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TEMPERATURE FIELD DETERMINATION OF A TUNGSTEN CARBIDE CUTTING TOOL USING INVERSE PROBLEMS AND COMSOL

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Abstract. *In this paper, a methodology is presented to estimate the heat flux generated in the contact region between the chip and the tool. In the estimation of heat flux, a comparison is made between three methodologies: Classic Specified Function (SFSM), iterative SFSM and Time Traveling Regularization (TTR). With the estimated heat flux the temperature distribution in the cut region was calculated, the tool hotspot and the influence of the aluminum oxide and titanium nitride coatings on the tool was analyzed. The estimated heat fluxes had little variation between the different techniques used and the temperature had the biggest difference about 3% in relation to the experimental one. The aluminum oxide coating presented a higher reduction of temperature in the cutting tool when compared to the titanium nitride coating.*

Keywords: Inverse Problem, Turning Process, Numerical Heat Transfer, Optimization, Tungsten Carbide

1. INTRODUCTION

In machining processes, such as turning, practically all the mechanical energy involved in the cutting is transformed into thermal energy, that is, it converts into heat. Heat is associated with the plastic deformation of the material, the formation and the shear of the chip and, to a lesser extent, the friction between chips and the output surface. It is estimated that about 10% of the heat generated in the turning process is driven by the cutting tool. At first, this percentage may not seem to be of great significance, however, not rarely, this heat may cause the cutting tool to reach temperatures up to 1500 K. (Diniz et al., 2013). The development of high temperatures makes the cutting tool more susceptible to wear, mainly due to the diffusion phenomenon, which is stimulated by the increase in temperature, and due to the reduction of its hardness, which leads to the appearance of abrasive wear. In addition to wear, which results in a shorter service life of the carbide inserts, the heat causes the dilatation of the tool, thus making it difficult to obtain fine tolerances and high qualities in surface finishing. As presented, the heat and the high temperatures that affect the cutting tool cause several problems to the turning process, therefore a thermal analysis is of fundamental importance in order to obtain more efficient cutting tools and to improve productivity in machining processes.

The use of coatings for cutting tools has been widely disseminated as a way to reduce wear, including those resulting from thermal effects. Previous studies have already shown reductions of up to 375 K in coated inserts compared to uncoated ones (Marusich et al., 2002). Brito et al. (2009) have carried out a thermal study of how the coating layer thickness influences the diffusion of heat in the cutting insert. The coated carbide inserts represent about 80-90% of the cutting tools used in the machining industry (Sandvik, 2018). Thus, in the thermal study of cutting tools, it is important to perform an analysis in this type of cutting insert. In this work, the thermal behaviors of three different tools are compared: one coated with titanium nitride (TiN), one coated with aluminum oxide (Al_2O_3) and one without any coating.

The responsible for the high temperature in the cutting tool is the heat flux generated while machining, and it depends on the cutting conditions used in the cutting process. Therefore, the knowledge of this flux is important for the characterization of the thermal stresses to which the cutting insert will be subjected. The estimation of the heat flux is obtained by means of Inverse Heat Conduction Problems (IHCP), which, in short, is the creation of mathematical models in which it is possible to accurately represent the physics of the thermal problem without the need to spend time and money on experimental procedures. As pointed out in Carvalho et al. (2006), the direct and experimental measurement of temperature in a metal insert during turning is difficult, due to the machining movements, severe conditions and accessibility restrictions in the regions of interest. In this way, it is applied the inverse problems in heat transfer in the machining area, in which there are many processes where parameters are unknown or impossible to measure directly. Often, the analytical solution to these problems is difficult to obtain or even impossible because of the complexity of the mathematical terms involved. Therefore, a numerical solution of the thermomechanical model is chosen because it has

fewer restrictions and does not require hermetic conditions (Abukhshim et al., 2006). The Finite Element Method (MEF) was used in order to determine the heat flux and to make possible the thermal analysis. The techniques of the Sequential Function Specification Method (SFSM) and Time Traveling Regularization (TTR) (Silva et al., 2018a) are used together.

