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INVERSE PROBLEM TECHNIQUE AND COMSOL IN THERMAL CHARACTERIZATION OF A MACHINING PROCESS

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Abstract

This work proposes the use of inverse problem techniques in connection with COMSOL, with the aim to estimate the heat flux and the temperature field on a turning cutting tool in transient regime. Specification function, which is an inverse problem technique, was implemented in a 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. The validation of the methodology is carried out by comparing the numerical results of the temperature with the experimental ones.

Nomenclature

F	objective function
h	heat transfer coefficient, W/m^{2}K
k	thermal conductivity, W/mK
M	general time index
q_0''	unknown heat flux, W/m^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, m/s^2
η	the outward drawn normal to the surface

Subscripts

p	index of points

Superscript

np	number of points
ns	number of temperature sensors

1. INTRODUCTION

Many engineering processes have their efficiency affected by high temperature values. An example is machining process in which the lifespan of the cutting tool is highly affected by high temperatures. The right knowledge about these temperature values and heat flux applied in this process enables the development of more efficient cooling techniques. 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. Thus, the use of inverse heat conduction techniques conveys a good alternative to obtain these temperatures, since these techniques allow the use of experimental data obtained from accessible regions. Inverse problems consist of obtaining the value of a variable through the measurement of another variable measured directly. These 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 proposed the combination of inverse techniques and analytical or numerical heat transfer solutions to analyze the thermal fields during machining processes. One way to study the heat transfer problem is to know the heat flux to determine the temperature fields from the solution of the heat diffusion equation. In literature, this methodology is called direct problem in heat transfer. However, during machining the experimental heat flux is unknown and inverse techniques have to be used to predict this parameter. This proposal estimates the transient heat flux from a numerical model based on heat diffusion equation by using inverse problems and experimental temperatures measured at accessible regions of the sample.

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 900ºC [1]. High temperatures cause changes in the microstructure of the tool during machining, change their physical chemical properties reducing their capacity to mechanical stress that appear during their use [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 quality of the end product. 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. According to [3], [4] were the first to study the applied heat flux in cutting tools, as those used in turning. Since then, several other researchers have studied the subject. These studies involve experimental techniques like the use of thermocouples inserted in micro holes in the tool, [5], and experimental infrared chambers, [6]. Other ways to measure the temperature in a cutting tool are mentioned by [4], like the optical pyrometer, tool–workpiece thermocouple, among others. Along the years, the instrumentation techniques have also evolved. [7] have also used thermocouples in their studies on the temperature of the cutting tool; however these thermocouples were fixed by capacitive discharge. New optical pyrometer and infrared chambers presenting better precision and shorter response time have been used nowadays, as in [8]. However, in some situations, analytical methods have been used to predict temperature fields on a cutting tool, as in [9]. Although the means of instrumentation have also evolved, the direct measuring of the temperature in a machining process is difficult due to the relative movement of the workpiece and the presence of chips. Hence, the right instrumentation must be used to measure the temperature fields on the tool. Even though there is a variety of instruments that may be used to measure temperature fields on a cutting tool, there must be criteria to select them, for each instrument convey advantages and disadvantages when applied in a determined situation. The thermocouples, for example, may be reliable, however the presence of chips in the cutting operation may damage them, and the use of micro holes to insert them change the geometry of the tool, leading to mistaken results. The chambers and pyrometers are not subject to damages by the presence of chips and changes in the geometry of the tool, but can not capture the temperature on the exact region in contact with the cutting tool and the workpiece.

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. The most common are, respectively, the finite difference method and the finite element method. Later, the finite element method also emerged. Each of these methods has its own characteristics. The finite difference method had its spread in fluid dynamics problems due to its ability to deal with non-linear terms while the finite element method is the typical method to solve purely diffusive problems, [10]. The finite element method presents a characteristic of being conservative in terms of elements, that is, it balances energy, momentum and mass in all the elements of the mesh, which does not occur with the aforementioned methods. More than one numerical method may be used in a certain application, aiming to explore the strengths of each numerical method, as in [11].

