COMPARISON OF INVERSE METHODS IN THE DETERMINATION OF HEAT FLUX AND TEMPERATURE IN CUTTING TOOLS DURING A MACHINING PROCESS

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Abstract. *During machining, high temperatures are generated in the region of tool cutting edge. These temperatures have a controlling influence on the rate of wear of the cutting tool and on the friction between the chip and the tool. However, direct measurement of temperature using contact type sensors at the tool-work interface is difficult to implement due to the rotating movement of the workpiece and the presence of the chip. Therefore, the use of inverse heat conduction techniques represents a good alternative since these techniques takes into account temperatures measured from accessible positions. This work proposes a comparison of the inverse techniques Golden Section, Function Specification, Simulated Annealing and Dynamics Observers Based on Green's Function. They are used in a experimental methodology to determine the thermal fields and heat generated in the chip-tool interface during machining process. A numerical 3-D transient thermal model was developed to take into account both the tool and toolholder assembly. The direct problem is numerically solved by using the finite difference method discretized with a non-uniform grid. An objective function representing the difference between experimental and theoretical values of the temperature is minimized. The obtained results are validated by controlled experiments in laboratory and qualitative analyses. Some of the cited procedures are in the specific computational code INV3D. The program INV3D still contains a series of functions that help in the acquisition of the experimental data, in the generation of the three-dimensional mesh and in the analysis in graphical environment.*

Keywords*: inverse problems, heat conduction, optimization, heat flux identification, machining process.*

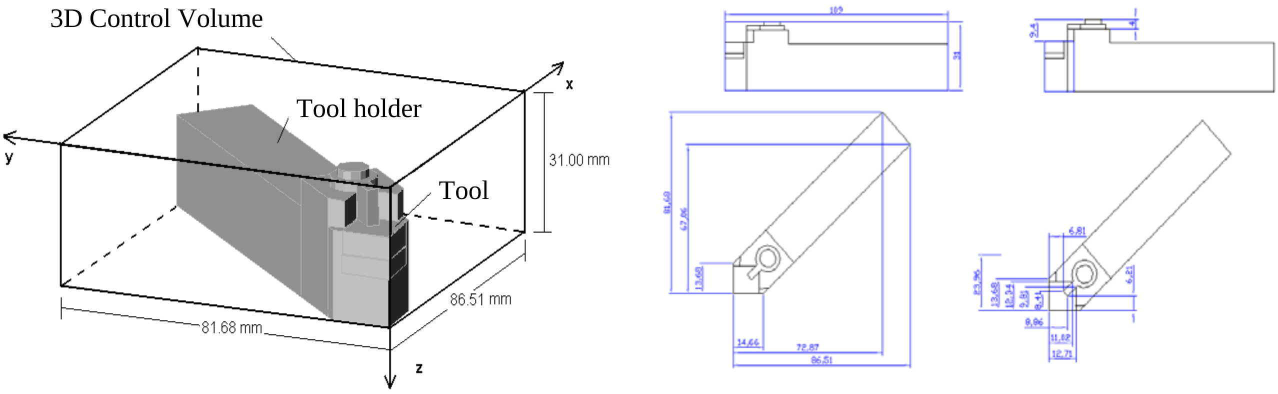
1. INTRODUCTION

The inverse problem technique consists of an optimization problem, where a functional that takes into account the experimental field of temperature and the theoretical field of temperature induced by a determined heat flux is minimized. In particular, the special case of estimate the surface condition from measurements in accessible regions has been known as inverse problems in heat conduction (Beck *et al*., 1985). In many situations, it is very difficult to determine the amount of heat which enters or leaves a material. However, thermocouples and instruments allow to measure with good accuracy the temperature of the material in some positions. In contrast with direct problems the inverse problems techniques do not depend on the boundary conditions. They are also unstable techniques, where small changes in the data (for example, temperature measured in the interior of the sample), can produce great or even unlimited deviations in the solution of the problem (heat flux calculated from these temperatures) (Beck *et al*., 1985). Thus, those problems known as ill-posed problems are difficult to solve, especially if the noise is present in the measured sign. The inverse problems techniques are found in several areas of the science and engineering. For example: mechanical, aerospace and chemical engineers, mathematician, doctors and other areas. The main characteristic of this approach is to obtain the solution of the physical problem in an indirect way. As an example, it can be mentioned the determination of thermal fields in surfaces without access. In this case, the obtainment of the frequency response function of complex structure. Another example is the diagnostic of some illnesses by computerized tomography. In all the cases the boundary conditions of these problems are not known or are difficult to obtain, because generally, these problems present complex dimensional characteristics and do not have direct solution. Many works have been based in the techniques of inverse problems for solving a great variety of problems (Scott & Beck, 1989, Flach & Ozisik, 1992, Reinhardt, 1993, Blanc *et al*., 1997, Lima *et al*., 2000, Lima e Silva *et al*., 2003, Carvalho *et al*., 2004). New methodologies for the solution of inverse problems in heat conduction have been developed to solve problems of engineering and applied mathematics. In this work a comparison of four inverse problems techniques (Golden Section, Function Specification, Simulated Annealing and Dynamics Observers) to estimate heat flux and consequently the temperature at the chip-tool interface is proposed. Then, the determination of thermal fields can be used to minimize the wear of cutting tool and thus to reduce the production costs. Hence, more efficient processes of cooling can be developed. The thermal model takes into account both the tool and tool holder assembly. A transient three-dimensional heat conduction model discretized with a non-uniform grid is used to calculate the temperature. The variation of the heat transfer coefficient with temperature is also considered. In the validation of the proposed methodology, the techniques of inverse problems were used in controlled experiments in laboratory. The software INV3D version 1.0 was developed to solve of the involved problems. The program INV3D still contains a series of functions that help in the acquisition of the experimental data, in the generation of the three-dimensional mesh and in the analysis in graphical environment

