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Research paper

Experimental investigation of thermal aspects in a cutting tool using comsol and inverse problem

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H I G H L I G H T S

- Nonlinear inverse problem and COMSOL to estimate heat flux on a turning cutting tool.
- Improvements on previous work to study the complex geometry of machining processes.
- Several tests using cemented carbide tools were performed to check the methodology.
- COMSOL adjusts any boundary conditions and models the geometries.

A R T I C L E   I N F O

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A B S T R A C T

The direct measurement of the temperature in a machining process is difficult to accomplish due to the movement of the piece as well as the presence of chips. Thus, the use of inverse heat conduction techniques convey a good alternative to obtain these temperatures, since these techniques allow the use of experimental data obtained from accessible regions. This work proposes the use of a nonlinear inverse problem technique in connection with COMSOL to estimate the heat flux and the temperature field on a turning cutting tool in transient regime. The main purpose of the present work is to show the improvements performed in relation to the authors' previous work to develop the complex geometry of a machining process. Specification function, which is an inverse problem technique, was implemented in a MATLAB program to estimate the heat flux applied on the tool, from the experimental temperature records. Once the heat flux is known, COMSOL is again utilized to obtain the temperature field on the cutting tool. A comparison of the numerical and experimental temperature results validates the methodology.

1. Introduction

Several engineering processes have their performance and quality affected by high temperature values. A typical example is the machining process in which cutting tool temperatures may be higher than 900 °C [1]. High temperatures change the microstructure and physical properties of the tool during machining, thus reducing their capacity to resist mechanical stress [2]. The direct consequence of these alterations is the reduction of their lifespan and performance. This leads to high operation costs and reduction of the end product quality. The right knowledge of the temperature values and applied heat flux, in this kind of process, results in advantages like the development of more efficient cooling techniques as well as better specifications of the cutting parameters in machining processes. These temperatures have a controlling influence on the wear rate of the cutting tool as well as on the friction between the chip and the tool. However, the direct measurement of the temperature in a machining process is difficult to accomplish due to the movement of the piece as well as the presence of chips. The application of inverse heat conduction techniques has proven to be a good option to achieve these temperatures. Inverse problems consist of obtaining the value of a variable through the measurement of another variable measured directly [3]. These

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Nomenclature

c	specific heat, $WsKg^{-1}\,K^{-1}$
F	objective function
h	heat transfer coefficient, $Wm^{-2}\,K^{-1}$
k	thermal conductivity, $Wm^{-1}\,K^{-1}$
M	general time index, s
q_0''	unknown heat flux, Wm^{-2}
q_M	estimated heat flux, Wm^{-2}
r	number of future time steps
T	numerical temperature, °C
t	time, s
T_∞	the medium temperature, °C
T_0	initial temperature, °C
Y	experimental temperatures, °C
x	Cartesian coordinate, m
y	Cartesian coordinate, m
z	Cartesian coordinate, m

Greek

α	thermal diffusivity, ms^{-2}
η	the outward drawn normal to the surface

Subscripts

j	index of sensors
p	index of future time steps

Superscript

np	number of points
ns	number of sensors

techniques often use optimization algorithm in order to minimize the error between the calculated and real value of the variable in question. Nowadays, several researchers have proposed the combination of inverse techniques and numerical heat transfer solutions to analyze the thermal fields during machining processes.

Conveying a greater availability of computational resources, the use of numerical methods gained terrain, and it did not take long before they started being used, along with experimental methods in the studies of temperature fields on cutting tools. A three-dimensional finite difference-based model to predict temperature in machining processes was presented in Ulutan et al. [4]. The FDM based model proposed in this paper offered very rapid and reasonably accurate solutions. The simulated results were validated with infrared thermal measurements which were determined from the machining of AISI 1050 and AISI H13 materials under various cutting conditions. In the study of Wang et al. [5] an analytical and numerical model for cutting temperature prediction of 316L stainless steel was developed. The simulation model was set up in commercial FEM software of Abaqus 6.8, which is good at nonlinear dynamic calculation. An ALE finite element model, which combines the advantages of both Lagrangian and Eulerian techniques, was used. The Johnson–Cook plasticity model was used to model the workpiece material. The analytical modeling and FEM modeling results match very well. In Yang et al. [6] the temperature distribution of the micro-cutter in the micro-end-milling process was investigated by numerical simulations and experimental approach. Micro-end-milling processes were modeled by the three-dimensional finite element method coupling thermal–mechanical effects. The micro-cutter cutting temperature distribution, the effect of various tool edge radii on cutting force, and the effective stress during micro-end-milling of aluminum alloy Al2024-T6 using a tungsten-carbide micro-cutter were investigated on. The simulation results showed that the greater the tool edge radius the higher cutting forces, while the effective stress and mean cutting temperature decrease slightly.

Inverse techniques have already been used to study temperature fields on a cutting tool. The solution of a three-dimensional inverse heat conduction problem using an Evolutionary Algorithm (EA) was demonstrated in Woodbury et al. [7]. The heat flux on the tool during the turning process was determined by using evolutionary operations combined with measured temperatures on the tool surface. The three-dimensional conduction in the tool and tool holder was simulated using FLUENT. In Luchesi and Coelho [8], an inverse method was proposed to estimate the heat sources in the transient two-dimensional heat conduction problem in a rectangular domain with convective bounders. The nonhomogeneous partial differential equation (PDE) is solved by using the Integral Transform Method. The test function for the heat generation term was obtained by the chip geometry and thermomechanical cutting. Then the heat generation term was estimated by the conjugated gradient method (CGM) with adjoint problem. The sequential function specification method was used to estimate the transient heat flux imposed on the rake face of a cutting tool during the cutting operation with two different assumptions [9]. In one of them, the thermal conductivity is assumed to be constant, and in the other one it varies with the temperature. The cutting tool was modeled as a three-dimensional object. Simulated temperature data was used to recover the heat flux on the cutting tool surface using linear as well as nonlinear solutions.

