

ENCIT-2018-0445

NUMERICAL ANALYSIS OF THE INFLUENCE OF COATINGS IN A CUTTING TOOL USING COMSOL

Diego Corrêa Ferreira

Sandro Marcondes de Lima e Silva

Universidade Federal de Itajubá, Instituto de Engenharia Mecânica – IEM, Laboratório de Transferência de Calor – LabTC, Campus Prof. José Rodrigues Seabra, Av. BPS, 1303, Bairro Pinheirinho, Itajubá – MG, CEP 37500-903
e-mail: diegoc.ferreira@unifei.edu.br, metrevel@unifei.edu.br

Luís Felipe dos Santos Carollo

Centro Universitário de Itajubá – FEPI, Itajubá, MG, Brasil
e-mail: felipecarollo@yahoo.com.br

Abstract. *The determination of the thermal field in a turning process is fundamental to improve the process quality. Recently, the carbide tools have been coated with ceramic materials that present insulating characteristics. This work presents the thermal effects of coating in a carbide tool during a turning process using the COMSOL® software and a non-linear inverse problem. The thermal model consists of a coated carbide tool, a tool holder and a shim described by the transient three-dimensional heat diffusion equation with heat loss by convection and radiation. The unknown heat source was obtained through the Specification Function Method. In order to validate the methodology, the heat input was compared with previous work. Titanium nitride (TiN) and aluminium oxide (Al₂O₃) are utilized as the coating materials. Both coatings presented the expected behavior when less heat is dissipated to the cutting tool substrate. The coated carbide tools presented higher maximum temperatures in the contact area than the uncoated carbide tool. The study also found that as the coating thickness increases the maximum temperature in the contact area also increases. The results presented in this work may help the development of new coated carbide tools with a longer lifespan.*

Keywords: *Inverse problems, Coatings, Heat flux estimation, Cutting process, COMSOL.*

1. INTRODUCTION

Reducing machining costs and the bad effects caused by using cooling lubricants are the main advantages of dry machining. However, to better understand the physical phenomena involved in this process, it is necessary to model it in the most realistic way (Deppermann and Kneer, 2015). It is difficult to determine the temperature on the tool-chip interface due to the movement of the workpiece, chip obstruction and the small tool-chip contact area (Lazard and Remy, 2008).

Experimental methods have their limitation to determine this temperature. In embedded thermocouple method, the position of the thermocouple close to the tool-chip contact area can interfere in the heat flux. Infrared methods also have their limitation, once it is not possible to measure the temperature directly due to chip obstruction on the rake face. Lately, numerical methods, like finite element method and finite difference method, have also been applied to simulate the tool-chip interface temperature. Nevertheless, without precisely knowing the heat flux at tool-chip interface, these methods cannot determine the cutting temperature directly (Liang *et al.*, 2013). Thus, inverse heat conduction techniques represent a good alternative to obtain this temperature. These techniques allow the use of experimental data obtained from accessible regions (Brito *et al.*, 2015)

In order to better represent the thermal model in turning, Brito *et al.* (2015) considered a more realistic geometry for the previous work of Brito *et al.* (2009) and Carvalho *et al.* (2006). The Specification Function and the commercial software COMSOL® were used to estimate the heat flux and the temperature field at the contact area in a cutting tool. The inverse heat conduction method has also been applied in the study of other machining processes. The amount of energy transferred to the workpiece during electric discharge machining process (EDM) was estimated using the Lavenberg-Marquardt method (Shabgard and Akhbari, 2016). Almost all the energy is lost through convection and radiation to the dielectric fluid and by conduction via the tool.

This work is an improvement of the work developed by Brito *et al.* (2015). The main difference consists of having non-linear conduction, convection and radiation in the COMSOL® model, differently from Brito *et al.* (2015) who used CFX®. A new analysis of the maximum, minimum and average temperatures in the contact area interface is also presented. A numerical code in MATLAB® in connection with COMSOL® is used to calculate the heat flux. Once the heat flux is known, COMSOL® is again used to solve the transient heat diffusion equation and obtain the temperature field in the model. The heat flux estimated in this work is compared with the heat flux of previous work to validate the

methodology. The differences of the maximum temperature in the contact area between the coated and uncoated carbide tool of different coating thicknesses are also evaluated.

