©gopalax -International Journal of Technology And Engineering System(IJTES): Jan –March 2011- Vol.2.No.2.

3-Dimensional Thermal Mapping of Workpiece during Dry Milling using Finite Element Methods

Satindra N. Bhattacharya[1], Gourab Chakraborty[2] and Dipankar Bose[3]

[1,2,3]National Institute of Technical Teachers' Training and Research /Mechanical Engineering, Kolkata, India
Email: [1]satindrab, gourab001@gmail.com
[2]Email: dipan88@yahoo.co.in

***Abstract*— Over the years, metal cutting researchers have developed a number of modeling techniques among which the Finite Element Method (FEM) has particularly become the most popular tool for simulating metal cutting processes. It is already known that during machining, the maximum temperature generated is on the chip-tool interface. Though majority of the heat generated is taken away by the chip, the amount of heat distributed in the work piece greatly affects the quality of machined part. In this study, the temperature distribution in the work piece is simulated using Finite Element Methods. For this, a special experimental set up has been fabricated where end milling of a H11 work piece was carried out in dry condition as today's manufacturing industry would like to embrace dry machining for both environmental and economic reasons. The temperature reading is taken using Alumel-Chromel (k type) thermocouple with the help of a Datalogger (DT-85). This temperature reading was further used as input for 3-D transient thermal modeling of the work piece during machining.**

***Index Terms*—Transient Temperature Distributions, End Milling, Finite Element Modeling, Machining Temperature, Thermocouple.**

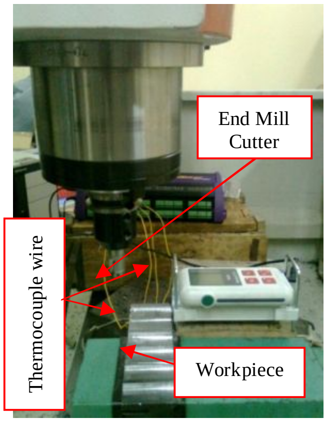
I. INTRODUCTION

The knowledge on the temperature distribution in workpiece is a matter of great importance due to the severe effects of intense local heat generated during machining which could affect the heat treatment or artificial aging properties, hardness and residual stresses of the material, all of which affect the fatigue life of the component [1]. It have been distinguished that there are three regions of intensive heat generation, namely the primary deformation zone (shear plane), the chip-tool interface frictional zone or the secondary deformation zone and the tool-work piece interface zone [2]. Different types of methods have been developed for thermal mapping of cutting tools, work piece and chips for example: analytical methods [3], experimental and numerical (simulation) methods [4], hybrid techniques and heat source methods. Many researchers have worked on temperature measurement and prediction. A review of some experimental measurement was made by Komanduri and Hou [5]. A new approach have been shown by Pittalà and Monno[6] for prediction of temperature of Ti-6Al-4V work piece in Face Milling. They used infrared camera to measure the work piece temperature and then a rheological model was developed and calibrated using different milling tests. Again a model of cutting induced work piece temperatures during dry milling was developed by Richardson, Keavey and Dailami [7]. A related work was also carried out by Rai and Xirouchakis[8] where prediction of work piece transient temperature distribution and deformations caused during milling were analyzed using FEM. A remarkable work was done on the determination of temperature at the chip-tool interface using an inverse thermal model by Carvalho, Lima e Silva, Machado and Guimar˜aes[9] . They developed a thermal model from a numerical solution of the transient 3-D heat diffusion equation that considers both the tool and the tool holder assembly whereas Finite Volume Method was used to determine the solution equation. Temperature distribution in the cutting zone in turning process was further investigated by Grzesik, Bartoszuk and Niesłony [10] for differently coated tools using finite element modeling. The influence on cutting speed and feed for the distribution of temperature field about cutting area in plunge milling of Ti alloy was explored by Qin, Liu, Jia and Ji [11]. A 3D finite element method was again used for temperature modeling in drilling process by Mieszczak and Lis [12] which includes heat generation due to friction and plastic deformation.

In this study, a transient FEM model is developed in ANSYS to find out the 3-dimensional temperature distribution in the AISI H11 workpiece after taking temperature measurements using tool-work thermocouple techniques while end milling in dry condition.

