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Tool Temperature Prediction during Machining by FEM with Experimental Validation

A. Fata[1], M. Bagheri[2,*], P. Mottaghizadeh[3]

[1] Department of Industrial Engineering, Hormozgan University, Bandarabbas, Iran
[2]Student of Chemical Engineering, Amirkabir University of Technology (Tehran Polytechnic), Tehran, Iran
[2]Department of Chemical Engineering, Amirkabir University of Technology (Tehran polytechnic), Tehran, Iran

ABSTRACT

In the present paper, the three-dimensional temperature field of tool is determined during the machining and compared with experimental work on C45 workpiece using carbide cutting tool inserts. During the metal cutting operations, high temperature is generated in the tool cutting edge which influence on the rate of tool wear. Temperature is most important characteristic of machining processes; since many parameters such as cutting speed, surface quality and cutting forces depend on the temperature and high temperatures can cause high mechanical stresses which lead to early tool wear and reduce tool life. Therefore, considerable attention is paid to determine tool temperatures. The experiments are carried out for dry and orthogonal machining condition. The results show that the increase of tool temperature depends on depth of cut and especially cutting speed in high range of cutting conditions.

KEYWORDS: Temperature Measurement, Finite Element Method, Thermal Fields, Machining.

INTRODUCTION

The metal cutting is a complex process. During the process, as a result of plastic deformation and friction cause heat generation occurs. Can presume all the cutting energy required is converted to heat. The temperature rises in the cutting zone and can affect the material behavior and formation of tool-chip. The maximum temperature occurs at the tool-chip interface and fracture considerably can increase in this temperature. Many parameters such as cutting speed, surface quality, cutting forces depend on the temperature. Then determination of distribution temperature has been one of the major subjects in the machining researches.

Temperature prediction is one of the most complex subjects in the metal cutting and is extremely difficult to develop an accurate temperature prediction model in machining. Temperature prediction is a challenge due to the complexity of the contact phenomenon in the metal cutting process [1].

In order to obtain cutting forces, specific cutting energy and appropriate temperature for coated tool material, various models are simulated; then appropriate cutting condition which is very important is defined. Many studies on the prediction of cutting temperature are accomplished that present simulation of cutting forces, stresses and temperature fields on chip, tool and workpiece. Cases in point are analyzing rounded edge tools [2], analysis on the friction modeling in orthogonal machining [3], analyses the temperatures in hard turning [4] and Finite element modeling of temperature distribution in the cutting zone in turning processes with differently coated tools [5].

The primary effect of temperature is on tool wear. There are various tool wear mechanisms [6]. Furthermore, the tool longevity can be determined by the maximum temperature in the tool rake face. However, the maximum temperature and the temperature gradient effects can cause subsurface deformation, metallurgical structure change and mechanical properties alteration in the machined surface.

In the hard turning process, because of the high hardness of the workpiece materials, high temperatures and high mechanical stresses are created which lead to the early tool wear and reduce the longevity of tool; besides, they increase the forces and tensile residual stresses, affect the surface finish and cause white surface layer to damage [7]. Numerous attempts have been made to measure the temperature in the machining operations [8,9]. One of the most extensively used experimental techniques to measure the temperature in machining is the use of thermocouples.

Locating temperature measuring instruments much close to the cutting edge is very difficult. Due to the lack of experimental data verifying the proposed mathematical models, most published articles rely on the few published experimental data [10]. The infrared radiation technique (IR) is the second most used method of temperature measuring. In this case, the surface temperature of the body is measured based on its emitted thermal energy. In some cases the IR technique indicated lower temperatures than the thermocouple method did.

In this paper, temperature is measured with an infrared pyrometer during orthogonal cutting condition. Also, the effect of cutting speed, feed rate and depth of cut on the tool temperature (rake face) were considered. Finally, by the use of experiments, an equation for estimating of tool temperature was developed.

***Corresponding Author:** Mostafa Bagheri, Student of Chemical Engineering, Amirkabir University of Technology (Tehran Polytechnic), Tehran, Iran. E-mail: m.bagheri@aut.ac.ir

THERMAL MODELING

Heat balance

In order to solve the problem with finite element method (FEM), analytical solution of the problem was reviewed by choosing each element as a control volume. From the first law of thermodynamics, the rate of difference between thermal and mechanical energy entering and exiting the control volume summing to the rate of heat generation is equal to the rate of energy stored within the control volume. This principal can be written as

$$\dot{E}_{in} - \dot{E}_{out} + \dot{E}_{generated} = \dot{E}_{stored} \quad . \qquad (1)$$

Heat Conduction

The rate of heat conduction to the control volume with the dimensions of dx, dy and dz from x, y and z directions, are called $\dot{Q}_x$, $\dot{Q}_y$ and $\dot{Q}_z$, respectively. The rate of heat conduction in three directions is defined as

$$\begin{aligned} \dot{Q}_x &= -kA\frac{\partial T}{\partial x} = -kdydz\frac{\partial T}{\partial x} \\ \dot{Q}_y &= -kA\frac{\partial T}{\partial y} = -kdxdz\frac{\partial T}{\partial y} \qquad (2) \\ \dot{Q}_z &= -kA\frac{\partial T}{\partial z} = -kdxdy\frac{\partial T}{\partial z} \quad . \end{aligned}$$

Here, k is the thermal conductivity and A is the area of the surface that is exposed to this heat conduction.

