INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH & DEVELOPMENT

ISSN: 2278 – 0211

# Modelling Of Temperature Profile In Metal Cutting Process

**Mr. Lathiya Dharmesh kumar**
PG (Pursuing)
Mechanical Engineering Department
Laxmi Narain College Of Technology, Bhopal, India
**Mr. Viswakarma Ajay**
Assistant Professor
Mechanical Engineering Department
Laxmi Narain College Of Technology, Bhopal, India

***Abstract:***

*A large amount of heat is generated during machining process as well as in different process where deformation of material occurs. The power consumed in metal cutting during cutting operation is largely converted into heat. The studies of temperature fields in machining are very important for the development of new technologies aiming to increase the tool life and to reduce production costs. Determination of the maximum temperature during machining process and its distribution along the rake surface are of much importance as it influences the tool life and the quality of machined part. In the present work, numerous methods have been discussed to approach the problem of temperature distribution such as experimental, analytical and numerical analysis. In addition, temperature measurement techniques used in metal cutting are briefly reviewed. Furthermore, an attempt has been made to develop analytical thermal model to determine the temperature during the cutting process. The model is developed using MATLAB software and generated results will be compared with the published work, for different workpieces and cutting conditions.*

***Key words:*** *Shear zone, frictional zone, temperature distribution, MATLAB software.*

**1.Introduction**

Heat partition and the temperature rise distribution in the moving chip as well as in the stationary tool due to frictional heat source at the tool-chip interface in metal cutting are determined analytically using functional analysis. An analytical model is developed that incorporates two modifications to the classical solutions of Jaeger's (1942) moving band (for the chip) and stationary rectangular (for the tool) heat sources for application to metal cutting. It takes into account appropriate boundaries (besides the tool-chip contact interface) and considers non-uniform distribution of the heat partition fraction along the tool-chip interface for the purpose of matching the temperature distribution both on the chip side and the tool side. Using the functional analysis approach, originally proposed by Chao and Trigger (1951) a pair of functional expressions for the non-uniform heat partition fraction along the tool-chip interface, one for the moving band heat source (for the chip side) and the other for the stationary rectangular heat source (for the tool side) are developed. Further, the temperature rise distribution in metal cutting due to the combined effect of shear plane heat source in the primary shear zone and frictional heat source at the tool-chip interface is considered. The MATLAB programs are developed for the equations of analytical model, which reduces the calculation time.

During machining of metals, considerable heat is generated when conservation of mechanical energy takes place. There are three distinct regions in which heat is generated as shown in Figure 1

- The shear zone where heat is generated due to plastic deformation of workpiece material.
- The tool-chip interface zone where heat is generated due to frictional rubbing between the rake face of the tool and chip.
- The tool-work interface zone where heat is generated due to frictional rubbing between the flank face of the tool and work piece.

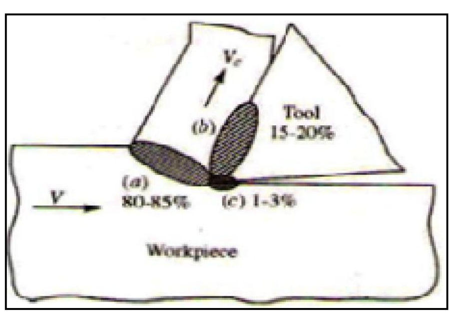


*Figure 1: Source of Heat in Machining*

About 80-85% of the heat is generated in the shear zone, while tool-chip contributes 15-20% and tool-work interfaces contributes 1-3% respectively. Experiments show that about 80% of the heat generated is carried away by the chip, 15-20% flows into the tool, and less than 5% is conducted into the workpiece. This distribution of heat in chip, tool and workpiece during the machining process is called heat partition.

