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MEASUREMENT AND NUMERICAL SIMULATION OF THE CUTTING TEMPERATURE IN CUTTING TOOL DURING TURNING OPERATION

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Abstract

In many manufacturing processes particularly during metal removing processes, it is sometimes desirable and often necessary to have information on the quantity of heat produced and therefore the increase in temperature and its distribution, heat generated at the tool-workpiece interface during machining is an important factor to solve the metal cutting problems such as dimensional accuracy, the surface integrity and the life of the tool. In the present work, the evolution of the cutting temperature was studied using a combined experimental and numerical approaches; the thermocouple method was used to measure the cutting temperature for turning operations of the steel AISI 1060. 3D cutting model was used to simulate and predict the thermal phenomenon of the heat propagation in the cutting tool, using digital COMSOL simulation software. Based on a comparison between the results of two approaches; numerical and experimental, it was found a correspondence to go up to 96%, taking into account the maximum temperature.

Keywords: Turning process, Temperature measurement, COMSOL Multiphysics, Finite element.

1. Introduction

Due to the high cost involved in obtaining machining data experimentally, there are strong motivations for development of methodologies for description of different machinability phenomena using a numerical approach [1].

Nomenclatures

C_p	Specific heat capacity (*J/kg·°C*)
D	Inserts circle (mm)
D	Depth of cut (mm)
F	Feed rate (mm/rev)
H	The heat transfer coefficient by convection *(W / m2 . °C)*
K	Thermal conductivity coefficient $\left(W/m.^{0}c\right)$
L	Edge length of insert (mm)
N	Rotation speeds (rev/min)
ρ	Material density (Kg/m^3)
q_0	Heat flux (W /m^2)
r	Corner radius of insert (mm)
s	Thickness of insert (mm)
$TC1$	Temperature of thermocouple 1
$TC2$	Temperature of thermocouple 2
$TC3$	Temperature of thermocouple 3
T_∞	Environment temperature

Greek Symbols

ρ	Material density *(Kg/m^3)*

Abbreviations

FEM	Finite Element model
WP	Work piece

Cutting is one of the most important and common manufacturing processes in industry. Machining is not an easy process to study and to model, due to the inherent difficulty to know exactly what happens in the region around the tool tip [2]. Thermal consideration of hard machining processes is very important for tool wear mechanisms and heat penetration into the subsurface layer, which leads to the formation of the white layer and determines the distribution of residual stresses [3]. However, there is plenty of evidence in literature that machining processes generate an important heat and the temperature has a great influence on cutting tool wear since it modify the thermal, mechanical, thermomechanical and metallurgical properties [1,4]. Many problems are still remaining unsolved, one of these problems deals with heat transfer at tool contact interfaces. Various experimental techniques (thermocouple, infrared system, etc.) have been developed to evaluate the cutting temperature during machining operations [4]. The determination of the maximum temperature and temperature distribution along the rake face of the cutting tool is of particular importance due to its controlled influence on tool life [2]. Simulation of the actual metal cutting and chip formation process is very time consuming, even with modern software packages and computers [1]. Finally, it is possible to simulate chip formation, and determine approximate machining forces in a cutting operation with 2D or 3D models [5].

The present study is made to predict tool temperature distribution numerically using 3D Finite Element (FE) methods in a turning operation. The results obtained from these simulations are used to perform unsteady state heat transfer analysis using COMSOL Multiphysics 4.3b.

In this work, tool temperature distributions has been measured using thermocouple, the temperatures obtained by computer simulation are compared with the temperatures obtained by the experimental measurements.

2. Experimental Set-up

Thermocouples are known to be very popular transducers for measuring temperature. The tool works thermocouple technique is a widely used technique [6, 7and 8]. The k-type thermocouple was chosen for measuring the temperature in this work. This technique was preferred as it is inexpensive, easy to calibrate, has a quick response time and good repeatability during experiments. A mineral insulated, metal sheathed, k-type thermocouple with Digital micro voltmeter of ranges between 200°C and 1200°C. The cutting conditions are rotation speeds (N) is varied from 440 to 2500 rev/min, feeds rate (f) from 0.045 to 0.225 mm/revs, and depth of cuts (d) from 0.25 to 1.5 mm. Tungsten carbide coated inserts was used for the turning tests, these inserts are manufactured by SANDVIK. Coated carbide inserts as per ISO specification P25. The parameter levels were chosen within the intervals based on the recommendations by the cutting tool manufacturer. Universal turning machine tool was used in the experiments. All tests were performed dry.