2. DEVELOPMENT THEORY

2.1 The 3-D Models

The 3-D models consist of a coated and uncoated carbide tool (Figure 1), an AISI 1045 steel tool holder and a carbide shim (Figure 2). These models were applied in the simulation in order to compare the thermal gradient when the coating is used in the tool during the cutting process. This coating is present on the rake face of the cutting tool, where the workpiece and the cutting tool are in contact. A thin layer placed on the top surface of the substrate of the cutting tool represents the coating. The thermal contact between the coating and the substrate is considered perfect.

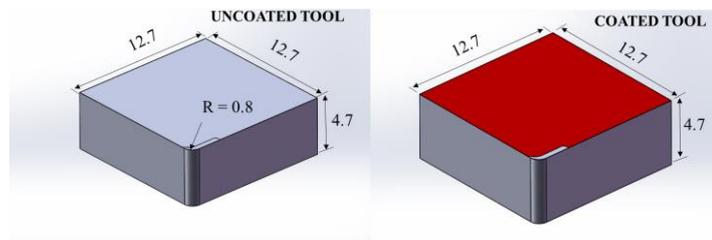


Figure 1. Fundamental dimensions of the 3-D coated and uncoated tool.

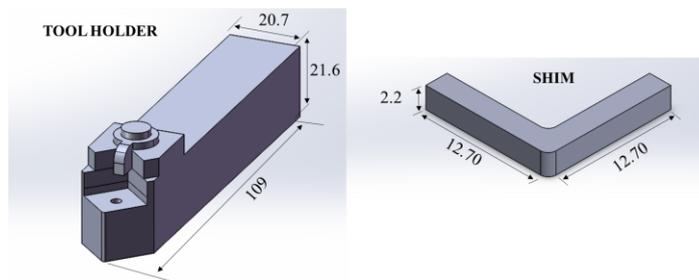


Figure 2. Fundamental dimensions of the 3-D tool holder and shim.

Figure 3 presents the contact area between the cutting tool and the workpiece, where the heat flux is applied during the cutting process. This region was measured by Carvalho *et al.* (2006) using an image system program with a video camera. The cutting tool, shim and tool holder surfaces which are in contact with air are submitted to the boundary conditions of natural convection and radiation. The thermal contact between the carbide tool, shim and tool holder was considered perfect.

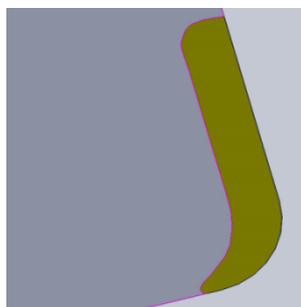


Figure 3. Numerical contact area on the computational model used in the present work.

2.2 Thermal Model

The thermal model may be described by the non-linear transient three-dimensional diffusion equation:

$$\frac{\partial}{\partial x} \left(k(T) \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(k(T) \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(k(T) \frac{\partial T}{\partial z} \right) = \rho c(T) \frac{\partial T}{\partial t} \quad (1)$$

where x , y , and z are the Cartesian coordinates, t the physical time, T the temperature, k the thermal conductivity, c the specific heat and ρ the density.

Subject to the boundary conditions of convection and radiation:

$$-k(T) \frac{\partial T}{\partial \eta} (x, y, z, t) = h(T)(T - T_{\infty}) + \sigma \varepsilon (T) (T^4 - T_{\infty}^4) \quad (2)$$

where k is the thermal conductivity, η the normal direction, h the heat transfer coefficient by convection, σ the Stefan-Boltzmann constant, ε the emissivity, and T_{∞} the room temperature.

In the contact area, the boundary condition of the imposed heat flux, q'' is applied:

$$-k(T) \frac{\partial T}{\partial z} (x, y, 0, t) = q'' \quad (3)$$

The initial condition of the prescribed temperature is used for the entire domain as:

$$T(x, y, z, 0) = T_{\infty} \quad (4)$$

The solution of the previous equations is obtained with the use of the finite element method, through the commercial software COMSOL® Multiphysics 5.2.

