

ESTIMATION OF CUTTING TEMPERATURE DURING TURNING

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Abstract : Cutting temperature plays a very important role in metal cutting. The extent of the tool wear, degree of plastic deformation of the cutting edge and composition changes in the work piece material are influenced by cutting temperature. Of the several methods available for measuring cutting temperature, the tool-work thermocouple technique is the most widely used. Apart from the problem of a reliable calibration, frequent short-circuiting by the chip complicates measurement of thermo e.m.f in this method. This problem becomes more acute when multi-coated inserts with sculptured rake face geometry are used. The above mentioned problems associated with the tool-work thermocouple prompted an attempt to develop a new technique to predict cutting temperature during turning. In this method two standard k-type thermocouples were planted at the interface between the tool insert and the tool holder symmetrically . The bottom of the insert and the two sides were insulated for thermal isolation of the insert from the tool holder. The temperatures at these nodal points as measured by the thermocouples were correlated to cutting temperature using finite volume technique. An estimate of the effective heat transfer coefficient of the environment prevailing during cutting operation which is essential for developing this model was determined experimentally by a systematic procedure described in this paper.

Key words: cutting temperature, nodal temperature, and finite volume method.

1 INTRODUCTION

Cutting temperature plays a vital role in metal cutting. Many of the mechanisms of tool wear are directly linked to cutting temperature. Higher cutting temperatures can impair the surface finish and dimensional accuracy. Warming up of the cutting fluid can lead to its disintegration resulting in poor cutting performance. Hence a reliable measure of cutting temperature can be effectively used to achieve a better control over the cutting performance. It can act as an index of tool wear as well as the integrity of the surface generated. Of the several methods available for measuring cutting temperature, the tool work thermocouple technique is the most widely used. But the calibration of tool work thermocouple is not easy and this becomes the most tedious especially when the cutting tools are in the form of inserts. Recently several special techniques were tried to measure cutting temperature. A scheme for measuring cutting temperature online is proposed in by Chow and Wright [1]. In this method the signals from a standard thermocouple located at the bottom of the tool insert is used to predict the tool-chip interface temperature. A finite element technique has been used to correlate the remote temperature with the interface temperature. It is claimed that this method can be used to estimate the interface temperature for an interrupted cut also. A mathematical model for determining the average cutting temperature using a thermocouple positioned at a predetermined location beneath the trailing edge of the cutting tool is proposed by Lipman et al., [2]. The set of equations representing heat flow was solved using numerical techniques so that the model can offer details of distribution of temperature at different locations of the tool. A method of measuring cutting temperature using two standard k-type thermocouples located beneath the tool insert is presented by Groover and Kane [3]. An on line estimation of cutting temperature was possible within about 1 sec after the commencement of cutting was possible using this method. Use of digital computer

simulations of heat transfer process using finite difference method lead to the formulation of simple sets of equations to estimate the cutting temperature from the signals received from the two remote thermocouples. This method is relatively insensitive to variation in tool material and work material. An empirical method for predicting cutting temperature using response surface methodology in terms of speed, feed and depth of cut is proposed by Wu and Meger [4]. In the present work two standard k-type thermocouples were planted at the interface between the cutting tool insert and the tool holder at two symmetrical locations. The bottom of the insert and the two sides were insulated for thermal isolation of the insert from the tool holder. The average temperatures of these nodal points was correlated to cutting temperature using finite volume techniques.

2 THE FINITE VOLUME METHOD

An attempt was made to develop a model using finite volume method for predicting the cutting temperature in terms of the nodal temperature. The motivation for this attempt stemmed out from the fact that finite volume techniques are based on the conservation of physical quantities. Since the present problem involves the conservation of thermal energy, this technique is expected to offer a better correlation between the nodal temperature and the cutting temperature. In this method, the integration of the governing equation results in an equation, which expresses the efflux of the related quantities governing the physical phenomena. Finite Volume techniques can provide realistic solutions to physical problems even when the grid is somewhat coarse. Finite volume schemes can be generally categorized into two groups, cell-centered scheme and nodal point scheme[5]

In cell-centered scheme, the dependent variable is evaluated at the center of the element. Fig.1 shows the cell-centered scheme. Dependent variable T is to be solved for at node 5, which is located at the center of the element $abcd$. Points 1,2,3 and 4 are the adjacent cell centers. In Nodal point scheme the dependent variable is calculated at the vertices of the elements. The cell-centered scheme is employed in the present analysis.

