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THERMAL ANALYSIS IN TIN AND AL_2O_3 COATED ISO K10 CEMENTED CARBIDE CUTTING TOOLS USING DESIGN OF EXPERIMENT (DOE) METHODOLOGY

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Abstract

This paper is concerned with the effect of variations in the thickness of the tool coating on the heat transfer in cemented carbide tool substrates (ISO grade K10). Titanium nitride (TiN) and aluminum oxide (Al_2O_3) with thickness values of 1 and 10 µm were used as coatings. In order to increase tool life and reduce costs, the thermal parameters of the turning operation are investigated aiming a more uniform temperature distribution in the cutting zone. Boundary conditions by convection and heat flux are known, as well as the thermophysical properties of the tool and coating involved in the numerical analysis. Two commercial softwares were used and the proposed methodology was validated experimentally under controlled conditions. Design of experiments (DoE) was used to identify the optimal parameters in order to obtain the maximum temperature difference (ΔT) between the tool substrate and the coating. The cutting tool temperature distribution is discussed and a thermal analysis on the influence of the coating is presented. Finally, the results are discussed and compared with data available in the published literature.

Keywords: TiN and Al_2O_3 coatings, cutting tool, DoE, finite volume method, heat transfer.

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1. Introduction

Machining processes generate enough heat to deform the materials involved: the chip and the tool. This level of heat is a factor that strongly influences tool performance. Friction wear and heat distribution affect the temperature on both the chip and tool. In order to increase tool life, its surface can be coated with materials having thermal insulation features that reduce tool wear. Hence, the influence of coatings on heat transfer and friction wear is an area of study that deserves an in-depth investigation.

A review on the literature suggests that most orthogonal metal cutting simulations are designed for uncoated cemented carbide tools. In recent years, however, an opposite trend has emerged, using single and multiple coatings. In Marusich *et al.* (2002), for example, the authors carry out a simulation using a numerical model based on the Finite Element Method (FEM). The Thirdwave AdvantEdge® software is used to simulate the chip-breakage of coated and uncoated tools. With multi-layered coatings, one result shows a temperature reduction, for the tool substrate, of 100 °C. Grzesik (2003) studied the cutting mechanisms of several coated cemented carbide tools and found that the tool-chip contact area and the average temperature of the tool-workpiece interface change according to the coating. Grzesik did not explain, however, whether the coatings are able to thermally insulate the substrate.

Yen *et al.* (2003) and Yen *et al.* (2004) offer the first comprehensive assessments, using FEM, of an orthogonal cutting model for multi-layer coated cemented carbide tools. In their model, the authors analyze, both individually and as a group, the thermal properties of the following three layers: titanium carbide, (TiC), aluminum oxide (Al_2O_3), and titanium nitride (TiN). They consider a layer with equivalent thermal properties. Their results indicate that the fine width coatings of an Al_2O_3 intermediary layer do not significantly alter the temperature gradients for a steady state between the chip and the tool substrate. Rech *et al*. (2004) and Rech *et al*. (2005) worked with the qualification of the tribological system "work material-coated cemented carbide cutting tool-chip." Their aim was to better understand the heat flux generated during the turning operation. Their methodology, applied to several coatings deposited on cemented carbide inserts, showed that the coatings possess no significant influence on the substrate thermal insulation.

Kusiak *et al.* (2005) analyzed how several coatings on a cutting tool influenced heat transfer. They performed this analysis with an analytical model of their own. For actual cutting conditions, the authors carry out an experimental work on turning AISI 1035 steel to examine the behavior of different coated inserts. Their results showed that, while the other coatings fail to significantly modify the thermal field, the Al_2O_3 coating yielded a slight reduction on the heat transferred to the tool.

Coelho *et al.* (2007) used FEM to simulate the performance of polycrystalline cubic boron nitride (PCBN) tools when turning AISI 4340 steel, Coelho use titanium aluminum nitride (TiAlN) and aluminum chromium nitride (AlCrN) coated and uncoated cutting tools. The simulations performed indicate that, regardless of the coating, the temperature on the tool-chip interface was approximately 800 °C with an flank wear was absent.