Heat Convection

Another way of heat transfer is convection from the system to the surrounding air; the heat convection rate is directed from the control volume to the surrounding air which can be written as following.

$$\dot{Q}_{conv} = h_a A\left(T - T_\infty\right) \qquad (3)$$

Here, h_a is the convection coefficient between the element and the ambient air flowing around. The temperature of ambient air is considered equal to the room temperature; therefore, room temperature is boundary condition. Some elements are not in contact with air so this term becomes zero for them.

Heat Generation

The amount of generated heat depends on heat generation rate per control volume unit

$$\dot{E}_{generated} = \dot{q}dxdydz \quad . \qquad (4)$$

The values of generated heat are obtained from the force and velocity factors along shear and friction dimensions, as can be seen in following.

$$\dot{q}_s = F_s V_s = \frac{\tau hV\cos\left(\alpha_n\right)}{\sin\left(\alpha_n\right)\ \cos\left(\phi_n - \alpha_n\right)} \qquad (5)$$

$$\dot{q}_f = F_f V_c = \frac{\tau hV\sin\left(\beta_n\right)}{\cos\left(\phi_n + \beta_n - a_n\right)\sin\left(\phi_n - a_n\right)} \qquad (6)$$

In these equations, h is the uncut chip thickness which corresponds to feed rate in turning; V is the cutting velocity; τ is the shear flow stress; α_n, β_n and ϕ_n are the normal rake angle, normal friction angle and normal shear angle, respectively. These values of heat generation are found per unitdepth of cut; but multiplying them by depth of cut would give the actual values.

Heat Stored

The amount of heat stored within the control volume depends on volume, density ρ, specific heat capacity C, and the rate of temperature change in the control volume.

$$\dot{E}_{stored} = \rho C\frac{\partial T}{\partial t}dxdydz \qquad (7)$$

It is assumed that heat flows from all surrounding objects and enters to the control volume; therefore, the heat balance equation can written as follow.

$$\dot{Q}_x + \dot{Q}_y + \dot{Q}_z + \dot{Q}_{conv} + \dot{Q}dxdydz = \rho C \frac{\partial T}{\partial t} dxdydz \qquad (8)$$

In (8), $\dot{Q}$ is defined as the following term.

$$\dot{Q} = \dot{q}_s + \dot{q}_f \qquad (9)$$

EXPERIMENTAL SET-UP

The stand-alone temperature measurement work-station consisted of an infrared pyrometer, mounted on the cross slide of the lathe and placed directly over the tool rack face during the cutting tests, and the analysis software mounted on a personal computer. Cutting force, feed force and tool temperature were measured by dynamometer simultaneously. To record the data from dynamometer, an oscilloscope model Yokogawa DL-4200 and written software were used. The total time of sampling is 60000 ms and the total samples are 60 in quantity.
The cutting parameters were used in the following experiments are shown in Table .1:

Table 1. Cutting parameters for different tests

Cutting speed (V)	131, 185, 263, 528, 733 (mm/s)
feed rate	0.08 (mm/rev)
Depth of cut (h)	1.5 (mm)

RESULT

The transient temperature distributions were measured on the rake face of cutting tool inserts. Temperature field observed on the tool is measured with an infrared camera, and compared to simulations for three dimensional tool temperature field, concerning the maximum rake face temperature at the tool from an orthogonal point of view.

As mentioned earlier, the focus in this investigation is the quantitative analysis of the IR images at the end of each cut after the feed was stopped. The IR images were recorded on videotape, and were analyzed subsequently by using the software Image.

The temperature signals were measured by an immobile, wholly digital and fast compact pyrometer for a calibrated temperature range of -3 to +900 degrees centigrade. The laser pilot lights direct the pyrometer to the measuring position. The size of the measurement spot was 0.3 mm, which corresponded to a distance to the measurement surface of 0.2 m. The pyrometer had a response time of 250 ms. Temperature of point A on the insert has been measured, as shown in Fig. 1. This position is alongside the leading edge at 1mm from the cutting edge so that the effect of chip obstruction during machining could be avoided.