2.1. Work piece material

The work material used as the test specimen was AISI 1060 medium carbon steel. A cylindrical bar with the following dimensions 300 mm in length and 60 mm in diameter was used for the tests, commonly used in industry aerospace, automotive and mechanical. The chemical compositions of the workpiece material are given in Table 1.

Table 1. Chemical Compositions.

C	Cr	Mo	Si	Mn	P
0.45	1.2	0.14	0.25	0.67	0.008

2.2. Machine tool used

The machine used in our study is a universal tower EMCO mark, model MAXIMAT V13, of engine power 9.5 KW. It has the following characteristics:

- Range of feed rates: : 0,009 à 5,6 mm/rev
- Range of rotation speeds: 30 à 2500 rev/min.

2.3. Measurement of tool temperature distributions

The accuracy of measured temperature depends on several parameters such as the experimental set up, physical acquisition data system and physical characteristic of the tool [9]. The typical set-up used for the temperature measurements is shown in Fig.1. The thermocouples were attached using capacitive discharge welding at the insert (TC1, TC2 and TC3); all test specimens were manufactured in carbon steel a cylindrical bar, with the same characteristics and mechanical properties. The temperatures (TC1, TC2 and TC3) are directly recorded during the machining test with a data acquisition system controlled by a microcomputer with specific software (PHYWE Cobra3) was used to acquire signals from the *K* type thermocouples. Cutting conditions which were taken for analysis and numerical validation is as follows:

- Rotation speeds: N = 440 and 2500 rev/min
- Feed rate: f = 0.045 mm/rev.
- Depth of cut: d = 0.5 and 1.5 mm.

The measured temperature data were analysed and the results were used as input data onto the FEM simulation.

Fig. 1. The experimental setup used for the temperature measurements.

To measure the temperature of the tool-chip interface, we have implemented three thermocouple type K in the cutting insert. The mounting of the thermocouples is shown in Fig. 2.

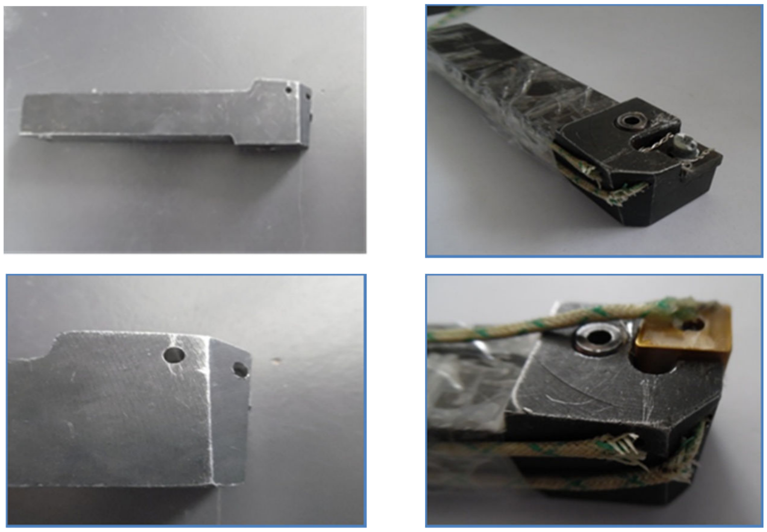
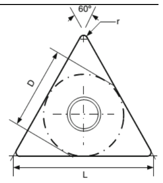


Fig. 2. The mount mode of the thermocouples on the cutting tool.

3. Finite Element Model and Simulation

Finite element method has been widely used to investigate quantities difficult to measure in the cutting process [10]. The thermal expansions of the tool and the work-piece can be calculated prior to actual turning using finite element (FE) models in order to adapt the nominal depth of cut accordingly [11]. The tool temperature distribution when machining in the orthogonal cutting geometry is simulated using the commercial software COMSOL Multiphysics 3D Fig. 3. The numerically determined temperatures are afterwards compared with the experimentally measured temperatures. The dimensions of the modelled insert are shown in table 2.

