Module 2

Mechanics of Machining

Lesson
11
Cutting temperature – causes, effects, assessment and control

Instructional Objectives

At the end of this lesson, the students would be able to

(i) Identify the causes of development of heat and temperature in machining
(ii) State the effects of cutting temperature on cutting tool and job
(iii) Determine the value of cutting temperature
- Analytical methods
- Experimental methods

(iv) Evaluate the roles of variation of the different machining parameters on cutting temperature.
(v) Point out the general methods of controlling cutting temperature.

(i) Sources and causes of heat generation and development of temperature in machining

During machining heat is generated at the cutting point from three sources, as indicated in Fig. 2.7.1. Those sources and causes of development of cutting temperature are:

- Primary shear zone (1) where the major part of the energy is converted into heat
- Secondary deformation zone (2) at the chip – tool interface where further heat is generated due to rubbing and / or shear
- At the worn out flanks (3) due to rubbing between the tool and the finished surfaces.

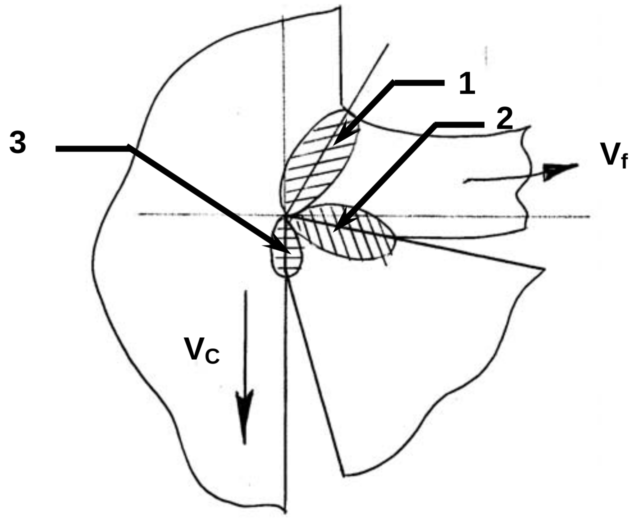

Fig. 2.7.1 *Sources of heat generation in machining*

The heat generated is shared by the chip, cutting tool and the blank. The apportionment of sharing that heat depends upon the configuration, size and thermal conductivity of the tool – work material and the cutting condition. Fig. 2.7.2 visualises that maximum amount of heat is carried away by the flowing chip. From 10 to 20% of the total heat goes into the tool and some heat is absorbed in the blank. With the increase in cutting velocity, the chip shares heat increasingly.