2. THEORETICAL FUNDAMENTAL

2.1. Thermal model

In Figure 1a the schematic model for the thermal problem of machining is presented. The tool and the tool holder are generated from a three-dimensional control volume (perfect paving stone). Where the dimensions of the control volume are: 86.51 x 81.68 x 31.00 mm. 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. In this work the heat diffusion problem is solved using Cartesian coordinates. The tool and tool holder are located in the calculation domain from the supply of their dimensions presented in Fig. 1b. The cutting toll was considered without chip breaker. Besides, the material of the tool and tool holder are considered homogeneous and the thermal properties are not temperature dependent. During the experiment the cutting fluid was not used. Hence, as boundary conditions, all the faces of the tool and tool holder assembly are submitted to a variable heat transfer coefficient $h(x,y,z,t)$.



a) b)

Figure 1. a) Three-dimensional thermal problem of the tool and tool holder b) Dimensions of the tool and tool holder assembly

The thermal problem presented in Fig 1a can be described for the heat diffusion equation as:

$$\frac{\partial}{\partial x}\left(\lambda_i \frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda_i \frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda_i \frac{\partial T}{\partial z}\right)=(\rho Cp)_i \frac{\partial T}{\partial t} \tag{1}$$

where the index i represents the position in the assembly as follows: i = 1 represents the tool cutting; i = 2 represents the tool shim and i = 3 represents the tool holder. It can be observed in this figure that a great part of the tool holder surface is exposed to the environment, as well as, part of the superior surface and lateral of the tool. The only region of the superior surface of the tool not exposed to the environment, is subjected to the thermal flow $q''(t)$. This heat flux is due to the chip-tool interface contact and is identified by the contact area A_c. The boundary conditions imposed to the problem presented in the Eq. (1) can be written by

$$-\lambda_i \frac{\partial T}{\partial \eta}=h(T-T_\infty) \tag{2}$$

on the regions exposed to the environment and

$$-\lambda_i \frac{\partial T}{\partial \eta}=q''(t) \tag{3}$$

at the interface defined as A_c, where η represents the normal outside in the coordinates *x*, *y*, and *z*, *T* the temperature, T_∞ the room temperature, λ the thermal conductivity, ρCp the product of the density and specific heat and *h* the heat transfer coefficient. The initial condition is

$$T(x, y, z, o) = T_o \tag{4}$$

where T_o represents the initial temperature of the tool, shim and tool holder.

2.2. Numerical solution of the direct problem

For the solution of Eq. (1) a numerical modeling based on the implicit finite differences method was developed (Carvalho, 2005). Based on the dimensions furnished in the Fig. (1b), the tool, shim and tool holder assembly was discretized from an irregular three-dimensional mesh as presented in Fig. (2). An additional difficulty that appears with the numerical discretization is the necessity of coincidence of the positioning of the temperature sensor (thermocouple) with the center of a discrete volume (finite). To avoid this problem, a Cartesian grid generator was developed to adapt to any kind of geometry and to allow the building of the grid from specific points defined by the localization of the sensors (software INV3D).

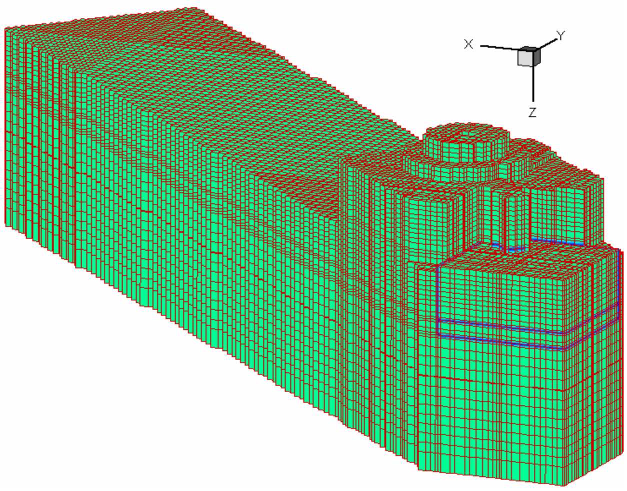


Figure 2. Non-regular finite volume mesh for the assembly tool, shim and tool holder.

