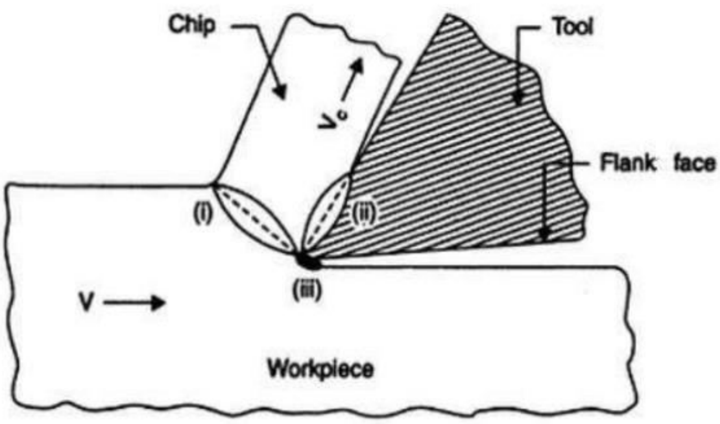
ME338 – Manufacturing Process II
Lecture 6 : Thermal aspects in Machining

Pradeep Dixit
Department of Mechanical Engineering,
Indian Institute of Technology Bombay

Why is heat generated in machining ?

- In the elastic deformation:
  - Energy required for deformation is stored in the materials as strain energy and thus, no heat is generated
- In plastic deformation of metal machining:
  - Most of the energy used in converted into heat
- What are the regions where plastic deformation is taking place :
  - Primary shear deformation zone
  - Secondary chip tool interface
  - Territory Work-tool interface



Heat generation zones

- Region 1: Primary shear zone
  - Actual plastic deformation occurs, so heat is generated
  - Portion of this heat is carried by the chip, so chip temperature increses
  - Rest of the heat is retained by the workpiece
- Region 2: Tool-chip interface
  - Chip slides through the rake surface. Friction > heat generation
  - Portion of this heat is carried by the chip, so chip temperature further increses
  - Rest of the heat is transfered to cutting tool
  - Amount of heat generation depends on chip speed (and thus, cutting speed)
  - Tools are also coated with heat-resistant thin films for increased tool life
- Region 3: Tool-workpiece interface
  - In practical applications, tool edge does not remain sharp and becomes dull
  - Portion of Tool flank surface rubs against the workpiece
  - This heat is shared by tool, workpiece and coolant
  - This heat generation increases with the cutting time as the tool wears out

How material properties affect temperature

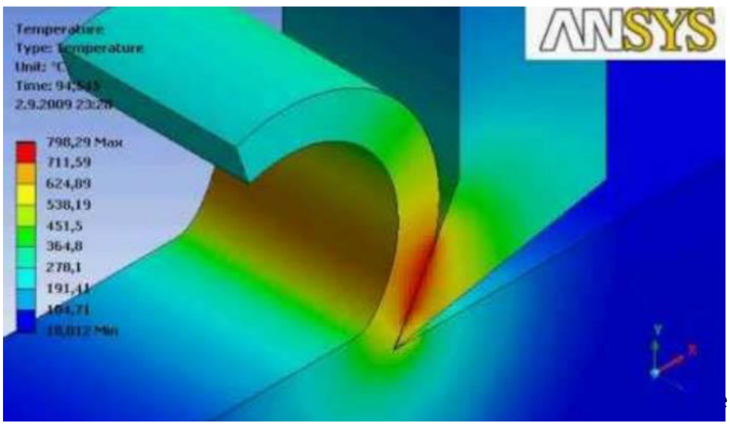
- Amount of heat generated depends upon
  - Cutting parameters : cutting speed, use of coolants
  - Tool geometry : rake angle, nose radius
  - Material properties of workpiece and tool: specific heat, thermal conductivity
- Material properties:
  - In low strength material, heat generation and increased tool temperature is not issue
  - Higher hardness and tensile strength materials (Ferrous, Titanium, etc) , require more cutting force, thus increased tool temperature is high and therefore tool wear rate is very high
  - Lower thermal conductivity of workpiece >> more rise in temperature