Many papers about machining processes have been published using IHCP. Among them, the work of Carvalho et al. (2006), in which a mathematical model was developed to estimate the surface heat flux of a carbide cutting tool in turning machining; Huang et al. (2018a) have developed a method for estimating the online heat flux in the cutting tool during a turning machining process; Huang et al. (2018b) has improved the thermal model used to estimate the heat flux in turning considering that the heat flux is a function of space and time in the contact region between chip and tool.

The present work presents a thermal study of a carbide cutting tool during turning process, in different configurations. Therefore, the objectives of the article are: the estimation of the heat flux to which the cutting tool is subjected during the turning process and the determination of its temperature distribution, as well as the identification of its hot spot. After that, a thermal analysis of the influence of the coatings on carbide cutting tools was performed.

2. METHODOLOGY

2.1   The thermal model

Due to the large temperature variations during the machining process, a non-linear thermal model should be considered. As showed in Fig. 1, the domain is composed of three subdomains: cutting tool (Ω_1), tool holder and chock (Ω_2 and Ω_3) and coating (Ω_4). Each subdomain has its own thermal properties, which are functions of temperature. Considering a transient heat flux $q(t)$, the problem is modeled by the transient and non-linear equation of heat diffusion, Eq. (1.a), as well as the initial condition, Eq. (1.b), and the boundary conditions of prescribed flux, convection and radiation, Eqs. (1.c – 1.e).

$$\frac{\partial}{\partial x}\left(k_j(T)\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_j(T)\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_j(T)\frac{\partial T}{\partial z}\right)=\rho_j(T)c_{p_j}(T)\frac{\partial T}{\partial t} \tag{1.a}$$

$$T(x,y,z,0)=T_\infty \tag{1.b}$$

$$-k_j(T)\frac{\partial T}{\partial n}=q(t) \tag{1.c}$$

$$-k_j(T)\frac{\partial T}{\partial n}=h(T-T_\infty) \tag{1.d}$$

$$-k_j(T)\frac{\partial T}{\partial n}=\varepsilon\sigma\left(T^4-T_\infty^{\ 4}\right) \tag{1.e}$$
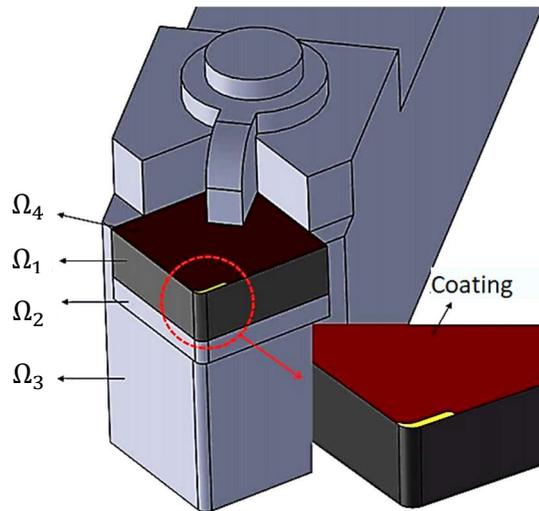

Figure 1. Model (domain and subdomains).

2.2 The inverse problem of heat flux estimation

To estimate the heat flux at the tip of the cutting tool it is necessary to minimize the objective function S, which consists of the sum of the square of the residuals between the experimental temperatures, Y, and the estimated temperatures, T, as shown in Eq. (2).

$$S = \sum_{i=1}^{r} \left(Y_{m+i-1} - \hat{T}_{m+i-1} \right) \tag{2}$$

There are several methods for solving a inverse heat conduction problem. In this work, it is compared the solutions of three techniques: the Time Traveling Regularization (TTR), method that can be verified in (Silva et al., 2018b); the classical Sequential Function Specification Method (SFSM) (Beck et al., 1985), whose estimated temperatures are calculated by an approximation of Duhamel's Theorem; the iterative Specified Function Method (Woodbury, 2003), in which the estimated temperatures are calculated through a Taylor series approximation and the heat flux value is corrected iteratively over the same time interval.

In the SFSM, a numerical approximation of Duhamel's theorem and the functional form constant given by Eq. (3) are used, the temperatures of a given coordinate can be calculated only by knowing the initial temperature, the heat fluxes, q_m, and the coefficients of thermal sensitivity, X_i, from previous time points.