Sahoo (2009) reports an experimental study on the wear characteristics of electroless nickel-phosphorus (Ni-P) coatings sliding against steel. Sahoo (2009) optimized the coating process parameters aiming minimum wear. The optimization based on L_{27} Taguchi (Ross, 1995; Taguchi, 1986) orthogonal design, takes into account four process parameters: bath temperature, concentration of nickel source solution, concentration of reducing agent, and annealing temperature. The author observed that the two most significant factors influencing the wear characteristics of electroless Ni-P coating were the annealing and bath temperatures.

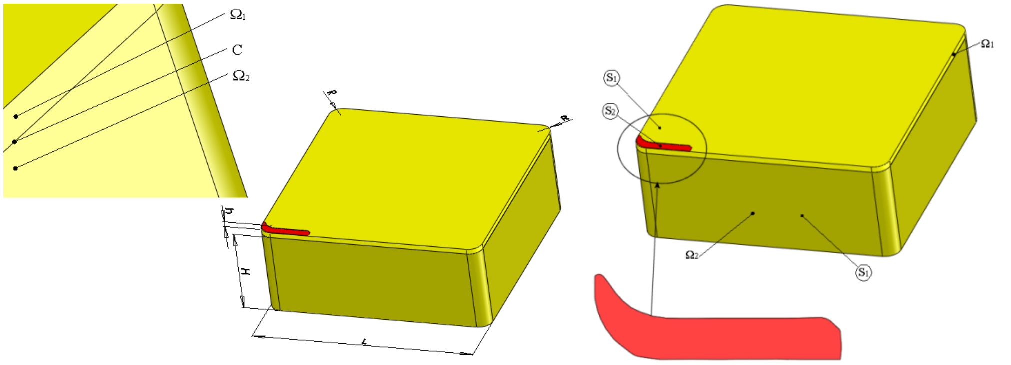
The aim of the present work is to numerically analyze how the coatings on cutting tools influence heat transfer during the cutting process. It is intended to verify the thermal and geometrical parameters of the coated tool, striving for a more adequate temperature distribution in the cutting region. In order to obtain the cutting tool temperature field, ANSYS CFX® Academic Research software v.12 was used. Additionally, a cutting tool with a single coating layer was used, as reported by Rech *et al.* (2005).

In this work, eight cases were analyzed, all with cutting tools having a single layer coating, varying in thickness (*h*) from 1 μm to 10 μm. Different coating materials were investigated with two types of heat fluxes used on the tool-chip interface.

The design of experiments (DoE) is used owing to the fact that it is the most economical and accurate method for performing process optimization. The DoE accelerates the understanding on the influence of the process parameters by determining which variables are critical to the process and at which level. This investigation required the evaluation of the effects of three variables (Montgomery, 2000). To ascertain the key relationships among them, DoE was used to find the best studied case of each simulation carried out. The temperature fields on the cutting tools were thus obtained. Finally, a numerical analysis of the thermal influence of these coatings is presented.

2. Problem Description

Figure 1 presents the thermal model for heat conduction in a cutting tool and the regions for imposing boundary conditions. The tool geometry, within the computational domain, is represented respectively by Ω_1 and Ω_2, the coating solids of height *h*, the cutting tool substrate of height *H*, and interface *C* between the coating and the substrate. Only one type of material was considered for the cutting tool with dimensions 12.7x12.7x4.7 mm, with a nose radius *R*=0.8 mm and heat flux region S_2 with an area of approximately 1.424 mm^2. The coating thickness values adopted were: *h*=1 and 10 μm.

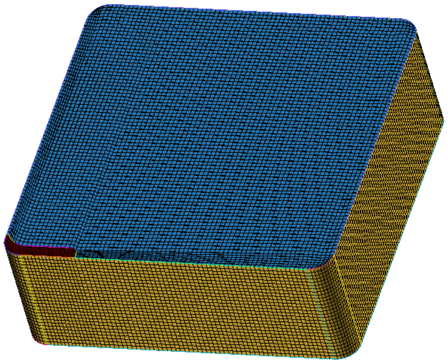


(a) (b)

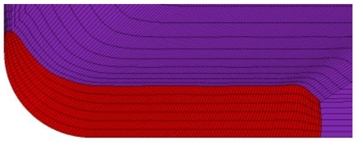
Figure 1. Coated cutting tool: (a) interface detail and (b) heat flux region

