Proceedings of ENCIT 2014 15th Brazilian Congress of Thermal Sciences and Engineering

November 10-13, 2014, Belém, PA, Brazil

THE USE OF COMSOL® TO CALCULATE THE TEMPERATURES ON EQUIVALENT MONITORED EXPERIMENTAL POINTS USING ESTIMATED HEAT FLUX

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Abstract. *This paper presents the results of simulations in heat transfer by using the commercial software COMSOL Multiphysics® v4.4. The differential equations are solved by using Finite Elements Method existent on this commercial package. These simulations are based on controlled experiment carried out in the Heat Transfer Laboratory of the Federal University of Uberlândia (UFU), in Brazil. The main goal of this study was to investigate the impact of thermal contact resistance on temperature. Thermocouples were inserted on many surfaces in order to measure experimental temperatures. In past work, the heat flux was estimated by Inverse Problems technique by the authors of the present work. By using the estimated heat flux, simulation was performed to calculate the temperatures on equivalent monitored experimental points. Two simulations were done, one considering thermal contact resistance between the cutting tool, the shim and the workpiece and another in which the contact resistance was disregarded. The results between these two simulations were compared. This work presents better results for the calculated temperatures with contact resistance than those presented in literature.*

Keywords: *heat conduction, COMSOL Multiphysics® v4.4 package, air resistance, cutting tool*

1. INTRODUCTION

The research related to basic studies of industrial processes always enables the development of manufacturing operations not only as locally but also on a global scale. Therefore, since the machining process is used in most productive segments, it is important to treat the parameters which lead its scientific principles and technological innovations. Treating the analysis of the distribution of temperature field, as well as the study of heat flow in cutting tools during machining operations is a task that requires complex methods to obtain reliable data on each process. This is due to the fact that machining processes involve high temperatures and it is difficult to measure this parameter in the wear region. Temperatures may exceed 900°C in the cutting tool (Trent and Wright, 2000). Thus, the precise estimation of this temperature leads to numerical procedures in order to establish a research to optimize the use of cutting tools providing improvement in their performance and durability. By studying the characteristics of the cutting tool adopted, it is possible to prove that the use of inserts is a way to alleviate the stresses arising from the operations of milling, boring, turning, etc. Furthermore, these analyses aim to increase the life of cutting tools as can be seen in Smith (2011) who made a study about the cutting conditions to extend tool life and show some of the problems that reduce it and show high temperatures as a big problem. Yang et. al. (2011) shows a similar study, where the performance of the tool was enhanced, reducing production costs and increasing industry's profit. Therefore, it allows, through numerical studies, an increase in cutting speed and a reduction in the use of lubricants and refrigerants, optimizing the time in the industry and minimizing impacts on the environment.

Based on this information, the authors of this paper used a software package and proposed a numerical analysis to assess the impact of the thermal contact resistance existing between the parts of the cutting tool, shims, and tool holder on the temperatures observed in a machining process. The issues addressed in this paper were partly discussed by Carvalho et al. (2006), in a study that analyzed the high temperatures generated in chip-tool interface during machining processes. Brito et al. (2014) used the experimental results from Carvalho et al. (2006) to estimate the heat flux, since direct measurement of heat flux is difficult to implement due to the difficulty of positioning the thermocouples on chip-tool interface, heat flux was used as input in the numerical simulations presented in this paper. With the heat flux in question the temperatures were obtained by using the Finite Element Method as in the study of Chen et al. (2013). The numerical location of the thermocouples described by Carvalho et al. (2006) was included in the numeric simulations, so that numerical and experimental results were subsequently compared. This work aims to show the results of simulations that were performed in the geometry, shown in Fig. 3, analyzing the thermal impact of different boundary conditions over the final result. However, as a part of a scientific academic research, this work analyzes only the heat transfer in the assembly studied. Thermal contact resistance (TCR) was considered as the boundary condition.

