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# USING INVERSE TECHNIQUES TO SOLVE HEAT TRANSFER PROBLEMS WITH APPLICATION TO A HIGH-SPEED STEEL TOOL DURING A TURNING MACHINING PROCESS

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***Abstract:*** *In the turning process, mechanical energy is transformed into heat due to the friction between the tool and the workpiece and the plastic deformation of the chip. Thus, turning procedure can be approached as a thermal problem, since the aforementioned process causes a high temperature gradiente. Due to the movement of the workpiece during the cutting process and the presence of an insert, there is a constraint when measuring the temperature at the interface between the insert and the tool. Thus, the use of efficient numerical techniques is necessary for the analysis of the thermal problem. In this sense, reserachers from the heat transfer laboratories of the Federal Universities of Uberlândia (UFU) and Itajubá (UNIFEI) have been developing specific computer programs. Such programs together with commercial packages, which use inverse techniques, are used to determine the heat flux and temperature distribution in a machining process. A three-dimensional transient thermal model is used with tetrahedral elements in an unstructured mesh. To solve the inverse problem, some inverse techniques provided by COMSOL were used in this work, such as Nelder-Mead (NM) and Levenberg-Marquardt (LM). Another inverse technique used is the Linear Specified Function (LSF), which is written in MATLAB environment. Such technique is used in conjunction with COMSOL Multiphysics, by interfacing MATLAB with the commercial COMSOL package via LiveLink for MATLAB. To validate the computational package, experimental data from previous work by the current authors are used. Given these data, the numerical results obtained are compared. Then, the effectiveness of the LM technique to solve the thermal problem is therefore consolidated in order to result in more suitable computational cost ratios. The percentage deviations of the estimated numerical temperatures, for the case at 900 rpm, reached agreable values of up to 1.45%. Hence, this condition points out the procedure effectiveness. The percentage deviation of the heat flux estimated in this work with that estimated by LSF, by these authors in previous works, was up to 1.78 %.*

***Keywords:*** *COMSOL, free cutting steel tool, three-dimensional heat conduction, inverse methods, high speed steel tool.*

## 1. INTRODUCTION

The beginning of the implementation of machines in industry was initially due to the industrial revolution in the 18th century. Initially they were intended for textile production and later for the transformation, machining and metal forming. Such practices have been widely developed up to the present day, due to the growing demand for production and technological advances, which continue to occur at an ever-increasing pace. Thus, it is noted that manufacturing is a sector of the world economy that is constantly changing and growing, so much so that it can be expected that the current processes will be improved in the future, as engineering and technology develop.

Among the various manufacturing techniques developed, machining stands out, which is defined as the entire mechanical process in which the part is the end result of a material removal procedure, which can be subdivided into grinding, turning, milling, drilling and among other types. The factors that most influence the machining processes are the type and composition of the material to be machined, the machine tool, the cutting fluids for cooling and the cutting tool, and the application method (also called machining parameters). However, there are associated sub-factors that are linked to different areas of engineering studies, such as the thermal and vibration effects of the cutting tool. The study of these sub-factors is fundamental to increase the efficiency, quality of the process, and preservation of the useful life of the cutting tools, which reflects directly on the ability to supply the growing demand of the high-quality standard demanded by the market.

When it comes to the turning machining process, the study method of this article, and evaluating the conditions and effects from the thermal point of view, mechanical energy is transformed into heat due to friction between the cutting tool and the workpiece, and the plastic deformation of the chip. Thus, turning can be studied as a thermal problem, in which it has a heat-generating energy source that is supplied by the cutting tool, generating a temperature gradient. From this study, one can relate the cutting parameters applied to the thermal effects that are produced by the tool, favoring the discovery of specific conditions that increase tool life even under extreme working conditions.

## 2. THEORETICAL FOUNDATIONS

### 2.1 Experimental methods for obtaining the temperature at the cutting interface

The heat input to which cutting tools are exposed in a machining process can cause a reduction in wear resistance. Above 727 °C, materials based on iron and carbon in their structure, may begin to present the formation of a microconstituent called austenite, which is characterized by higher ductility and lower mechanical strength. The macroscopic impact of the austenite formation in a cutting tool would be the reduction of its useful life, due to the compromise of the wear resistance. Given these situations, it is essential that efficient ways to determine the thermal fields in the wear region of a cutting tool be developed. With this, some methods and models, mathematical and experimental, have been studied and developed by several authors, which some of these will be cited below.