Another consequence of the evolution of computers is the development and increasing use of *inverse techniques*. Inverse techniques consist of obtaining the value of a variable of interest through the measuring of another property which may be measured directly from a region of easy access. Therefore these techniques seem to be a good alternative for thermal analysis in machining processes once they allow, for example, the obtaining of the temperature fields and the applied heat flux on a cutting tool from the temperature signal obtained at a single point of easy access.

Inverse techniques have already been used to study temperature fields on a cutting tool, as in [6] and [12]. In such situations, the temperatures on the cutting tool are obtained by using thermocouples inserted close to the rake face as in [7], [13], [14], [15] and [16]. An alternative to the use of thermocouples is the infrared chamber, as in [15]. Due to the nature of the process, which precludes the direct measurement of the heat flux on the rake face, inverse technique such as Golden Section, Specification Function among others have been used, in several of these studies, to estimate heat flux applied on the tool.

This work proposes the use of inverse problem techniques with the commercial software COMSOL® 4.3, to estimate the heat flux and the temperature field, in a transient regime, in a turning cutting tool. A Fortran program, with implemented inverse technique, Specification Function, was developed to estimate the heat flux applied on the cutting tool, from experimental temperature records, in a determined point. Once the heat flux is estimated, the software COMSOL® 4.3 is once again used to obtain the temperature field in the cutting tool. The validation of the methodology is done by comparing the numerical temperature results with the experimental data.

2. PROBLEM DESCRIPTION

2.1 Thermal Model Set

The problem dealt with in this work is represented by Figs. 1a and 1b. The Figure represents a set consisting of a cutting tool, a hard metal, 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. A perspective is shown in Figure 1a, whereas a blown up view of the set is shown in Fig. 1b.

The heat diffusion equation ruling this problem may be given as:

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

Subject to the following boundary conditions

$$-k\frac{\partial T}{\partial z}(x,y,0,t)=q_0'' \text{ on the contact interface with the workpiece (Fig. 1b)} \tag{2}$$

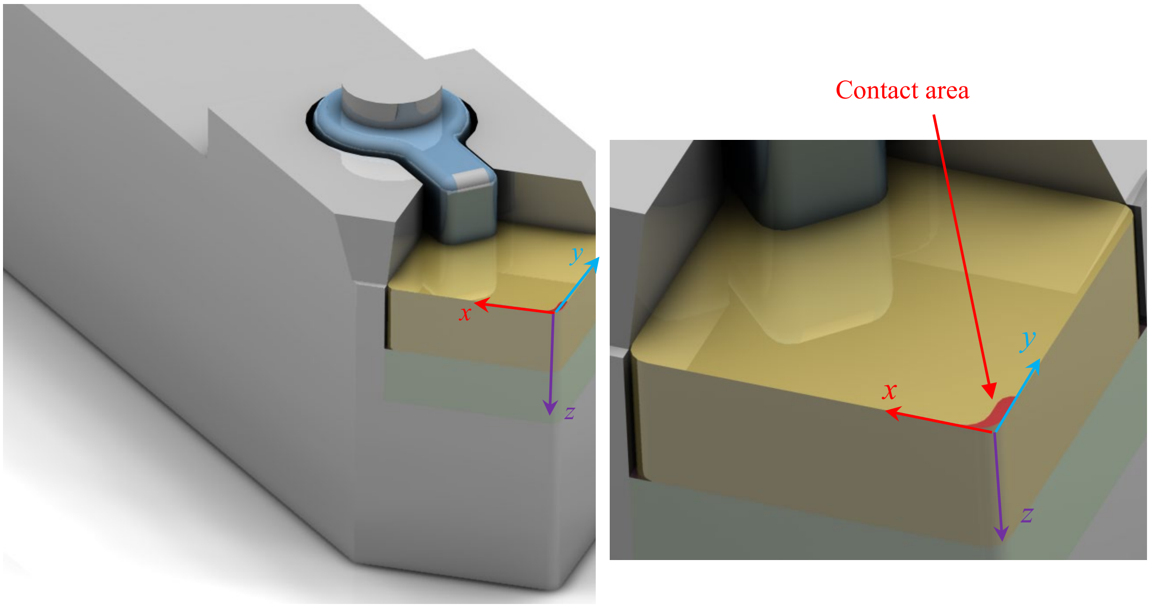
and

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

and having the following as the initial condition

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

As the linear Function Specification method was used in this work, the thermal properties were consideed constant.



a) b)

Fig. 1. a) Tool set, Shim and Tool holder, and b) Detail of the contact interface between the tool and the workpiece.

