

THERMAL ANALYSIS OF A CARBIDE COATED CUTTING INSERT USING COMSOL®

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Abstract. During the turning process, a considerable amount of the machine energy is transformed into heat near the surface of the cutting insert. Almost all the technical and economical problems of the process are directly or indirectly caused by the generation of this heat. In the past few years, tool inserts have been coated with materials that provide minor wear with thermal insulation features, aiming to increase the tool life. Determining the cutting temperature during the turning process is one of the most important factors to understand the turning tool performance. Thus, it is important to develop efficient methods to determine this temperature. This work proposes to simulate the heat phenomenon, in transient regime, of a cutting tool considering the presence of the coating, convection and radiation. The results showed the coating effect for different coating thickness values. Numerical and experimental results are compared to validate the methodology.

Keywords: Thermal analysis, COMSOL, Cutting insert, Coating.

1. NOMENCLATURE

		Greek symbols	
T	Temperature, °C	k	Thermal conductivity, Wm^{-1}K
T_{∞}	Room temperature, °C	α	Thermal diffusivity, ms^{-2}
x, y, z	Cartesian coordinates, m	ε	Emissivity
t	time, s	η	the outward drawn normal to the surface
h	Heat transfer coefficient, Wm^{-2}K	σ	Stefan-Boltzmann constant, $\text{Wm}^{-2}\text{K}^{-4}$
q_0''	Imposed heat flux, Wm^{-2}		
T_{CI}	Temperature on the chip-insert interface, °C		
T_{CS}	Temperature on the coating-substrate interface, °C		
$\Delta T_{\text{UNCOATED}}$	$T_{CI} - T_{CS}$ for the uncoated insert, °C		

2. INTRODUCTION

A considerable amount of the consumed energy in the turning process is transformed into heat near surface of the cutting insert. Most of the technical and economical problems of the process are directly or indirectly caused by the generation of this heat. With an increasingly competitive market, higher cutting speeds and higher feed rates are used in machining processes aiming to increase productivity. Using higher cutting speeds and higher feed rates more heat is generated during the process, damaging the insert performance (Trent and Wright, 2000).

In the past few years, the tool inserts have been coated with materials that provide minor wear with thermal insulation features. The first feature is that it makes the major part of the heat generated during the process go to the chip. The second is that it reduces the insert wear. Both are responsible to increase the tool life of the cutting insert.

Determining the cutting temperature during the turning process is one of the most important factors to understand the turning insert performance. However, due to the movement of the workpiece and difficulty of accessing regions, even in simple machining conditions, the determination of the temperature in the insert-chip interface is troublesome. Thus, it is important to develop efficient methods to determine this temperature.

The first documented work relating to the temperature study during the turning process of metals was conducted by Thompson (1798). The author examined the mechanical equivalent of heat during the drilling process of a brass workpiece. Later, Taylor (1907) recognized the influence of the heat in his article "On the art of cutting metals". Taylor's studies were crucial for the development of the high speed steels. Therefore, the quantitative and precise determination of temperatures during the metal cutting process in terms of measure was first conducted by Shore (1925), Gottwein (1925) and Herbert (1926) almost at the same time. These authors measured the temperature in the process using thermocouples. Several methods have been proposed to determine the temperature since then. Some authors used analytical methods to solve the thermal problem (Rapier, 1954; Young and Chou 1994), whereas others

used experimental methods (Boothrouyd, 1961; Shaw, 1984; Stephenson, 1991; Carvalho *et al.*, 2006; Mitsuichi *et al.*, 2015).

Insert coating appeared in the 1960's due to the advance in the field of materials. In the beginning, the inserts were coated by the CVD process (*Chemical Vapour Deposition*) and later on by the PVD process (*Physical Vapour Deposition*). Nearly 80% of the turning processes are carried out using coated inserts (Balzers, 2002). Rупpi *et al.* (1998) studied the one layer coating properties of TiC, TiN, TiCN and Al₂O₃. These inserts were used for turning hardened steels and steels. Grzesik and Nieslony (2004) showed that depending on the type of coating of the cemented carbide insert, the contact area at the chip-insert the average temperature at the interface is modified. Rech *et al.* (2005) concluded that the coating is not a thermal barrier in continuous cutting processes, but only in interrupted cutting process especially at high cutting speeds. Brito *et al.* (2009) studied the coating influence in the cutting insert considering its thickness variation. They utilized cemented carbide and diamond substrate and TiN and Al₂O₃ coatings. The coatings did not show satisfactory results in continuous cutting process. Brito *et al.* (2015) continuing the work of Carvalho *et al.* (2006) and Brito *et al.* (2009) proposed a more complex geometry to represent the numerical model of the turning problem. To solve this problem, the authors used a nonlinear inverse heat conduction technique with the commercial software COMSOL®.