The one developed by Kshetri & Ajay (2020), focused on the analysis of the flow coefficient and heat transfer during the turning process in a given steel alloy, aiming to develop a mathematical model that is able to predict the heat generation in cutting tools according to the different parameters that influence the turning process. The author reinforced the idea that the temperature variation during the turning process is the main cause of wear and reduced cutting tool life, which indicates that the analysis of heat transfer in this process is of utmost importance. Therefore, based on the previous premise, an experimental investigation of the heat transfer coefficient and heat flux in the cutting tool through the progressive variation of speed and depth of cut was performed, from this, an infrared camera (Testo 870) was used to obtain the temperature values. This experiment was done without the presence of cooling media, with the use of an aluminum alloy (7068), as material to be machined, and a carbide cutting tool coated with titanium nitride. From the experimental data obtained, a comparison was made with those obtained through an analytical model that was developed with the help of MATLAB software, more specifically the Simulink tool, resulting in highly satisfactory data in relation to the data obtained experimentally. However, it was concluded that: the tool temperature exceeded 210 °C for a maximum depth of cut, and continued growing according to the gradual increase of this same parameter; the cutting time in the process was one of the factors responsible for generating high temperatures in the tool; and that the heat transfer coefficient increased according to the increase of the cutting speed, reaching the plateau of 197 W/m$^2$-K for the maximum value of the parameter.

In turning, the great difficulty in experimental developments, for estimation of the heat transfer rate in the cutting tool, is to obtain the temperature in the wear region of the tool, so that inverse methods can be used to know this heat flux and thus be able to estimate the thermal field on the surface that in direct contact with the machined part. Soler et al. (2019), in turn addressed, the determination of the emissivity and temperature of the cutting surface of the tool during the turning process, in an AISI 4140 steel, where it was developed in this work a method to gauge the temperature at the tip of the cutting tool during turning through the use of a thermal camera with infrared technology, which is combined with a new calibration method that makes it possible to determine estimates of the emissivity on the tool surface. In addition, the work effectively presents the thermal field of the exit surface of the cutting tool during turning of the aforementioned steel. As a result of the work, some statements regarding emissivity were obtained, such as the statement that there is a significant change in emissivity when the tool is oxidized, increasing by about 55%. Concomitantly, it was concluded that for the study of wear generated in the cutting tool, obtaining the temperature is a more valid indicator than the acting forces, which proves to be a good research field for the analysis of tool wear.

### 2.2 Numerical and inverse techniques for solving thermal machining problem

#### 2.2.1 Numerical techniques

Due to the fact that numerical methods are widely used to solve the thermal problem in various forms of machining, there is in the literature, a large amount of work developed. Among these, there is the work of (Kanellos et al., 2019), in which a numerical simulation was developed for the machining process using FEM (Finite Element Method) and CFD (Computational Fluid Dynamics) based simulations as an approach. The author initially mentions that the most important aspect for the cutting process in machining is the determination of the effects of cooling conditions on the cutting tool. Thus, in numerical models developed for metal cutting, such conditions are described according to the convective coefficient of heat transfer, which is usually determined empirically by studying the physical characteristics of the material properties. With this, we aimed to numerically calculate this heat transfer coefficient using a hybrid FEM-CFD model, i.e., using Abaqus/Explicit software from Dassault Systems® for the thermomechanical part of the simulation and ANSYS® CFX software for the fluid dynamic part of the simulation. Thus, after the end of the development of the numerical solution, satisfactory results were obtained, indicating the applicability and efficiency of the developed simulation.

It is also worth mentioning, that prepared by Clavier et al. (2021), who presented a numerical analysis of the tribological and geometrical impacts caused by cutting tool wear on the thermomechanical loads for the turning process of 15-5PH steel. Initially, the author states that the finishing phase in the turning machining process is one of the operations that generate the most residual stresses on functional surfaces, which in turn are determined from the thermomechanical loads that are applied to the machining surface over time. Moreover, these mentioned loads are directly related to the cutting conditions and the selection of the cutting tool system applied, i.e., they are totally dependent on the tool wear caused over the machining time. Thus, it was observed that at least two parameters are modified during the process: the cutting tool geometry and the tribological phenomenon between the cutting tool and the workpiece. With this, since the generated thermomechanical effects can be estimated with the use of a numerical model, the work aimed to investigate the sensitivity of the tribological and geometrical parameters for the loads in question for the machined surface in an orthogonal cutting operation. Furthermore, the work aimed to perform the analysis of plastic deformation, heat generation and temperature corresponding to the zone near the machined surface. Therefore, the results pointed out that the cutting tool geometry is a dominant factor for controlling the thermomechanical loads compared to the tribological parameters.

