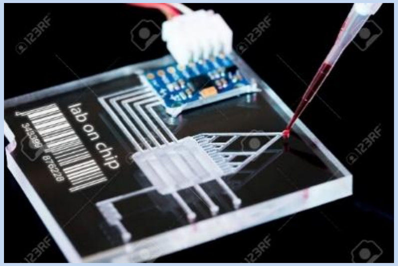
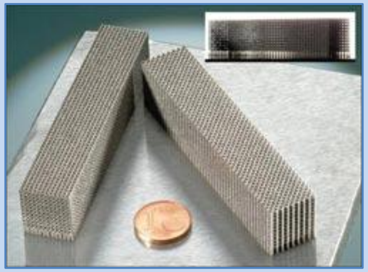
# Micro Turning

Fule injection nozzles; 0.4mm dia




Lab on chip

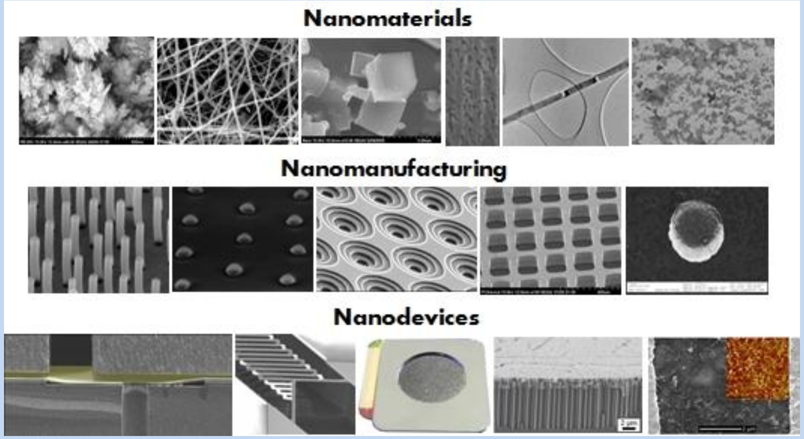
Nozzles for printers ; 0.4mm dia



Micro heat exchangers

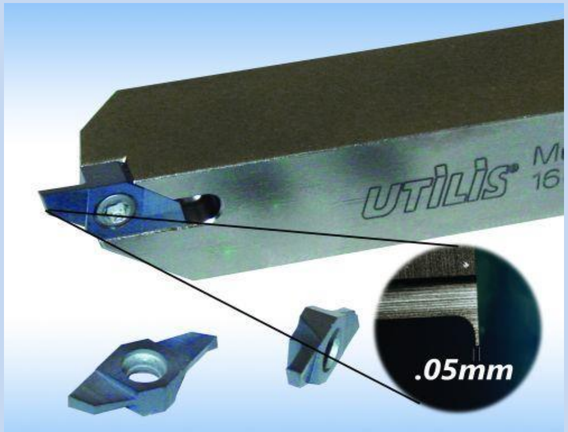
Spinneret holes

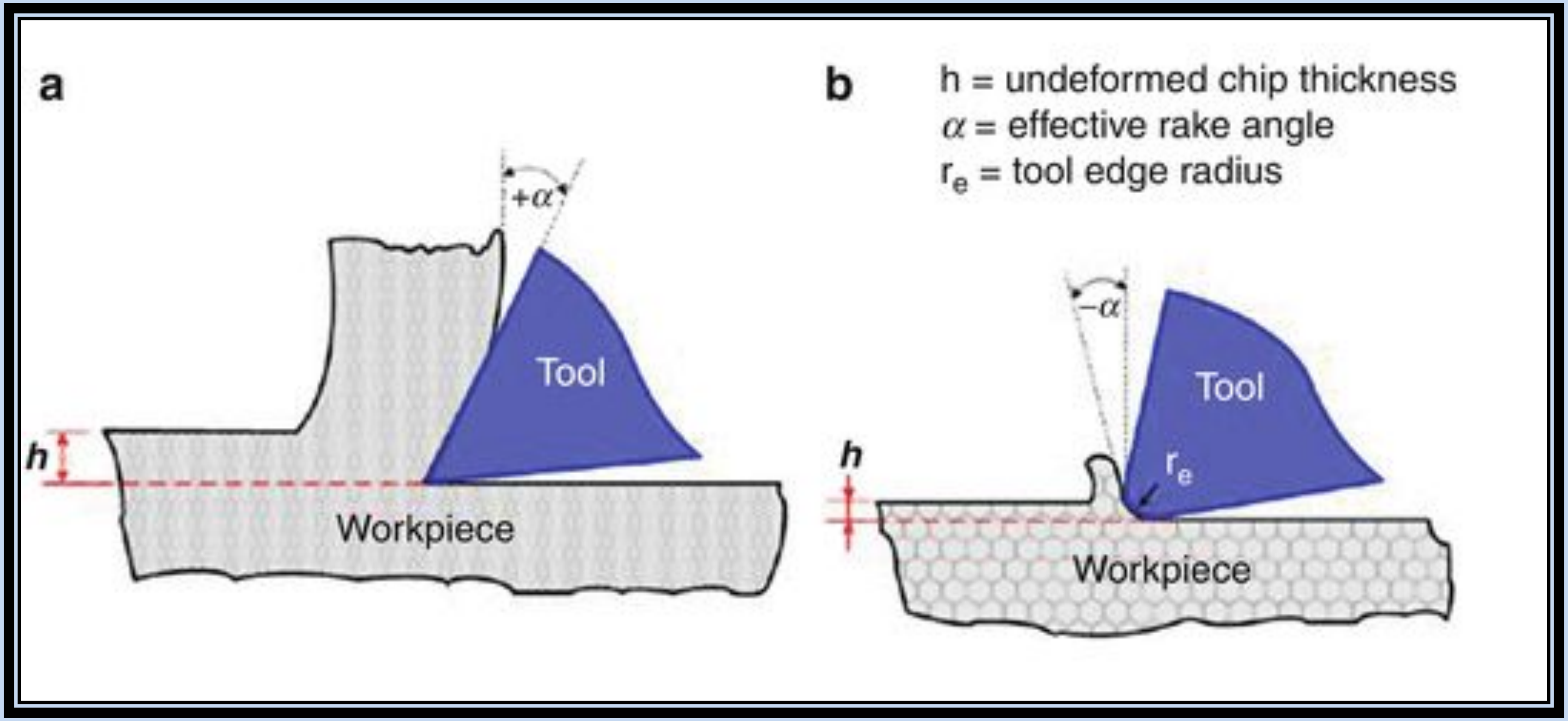
Micro reactors; 0.4mm dia
0.1-0.5mm, length 1 – 10mm




