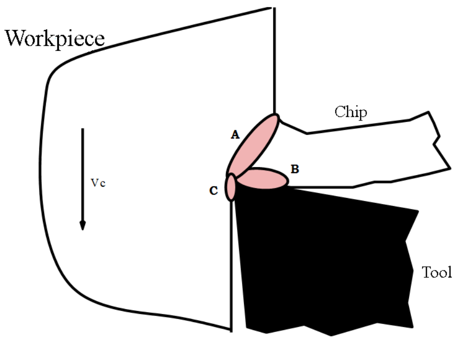
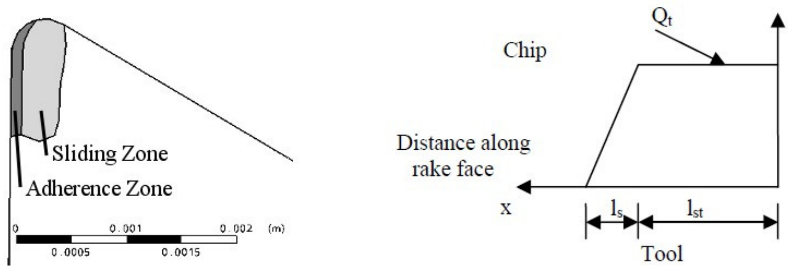


Figure 1. Main regions at cutting zone.

According to Shaw (1997) an analytical study allows a first approach of the distribution of heat generated due to plastic deformation of the material, so it must be assumed that: all the energy of deformation in the region "A" and Region "B" is converted into heat energy; That energy is concentrated on a flat surface and uniformly distributed; The heat generated is not dissipated into the environment during the formation of chips. Shaw also says that even with these approaches it is still complex to estimate the heat distribution since a portion of the energy from region "A" will be removed by convection by the chip and a portion will flow to the workpiece and, in region "B", a portion will be dissipated to the chip and an other will flow to tool.

As noted by Trent (1963), in the adhesion zone, the chip material in contact with the tool is practically stationary, and there is a zone of intense shear within the material portion of the chip just above the contact area, called flow zone, where there is a gradient of velocities. As shown in Fig. 2a, around the area of grip there is a region called the sliding zone where the interaction between chip and tool is governed by the friction condition of Amonton Coulomb's law due to lower normal stress there present and it decreases to zero where it loses contact with the tool.

Wright and Trent (1974) suggested that the phenomenon of contact along the length of tool-chip interface consists of adhesion and sliding regions, and the distribution of heat follows the same trend as the stress of friction, as shown in Figure 2b. The friction is distributed uniformly from cutting edge to the end of the adherence zone and then gradually decreases until the end of contact length. Assuming that all the energy resulting from friction is converted into heat, the authors concluded that the generation of heat may not be uniformly distributed along the chip output surface.



(a) Considered heating zones (b) Heat flux distribution

Figure 2. Main heat sources and theirs respective heat flux distributions.

2.1. Numerical Procedure

The toolholder domain, showed on Fig. 3, need to be solved by the conduction heat transfer differential equation. For this case was used the hypotheses of transient solution with constant physical properties and no volumetric heat generation. The contacts between all components were adopted as perfect and radiation heat transfer had being neglected. By this way, the conduction heat transfer differential equation for each component was represented by Eq. (1).

$$\rho . c_p . \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) + q \qquad (1)$$

The simulations were done using the ANSYS CFX® solver module. It was used a transient model for by simulating determine the internal energy evolution for all components of toolholder and each component was considered one domain, as represented on Fig. 3.

The physical properties of each material were adopted as constant for temperature variations ans was used the default values of the software except for the toolpiece. For the toolpiece material it was adopted the values used by Lima, (2001). The adopted values for each component can be seen on Tab. 1.