The COMSOL *Multiphysics* is FEA software (Finite Element Analysis) based on advanced numerical methods to model and solve physical problems. Gerlich *et al.* (2013) presented a software validation for a calculation of heat transfer in buildings. The heat transfer calculation in the COMSOL *Multiphysics* was validated by the comparative verification provided by the International Energy Agency and by the comparison with measured data in real building segment. Greiby *et al.* (2013) used an ordinary least square and a sequential estimation method in MATLAB with COMSOL to sequentially estimate a temperature-dependent thermal conductivity of a cherry pomace. Suarez *et al.* (2013) studied the heat transfer in solids using infrared photothermal radiometry and simulation using COMSOL *Multiphysics*. The good agreement between the results of numerical simulation and experimental data showed the potential of the software for the interpretation of photothermal experiments.

3. THEORETICAL FORMULATION

3.1 Problem description

The numerical thermal model is a coated and uncoated carbide cutting insert with the same dimensions, presented in Fig.1 and Fig.2. These two numerical models are used in the simulation to compare the coating effect on the thermal gradient created in the insert during the cutting process. The insert geometry used is from Brito *et al.* (2015). Both models are subject to the boundary conditions of imposed heat flux, convection and radiation.

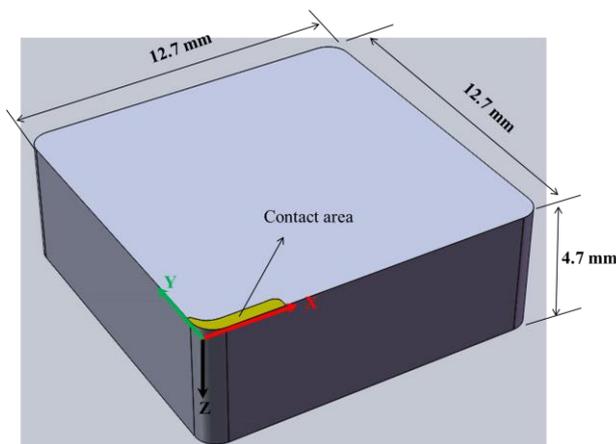


Figure 1. Uncoated insert.

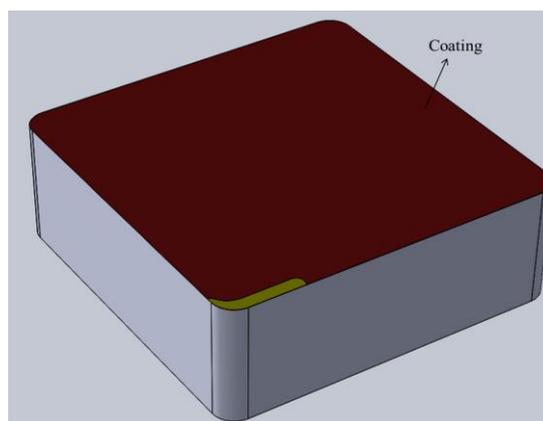


Figure 2. Coated insert.

The contact area is the contact interface between the insert and the workpiece, where the heat flux is applied during the cutting process. The other insert surfaces, which are in contact with the air, are subject to constant convection and radiation. In order to measure the contact area, an image system program with video camera Hitachi CCD, KP-110 model, an AMD PC- K6 450 MHz and the GLOBAL LAB image software were used by Carvalho *et al.* (2015). The experimental contact and the numerical contact area of this work are presented in Fig.3a and b.