This work proposes the use of inverse problem techniques with the commercial software COMSOL® 5.0 to estimate the heat flux and the temperature field in the contact area under transient regime, in a turning cutting tool. A MATLAB program, with the Specification Function technique, was developed to estimate the heat flux applied on the cutting tool, by using experimental temperature records. The nonlinear problem was considered which means that the thermal model took into account the dependence of the thermal properties on temperature. The validation of the proposed methodology was accomplished in controlled experiments in laboratory.

2. Theoretical formulation

2.1. Temperature model

The problem dealt with in this work is represented by Fig. 1a, which shows a set consisting of a hard metal cutting tool, a wedge positioned under the cutting tool between the tool and the tool holder. There is also a staple and a bolt to fix the set. Fig. 1a presents the schematic model for the thermal problem of machining. The heat generation during the machining process is indicated by a distribution of unknown heat flux $q''(x,y,t)$, over the arbitrary area by x and y. A blown up view of the set is shown in Fig. 1b.

The heat diffusion equation ruling this problem is the nonlinear transient three-dimensional system given as:

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

subject to the following boundary conditions

$$-k(T)\frac{\partial T}{\partial z}(x,y,0,t)=q_0'', \quad (2)$$

on the contact interface with the workpiece (Fig. 1b),

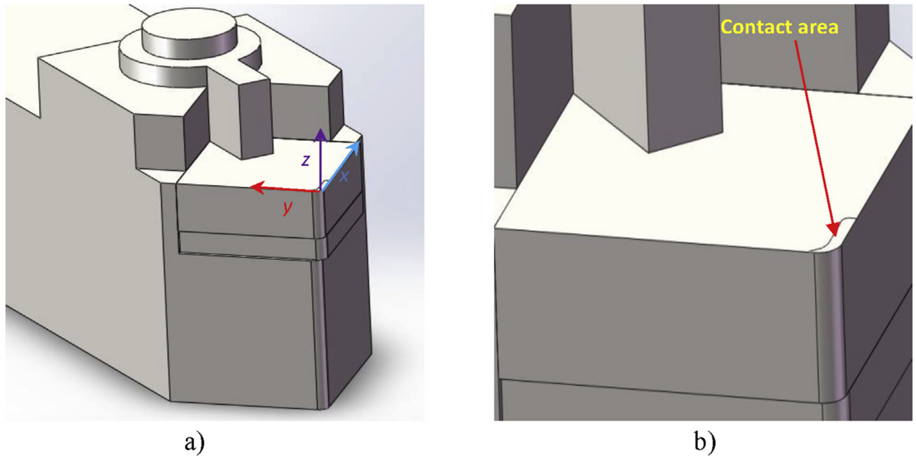

Fig. 1. a) Thermal problem scheme and b) detail of the contact interface between the tool and the workpiece.

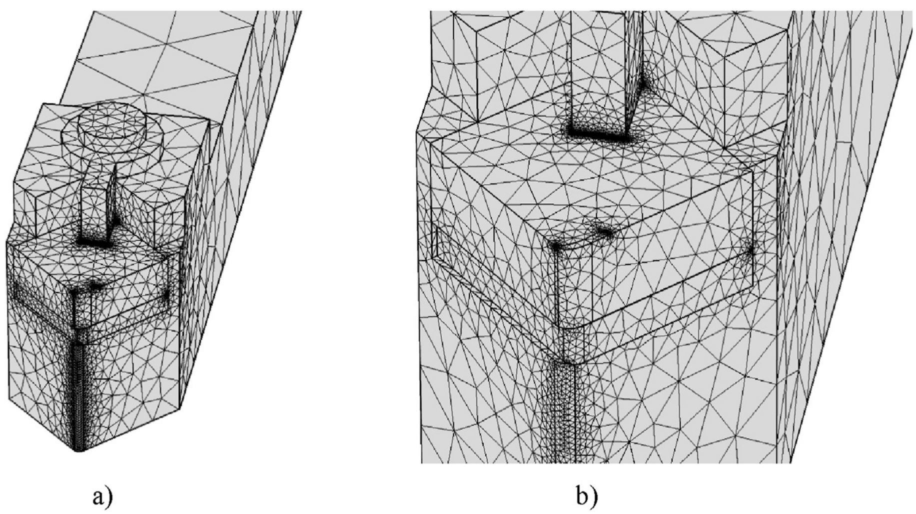

Fig. 2. a) The tetrahedral grid with 108058 elements and b) a closer view.