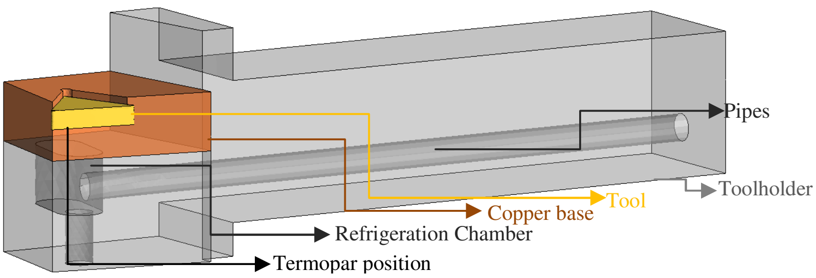


Figure 3. Representation of the toolholder components used in numerical simulations.

Table 1. Physical properties used in numerical simulations.

Domain	Material	Thermal Conductivity (W/m.K)	Density (kg/m^3)	Specific Heat Capacity (J/kg.K)
Tool	Tungsten carbide (1)	43,1	15800	173.33
Tool base	Copper	401	8933	385
Toolholder body	Steel	60.5	7854	434

(1): Property obtained from the literature (Lima, 2001)

The boundary conditions were determined or estimated based on physical processes observed on the experimental procedure. For this case, different boundary conditions on the surfaces were considered:

- **External surface of Toolholder, Cooper Base and Tool exposed to air:** an estimated heat transfer coefficient was adopted. The estimative is based on the fact that there is a combined effect with free convection and forced convection with $h=10\ W/m^2.K$. The ambient temperature was adopted the same of the toolholder startup temperature.
- **Refrigeration Chamber:** on this rerion the boundary condition depends on the simulation type. For the toolholder dry condition it considered that this surface was insulated. For the case of toolholder with internal refrigeration the heat flux is transferred to fluid by convection, the value of the heat transfer coefficient for this case was adopted to better coincide with experimental results and the bulk temperature of the fluid is the temperature of phase change. It shall be noted that, initially, it was proposed a defined temperature condition on surface but the representation of the experimental results for this case was not consistent.
- **Heating Zone**: is represented by two different surfaces: the Adherence Zone (Zad) and the Sliding Zone (Zes). For the Adherence Zone it was assumed an area of same size of the non-deformed chip and boundary condition of second kind or specified heat flux. The Sliding Zone was approximated as the rank wear area. The total heat flux for this region was iteratively determined based on the coincidence with experimental results obtained from the experimental procedure. Was assumed the hypothesis that the heat flux on the 'Zes' is half of the 'Zad', consideration adapted from the hypotheses of heat flux change with distance presented on Fig. 2.

2.2. Experimental Setup

The machining experiment aims to calibrate the numerical model by comparing the measured temperature with the temperature obtained in simulation for certain control points. The tests aim to represent cutting conditions usually used in different situation. The procedure developed for that consists on preparation of workpieces, assembling the refrigeration system and temperature measurement system, and then proceed with the tests and processing of results.

The workpiece specimens for the tests consists of a cylindrical body of a heat-resistant austenitic steel, hardenable by precipitation, of type Chromium-Nickel-Manganese-Nitrogen-Niobium, produced by the steel rolling process under the Villares Metals VV56 trade name. The dimensions of the specimen are 155 mm length by 50 mm diameter and 1mm x 10º chamfers on the faces to allow smooth entry of the cutting tool in machining.

The toolholder used is a prototype with dimensions similar to a conventional, but with a refrigeration chamber near the seat tool, called as "cold pool", connected by pipes to an external circulation system, responsible for maintaining a constant flow of refrigerant fluid type R22. The aim is that the fluid reaches the phase change (which occurs at a temperature of 24 ºC at 1 atm), thus improving heat removal from the machining region. The same toolholder is used for both methods, but in dry cutting the refrigeration chamber and the pipes are intended to be filled with stagnant air.

Was employed a K-type thermocouple positioned just below the tool, a region where there is an expectation of higher temperatures. The thermocouple was housed in a small cavity made in the body of the toolholder, was applied a thermal paste to improve the thermal contact condition. In Figure 3 you can see the position of the thermocouple and the characteristics of the prototype.

Table 2. Cutting paramiters.