Table 2. Dimensions of the modelled insert [12].

S (mm)	r (mm)	L (mm)	D (mm)	
3.5	**4**	**16.5**	**3**	

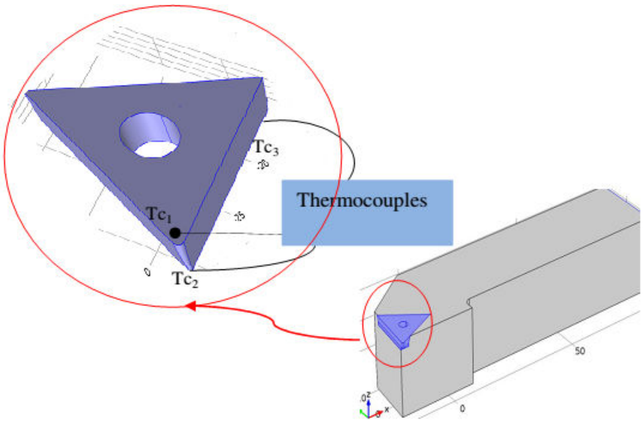


Fig. 3. Schematic illustration of the locations on the insert where the thermocouples were embedded.

4. The 3-D Thermal Model and Boundary Conditions

A FEM is widely used, since it allows treating the problem in 3D case with fewer simplifying assumptions, unlike analytical approaches [13]. In simulation, the temperature fields in the WP, the tool and the chip can be calculated over the whole period of time [14].

The general equation of conduction in a Cartesian coordinate system (x, y, z) is established and given as follows:

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

or $\alpha = \dfrac{k}{\rho c_p}$ is called the thermal diffusion coefficient

To determine the temperature field in the turning process, the boundary conditions must be given, which is shown as follows:

- Heat exchange with environment

$$-k \frac{\partial T}{\partial z} = h\left(T - T_\infty\right) \tag{2}$$

- Heat with the work-piece

$$-k \frac{\partial T}{\partial z} = q_0 \tag{3}$$

- In the remaining region of the set

$$-k \frac{\partial T}{\partial \eta} = h(T - T_\infty) \tag{4}$$

- Initial condition

$$T\left(x, y, z, t\right) = T_0, \quad \text{at} \quad t = 0 \tag{5}$$

The use of COMSOL for numerical resolution of differential equations that rule the physical phenomenon investigated should be highlighted. Also, COMSOL allows adjusting any boundary conditions, as well as modelling the geometry so as to faithfully represent the system investigated [15].

5. Results and Discussion

Simulate and measured temperature distributions of the tool are depicted in Fig. 4 A and B. The temperatures variations measured experimentally and simulated are as a function of time, the cutting tool used is a triangular uncoated insert.

Figure 4 A and B shows the simulated cutting temperature distribution in turning process at a spindle speed of 440 rev/min and 2500 rev/min, can be seen from these figures, the maximum value of cutting temperature lie in tool-chip interface and is higher than the temperature in shear deformation zone.

The comparison between finite element simulation curve and experimental curve of cutting temperature as can be seen from these two figures, there is an agreement between FEM simulation and the experimental curves, we can see too that the results of the finite element simulation and experimental results are consistent, showing its accuracy and the feasibility of the simulation with FEM.

Figure 5 shows the evolution of temperature versus time for the three positions (TC1, TC2 and TC3) successively; it shows the very hot areas (red), warm (yellow), medium (green and cyan) and finally the cooler (blue).