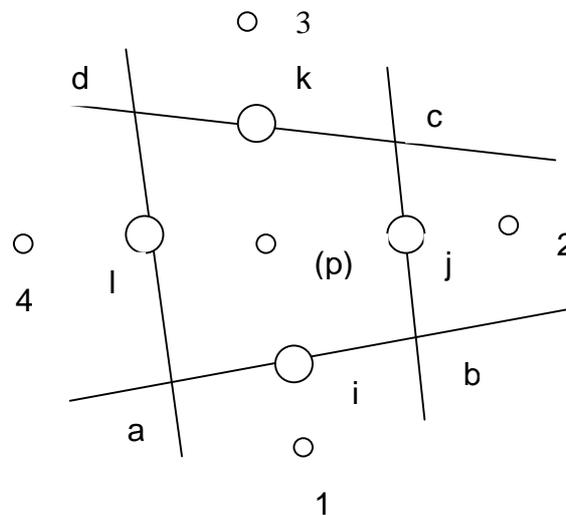


Figure 1.The Cell centered scheme

2.1 Formulation of a thermal problem using Finite Volume Method

Fourier's equation for two dimensional heat conduction can be stated as

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} = \frac{1}{\mathbf{a}} \frac{\partial T}{\partial t} \quad (1)$$

Where \mathbf{a} is the thermal diffusivity, Considering a quadrilateral element $abcd$ as shown in Fig 1 and the Integrating the equation (1) over the cell $abcd$ and considering steady state conditions, the

discretized equation relating the cell centered value with the cell centered values of the adjacent neighbors can be expressed as

$$T_1 C_1 + T_2 C_2 + T_3 C_3 + T_4 C_4 + S = T_p C_p \quad (2)$$

where

$$C_1 = \frac{1}{A_{a1bp}} [\Delta y_{ab}^2 + \Delta x_{ab}^2]$$

$$C_2 = \frac{1}{A_{b2cp}} [\Delta y_{bc}^2 + \Delta x_{bc}^2]$$

$$C_3 = \frac{1}{A_{c3dp}} [\Delta y_{cd}^2 + \Delta x_{cd}^2]$$

$$C_4 = \frac{1}{A_{d4ap}} [\Delta y_{da}^2 + \Delta x_{da}^2]$$

$$S = \frac{(T_b - T_a)}{A_{a1bp}} (\Delta y_{1p} \Delta y_{ab} + \Delta x_{1p} \Delta x_{ab}) + \frac{(T_c - T_b)}{A_{b2cp}} (\Delta y_{2p} \Delta y_{bc} + \Delta x_{2p} \Delta x_{bc})$$

$$+ \frac{(T_d - T_c)}{A_{c3dp}} (\Delta y_{3p} \Delta y_{cd} + \Delta x_{3p} \Delta x_{cd}) + \frac{(T_a - T_d)}{A_{d4ap}} (\Delta y_{4p} \Delta y_{da} + \Delta x_{4p} \Delta x_{da})$$

$$C_p = \frac{1}{A_{a1bp}} (\Delta y_{ab}^2 + \Delta x_{ab}^2) + \frac{1}{A_{b2cp}} (\Delta y_{bc}^2 + \Delta x_{bc}^2) + \frac{1}{A_{c3dp}} (\Delta y_{cd}^2 + \Delta x_{cd}^2) + \frac{1}{A_{d4ap}} (\Delta y_{da}^2 + \Delta x_{da}^2)$$

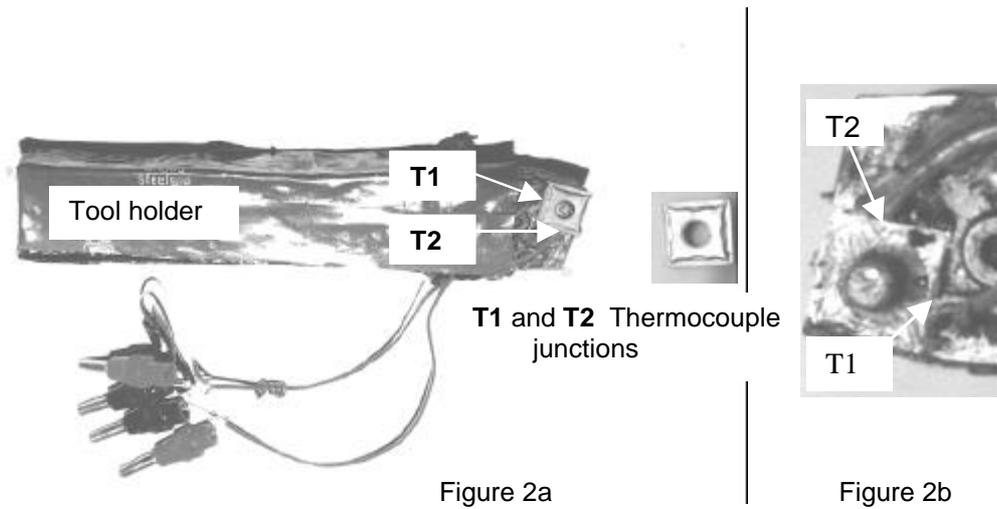
2.2 Method of solution

The physical domain is divided into a finite number of no overlapping quadrilateral cells using a grid generation program .A code was developed in FORTRAN for solving equation (2) as per the algorithm shown below.