At room temperature, the thermal parameters of the materials investigated (substrate and coating) were as follows: ISO K10 cemented carbide tool with density ρ=14,900 kg.m^{-3} (Engqvist *et al.,* 2000), specific heat capacity C_p=200 J.kg^{-1}.K^{-1} and thermal conductivity k=130 W.m^{-1}.K^{-1} at 25 ºC (Engqvist *et al.,* 2000), TiN coating with ρ=4,650 kg.m^{-3} (Yen *et al.,* 2004), C_p=645 J.kg^{-1}.K^{-1} (Yen *et al.,* 2004) and k=21 W.m^{-1}.K^{-1} at 100 ºC (Yen *et al.,* 2004), Al_2O_3 coating with ρ=3,780 kg.m^{-3} (Yen *et al.,* 2004), C_p=1,079 J.kg^{-1}.K^{-1} (Yen *et al.,* 2004) and k=28 W.m^{-1}.K^{-1} (Yen *et al.,* 2004).

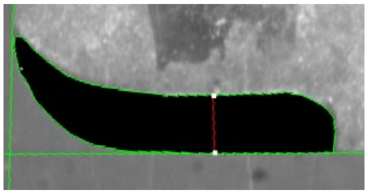
Figures 2a and 2b show one of the meshes formed by hexahedral elements and used in the numerical simulation. Figure 2c shows a typical contact area (A) on the tool-chip interface and the area used in the numerical simulation of the present work (A=1.4245 mm^2). From Carvalho *et al.* (2006), the following cutting conditions were used: cutting speed of v_c=209.23 m/min, feed rate of f=0.138 mm/rot, and cutting depth of p=3.0 mm.



(a) Typical hexahedral mesh used.



(b) Partial detail of the S_2 heat flux region with *A* area in red color.



(c) Video image of the S_2 contact area on the chip-workpiece-tool interface (Carvalho *et al.*, 2006).

Figure 2. Non-structured mesh (a), mesh detail (b), image of the flux area (c).

2.1. Boundary Conditions

The present analysis assumed the following hypotheses: three-dimensional geometrical domain; transient regime; absence of radiation models; thermal properties, such as ρ, k, and C_p are uniform and the temperatures are independent for the coating layer and the substrate body; there is a perfect thermal contact and no thermal resistance contact between the coating layer and the substrate body; the boundary conditions of the heat flux $q''(t)$ are uniform and the time is variable; the boundary conditions of the heat transfer coefficient h and room temperature T_∞ are constant and also known; there is internal heat generation neither on the coating layer nor on the substrate body.

The heat diffusion equation is subject to two types of boundary conditions: imposed time-varying heat flux in S_2 and constant convection in S_1 of the cutting tool. The initial temperature conditions are described for the thermal states of the substrate and coating solids as T_i=29.5 ºC.

3. Numerical Method

The solution of the continuity, momentum, and energy equations uses the Fluid Dynamics Calculus using the Finite Volume Method (FVM) with Eulerian scheme for the spatial and temporal discretization of the physical domain, using a finite number of control volumes (Versteeg and Malalasekra, 2007 and Löhner, 2008).

Through this method, the control volume elements follow the Eulerian scheme with unstructured mesh (Barth and Ohlberger, 2004). Using this approach, the transport equations may be integrated by applying the Gauss Divergence Theorem, where the approximation of surface integral is done with two levels of approximation. Firstly, the physical variables are integrated into one or more points on the control volume faces. Secondly, this integrated value is approximated in terms of nodal values. This approximation represents, with second order accuracy, the average physical quantity of all the control volume (Shaw, 1992). More details on the concepts involved in FVM may be found in Barth and Ohlberger (2004), where the authors explore discretization techniques, integral approximation techniques, convergence criteria, and calculus stability.

4. Numerical Validation

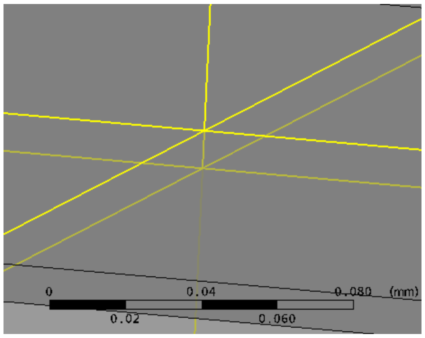
The commercial software used here was validated extensively by comparing this work's results of with those obtained in experimental and numerical investigations. For example, we compared our software's numerically obtained temperatures with those obtained, both numerically and experimentally, by Carvalho *et al.* (2006). The largest deviation was 6.07 %. In most of the simulated cases, the number of nodal points was 501,768 and the number of hexahedral elements was 481,500.