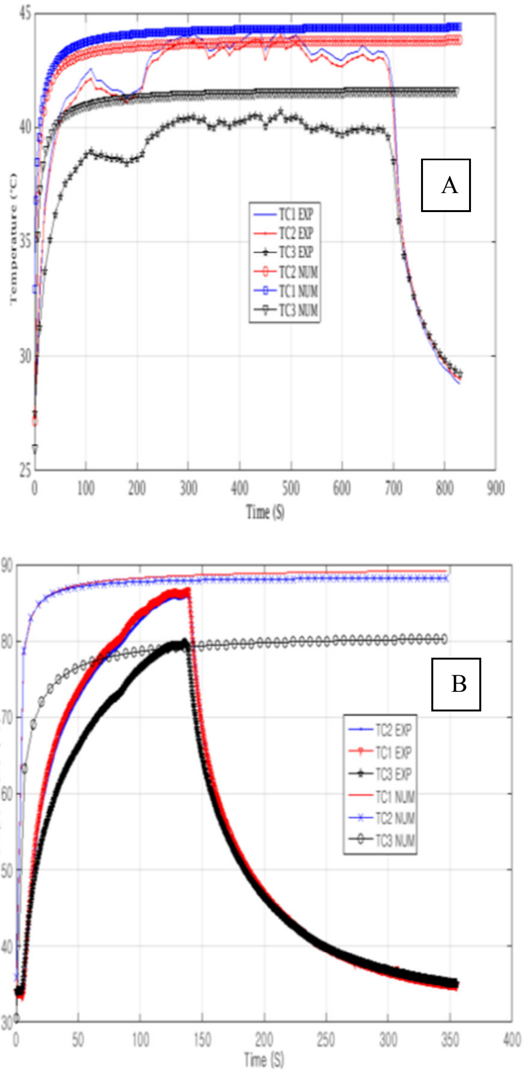


Fig. 4. Comparison between experimental and numerical temperature evolution at thermocouples TC1, TC2 and TC3 during machining as a function of time, A and B.

About 158122 tetrahedron elements have been used with 4 nodes for meshing the insert at cutting time equal 60 s is shown in Fig. 5.

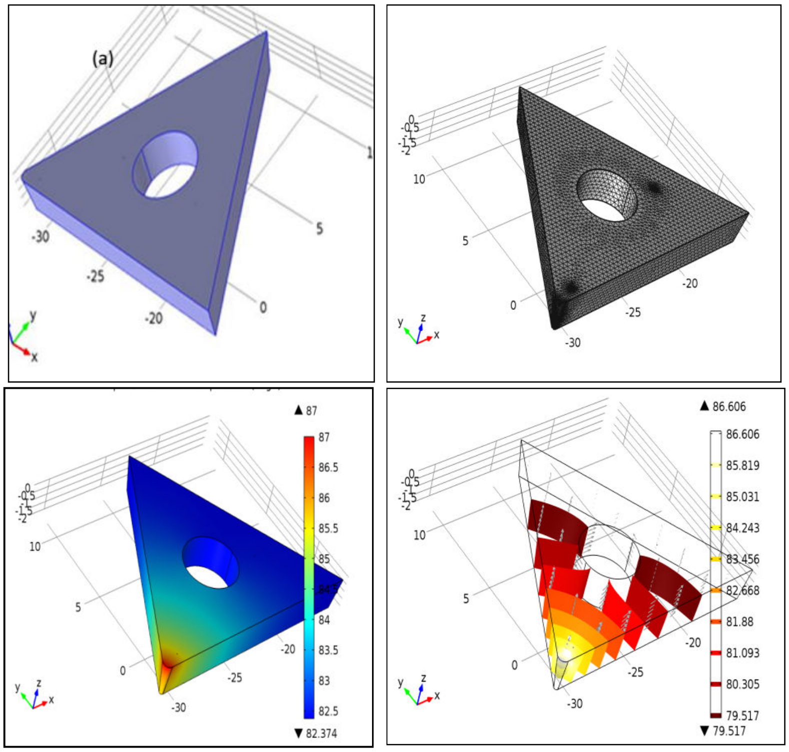


Fig. 5. Heat flux and temperature distributions in the insert at cutting time equal 60 s and insert mesh.