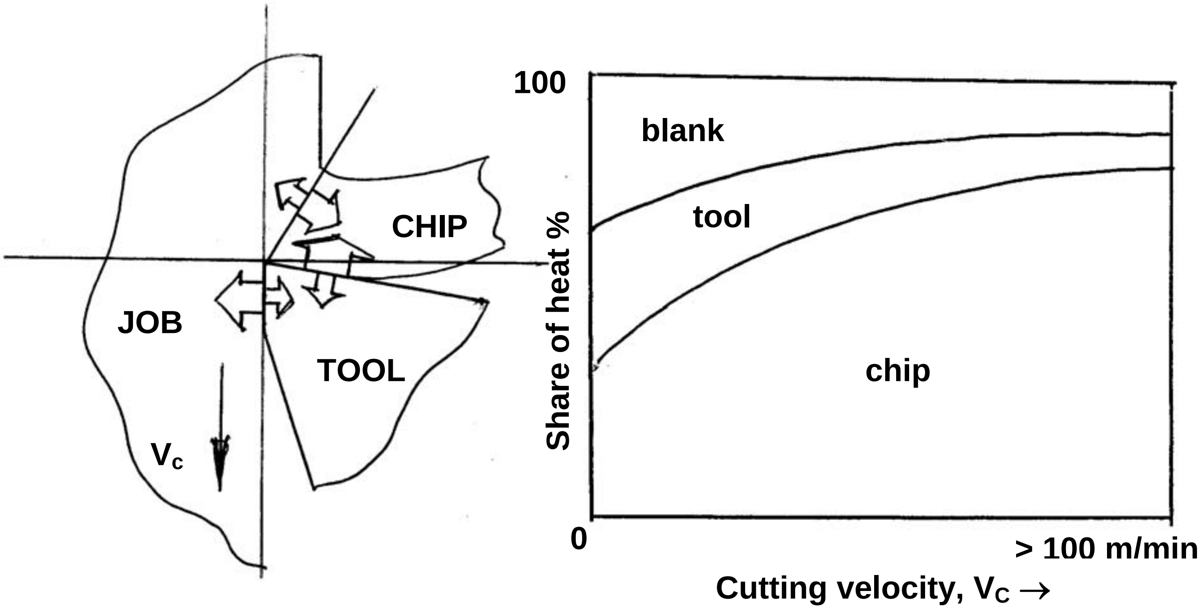

Fig. 2.7.2 *Apportionment of heat amongst chip, tool and blank.*

(ii) Effects of the high cutting temperature on tool and job.

The effect of the cutting temperature, particularly when it is high, is mostly detrimental to both the tool and the job. The major portion of the heat is taken away by the chips. But it does not matter because chips are thrown out. So attempts should be made such that the chips take away more and more amount of heat leaving small amount of heat to harm the tool and the job.
The possible detrimental effects of the high cutting temperature on cutting tool (edge) are

- rapid tool wear, which reduces tool life
- plastic deformation of the cutting edges if the tool material is not enough hot-hard and hot-strong
- thermal flaking and fracturing of the cutting edges due to thermal shocks
- built-up-edge formation

The possible detrimental effects of cutting temperature on the machined job are:

∆ dimensional inaccuracy of the job due to thermal distortion and expansion-contraction during and after machining
∆ surface damage by oxidation, rapid corrosion, burning etc.

Δ induction of tensile residual stresses and microcracks at the surface / subsurface

However, often the high cutting temperature helps in reducing the magnitude of the cutting forces and cutting power consumption to some extent by softening or reducing the shear strength, τ_S of the work material ahead the cutting edge. To attain or enhance such benefit the work material ahead the cutting zone is often additionally heated externally. This technique is known as Hot Machining and is beneficially applicable for the work materials which are very hard and hardenable like high manganese steel, Hadfield steel, Ni-hard, Nimonic etc.

(iii) Determination of cutting temperature

The magnitude of the cutting temperature need to be known or evaluated to facilitate

- assessment of machinability which is judged mainly by cutting forces and temperature and tool life
- design and selection of cutting tools
- evaluate the role of variation of the different machining parameters on cutting temperature
- proper selection and application of cutting fluid
- analysis of temperature distribution in the chip, tool and job.

The temperatures which are of major interests are:

θ_S : average shear zone temperature
θ_i : average (and maximum) temperature at the chip-tool interface
θ_f : temperature at the work-tool interface (tool flanks)
θ_{avg} : average cutting temperature

Cutting temperature can be determined by two ways :

- analytically – using mathematical models (equations) if available or can be developed. This method is simple, quick and inexpensive but less accurate and precise.
- Experimentally – this method is more accurate, precise and reliable.

- **Analytical estimation of cutting temperature, θ_S**

(a) Average shear zone temperature, θ_S

Equation(s) have to be developed for the purpose. One simple method is presented here.

The cutting energy per unit time, i.e., $P_Z V_C$ gets used to cause primary shear and to overcome friction at the rake face as,

$$P_Z.V_C = P_S.V_S + F.V_f \qquad (2.7.1)$$

where, V_S = slip velocity along the shear plane
and V_f = average chip – velocity
So, $P_S.V_S = P_Z.V_C – F.V_f$

Equating amount of heat received by the chip in one minute from the shear zone and the heat contained by that chip, it appears,

$$\frac{A.q_1(P_Z.V_C - F.V_f)}{J} = c_v a_1 b_1 V_C(\theta_S - \theta_a) \qquad (2.7.2)$$

where, A = fraction (of shear energy that is converted into heat)
q_1 = fraction (of heat that goes to the chip from the shear zone)
J = mechanical equivalent of heat of the chip / work material
C_v= volume specific heat of the chip
θ_a = ambient temperature
$a_1.b_1$ = cross sectional area of uncut chip
= ts_o

Therefore, $$\theta_s = \frac{Aq_1(P_Z.V_C - F.V_f)}{Jts_oV_C} + \theta_a \qquad (2.7.3)$$

or, $$\theta_s \cong \frac{Aq_1(P_Z - F/\zeta)}{Jts_o} \qquad (2.7.4)$$

Generally A varies from 0.95 to 1.0 and q from 0.7 to 0.9 in machining like turning.