2.2 Direct Problem Solution.

The direct problem consists in solving the heat diffusion equation according to the boundary conditions mentioned above. The COMSOL® 4.3 program, which solves thermal problems by using the finite element method, is used for this purpose.

2.3 The Inverse Problem.

The inverse technique adopted in this work is the Specification Function [17]. This technique demands, first, the sensitivity coefficient calculation, which is done numerically from Duhamel Theorem [18]. The sensitivity coefficient is then obtained with the use of a numerical probe which follows the temperature change, in the point equivalent to that on which the thermocouple was placed in the experiments. Once the sensitivity coefficient is at hand, the head flux is estimated with the use of a Fortran language program. The methodology is represented in Fig. 2.

Another important parameter is the value of future time steps *r*. In the Specification Function technique, a determined value of future time steps *r* is used to estimate the heat flux at present instant. 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

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

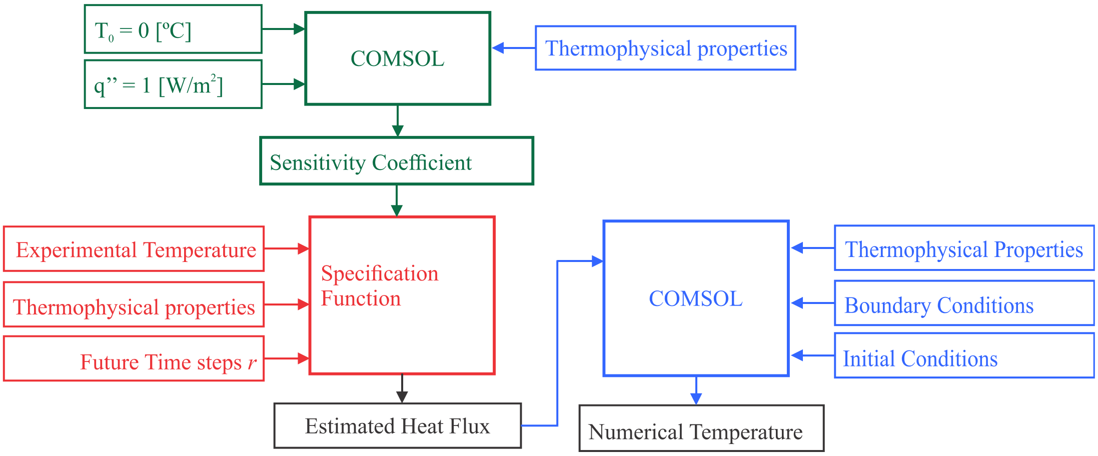


Fig. 2. Methodology for the use of the Specification Function for the tridimensional thermal model, in transient regime with the COMSOL®.

3. VALIDATION

The validation of the methodology was carried out according to [18]. The experiments were accomplished under controlled condition, in which the heat flux and the temperatures were measured from a homogeneous AISI 304 stainless steel sample of 60.0 x 100.0 x 9.5 mm. The experimental apparatus is represented in Fig. 3.

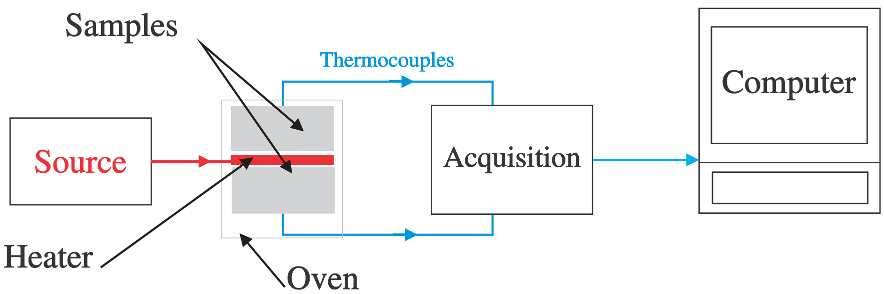


Fig. 3. Experimental Apparatus used to validate the proposed methodology.