Extrusion dies for micro wires

# Micro Turning

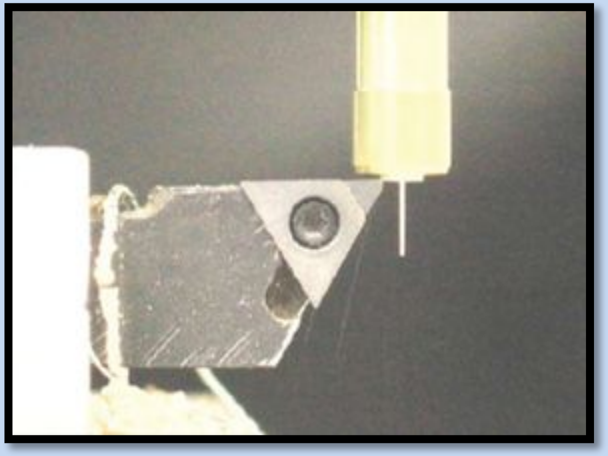



For obtaining Axis-symmetric Micro components

# Micro Turning

**Micro turning is an effective way to produce micro cylindrical or rotational symmetry components.**

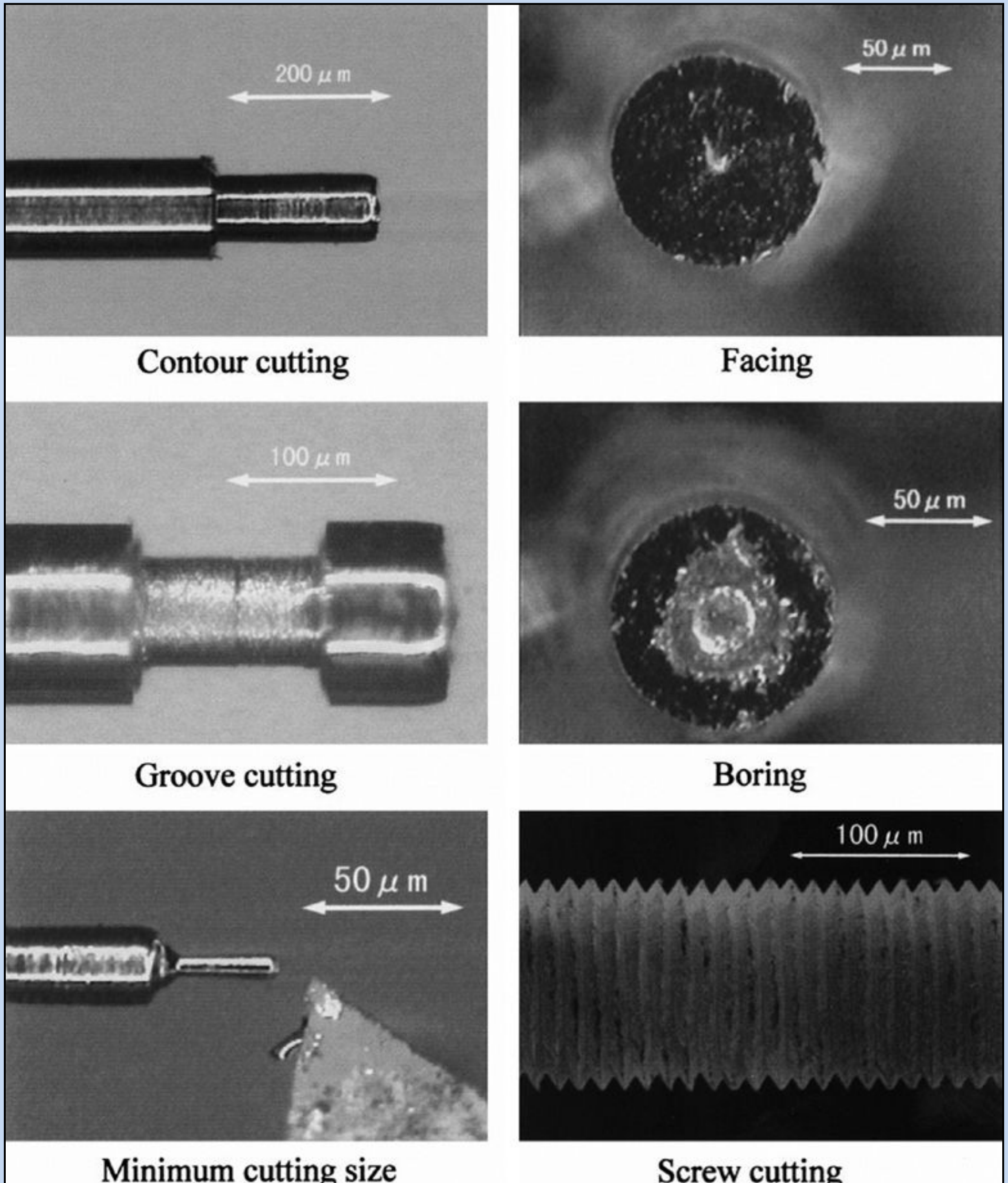


Micro cutting process


Micro turned shaft

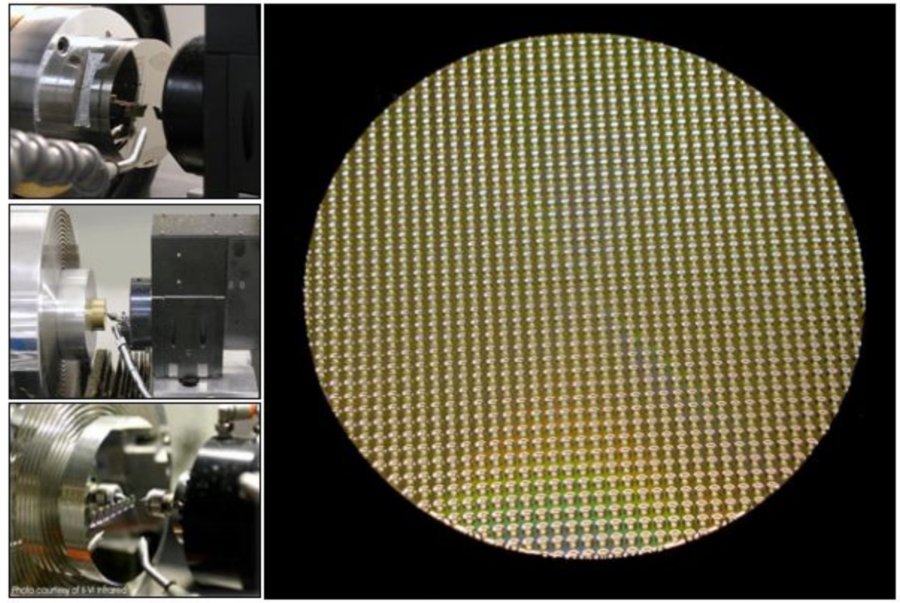
-  A micro part with the high aspect ratio can be achieved using the micro turning.
-  The most serious problem encountered during micro turning is the cutting force which tends to bend the work piece, and the machining force influences machining accuracy and the limit of machinable size