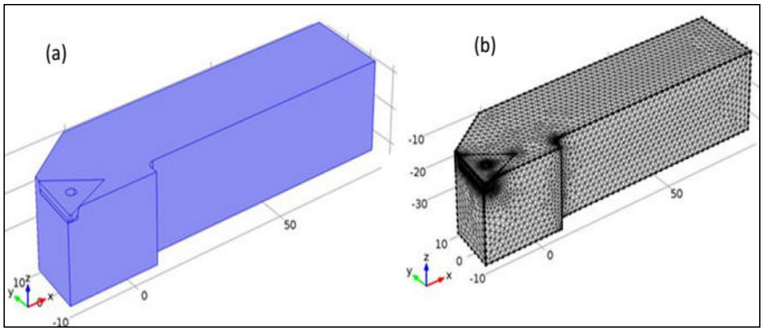
Figure 6 represents the evolution of the temperature in the cutting insert and tool holders from the piece tool interfaces contact point obtained by numerical method.

Figure 7 shows the presence of two regimes: a regime that corresponds to the rapid decrease in temperature (at t = 1s) and a quasi-stable regime corresponding to a quasi-stagnation temperature along the cutting insert. This regime becomes more stable with a large cutting time.

6. Error of the numerical model

Errors were calculated by the difference between the main experimental value and numerical value. The error values can be calculated using equation (6).

$$e_i = \left(\frac{\left| H_m - H_p \right|}{H_m} \right) \times 100\% \tag{6}$$



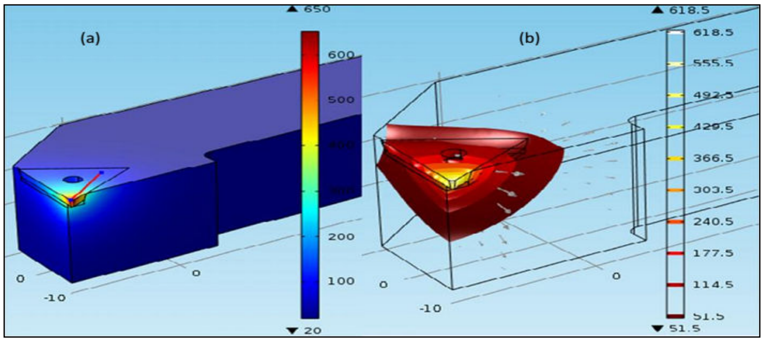


Fig. 6. The temperature distribution isotherms and three-dimensional in the cutting insert and tool holder.

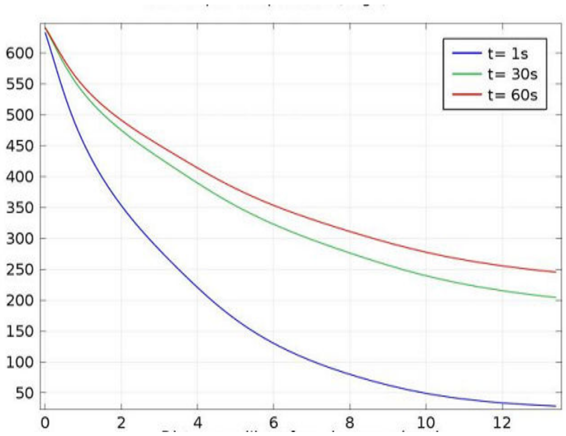


Fig. 7. The evolution of cutting temperature in the insert from the point of contact piece - tool.

7. Conclusions

An attempt is made to predict unsteady state tool temperature distribution using 3D orthogonal metal turning simulations in COMSOL Multiphysics. The results from these simulations are used to perform unsteady state heat transfer analysis. To validate finite element simulation result of turning process, the cutting temperature experiment was carried out with the same cutting conditions as that used in finite element simulation. Tool temperature distributions are measured using the Thermocouple technique. The following conclusions can be drawn:

- The numerical model percentages of error and accuracy were 3.57% and 96.43%, respectively, indicating that the numerical approach can accurately predict the cutting temperature of the steel AISI 1060.
- The numerical approach could be an economical and successful method for prediction of cutting temperature in the tool.
- The study of the cutting temperature evolution by the two approaches shows that this temperature becomes more stable in the cutting tool for a large cutting time.
- Modelling and numerical simulation can provide a fast, economical and very effective to reproduce the cutting phenomena and estimate the quantities characterizing the thermomechanical processing of materials (temperature, efforts, stress, strain, etc.).

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