Method aplied	Dry cutting				With internal cooling system			
Experiment	**Test**	**1**	**2**	**3**	**1**	**2**	**3**	**4**
Feed rate (mm/rev)	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1
Depth of cut (mm)	0,5	1	1	1	1	1	1	1
Cutting speed (m/min)	102	121	118	166	151	167	122	107

For the established methodology for the experimental procedure were made two cuts in each workpiece for each test. The tests were repeated for different cutting speeds to examine the severity of each in each method of cooling. The initial and final diameter of the workpiece was used to calculate cutting speeds mean, described in Tab. 2.

The acquisition of temperature data was made at intervals of 1 second by a National Instruments® hardware. The data were exported in format. "ASCII" to be plotted the curves of temperature versus time.

3. RESULTS AND DISCUSSIONS

The behavior of the heating curve a point near to the heat source has a characteristic similar to an exponential curve, differing only by having an inclination almost constant of temperature after a defined time, it is possible note this kind of behavior at the experimental curves. Thus, the analysis of the behavior of the temperatures at the point will be based on split the curve in two distinct regions that represent each of these steps. The periods of each will be characterized by the times represented by "t1" and "t2" as shown in Fig. 4. To simplify the comparison of results, the second period was approximated by a straight average obtained by linear regression of the curve to a common interval for all tests.

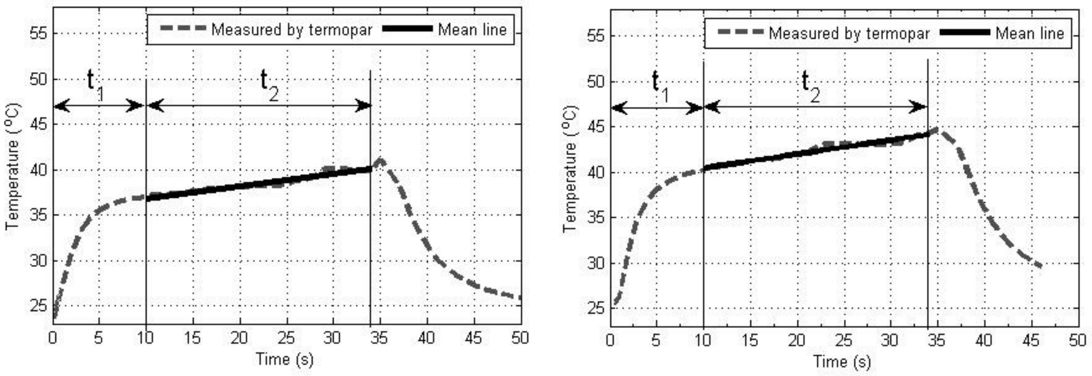


Figure 4. Time characterization for different regions "t_1" and "t_2" on temperature evolution.

The heat flux entering the system has influence on the rate of temperature change, the peak temperature and the moment of transition between the two periods. For higher heat fluxes, the transition time from first to second period is greater and there are higher temperatures and steeper inclination.

The experimental results were used to allow the determination of some parameters of the proposed problem. The adjustment was done using the principles of inverse problem but using an iterative correction of the parameters until which the representation of the physical test were adequately represented by the numerical model. The simulation of an equivalent time to the experimental test and comparison of heating curves for respective points resulted in the boundary conditions are presented in Tab. 3.

Based on these parameters determined from the experimental tests was possible to verify the behavior of the temperature profile for a larger machining time: 30 minutes continuous. For the model with cooling was used an average heat transfer coefficient for the surfaces in contact with the fluid, hi = 1850W/K.m2.

This increase in time of the process allows the heat diffusion to reach regions of the toolholder further away from the energy source. For dry cutting, in which the only way to dissipate heat is to the environment by natural convection, the heat transfer coefficient at external surfaces becomes a factor for the equilibrium condition. Were simulated two values of "hext", 10W/K.m2 and 35W/K.m2 , the first is a value widely used in solving problems of natural convection, which is the value adopted as the reference and the second is the highest value found in the bibliography searched for natural convection (INCROPERA and DEWITT, 1998).