1. The boundary temperatures were specified
2. Initial temperatures were assumed at all the cell centers.
3. Equation (2) is solved.
4. The error is calculated as $\epsilon = \sum |T_p^n - T_p^{n+1}|$
5. $T_p \leftarrow T_p^n$
6. Calculations are repeated from step (2) if $\epsilon > 10^{-3}$

2.3 Measurement of average nodal temperature

Two standard k-type thermocouples were planted at the interface between the cutting tool insert and the tool holder symmetrically. Photograph of the tool on the tool holder along with the thermocouples is shown in Figures (2a) and (2b). The bottom of the insert and the two sides were insulated for thermal isolation of the insert from the tool holder. Two digital milli voltmeters were employed to achieve simultaneous measurement of nodal temperatures. The nodal temperatures were measured 60 seconds after the commencement of the cutting experiment. This was done to achieve a steady state thermal condition in the insert.



Figures 2a and 2b Photograph showing the locations of the thermocouple junctions on the insert

2.4 The boundary conditions

The bottom of the insert and the two sides that are in contact with tool holder were insulated for thermal isolation of the insert from the tool holder. Insulation boundary condition was assumed on these three sides. Convective boundary condition was assumed on the other three sides, which were exposed to atmosphere as shown in Fig. 5

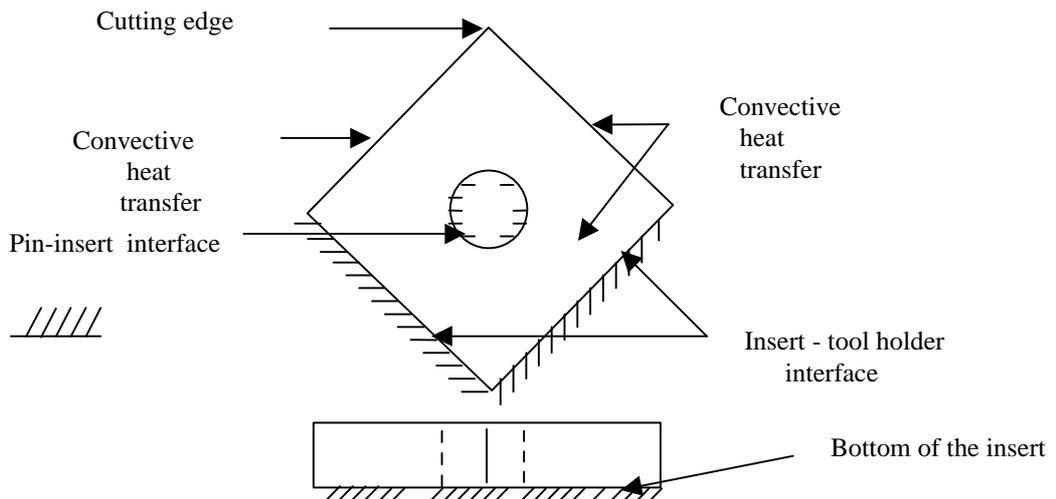


Figure 3. Imposition of boundary conditions on the insert

2.5 Determination of convective heat transfer coefficient (h)

An accurate and realistic estimate of the effective heat transfer coefficient for the environment prevailing during cutting operation is indispensable for the successful determination of cutting temperature in this approach. This was accomplished by a systematic procedure as detailed below.

1. Cutting temperature was determined at specified cutting conditions, which facilitated minimum chip shorting using tool-work thermocouple technique. The experiment was repeated thrice to determine the average cutting temperature and the corresponding average nodal temperature
2. A convective heat transfer coefficient of $200 \text{ W/m}^2 \text{ } ^\circ\text{k}$ was assumed arbitrarily and the program was run after imposing the cutting temperature on the model to calculate the average nodal temperature. The average nodal temperature thus calculated was much higher than the experimental value which implies that the actual value of h is higher than the assumed value.
3. The value of h was increased in steps of $50 \text{ W/m}^2 \text{ } ^\circ\text{k}$ and the nodal temperature calculated during each step was compared with the measured value.
4. The procedure was repeated and it was found that fairly good matching was possible when the h value was assumed as $700 \text{ W/m}^2 \text{ } ^\circ\text{k}$. Thereafter the h value was increased in steps of $10 \text{ W/m}^2 \text{ } ^\circ\text{k}$ and finally when the h value was $750 \text{ W/m}^2 \text{ } ^\circ\text{k}$, there was a perfect matching between the experimental values and the calculated values. Hence the convective heat transfer coefficient was fixed as $750 \text{ W/m}^2 \text{ } ^\circ\text{k}$ in the present work