(b) Average chip – tool interface temperature, θ_i

Using the two dimensionless parameters, Q_1 and Q_2 and their simple relation (Buckingham),

$$Q_1 = C_1.Q_2^n \qquad (2.7.5)$$

where, $$Q_1 = \left(\frac{c_v\theta_i}{E_c}\right) \text{ and } Q_2 = \left(\frac{V_Cc_va_1}{\lambda}\right)^{0.5}$$

E_C = specific cutting energy
c_v = volume specific heat
λ = thermal conductivity
c_1 = a constant
n = an index close to 0.25

Therefore, $$\theta_i = c_1E_C\sqrt{V_ca_1/\lambda c_v} \qquad (2.7.6)$$

Using equation 2.7.6 one can estimate the approximate value of average θ_I from the known other machining parameters.
[There are several other models available for the cutting temperatures – see in books and journals]

- **Experimental methods of determination of cutting temperature**

Amongst θ_S, θ_i, and θ_f, θ_i is obviously the highest one and its value is maximum almost at the middle of the chip – tool contact length. Experimental methods generally provide the average or maximum value of θ_i. Some techniques also enable get even distribution of temperature in the chip, tool and job at the cutting zone.
The feasible experimental methods are :

- Calorimetric method – quite simple and low cost but inaccurate and gives only grand average value
- Decolourising agent – some paint or tape, which change in colour with variation of temperature, is pasted on

the tool or job near the cutting point; the as such colour of the chip (steels) may also often indicate cutting temperature

- Tool-work thermocouple – simple and inexpensive but gives only average or maximum value
- Moving thermocouple technique
- Embedded thermocouple technique
- Using compound tool
- Indirectly from Hardness and structural transformation
- Photo-cell technique
- Infra ray detection method

The aforesaid methods are all feasible but vary w.r.t. accuracy, preciseness and reliability as well as complexity or difficulties and expensiveness.
Some of the methods commonly used are briefly presented here.

- **Tool work thermocouple technique**

Fig. 2.7.3 shows the principle of this method.

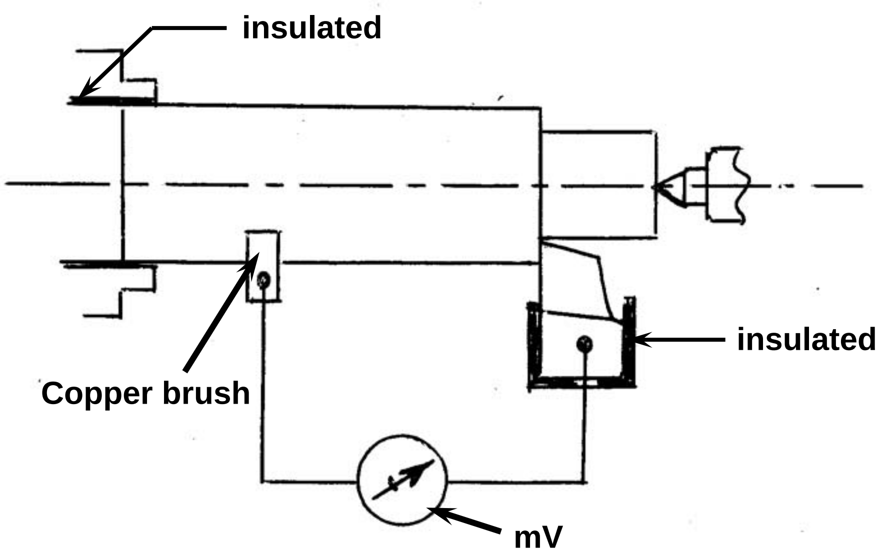

Fig. 2.7.3 *Tool-work thermocouple technique of measuring cutting temperature.*

In a thermocouple two dissimilar but electrically conductive metals are connected at two junctions. Whenever one of the junctions is heated, the difference in temperature at the hot and cold junctions produce a proportional current which is detected and measured by a milli-voltmeter. In machining like turning, the tool and the job constitute the two dissimilar metals and the cutting zone functions as the hot junction. Then the average cutting temperature is evaluated from the mV after thorough calibration for establishing the exact relation between mV and the cutting temperature.
Fig. 2.7.4 typically shows a method of calibration for measuring average cutting temperature, θ_{avg}, in turning steel rod by uncoated carbide tool.