#### 2.2.2 Inverse techniques

The works cited in the previous topics, start from the assumption where the cause of the thermal problem, the heat transfer rate in the wear region, is known or can be measured. Thus, this variable is taken as the starting point for the solution of these types of thermal problems, defined in the literature as direct problems, where knowing the cause, one can measure the effects. On the other hand, there is another technique that consists in using the characteristics and/or intensity of the effects to arrive at the knowledge of the causes. This methodology is defined as inverse problems, which use several sophisticated mathematical and optimization techniques to solve the proposed problem.

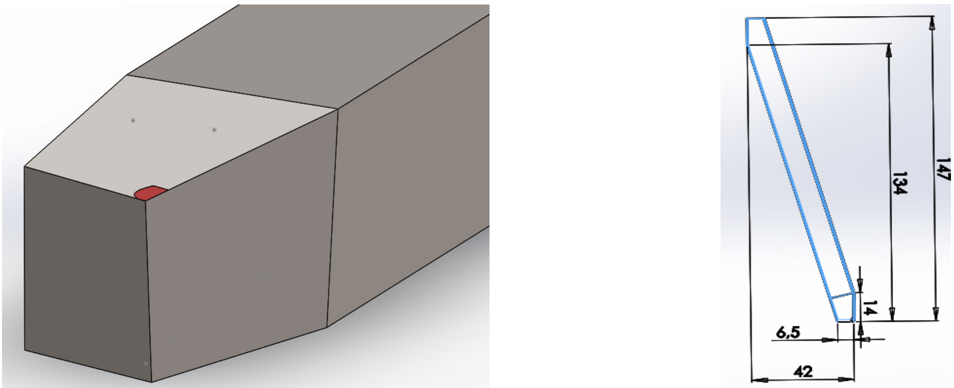
Dourado da Silva et al. (2021), addressed the simultaneous estimation of heat flux and temperature on the contact surface of the cutting tool for the machining process, through the use of an infrared camera. To do so, the solution of the inverse heat transfer problem was developed so that the temperature measurements could be obtained in real time. With this, the study is important to support the development of a wear monitoring system on the cutting tool and improve the understanding of the temperature distribution on it. Therefore, an infrared camera was used to obtain the temperature values, so as not to need the use of thermocouples, which make it difficult to take measurements due to the way they are coupled to the tool. Therefore, after obtaining the temperature values, the mentioned problem was solved by the finite element method, through the implementation of the software COMSOL Multiphysics. Finally, a computational software was developed, in order to facilitate the monitoring of the heat and temperature flow in the machining process. In addition, the use of the infrared camera for temperature monitoring proved to be effective, since the frequency of measurements is higher, decreasing the delay for the real-time estimation that was addressed.

Brito et al. (2015), worked on the experimental investigation of the thermal aspects in a cutting tool using the COMSOL software and the resolution of the problem through the inverse technique. Initially, the author mentions that the direct taking of the temperature measurement in a machining process presents a certain difficulty, due to the continuous movement of the part and the formation of chips. Therefore, the use of inverse heat transfer techniques to obtain temperature values proved to be a good alternative, since these techniques allow the use of experimental data obtained from other more accessible areas of the cutting tool. With this, the authors proposed the use of the nonlinear inverse problem technique through the application of COMSOL, which allowed obtaining the heat flux and the temperature field in a cutting tool in the transient regime. Such use was intended to show the improvements in performance obtained in relation to a previous work produced by the same authors to develop the complex geometry that involves the machining process. From the results obtained, a comparison between numerical and experimental temperature outputs was performed in order to validate the methodology, which in turn indicated a significant improvement for the estimation of heat flux and temperature in the turning machining process.

## 3. THEORETICAL FORMULATION

### 3.1 Thermal Model

The problem addressed in this paper is represented in Figure 3.1 where the representative model of the fast steel cutting tool used as geometry for solving the proposed problem is shown. This is the fundamental geometry and the marked region in red (Figure 3.1a) represents the tool-workpiece interface, where high temperatures and wear of the cutting tool occurs.




(a) (b)

Figure 3.1 - Fast steel cutting tool for 900 rpm rotation: a) three-dimensional view with critical region highlighted in red; b) main dimensions of the cutting tool [mm].