# Samples micro turned by the micro turning system.



# Diamond Turning:

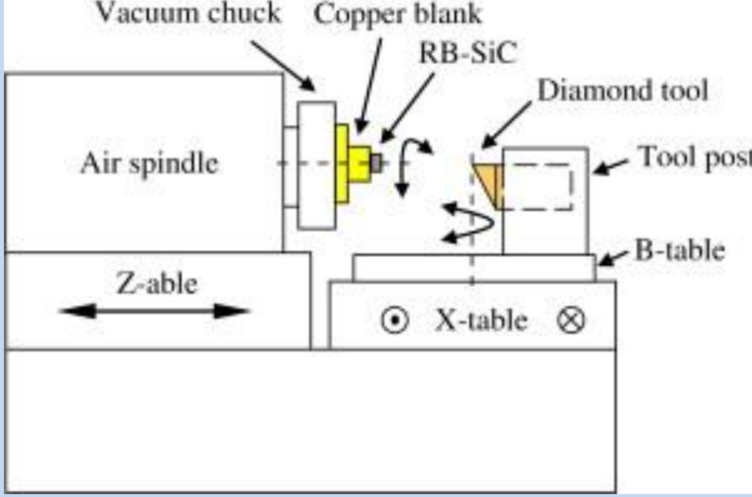
- Diamond turning of the micro structured surface can be regarded as another group of micro cutting.
- With the aid of fast tool servos (FTS), complex micro structured surfaces can be generated by diamond turning.



The Fast Tool Servo systems enable the diamond turning of surface structures such as micro prisms, lens arrays, torics and off-axis aspheres with departures up to 1000 microns.