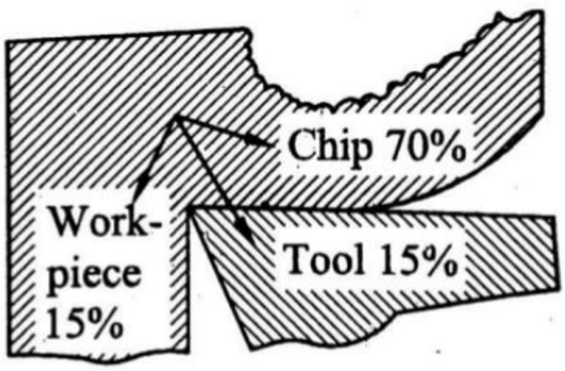
How cutting parameters affect temperature

- High machining speed is desired for high productivity, but high tool wear
- Shear angle affects the heat generation process
  - Larger shear angle > smaller shear plane area >> smaller shear force, >> small heat generation
- Positive rake angle > lower cutting force > lower temp
- Larger nose radius > more contact with tool surface > more heat conduction
- Large cross section of tool shank > more heat conduction > lower temperature
- Increasing cutting speed > higher friction > more rise in temperature
- Increasing feed, depth of cut also result in higher temperature
- Application of cutting fluid will lower temperature rise

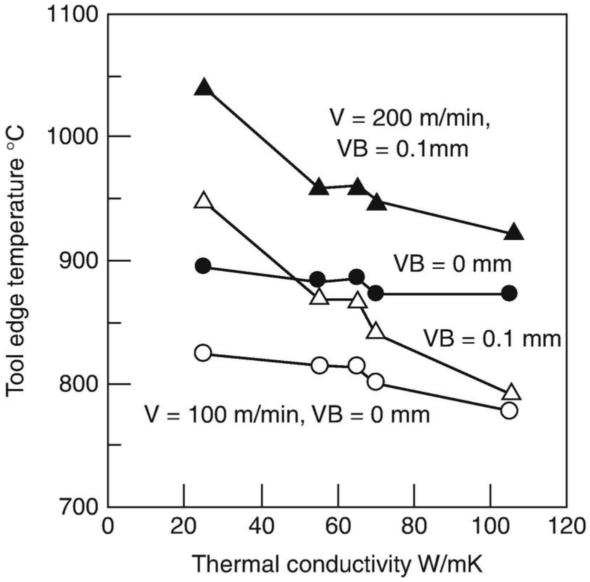
Temperature effect on cutting tool

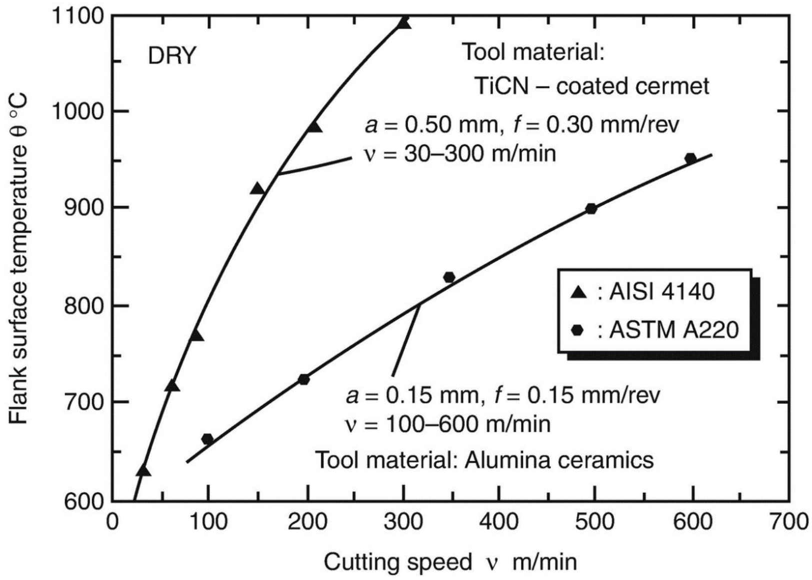
- Heat is distributed between chip (~70%), tool (~15%) and workpiece (~15%)
- Temperature may reach beyond 700°C (beyond recrystallization temp)
- Effect on cutting tool:
  - Thermal expansion of the cutting tool
  - Plastic deformation of cutting edges
  - Formation of build up edge > poor surface finish, dimensional inaccuracy
  - Rapid tool wear
- Increased heat causes uneven dimensional changes in the part being machined, making it difficult to control its dimensional accuracy and tolerances