The inverse technique adopted in this work is the Specification Function. A MATLAB program with the software COMSOL® *Multiphysics* 5.2 was used to estimate the heat flux.

$$F = \sum_{i=1}^{nt} \sum_{j=1}^{ns} (Y_{ij} - T_{ij})^2 \quad (5)$$

where F is the objective function, i is the index to measure time, nt represents the total time of temperature measurements, j is the counter for the number of sensors and ns represents the number of temperature sensors.

2.3 Thermal properties

The thermal properties used in this work were obtained from Ferreira *et al.* (2018), where the author presented the equations for the properties built from data fitting found in literature.

2.4 Experimental Procedure

One of the major problems in the thermal analysis of a turning process is accurately to know the heat flux at the tool-chip interface. This work uses the experimental temperature data obtained by Carvalho *et al.* (2006) to estimate the heat flux. The machining test was carried out in a conventional lathe IMOR MAXI-II-520-6CV without coolant. The material used in the experimental test was a cylindrical gray cast iron bar FC 20 EB 126 ABNT of 77 mm in external diameter. The insert and tool holder used were cemented ISO SNUN12040408 K20/Brassinter and ISO CSBNR 20K12/SANDVIK COROMAT, respectively. The temperatures were measured on accessible locations of the insert, the shim and the tool holder by using type K thermocouples (30 AWG) linked to a data acquisition system HP 75000 Series B controlled by a PC (Fig. 4). The location of the thermocouples used in the simulations and the cutting conditions to obtain the temperature data was according to the work of Brito *et al.* (2015).

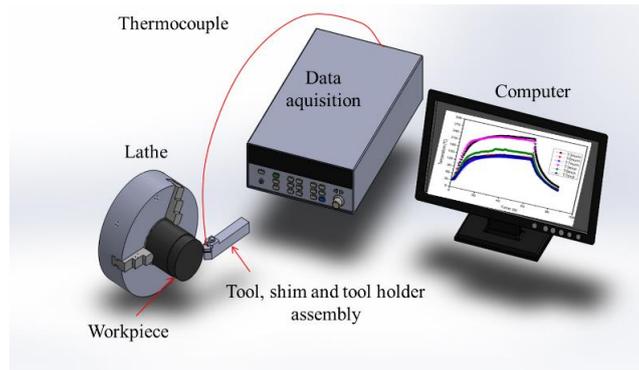


Figure 4. Experimental apparatus used to acquire the temperature signals in the tool during turning.

3. RESULT ANALYSIS

3.1 Heat Flux

Once the experimental temperature values are known, the heat flux in the contact area can be calculated by minimizing the objective function (Eq. 5). Figure 5 presents the results of the heat flux obtained in this work and also compares with the heat flux results from Brito *et al.* (2015). Despite the fact of being the same physical problem, there are some differences among the heat flux values for each work. Brito *et al.* (2015) made some geometric simplifications like using a solid shim instead of an L shape shim. Therefore, the authors did not take into account the variation of the heat transfer coefficient by convection and radiation in the numerical model. When this non-linearity is accounted, a higher estimated heat flux is expected due to a higher heat loss by convection and radiation.

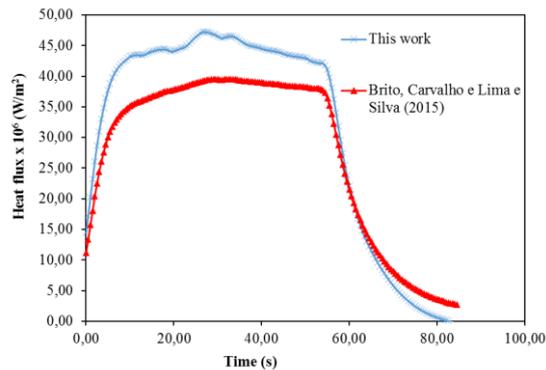


Figure 5. A Comparison of the estimated heat flux of this work and Brito *et al.* (2015).

3.2 Uncoated Carbide Tool

The temperature profile can be achieved by knowing the heat flux value in the contact area between the workpiece and the cutting tool. The first simulation was carried out considering an uncoated carbide tool. A numerical probe was placed in the contact area in order to obtain the temperature in this region. Through the software, the maximum, the average and the minimum temperature values can be calculated (Fig. 6). High variations of the temperature values can be observed in this figure, even with the small value of the contact area (1.43 mm²). The maximum temperature reached was around 1097°C, the average temperature reached was around 963°C and the minimum temperature was also around 626°C. Figure 7 shows the isothermal temperature lines in the region near the contact area at instant $t = 28$ s.