Table 3. Numerical parameter estimated by experimental tests performed.

Model simulation	Cut	Heat Transfer Coefficient at External Surfaces (W/K.m2)	Heat Transfer Coefficient at Internal Surfaces (W/K.m2)	Heat flux at "Zad" (W/m2)	Heat flux at "Zes" (W/m2)
Dry cutting	1st	10	Adiabatic	108	5.107
	2nd			8,15.107	4,08.107
With internal cooling	1st	10	2000	8.107	4.107
	2nd		1700	9,1.107	4,55.107

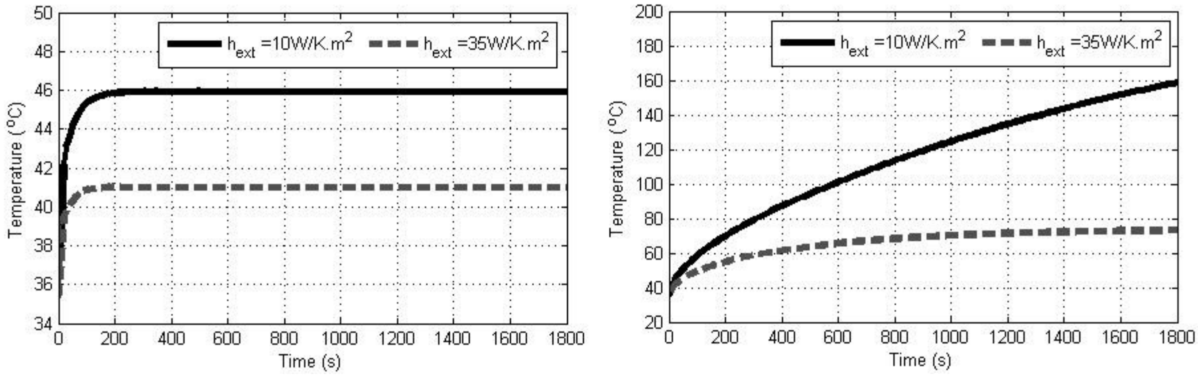


Figure 5. Effect of external heat transfer coefficient on long term solution.

The results for the evolution of temperature profile at the point where the thermocouple was placed on the experimental test are shown in Fig. 5. Firstly, it is noticed that there is a wide difference in the time required to reach steady state between cases with and without coolant. Based on the time used for tests, about 40 seconds, notice that the internal cooling system has almost reached its steady state, but the dry method still tends to suffer a strong warming over time. In fact, for dry cutting system does not perceive a clear condition of steady state even after 30 minutes have elapsed. In the case of higher heat transfer coefficient this condition appears to be closer. The variation of the heat transfer also implies a significant change in the temperature profile for dry cutting, reaching a difference of up to 100 ºC at the hottest point, been occurred at a critical position of the tool.

Although less susceptible, the case with internal cooling also shows variations for temperature profile. Considering the values of maximum temperature on the tool there is very little variation in temperature, a decrease of about 6 °C due to the rising value of "hext", whereas the temperature in the cutting area is about 1000 ºC indicating that this is a parameter of minor influence in this situation.

The confirmation of the presented justifications can be made using the Fig. 6, which allows for a comparison, showing the contribution of each mechanism in heat dissipation in each model. By analyzing these results it is possible to verify that when over the presence of the coolant to heat loss through the outer surface takes a secondary role, contributing approximately one fourth of the total heat extracted. Thus, the energy transmitted directly to the internal fluid allows the system to reach steady state quickly and contributes to the reduction of temperature on the whole set, mainly at the chip-tool contact. This implies, according to what is available in the literature, in longer tool life. Although this phenomenon is difficult to verify in short test, the results show that they would be far more efficient in the case of long-term processes.