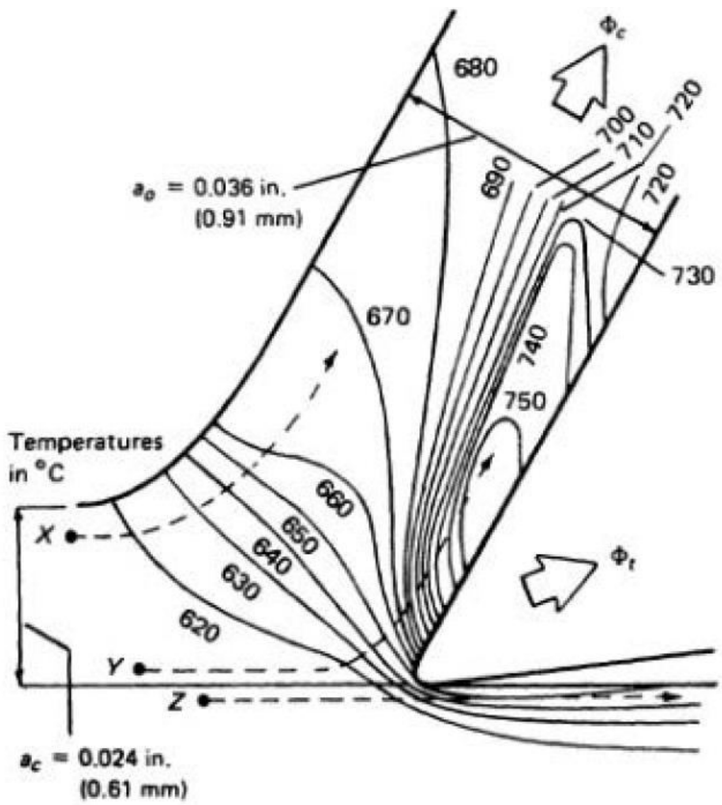


Effect of Thermal conductivity & Cutting speed





Temperature distribution in work piece and tool



For machining mild steel, cutting speed is 0.38 m/s), width of cut is *6.35* mm. Normal rake is 30 degree, and the workpiece temperature is 611°C

Point X, Y and Z:

Point X is moving towards cutting tool and passing through primary shear zone.

Point Y will experience both primary as well as secondary shear zone

Point Z is inside the material

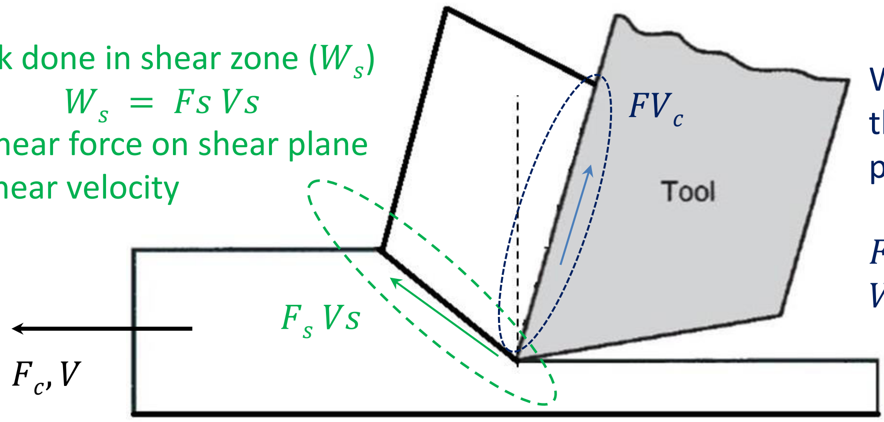
Work done in cutting action

Work done in shear zone (W_s)

$$W_s = Fs\, Vs$$

F_s Shear force on shear plane

V_s shear velocity



Work done in overcoming the friction + secondary plastic deformation (W_f)

$$W_f = F\, Vc$$

F friction force on rake

V_c chip velocity

- Total work done in cutting action $W_c = FcV = W_s + Wf$
  - Work done in shearing $W_s = Fs\, Vs$
  - work done in friction $W_f = FV_c$
- Assuming no losses, total work done W = work supplied by electric motor W_m
- W_m = Work consumed in cutting action + Work done in feeding motion
- W_m ≈ Work consumed in cutting action W_c (neglecting work in feeding motion)
- $W_m \approx W_c = Ws + Wf$;
- $F_cV = FsVs + FVc$