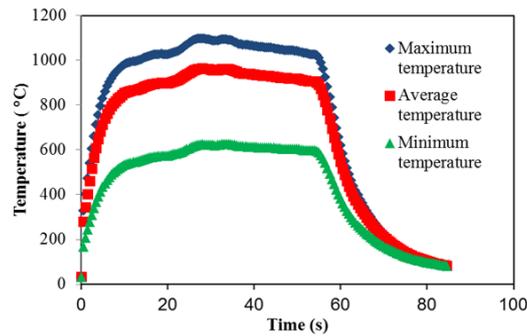


Figure 6. Maximum, average and minimum temperatures in the contact area.

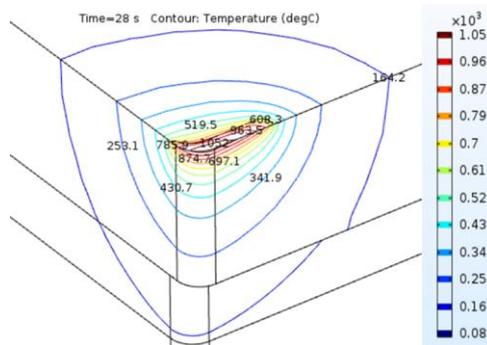


Figure 7. Isothermal temperature lines in the region near the contact area.

3.3 Coated Carbide Tool

The simulation described in Section 3.2 is repeated, but now considering the coating which is represented by a thin 10 μm thick layer. Figure 8 presents the isothermal temperature lines in the region near the contact area on the coated tool of TiN and Al_2O_3 at instant $t = 28$ s.

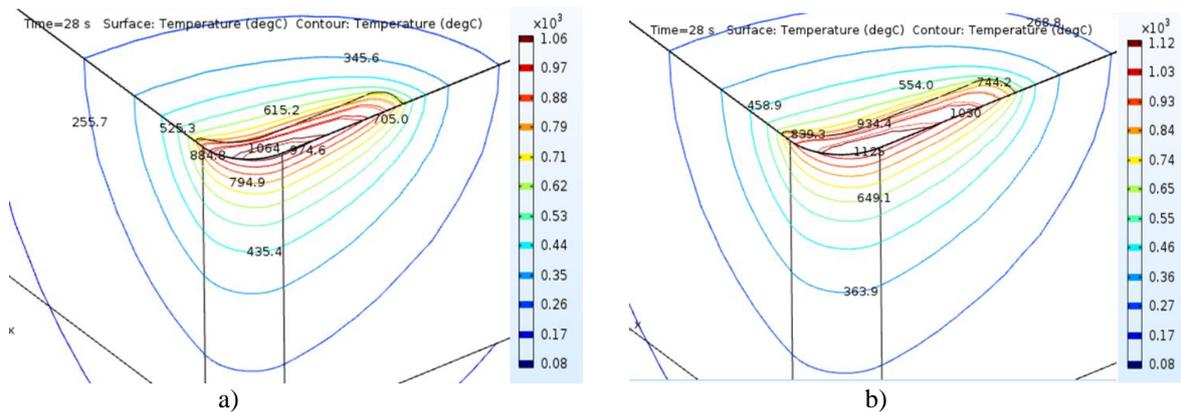


Figure 8. Isothermal temperature lines in the region near the contact area: a) TiN and b) Al_2O_3 .

By analyzing Figures 7 and 8, it can be noticed that the temperature in region of the contact area is higher on the coated tool than the uncoated tool. In order to better understand these results, Fig. 9a presents the maximum temperature in this region at instant $t = 28$ s, on the uncoated tool, TiN coated tool and the Al_2O_3 coated tool. Figure 9b shows the temperature differences between the coated tools and the uncoated tool.