In numerical modeling, the boundary condition plays a key role when utmost accuracy is desired. Thermal contact resistance (TCR) was chosen to analyze the impact upon results. TCR is a phenomenon that occurs between two contacting surfaces, stemmed from the layer of air that forms in the interstices between two contacting bodies. Commercial package COMSOL Multiphysics® v4.4 - used to solve heat transfer problems using the finite element method - was used to solve a direct problem with the purpose of analyzing the impact of TCR on the findings of this study. The heat diffusion equation was used to define the physics problem of heat transfer in a model in three dimensions described in this paper, as previously discussed.

2. EXPERIMENTAL PROCEDURES

To obtain experimental data, the experiments were carried out by Carvalho et. al. (2006) at UFU, by using a conventional lathe IMOR MAXI II 520 of 6 Horse Power HP, and a HP 75000 B data acquisition system, with E1326B voltmeter commanded by a computer, to which a K type thermocouple is connected to measure the temperature. The experimental assembly is represented in Fig. 5.

The cutting tool chosen for the tests is a cemented carbide tool (code ISSO SNUN 120412 H1P – K10) and the respective tool holder (code ISSO CSBNR 20K12). Grey cast iron bodies ABNT FC 20 EB 126a, bearing 77 mm in diameter and 77 mm in length were used as body of proof. Five experiments were carried out to guarantee the repeatability of the results. In each test, 300 temperature values were taken at a time interval of 0.5 s.

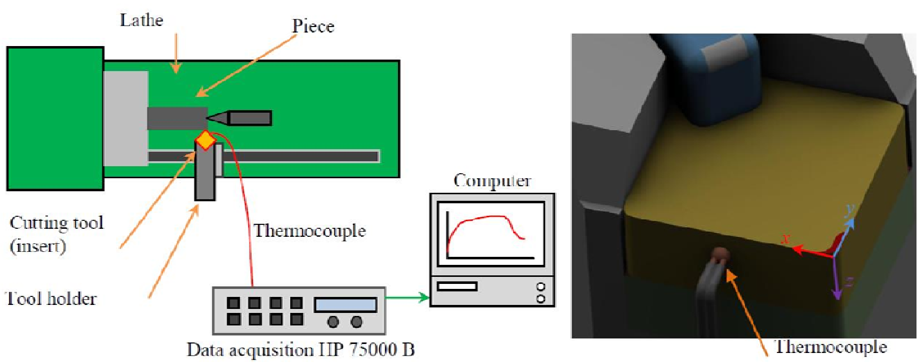


Figure 1. Experimental apparatus used to acquire the temperature signals in the tool during machining (Carvalho et. al., 2006).

3. PROBLEM DESCRIPTION

3.1 Thermal Model Assembly

The problem presented in this work is shown in Fig. 3. This figure presents an assembly consisting of a cutting tool, a shim positioned under the cutting tool between the cutting tool and the tool holder. There is also a staple and a bolt to fix the set. A perspective is shown in Fig. 3.

The transient heat diffusion equation, which governs the physical problem of this work, is presented below:

$$\left(\rho c_p\right)\frac{\partial T}{\partial t} = \lambda \nabla^2 \left(T\right) \tag{1}$$

where λ is the solid thermal conductivity, W/(m.K); c_p is the solid specific heat capacity, J/(kg.K); ρ is the solid density, kg/m^3.

The boundary conditions have been given as:

$$-\lambda \frac{\partial T}{\partial \eta} = q_I^{''}\left(t\right) \text{ on the tool-workpiece contact interface,} \tag{2}$$

where $\partial T/\partial \eta$ is the derivative along the normal direction of the surface of the set, and in the contact area between the tool and the workpiece. The heat flux $q_I^{''}\left(t\right)$ is applied to the contact area, W/m^2:

$$-\lambda \frac{\partial T}{\partial \eta} = h\left(T - T_{\infty}\right) \qquad (3)$$

is applied in the remaining regions of the set, where h is the heat transfer coefficient, ($W/m^2.K$).