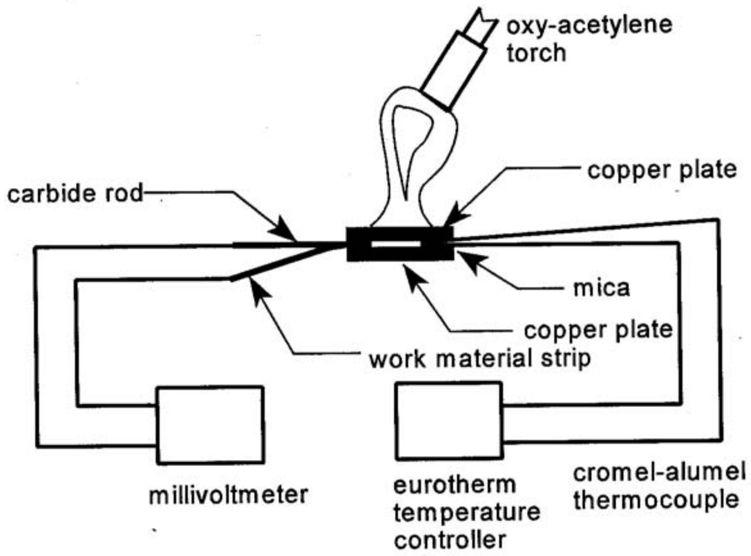

Fig. 2.7.4 *Calibration for tool – work thermocouple.*

- Moving thermocouple technique

This simple method, schematically shown in Fig. 2.7.5, enables measure the gradual variation in the temperature of the flowing chip before, during and immediately after its formation. A bead of standard thermocouple like chrome-alumel is brazed on the side surface of the layer to be removed from the work surface and the temperature is attained in terms of mV.

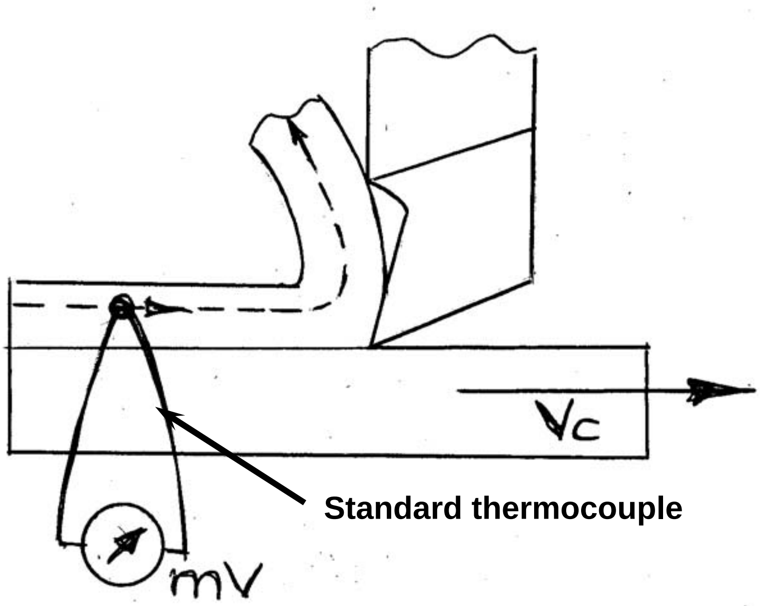

Fig. 2.7.5 *Moving thermocouple technique*

- Embedded thermocouple technique

In operations like milling, grinding etc. where the previous methods are not applicable, embedded thermocouple can serve the purpose. Fig. 2.7.6 shows the principle. The standard thermocouple monitors the job temperature at a certain depth, h_i from the cutting zone. The temperature recorded in oscilloscope or strip chart recorder becomes maximum when the thermocouple bead comes nearest (slightly offset) to the grinding zone. With the progress of grinding the depth, h_i gradually decreases after each grinding pass and the value of temperature, θ_m also rises as has been indicated in Fig. 2.7.6. For getting the temperature exactly at the surface i.e., grinding zone, h_i has to be zero, which is not possible. So the θ_m vs h_i curve has to be extrapolated upto $h_i = 0$ to get the actual grinding zone temperature. Log – log plot helps such extrapolation more easily and accurately.