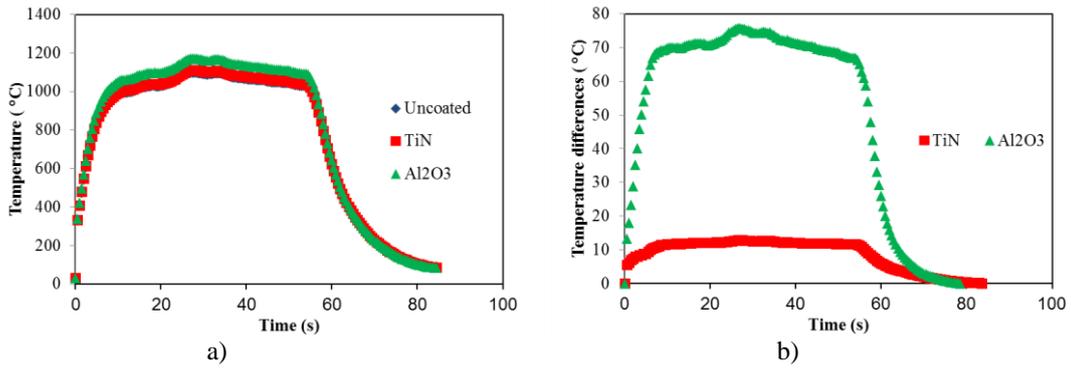


Figure 9. a) Maximum temperatures in the coated area of the uncoated and coated tools and b) temperature differences between the coated and the uncoated tools.

It can be verified in Fig. 9a that the curves of maximum temperature of the coated and uncoated tools have the same behavior. The maximum temperature curve of the TiN coated tool overlaps the maximum temperature curve of the uncoated tool, not presenting a relevant temperature difference. This fact can be noticed in Fig. 9b at instant $t = 28$ s. The maximum temperature difference between the TiN coated tool and the uncoated tool is around 12.7° C. For the Al₂O₃ coated tool the maximum temperature curve is above the maximum temperature curve of the uncoated tool, as can be seen in Fig. 9a. In Figure 9b, at instant $t = 28$ s, the maximum difference of temperature between the Al₂O₃ coated tool and the uncoated tool is around 75.5 °C. In the work of Brito *et al.* (2009) the maximum temperature difference obtained was around 8.2 °C using the same 10 μm thick coated carbide tool.

Observing the previous figures, it can be concluded the coating retains the heat on the top face of the cutting tool, not letting the heat penetrate the cutting tool substrate and thus increasing the cutting tool lifespan. The Al₂O₃ coating presents a better insulating characteristic than the TiN since it has a lower thermal conductivity value.

3.4 Coated Thickness Influence

As previously shown, the coatings used in the cutting tools have insulating characteristics and play the role of protecting the substrate of the cutting tool with respect to heat. To further evidence this effect, the simulations of Section 3.3 are repeated considering thicker coatings: 20 μm, 50 μm and 100 μm (Tab. 1 and Fig. 10).

Table 1. Differences of the maximum temperatures in the contact area between the coated and uncoated tool for different coating thickness.

Coating thickness (μm)	TiN	Al ₂ O ₃
10	12.7 °C	75.5 °C
20	25.2 °C	151.5 °C
50	61.1 °C	351.8 °C
100	117.1 °C	663.5 °C

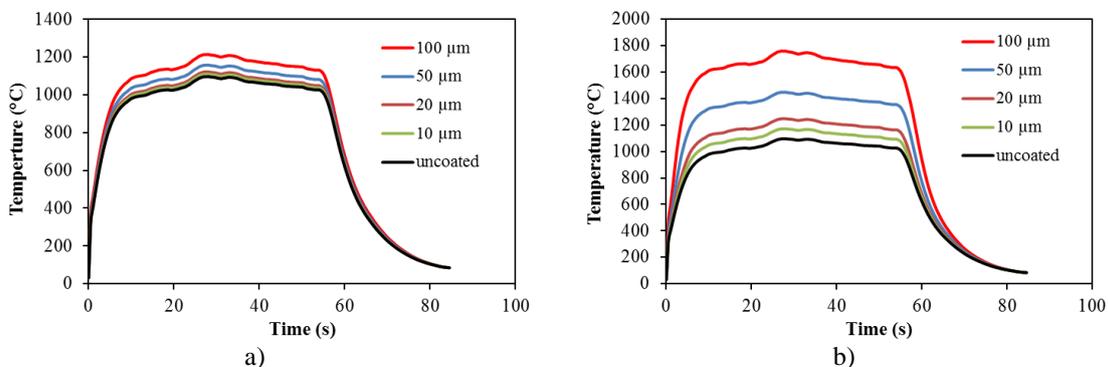


Figure 10. Maximum temperature curve in the contact area for different coating thickness values: a) TiN and b) Al₂O₃.