This problem, is governed by the heat diffusion equation as presented in Eq. (1):

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

Submitted to the following boundary conditions: heat flux in the wear region and convection on the remaining regions, as follows:

$$-k(T)\frac{\partial T}{\partial z}(x,y,0,t) = \dot{q}_0 \quad (2)$$

$$-k(T)\frac{\partial T}{\partial \eta} = h(T - T_\infty) \quad (3)$$

and the initial condition:

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

The direct heat transfer problem, consists of solving the heat diffusion equation considering the boundary conditions of the system. For this, the commercial software COMSOL® Multiphysics 6.0 was used. A three-dimensional transient thermal model with a tetrahedral and unstructured mesh were used. This software allows adjustments to the boundary conditions, in addition to modeling the geometry under study, so as to faithfully represent the system under investigation, as can be seen in Figure 3.3.

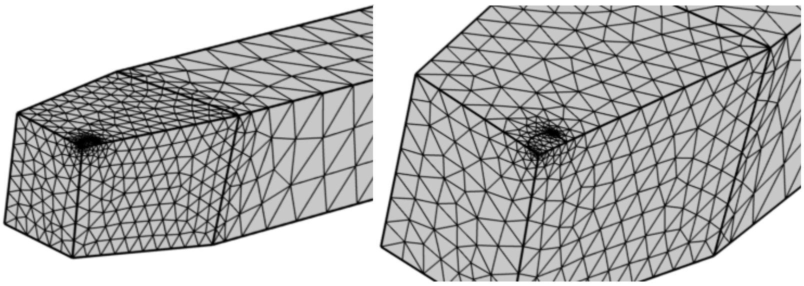


Figure 3.3 - Tetrahedral mesh with 5,507 elements overlaying the cutting tool for the 900 rpm case.

**3.1 The Inverse Problem**

To solve the inverse problem of this present work, three techniques were put into focus, Linear Specified Function (LSF), Levenberg-Marquardt (LM) and Nelder-Mead (NM). A study about these techniques was carried out in order to define which one could return a better cost-benefit when it comes to solving the inverse problem, this analysis will be better discussed in the next subtopic.

The Specified Function, developed by Beck, Blackwell and Clair Jr. (1985), is based on the use of future time steps and the inversion of a convolution integral. For Beck et al. (1985), the heat flux components are used in the estimation algorithm. The method consists of assigning a temporary functional form for the transient surface heat flux for instants higher than the current estimation time, M. In this case the forms can be constant, parabolic, exponential, or cubic. The simplest specified function procedure is the one that uses a sequence of constant straight-line segments as the functional form to describe the behavior of the surface heat flux for future times. In this way it is temporarily considered that various future heat flux components are constant with time. In this technique, a given value of the future time steps ***r*** is used to estimate the heat flux at the present instant, Beck et al. (1985). In solving the inverse problem, the Specified Function seeks a heat flux value that minimizes the objective function, Eq. (5), for each time step.

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

Levenberg-Marquardt, the second optimization method posed as an option for solving the inverse problem, was developed by Kenneth Levenberg and Donald Marquardt. This method provides a numerical solution to the minimization problem of a nonlinear function. It mixes the steepest descent method and the Gauss-Newton method, inheriting the speed of the latter and the stability of steepest descent. According to that published by Cui (2016), the inverse problem can be solved as a minimization problem of the objective function Eq. (6), where M is the number of measured temperatures, Y is the vector of inverted parameters, N is the number of parameters to be inverted, ti* and ti are the measured and calculated temperatures, respectively.

$$S(Y) = \sum_{i=1}^{M} \left(t_i^{*} - t_i(Y)\right)^2 \tag{6}$$

The inverse parameter vector can be written as,

$$Y_k^{P+1} = Y_k^P + \delta^P \tag{7}$$

where P is the number of iterations and δ is the increment, which will be determined by Eq. (8).

$$[J^T J + \mu \, diag(J^T J)]\delta = J^T [t_i^{*} - t_i(Y)] \tag{8}$$

In Eq. (8), J refers to the sensitivity coefficient matrix, μ is the jump factor, which is adjusted at each iteration, and diag represents the diagonal terms of the subsequent matrix.

$$J = \begin{pmatrix} \frac{\partial t_1(Y)}{\partial Y_1} & \frac{\partial t_1(Y)}{\partial Y_2} & \cdots & \frac{\partial t_1(Y)}{\partial Y_N} \\ \frac{\partial t_2(Y)}{\partial Y_1} & \frac{\partial t_2(Y)}{\partial Y_2} & \cdots & \frac{\partial t_2(Y)}{\partial Y_N} \\ \vdots & \vdots & \vdots & \vdots \\ \frac{\partial t_M(Y)}{\partial Y_1} & \frac{\partial t_M(Y)}{\partial Y_2} & \cdots & \frac{\partial t_M(Y)}{\partial Y_N} \end{pmatrix} \tag{9}$$

The sensitivity coefficients, Eq. (9), are the basis for the inverse problem solving method via Levenberg-Marquardt, these are usually calculated by numerical differentiation.