## 2.Temperature Distribution

### *2.1 Temperature Rise Due To Shear Plane Heat Source*

Hahn (1951) developed a totally new direction for the analysis of the shear plane heat source without the need for heat partition to avoid compensation for the flow of heat carrying material. He used an oblique moving band heat source model based on the true nature of the chip formation process.Hahn (1951) solved his equation starting from the available solution for an in infinitely long instantaneous line heat source from Carslaw and Jaeger (1959). We have used Hahn's (1951) Eq. as an infinitely long moving line heat source.

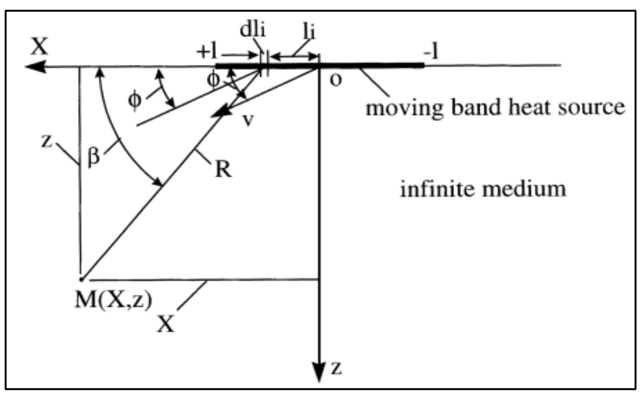


*Figure 2: Schematic of model of a band heat source moving obliquely in an infinite medium (Hahn's, 1951)*

The solution for an infinitely long moving line heat source in an infinite medium can be used for calculating the temperature rise at any point M caused by a differential segment dli is given below, (Hahn's, 1951)

$$\theta_M = \frac{q_{pl}}{2\pi\lambda} e^{-XV/2a} K_o \frac{RV}{2a}$$

1

heat liberation intensity of this heat source $q_l$ is $q_{pl}dl_i$. The distance R between the line heat source and the point M is $\sqrt{(X - l_i)^2 + z^2}$, and the projection of this distance in the direction of motion is R cos $(\beta - \emptyset)$ (where $\beta = sin^{-1}(z/R)$). The temperature rise at point M caused by this segmental line heat source is given by

$$\theta_M = \frac{q_{pl}a}{\pi\lambda V_x}\int_{X-L_s}^{X+L_s} e^{-u}K_o[\propto u]du$$

2

The integral part of above Eq. is a non-dimensional temperature rise due to oblique moving band heat source and is given by

$$\frac{\pi\lambda V\theta_M}{q_{pl}a} = \int_0^{X+Ls} e^{-u\cos\phi}K_o[u]du + \int_0^{X-Ls} e^{-u\cos\phi}K_o[u]du$$

3

Where li = -l, u =V(X + l)/2a = X +Ls; and where li = +l, u = V(X - l)/2a = X – Ls. For ϕ =0, above Equation is the same as Jaeger's (1942) Equation solution.

2.1.1.Modification Of Hahn's (1951) Solution

For an oblique band heat source moving in an infinite medium using an alternative coordinate system with one of its axes in the direction of motion.

An alternative moving coordinate system is considered for ease of derivation of the equation for an oblique moving heat source in a semi-infinite medium, based on Hahn's (1951) work. In Fig. 3, the X-axis of the moving co-ordinate system is in the direction of the motion, the origin o of which coincides with one end of the band heat source oA and angle is defined as the oblique angle (the angle between the heat source and the z-axis).

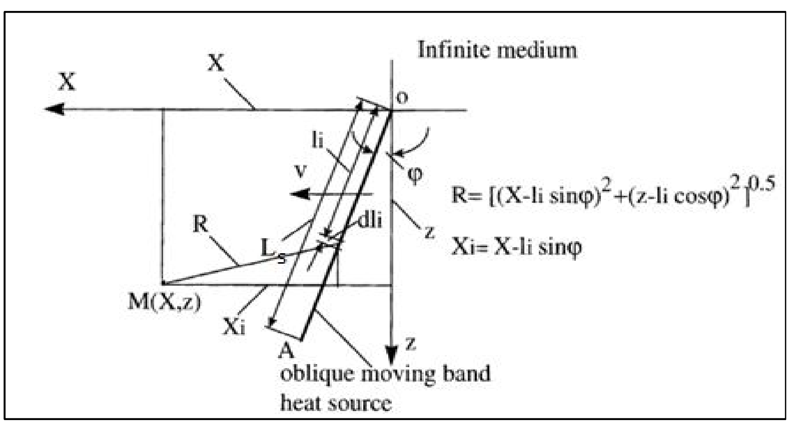


*Figure 3: Schematic of an oblique moving band heat source in an infinite medium*