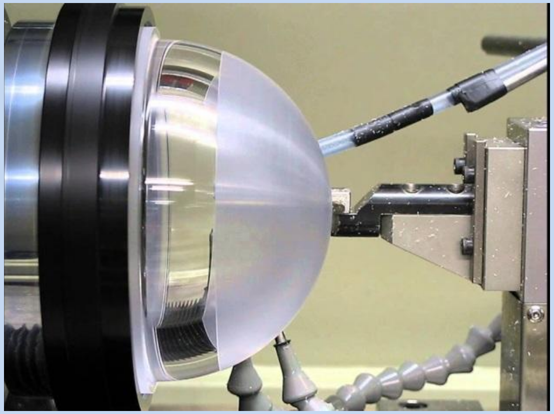
The FastCom FTS controller provides tool position commands for the Fast Tool Servo at update rates up to 25kHz. Position commands (including tool compensation) are calculated in real time, without interpolation, utilizing inputs from the existing encoders on the machines axes.

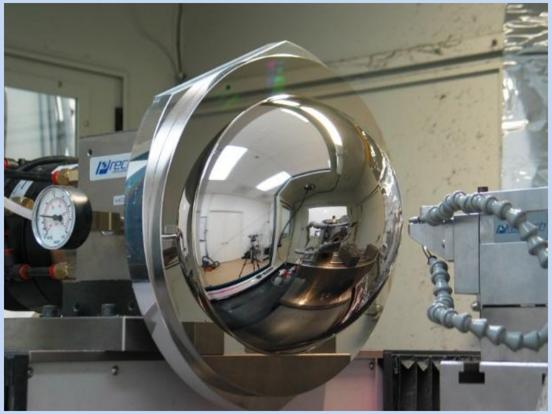
| Three Models | FTS 1000 | | FTS 500 | | FTS 70 |
|---|---|---|---|---|---|
| Travel | 1000µm ≈ 119hz | 250µm ≈ 238hz | 500µm ≈ 168hz | 250µm ≈ 238hz | 70µm ≈ 100hz |
| Max Acceleration | 300 m/sec$^2$ | | 300 m/sec$^2$ | | 3000 m/sec$^2$ |
| Typical Form | <0.6 µm PV | | <0.3 µm PV | | <0.3 µm PV |
| Typical Finish | <9 nm Ra | | <5 nm Ra | | <3 nm Ra |
| Servo Band Width | 1000Hz | | 1000Hz | | 900Hz |

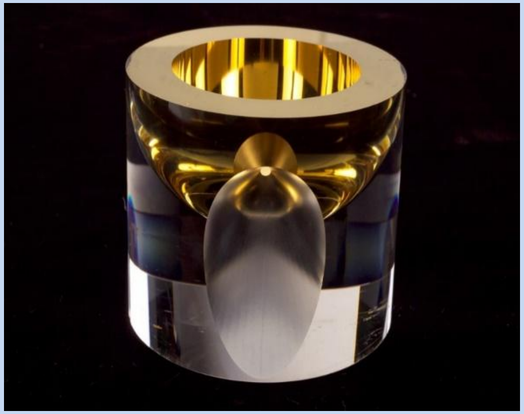



## Diamond Turning

- Surface finish in few 10s of nm
- Highest accuracy turning machine
- Requires strict temperature control
- Primarily used to produce precision lens







Diamond Turning of optical Parts

# Size Effects

- Size effects resulting from the small ratio of uncut chip thickness to tool edge radius will be a dominant factor for material removal mechanism and chip generation physics in micro cutting.
- Cutting, ploughing, or slipping phenomenon will occur predominated by this ratio, and eventually influences cutting processes such as surface finishes and surface integrity.

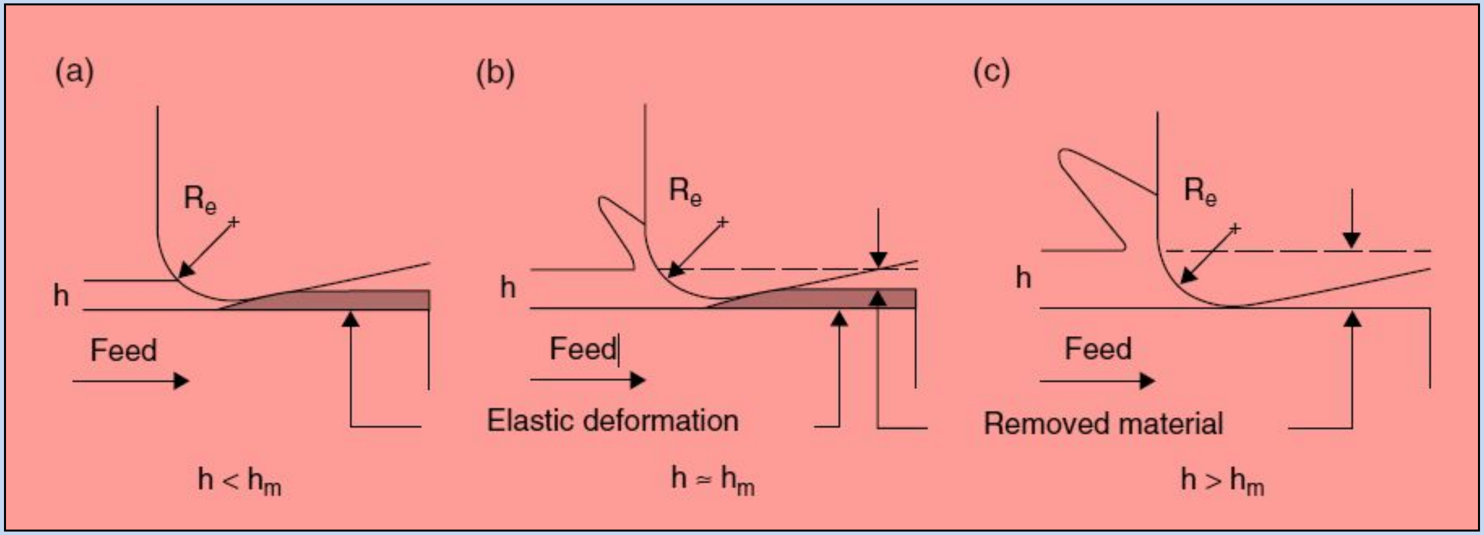
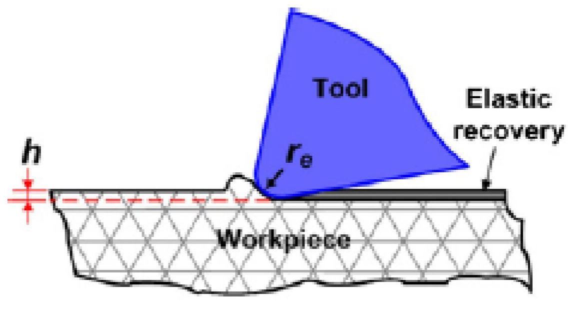