The method proposed by John Nelder and Reger Mead in 1965, Nelder-Mead, is the third option in this paper for solving the inverse problem. It also seeks to find the maximum or minimum of an objective function in a multidimensional space. Its efficiency, is based on the ability of good adaptation of the curvatures of the functions. However, the geometry of the problem can be shaped to such an extent that convergence to stationary points may not occur.

Nelder-Mead, like Levenberg-Marquardt, is included in the COMSOL Multiphysics optimization package, and is a robust approach that can be used to find the optimal point for a wide range of functions, making it a great tool for solving a variety of inverse character problems and other models. On the downside, Nelder-Mead can have a slow convergence speed.

## 4. VALIDATION OF THE PROPOSED PROBLEM

The present work uses the experimental and numerical results of Carvalho (2005), in order to make a comparison with the results obtained by COMSOL Multiphysics. An alternative for validation is to set up a controlled experiment, where heat flux and temperature are measured at the cutting tool (Figure 3.5). Thus, in the experimental process, a carbide tool with dimensions of 0.0127 x 0.0127 x 0.0047 m was used by Carvalho (2005). A heat flux transducer, two precisely calibrated thermocouples and an electric kapton heater were used in this tool. The heater was connected to a digital power supply, the heat flux transducer was inserted between the heater and the tool in order to measure the heat supplied to the tool. The heat flux and temperature signals were acquired by an HP 75000 series data acquisition system controlled by a PC.

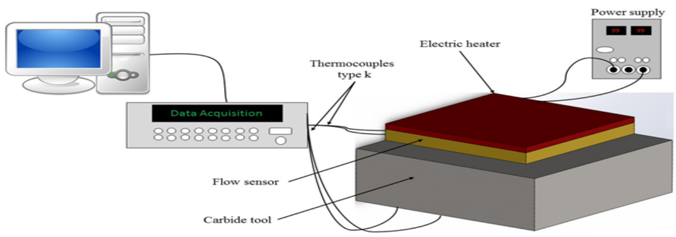
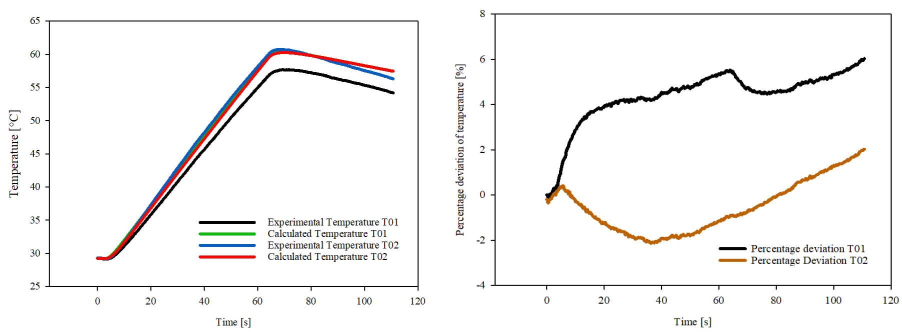



Figure 4.1 - Sketch of the experimental setup used in the validation.

### 4.1 Validation of the Direct Problem

The results of the validation are presented in Figure 4.2, which shows the comparison between temperatures T01 and T02 measured in Carvalho's (2005) experiment estimated by COMSOL. In both was used the experimental heat flux measured by Carvalho's (2005) experiment. Figure 4.2b shows a maximum percentage deviation of 5.56 %.




(a) (b)

Figure 4.2 - Direct problem: a) Comparison of experimental and calculated temperatures based on the heat flux measured in Carvalho's (2005) experiment; b) Percentage deviations.

### 4.2 Validation of the Inverse Problem

Once the direct problem is validated, the next step is to validate and analyze the inverse techniques. This study was based on the controlled experiment of Carvalho's (2005) dissertation, where the data obtained in these experiments (heat flux, temperatures at certain points) were used as comparative parameters for numerical simulations, using COMSOL and MATLAB.