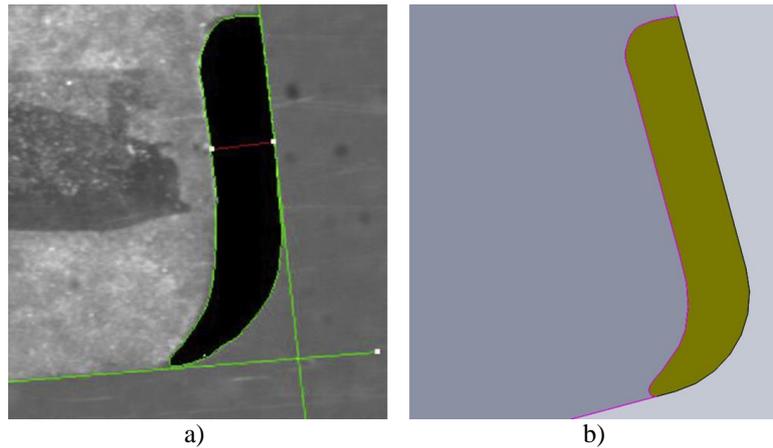


Figure 3. a) Image treatment of the experimental contact area and b) numerical area on the computational model.

The thermophysical properties for the substrate and the coating (Tab.1) were obtained from Brito *et al.* (2015), Grzesik *et al.* (2009) and Yuste *et al.* (2010). All the thermophysical properties were considered constant and also some simplifying hypotheses were adopted such as: perfect thermal contact between the substrate and the coating, constant medium temperature and no internal heat generation in the substrate and the coating.

Table 1. Thermalphysical properties of the substrate and the coating of the material.

Element	k	c_p	ρ	ε
Carbide substrate	87	225	14950	0.80
TiN	21	4650	645	0.22

The thermal problem presented is a direct problem, having all boundaries and initial conditions known. The heat flux, the convection coefficient and the initial temperature are extracted from Brito *et al.* (2015). The equations to solve the models are shown as follows.

3.2 Thermal model

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

$$\frac{\partial^2 T}{\partial x^2}(x, y, z, t) + \frac{\partial^2 T}{\partial y^2}(x, y, z, t) + \frac{\partial^2 T}{\partial z^2}(x, y, z, t) = \frac{1}{\alpha} \frac{\partial T}{\partial t}(x, y, z, t) \quad (1)$$

Subject to the following boundary conditions of convection and radiation:

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

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

$$-k \frac{\partial T}{\partial z}(x, y, 0, t) = q_0'' \quad (3)$$

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

$$T(x, y, z, 0) = T_0 \quad (4)$$

3.3 Numerical solution

The diffusion equation presented in section 3.2 is solved by using the commercial software *COMSOL Multiphysics* 5.2[®]. The software divides the geometrical domain into smaller parts and applies the equations that rule the problem to these parts. The insert geometry was designed by CAD software and later exported to COMSOL.

The heat flux at the contact area was estimated by Brito *et al.* (2015) using the Specification Function method. The average coefficient of heat transfer by convection adopted was $20 \text{ W/m}^2\text{K}$, while the initial temperature utilized was 31.06°C .

4. EXPERIMENTAL PROCEDURE

4.1 Emissivity determination

To determine the emissivity of a cemented carbide tool, a controlled experiment was carried out in the Heat Transfer Laboratory (LabTC) at the Federal University of Itajubá (UNIFEI). The data acquisition Agilent 34980A, a digital power supply MCE 1051, a thermographic camera FLIR T450sc, a $50 \times 50 \times 0.25 \text{ mm}$ resistive Kapton heater, a carbide cutting insert and thermocouples type K were used for these experiments. Figure 4 presents a picture of the experimental setting used for this experiment. To accomplish the experiment, the insert was heated on one surface by the resistive heater connected to the power supply MCE 1051. The surfaces were subject to loss due to convection and radiation until they reached the steady regime. The temperature of the insert was measured with the use of the data acquisition controlled by a PC. When the steady state was reached, the emissivity was checked by comparing the temperature measured by the camera FLIR T450sc and the temperatures indicated by the acquisition. The temperature of the sensor was adjusted to the temperature of the sample through the variation of the emissivity of the material.

