ANALYTICAL AND NUMERICAL HEAT DISTRIBUTION AIMING AT THE COOLING FLUID CHARACTERIZATION IN MACHINING PROCESS

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Abstract *The efficiency of the cooling fluid in the machining process can be assessed by finding the convective heat transfer coefficient in the mathematical problem that describes the physical process of metal cutting . The convective coefficient provides the classification of the fluid with respect to its effectiveness in cooling the workpiece and the tool, improving process the productivity. The convective coefficient depends on various parameters such as fluid viscosity and velocity as well as the geometric dimension and workpiece surface. The majority of the studies about the convective coefficient imposed hypothesis to simplify the mathematical model, which takes the experiment out the real context in shop floor. In addition, they are often solved by numerical methods. Numerical solutions presents, however, a number of drawbacks too. For example, it is usually quite difficult to have an overall impression of the dependence of the behavior of a system on its parameters. This type of information is readily available from analytical solutions. In another way, the analytical solution needs a strong mathematical theory. The dynamic aspects of the cutting process need to be addressed by FEM (Finite Element Method) analysis. FEM is an approximation method for studying continuous complex physical systems, used in structural mechanics, electrical field theory, fluid mechanics and today more than ever this method has been usuful due to the fast improvement of computer hardware and software. This makes finite element calculations, previously complicated, to become viable. The application of FEM to machining process gives results in real-time and with any parameters. The present paper comparean analytical model of the heat transfer subject to Robin boundary condition and the simulation of the same problem with the Software Abaqus. This software is general purpose one, designed to model the behavior of solids and structures under externally applied loading..*

Keywords*: heat conduction, convective coefficient, FEM, machining*

1. INTRODUCTION

Chip formation processes convert mechanical energy into heat through plastic deformation of the chip and friction between tool and workpiece. The heat transfer in the chip formation area is important to the performance of the tool and, consequently, to the process as a whole (Carvalho, 2005).

Workpiece heating during the machining process influences the workpiece accuracy as well. Therefore, the decrease in the tool life and the inaccuracy increase the costs and can create economic problems for the industries. Due to the large growth and development of machining processes and the demand for environmental sustainability, new cutting fluid has been developed. A real measurement of its effectiveness in cooling the workpiece and tool, together with improvement in process productivity is still necessary.

Minimize the use of cutting fluid has also been a very important issue for industries nowadays. Dry cutting, also known as ecological machining, and cutting with a minimum quantity of lubricant (MQL), in which a very low amount of fluid is used are attempts in that field. The MQL name is given to the process of pulverizing a very small amount of oil (less than 30 *ml/h*) in a flow of compressed air. Some researchers concluded that MQL could reduce the temperature on the chip formation zone, maintaining it at levels low enough to avoid tool material deterioration.

Modeling heat distribution in cutting during machining operations has been another step into understanding the role of cutting fluids in machining. In the literature there are a number of methods to analyze cutting temperature: experimental methods, such as embedded thermocouple and thermal radiation. There are also analytical methods, such as mathematical modeling through differential equations, which uses several techniques of numerical solution for differential equations, such as FEM models. The commercial software ABAQUS, for example uses numerical solutions to solve the equations.

Cutting processes simulation will be effective for improving cutting tool design and selecting optimum working conditions, especially in advanced applications such as in the machining of dies and moulds. This technique will reduce time consumption and expensive experimental testing (Ceretti, Lucchi and Altan, 1997).

The finite elements method (FEM) has become the main tool for simulating the machining process. Finite element models are widely used to calculate stress, strain and temperature distribution on the primary and secondary shear zone as well as into the interfaces between tool, workpiece and chip. In consequence, temperature distribution in the tool, chip and workpiece, as well as cutting forces, plastic deformation (shear angle and chip thickness), chip formation and possibly its breaking can be determined faster than by using costly and time consuming experiments (Grzesik, 2005).