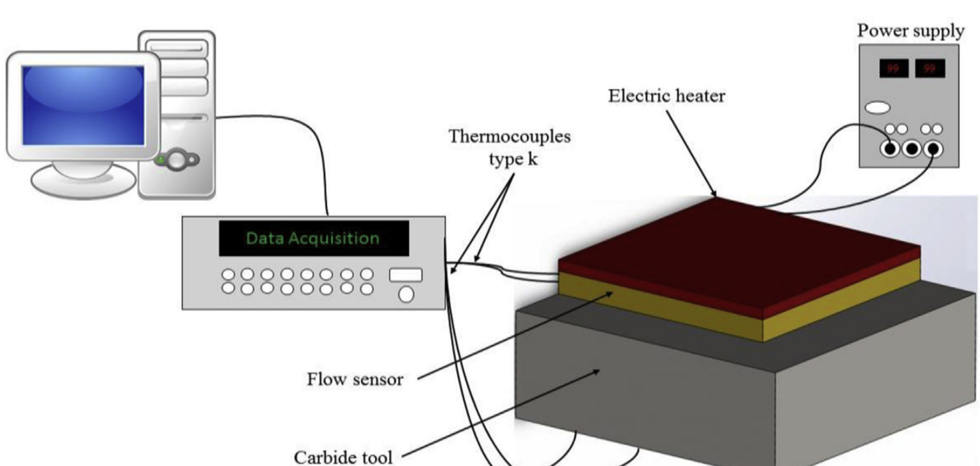

Fig. 3. Sketch of the experimental apparatus used in the validation.

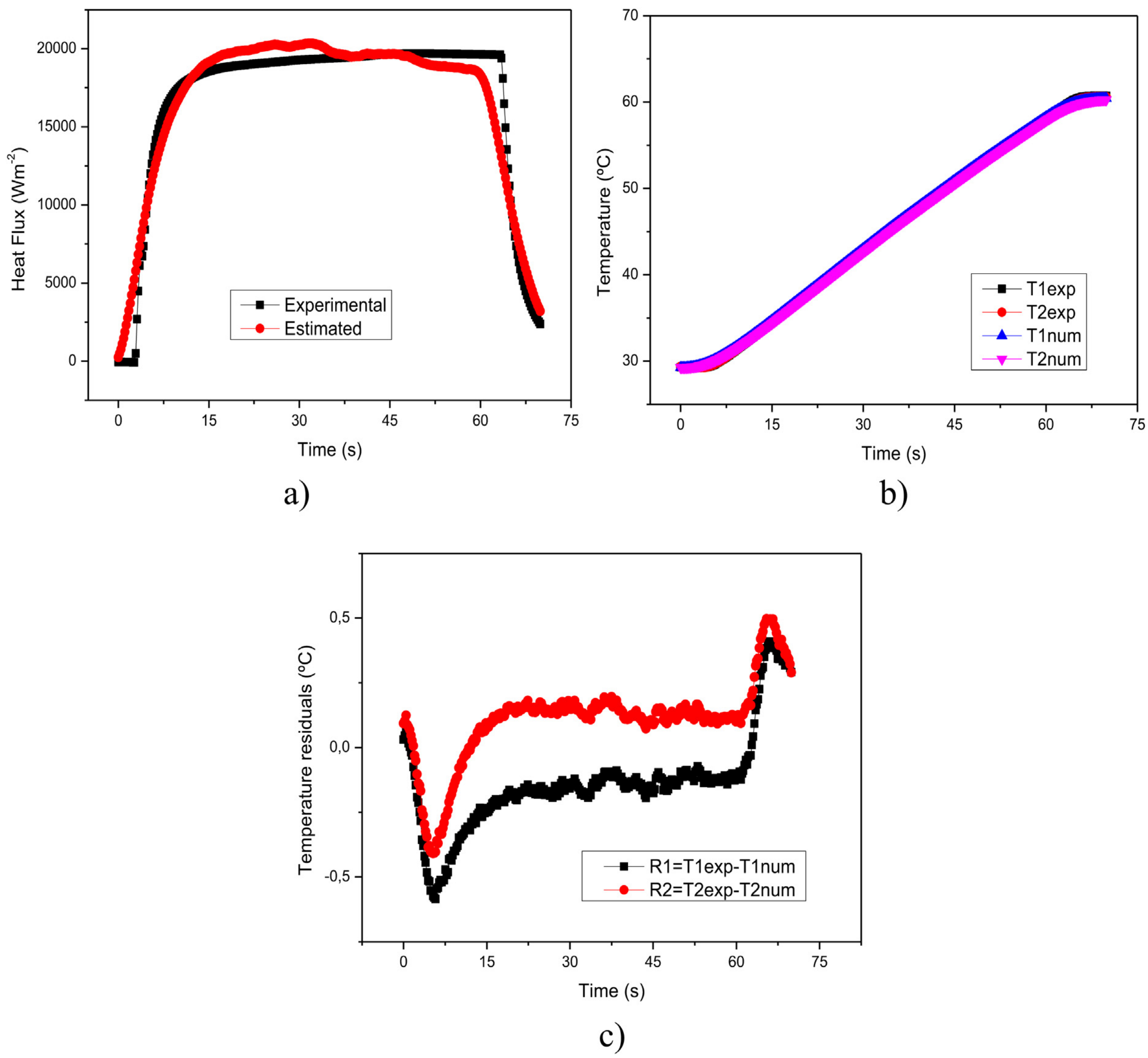

Fig. 4. a) Experimental and estimated heat flux, b) experimental and calculated temperatures, and c) temperature residuals.