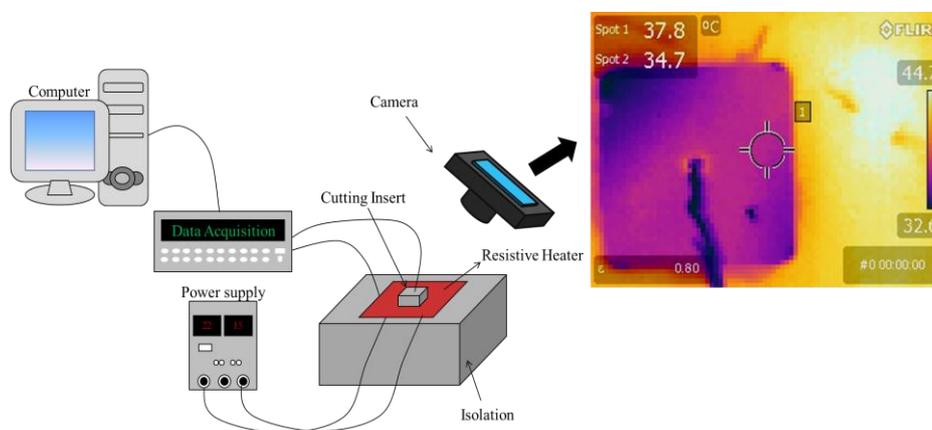


Figure 4. Experimental apparatus for the measurement of the emissivity.

5. VALIDATION OF THE METHODOLOGY

In order to validate the methodology a controlled experiment (Fig. 5a) was carried out by Brito *et al.* (2015) using a $0.0127 \times 0.0127 \times 0.0047 \text{ mm}$ cemented carbide insert. A heat flux transducer and two thermocouples previously calibrated and a kapton resistive heater were used on this insert. This heater was connected to a digital power supply (MCE). The heat flux transducer was located between the heater and the insert in order to measure the heat supplied to the insert (Fig. 5b). The heat flux and temperature signals were acquired by an HP data acquisition system Series 75000, controlled by a PC. Temperatures were measured by using type K thermocouples (30 AWG) welded by capacitive discharge and calibrated by using a bath temperature calibrator ERTCO with a stability of $\pm 0.01^\circ\text{C}$.

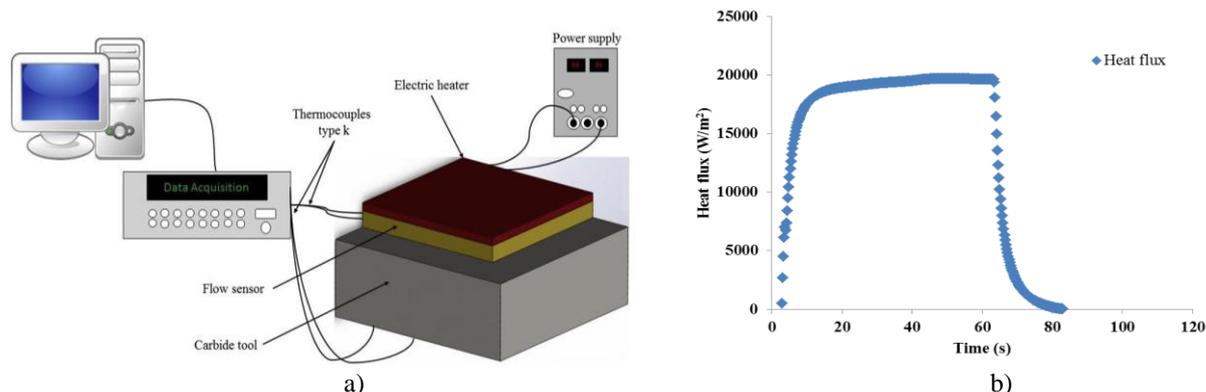


Figure 5. a) Sketch of the experimental apparatus used by Brito *et al.* (2015) and b) Measured heat flux.

One improvement of this work is the presence of the radiation which was not considered in Brito *et al.* (2015). Figure 6a shows the comparison between the numerical and experimental temperatures of the insert used in the test and Fig. 6b presents the temperature residuals.