Several authors concluded that experimental, analytical methods and numerical methods working together can bring better results for the analyses of the machining process. The analytical approach provides an equation to find the convective coefficient; however, the numerical simulation can ensure the validity of many models with such value as input.

The present work studies the temperature distribution of a cutting process modeled by ABAQUS FEM software and the results are compared to those obtained by an analytical model.

2. TEMPERATURE ESTIMATION THROUGH NUMERICAL METHODS

The ABAQUS software is one of the most used for FEM simulation. The graphical interface of ABAQUS allows the user to define the geometry of the part, assign the material properties to it, and apply conditions to control the problem, fast and efficiently, with automatic mesh generation on the body to be examined. Furthermore, it enables modeling complex shapes and the occurrence of deformations too. The FEM is the numerical method used to solve problems due to its characteristics of flexibility and numerical stability and also can be implemented as a computer program. The basic concept of the technique is the subdivision of a region into sufficiently smaller regions so that the solution in each small region and transfer information from the old to the new mesh through interpolation (Chen and Black, 1994). In this study, there has been assumed the following three hypotheses:

-The model is Lagrangian;
-The tool, workpiece and chip are homogeneous and isotropic;
-The model is in two dimensions (2D).

For the finite element modeling (FEM) of metal machining processes, the boundary conditions at the tool–chip interface are usually formulated in terms of the interface heat transfer coefficient (Iqbal, 2008). One of the main problem to simulate chip formation in long computing time needed to solve such complex problem, involving large and nonlinear deformation, with coupled heat problem. To actually simulate material rupture such as in the chip formation problem, the Explicit spends several hours of processing to simulate milliseconds of machining. A solution to this problem was to divide the simulation in several steps. The first one simulates the chip formation properly and captures the heat flowing to the tool and to the workpiece. Provide that these two quantities became stable a second step takes those values and simulates the heat dissipation throughout the workpiece and tool for long periods of time using the Implicit algorithm, which can be solved in few minutes of processing.

The FEM was used for the coupled thermomechanical problem, and the Johnson-Cook equation was used to define material behavior and also its rupture (Mousavi, 2008).

The material model proposed by Johnson-Cook is one of the most convenient and also one that produces excellent results to describe the behavior of the material in the formation of the chip (Coelho, 2005). The stress, as a function of strain, strain rate and temperature is given by Equation (1), and deformation for failure by Equation (2) below:

$$\overline{\sigma} = (A + B\overline{\varepsilon}^n)\left[1 + C\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right]\left[1 - \left(\frac{T - T_0}{T_m - T_0}\right)^m\right] \tag{1}$$

$$\bar{\varepsilon}^{pf} = (d_1 + d_2 \exp d_3\sigma^*)\left(1 + d_4 \ln(\frac{\varepsilon^p}{\varepsilon_0})\right)\left[1 - d_5 \frac{T - T_0}{T_m - T_0}\right] \tag{2}$$

where the constants d_1, d_2, d_3, d_4 and d_5 are given for the implementation of the Johnson-Cook formulation in ABAQUS and $\sigma^* = \sigma_m / \overline{\sigma}$. The specific constants are listed in Table 1 (Johnson and Cook, 1985).

Table 1 – Johnson-Cook Constants for stress and strain, Equations (1) e (2)

	A	*B*	*C*	*n*	*m*	d_1	d_2	d_3	d_4	d_5	Melting Temperature (K)	Transition Temperatura (K)
AISI 4340	792	510	0.014	0.26	1.03	0.05	3.44	- 2.12	0.002	0.61	1793	305

The simulation of the machining was performed using a workpiece made of AISI4340 steel with length 0.003*mm,* height 0.0003*mm,* and carbide as the cutting tool. The cutting tool dimensions and geometry is show in Fig. 1.
Cooling fluid had a transfer heat coefficient of 2000 *W/m²,* by Incropera and Witt (1985), which can be a reasonable value for water, based one. The convection of heat dissipation was used only on the second step, which uses the heat flow as input on the workpiece.