Specific cutting energy

- Specific energy u = Total energy consumed $(F_c V)$/ volume of metal removed
  - $u = F_c V / V w t_1$
- Specific cutting energy u_c: $F_c / w t_1$
- Specific shear energy u_s: $F_s / w t_1$
- Specific friction energy u_f: $F / w t_1$
- $u_c = us + u_f$
- $W_c = W_s + W_f$
  - W_c = Power consumed in machining = $F_c V = u_c (V w t_1)$
  - W_s = Power consumed in primary shear zone = $F_s V_s = u_s (V w t_1)$
  - W_f = Power consumed in overcoming friction in secondary zone = $F V_c = u_f (V w t_1)$

- Typically, 60-70% of the energy in the metal cutting is consumed in the shear zone alone
- Remaining 40-30% is consumed at the tool-chip interface (assuming a perfectly sharp tool)
  - Energy consumed in the Tool-workpiece contact (due to tool rubbing) is neglected

Temperature in primary shear zone

- Power consumed in Shear zone $W_s = W_c - W_f$
  - $W_s = F_c V - F V_c$
- Cutting velocity (V) and chip velocity (V_c) are related by chip thickness ratio (r)
  - $V_c = rV = \frac{\sin\phi}{\cos(\phi - \alpha)} V$
- $W_s = F_c V - F V_c = V(F_c - Fr)$
- From experimental analysis, it is observed that typically, 60-70% of the energy in the metal cutting is consumed in the shear zone alone
- Majority of the energy consumed in the shear zone (W_s), goes into the chip
- Remaining energy is more or less equally distributed and goes into the cutting tool and the workpiece

Temperature in primary shear zone

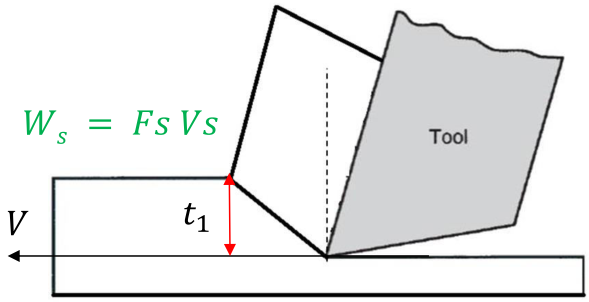
- If γ is fraction of primary heat which goes to the work piece, then (1- γ) will taken by chips
- Value of γ depends upon shear angle ϕ and thermal conductivity k

$$\gamma = 0.15 \ln\left(\frac{27.5}{\lambda \tan\phi}\right) \qquad \lambda = \frac{\rho c V t_1}{k}$$

γ : fraction of primary heat which conducted to the work piece,
ρ: density of workpiece material
c: specific heat of workpiece material
k: thermal conductivity of workpiece material
V : cutting velocity
t_1 : uncut chip thickness

Temperature in primary shear zone

$$W_s = F_c V - F V_c$$



- If γ: fraction of primary heat which conducted to the work piece, then (1- γ) fraction will taken by chips.
- Heat taken away by the chips: $(1-\gamma)W_s$
- Ignoring heat loss to atmosphere,
- Heat taken by chip = heat absorbed by chip
- Heat absorbed by chip: $mc\Delta\theta$
- Mass of material removed per unit time : $m = Vwt_1\rho$
- Temperature rise of material passing through shear zone: $\Delta\theta = \dfrac{(1-\gamma)W_s}{Vwt_1\rho c}$

Temperature in secondary shear zone

- Maximum temperature rise $\Delta\theta_f$ when material passes through the rake surface

$$\Delta\theta_f \approx 1.13\sqrt{\frac{\lambda t_c}{l}}\left(\frac{W_f}{\rho c V w t_1}\right) \qquad \lambda = \frac{\rho c V t_1}{k}$$

- Here, l is the length of contact between tool and chip

$$\frac{l}{t_c} = [1 + \tan(\phi - \alpha)] \qquad \Delta\theta_f = 1.13\sqrt{\frac{1}{\rho c V t_1 k[1 + \tan(\phi - \alpha)]}}\frac{W_f}{w}$$

- Average temperature rise of material passing through secondary shear zone

- Final temperature is given as :
  - $\theta = \theta_0 + \Delta\theta_s + \Delta\theta_f$

Example 3

- A planing process is being used to machine a 300 mm x 300 mm x 25 mm flat mild steel block. The sharp single point cutting tool has a normal rake angle α = 10°. Other process parameters are as follows: cutting speed V = 2 m/s, undeformed chip thickness = 0.25 mm, width of cut per pass w = 2.5 mm, deformed chip thickness = 0.83 mm. The cutting and thrust forces were measured during each pass with a cutting force dynamometer and found to be as follows: F_c = 890N and F_t = 667 N. Assume Planing is an orthogonal cutting process.
- Calculate the percentage of total power dissipated in the primary zone of deformation (shear zone).