In Figure 6 it is possible to confirm the hypothesis that the condition of steady state was not reached for the case of the toolholder without internal cooling. A quick review of the final condition for this case shows that the rate of heat produced is lower than the value that is provided by the machining process. As in this case the surfaces of the chamber is considered as adiabatic, the energy balance in the tool indicates that part of the energy is still being used to heat the toolholder. Thus, there is a tendency in these cases of increases the temperature. For the case of machining with internal cooling the sum of the heat extracted by the cavity and the external surface are compatible with the value of the energy supplied to the set. Thus, the condition of steady state was obtained and there is no tendency of increasing temperature.

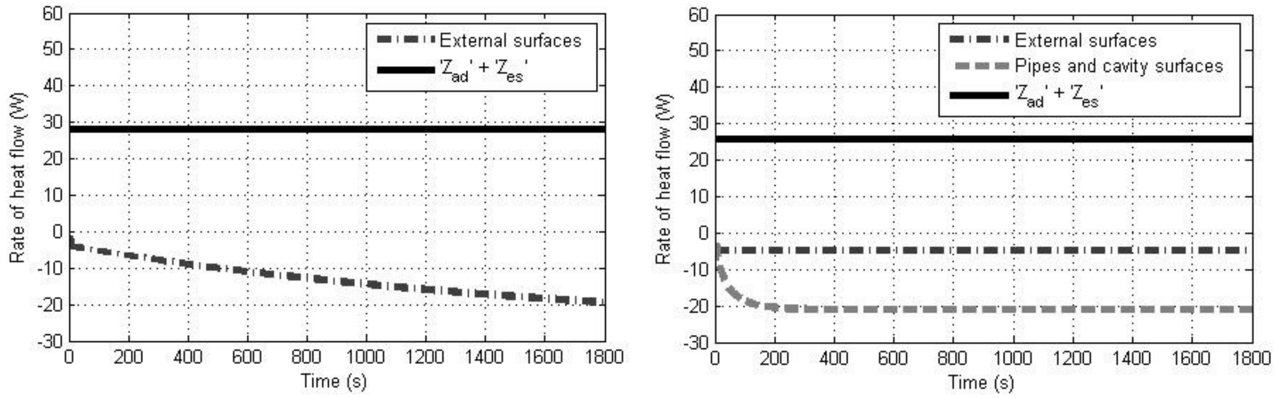


Figure 6. Global heat removal by external convection and refrigeration chamber.

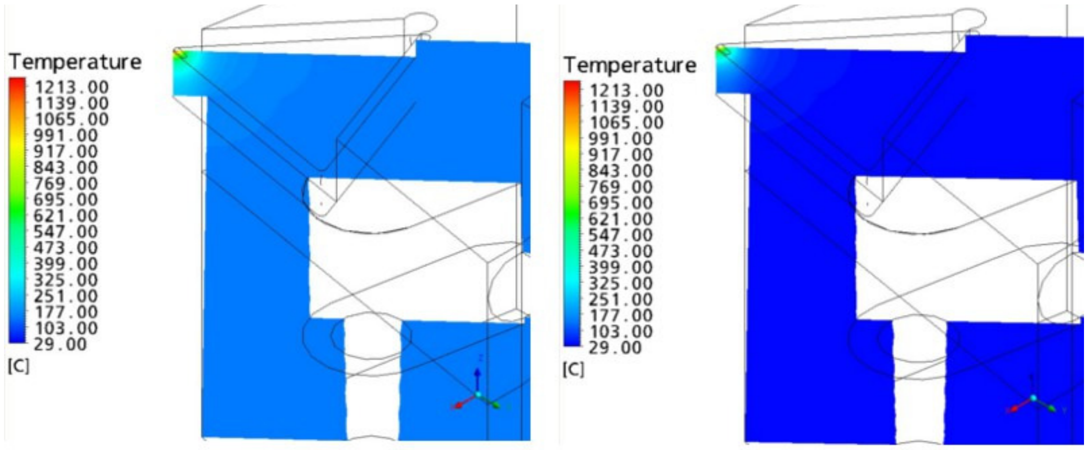


Figure 7. Temperature profile on toolholder machining cross section.