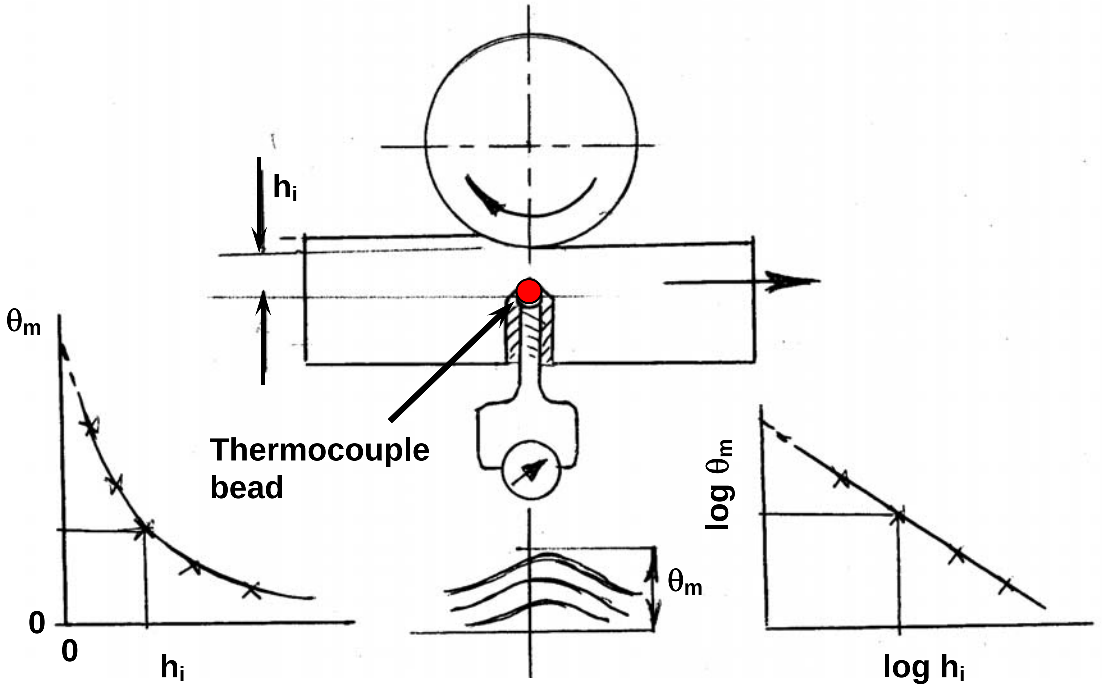

Fig. 2.7.6 *Embedded thermocouple technique*

- Measurement of chip-tool interface temperature by compound tool

In this method a conducting tool piece (carbide) is embedded in a non conducting tool (ceramic). The conducting piece and the job form the tool-work thermocouple as shown in Fig. 2.7.7 which detects temperature θ_i at the location (L_i) of the carbide strip. Thus θ_i can be measured along the entire chip-tool contact length by gradually reducing L_i by grinding the tool flank. Before that calibration has to be done as usual.

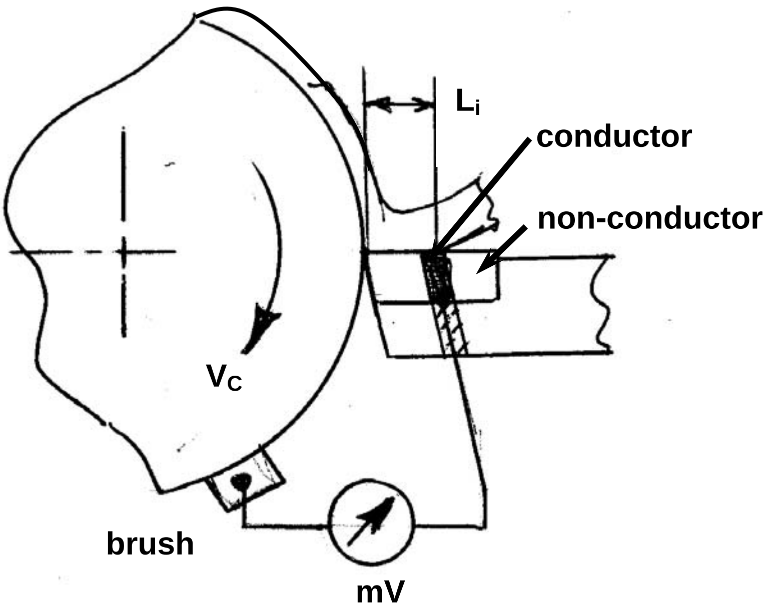

Fig. 2.7.7 *Compound rake used for measuring cutting temperature along rake surface*