Once the heat flux determination demands the manipulation of experimental data, the numerical model must not have any limitation on the time duration of the experiment or measurement interval of the experimental temperature. Amongst the several existing numerical techniques, the finite differences method with implicit formulation was used. The direct problem is reduced to the solution of the linear algebraic equations system. For the solution of this system the Successive Over Relaxation method (SOR) is used with a relaxation coefficient $W = 1.95$ (more details about this method can be found in Carvalho, 2005).

2.3. Inverse problems in heat transfer

What are inverse problems? This is a classic question and the answer can be simple: an inverse problem determines the unknown causes basing on the observation of their effects. The inverse problems in heat conduction can be considered as a special class inside the techniques of inverse problems. The main characteristics of these problems are: to use measured temperatures, to model the thermal problem basing on the heat diffusion equation and to have as objective the estimation of a thermal parameter, for example, the estimation of the heat flux. It can be verified that the machining problem fits perfectly in this category of problem, once the determination of temperature distribution at the chip-tool interface by direct measurement is extremely complicated. However, the information of the measured temperatures in accessible regions can be used to estimate the heat transfer rate at the chip-tool interface and from it to calculate the temperature in any desired point. This is one of the main objectives of this work, in other words, to apply the inverse heat conduction technique to determine heat transfer rate at the cutting interface. In this work, the thermal flux which flows in the chip-tool interface is obtained using the inverse problem techniques described below. Basically, this technique minimizes a square error function based on the difference between experimental, *Y*, and calculated, *T*, values of temperature. Thus, the objective function, S_{mq}, to be minimized can be written as

$$S_{mq} = \sum_{i=1}^{ntherm} \left(Y(x,y,z,t)_i - T(x,y,z,t)_i \right)^2 \qquad (5)$$

where *ntherm* represents the number of thermocouples used.

2.3.1. Golden section method

The golden section method for estimating the maximum, minimum, or zero of a one-variable function is a popular technique for several reasons. First, while the function is assumed to be unimodal, it does not need continuous derivatives. Secondly, as opposed to polynomial or other curve-fitting, the rate of convergence for the golden section method is known. Finally, the method is easily programmed for solution on the digital computer. Basically the golden section method is an iterative process where the search interval reduces approximately 62% of the previous iteration interval, until it finds the lesser value of the objective function.

2.3.2. Simulated annealing

Simulated annealing (SA) is a global stochastic optimization method that originated in the computational reproduction of the thermal process of annealing, where a material is heated and cooled slowly in order to reach a minimum energy state. In the SA method, starting from an initial configuration, a new configuration is generated randomly. If this new configuration has a smaller value of objective function (in a minimization context), then this new configuration will become the current configuration. Otherwise, a stochastic test is applied to indicate whether or not the new configuration will be accepted. This process of movement-acceptation is repeated, and as the number of analyzed alternatives increases, the acceptance probability of the worse configurations is gradually reduced. Due to the possibility of carrying out "wrong way" movements, the search can move from a local optimum toward the global optimum to avoid being trapped in a poor local solution.

2.3.3. Function specification method

The function specification procedure is so called because the explicit underlying nature of the function being estimated is assumed or specified (Beck *et al*., 1985). Typically, a simple form such as piecewise constant or piecewise linear function is assumed. In the sequential function specification method, the functions components are determined one at a time in sequence rather than all at once in a batch process.

2.3.4. Dynamic observers based on Green’s function

Dynamic observers are proposed as a solution algorithm for the inverse heat conduction problem (IHCP) of reconstructing a time-dependent surface heat flux at the boundary of a linear heat conductor. The derivation of optimal observer equations follows directly from a novel interpretation of the IHCP in the frequency domain: Solving the IHCP is viewed as a filter design problem in which the reconstructed heat flux is obtained by low-pass filtering of the true heat flux.

3. VALIDATION OF THE INVERSE TECHNIQUES AND THE NUMERICAL MODEL

A great difficulty in the solution of inverse heat conduction problems is the validation of the used technique. This difficulty is inherent to the problem, once the validation of the estimated 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 do a controlled experiment, in which, the heat flux and the temperature were measured at the cut tool. Later, these signals would be compared with the estimated heat flux and the calculated temperature in the Inv3D for each one of the mentioned techniques of inverse problems above. In this sense, before the analysis of the real process of machining, an experiment with controlled conditions was done. In this case, a cemented carbide tool with dimensions of 0.0127 x 0.0127 x 0.0047 m was used. A heat flux transducer and two thermocouples previously calibrated (Carvalho, 2005) and a kapton electric heater were used on this tool. The electrical heater was connected to a continuous source current (MCE) that provides the heat generation (Joule effect). The heat flux transducer was located between the heater and the tool, in order to measure the heat supplied to the tool. The temperatures at the tool were measured with two thermocouples. The signals of heat flux and temperatures are acquired by a data acquisition system HP Series 75000 with the voltmeter E1326B controlled by a PC. To guarantee a better thermal contact, a thermal paste was used between the transducer and tool. Capacitor discharge was used to attach the thermocouples to the plate surface (Vilarinho, 2001). Figures 4 and 5 present respectively the heat flux and the temperatures on the tool.