The initial conditions have been given as:

$$T(x, y, z, t) = T_0 \text{ at } t = 0. \qquad (4)$$

3.2 Direct Problem Solution

The transient heat diffusion equation is solved according to the boundary conditions defined above. The COMSOL Multiphysics® v4.4 package, which solves thermal problems by using the Finite Element Method, is used for this purpose. The heat diffusion equation defines the physical problem of heat transfer in a three dimensional modeling in this work, as previously mentioned. The boundary condition addressed in this study is the effect of thermal contact resistance on temperature. The TCR values applied to the component parts of the machining equipment were taken from the literature. Simulation scenarios considered the properties of air at 300 K and the existence of a gap of 10 μm between the surfaces involved. The thermal properties applied to air were: λ = 0.026 W m^{-1} K^{-1} and α = 22.5 x 10^{-06} m^2/s (Incropera et al., 2007). The properties considered for the materials involved were: tool holder, made of AISI 1045 steel with the following thermal properties: ρ = 7850 kg m^{-3}, c_p = 486.126 J kg^{-1} K^{-1}, and λ = 49.8 W m^{-1} K^{-1}. The cutting tool's properties were ρ = 14900 kg m^{-3}, c_p = 195.45 J kg^{-1} K^{-1}, and λ = 43.1 W m^{-1} K^{-1} (Grzesik et al., 2009). The shim was assigned the same thermal properties as the cutting tool.

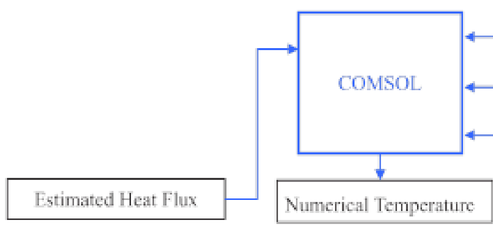
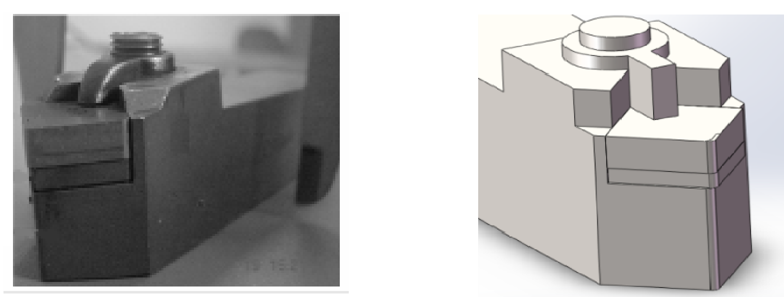


Figure 2. Methodology used in the simulation for the tridimensional thermal model, in transient regime with the COMSOL Multiphysics® v4.4 package.

3.3 Numerical Model

The geometry used in the simulations was designed on commercial software package SolidWorks based on the tool described in the experiments run by Carvalho et al. (2006). Both are presented in Figure 3.



a) b)

Figure 3. a) set of tools, shim, and actual support tool (Carvalho et al, 2006); b) model used in this study.

The indication of the contact area of the cutting tool is an important step in the design of the equipment geometry and a significant source of error in the solution of the thermal model problem. Methods to identify this area have been described in the literature, and much has been published on image analysis packages (Jen and Gutierrez, 2000). This method was also used in our study. Although contact areas of various shapes were studied, the interface contact areas analyzed in this study were obtained from only three tests performed under equal cutting conditions. Contact areas were measured with the aid of an imaging system equipped with a Hitachi KP-110 CCD camcorder, a PC with an AMD® K6 450 MHz processor, and image package GLOBAL LAB®. A typical contact area is shown in Figures 4a and 4b. The contact area measured 1.41 mm^2 and was obtained at an advance rate of 0.138 mm/rev, a cutting rate of 135.47 m/min, and a cut depth 5.0 mm.

Another important factor to be considered in the modeling of the studied geometry is the location of the points where temperatures were measured in the actual experiment. Measurement points must be accurately positioned in the model to be simulated in order to mitigate the error embedded in the measured results. Figure 5 shows the position of the thermocouples in the designed geometry. Table 1 shows the thermocouple positions in relation to the point of origin of the designed geometry.

a) b)

Figure 4. a) Contact area treated images (Carvalho et at, 2006); and b) contact area in the computer model.