The temperature rise at any point M(X, z) caused by any one of those segments, [using Eq. (1)], is given by

$$\theta_M = \frac{q_{pl} dl_i}{2\pi\lambda} e^{-(X - l_i \sin\varphi)V/2a} K_0 \left[\frac{V}{2a}\sqrt{(X - l_i \sin\varphi)^2 + (z - l_i \cos\varphi)^2}\right] \quad 4$$

$$\frac{V}{2a} = (X - l_i \sin\varphi) = u, X - l_i \sin\varphi = \frac{2au}{V}, l_i = \left(X - \frac{2au}{V}\right)/\sin\varphi, dl_i = -\frac{2a}{V\sin\varphi} du$$

When $l_i = 0, u = VX/2a$; and when $l_i = L_s, u = V\,(X - Lsin\varphi)/2a$

$$\text{Thus,}\ \theta_M = \frac{q_{pl}}{\pi\lambda} \frac{1}{V\sin\varphi} \int_{u=V(X-Lssin\varphi)/2a}^{VX/2a} e^{-u} K_o \left[\sqrt{u^2 + \frac{V^2}{4a^2}\left(Z - \frac{X - 2au/V}{\tan\varphi}\right)^2}\right] du \quad 5$$

For any one of the segmental moving line heat source d$l_i$ (see Fig. 3.8): $q_l = q_{pl} dl_i$; the distance between point M and the primary segmental line heat source, R1, is $\sqrt{(X - l_i sin\varphi)^2 + (z - l_i cos\varphi)^2}$; the distance between point M and the image source, R2, is $\sqrt{(X - l_i sin\varphi)^2 + (z + l_i cos\varphi)^2}$; and the projection of these distances on the X-axis (direction of the motion) is $(X - l_i sin\varphi)$.

The non-dimensional temperature rise at any point M caused by the entire oblique moving band shear plane heat source including its image heat source is given by

$$\theta_M = \frac{q_{pl}}{2\pi\lambda} \int_{l_i=0}^{L} e^{-(X - l_i \sin\varphi)V/2a} \left\{K_0 \left[\frac{V}{2a}\sqrt{(X - l_i \sin\varphi)^2 + (z - l_i \cos\varphi)^2}\right] + K_0 \left[\frac{V}{2a}\sqrt{(X - l_i \sin\varphi)^2 + (z + l_i \cos\varphi)^2}\right]\right\} dl_i \quad 6$$

The first term in the brackets is due to the shear plane heat source and the second term is due to its image heat source.

*2.2.Temperature Rise due to Frictional Heat Source at the Tool-Chip Interface*

Modification to Jaeger's (1942) Moving-Band Heat Source Solution (for the Chip Side) Considering The Effect Of An Additional Boundary (Top Side Of The Chip)