Figure 4.3 shows the comparison between the experimental and estimated heat flux by the three techniques.

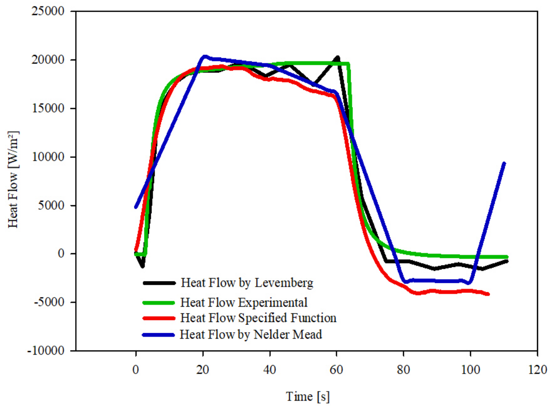
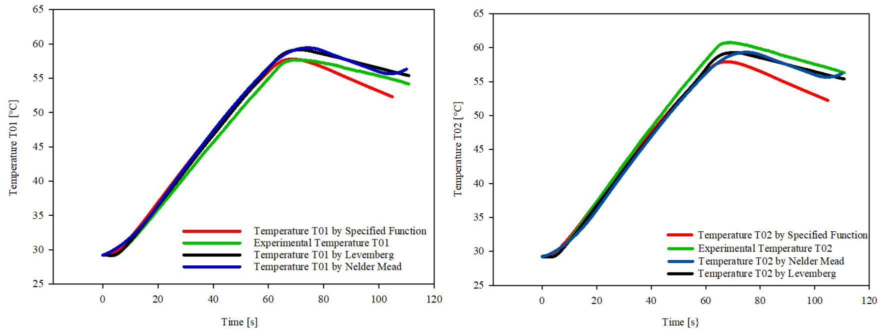



Figure 4.3 - Comparison between experimental and estimated heat flux from the inverse techniques.

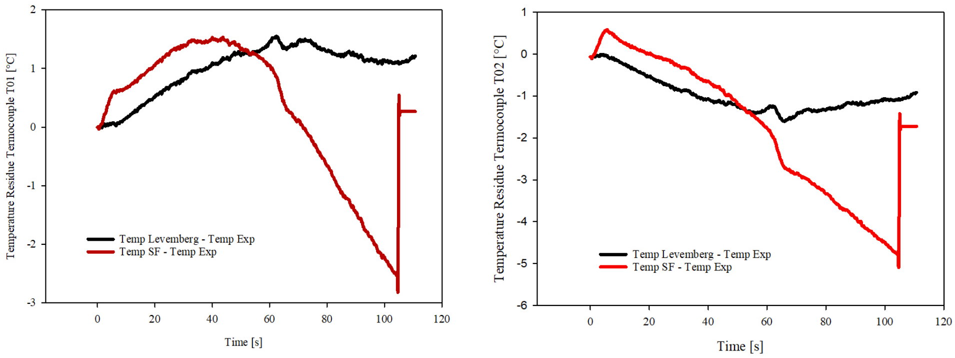
Three techniques present satisfactory results regarding the estimation of the heat flux. Furthermore, Figure 4.4a and 4.4b shows a good approximation between the numerical temperatures estimated by each technique and the experimental temperatures for thermocouples T01 and T02.




a) b)

Figure 4.4 – Comparison between numerical and experimental temperatures.

Note that, considering the effective time of the experiment, time in which the electric heater remains on, the temperatures behave in an almost similar way, this can be seen in Figure 4.5, where it is shown low residual temperatures in the effective time of the experiment, taking into account the two thermocouples of the experimental apparatus (T01 and T02). In this same figure, there is no residual temperature data for the NM method, because due to the computational cost that this method requires, the time was discretized in larger steps and even so, it was the method that required more computational time to solve the inverse problem (see Table 4.1).




(a) (b)

Figure 4.5 - Temperature residual: a) Thermocouple T01 b) Thermocouple T02.