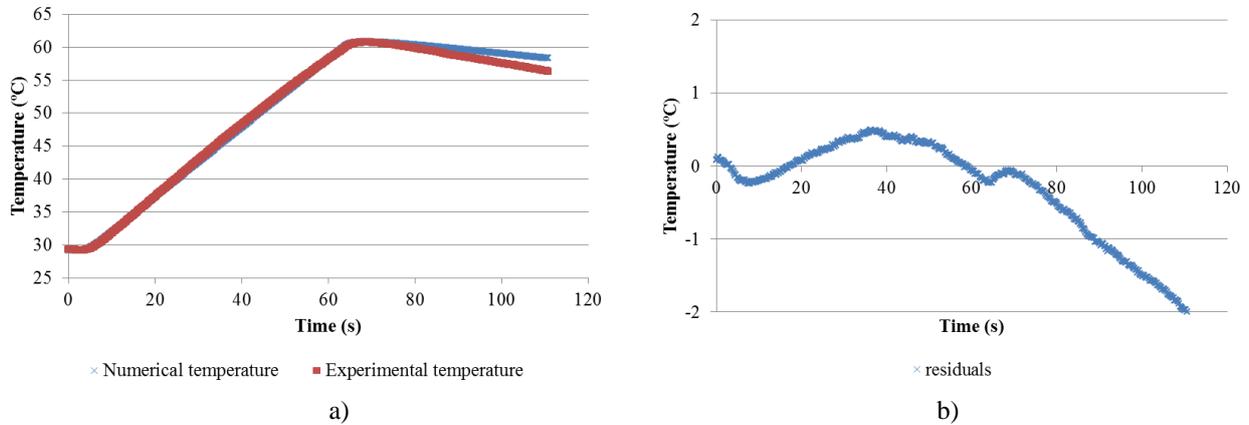


Figure 6. a) Numerical and experimental temperatures, and b) Temperature residuals.

6. RESULTS

In order to investigate the temperature distribution for a time interval t during the turning process, simulations of the uncoated and coated insert were performed. The main objective is to analyze the thermal influence of the thickness variation of coated cutting inserts. The coating adopted in the simulation was Titanium Nitride (TiN) with thickness of 10, 20, 50 and 100 μm . In the coated insert simulation two numerical positions on coordinate z were used to obtain the temperature values, one on the chip-insert interface and the other on the coating-substrate interface (Fig. 7). For the uncoated and coated insert simulation, the position remained the same for $x = 2 \text{ mm}$ and $y = 0.25 \text{ mm}$; however only the thickness of the coating varied.

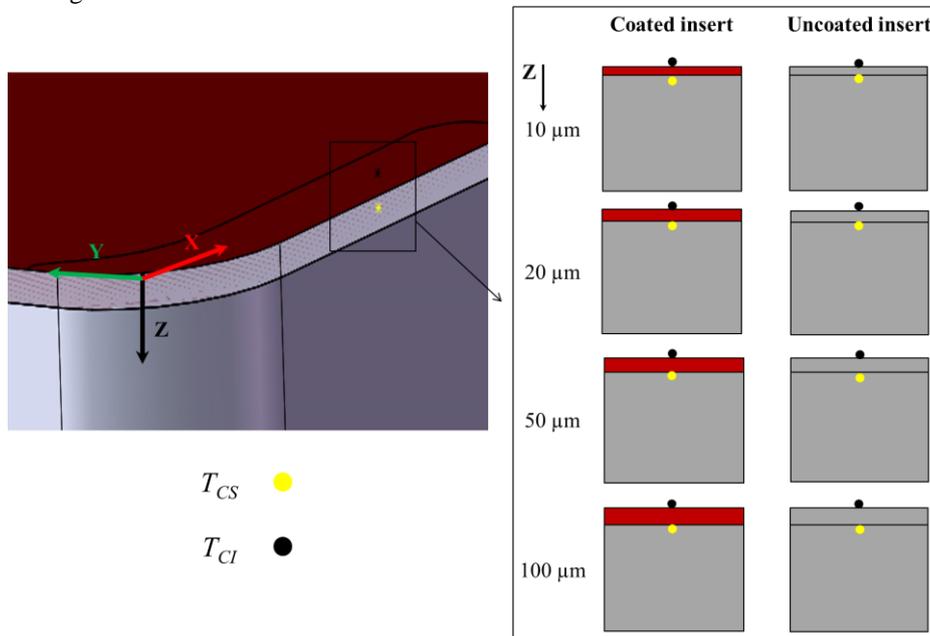


Figure 7. Numerical positions to obtain the temperature for the coated and uncoated insert.