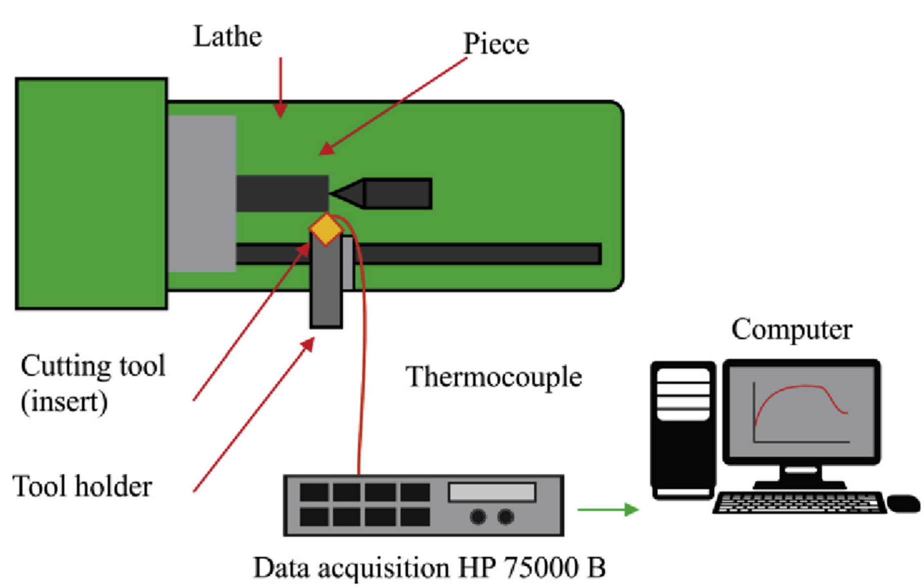

Fig. 5. Experimental apparatus used to acquire the temperature signals in the tool during machining.

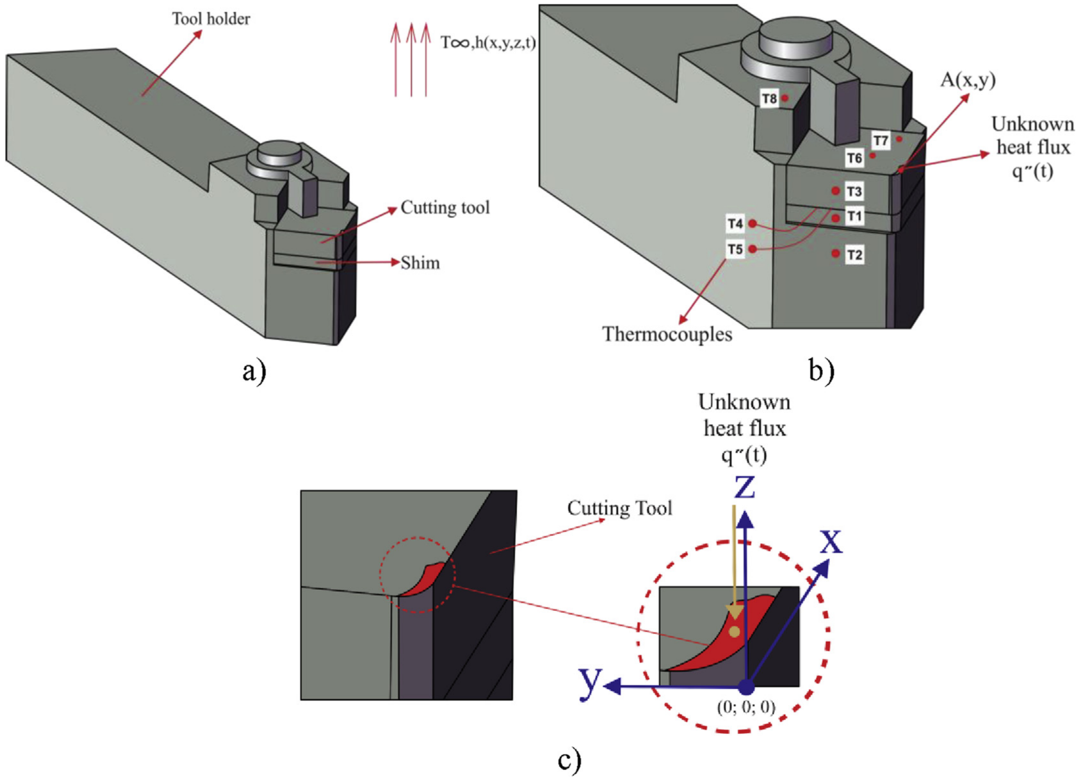

Fig. 6. a) Tool and tool holder assembly, b) detail of the positions of the thermocouples welded to the tool and c) a close view of the origin and orientation.

Table 1
Locations of the thermocouples shown in Fig. 6b.

Position/thermocouple	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	9.4

Table 2
Cutting conditions.

Cutting parameters	Test 1	Test 2
Feed rate	0.138 mm/rev	0.138 mm/rev
Cutting speed	135.47 m/min	135.47 m/min
Depth of cut	5.0 mm	1.0 mm
Final diameter	72 mm	76 mm

$$-k(T)\frac{\partial T}{\partial \eta} = h(T - T_\infty), \text{ in the remaining regions of the set} \quad (3)$$

and having the following as the initial condition

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

where T is the calculated temperature, h is heat transfer coefficient by convection, T_∞ the room temperature, q''_0 the unknown heat flux, and $k(T)$ and $c(T)$ temperature dependent thermal conductivity and specific heat, respectively.