Table 4.1 shows a comparison between the computational time spent by each technique in solving the inverse problem. Note that the Nelder-Mead technique presents a high computational time, a fact that has already eliminated this method from the options for solving the problem proposed in this work.

| Ranking | Reverse Technique | Computational Time [min] |
|---|---|---|
| 1° | Specified Function | 5 |
| 2° | Levenberg-Marquardt | 5 |
| 3° | Nelder-Mead | 4441 |

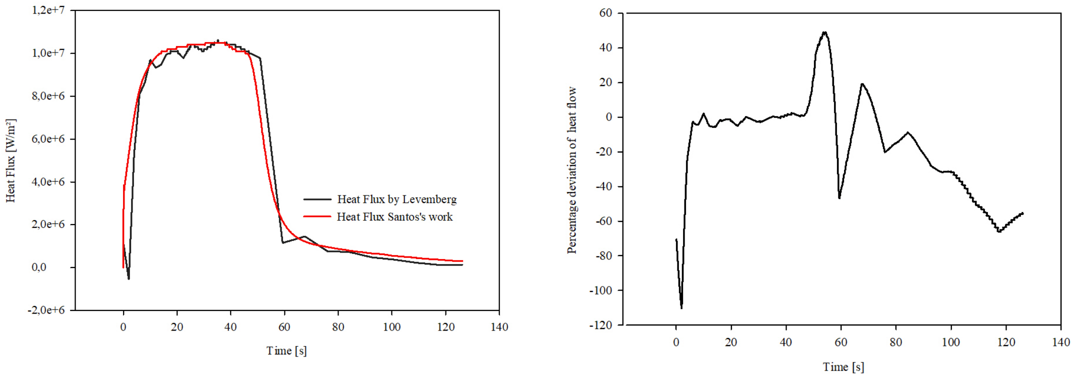
Table 4.1 - Computational time for the solution of each inverse technique

Therefore, taking into account table 4.1 and Figures 4.4 and 4.5, the selected technique was Levenberg-Marquardt, because it presents a low computational time for solving the problem and excellent estimated temperatures, approaching well the experimental temperatures. In addition, the use of this method is more practical, because all modeling can be done within COMSOL, a fact that does not apply to the Technique of the linear specified function, because it depends on the communion between two software to solve the inverse problem, MATLAB and COMSOL.

## 5. RESULTS AND DISCUSSIONS

Based on Figure 3.1, the geometrical and physical characteristics of the experiment, performed by Carvalho (2005), a model was assembled and discretized in COMSOL 6.0. The temporal aspects in the model were discretized to follow the same characteristics of what was proposed in the experimental apparatus, using a time step of 0.112 seconds for output data storage, with an experiment time of 126 seconds, thus totaling 1,128 measurements/data storage during the experiment.

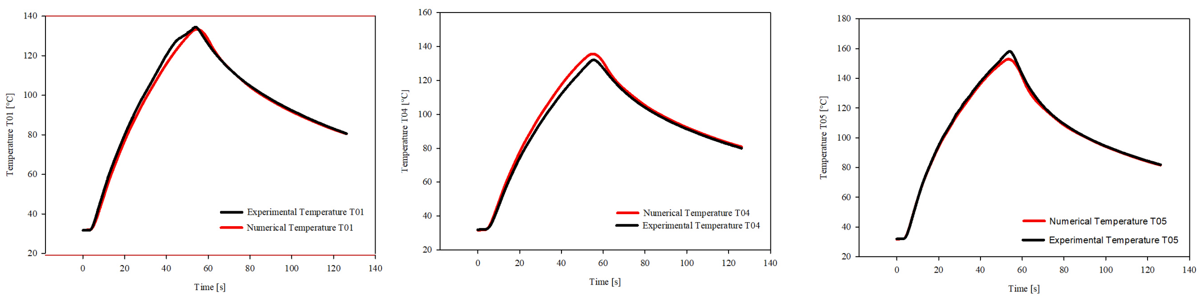
Figure 5.1a shows the heat flux estimated by Levenberg-Marquardt and the heat flux estimated in the work of Santos (2008), who used the Simulated Annealing method. Note that both estimated fluxes had an approximate behavior, the percentage deviation between these heat fluxes can be seen in Figure 5.1b, note that during the effective cutting time, until approximately 58 seconds, the percentage deviation remained low and showed a more pronounced difference at the time when it is characterized the removal of the cutting tool.




(a) (b)

Figure 5.1 - a) Comparison of the heat flux estimated by Levenberg and flux estimated in the work of Santos (2008), b) Percentage deviation between the fluxes estimated in the present work and in the work of Santos (2008).

A comparison between the experimental temperatures of Carvalho (2005) and the estimated temperatures considering the heat flux estimated by Levenberg-Marquardt can be seen in Figure 5.3. Note that for all cases, the results were quite satisfactory, Figure 5.4 shows a maximum deviation of 1.5 %.




(a) (b) (c)

Figure 5.3 - Comparison between the numerical temperatures obtained by Levenberg-Marquardt and the experimental temperatures taken from the work of Carvalho (2005): a) Thermocouple T01; b) Thermocouple T04; c) Thermocouple T05.