Equation (4) shows the use of the Duhamel integral approximation for the calculation of the T_m temperature, the estimated temperatures are calculated as a function of the heat flux, as shown in Eq. (4).

$$q_m =/q_{m+1} = \cdots = q_{m+r-1} \tag{3}$$

$$\hat{T}_k = T_0 + \sum_{n=1}^{k} q_n \Delta X_{k-n} \tag{4}$$

where k is the time index, and X is the thermal sensitivity coefficient that is defined by Eq. (5):

$$X_m(r,t) = \frac{\partial T(x,t)}{\partial q_m} \tag{5}$$

where r is the vector representing the position of the temperature sensor in the domain. In this way, the heat flux can be calculated directly at each time interval m by Eq. (6).

$$q_m = \frac{\sum_{i=1}^{r}(Y_{m+i-1} - T_{m+i-1})X_i}{\sum_{i=1}^{r} X_i^2} \tag{6}$$

.

In the iterative SFSM, the estimated temperature is calculated as a function of the heat flux variation term Δq, as showed in Eq. (7).

$$\hat{T}\Big|_{q+\Delta q} = \hat{T}\Big|_{q} + \frac{\partial T}{\partial q}\Delta q \tag{7}$$

Thus, the flux increment is calculated through Eq. (8), while the heat flux is computed iteratively by Eq. (9):

$$\Delta q = \left([X]^T[X]\right)^{-1}[X]^T\left([Y]-[T]\right) \tag{8}$$

$$q_m^{(i+1)} = q_m^{(i)} + \Delta q_m^{(i)} \tag{9}$$

all the terms on the right-hand side of Eq. (8) are vectors of length r.

In the TTR technique for each time step a value is given for the initial interval in which is contained the heat flux that minimizes the S function. In this method the estimated temperatures are calculated numerically in each iteration by

COMSOL. These temperatures are exports to another program through the COMSOL Livelink, in which it is implemented the Golden Section Method that optimizes the objective function *S*. Once the method converges to the current time step m, it proceeds to step with a new value for the initial heat flux interval.

In this paper, experimental data from Carvalho et al. (2006) were used. The experiment was carried out in a common lathe with a carbide tool machining gray cast iron. A type K thermocouple was attached to an accessible region of the tool. The cutting conditions were: cutting speed of 2.25 m/s, feed rate of 0.00014 m/revolution and depth of cut of 0.003 m. Figure 2 presents the contact area between the chip and the cutting tool which was determined experimentally. In an electronic microscope the worn-out region was verified after machining and with the aid of an image analysis software, it was possible to accurately model the surface and export it to the three-dimensional model. The area corresponding to the boundary condition of heat flux is 0.000000411 m².
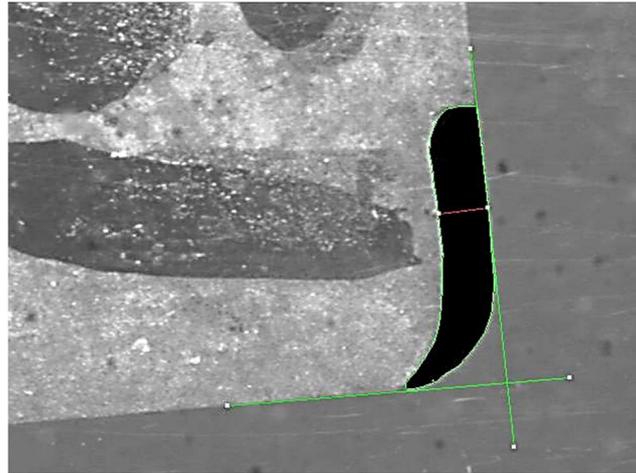

Figure 2. Contact area between the chip and the cutting tool seen by a microscope (Ferreira, 2017).

3. RESULTS

The turning process lasted around 60 s and the temperature data were acquired with a time interval of 0.5 s. The chosen point for the fixation of the thermocouple was initially at 203.9 K and reached a maximum temperature of 460.3 K.

In Fig. 3a, it can be noticed that the iterative techniques TTR and iterative SFSM obtained results with little divergence. The classical SFSM technique presented a heat flux curve with lower values and a little delay. Figure 3b shows the temperatures calculated from the estimated heat fluxes and they are compared with the experimental temperature.