5. Results and Discussion

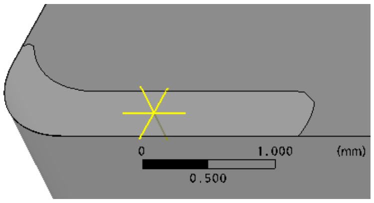
Eight cases were selected to investigate the temperature distribution for a time interval *t*. The main goal is to study the influence of heat flux and variations in the coating thickness on the heat flux.

Table 1. Numerical results obtained from the temperature values after 63.14 s.

Case	**Coating/ Thickness µm**	**Heat flux $W.m^{-2}$**	**Chip-Tool Temperature T_{CT} °C**	**Coating-Substrate Temperature T_{CS} °C**	**Temperature Difference $T_{CT} - T_{CS}$ °C**
1	TiN/1	$q_1''(t)$	86.71	86.53	0.18
2	TiN/1	$q_2''(t)$	601.72	599.86	1.86
3	TiN/10	$q_1''(t)$	87.28	86.46	0.82
4	TiN/10	$q_2''(t)$	607.37	599.17	8.20
5	Al_2O_3/10	$q_1''(t)$	87.08	86.55	0.53
6	Al_2O_3/10	$q_2''(t)$	604.90	599.59	5.31
7	Al_2O_3/1	$q_1''(t)$	86.72	86.55	0.17
8	Al_2O_3/1	$q_2''(t)$	601.28	600.90	0.38



(a) Detail of the two temperature monitoring points.

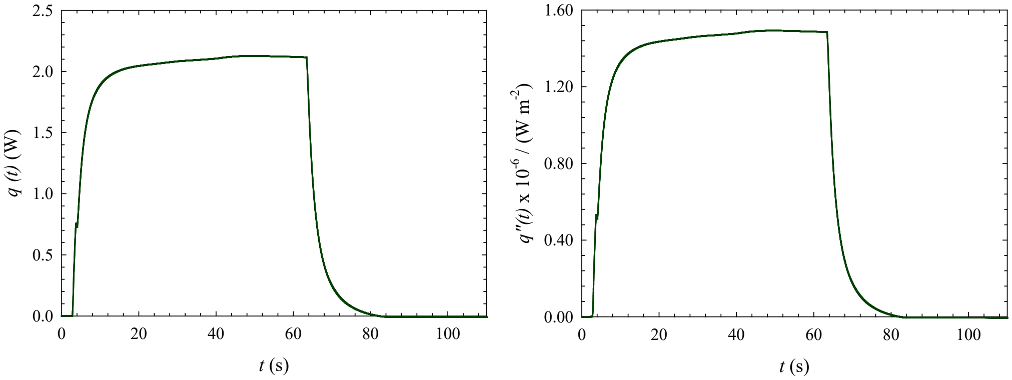


(b) Position of temperature monitoring.

Figure 3. Temperature monitoring points located on and under the 10 µm TiN coating layer.

Table 1 shows temperature values obtained after cutting for 63.14 s on the chip-tool (CT) and the coating-substrate (CS) interfaces. This was determined using the ANSYS CFX® Academic Research software, v.12. For the 10 µm coating with flux $q_2''(t)$, case 4 (TiN coated K10 substrate) had the highest calculated temperature difference. For 1 µm coating thickness with flux $q_1''(t)$, case 7 (Al_2O_3 coated K10 substrate) had the lowest calculated temperature difference.