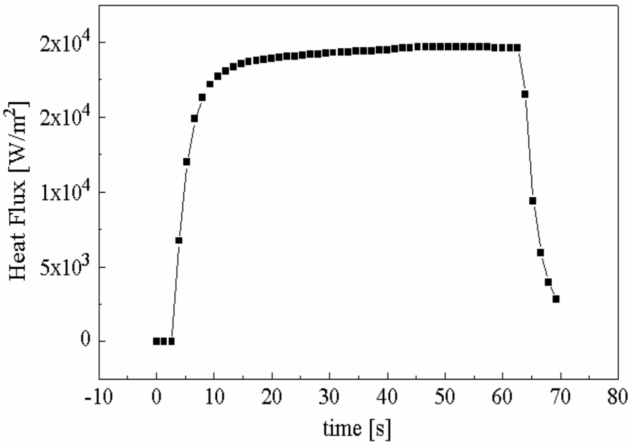


Figure 4. Experimental heat flux

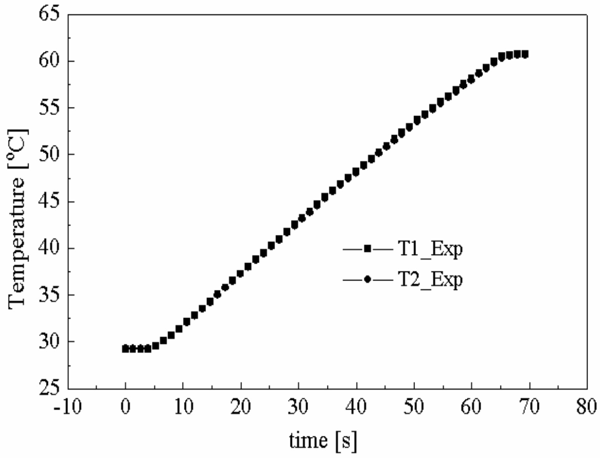


Figure 5. Experimental temperatures

The solution of the direct problem for a three-dimensional non-uniform grid with 13824 points is presented in Figure 6 for the two temperatures. The values of thermal properties used to calculate these temperatures are λ = 43.1 W/m.K and α = 14.8 x 10^{-06} m^2/s and the minimum distance among the grid points *x*, *y* and *z* are respectively 0.0005, 0.0005 and 0.0002 m. The time steps, Δt, was 1.3 s. As boundary conditions, it was considered that all the faces were submitted to a constant convection heat transfer coefficient (h = 20 W/m²K). It can be observed in Fig. 6 a good agreement between the temperatures experimental and calculated by the INV3D. This fact is more evident when the residuals are analyzed (Fig. 7). In this case, the maximum residual obtained was 0.88 ºC, which represents approximately an error of 1.46 %.