II. EXPERIMENTAL PROCEDURE

The machining tests were carried out in a CNC vertical milling machine (Surya:VF 30 CNC VS) without coolant. The material used in the experimental tests was alloy steel of grade AISI H11 in the form of rectangular plate with size of 175 mm × 50 mm × 20 mm. The insert and cutter used were a Mitsubishi made AOMT123608PEER-M insert with coating grade of VP15TF and APX3000R202SA20SA cutter from the same manufacturer. A slot was made from the opposite face of the machined surface along the thickness of the workpiece through which thermocouple wires inserted into the workpiece to pickup temperature measurement during machining as shown in Fig. 2. The other ends of these thermocouple wires were connected to a Datalogger (Model: DT 85) which is nothing but a data acquisition system and was programmed to record temperature readings at an interval of 20 milliseconds.



(a)

(b)

Figure 1. Experimental setup (a) view of the tool and workpiece setup (b) datalogger with K-type thermocouples connected to workpiece.

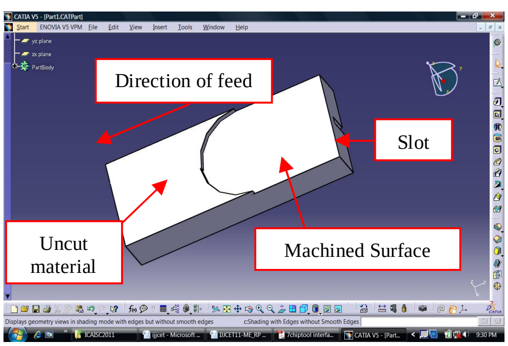


Figure 2. View of workpiece model showing slots for thermocouple inserts at the backside

The machining parameters were chosen considering higher cutting speed along with moderate depth of cut which is a popular choice in general practice. Following are the parameters chosen for the end milling of AISI H11 workpiece having average hardness of 25 HRC:

Cutting speed = 209.752 m/min

Depth of cut = 1.25 mm

Feed/tooth = 0.25 mm

The physical properties of the workpiece material required for Finite Element Modeling are given in table I.

TABLE 1 PHYSICAL PROPERTIES OF AISI H11

S. No.	Property	Unit	Value
1	Density	g/cc	7.60
2	Coefficient of thermal expansion	W/m-K	29.6
3	Specific heat	J/g-°C	0.460

III. FEM MODELING

Usually, one knows thermal boundary conditions such as the environmental temperature or the value of a heat source, but not the temperature field in the entire body. This is the subject of heat-transfer calculations.

Conduction along with convection does take place for one, two, and three-dimensional problems. Boundary conditions and forcing functions include prescribed heat flux, insulated surfaces, prescribed temperatures, and convection.

The one-dimensional case of heat transfer is generally considered when there exists mass transport phenomenon. Here a three-dimensional case of axial symmetry is developed in detail using appropriately modified two-dimensional elements and interpolation functions. Heat transfer by radiation has been omitted in this study, owing to the nonlinear nature of radiation effects. However, we examine transient heat transfer and include an introduction to finite difference techniques for solution of transient problems.

The procedure for assembling the global equations for a three-dimensional model for heat transfer analysis is identical to that of one- and two-dimensional problems. The element type is selected (tetrahedral, brick, quadrilateral solid, for example) based on geometric considerations, primarily. The volume is then divided into a mesh of elements by first defining nodes (in the global coordinate system) throughout the volume then each element by the sequence and number of nodes required for the element type. Element-to-global nodal correspondence relations are then determined for each element, and the global stiffness (conductance) matrix is assembled. Similarly, the global force vector is assembled by adding element contributions at nodes common to two or more elements.

$$T(x, y, z) = \sum_{i=1}^{M} N_i(x,y,z)T_i = [N][T] \quad (1)$$

Where, N = Nodes

M = No. of nodes

The latter procedure is straightforward in the case of internal heat generation, as given by 'generalized temperature distribution discretization equation' (1). However, in the case of the element gradient terms, the procedure is best described in terms of the global boundary conditions as shown in (2).

$$\{f_q^{(e)}\} = -\oint_A (q_x n_x + q_y n_y + q_z n_z)[N]^T dA \quad (2)$$

Where, q_x, q_y, q_z = Component of internal heat generation

n_x, n_y, n_z = Cartesian component of the outward unit normal vector of surface area

In the case of three-dimensional heat transfer, we have the same three types of boundary conditions as in two dimensions: (1) specified temperatures, (2) specified heat flux, and (3) convection conditions.