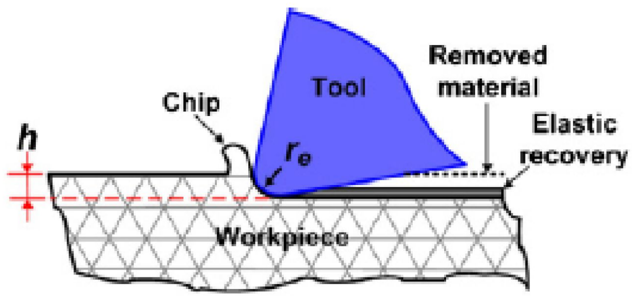

**Fig : Size effect in typical Orthogonal cutting process**

# Mechanisms of Material Removal…..

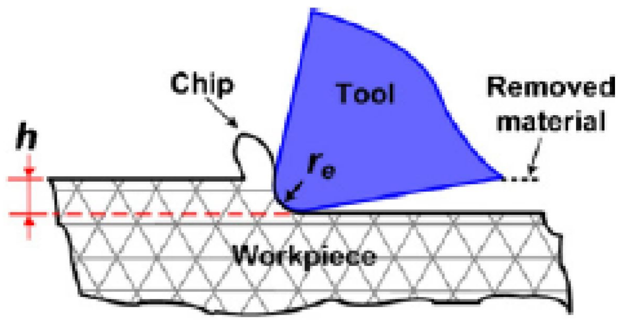


(a) $h < h_m$

Elastic deformation



(b) $h \equiv h_m$



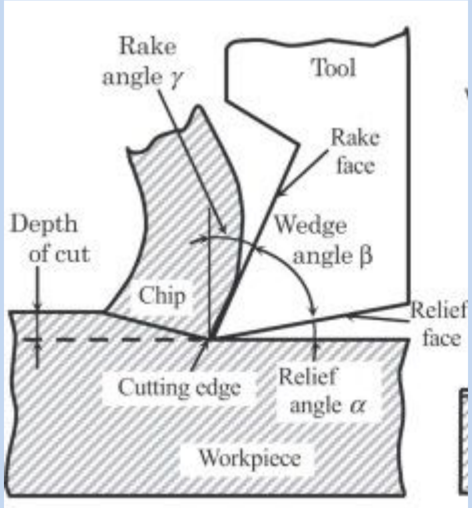
(c) $h > h_m$