The direct problem consists in solving the heat diffusion equation according to the boundary conditions (Eqs. (1)–(4)). The COMSOL® 5.0 program, which solves thermal problems by using the finite element method, is used for this purpose. The use of COMSOL for the numerical resolutions of differential equations that rule the physical phenomenon investigated should be highlighted. Also, COMSOL allows adjusting any boundary conditions, as well as modeling the geometry so as to faithfully represent the system investigated as presented in Fig. 2.

2.2. The inverse problem

The inverse technique adopted in this work is the Specification Function. As the Inverse Heat Conduction Problem (IHCP) at hand is a nonlinear one, sensitivity coefficients are function of $_{qM}$, and the next components of Taylor expansion would not be equal to zero (as in the case for linear IHCP). Therefore, it is necessary to recalculate the sensitivity coefficients at each time step [9,10]. In the Specification Function technique, a determined value of future time steps r is used to estimate the heat flux at present instant [3]. In the resolution of the inverse problem, the Specification Function searches for a heat flux value that minimizes the objective function given in Eq. (5), for each time step

$$F = \sum_{p=1}^{r}\sum_{j=1}^{ns}\left(Y_{j,M+p-1} - T_{j,M+p-1}\right)^2 \quad (5)$$

3. Validation of the methodology proposed

A great difficulty in the solution of inverse heat conduction problems is the validation of the technique used. This difficulty is inherent to the problem, once the validation of the estimated

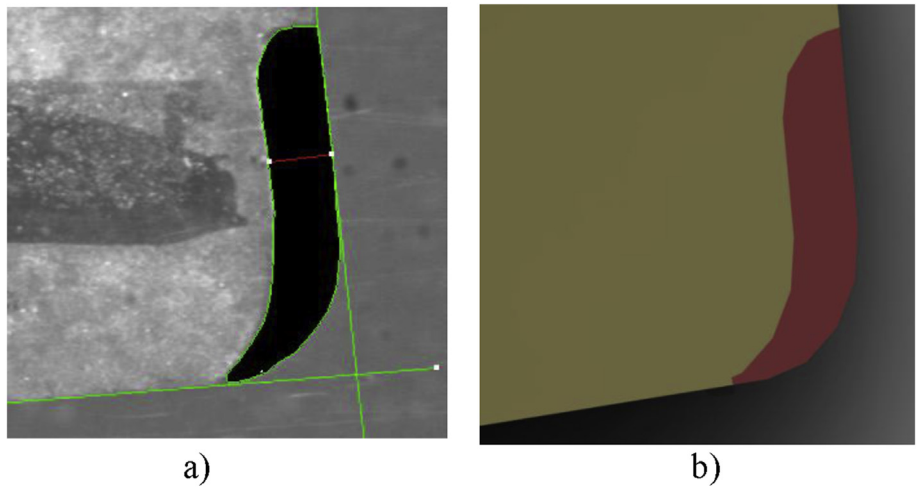

Fig. 7. a) Image treatment of the contact area and b) contact area on the computational model.

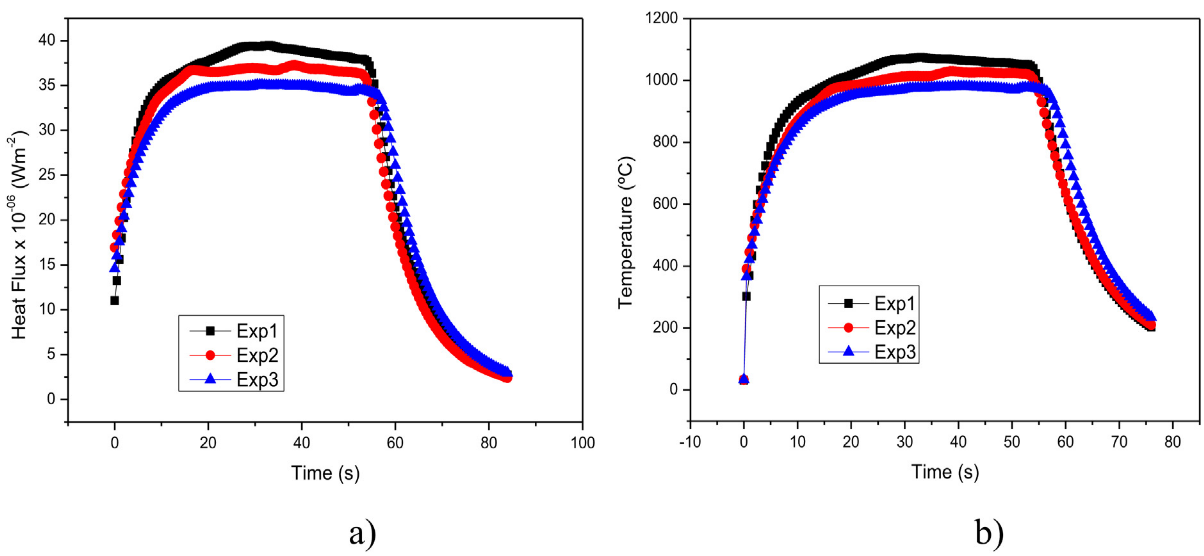

Fig. 8. Comparison of three repeated experiments for the same turning condition on the chip-tool interface a) heat flux and b) temperature.