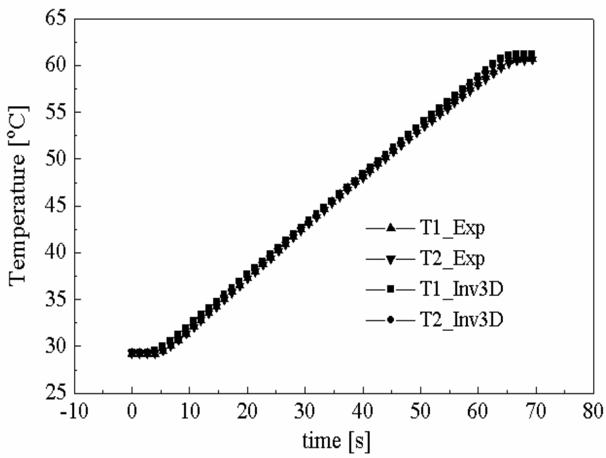


Figure 6. Comparison of the experimental and calculated temperatures

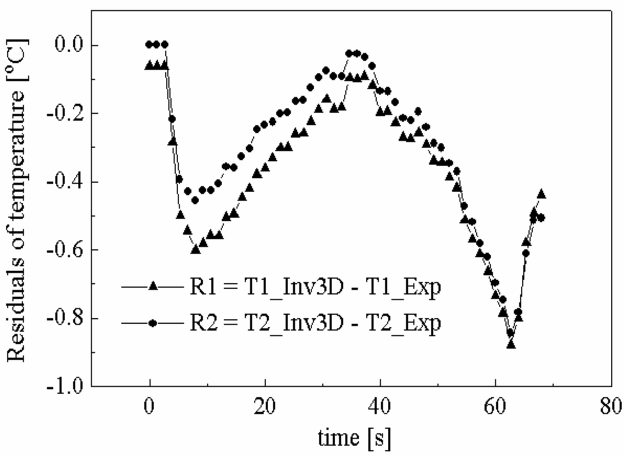


Figure 7. Residuals of temperature

Once the direct problem is validated, the next step is to solve the inverse problem. Thus, the heat flux generated at the tool is estimated from the temperatures presented in Fig. 5. For this the four techniques of inverse problem presented before are used. The results of estimated heat flux for these techniques are showed in Fig. 8. These results are compared with the measured heat flux (Fig. 4). It can be noticed that the four techniques used in this work presented good results when compared with the experimental heat flux. In this manner, these results validate each technique and show their efficiency. Figures 9a and 9b show a comparison among the experimental and estimated values of temperature for each thermocouple used in this work respectively. The residuals among the estimated and experimental values of temperature for each temperature are presented respectively in Figs. 10a and 10b. It can be seen in these figures that the maximum residual was obtained for the Golden section technique and it was 0.88 ºC, which represents an error of 1.46 %. The performance ranking for the four algorithm showed in Figs 10a and 10b was: the simulated annealing (mean residual 0.03521ºC), the function specification (mean residual 0.35705ºC), the golden section (mean residual 0.3744ºC) and the dynamic observer based on Green's function (mean residual 0.43922ºC).

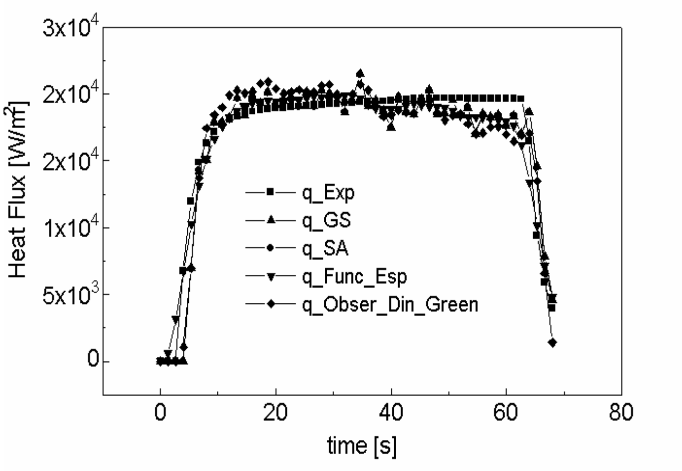
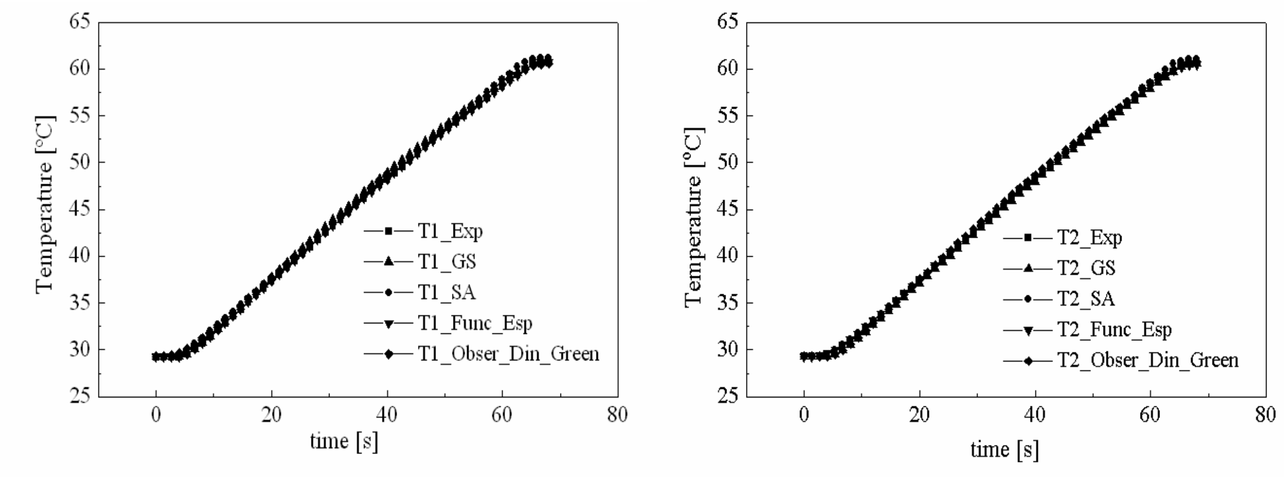
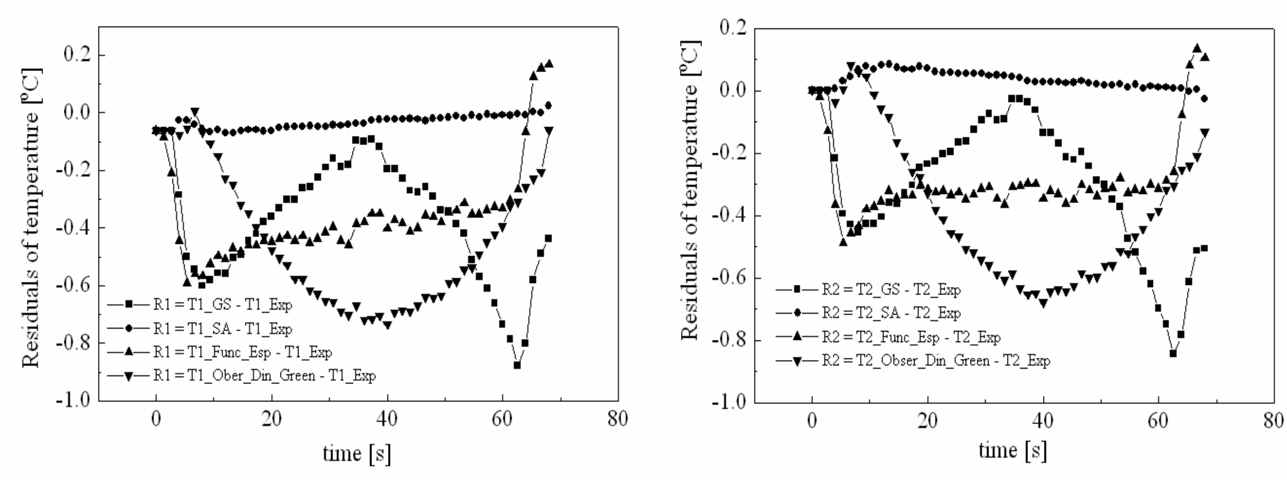