Figure 8a presents the heat flux used to calculate the temperature in the simulations. This heat flux has the duration of 84.5 s with a time interval of 0.5 s. In the first ten seconds, the heat flux intensity increased abruptly. From 10 to 55 seconds, the heat flux stabilized. From this point, the heat flux intensity decreased up to the final instant when the turning process was interrupted (Brito *et al.*, 2015). Figure 8b shows the comparison of the temperature on the chip-insert interface between the uncoated and coated insert for coatings of different thicknesses.

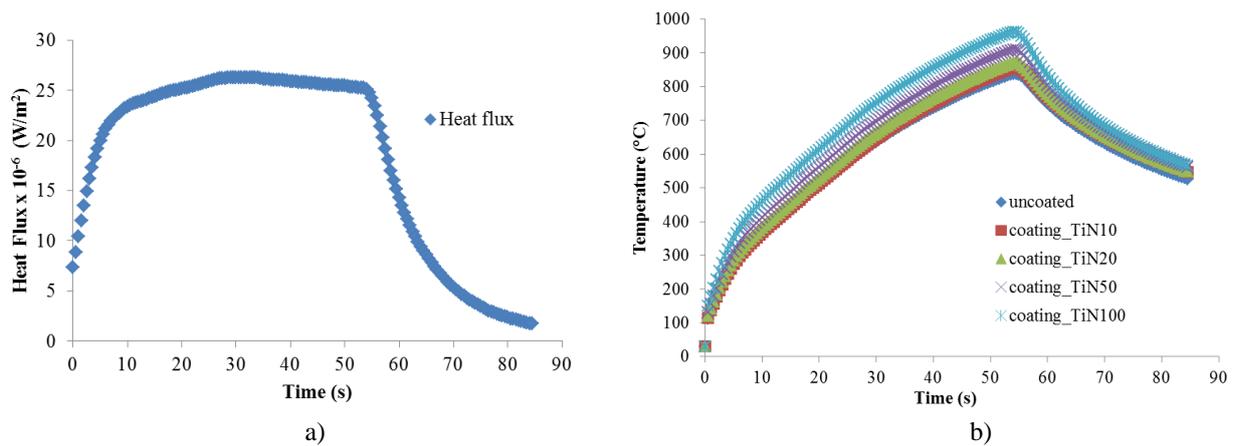


Figure 8. a) Heat flux adopted in the simulation and b) Comparison of the temperatures on the chip-insert interface.

It can be observed in Figure 8b that the temperatures in the coated inserts, for all the coating thicknesses, are higher than the temperature in the uncoated insert. Thus, the coating holds the heat and protects the substrate. To better understand it, Figs. 9 to 12 present the difference of the temperature on the chip-insert (T_{CI}) and coating-substrate (T_{CS}) interfaces for each coating thickness and compare it with the uncoated insert. Table 2 presents the maximum temperature at instant 54.5 s for all cases.

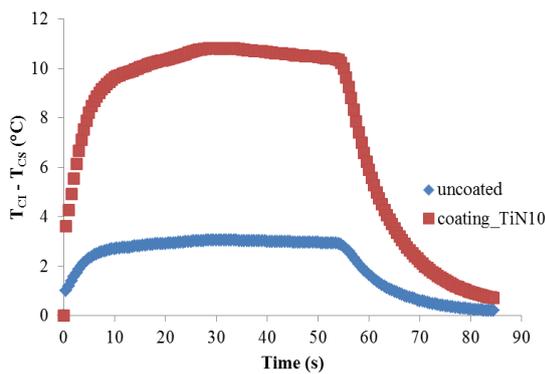


Figure 9. 10 μm coating insert x uncoated insert.