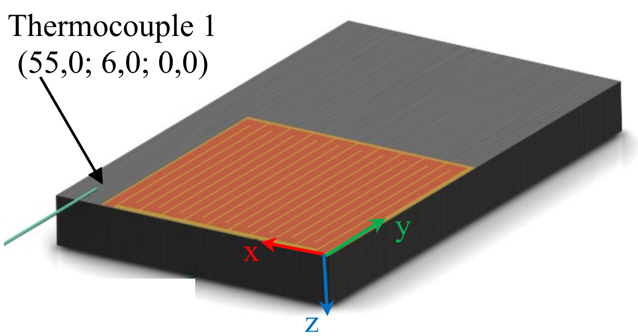


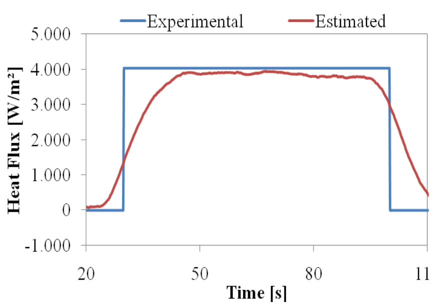
Fig. 4. Position of the thermocouples on the tridimensional model.

During the experiment, the homogeneous AISI 304 stainless steel samples were heated uniformly on their surface by a resistive *kapton* heater, with a 15 Ω resistence and a heating area of 50.00 x 50.00 mm and 0.20 mm thick. As the heater has a smaller area than the surface area of the sample, a tridimensional heat propagation effect is obtained. This tridimensional problem has boundary condition of heat flux imposed in the heating region and isolated in the remaining regions [17]. Figure 4 shows the position of the heater and the thermocouple on the metal sample.

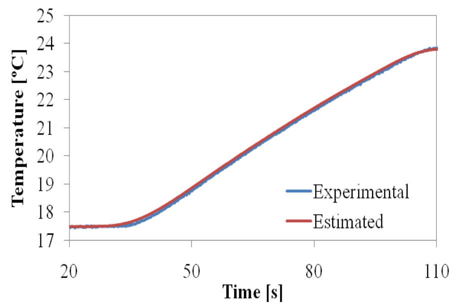
A digital source Instrutemp ST-305D-II was used to generate the heat flux, through *Joule* effect. The control of the applied heat flux intensity is done through the variations of the voltage and current parameters. To minimize the errors in the measurement of the heat flux, a symmetrical assembly was used. Moreover, the applied voltage and current values were measured by the multimeters Instrutherm MD-380 and Minipa ET-2042C, previouly calibrated. The convection effects are disregarded due to the use of polystyrene involving the assembly, so as to keep the width of 50 mm, in any direction. Furthermore, the whole set was placed inside a Marconi MA030 oven. The interstices between the samples are reduced with the use of Artic silver paste, thus improving the contact between the samples.

The solution of the tridimensional heat diffusion equation is obtained with the use of the finite element method, through the commercial software COMSOL® 4.3. For this, a computational thermal model was used to faithfully represent the experimental model of the sample. This model was discretized in a computational mesh of hexahedrical elements. In solving the discretized equations that rule the thermal model, a temperature field is obtained in any point of the sample. The mesh displays a refinement so as to have 60 elements in direction *x*, 100 elements in direction *y* and 20 elements in direction *z*, totalinrobablug 120.000 volumes.