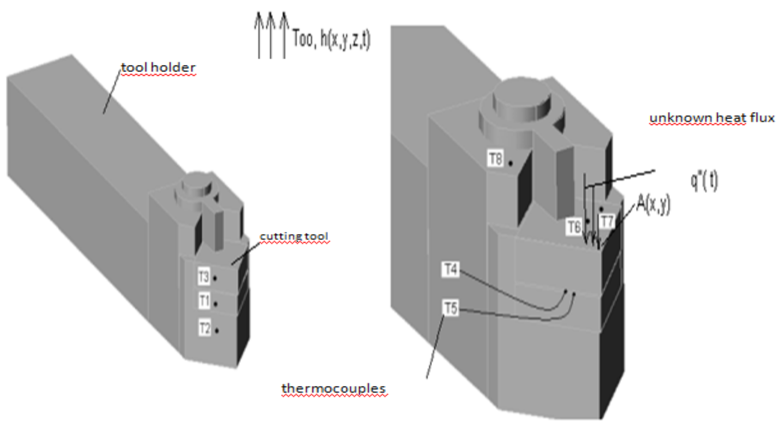


Figure 5. Detailed view of thermocouples welded to the tool.

Table 1. Location of the thermocouples shown in Fig. 5.

Position/Thermocouples	1	2	3	4	5	6	7	8
x (mm)	0.0	0.0	0.0	4.490	6.528	7.222	9.512	5.300
y (mm)	6.45	7.25	3.950	4.116	6.579	4.740	1.715	14.55
z (mm)	-6.55	-11.65	-2.12	-4.83	-4.83	0.0	0.0	5.4

4. VALIDATION

This work uses experimental temperature results from Carvalho et. al. (2006) under lab controlled conditions in order to compare with the numerical results obtained by the COMSOL Multiphysics® v4.4 package so as to validate them. The transient heat flux was estimated by Brito et. al. (2014), this heat flux is showed in the figure 7, and was utilized as input data in the present work. The validation was conducted by using the thermal properties of the ISO K10 12.7 mm × 12.7 mm × 4.7 mm isolate cemented carbide cutting tool, as showed in figure 6, with the following thermo physical properties: λ = 43.1 W m^{-1} K^{-1}, c_p = 332.94 J kg^{-1} K^{-1}, and ρ = 14,900 kg m^{-3}. To obtain the results in this present work, the number of elements utilized was approximately 119,943 domain elements, 19,152 boundary elements, and 1,712 edge elements. The following parameters were used in the tests: External temperature at 31.06 °C, constant and equal heat transfer coefficient at 20 W m^{-2} K^{-1}, total time of 84.5 s, and area subjected to heat flux of 108.16 mm^2. According to this study, it is clear that there was little difference as to the calculated temperature values. Moreover, the temperature residue among the meshes is practically negligible. In this numerical validation, it is concluded that the number of elements of the mesh is already enough to obtain good accuracy and low computational time simulations. For a mesh developed with a greater number of elements, the temperature value barely varies with mesh refinement. The COMSOL software proved satisfactory by considering only the cutting tool when compared to the physical results obtained by Carvalho et. al. (2006).

5. ANALYSIS OF THE RESULTS

In this section, the results of one of the eight monitored temperature points used by Carvalho et. al. (2006) will be presented. The proprieties of the thermal contact resistance between the cutting tool, shim, and the tool holder, when considering air for the thickness of 10.0 µm was the thermal conductivity of 26.3e-3 W m^{-1} K^{-1} according to Carvalho et. al. (2006). The data obtained from the simulations were presented as graphs. Two graphs were plotted for each temperature monitoring point, the first with the temperatures obtained in the simulations without TCR versus experimental temperatures and the second with the temperatures obtained when the impact of TCR was considered.