Example 3

$P_c = F_cV = (890)(2) = 1780$ W

$P_s = F_sV_s = R\cos(\phi+\beta-\alpha)V_s$

$R = \sqrt{F_c^2 + F_t^2} = 1112.2N$

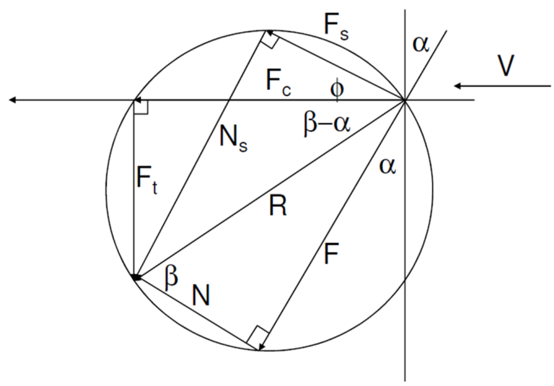
$$\tan\varphi = \frac{r\cos\alpha}{1 - r\sin\alpha} = \frac{(0.25/0.83)*\cos(10)}{1-(0.25/0.83)*\sin(10)} \Rightarrow \varphi = 17.3\deg$$

$$V_s = \frac{V\cos\alpha}{\cos(\varphi - \alpha)} = 1.986m/s$$

$P_s = F_sV_s = 1293.63$ W

% of total power dissipated in shear zone =

$$\frac{P_s}{P_c}\times 100 = 72.6\%$$



Example : Temperature rise

Determine the maximum temperature along the rake face of the tool when machining mild steel (ms), given

work material (ms) shear stress = 400×10^6 N/m^2,

$\alpha = 0°$, $v = 2$ m/sec, $t_1 = 0.25$ mm,

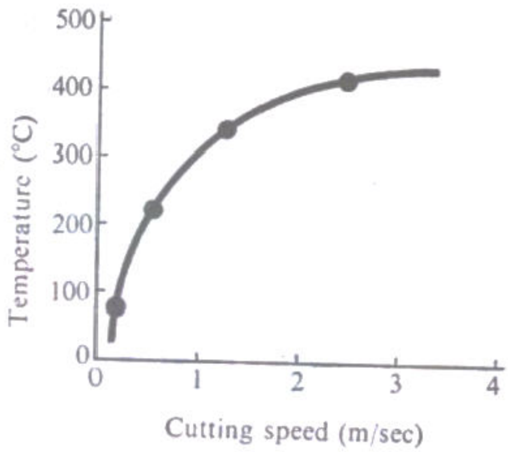
$w = 2$ mm, $\mu = 0.5$, $\rho = 7200$ kg/m^3,

$k = 43.6$ W/m-°C, $c = 502$ J/kg-°C, $\theta_0 = 40$°C.

Use the Lee and Shaffer shear angle relationship.

Overall temperature and cutting speed

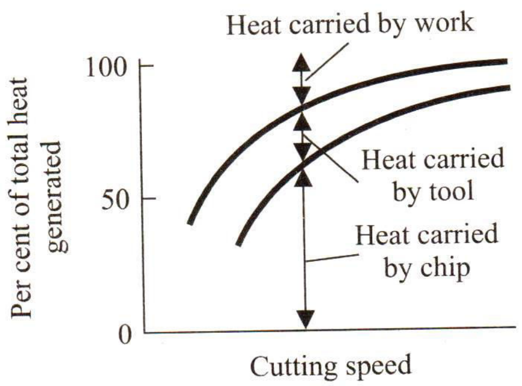
- Nature of variation in the overall chip-tool interface temperature (θ_{ov}) with major parameters can be determined through dimensional analysis
- $\theta_{ov} \propto U_c \sqrt{\frac{Vt_1}{k\rho c}}$
- Overall temperature rise is proportional to the square root of the cutting speed
- Cutting speed has major effect on the overall temperature rise