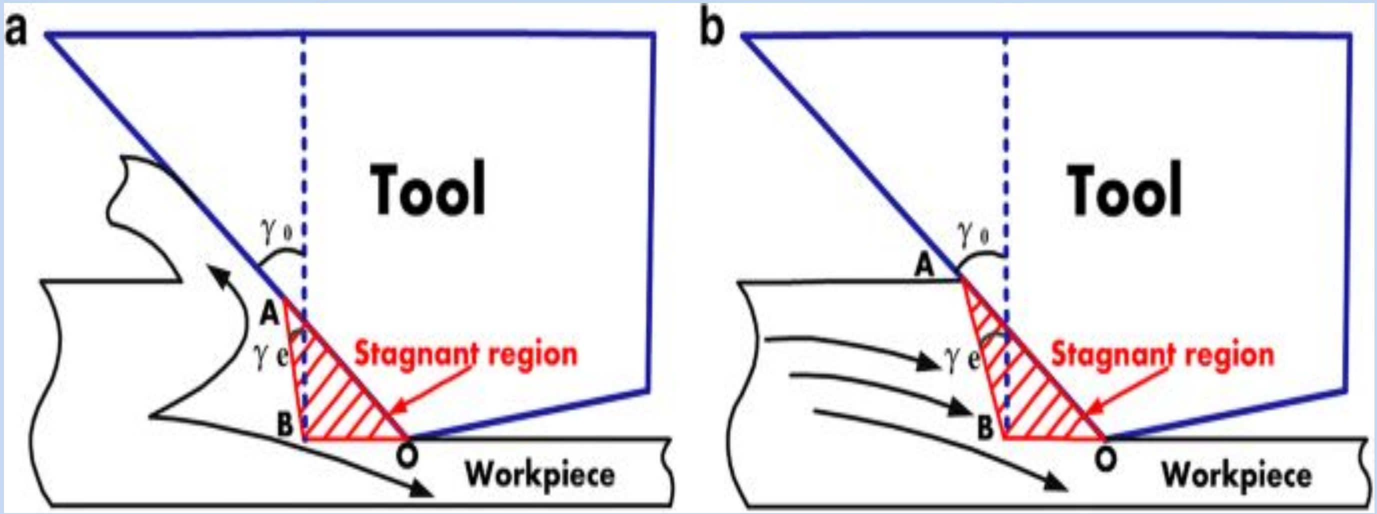
Elastic deformation and shearing

Aramcharoen et al

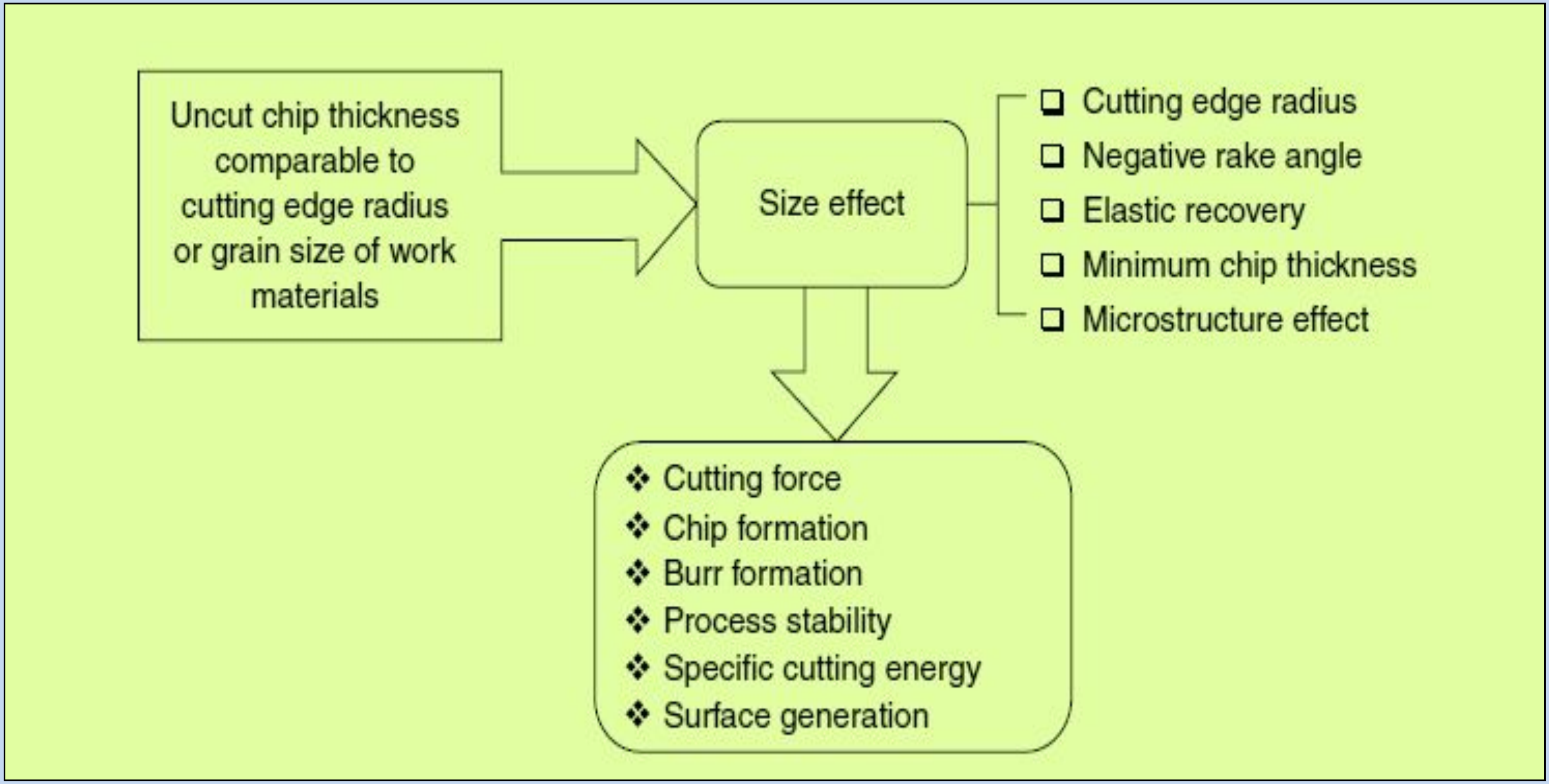
# Negative Rake angle

- When the cutting parameters, such as depth of cut or the uncut chip thickness, is on the same order of tool edge radius, the effective rake angle may become highly negative.