In the first step, which simulates the chip formation only, cutting speed was 150 *m/min* (2.5 *m/s)* with initial and ambient temperature of 305 *K*. Cutting time was time is 0.0012 seconds, which equals 3 *mm* of cutting extension. Tab. 2. shows the input data for the ABAQUS simulation, i.e., the properties of material used in the processes of machining.

Table 2 – Material Properties

Steel AISI 4340	
Thermal conductivity (W/m°C)	38
Coefficient of thermal expansion (μm/ m°C)	0,000032
Density (Kg/m³)	7838
Young´s modulus (Pa)	200
Poisson´s ratio	0,29
Specific Heat (J/kg/°C)	477
Carbide	
Thermal conductivity (W/m°C)	20
Density (Kg/m³)	14950
Young´s modulus (Pa)	400
Poisson´s ratio	0,21
Specific Heat (J/kg/°C)	210

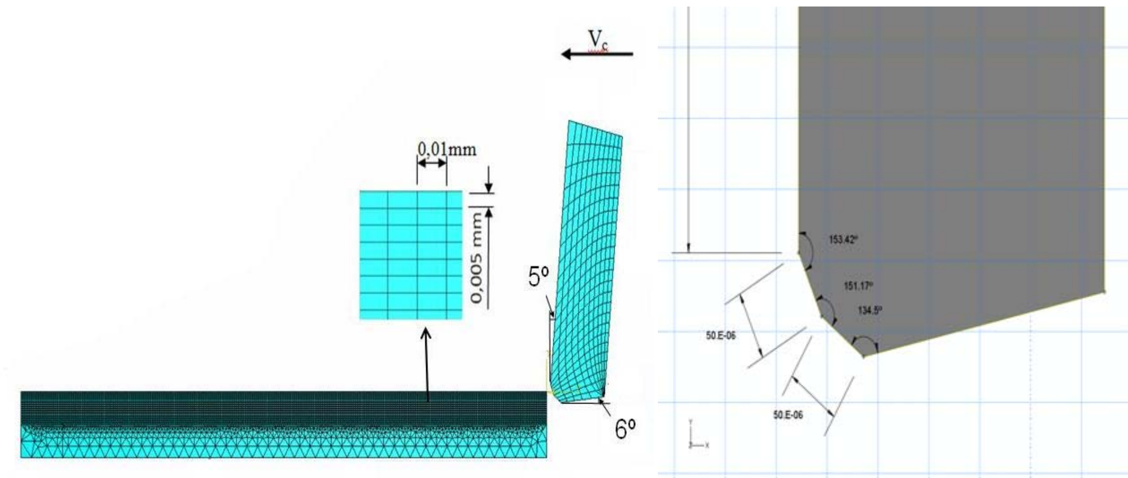
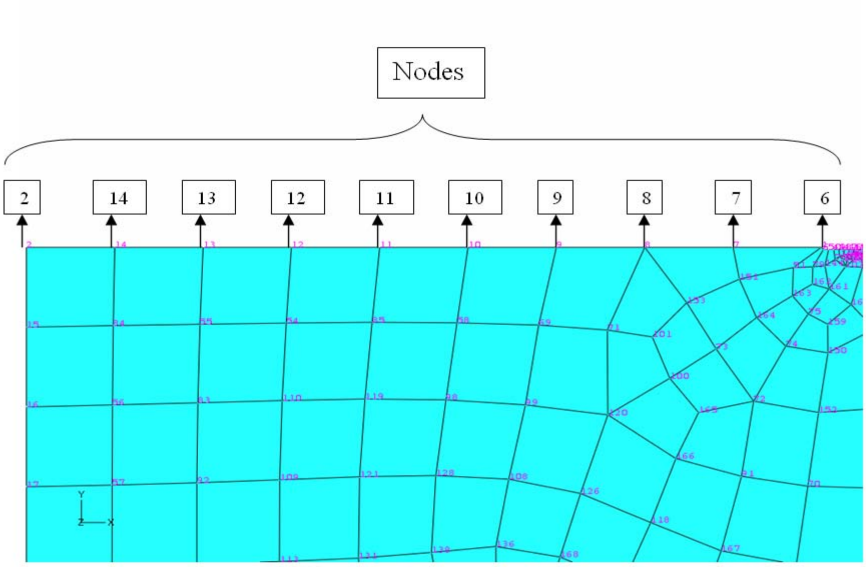