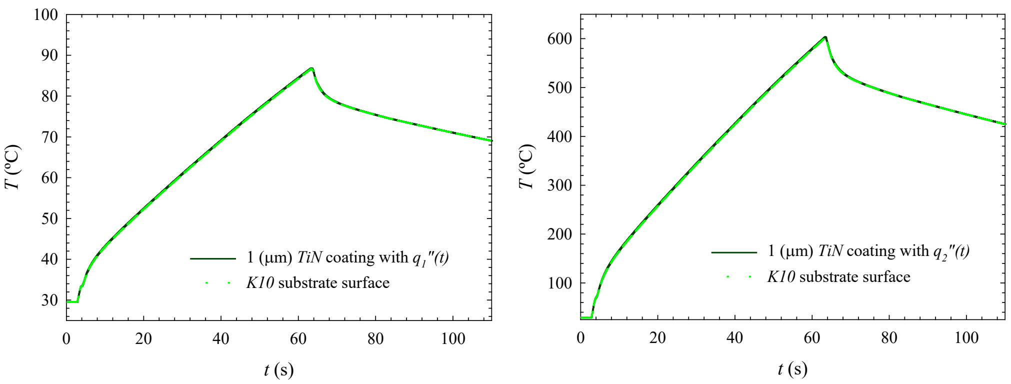
Figure 3 shows the two points where temperature was monitored during the simulation. For the coordinates on the tool substrate-coating interface: x=1.5 mm, y=0.25 mm and z=10 µm and on the coating: x=1.5 mm, y=0.25 mm and z=0 mm. Case 04 (Table 1), with a thickness of 10 µm, exhibited the greatest temperature decrease, dropping 8.20 °C (from 607.37 to 599.17 ºC). Figures 4a and 4b show, respectively, heat rate q and heat flux q_1'' W m^{-2} against cutting time.



(a) Heat rate q (t) (Carvalho *et al.*, 2006). (b) Heat flux $q_1''(t)$.

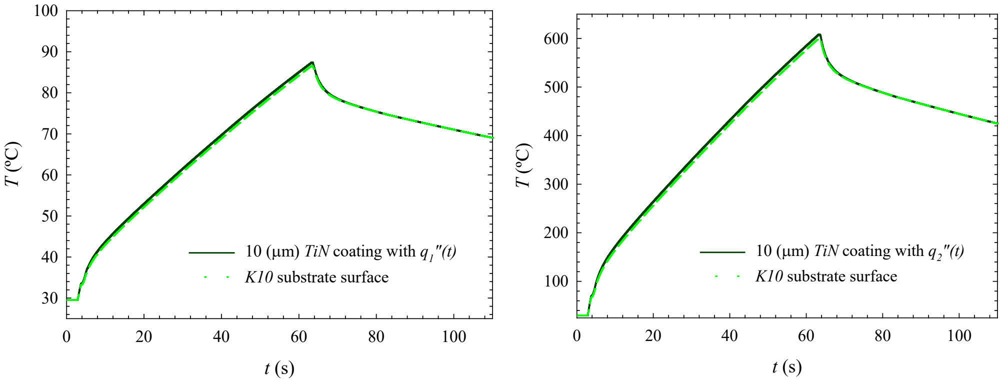
Figure 4. Heat rate and heat flux utilized in the present work.

Figures 5 through 8 show the simulation results for coated cutting tools. The influence of heat flux and coating thickness on the temperature fields on the chip-tool coating-substrate interfaces can thus be assessed. It can be seen that owing to the fact that the coating did not affect temperature reduction, it possesses negligible influence on thermal insulation.



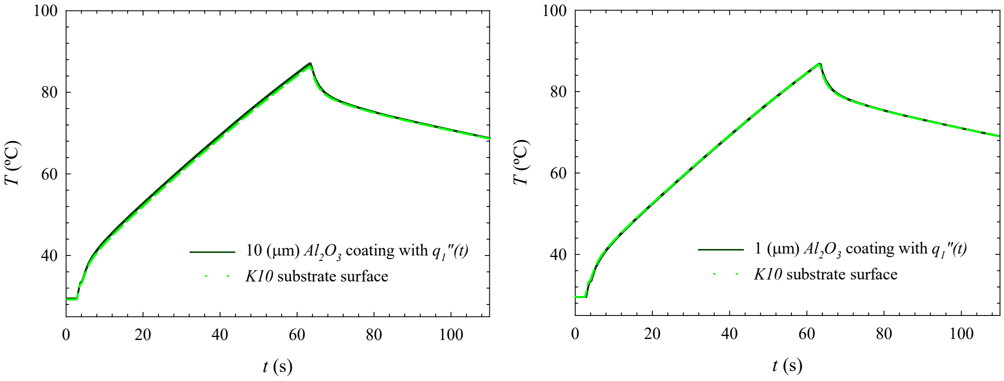
(a) (b)

Figure 5. Effect of heat flux variation on temperature (TiN coating with 1 μm thick).