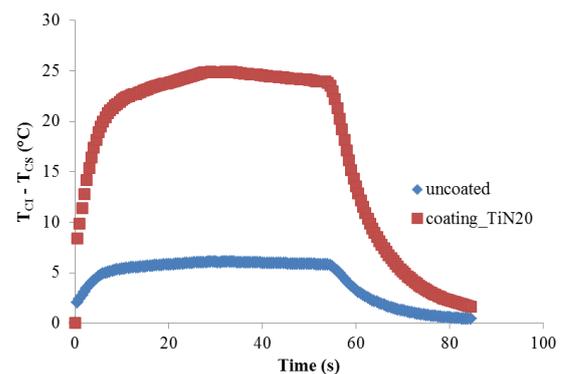


Figure 10. 20 μm coating insert x uncoated insert.

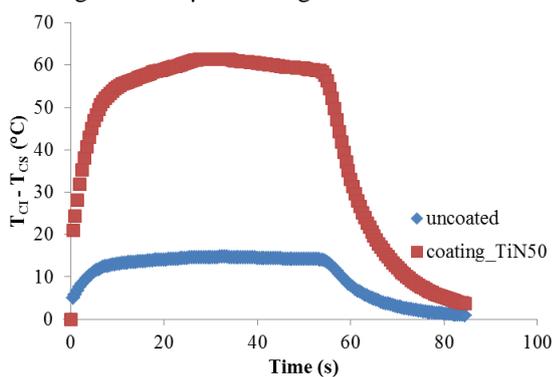


Figure 11. 50 μm coating insert x uncoated insert.

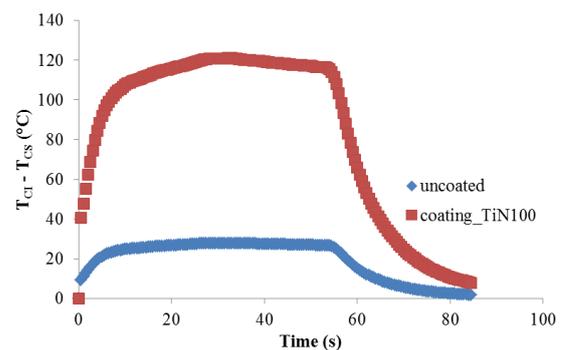


Figure 12. 100 μm coating insert x uncoated insert.

Table 2. Numerical results obtained from the temperature values at instant 54.5 s.

Coating	T_{CI} (°C)	T_{CS} (°C)	$T_{CI} - T_{CS}$ (°C)	$\Delta T_{UNCOATED}$ (°C)
10	857.94	847.73	10.21	2.88
20	871.36	847.85	23.51	5.72
50	909.84	852.19	57.65	13.87
100	961.94	847.89	114.05	26.30

It can be verified in Table 2 that even for thin coatings there was an increase in the temperature difference ($T_{CI} - T_{CS}$) when compared to the uncoated insert. The usual thickness for the coating of a cutting insert is between 10 to 20 μm . For thicker coatings, 50 and 100 μm , this difference is even larger. Figure 13 presents the simulation results for the uncoated insert, whereas Fig. 14 shows the simulation results for the coated insert with different coating thicknesses.