Figure 1: Workpiece and Insert dimensions

After the simulation machining process, was considered some nodes for temperature analyses and comparison between numerical results and analytical results. These nodes are showed in Fig. 2. In analytical model only the coordinate *x* was used because the model in this study is one-dimensional.



3. ANALYTICAL MODEL

The model is concerned with solving the inhomogeneous diffusion equation in the finite interval subject to the Robin conditions (Eq. 4):

$$\nabla^2 T(x,t) + \frac{1}{k} q(x,t) = \frac{1}{\alpha} \frac{\partial T(x,t)}{\partial t} \qquad 0 < x < l \qquad t > 0 \tag{3}$$

$$\left.\begin{aligned} k\frac{\partial T}{\partial x} + hT = 0 \qquad x = 0 \\ k\frac{\partial T}{\partial x} - hT = 0 \qquad x = l \end{aligned}\right\} \qquad t > 0 \tag{4}$$

$$T(x,0) = T_0 \tag{5}$$

The Green's function, acknowledge by Ozisik (1968), is used here to solve the model. Consider the following auxiliary problem for the same region.

$$\nabla^2 G(x,t\,|\,x',t) + \frac{1}{k}\delta(x-x')\delta(t-\tau) = \frac{1}{\alpha}\frac{\partial G}{\partial t} \qquad 0 < x < l, \qquad \tau > 0 \tag{6}$$

$$\left.\begin{aligned} k\frac{\partial G}{\partial x} + hG = 0 \qquad x = 0 \\ k\frac{\partial G}{\partial x} - hG = 0 \qquad x = l \end{aligned}\right\} \qquad t > \tau \tag{7}$$

$$G(x,t\,|\,x',\tau) = 0 \qquad if \quad t < \tau \tag{8}$$

The physical significance of this notation can be illustrated symbolically by writing it in form:

$$G(x,t\,|\,x',\tau) \equiv G(effect\,|\,impulse) \tag{9}$$

The solution of the problem, by Ozisik (1968), using the Green's function is:

$$T(x,t) = \int_{x'=0}^{l} G(x,t\,|\,x',0)\cdot T_0 dx' + \frac{\alpha}{k}\int_{\tau=0}^{t}\int_{x'=0}^{l} G(x,t\,|\,x',\tau)\cdot q(x,t)dx'd\tau \tag{10}$$

With

$$G(x,t\,|\,x',\tau) = \sum_{m=1}^{\infty} e^{-\alpha\beta_m(t-\tau)}\frac{1}{\eta(\beta_m)}\cdot X(\beta_m,x)\cdot X(\beta_m,x') \tag{11}$$

$$\eta(\beta_m) = \frac{1}{2}\left[\left(\beta_m{}^2 + \frac{h^2}{k^2}\right)\left(l - \frac{h}{k\left(\beta_m{}^2 + \frac{h^2}{k^2}\right)}\right) + \frac{h}{k}\right] \tag{12}$$

$$X\left(\beta_m,x\right) = \beta_m\cos\left(\beta_m x\right) + \frac{h}{k}\sin(\beta_m x) \tag{13}$$

$$\tan\beta_m l = 2\frac{h}{k}\left(\frac{\beta_m}{\beta_m{}^2 - \left(\frac{h}{k}\right)^2}\right) \tag{14}$$

is compared to the points of the same. The comparison between the analytical result, solution expressed by Eq. (10), and the numerical problem, simulated using ABAQUS software, will be through the standard error given by following equation:

$$\varepsilon = \frac{\sigma_X}{\sqrt{N}} \tag{15}$$

Where N is the dimension of space sample, $\overline{X}$ is mean of temperature and X_i is the punctual temperature.
And also by correlation linear given by

$$r = \sum_{i=1}^{N}\frac{(X_i - \overline{X})(Y_i - \overline{Y})}{(N-1)\sigma_X\sigma_Y} \tag{16}$$