- Photo-cell technique

This unique technique enables accurate measurement of the temperature along the shear zone and tool flank as can be seen in Fig. 2.7.8. The electrical resistance of the cell, like PbS cell, changes when it is exposed to any heat radiation. The amount of change in the resistance depends upon the temperature of the heat radiating source and is measured in terms of voltage, which is calibrated with the source temperature. It is evident from Fig. 2.7.8 that the cell starts receiving radiation through the small hole only when it enters the shear zone where the hole at the upper end faces a hot surface. Receiving radiation and measurement of temperature continues until the hole passes through the entire shear zone and then the tool flank.

- Infra-red photographic technique

This modern and powerful method is based on taking infra-red photograph of the hot surfaces of the tool, chip, and/or job and get temperature distribution at those surfaces. Proper calibration is to be done before that. This way the temperature profiles can be recorded in PC as indicated in Fig. 2.7.9. The fringe pattern readily changes with the change in any machining parameter which affect cutting temperature.

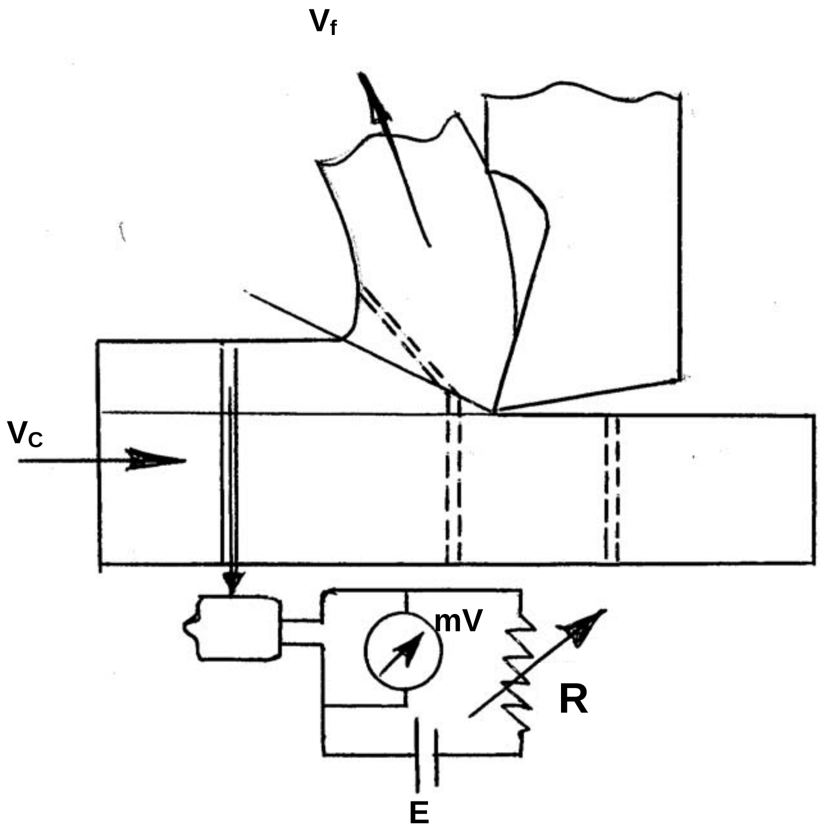

Fig. 2.7.8 *Measuring temperature at shear plane and tool flank by photocell technique*