It is possible to notice that in regions of great variation of heat flux great errors occur in the calculated temperatures. It is also observed that for this case, the temperatures calculated through the heat flux estimated by the classical SFSM technique obtained lower residue with a mean of 0.274 K and a standard deviation of 2.828 K. The other techniques presented similar results with a mean of 4.023 K for TTR and 3.560 K for iterative SFSM. In contrast, the lowest standard deviation in residue data was 2,690 K for TTR and the highest was 3.116 K for iterative SFSM. The largest difference between the experimental and numerically estimated temperatures represents only 3.2% of the temperature variation during the experiment.
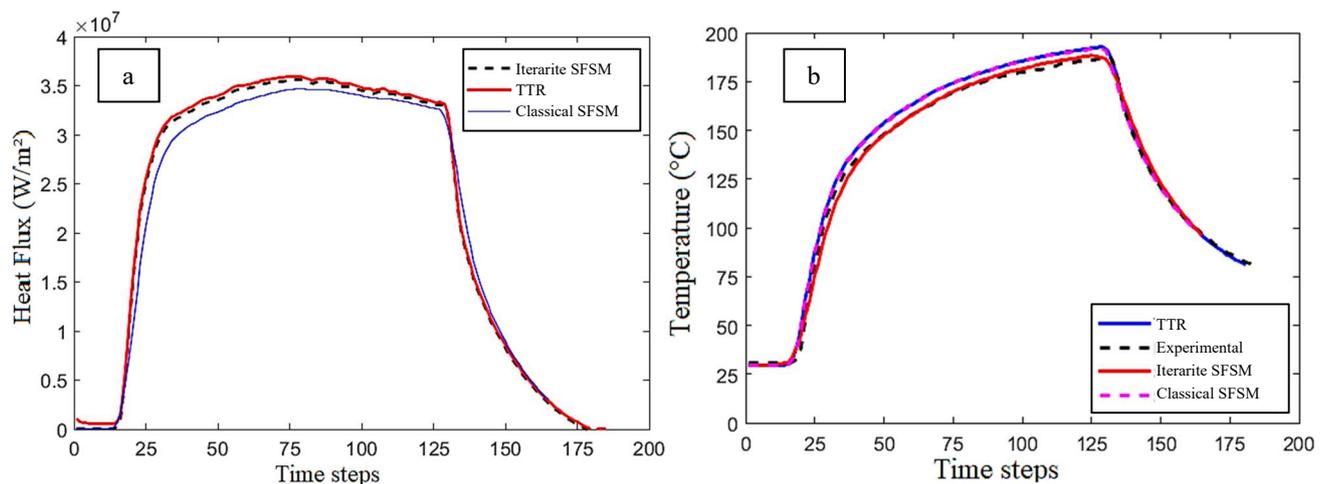
Figure 3. Estimated heat flux (a). Experimental and estimated temperatures (b).

Through the estimated heat flux, it is possible to calculate the temperature distribution throughout the tool over time Fig. 4b). Thus, it is possible to have an estimate of the maximum temperatures that act on the insert in order to predict its mechanical behavior. The tool hotspot, that is, the point that reaches the highest temperature is in the coordinates (x; y; z) = (0.0005808; 0.0000306; 0) m and reaches the maximum temperature of 1141 K. Figure 4a shows the position of the hotspot relative to the origin and the temperature distribution on the upper face of the cutting tool for time 41 s (time at which the process reaches maximum temperature).
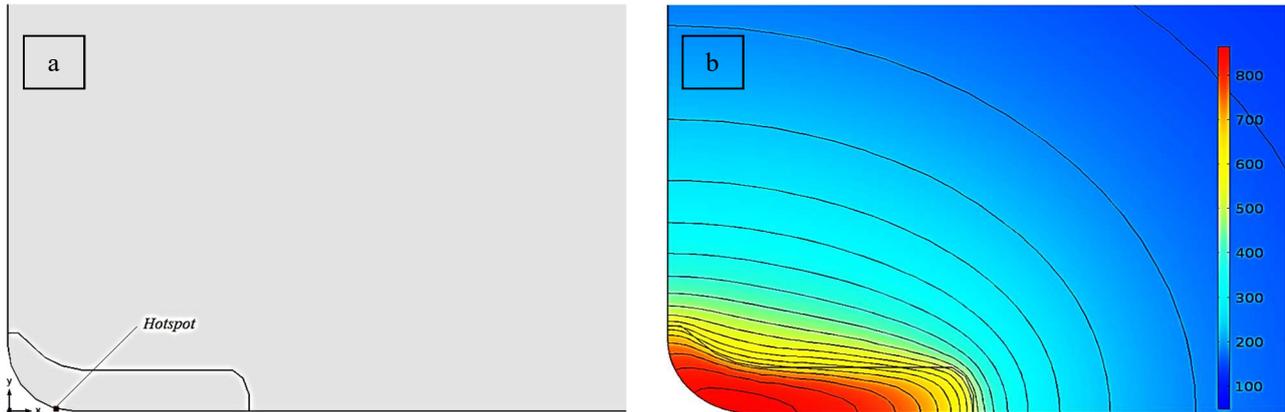