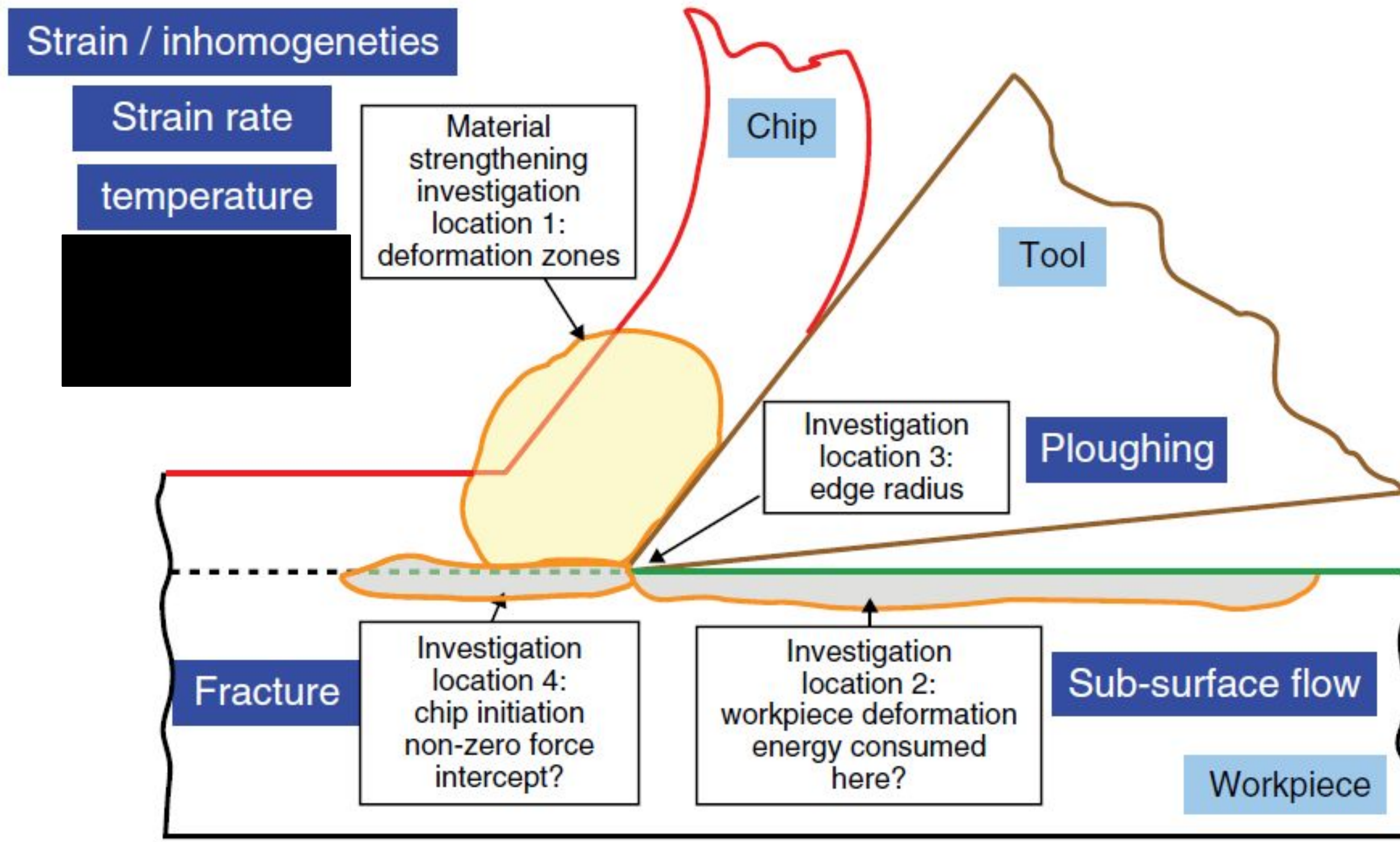


# Size effect in Micro cutting



# Size effect in Micro cutting



# Micro turning setup

Piezo electric dynamometer

Cutting insert

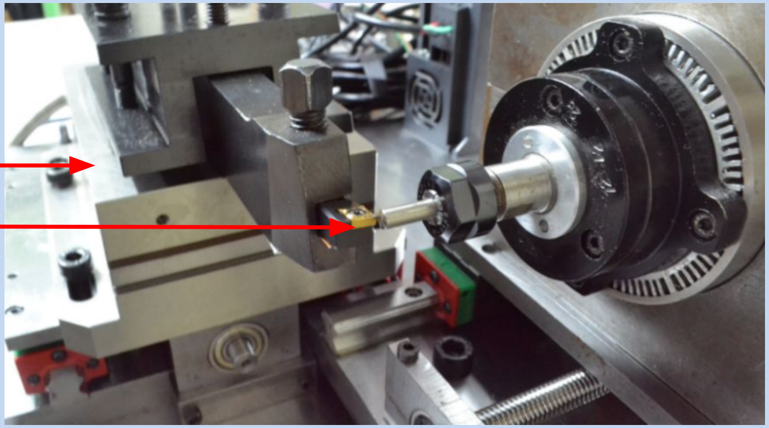
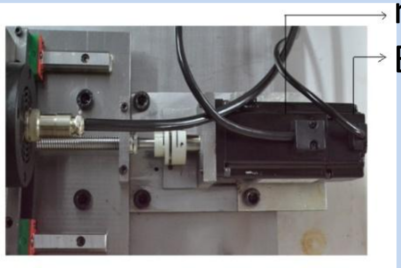