Figure 8. Experimental and estimated heat flux



a) b)

Figure 9. Comparison among the estimated and experimental temperatures a) thermocouple 1 and b) thermocouple 2



a) b)

Figure 10. Residuals of temperature a) thermocouple 1 and b) thermocouple 2

Table 1 presents the computational time to estimate the heat flux for the four inverse techniques. The PC used in the tests had the following configurations: Pentium IV, 2.6 Ghz and 512 Mb of memory. In this table, it is possible to verify the speed of the function specification and the dynamic observers technique when compared to the other techniques as golden section and simulated annealing.

Table 1. Computacional time to estimate the heat flux.

Inverse Technique	Computational time (minutes)
Golden Section	170
Simulated Annealing	300
Function Specification	10
Dynamic Observers Based on Green's Function	10

After validated the numerical thermal model and the inverse techniques by using a controlled experiment, the next step is to use the inverse techniques to estimate the heat flux and the temperatures in experimental machining processes.

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 gray cast iron FC 20 EB 126 ABNT in the form of cylindrical bar with an external diameter of 77 mm. The insert and tool holder used were a Cemented ISO SNUN12040408 K20/Brassinter and ISO CSBNR 20K12/SANDVIK COROMAT respectively. The gray cast iron workpiece with initial diameter of 77 mm. The temperatures were measured on accessible locations of the insert, the shim and the tool holder by using thermocouple K type and a data acquisition system HP 75000 Series B with a voltmeter E1326B controlled by a PC. Table 2 presents the location of thermocouple according to the coordinate system shown in Figure (11).

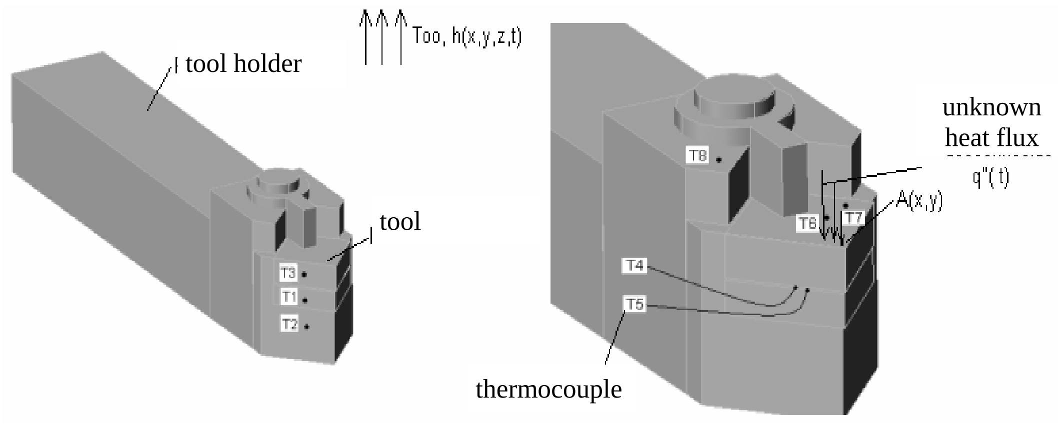
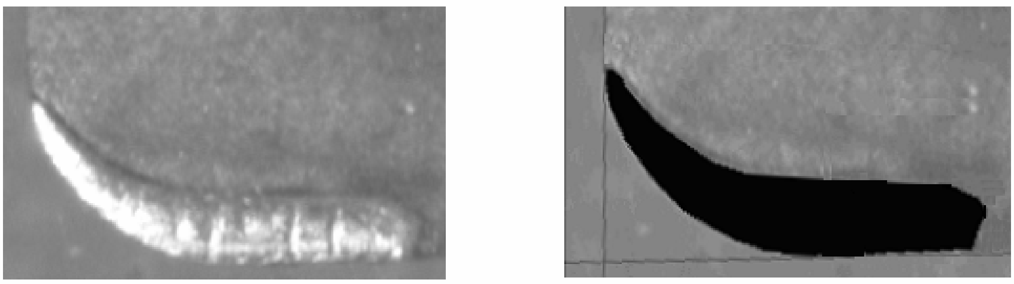


Figure 11. Location of the thermocouples T_1 to T_8

Table 2. Thermocouple location according to the coordinate system defined in Fig 11.