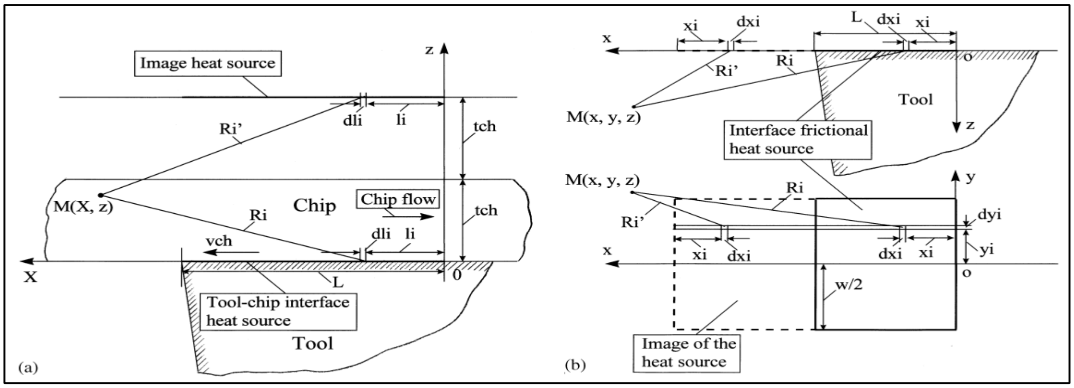


*Figure 4 (a): Schematic showing the heat transfer model for the frictional heat source at the tool-chip interface on the chip side considering as a moving-band heat source problem.*

*(b) Schematic showing the heat transfer model of the frictional heat source at the tool-chip interface on the tool side considering as a stationary rectangular heat source problem.*

The differential temperature rise at any point M(X, z) caused by the differential segmental line heat source [the one located at a distance li from the origin o of the coordinate system used as shown in Figure 4(a)] including its image line heat source by using the above solution is given by

$$\theta_M = \frac{q_{pl}}{\pi\lambda}\int_{l_i=0}^{L} e^{-(X-l_i)V/2a}\left[K_0(R_iV/2a) + K_0\left(R_i'V/2a\right)\right]dl_i \qquad 7$$

Where $R_i = \sqrt{(X-l_i)^2 + z^2}$, $R_i' = \sqrt{(X-l_i)^2 + (2t_{ch} - z)^2}$, $q_{l=}q_{pl}dl_i$

2.3.1.Modification To Jaeger's Stationary Rectangular Heat Source Solution (For The Tool Side) Considering The Effect Of Additional Boundary (Clearance Face)

For a moving-band heat source with a modified function of variable heat intensity shows] for the chip, the solution is given by

$$\theta_M = \frac{q_{pl}}{\pi\lambda}\left\{(B_{chip} - \Delta B)\int_{l_i=0}^{L} e^{-(X-l_i)V/2a}[K_0(R_iV/2a) + K_0(R_i'V/2a)]dl_i + 2\Delta B\int_{l_i=0}^{L}\left(\frac{l_i}{L}\right)^m e^{-(X-l_i)V/2a}[K_0(R_iV/2a) + K_0(R_i'V/2a)]dl_i + C\Delta B\int_{l_i=0}^{L}\left(\frac{l_i}{L}\right)^k e^{-(X-l_i)V/2a}[K_0(R_iV/2a) + K_0(R_i'V/2a)]dl_i\right\} \quad 8$$

For a stationary rectangular heat source with a modified function of variable heat intensity [as Eq.4.4.2 shows] for the tool, the solution is given by

$$\theta_M = \frac{q_{pl}}{2\pi\lambda}\left\{(B_{tool} + \Delta B)\int_{y_i=-b_0}^{+b_0} dy_i \int_{x_i=0}^{L}\left(\frac{1}{R_i} + \frac{n}{R_i'}\right)dxi - 2\Delta B\int_{y_i=-b_0}^{+b_0} dy_i \int_{x_i=0}^{L}\left(\frac{x_i}{L}\right)^m\left(\frac{1}{R_i} + \frac{n}{R_i'}\right)dxi - C\Delta B\int_{y_i=-b_0}^{+b_0} dy_i \int_{x_i=0}^{L}\left(\frac{x_i}{L}\right)^k\left(\frac{1}{R_i} + \frac{n}{R_i'}\right)dxi\right\} \quad 9$$