When the coating thickness value of both materials is increased, the maximum temperature in the contact area also increases (Fig. 10). Table 1 also shows this fact where the maximum temperature difference in the contact area

between the coated tools and the uncoated tool for different coating thickness values can be seen. Figure 11 presents the temperature field in the region near to the contact interface area for the uncoated tool and the Al_2O_3 coated tool for different thickness coating at the instant of $t = 28$ s. This figure shows the heat behavior when the thickness coating increases.

In Figure 11a, which represents the uncoated tool, can be noticed that the heat penetrates deeply the cutting tool substrate and consequently the temperature field is large. Inserting the coating in the cutting tool (Figure 11b) the temperature field begin decreasing slightly. Increasing the coating thickness (Fig.11c to Fig.11e) the temperature field decreases even more. It can be noticed by the red color in the figures. Thus, the coating holds the heat on the upper face of the cutting tool and did not let it goes to the cutting tool substrate which would be harmful for the cutting tool lifespan.

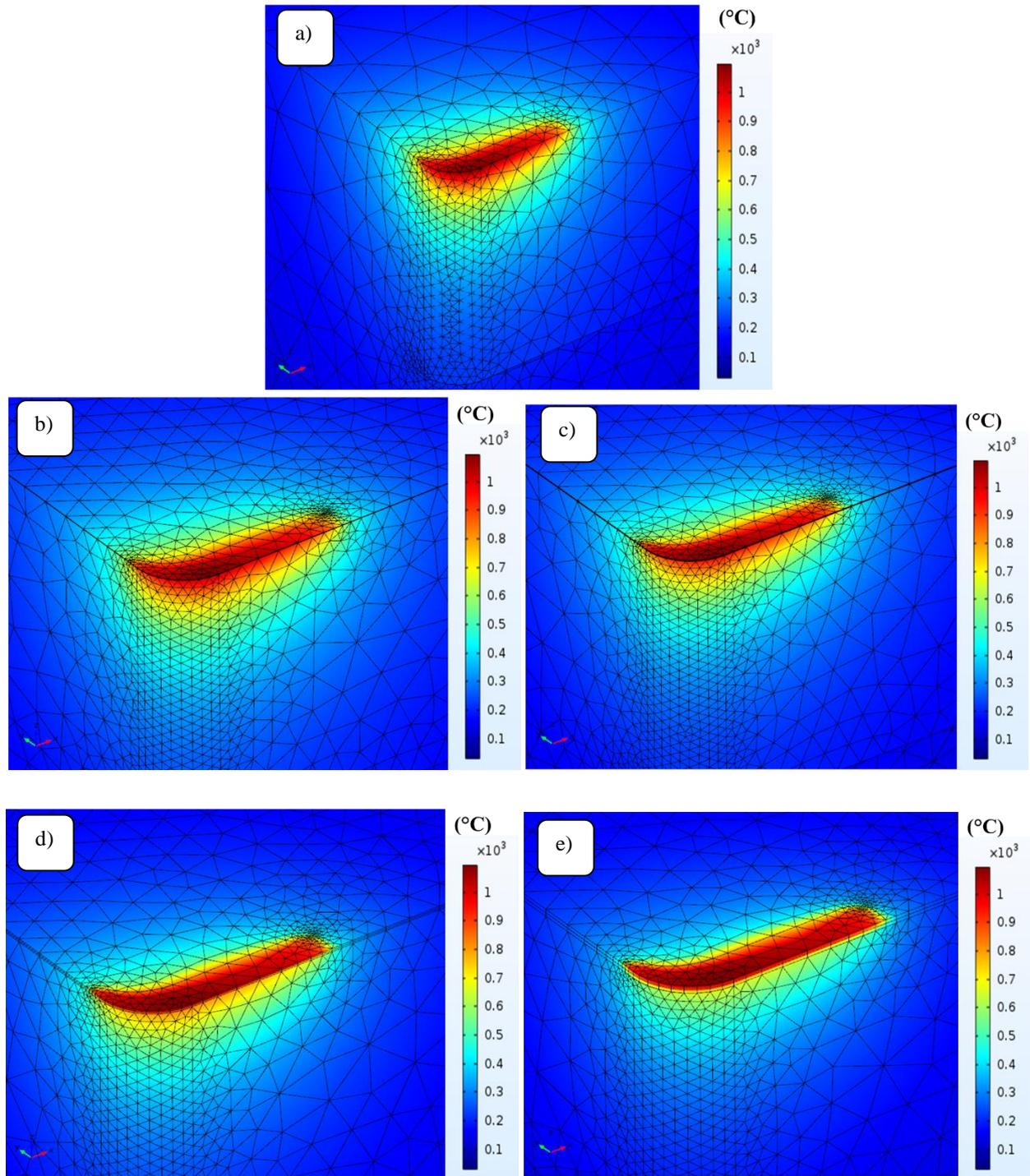


Figure 11. Influence of the Al_2O_3 coating thickness in the cutting tool temperature field: a) uncoated tool, b) $10\ \mu\text{m}$, c) $20\ \mu\text{m}$, d) $50\ \mu\text{m}$ and e) $100\ \mu\text{m}$.

4. CONCLUSIONS

This work presented the coating effect on the temperature field of the cemented carbide cutting tool. The coating effect was observed by comparing the peak temperature between the uncoated and coated material. The coating thickness was numerically increased to highlight the coating influence on the cemented carbide cutting tool. Despite the small contact area, the coated and uncoated carbide cutting tools presented a peak difference in the cutting region of 12.7 °C for the TiN and 75.5 °C for the Al₂O₃. The 10- μ m-thick coated tool models presented the expected behavior, once the maximum temperature in the contact area was higher when compared to the maximum temperature in the contact area of the uncoated