Both results will be calculated in the points on the workpiece which are shown in Fig. 2.To estimate the error for each the points a standard deviation was calculates using values of temperature calculated by the analytical model X_i and the average of simulation $\overline{X}$, according to Equation:

$$\sigma_X = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(X_i - \overline{X})^2} \tag{17}$$

4. RESULTS AND DISCUSSION

The numerical simulation divides in two steps. The first step is the simulation of chip formation and temperature distribution in order to find the heat flows into the tool and the workpiece, as it can be seen in Fig.3. The second step of the simulation, which can be seen in Fig.3, was used to let the heat dissipate into the two bodies (tool and workpiece) and to find the temperature distribution for long periods of time, (30 seconds) that was the amount of time considered long enough for the temperature to become stabilized. The final temperature distribution on tool and workpiece after 30 s can be seen in Fig. 4.

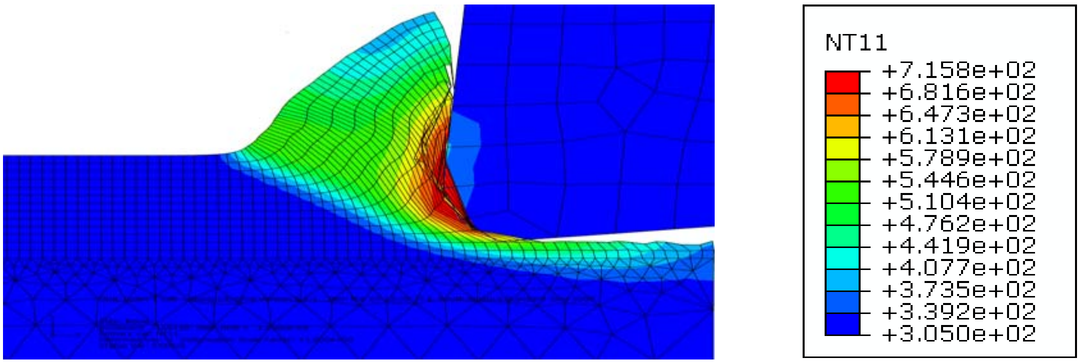


Figure 3. ABAQUS Temperature Simulation

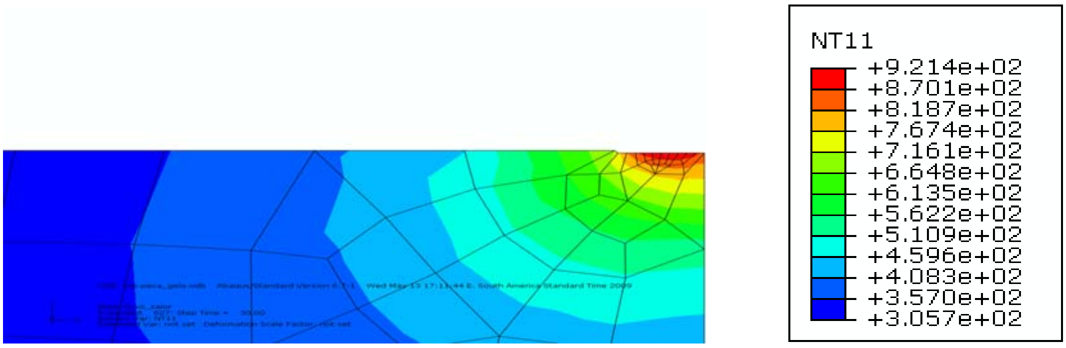


Figure 4. ABAQUS Temperature Distribution

After solving the analytical equations the best model was obtained for m=550 (Eq. (10)) and can be found in the Fig. 5. It can be observed that when m>550 (until 10.000) the curve goes far from the values simulated, while for m<550 the curve does not improve either.