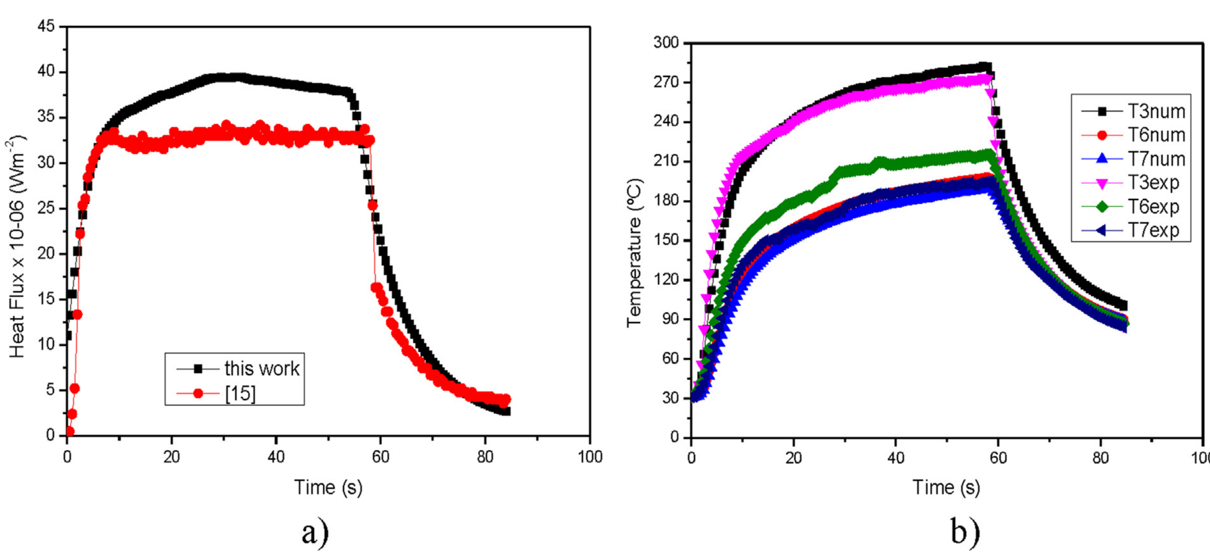

Fig. 9. a) Estimated heat flux and b) comparison between experimental and estimated temperatures for thermocouples T_3, T_6 and T_7.

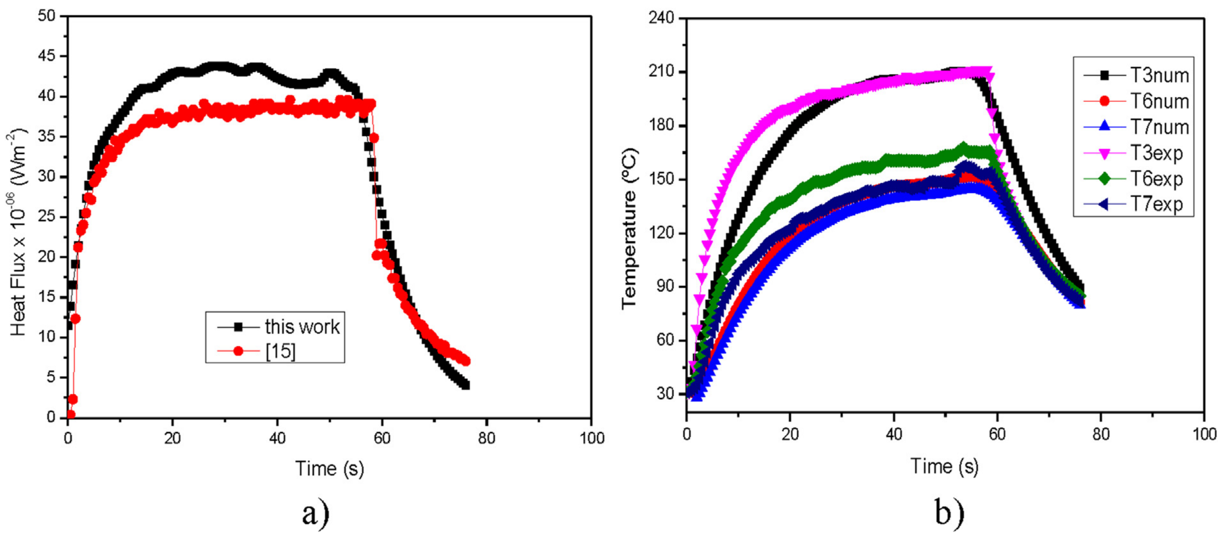

Fig. 10. a) Estimated heat flux and b) comparison between experimental and estimated temperatures for thermocouples T_3, T_6 and T_7.