tool. By increasing the coating thickness, the maximum temperature in the contact area also increases. The best results were obtained using the Al₂O₃ coating, once it has a thermal conductivity value lower than the thermal conductivity value of the TiN coating. Thus, the coating fulfils its role of protecting the substrate of the cutting tool with respect to heat.

5. ACKNOWLEDGEMENTS

The authors would like to thank CNPq, CAPES and FAPEMIG for their financial support.

6. REFERENCES

- Brito RF, Carvalho SR de, Lima e Silva SMM de, Ferreira JR, 2009. "Thermal analysis in coated cutting tools". *Int Commun Heat Mass Transf* 36:314–321. doi: 10.1016/j.icheatmasstransfer.2009.01.009
- Brito RF, Carvalho SR, Lima E Silva SMM, 2015. "Experimental investigation of thermal aspects in a cutting tool using comsol and inverse problem". *Appl Therm Eng* 86:60–68. doi: 10.1016/j.applthermaleng.2015.03.083
- Carvalho SR, Lima e Silva SMM, Machado AR, Guimarães G (2006) Temperature determination at the chip-tool interface using an inverse thermal model considering the tool and tool holder. *J Mater Process Technol* 179:97–104. doi: 10.1016/j.jmatprotec.2006.03.086
- Deppermann M, Kneer R, 2015. "Determination of the heat flux to the workpiece during dry turning by inverse methods". *Prod Eng* 9:465–471. doi: 10.1007/s11740-015-0635-6
- Ferreira DC, Magalhães ES, Brito RF, Lima e Silva SMM (2018) Numerical analysis of the influence of coatings on a cutting tool using COMSOL. *Int J Adv Manuf Technol* 97: 1305-1314. doi: 10.1007/s00170-018-1855-7
- Lazard M, Remy B, 2008. "Heat Flux and Temperature Estimation During Cutting Process Through Regularization Technique". 5th Eur. Therm. Conf. 1:
- Liang L, Xu H, Ke Z, 2013. "An improved three-dimensional inverse heat conduction procedure to determine the tool-chip interface temperature in dry turning". *Int J Therm Sci* 64:152–161. doi: 10.1016/j.ijthermalsci.2012.08.01
- Shabgard M, Akhbari S (2016) An inverse heat conduction method to determine the energy transferred to the workpiece in EDM process. *Int J Adv Manuf Technol* 83:1037–1045. doi: 10.1007/s00170-015-7651-8

7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.