## 3.Combined Effects In Temperature Distribution

Temperature rise due to the shear plane heat source and the tool-chip interface frictional heat source any point in the chip M(X, z) including the points at the tool-chip interface caused by the two principal heat sources [using Equations 6 and 8] is given by

$$\theta_M = \frac{q_{pl}}{\pi\lambda}\left\{(B_{chip} - \Delta B)\int_{l_i=0}^{L} e^{-(X-l_i)V/2a}\left[K_0(R_iV/2a) + K_0\left(R_i'V/2a\right)\right]dl_i + 2\Delta B\int_{l_i=0}^{L}\left(\frac{l_i}{L}\right)^m e^{-(X-l_i)V/2a}\left[K_0(R_iV/2a) + K_0\left(R_i'V/2a\right)\right]dl_i + C\Delta B\int_{l_i=0}^{L}\left(\frac{l_i}{L}\right)^k e^{-(X-l_i)V/2a}\left[K_0(R_iV/2a) + K_0\left(R_i'V/2a\right)\right]dl_i\right\} + \frac{q_{pls}}{2\pi\lambda}\int_{w_i=0}^{t_{ch}/\cos(\emptyset-\propto)} e^{-(X-X_i)V/2a}\left\{K_0\left[\frac{V}{2a}\sqrt{(X-X_i)^2 + (z-z_i)^2}\right] + K_0\left[\frac{V}{2a}\sqrt{(X-X_i)^2 + (2t_{ch} - z + z_i)^2}\right]\right\}dw_i, \quad 10$$

A reasonable heat transfer model for the calculation of the temperature rise in the tool caused by the shear plane heat source is to consider that part of the heat coming from the shear plane heat source through the chip and the tool-chip interface into the tool, acting as a stationary heat source located at the tool-chip interface. This heat source may be considered as an induced stationary rectangular heat source caused by the shear plane heat source. For the induced heat source, Equation 9 can be used. Thus the equation for the temperature rise consists of two terms although both use in Equation as shown in the following

$$\theta_M = \frac{q_{pl}}{2\pi\lambda_{tool}}\Bigg\{(B_{tool} + \Delta B)\int_{y_i=-b_0}^{+b_0} dy_i \int_{x_i=0}^{L}\left(\frac{1}{R_i} + \frac{n}{R_i'}\right)dxi$$
$$- 2\Delta B\int_{y_i=-b_0}^{+b_0} dy_i \int_{x_i=0}^{L}\left(\frac{x_i}{L}\right)^m\left(\frac{1}{R_i} + \frac{n}{R_i'}\right)dxi$$
$$- C\Delta B\int_{y_i=-b_0}^{+b_0} dy_i \int_{x_i=0}^{L}\left(\frac{x_i}{L}\right)^k\left(\frac{1}{R_i} + \frac{n}{R_i'}\right)dxi\Bigg\}$$
$$+ \frac{q_{pli}}{2\pi\lambda_{tool}}\Bigg\{(B_{ind} + \Delta B_i)\int_{y_i=-b_0}^{+b_0} dy_i \int_{x_i=0}^{L}\left(\frac{1}{R_i} + \frac{n}{R_i'}\right)dxi$$
$$- 2\Delta B_i\int_{y_i=-b_0}^{+b_0} dy_i \int_{x_i=0}^{L}\left(\frac{x_i}{L}\right)^{m_i}\left(\frac{1}{R_i} + \frac{n}{R_i'}\right)dxi$$
$$- C_i\Delta B_i\int_{y_i=-b_0}^{+b_0} dy_i \int_{x_i=0}^{L}\left(\frac{x_i}{L}\right)^{k_i}\left(\frac{1}{R_i} + \frac{n}{R_i'}\right)dxi\Bigg\}, \qquad 11$$

Where

$R_i = \sqrt{(X - x_i)^2 + (y - y_i)^2 + z^2}$, $R_i' = \sqrt{(X - 2L - x_i)^2 + (y - y_i)^2 +} z^2$, $x_i = l_i$,

**4.Results Of Thermal Model Computations**

For the case of conventional machining of steel with a carbide tool ($N_{Pe} \approx 5$-20), ) using the data of Chao and Trigger

$m \approx 0.22$ -0.26, $k = 16$, $C \approx 2.0$-2.2,

$q_{pli}$ =18000 J/cm$^2$s, $m_i$ =0.3, $k_i = 4$, $C_i = 0.2$, $B_{ind} = 1$, $\Delta B_i = 0.8$.