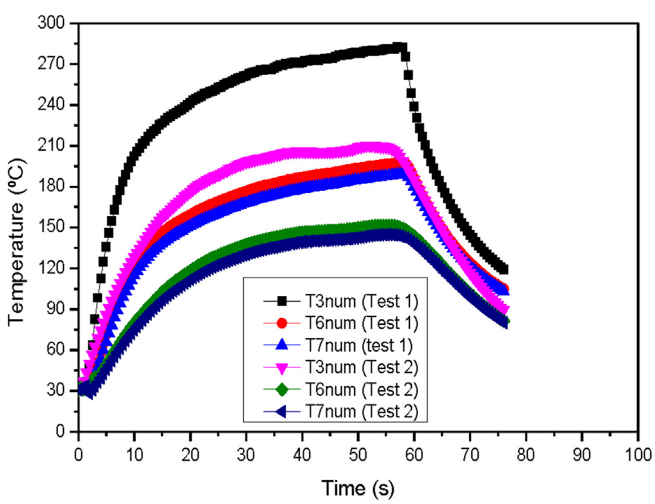

Fig. 11. Comparison between estimated temperatures in positions T_3, T_6 and T_7 for Tests 1 and 2.

heat flux requires the previous knowledge of the experimental heat flux. It is observed that in real inverse problems, as in machining process, the experimental heat flux is not known. Thus, an alternative for the validation of the inverse technique is to carry out a controlled experiment, in which the heat flux and the temperature are measured at the cutting tool (Fig. 3). In this case, before the analysis of the real machining process, a cemented carbide tool with dimensions of $0.0127 \times 0.0127 \times 0.0047$ m was used for the controlled experiment. A heat flux transducer and two thermocouples previously calibrated and a kapton electric heater were used on this tool. This heater was connected to a digital power supply (MCE). The heat flux transducer was located between the heater and the tool in order to measure the heat supplied to the tool. The heat flux and temperatures signals were acquired by a HP Series 75000 data acquisition system, 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 ± 0.01 °C.

The solution of the three-dimensional heat diffusion equation is obtained with the use of the finite element method, through the commercial software COMSOL® 5.0. For this, a computational thermal model was used to faithfully represent the experimental model of the sample. This model was discretized in a computational tetrahedral mesh. The validation results are presented in Fig. 4a–c. Fig. 4a presents a comparison between the experimental and estimated flux, whereas Fig. 4b compares the experimental and numerical temperatures. Fig. 4c presents the deviation between the experimental and numerical temperatures. The Specification Function method for r equal to 10 future time steps was used in Fig. 4a. In this validation the values of the temperature-dependent thermal properties of the cemented carbide tool (WC) were obtained from Grzesik et al. [11].

4. Experimental assembly in a real machining process

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. 5). The insert-tool holder assembly is shown in Fig. 6a. Table 1 presents the location of the thermocouples shown in Fig. 6b. Fig. 6c presents the location of the origin and orientation of the axes.

Many tests were carried out to observe the influence of cutting speed, feed rate and depth of cut in the temperature distribution. However, due to the 4000 words limit and 12 figures in this manuscript, the results are presented for only two tests. The test identifications with the cutting conditions are presented in Table 2. Each cutting condition was repeated three times to observe the repeatability. In each experiment the total number of measurements with each thermocouple was $nt = 180$ with a time interval of 0.5 s. The thermal conductivity and diffusivity of the tool (see Section 3) were obtained from Grzesik et al. [11].

The chip-tool contact area determination represents one of most important and delicate aspects among the main sources of errors in the solution of the thermal model problem. Some methods to identify this area can be found in the literature as, for example, the

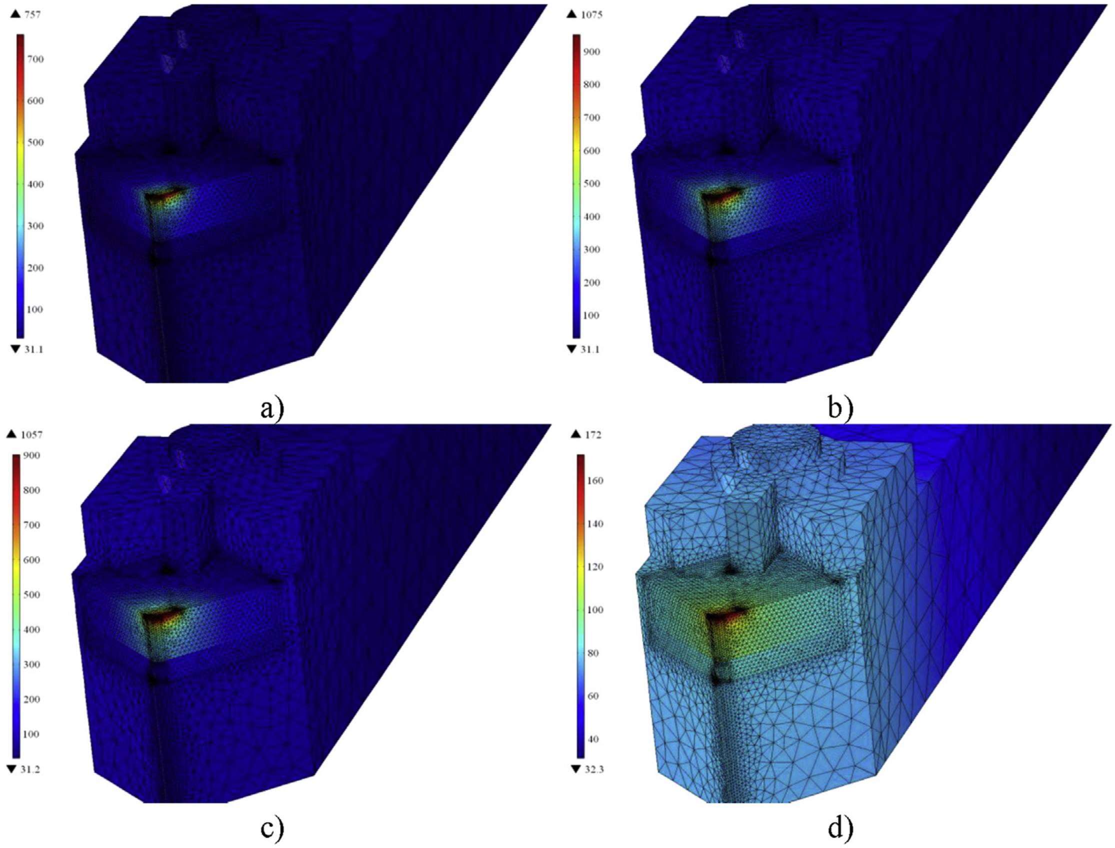

Fig. 12. Temperature field in the set at instants a) $t = 5$ s, b) 33.4 s, c) 50 s and d) $t = 80$ s.