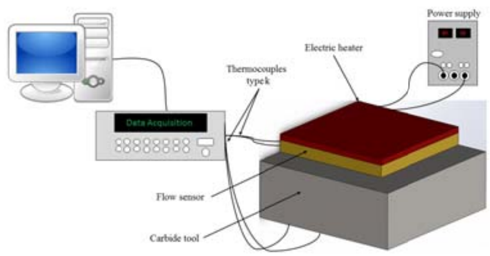


Figure 6. Schematic representation of the experimental apparatus used in validation.

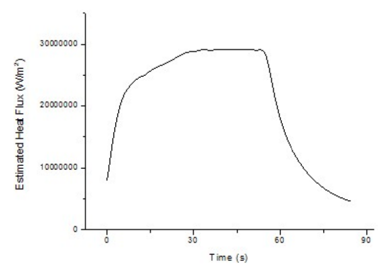
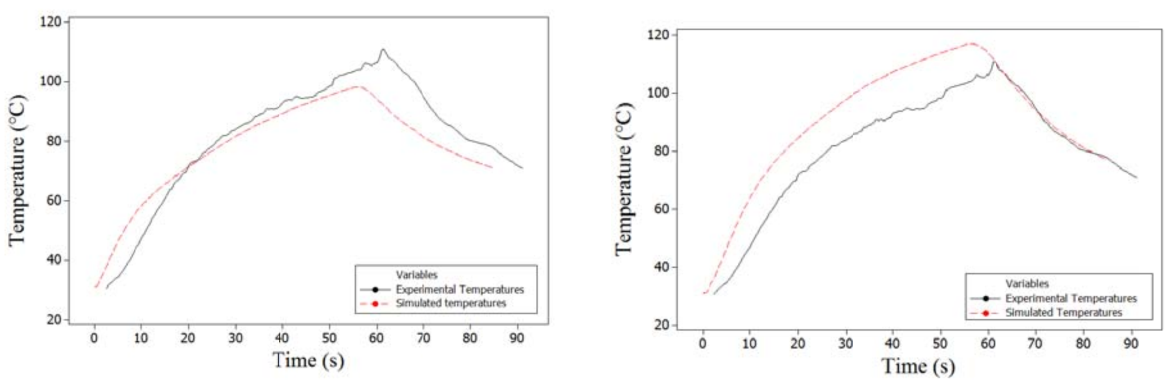


Figure 7. Estimated heat flux used as input data in the present study (Brito et. al., 2014)



a) b)

Figure 8. Comparison between experimental data (Carvalho et. al., 2006) and numerical temperature obtained in the present work without contact thermal resistance a) and with contact thermal resistance b) for thermocouple 1.