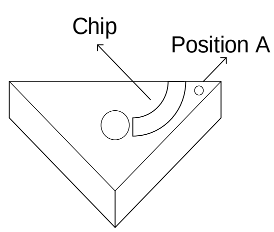
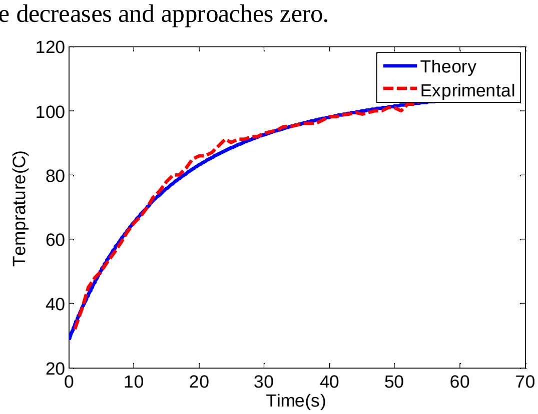


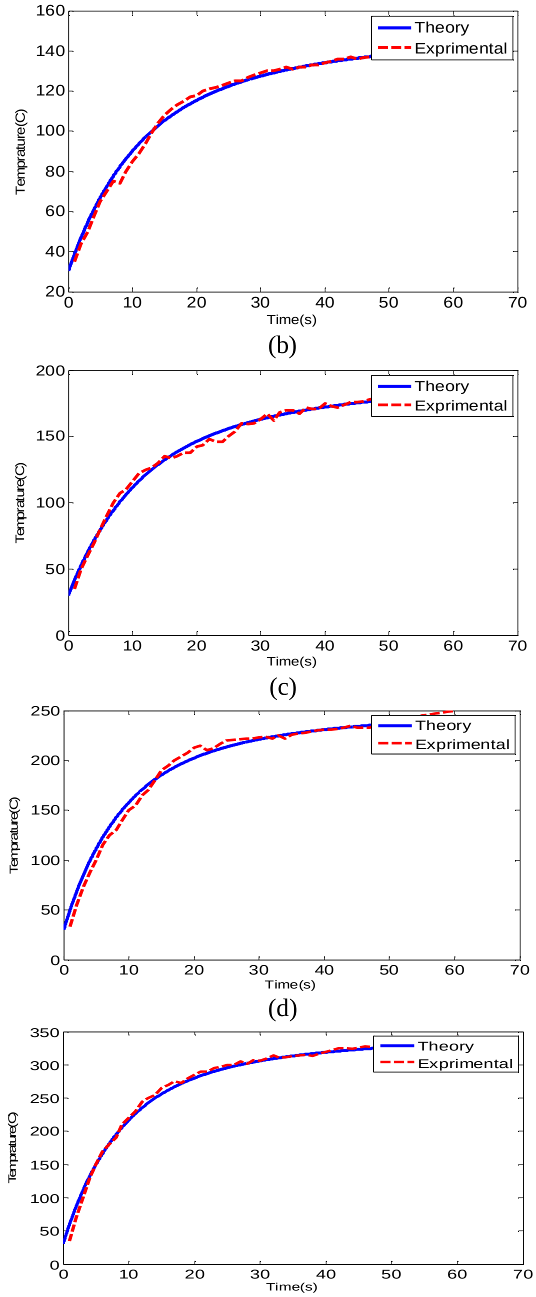
Fig. 1 Tool temperature measurement position (A) by infrared pyrometer

Temperature in Various Cutting speeds

In these tests, the cutting speed (V) is a variable parameter as indicated in table 1, and the feed rate and depth of cut are 0.08 mm/rev and 1.5 mm respectively. The results are achieved from infrared pyrometer, is illustrated in Fig. 2. It can be seen that in the beginning of the set-up, the amount of temperature is increased with a rather steep slope and as time progress, the slope of curve decreases and approaches zero.



(a)



(e)

Fig. 2. Tool temperature vs. Time in (a) V=131 mm/s, (b) V=185 mm/s, (c) V=263 mm/s (d) V=528 mm/s and (e) V=733 mm/s

CONCLUSION

In this paper, discusses the numerical implementation of the integration of tool wear models with FEM calculations and present an accuracy model of tool and compute three-dimensional temperature field on tool during machining and compare with experimental work on C45 work piece using carbide cutting tool inserts. This result can input to the residual stress prediction that is one of the other important current topics in the machining research.

Moreover, this work is to obtain relation between tool temperature and cutting conditions such as cutting speed, feed rate and depth of cut. According to performed experiments, the following results have been obtained:

1. As a result, this study reveals the effects of heat partition and resulting friction influence in the simulation of temperature for tool. As mentioned above, a good agreement was achieved between predicted and experimental cutting temperatures, indicating the validation of the proposed model
2. Different measuring techniques have to be integrated for obtaining consistent data in temperature revealing due to the complexity of machining processes.

3. With an increase in the cutting speed, feed rate and depth of cut, the tool temperature is increased and the cutting speed was found to be the most effective parameter in temperature rise, especially in high range of cutting conditions.

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