2.6 Correlation between nodal temperature and cutting temperature

To start with an arbitrarily selected temperature was assumed at the centers of all the elements. The boundary conditions were imposed and the running of the code yielded the cell center temperatures of all the elements. The temperatures at predefined nodal points were obtained by interpolating the cell center temperature of the elements that are connected to that node. The temperature specified at the tip of the insert was assumed to vary from 500°C to 1500°C in steps of 50°C . The temperatures at the nodal points where the thermocouples were located were back calculated from the details of the temperature assumed at the tool tip using the model developed. A set of data consisting of cutting temperature and the temperature at the predefined nodal point were obtained as detailed in Table 1. The data was used to establish a correlation between the cutting temperature and the nodal temperature by regression analysis as shown in Equation (3)

$$T_d = -209.44 + 7.978R \quad (3)$$

Where T_d is the temperatures at the tool tip during dry turning and R is the average temperature at the nodes as measured by the nodal thermocouples.

2.7 Experimental validation of the finite volume model

A systematic experimental procedure for checking the temperature predicted by the Finite Volume model was devised. Cutting experiments were conducted in a cutting velocity range of 40 to 120 m/min and feed ranging from 0.05 to 0.14 mm/rev at five levels. The depth of cut was kept at 1.25 mm. The work material was a cylindrical rod of hardened steel (AISI 4340) having a hardness of 45 HRC. Turning was carried out using multi coated hardmetal inserts with sculptured rake face. Nodal temperatures were measured using standard thermocouples located symmetrically at predefined nodal points as described early and the corresponding cutting temperatures were determined using the Finite Volume model during each trial. Cutting temperatures were measured using tool-work thermocouple technique as well, which formed a reference. The results are presented in Table 2. It is observed that there is good agreement between the cutting temperature as predicted by the Finite Volume model and that measured using the tool work thermocouple technique. The average error in

the prediction was as low as 6%, which proclaims the validity of this new technique for measuring cutting temperature.

Table 1 Cutting temperatures and the corresponding mean nodal temperature as calculated using Finite Volume method during dry turning

| No. | Temperature at the tip of the tool (°C) | Average temperature at the nodes R (°C) | No. | Temperature at the tip of the tool (°C) | Average Temperature at the nodes R (°C) |
|-----|---|---|-----|---|---|
| 1 | 500 | 88.915 | 12 | 1050 | 157.859 |
| 2 | 550 | 95.183 | 13 | 1100 | 164.126 |
| 3 | 600 | 101.45 | 14 | 1150 | 170.39 |
| 4 | 650 | 107.718 | 15 | 1200 | 176.66 |
| 5 | 700 | 113.98 | 16 | 1250 | 182.93 |
| 6 | 750 | 120.25 | 17 | 1300 | 189.19 |
| 7 | 800 | 126.52 | 18 | 1350 | 195.46 |
| 8 | 850 | 132.789 | 19 | 1400 | 201.73 |
| 9 | 900 | 139.056 | 20 | 1450 | 207.99 |
| 10 | 950 | 145.324 | 21 | 1500 | 214.267 |
| 11 | 1000 | 151.591 | | | |

Table 2 Comparison of the temperatures predicted by the finite volume model as a function of nodal temperature with that measured using tool-work thermocouple technique

| Exp. No | Cutting velocity V (m/min) | Feed f (mm/rev) | Mean nodal temperature R (°C) | Cutting temperature as predicted by FV model (°C) | Temperature as measured by tool-work thermocouple (°C) | % error |
|---------|----------------------------|-----------------|-------------------------------|---|--|---------|
| 1 | 40 | 0.1 | 125 | 787.8 | 827 | 4.74 |
| 2 | 53 | 0.1 | 135 | 867.5 | 930 | 6.72 |
| 3 | 80 | 0.1 | 149 | 979.2 | 1052 | 6.92 |
| 4 | 91 | 0.1 | 160 | 1067 | 1142 | 6.56 |
| 5 | 120 | 0.1 | 170 | 1146.8 | 1221 | 6.07 |
| 6 | 80 | 0.05 | 135 | 867.5 | 939 | 7.6 |
| 7 | 80 | 0.063 | 139 | 899 | 962 | 6.55 |
| 8 | 80 | 0.08 | 142 | 923 | 989 | 6.67 |
| 9 | 80 | 0.14 | 162 | 1082.9 | 1153 | 6.07 |

CONCLUSIONS

1. The proposed method can form a reliable means of predicting cutting temperature without necessitating any modifications in the cutting tool geometry as is necessary in the case of buried thermocouple technique
2. It can provide a more accurate method of predicting cutting temperature since the nodal temperatures are measured using standard thermocouples.
3. Cost of implementation of this method is much less when compared to pyrometry and other similar techniques and can be used as means of measuring cutting temperature on line.

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