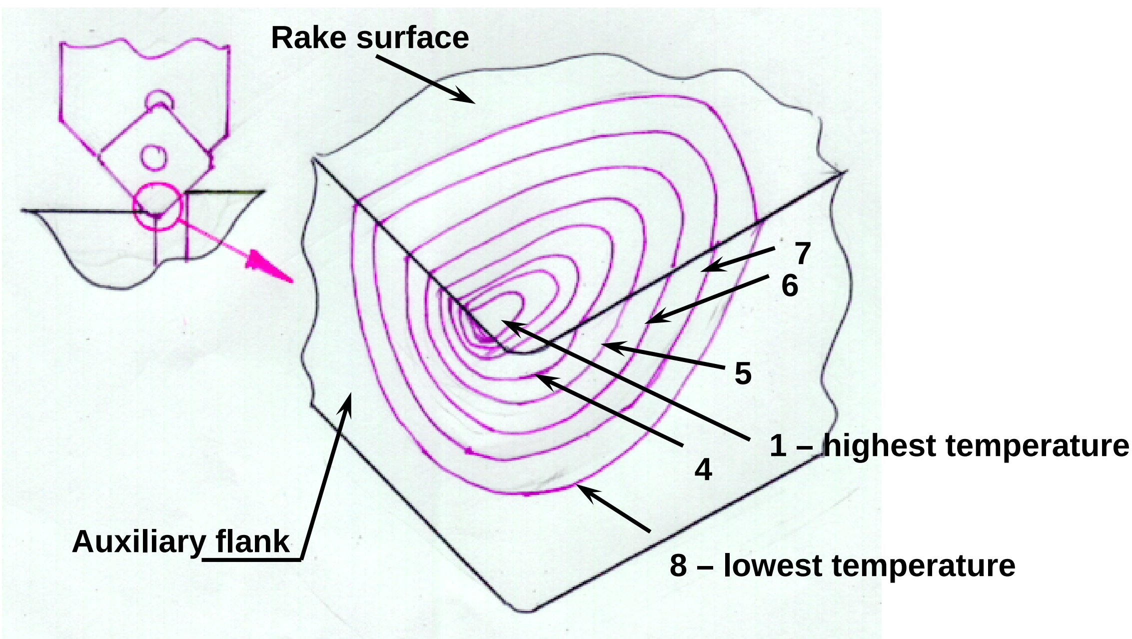

Fig. 2.7.9 *Temperature distribution at the tool tip detected by Infra ray technique*

(iv) Role of variation of the various machining parameters on cutting temperature

The magnitude of cutting temperature is more or less governed or influenced by all the machining parameters like :

- Work material : - specific energy requirement
  - ductility
  - thermal properties (λ, c_v)
- process parameters : - cutting velocity (V_C)
  - feed (s_o)
  - depth of cut (t)
- cutting tool material : - thermal properties
  - wear resistance
  - chemical stability
- tool geometry : - rake angle (γ)
  - cutting edge angle (ϕ)
  - clearance angle (α)
  - nose radius (r)
- cutting fluid : - thermal and lubricating properties
  - method of application

Many researchers studied, mainly experimentally, on the effects of the various parameters on cutting temperature. A well established overall empirical equation is,

$$\theta_i = \frac{C_\theta (V_C)^{0.4} (s_o \sin\phi)^{0.24} (t)^{0.105}}{\left(\frac{t}{s_o}\right)^{0.086} (r)^{0.11} (ts_o)^{0.054}} \qquad (2.7.7)$$

where, C_θ = a constant depending mainly on the work-tool materials

Equation 2.7.7 clearly indicates that among the process parameters V_C affects θ_i most significantly and the role of t is almost insignificant. Cutting temperature depends also upon the tool geometry. Equation 2.7.7 depicts that θ_i can be reduced by lowering the principal cutting edge angle, ϕ and increasing nose radius, r. Besides that the tool rake angle, γ and hence inclination angle, λ also have significant influence on the cutting temperature. Increase in rake angle will reduce temperature by reducing the cutting forces but too much increase in rake will raise the temperature again due to reduction in the wedge angle of the cutting edge.

Proper selection and application of cutting fluid help reduce cutting temperature substantially through cooling as well as lubrication.

(v) Control of cutting temperature

It is already seen that high cutting temperature is mostly detrimental in several respects. Therefore, it is necessary to control or reduce the cutting temperature as far as possible.

Cutting temperature can be controlled in varying extent by the following general methods:

- proper selection of material and geometry of the cutting tool(s)
- optimum selection of V_C – s_o combination without sacrificing MRR
- proper selection and application of cutting fluid
- application of special technique, if required and feasible.