use of image analyzer software [12] and the application of coatings [13]. In both processes, the area is measured after cutting. This procedure was also used here. However, in this work, the interface contact areas were obtained from the three tests carried out under the same cutting condition. 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. A typical contact area for Test 1 (Table 2) is presented in Fig. 7a and b.

The tool holder is AISI 1045 steel and its thermal conductivity and diffusivity were also obtained from Grzesik et al. [11]. The support below the tool has the same thermal properties as the tool. All the faces, except the chip-tool interface, were submitted to a constant convection heat transfer coefficient, $h = 20$ W/m^{2}K. Another important error source that must be taken into account is the thermal contact resistance existing among the tool, the shim and the tool holder. The thermal contact depends on many parameters and conditions such as contact nature, surface properties, pressures, etc. Although this problem is not treated here, the effect of this thermal contact is simulated as a 10 μm thick gap of air between the materials involved at 300 K. The air thermal properties used are $k = 0.026$ WmK^{-1} and $\alpha = 22.5 \times 10^{-06}$ m^{2}s^{-1} [14].

5. Results analysis

In this section, the results for the estimation of the heat flux and temperature calculations by using inverse problem technique Specification Function with software COMSOL 5.0 are presented. As aforementioned, for the study of the temperature field in the cutting tool, 3 experiments were carried out with no alterations in the assembly conditions or operations. Each experiment lasted 90 s, with temperature readings at every 0.5 s, totaling 180 temperature values. It is worth mentioning that in the beginning of the experiment, there is no contact between the tool and the workpiece, therefore the tool is found at uniform room temperature. The cutting time happened between the initial time and 60 s. After the 60th second, the cutting is stopped and the tool moves off the workpiece. And it is during the cutting time that heat flux is applied on the tool. Many simulations were performed as in Carvalho et al. [15] to analyze the influence of the value $h = 20$ Wm^{-2}K^{-1}.

The estimated heat flux and temperature in the process on the chip-tool interface for the Test 1 (Table 2) are, respectively, presented in Fig. 8a and b. The reliability and repeatability of the results can be observed in these figures, once the heat flux and the temperature were estimated for three experiments under the same machining condition. The small difference presented for each experiment may be credited to the inexact chip–tool contact area measurement errors. It turns out that during the process of turning, the heat flux and the temperature on the cutting interface tend to stabilize or go into permanent regime.

In Fig. 9a, the heat flux was estimated for Test 1 (Table 2) by using the Specification Function Technique for the future time steps parameter $r = 10$. In this figure, a comparison with the heat flux estimated in Carvalho et al. [15] is also presented. Tests were carried out with higher and lower values of future time steps to confirm this value of r. According to the graph, the heat flux is applied from the beginning of the machining process up to approximately 60 s. After this interval, the applied heat flux is null, that is, no machining occurs on the material. In the interval between 0 and 60 s, the average applied heat flux was approximately 37 MWm^{-2}. In Fig. 8b, a comparison between experimental and calculated temperatures in positions T3, T6 and T7 is presented. In this figure, good results can be seen when comparing estimated and experimental temperatures, especially for thermocouple T3. Only the results for the highest values of temperature are presented.

Fig. 10a presents the estimated heat flux for Test 2 (Table 2) by using the Specification Function for $r = 10$. A comparison between experimental and calculated temperatures in positions T3, T6 and T7 is presented in Fig. 10b. There is also good agreement when compared to the authors' previous work (Fig. 10a) as well as to the experimental temperatures (Fig. 10b). In addition, a comparison between the calculated temperatures in positions T3, T6 and T7 for Tests 1 and 2 is presented in Fig. 11. It may be noticed that the deeper the cut the higher the temperatures.

To complete, Fig. 12a–d show a representation of the temperature field in the tool set for Test 1 according to the COMSOL® program at time 5 s, 33.4 s, 50 s and 80 s, respectively. According to Fig. 12b there is a high temperature gradient in the insert.

6. Conclusions

The temperature field in any region of the tool set (insert, shim and tool-holder) was calculated from the heat flux estimation at the cutting interface. A significant improvement in the technique to estimate heat flux and temperatures in a machining process was presented in this work. For this, the Inverse Problem Specification Function Method and the COMSOL® 5.0 were joined. In addition, several cutting tests using cemented carbide tools were performed in order to check the model and to verify the influence of the cutting parameters on the temperature field. The use of COMSOL for the numerical resolutions of differential equations that rule the physical phenomenon investigated here should be highlighted, for these programs allow adjusting any boundary conditions, as well as modeling the geometry so as to faithfully represent the system investigated.

Conflicts of interest

The authors declare that there is no conflict of interests regarding the publication of this paper.

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