The Figure 7 shows the behavior of the temperature profile in a cross section after 30 minutes of machining to the cases with and without internal cooling, using the hext = 10 W/m²K. There is, in this case, a steep thermal gradient formed in the vicinity of the tool. Moreover, observing the scale, it is possible to note the significant temperature differences between the situations with and without coolant, it can be noted that temperatures in the system without internal cooling are significantly higher. An example of this is that after 30 minutes of machining the cutting edge temperature in the dry cutting continues to rise and has reached the value of 1243 °C. This temperature is close to the sintering temperature of the hard metal found in the literature, that is around 1400 °C, which certainly commits the hot hardness of the material. Otherwise the internal cooling allows the maintenance of the temperature to about 1027 °C, virtually the same as achieved in the first 10 seconds of machining.

The behavior of heat flux on the walls of the chamber to preset conditions can be seen in Fig. 8. In this case it is possible to observe that most heat dissipation occurs in the region closest to the tool and therefore also has the highest temperatures. However it is worth noting that copper acted as a great diffuser for the system, since the heat flux on the upper surface were uniformly distributed over the top of the chamber and the heat flow values were higher than the side closest to the cutting region.

Based on this analysis we can deduce that the factors of higher influence on the efficiency of the cooling system proposed are the format and dimensions of the fluid chamber arranged just below the base of the tool and the material of the base. An analysis of these parameters settings contributes to the optimization of the system, so is then applicable to verify the influence of each. The distribution of heat flow and the rate of heat transfer from the surface of the cooling pipes are directly proportional to the temperature gradient and the surface area, respectively.

Although the tool base made of copper represents a significant thermal benefit, it can, moreover, reduce the structural stiffness of the system and causes deformation of the copper, changing the projected angles of cutting. Thus, it is interesting to note the effects of using steel as the material of the tool base and analyze the thermal behavior of the system. Fig. 9 presents a comparative analysis of heat flow for the two cases and is easy to note that the use of steel provides a significant reduction in the intensity of heat flow in the initial instants. This phenomenon indicates that there may have been a large increase in thermal resistance of the system.

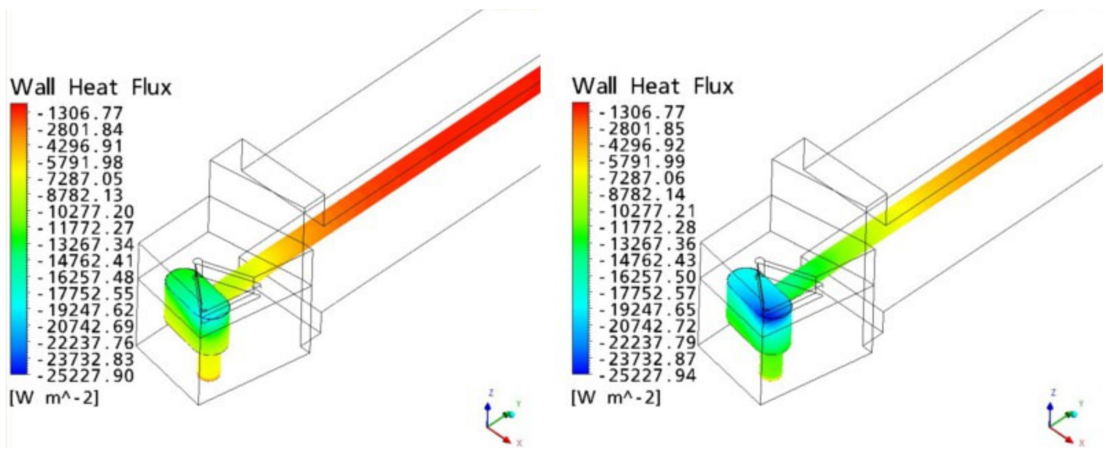


Figure 8. Temperature profile for refrigeration chamber surface using cooper base for tool.