The validation results are presented in Figs. 5a, 5b and 5c. Figure 5a presents a comparison between the experimental and estimated flux, whereas Figure 5b compares the experimental and numerical temperatures. The Specification Function method for *r* equal to 20 future time steps was used in Figure 5a. Figure 5c presents the deviation between the experimental and numerical temperature. In Figure 5c a systematic error of 0.1 ºC was presented, probably, this error happened due to the imperfection of the insulation.



a)



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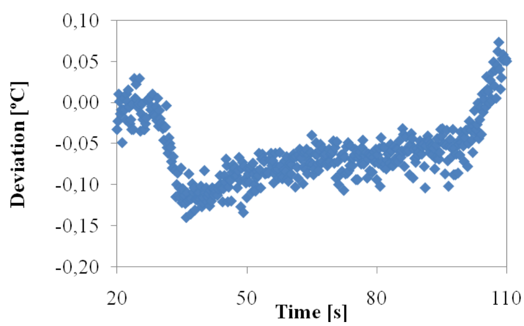


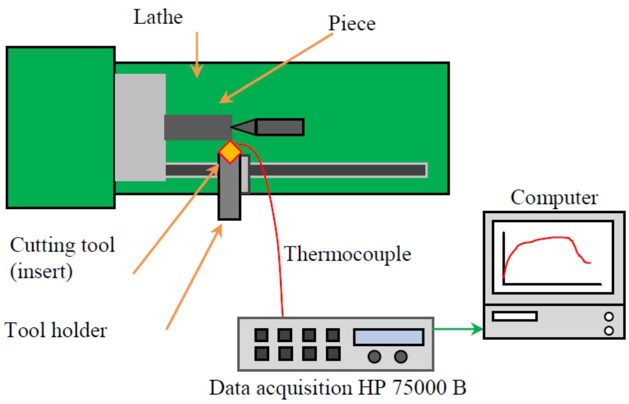
c)

Fig. 5. Comparison between the experimental results a) heat flux, b) temperature and c) deviation between the experimental and numerical temperatures.

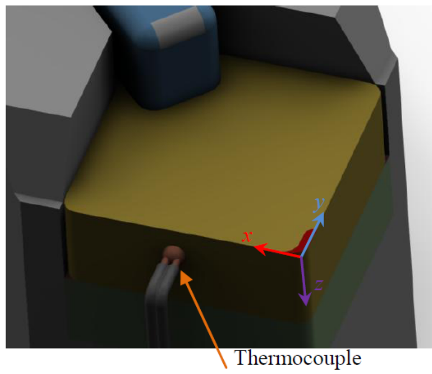
4. EXPERIMENTAL PROCEEDINGS

To obtain experimental data, the experiments were carried out by using a conventional lathe IMOR MAXI II 520 of 6 Horse Power, and a HP 75000 B data acquisition system, with E 1326B voltmeter, commanded by a computer, to which a K type thermocouple (30 AWG) is connected to measure a local temperature considerig an avergage heat transfer coefficient. The experimental assembly is represented in Fig. 6a. The detail that the thermocouple is welded by capacitive discharge may be observed in Figure 6b.

Taking the coordinate system placed on the tip of the tool as a reference, according to Figure 3b, the coordinates *x*, *y* and *z* the position of the thermocouple, in mm, are respectively (0; 3.95 and 11.52). The tool chosen for the tests is a hard metal 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 77mm in diameter and 77mm 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 0.5s.



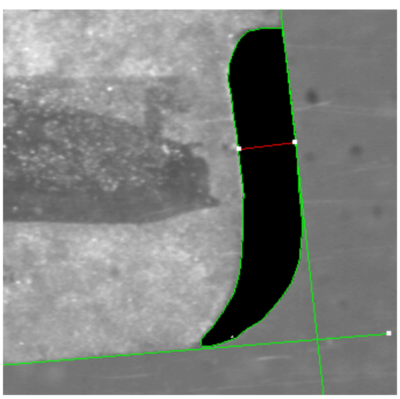
a)



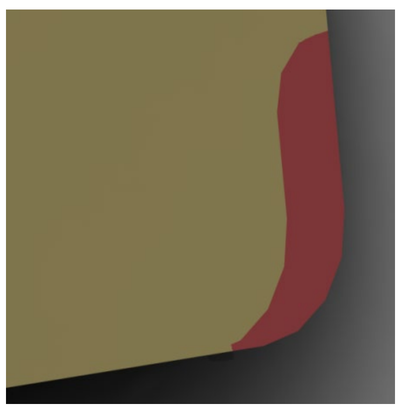
b)

Fig. 6. a) Experimental apparatus used to acquire the temperature signals in the tool during machining and b) detail of the position of the thermocouple welded to the tool.