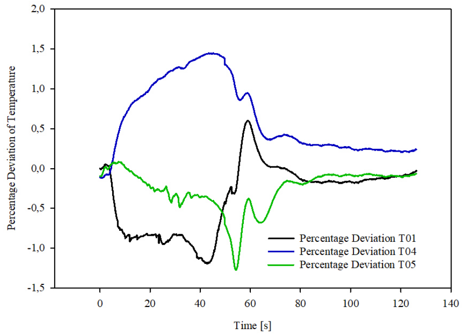
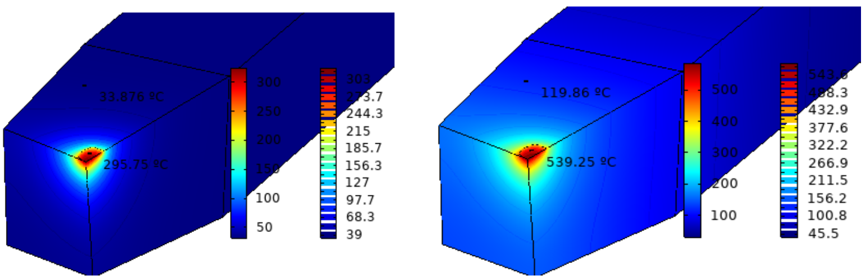



Figure 5.4 - Percentage Deviation between experimental and estimated temperatures.

Once the heat flux distribution and the temperature field in the cutting tool are known, it is interesting to know how the temperature behaves in the wear region of the cutting tool, where this is considered the critical region, because it presents the highest temperatures and wear rate. By solving the inverse problem, and estimating the heat flux, the temperatures at different points in the wear region can be pointed out. Figure 5.5 shows the evolution of the temperature field on the cutting tool, for relevant times of the machining process. The temperature at a specific point in the region was measured and its behavior was evaluated in the first moments of machining and when the cutting tool ceased to have contact with the workpiece. Note that in the first 5 seconds of the process, the cutting tool in question already presents a large thermal gradient and reaches temperatures exceeding 500 °C during the machining process.




a) b)

Figure 5.5 - Temperature field at the cutting tool for: a) t = 5 s; b) t = 58 s;

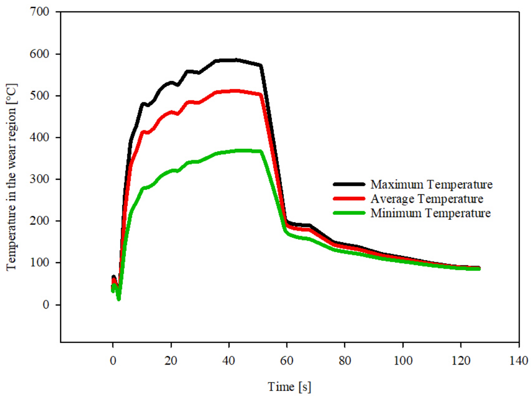



Figure 5.6 - Maximum, Average and Minimum Temperatures in the cutting interface region.

Figure 5.6 shows temperatures referring to the wear region which would be impossible to measure these measurements experimentally. Such a possibility is a great feature of inverse numerical methods. However, it is clear the effectiveness of this method for solving the proposed inverse problem, which pointed percentage deviations for the estimated heat flux in the order of 5%, Figure 5.1b, during machining. Furthermore, Levenberg-Marquardt showed excellent computational performance.

## 6. CONCLUSIONS

This work presented the solution of two thermal problems using COMSOL. The first one was an experiment under controlled conditions where the experimental heat flux and temperatures were measured in order to validate the proposed techniques. The second was the analysis of a real machining process, in which experimental temperatures were measured and the objective was to identify the heat flux developed at the chip-tool interface.

To solve the inverse problem, three techniques were put into focus: Linear Specified Function (LSF), Levenberg-Marquardt (LM) and Nelder-Mead (NM). Based on the results obtained, the effectiveness of the LM method for solving the proposed inverse problem was confirmed. The modeling can be solved directly on COMSOL, a fact that does not apply to the LSF. The NM technique was discarded due to high computational cost.

Furthermore, Levenberg-Marquardt showed excellent computational performance when applied to the machining process. The efficiency of the technique in solving the inverse problem was evident, with percentage deviations lower than 1.5% for temperatures and 5% for the estimated heat flux, when compared to literature data.

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