The first case, specified temperatures, is taken into account in the usual manner, by reducing the system equations by simply substituting the known nodal temperatures into the system equations. The latter two cases involve only elements that have surfaces (element faces) on the outside surface of the global volume.

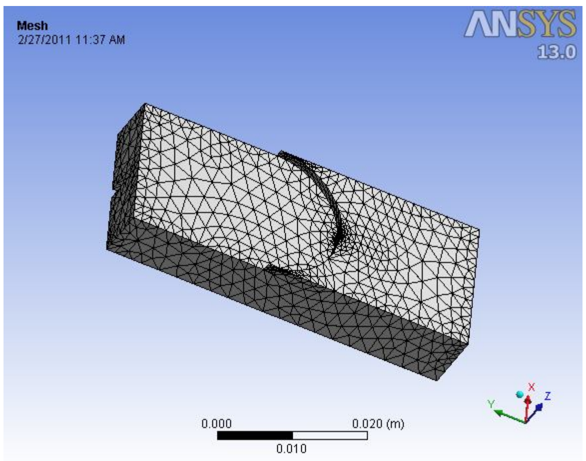


Figure 3. Workpiece after 3D tetrahedral mesh generation

To illustrate, the above Fig. 3 shows tetrahedral elements that share a common face in an assembled finite element model. Therefore, in case of inter-element boundaries (which are areas for three-dimensional elements) the element force terms defined by (2) sum to zero in the global assembly process.

IV. RESULTS AND DISCUSSIONS

The relationship between machining parameters and temperature generated at tool work piece interface has been calculated using the empirical relations as given in (1) and (2) with the help of a commercial software ANSYS. In Fig. 4 the chip is visibly a stepped material part in the inner surface of the cut and the field of higher temperatures is more extended in the chip. It could also be observed that the maximum temperatures of about a 450˚C are localized closer to the cutting edge but the tool contact area is comparatively cooler (about 400˚C). The 3-D temperature distribution is shown in the Fig. 4 and Fig. 5 from different viewports.

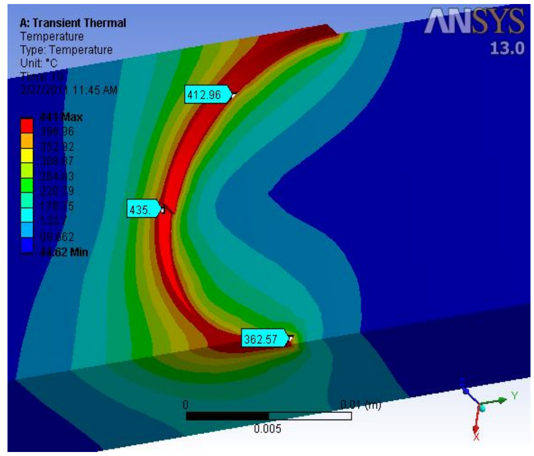


Figure 4. 3D transient temperature modeling of cutting zone

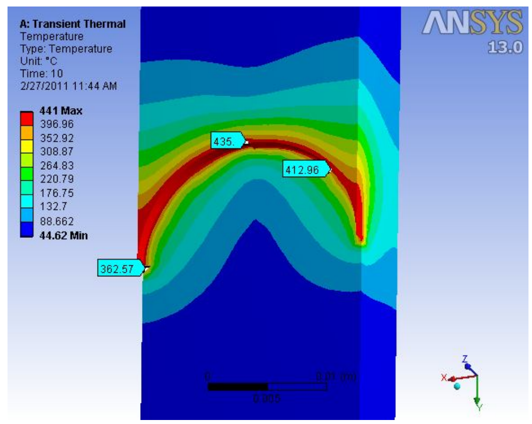


Figure 5. 3D transient temperature mapping of workpiece

The reason behind the generation of high temperature at the contact zone of tool edge radius is mainly because of the extrusion of work material and friction between tool edge radius and workpiece. After that, the fresh cut chip will flow into second deformation zone, where it will be continued to be extruded and will come in more contact with the tool, resulting in a greater friction. Therefore, the temperature in chip is generally higher than other contact zones, and its average temperature in normal machining conditions is high enough like 625˚C approximately [13].

As the experimentation has been carried out in dry condition i.e. without the application of cutting fluid, the heat dissipation is considerably less.

To understand the nature of temperature rise in a particular node, the temperatures of global maxima as well as of global minima for that particular node are to be plotted against iterations.