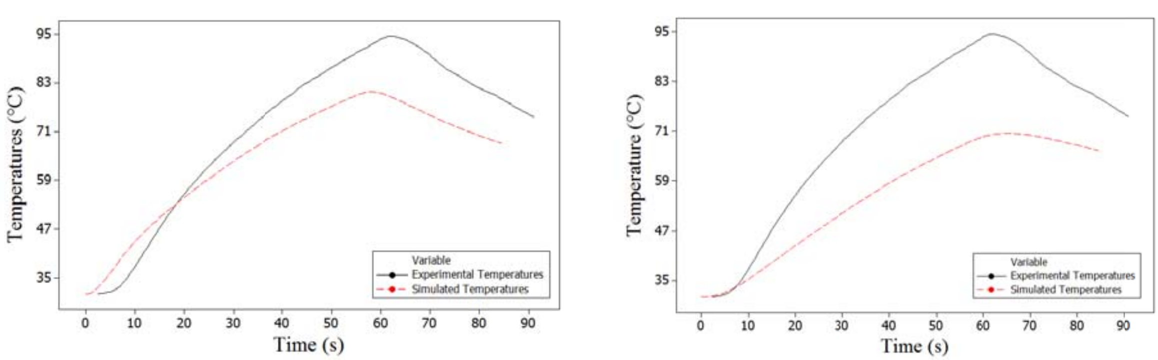


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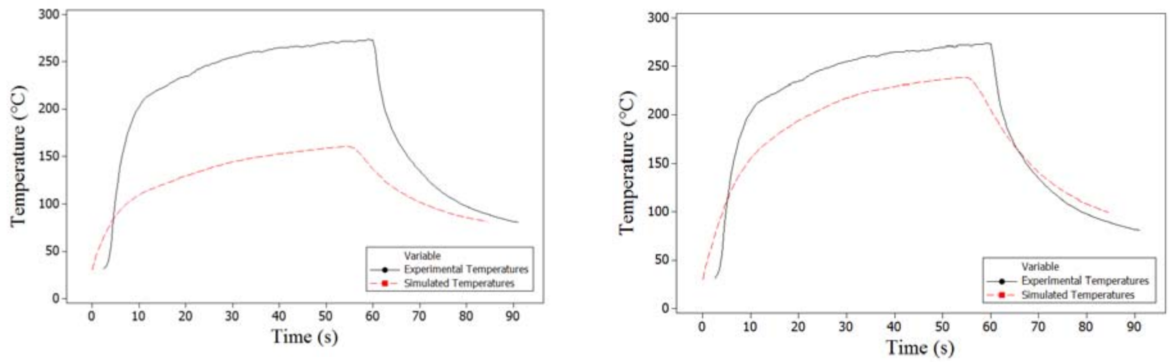
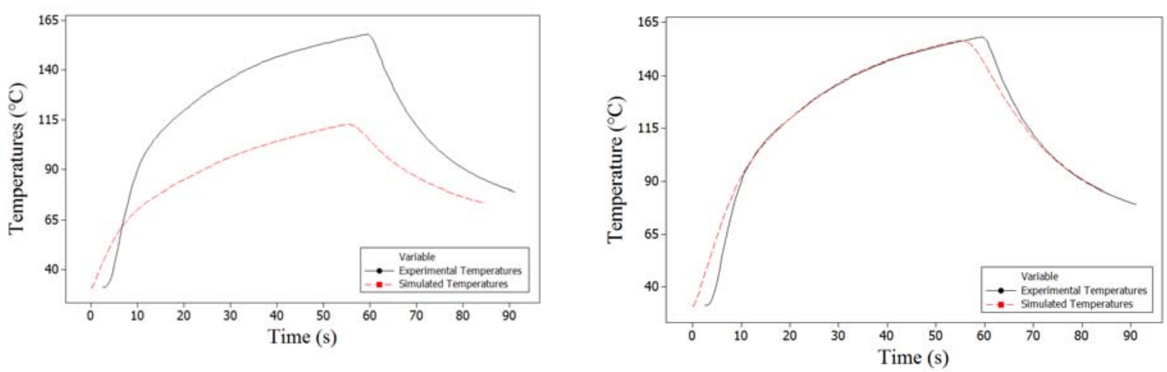
Figure 9. Comparison between experimental data (Carvalho et. al., 2006) and numerical temperature obtained in the present work without contact thermal resistance a) and with contact thermal resistance b) for thermocouple 2.



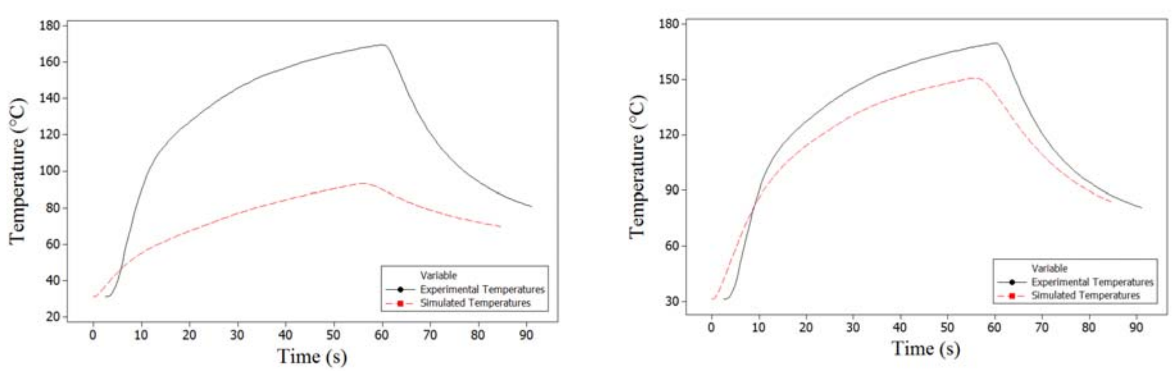
a) b)