Position/Thermocouple	1	2	3	4	5	6	7	8
X [mm]	0,000	0.000	0.000	4.490	6.528	7.222	9.512	5.300
Y [mm]	6.450	7.250	3.950	4.116	6.579	4.740	1.715	14.55
Z [mm]	15.95	21.05	11.52	14.23	14.23	9.400	9.400	4.000

The chip-tool contact area determination represents one of most important and delicate role among the main source of errors in the solution of the inverse problem. It can be found some methods to identify this area in the literature as, for example, the use of a software images analyzer (Jen & Gutierrez, 2000) or the application of coatings (Yen & Wright, 1986). In both process, the area is measured after cutting. This procedure is also used here. However, in this work, the average interface contact area is obtained from the three tests carried out with the same cutting condition. In order to measure the contact area an image system program with video camera Hitachi CCD, KP-110 model, a PC AMD K6 450 MHz and the GLOBAL LAB Image software were used. A typical contact area is presented in Figure (12).



a) b)

Figure 12. Chip-tool interface contact area: a) image acquired by the video; b) Image after signal treatment.

5. RESULTS FOR THE MACHINING PROCESS

In this work the thermal properties of the tool obtained from Sandvik do Brasil S.A. are λ = 43.1 Wm/K and α = 14.8 m^2/s. The material of the tool holder is AISI 1045 steel and the thermal properties are λ = 49.8 Wm/K and α = 14.8 m^2/s (Matweb, 2007). It was considered that the support below the tool had the same thermal properties of the tool. The heat flux was estimated for three inverse techniques for the following cutting condition: feed hate of 0.138 mm/rev, cutting speed of 217.72 m/min and depth of cut of 1.5 mm. Figure 13 presents the heat flux estimated for three inverse techniques. It can be observed in this figure that the heat flux was estimated by using the following techniques: golden section, the function specification and the dynamic observer based on Green’s function. In this case, for the simulated annealing technique was not possible to estimate the heat flux. However, the SA technique is a robust methodology of optimization, it requires many evaluations of the objective function. This fact allied to others such as the parameters adjustment of the SA (annealing and cooling) and the value identification for the convergence of the objective function; had contributed for an extreme increase of the computational time. Thus, it was impracticable to obtain the solution of the problem from the simulated annealing technique. It can also be seen in this figure that the heat flux estimated to the golden section technique tends to reach the steady state condition, while for the other techniques it decays after few seconds of machining. This fact is attributed to the uncertainties between the theoretical model and the experimental one. Some of these uncertainties are: the geometric simplifications, the errors in the process of dimension measurements of the involved materials, the values adopted for the thermal properties, the thermal contact resistance, the heat convection between the set and the air; the measured temperatures and the measurement of the chip-tool interface contact area. In this case, as the experimental heat flux is unknown, only a qualitative analysis of the obtained results is presented. The first stage of this analysis consists of comparing the experimental temperature measured in an accessible region of the tool with the calculated temperature from the heat flux presented in Fig. 13. The second stage is to determine the average temperature at the cutting interface for each instant of time and for each inverse technique and to compare the results with the literature.

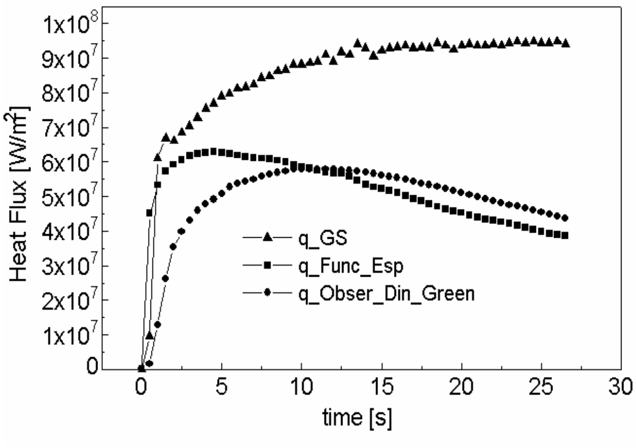


Figure 13. Heat flux estimated from three inverse problems techniques.