The general analysis gives that standard error, given by Eq. (14) for the difference between the analytical temperature and simulated temperature is 15. Standard deviation calculated by Eq. (16) is 49.5. Whereas N=10, where N is the number of points. The linear correlation of the data, given by Eq. (15) is 0.828, indicating that the strength and direction of a linear relationship between two data are large and positive.

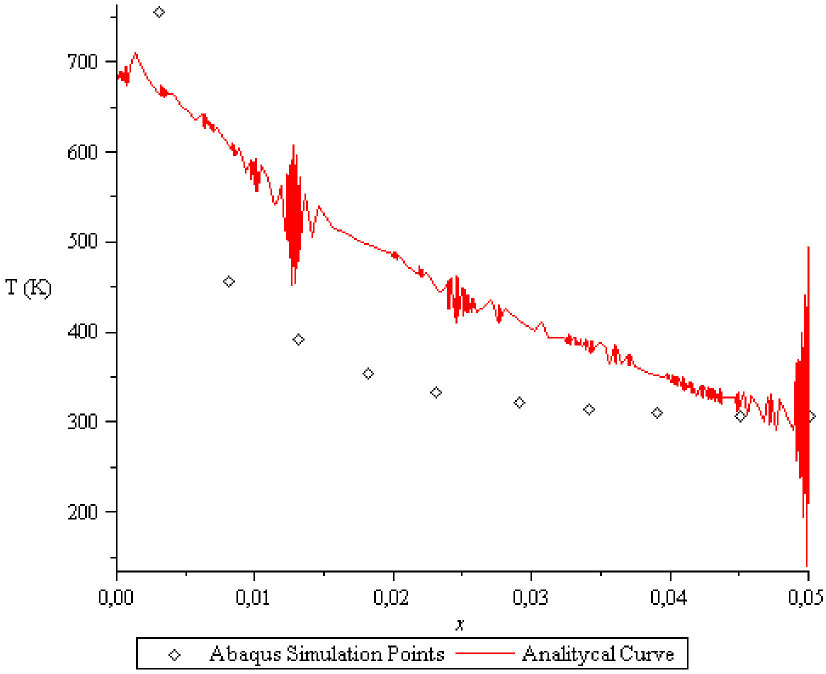


Figure 5. Simulation versus Analytical temperature at 30 *s* for several point on the workpiece

For each of the points plotted in the Figure 6 a standard deviation was calculated using Equation (16) for N=2 and results can be seen in the Tab. 3. The best results of the comparison are in the end of the piece when the temperature begins to approximate of the environment temperature.

Table 3 – Punctual analyses of Temperature comparison

Nodes**	**x***	**Simulated Temperature (X_1)**	**Analytical Temperature (X_2)**	**Standard Deviation** σ_X
6	0.003	756.7	663.0	46
7	0.008	458.5	589.0	65
8	0.013	393.0	534.3	70
9	0.018	355.4	495.6	70
10	0.023	335.2	458.8	61
11	0.029	323.3	418.3	47
12	0.034	316.1	391.2	37
13	0.039	311.7	356.0	22
14	0.044	309.2	314.0	2.4
2	0.05	308.0	302.9	2.5

* The coordinates y is 0.50127 for all x.
** See Fig. 1

3. CONCLUSION

Although the investigations still continue, the followings topics can be concluded at the present point in time of study:

Despite of the discrepancies between the curves obtained by both methods used, they have similar shapes, which indicate promising results and good enough to compare to experimental machining, to be performed in the future.

The linear correlation results can be seen as good; however, the standard deviation must be improved. Using experimental results there is hope that the analytical model can be further improved.

The best plotted of the analytical model was with *m*=550 and it must be investigated and compared with the physical phenomenon, which will be done in the near future.

In this context, the theoretical analysis validates the model on the machining process with some approximation. The next stage of the study is to use the inverse methods to find the convective coefficient *h* comparing it with experimental work.

4. ACKNOWLEDGEMENTS

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