Figure 4. Hot spot position (a). Thermal distribution on the top surface of the tool (b).

In order to observe the influence of the coating layer on the carbide insert were considered three different models: the first with TiN coating, the second with Al_2O_3 coating and the third without any coating. A 0.00002 m thickness was considered and the thermophysical properties of materials varying with temperature were taken from Ferreira (2017). It can be seen from Fig. 5a that the coatings function as thermal insulators, but in this case the temperature difference is not so significant. As shown in Fig. 5b, the decrease in temperature in the insert was higher for aluminum oxide coating with a mean of 295 K during the machining period and 289.6 K for titanium nitride. In compensation the cutting temperature reaching 1185 K for Al_2O_3 and 1213 K for TiN.
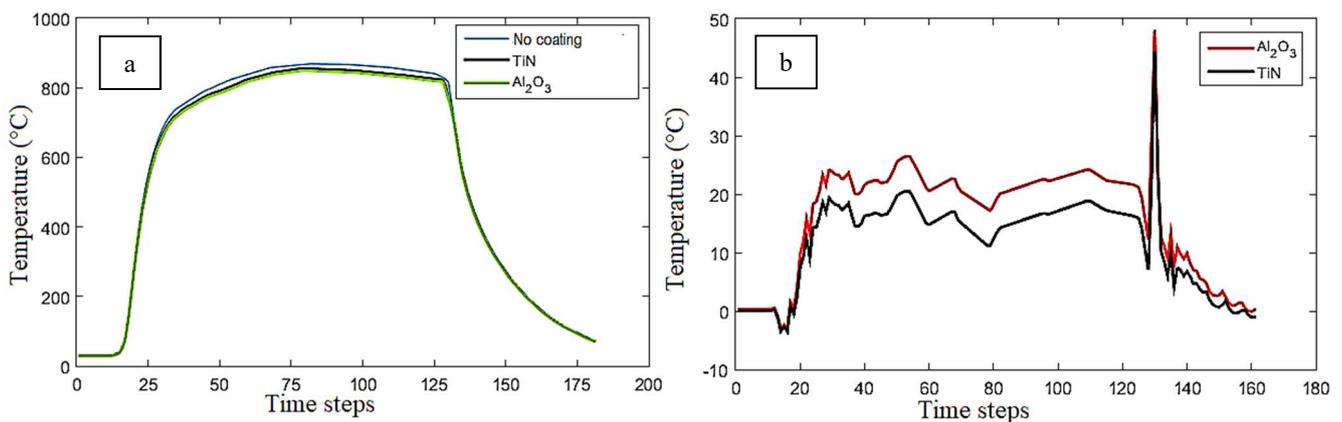

Figure 5. Comparison between the highest temperatures with and without coating (a). Decrease of temperature using coating (b).

4. CONCLUSIONS

The estimated heat flux was of the order of $3.5.10^7$ W/m². The temperatures obtained numerically presented a maximum difference of 3.2% of the experimental one. Using COMSOL it was possible to determine the tool hotspot that reached a maximum temperature of 1141 K. Finally, simulations were performed using the estimated heat flux and considering TiN and Al_2O_3 coatings. Regarding these coatead cutting tools, a decrease in temperature of approximately

295 K for Al_2O_3 and 289 K for TiN was observed. Therefore, for the cutting conditions used, the oxide coating gave the insert a better thermal protection.

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