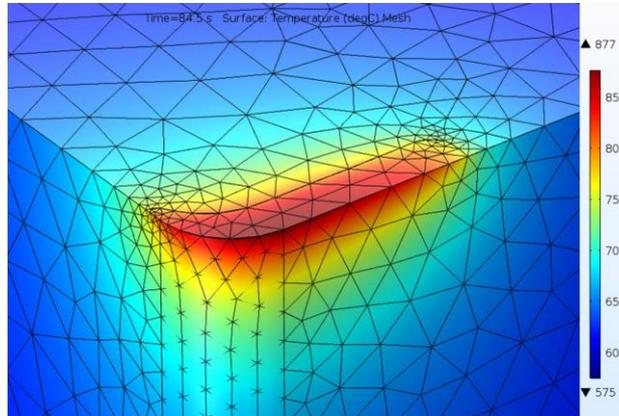
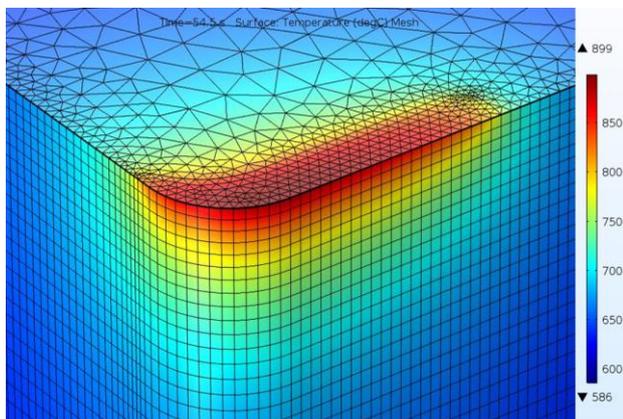
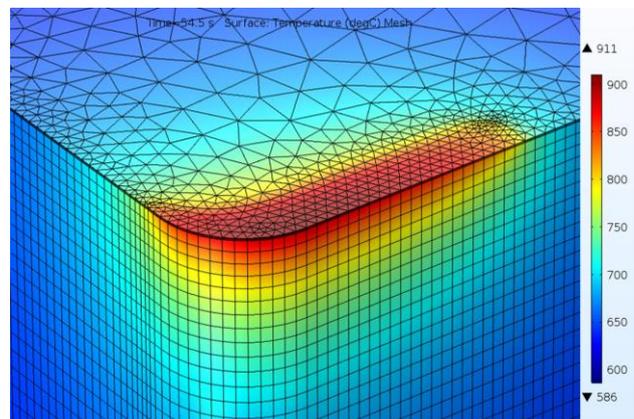


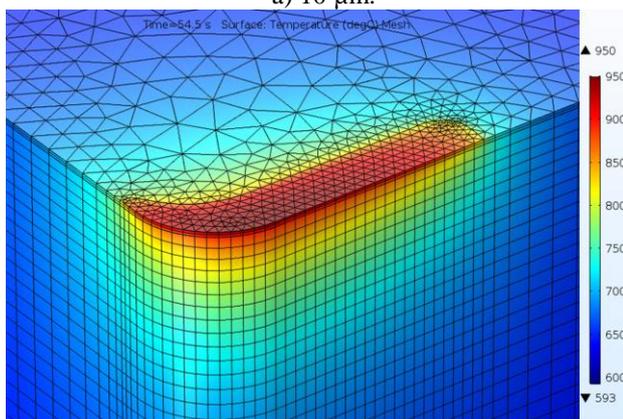
Figure 13. Temperature field of the uncoated insert.



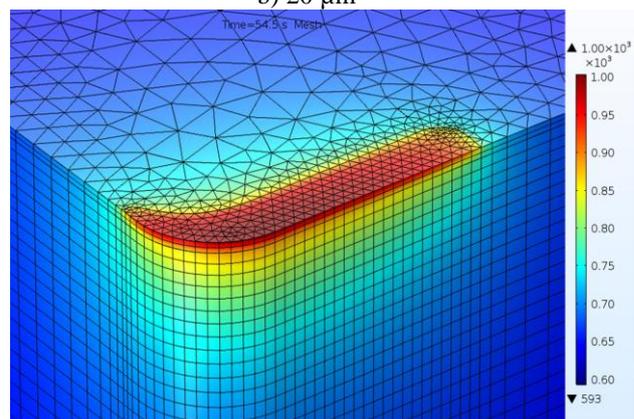
a) 10 μm .



b) 20 μm .



c) 50 μm .



d) 100 μm .

Figure 14. Influence of the coating thickness variation on the temperature field.

Figure 13 shows that the heat penetrates the substrate and consequently the temperature field is larger. In Figure 14, it is possible to see that the thicker the coating, the more it holds the heat on the top surface and protects the insert substrate (red region in the figure).

7. CONCLUSIONS

This work presented the coating effect on the temperature field of the cutting insert. For all the models with different coating thickness, the results presented the expected behavior, that is, less heat dissipates to the substrate. One

improvement of this work is the presence of the radiation, not considered in previous work. The good agreement between the numerical simulation results and experimental data showed the potential of the methodology applied to the resolution of thermal problems in turning.

8. ACKNOWLEDGEMENTS

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