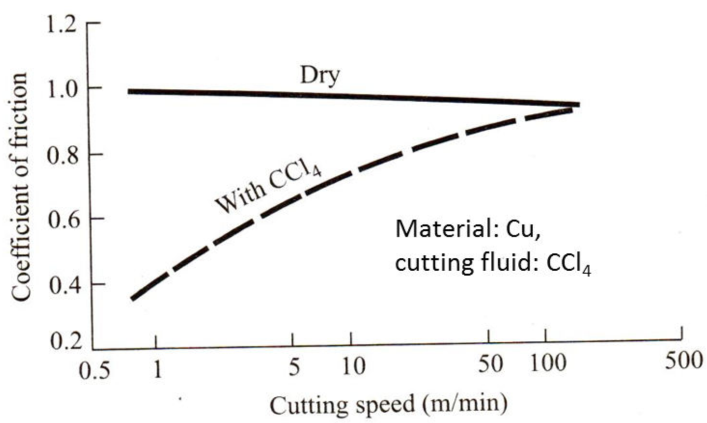
Role of cutting fluids in machining

- As temperature affects the tool wear, thus productivity
  - Need to reduce temperature to Increases tool life
  - Reduced friction on the rake surface
- Ways in which cutting fluid affects machining
  - Cooling down of chip-tool-work zone by carrying away generated heat
  - Reducing the coefficient of friction a chip-tool Interface
- Cutting fluids should have following properties:
  - Large specific heat and good thermal conductivity,
  - Low viscosity and small molecular size,
  - Suitable reactive constituent/ Nonpoisonous/Inexpensive
- Types of cutting fluids:
  - Water based (contains salt or soluble oils)
  - Mineral oil
  - Synthetic oil

Effect of cutting fluid – heat generation, friction

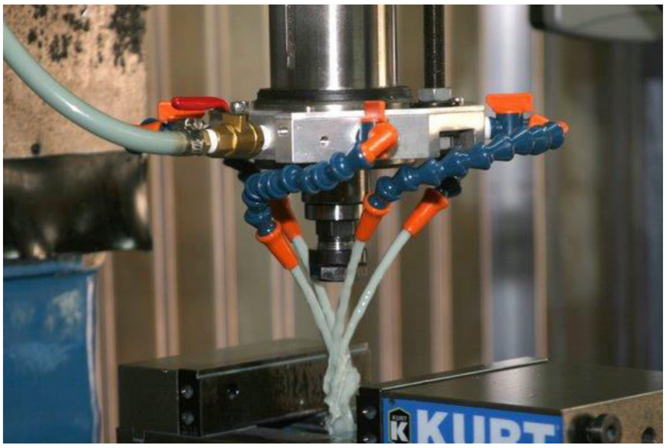


- At higher cutting speed, effectiveness of cutting fluids reduces as it take some finite time to work
- At higher speed, chip carries away most of the heat

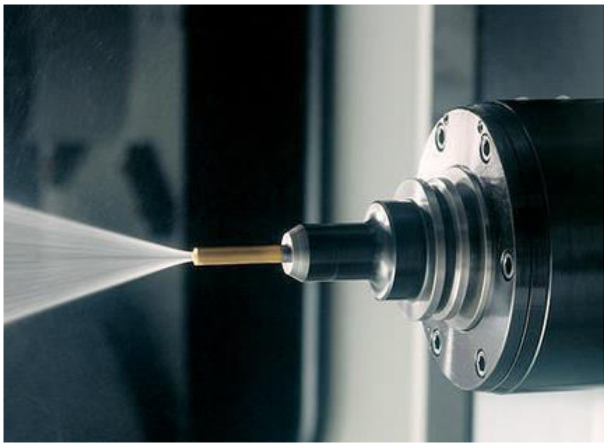


Cutting Fluid : Application methods

- Cutting fluid can be applied by several ways:
  - By using manual brush/ By flood exposure / Through spindle cooling
- Amount of cutting fluid should be minimum
  - Cutting fluid in form of Mist is a popular technique
  - Small droplets to ensure direct interaction with surface



Cutting Fluid : Spray cooling



Cutting Fluid : Through spindle cooling