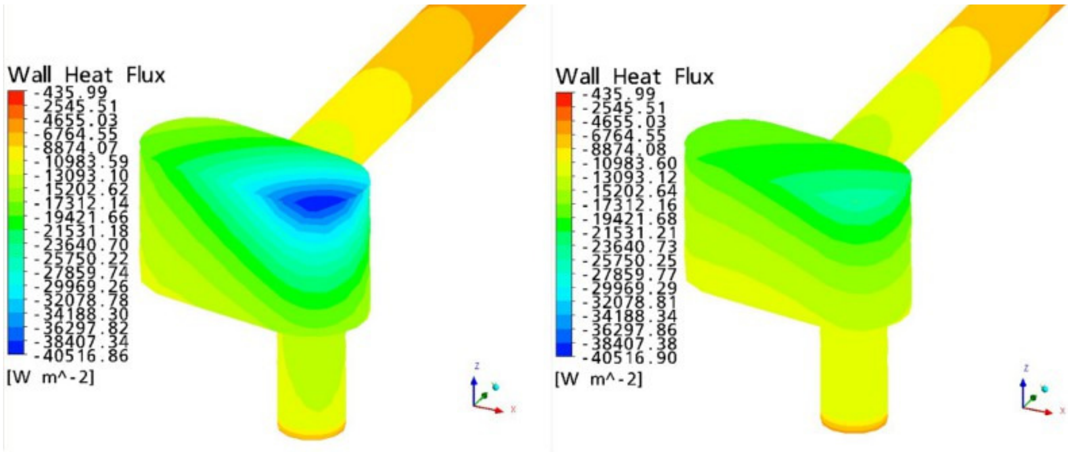


Figure 9. Temperature profile for refrigeration chamber surface using a steel base for tool.

The Fig. 10 shows the results for the temperature distribution using a tool base made of steel. The thermal balance and balance of heat fluxes were observed, indicating that the condition of steady state was also achieved in this case. However the figure shows changes in the level of temperature, indicating changes on thermal resistance of the system. These changes were caused by the lower thermal conductivity of steel which induced an increase in temperature of the tool tip. For this case the maximum temperature reached 1108.2 °C in 30 minutes of machining, an increase of about 80 °C if compared to the simulation with the copper base. This increase in temperature in the machining region makes unfeasible the use of this approach. An alternative would be to keep the base steel, but using a smaller thickness. Although this is a possibility, it was not analyzed in the context of this work.

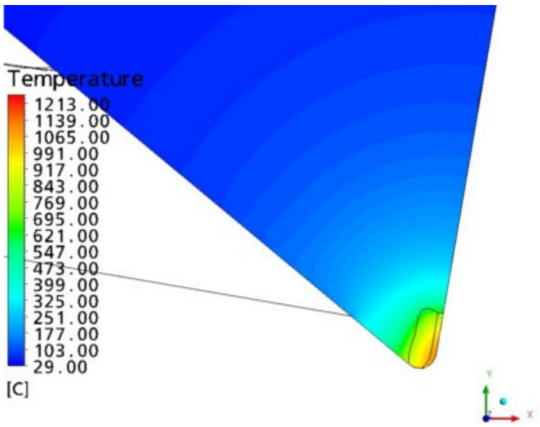


Figure 10. Temperature profile on tool using a steel base.

5. CONCLUSIONS

The development of this work has shown that there are good prospects for the functioning of the mechanism proposed in longer machining times, though its effectiveness can be verified only after a certain time of machining. Beyond this fact, it is also worth mentioning:

- When using the internal fluid the condition of steady state is reached in a shorter time and temperatures in the cutting region were lower as well;
- With the tests and simulation was observed that the numerical model calibrated by the experimental data showed results physically consistent and provided important parameters for further analysis;
- It was shown numerically that the effectiveness of the toolholder with internal cooling is only noticeable in machining processes that exceed the time required to reach steady state. During heating both the model, with and without coolant, has similar behavior.
- The importance of a better estimation of the external heat transfer coefficient is restricted to dry machining process with time enough to effectively heat the outside of the toolholder;

- Numerical analysis of replacing the tool base made of copper for steel resulted in a significant increase in temperature in the area of machining, although the time to reach the steady state condition was remained low. More detailed studies to determine a structure that combines the heat dissipation and structural rigidity must be made;

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