Figure 10. Comparison between experimental data (Carvalho et. al., 2006) and numerical temperature obtained in the present work without contact thermal resistance a) and with contact thermal resistance b) for thermocouple 3.



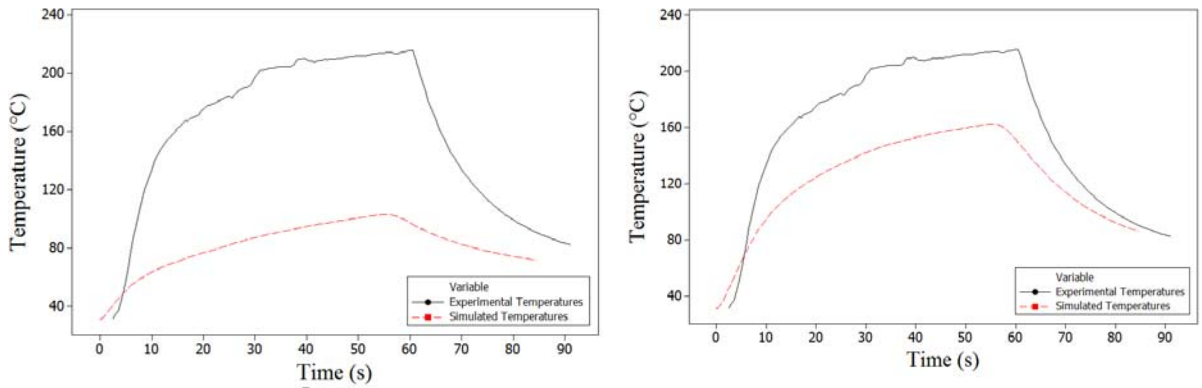
a) b)

Figure 11. Comparison between experimental data (Carvalho et. al., 2006) and numerical temperature obtained in the present work without contact thermal resistance a) and with contact thermal resistance b) for thermocouple 4.



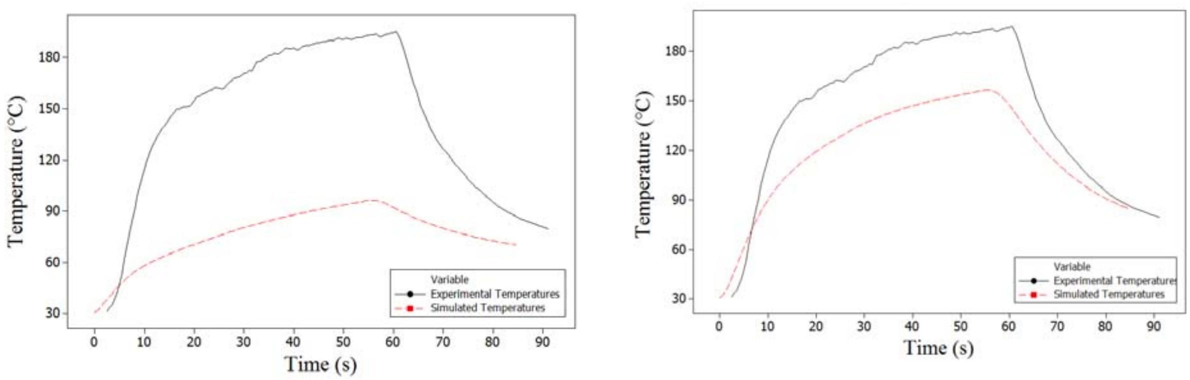
a) b)

Figure 12. Comparison between experimental data (Carvalho et. al., 2006) and numerical temperature obtained in the present work without contact thermal resistance a) and with contact thermal resistance b) for thermocouple 5.