| **Work material** | **Steel NE 9445** |
|---|---|
| Tool | Triple carbide, rake angle, $\alpha = 4°$ |
| Depth of cut | $t_c = 0.02489$ cm |
| Width of cut | w = 0.2591 cm |
| Cutting speed | $v_c = 152.4$ cm/s |
| Cutting forces | $F_c$ = 1681.3N, $F_t$ = 854 N |
| Chip thickness ratio | $r_c$ = 0.375 |
| Length of tool-chip contact | L = 0.1209 |
| **Thermal properties:** | |
| Work material: NE 9445 steel | $\lambda = 0.3888\, w/cm°C,\, a = 0.08234\, cm^2/s$ |
| Tool: Carbide | $\lambda_{tool} = 0.4190\, w/cm°C,\, a_{tool} = 0.1040\, cm^2/s$ |

*Table 1:Cutting data from Chao and Trigger for conventional machining of steel*

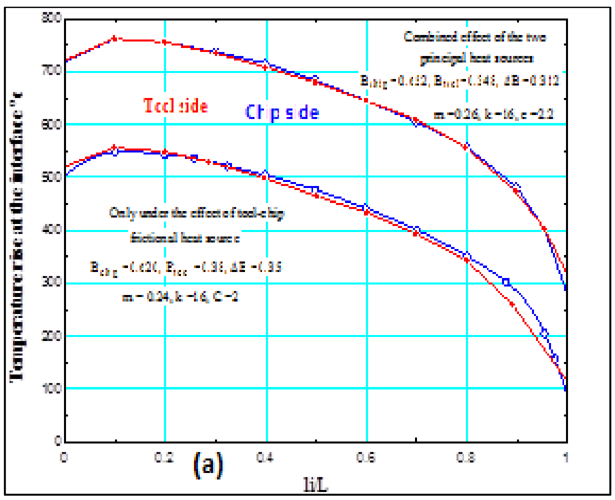


*Figure 5 (a:) the temperature rise distribution at the tool-chip interface (considering a moving-band heat source for the chip and a stationary rectangular heat source for the tool) calculated using the functional analysis method for the case of conventional machining of steel at a high Peclet number ($N_{Pe}$≈ 21). Top: combined heat source, bottom: only frictional heat source*

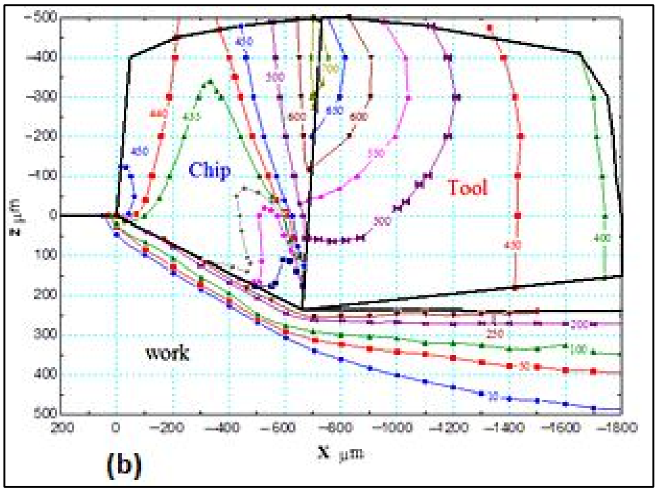


*Figure 5(b): Isotherms of the temperature rise in the chip, the tool, and the work material considering only the effect of the shear plane heat source for the case of conventional machining of steel with a carbide tool at high Peclet number ($N_{Pe} \approx 21$)*

**5.Discussion**

Chao and Trigger (1955) gave their experimental data of the average temperature rise at the tool-chip interface as 648 C for the case of conventional machining of steel using carbide tool. Considering the room temperature they used as 18.3 C, the measured average temperature rise at the tool-chip interface is 629.7 C. using the analytical method presented in this work with MATLAB programming the average temperature rise at the tool-chip interface is given by (refer to Figure5(b))

$\bar{\theta} = (717 + 764 + 756 + 738 + 715 + 685 + 649 + 607 + 557 + 495 + 279)/11$

$=632.9°C$.