The correct identification of the contact area between the tool and the workpiece was obtained with the use of an image treatment system, consisting of a Hitachi CCD camera, model KP 110, a computer and the image treatment software GLOBAL LAB IMAGE. A picture of the contact area is shown in Fig. 7a and in Fig. 7b, the respective area after the image treatment. The contact area value was 1.41mm², obtained for feed rate of 0.138mm/rot, cutting speed of 217.72mm/rot and depth of cut of 3.0mm.



a)



b)

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

5. RESULTS

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 4.3 are presented. The experimental temperature values were obtained with the performance of the experiments at Uberlândia Federal University as described in [7], whereas the validation of the use of Inverse Techniques and the Commercial Software was presented in [18].

For the study of the temperature field in the cutting tool, 5 experiments were carried out with no alterations in the assembly conditions or operations. Each experiment lasted 90s, with temperature reading a every 0.5s, totaling 180 temperature values. The cutting time happened between the initial time and 60s. After the 60s, 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. As in the beginning of the experiment, there is no contact between the tool and the workpiece; the tool is found uniformly at room temperature.

The main results obtained are presented in this section. The thermophysical properties presented in Tab. 1 are adopted in the numerical simulations [19]. The numerical model adopted does not consider the thermal contact resistance between the components of the set.

Table 1. Thermophysical properties adopted.

Element	Conductivity [W/mK]	Specific Heat [J/kgK]	Density [kg/m³]	Difusivity
Cutting Tool	43.1	332.94	14.900	8.688×10^{-6}
Wedge	43.1	332.94	14.900	8.688×10^{-6}
Tool Holder	49.8	486.13	7.850	13.050×10^{-6}

The sensitivity coefficient was calculated numerically with the use of the software COMSOL® 4.3, as the direct problem, using boundary conditions of heat flux of 1W/m² and initial temperature at 0ºC and an average convection coefficient of 20W/m²K. Many simulations were done in others author's work, as in [7], to analyse the influence of the value h = 20W/m²K. In Figure 8 the estimated heat flux is presented according to the Specification Function for r equal to 5 future time steps. Tests were carried out with higher and lesser values of future time steps to confirm this value of r. According to the graph, the heat flux is applied since the beginning of the machining process up to approximately 60s. After the time, the applied heat flux is null, that is, no machining occurs on the material. In the time interval between 0 and 60s, the average applied heat flux was approximately 55MW/m². The computacional time to estimate the heat flux by using the Function Specfication technique was 15 minutes in a Dual Core 2 PC.

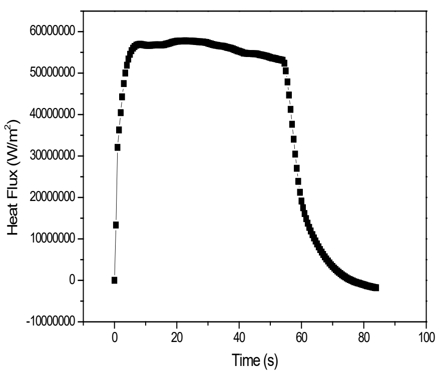
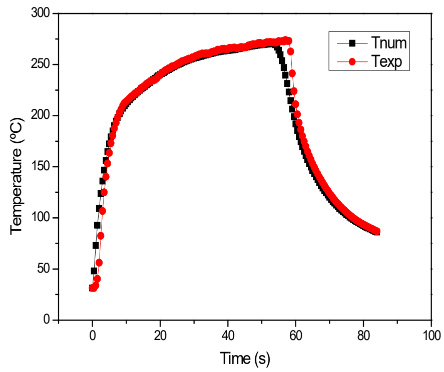


Fig. 8. Estimated heat flux.