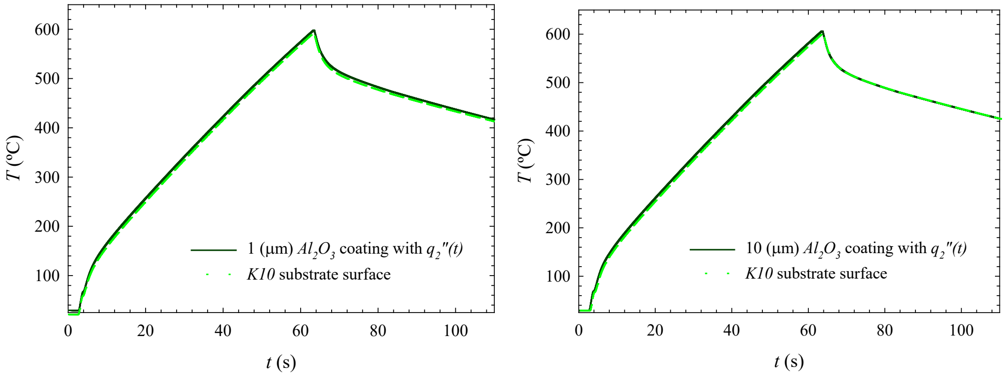
(a) (b)

Figure 6. Effect of heat flux variation on temperature (TiN coating with 10 μm thick)



(a) (b)

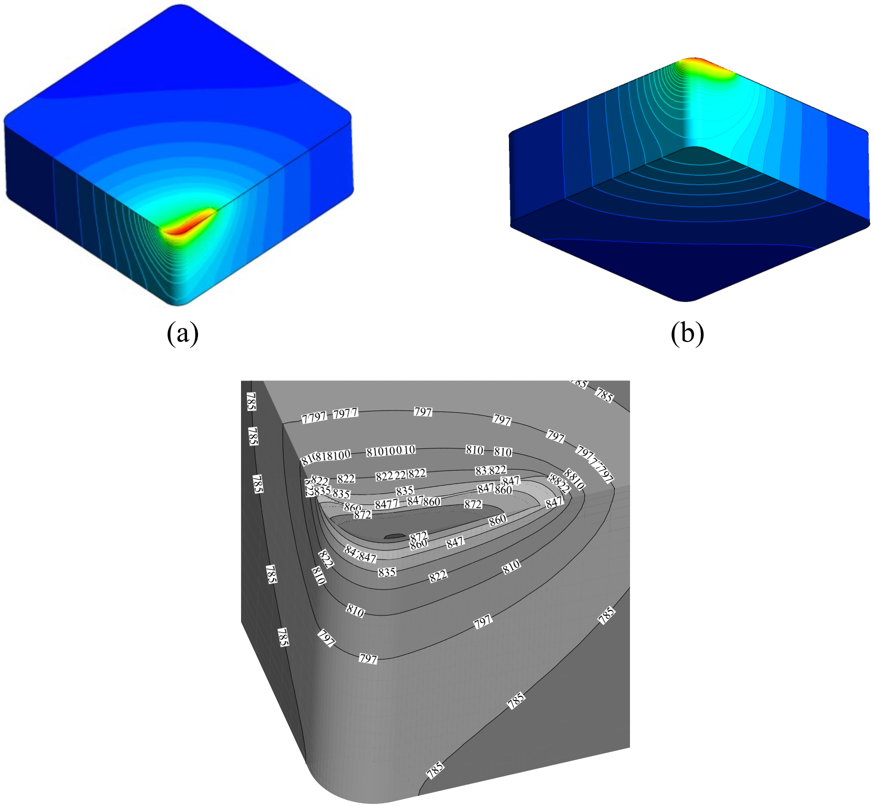
Figure 7. Effect of Al_2O_3 coating thickness variation on temperature with $q_1''(t)$ heat flux: (a) 10 μm thick and (b) 1 μm thick.



(a) (b)

Figure 8. Effect of Al_2O_3 coating thickness variation on temperature with $q_2''(t)$ heat flux: (a) 1 μm thick and (b) 10 μm.

Figures 9a, 9b and 9c show the temperature fields at instant 63.14 s on the top and bottom of the insert and the heat flux surface, respectively, for case 4 (TiN coating with 10 μm).



(a) (b)

(c)

Figure 9. Temperature fields on: (a) top and (b) bottom and (c) heat flux surface (measured in K) on the TiN coated tool (case 4) at instant t=63.14 s.