By comparing the numerical methods reported earlier (Dutt and Brewer, 1964 and Tay AO et al., 1974), it can be seen that the analytical method used here is much easier and significantly faster. Because by using Eq. (10) and (11) are analytical solutions which can be used to calculate the temperature rise at any point on the tool-chip interface including the average temperature rise very fast with the aid of MATLAB programming. Usually, the computational time per point is extremely short ( 5-10 s). Hence, the determination of the optimal combination of the values m, k, C, and B by the functional analysis method is neither tedious nor time-consuming.

## 6. Conclusion

The studies of temperature fields in machining are very important for the development of new technologies aiming to increase the tool life and to reduce production costs. Determination of the maximum temperature during machining process and its distribution along the rake surface are of much importance as it influences the tool life and the quality of machined part. Therefore, the present work is focused on the development of the thermal model of metal cutting process. A computer program in MATLAB is written to determine the temperature rise distribution in primary zone (shear zone) and secondary zone (tool-chip interface zone). Analysis of primary zone is based on the pioneering work of Hahn (1951) on the moving oblique band heat source solution with an appropriate image source and boundary conditions. For analysis of the tool-chip interface zone, Chao and Trigger's (1955) pioneering work on the frictional heat source at the tool-chip interface using the modified Jaeger's (1942) moving band (for the chip) and stationary rectangular heat source (for the tool) solutions with non-uniform distribution of heat intensity are considered. Five different cases of metal cutting, namely, conventional machining of NE 9445 steel and AISI 1045 steel with a carbide tool, ultraprecision machining of aluminium with a single-crystal diamond, AL 6082-T6 and AL6061-T6 aluminium alloy with carbide tool are verified with the experimental results presented in the literature. Good agreement between the results generated using present method and experimental results presented in the literatures are found. Further, isotherms of the temperature rise distribution in the chip, the tool, and the workmaterial are developed and found in good agreement with experimental results presented in the literatures. The analytical method is found to be much easier, faster, and more accurate to use compared to numerical methods. The analytical model also provides a better physical understanding of the thermal process in metal cutting.

## 7. Reference

1. Carlsaw H. S. and Jaeger J. C., 1959. Conduction of heat in solids. Oxford, UK: Oxford University Press.
2. Chao B. T. and Trigger K. J., 1953. The significance of thermal number in metal machining. Transactions of the ASME, 75; 109-20.
3. Chao B. T. and Trigger K. J., 1958. Temperature distribution at the tool- chip and tool- work interface in metal cutting. Transactions of the ASME, 80; 311-20.
4. G. K. Lal, 1996. Introduction to machining Science. New age international limited.
5. Hahn R. S., 1951. On the temperature developed at the shear plane in the metal cutting process. Proceedings of the First US National Congress of Applied Mechanics, 661-6.
6. Komanduri R., 1993. Machining and grinding: a historical review of the classical papers. ASME Applied Mechanics Review, 46(3); 80-132.
7. Komanduri R. and Zhen Bing Hou., 2000. Thermal modeling of the metal cutting process *Part I: temperature rise distribution due to shear plane heat source. International Journal of Mechanical Sciences, 42(9); 1715-1752.
8. Komanduri R. and Zhen Bing Hou., 2000. Thermal modeling of the metal cutting process*Part II: the temperature rise distribution due to the frictional heat source at the tool-chip interface. International Journal of Mechanical Sciences, 43(1); 57-88.
9. Komanduri R. and Zhen Bing Hou., 2000. Thermal modeling of the metal cutting process *Part III: temperature rise distribution due to combined shear plane and frictional heat sources. International Journal of Mechanics and Engineering Science, 43(1); 89-107.