The comparison between the experimental and estimated temperatures is presented in Fig.9a. Small differences may be observed in the initial and final instants of the machining; however, during the cutting period, there was correspondence between the estimated and experimental temperature values (Fig. 9b). By disregarding the initial and end regions of the turning, the difference between the estimated and experimental temperatures was around 0.32%, presenting a greater difference of values of 1.04%. These disagreements occur as a consequence of the difficulty that the Specification Function presents when dealing with discontinuities in the parameters to be estimated, which, in this work is heat flux. This difficulty is due to the fact that the method is based on the calculation of the temperature variation rate according to the applied heat. In practice, these discontinuities represent the instant in which the heat flux goes from a null value to a high one, at the beginning of the machining procedure, as well as the instant the heat flx does from this high value and becomes null again.



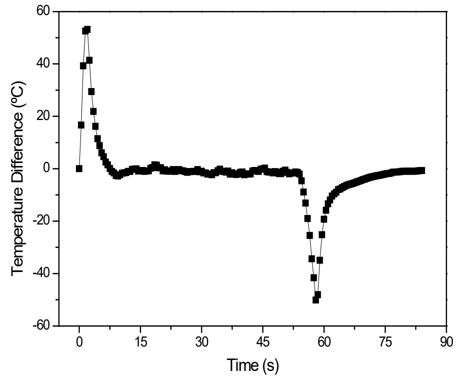


Figure 9. a) Comparison between the experimental and estimated temperatures and b) temperature difference $Y - T$.

To complete, Figure 10 shows a representation of the temperature Field in the tool set according to the COMSOL® program at time 30s and 60s in Figs. 12a and 12b respectively.

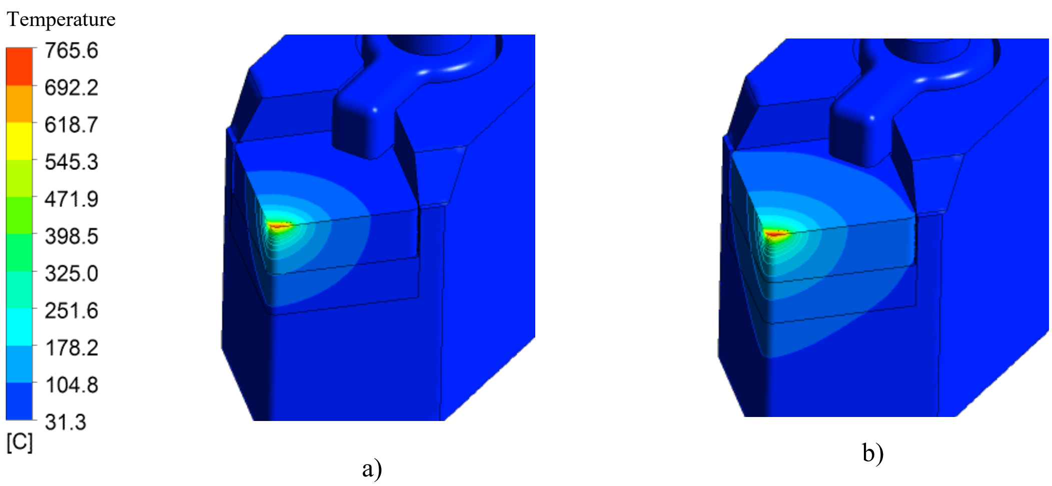


Fig. 10. Temperature field in the set at instants a) t = 30s and b) t = 60s.

6. CONCLUSIONS

This work presented the technique to estimate heat flux and temperature in a machining process, joining Inverse Technique and the COMSOL® program. The Inverse Techniques are promising to estimate parameters that may not be measured directly through any other variable. The use of commercial packages for the numerical resolutions of differencial equations that rule the physical phenomenon investigated 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. Although the combination of the Inverse Technique and the COMSOL® 4.3 program has presented satisfactory results in the estimation of heat flux and temperature, improvements on how to use multiple signals of temperature measurements should be implemented in the Specification Function method.

7. ACKNOWLEDGEMENTS

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