In Table 3, the computational time to estimate the heat flux is presented. The PC configuration is the same presented in Section 3. In this table, it can also be observed the speed of the function specification and the dynamic observers techniques when compared to the other techniques as golden section and simulated annealing. Figure 14 presents the comparison between the experimental temperature measured by thermocouple 3 and the calculated temperatures from the heat flux presented in Fig. 13. A good agreement can be noticed between experimental and calculated temperatures for golden section technique. Nevertheless, in the other techniques the maximum residue is 100 ºC. Figure 15 presents the average temperature at the cutting interface for each time. It is verified in literature that the majority of works present only the average temperature at the cutting interface. It means, they assume that the machining process happens in steady state. Few works are concerned to analyze the transient process, in other words, the variation of the temperature at the chip-tool interface during the period of turning. This occurs because the thermal analysis at the tool is highly complex and involves a great amount of variables that directly interfere in this process. Amongst the analyzed papers, two presented results for the same materials and cutting conditions of this work. Stephenson (1991) determined the average temperature at the chip-tool interface for four different thermal models in steady state. The obtained results are still compared to experimental data. For a cutting speed of 230 m/min, the average experimental temperature at the cutting interface was 800 ºC, whereas the calculated temperature presented variations from 500 ºC to 820ºC (Stephenson 1991). In the work of Stephenson (1991) a constant feed hate of 0.117 mm/rev was considered. Although the cutting conditions of Stephenson (1991) are not the same of this work, the experimental and theoretical temperatures coincide with the temperatures presented in Figure 15. In Melo (1998) the techniques of inverse heat conduction problems were used to determine the temperature at the chip-tool interface. In Melo (1998) the presented methodology was based in the work of Lin *et al.* (1992), in which the solution of thermal problem of machining was developed from an ellipsoidal one-dimensional model. For the solution of the inverse problem, Melo (1998) used the function specification method. For a cutting speed of 206 m/min, feed hate of 0.176 mm/rev and depth of cut of 1.75mm, Melo (1998) determined a maximum temperature at the cutting interface of 950 ºC. It can be seem in Fig. (14) of this work that the maximum temperature was approximately 900ºC. By using the tool-work thermocouple method, Fernandes (1992) also found similar results.

Table 3. Computacional time to estimate the heat flux.

Inverse Technique	Computational time (minutes)
Golden Section	5760
Simulated Annealing	-
Function Specification	240
Dynamic Observers Based on Green's Function	240

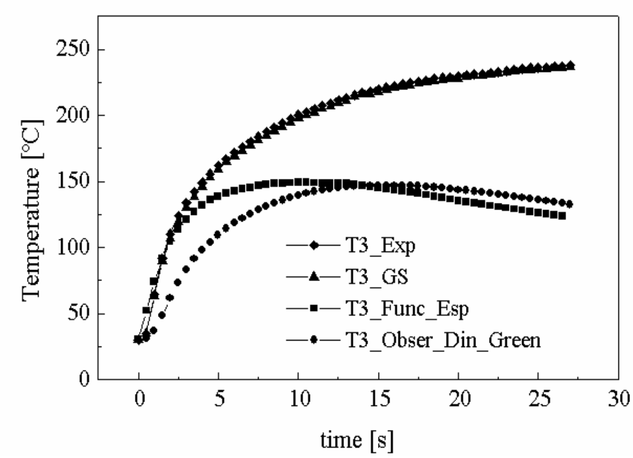


Figure 14. Comparison of the experimental and theoretical temperatures for thermocople 3

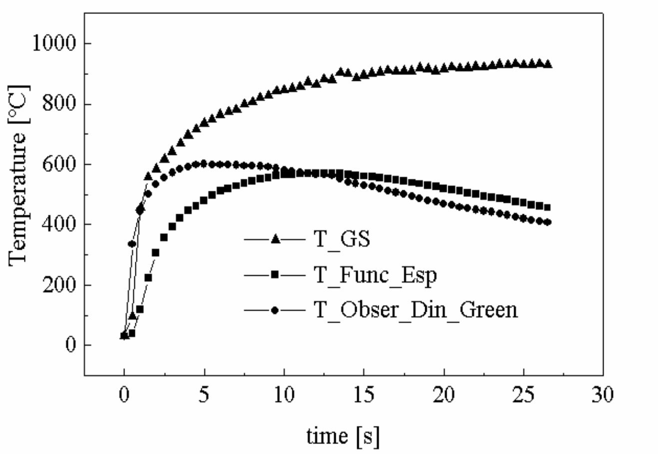


Figure 15. Temperature at the cutting interface

From the presented results and the analyzed works, it can be said that until now none of the existing technique is universally accepted as absolute (Machado and Silva, 2004). In reality, what exist are attempts to understand the basic points of the heat transfer process during the machining by turning. It is important to say that the understanding is the closer step to foresee the performance of this manufacture process. The proposal of this work is based on this principle, that is, in trying to understand this process of heat transfer. For this, it was presented a more complete thermal study, based on a real thermal model and the analysis of the performance of inverse techniques.

6. CONCLUSIONS

In this work a comparison of the inverse techniques Golden Section, Function Specification, Simulated Annealing and Dynamics Observers Based on Green's Function was presented. For the validation of the proposed methodology, the techniques of inverse problems were used in controlled experiments in laboratory. All the inverse techniques presented good results to estimate the heat flux. The differences were less than 5 % for all the techniques in a comparison with the measured temperature. The use of these techniques in an experimental methodology to determine the thermal fields and heat generated in the chip-tool interface during machining process also presented satisfactory results. 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. The contributions of this work are the development of a numerical 3-D transient thermal model that takes into account both the tool and toolholder assembly and the analysis of several inverse techniques when applied to the machining thermal problem.

7. ACKNOWLEDGEMENTS

The authors would like to thank CNPq, FAPEMIG and CAPES, Government Agencies for the financial support without which this work would not be possible.

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