5.1. Design of Experiment (DoE)

The DoE was configured with 3 factors (thickness, heat flux and coating material) at two levels (-1 and +1) aiming to determine their influence on the temperature field. The coatings were TiN and Al_2O_3, the thickness values were 1 µm and 10 µm and the heat flux values were 1 and 10 times (Montgomery, 2000). Table 2 shows the parameters specified for the design of experiment. The experiments were planned and analyzed with the Minitab® Inc. v.14 software.

Figure 10 shows the factors main effects on the temperature gradient (ΔT). The best levels defined for the parameters are a TiN coating, coating thickness of 10 µm and heat flux of $q_2''(t)$. This combination presented the highest temperature gradient.

Table 2. DoE matrix.

Trial no.	Parameter			
	Coating	Thickness h µm	Heat Flux	Difference of temperature ΔT ºC
1	Al_2O_3	10	10	5.31
2	TiN	10	1	0.82
3	TiN	1	1	0.18
4	TiN	10	10	8.20
5	Al_2O_3	10	1	0.53
6	Al_2O_3	1	10	0.38
7	TiN	10	1	0.82
8	TiN	1	10	1.86

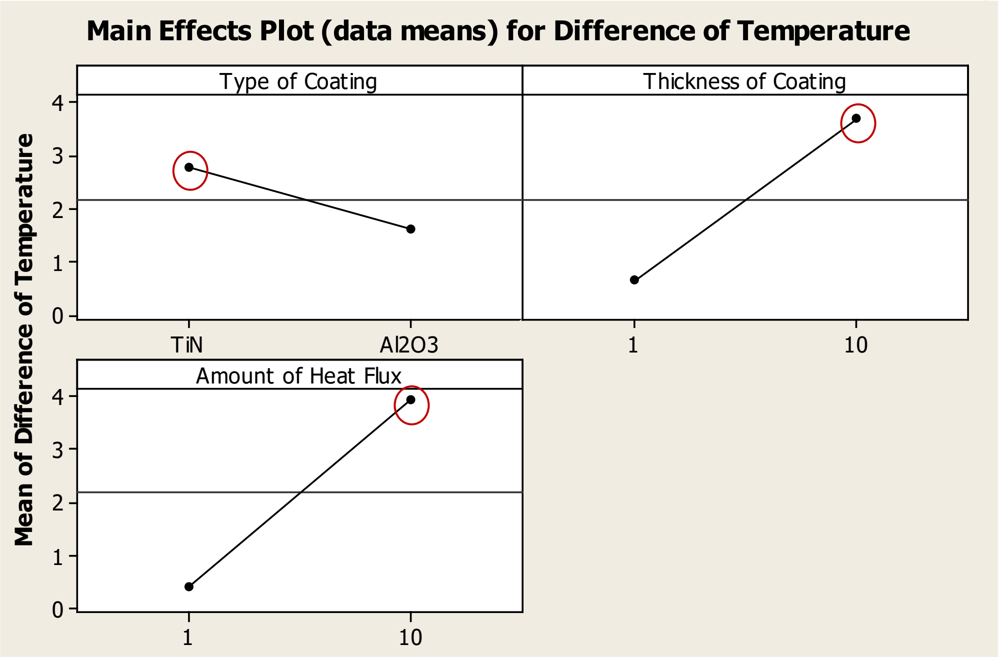


Figure 10. Influence of the main effects on the temperature gradient.

6. Conclusions

One of the contributions of this work is its numerical approach. This methodology permits the simulations of complex geometrical forms. It also includes, relative to experimental cases, a more realistic heat flux (Carvalho *et al.*, 2006). In addition to that, the following conclusions can be drawn regarding the numerical results obtained for the thermal model of heat transfer in coated cutting tools:

- For a uniform heat source varying in time with constant surface contact between chip and tool, the coatings may slightly influence the temperature on the tool. This is true, however, when the thermal properties of the coating are rather different from those of the substrate, even for a thin coating (1 μm thick).
- During continuous cutting, the coating on the cemented carbide tool presented unsatisfactory results. The calculated temperature gradient was lower than for those found in the literature.
- None of the films analyzed showed a significant change in the temperature gradient across the tool coating.
- The DoE methodology proved to be an excellent tool for test planning. The best levels defined for the highest temperature gradient in the coated cutting tool were obtained with a coating of TiN with a thickness of 10 μm at the highest heat flux.
- Future studies should consider the influence of temperature variation on the thermal conductivity k and specific heat capacity C_p.

7. Acknowledgements

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