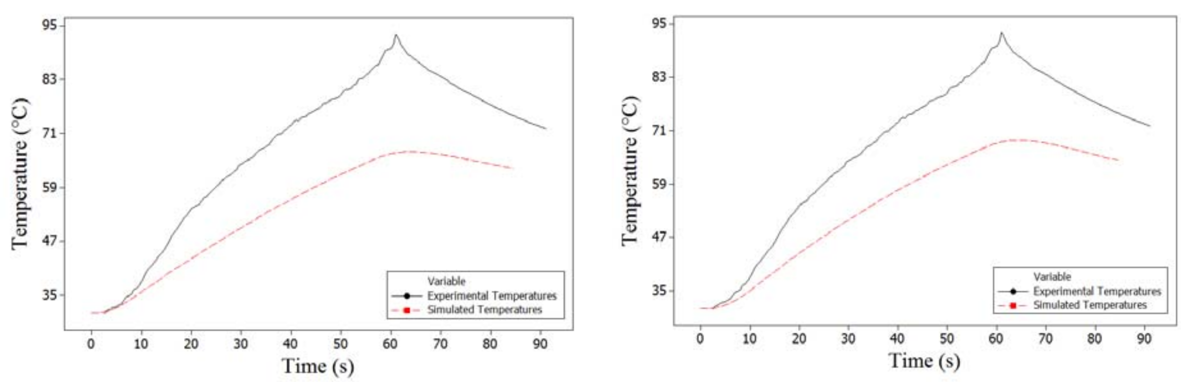
a) b)

Figure 13. Comparison between experimental data (Carvalho et. al., 2006) and numerical temperature obtained in the present work without contact thermal resistance a) and with contact thermal resistance b) for thermocouple 6.



a) b)

Figure 14. Comparison between experimental data (Carvalho et. al., 2006) and numerical temperature obtained in the present work without contact thermal resistance a) and with contact thermal resistance b) for thermocouple 7.



a) b)

Figure 15. Comparison between experimental data (Carvalho et. al., 2006) and numerical temperature obtained in the present work without contact thermal resistance a) and with contact thermal resistance b) for thermocouple 8.

The analysis of obtained results revealed that in most monitoring points the curves derived from numerically simulated data were considerably close to the curves produced from experimental data when thermal contact resistance was considered. This finding can be seen more clearly in the graphs shown in Figs. 12 and 13, in which the differences between the two curves were greater. Another noteworthy finding was the difference in results related to how far thermocouples were to the face where TCR was applied. Thermocouple 2, described in Fig. 9, had the worst result. This occurred probably due to the significant distance between the thermocouple and the face where RTC was applied.

Thermocouples 4 and 5, described in Figs. 11 and 12, respectively, showed significant improvements when TCR was considered, and both were positioned directly over the face in which the boundary condition was applied.

6. CONCLUSIONS

This work presented how the heat flux, estimated with inverse problem techniques in past work by Brito et. al. (2014), and numerical temperatures obtained in COMSOL Multiphysics® v4.4 package are close to the experimental model done by Carvalho et. al. (2006) when considering contact resistance between the cutting tool and the shim. Although results were satisfactory, some sources of error have been observed and should be considered in future studies. The most significant were: heat flux used in this study was derived from estimations published in another study; the differences between the actual model and the one used in this study; the fact that the variations of thermal and physical properties of the material with temperature were disregarded. However, TCR yielded significant improvements and should be used in future studies. By considering the need to reduce the cutting tools costs in industry, studies like this can show an effective method to find the optimum temperature field with the use of commercial software packages from which results closer to real are possible to be obtained.

7. ACKNOWLEDGEMENT

The authors would like to thank the Brazilian Federal Agency for the Support and Evaluation of Graduate Education - CAPES for their financial support.

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