Exercise 2.7

Problem 1

Analytically estimate the average shear zone Temperature, θ_s for plain turning of a mild steel rod of diameter 100 mm by a carbide tool of geometry

-6^o, -6^o, 6^o, 6^o, 15^o, 75^o, 1.2 (mm) NRS at speed 400 rpm, feed 0.12 mm/rev and depth of cut 3.0 mm under dry condition when the followings were noted:

Main cutting force component, P_Z= 1200 N

Frictional force at the rake surface, F = 500 N

Chip thickness, a_2= 0.6 mm

Assume : 80% of mechanical energy gets converted into heat, 90% of the heat generated at the shear zone goes into the chips, Mechanical equivalent of heat, J = 4.2 J/Cal, Volume specific heat of mild steel,ρ_v=3554KJ/m^3 ^oC

Ambient temperature,θ_a = 25^o

Solution :

- The general expression for average shear zone temperature, θ_s is,

$\theta_s = Aq(P_Z V_C — FV_f)/(Jr_v V_c t s_o) + q_a$

- where given,

A = 0.8 $\quad$ s_o = 0.12 mm/rev

q = 0.9 $\quad$ t = 3.0 mm

P_Z = 1000 N $\quad$ V_C= πDN/ 1000 m/min=125.6m/min

J = 4.2 J/Cal $\quad$ ρ_v = 825 Kcal/m^3/^0C

- chip velocity, $V_f = V_c/\zeta$

where $\zeta = a_2/a_1 = a_2/s_o \sin\phi$

given a_2 = 0.6 and $\phi = 75^o$ / ζ = 0.6/(0.12xsin75^o) = 5.176

Hence, V_f = = V_c / ζ = 125.6 / 5.176 =24.264 m/min

Thus,

$$\theta_S = \frac{0.8x0.9(1200x125.6 - 500x24.264)}{4.2x825x125.6x0.12x3x10^{-6}} + 25 = 643^oC \quad \textbf{answer}$$

Problem 2

From dimensional analysis,

$Q_1 = \rho_v\, \theta_I/E_c$ and

$Q_2 = (Va_1/\, \rho_v\, \lambda)^2$

where $Q_1 = C_1.Q_2^{0.25}$ and C_1 is a constant, = 121.

Material-A is machined at 150m/min and feed of 0.2 mm/rev under orthogonal turning with principal cutting edge angle, $\phi = 90^o$. Determine the interface temp. θ_i for this material?

Given:

Properties	λ **Kcal/m-hr-sec**	ρ_v **Kcal/m^3/^{o}C**	σ_u **Kg/mm^2**	**Δ- % elong.**	**ζ -chip red. Coeff.**
	40	800	40	0.2	2.5

- Given the relations :

  $Q_1 = \rho_v \theta_I / E_c$

  $Q_2 = (V_C a_1 / \rho_V \lambda)^2$

  and $Q_1 = C_1.Q_2^{0.25}$

- Combining those equations :

  $\theta_I = C_1 E_c (V_c a_1 / \rho_V \lambda)^{0.5}$ where

  θ_I = average chip-tool interface temp.

  C_1 = constant = 121

  E_c = specific cutting energy of the work material by a given tool in a given environment

  V_c = cutting velocity, m/min

  a_1 = uncut chip thickness = $s_o \sin\phi$ mm

- $E_c = (P_z.V_c / ts_o V_c) = (ts_o \tau_s f V_c)/(ts_o V_c)$

  $= \tau_s f$ N/mm^2 where, τ_s = dynamic yield shear strength of the work material

  and f = form factor

- For material A

  $\tau = 0.74 \Delta \sigma_u 6^{0.6\Delta}$; σ_{UA}= 40 kg/mm^2

  $\Delta = 0.2$ and $f = \zeta_A - \tan\gamma + 1 \cong \zeta_A + 1 = 2.5+1 = 3.5$

- Hence for material A

  $E_c = (0.74 x 40 x 6^{0.6 x 0.2}) x 3.75$ kg/mm^2

- $\theta_{iA} = C_1 x E_{CA} (V_c a_1 / \rho_{VA} \lambda_A)$

  given $c_V = 800$, $\lambda_A = 40$ and $C_1 = 121$

  $\theta_{iA} = 121 \{E_{CA} (V_c a_1 / c_{VA} \lambda_A)^{0.5}\} = 500^o C$ answer