It could be noted that, a global maximum is the highest value of the function within the entire domain; there can only be one global maximum whereas a global minimum is the lowest value of the function within the entire domain and there can only be one global minimum.

Fig. 6 shows the plot of global maxima temperature (along Y-axis) against load steps (along X-axis) for an arbitrary node selected from the cutting edge-work contact zone. For this plot, 10 nos. of load steps are shown and each of which is further subdivided into 13 nos. of sub-steps.

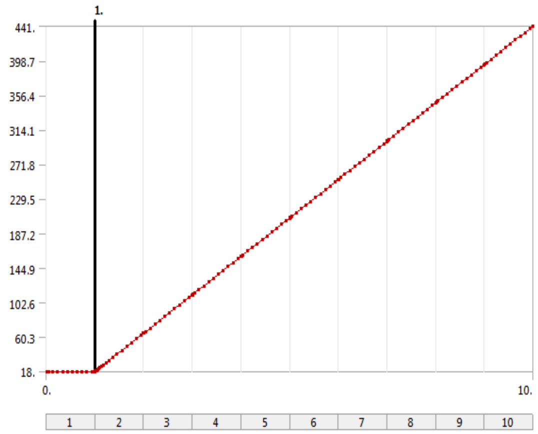


Figure 6. Temperature-Global maxima(Y axis) vs. Load steps (X axis)

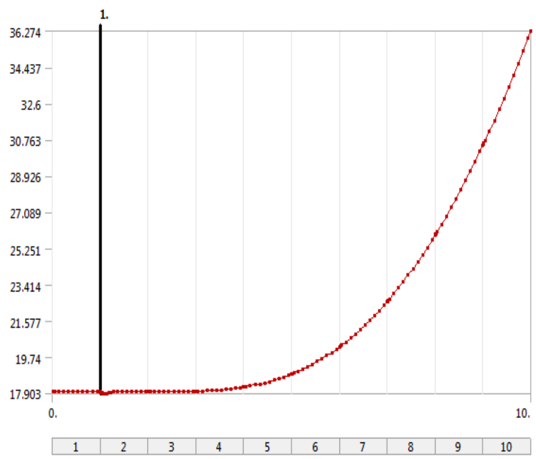


Figure 7. Temperature-Global minima(Y axis) vs. Load steps (X axis)

Similarly, Fig. 7 represents the rise of temperature-global minima along with the load steps for the same node selected earlier.

In contrast to the global minima, a local minimum value of a function is the lowest value of a function within a very small interval; there can be more than one local minimum within the domain of the domain whereas a local maximum value of a function is the highest value of a function within a very small interval and there can be more than one local maximum within a domain.

In some cases, the global maximum of a function is the same as one of the local maximums of the function, and the global minimum of a function is the same as one of the local minimums of the function.

Global maximums and global minimums can be found at the endpoints of a closed domain; local maximums and local minimums cannot be found at the endpoints of a closed domain.

Here an approach is shown which simulates cutting process with adaptive meshing method. In the simulation, finite element meshes at deformation zone are re-meshed at fixed time interval. At the same time, physical solutions are coupled with new mesh node. Therefore, mesh distortion phenomenon is avoided, and chip is separated from workpiece finally.

From the Fig. 4 it is clear that a formation of chip phenomenon is undergoing at the tool-work piece contact region and at that shear plane plastic deformation has already started. The temperature at the cutting tool–chip position is higher, whereas temperature has fallen rapidly at the cut positions. The time required in cutting one single layer of material with a single rotation of the cutter is approximately 150 milliseconds for this particular experimental conditions i.e. having cutter speed of 3340 rpm for a width of cut of 20 mm. Thus, a good understanding of temperature distribution in workpiece could be gathered from this simulation which further helps to analyze the rapid cooling or quenching of workpiece materials causing surface hardening where rapid change in plastic–elastic zone effects on the yield strength of the material.

V. CONCLUSIONS

In this paper, 3D transient thermal FEM modeling is used to predict machining induced heat generation in a workpiece. Mechanisms of heat generation and temperature distribution due to cutting deformation and chip formation are taken in account and found that the heat generated during machining with chosen parameters is quite high and could not be overlooked as it affects the properties of the machined surface. This technique is quite useful while designing machining parameters and thus adverse affect of heat generated due to machining on the workpiece could easily be avoided.

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