Fig. Closer view of micro turning setup

Servo motor

Encoder

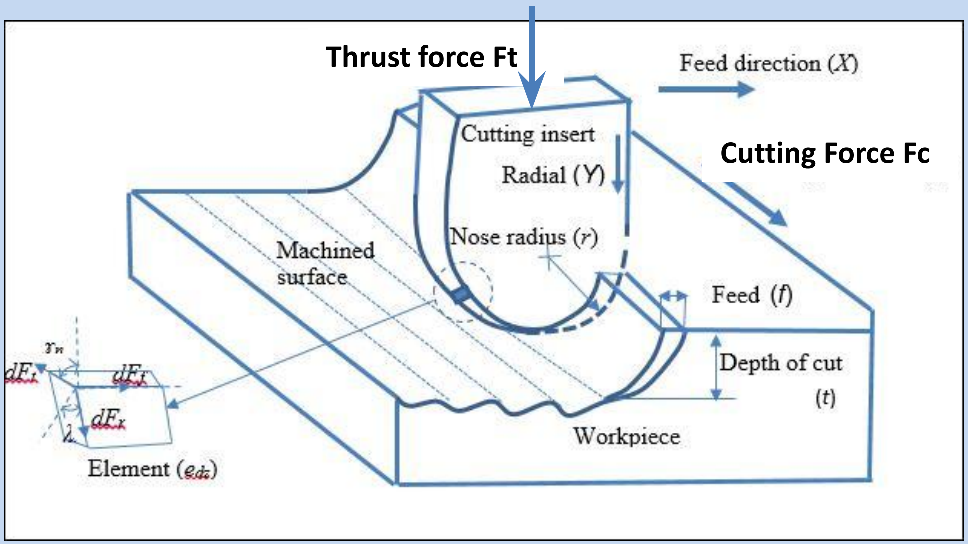


**Encoder drive**

- The experimental setup for conducting experiments is shown in *Figure,* consists of X and Z axis linear slides which is used for controlling the depth of cut and feed respectively.

# Specific Cutting Energy and Micro Cutting Force

- Specific cutting energy can be defined as the energy consumed in removing a unit volume of material.
- The forces acting on the tool and work piece during orthogonal cutting.
- The forces can be separated into two mutually perpendicular components which can be directly measured by a dynamometer




- **Cutting force *Fc***. This force is in the direction of cutting, and same direction as the cutting speed v.
- **Thrust force *Ft***. This force is perpendicular to the cutting force.

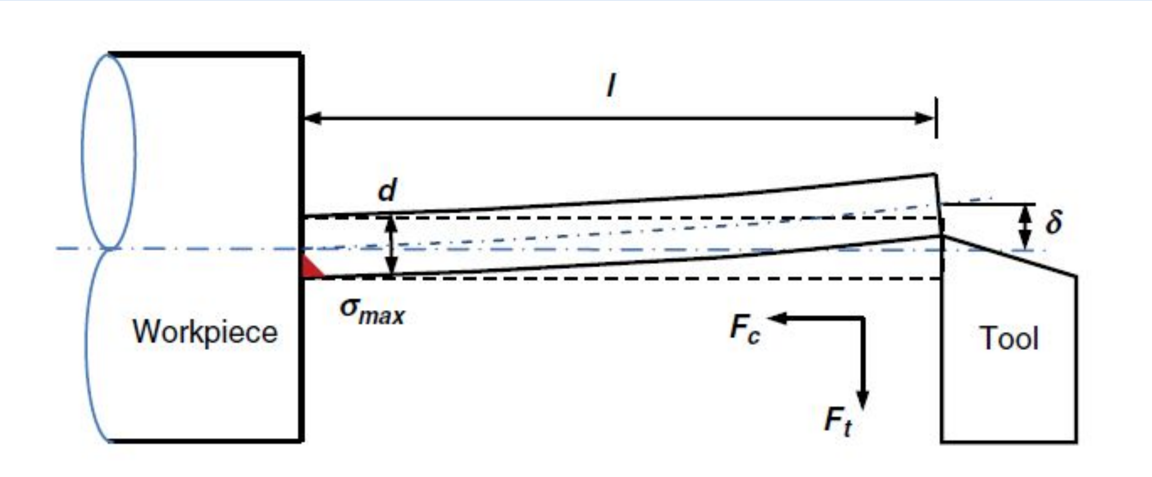
**The specific cutting energy,** *E*, is calculated by dividing the cutting force by the chip area

$$E = \frac{P}{MRR} = \frac{F_c v}{vbd} = \frac{F_c}{bd} \left(\text{in J/mm}^3, \text{N/mm}^2 \text{or MPa}\right)$$

- **Where *P* is the rate at which energy is consumed in the cutting process in N · mm/s;**
- ***MRR* is the material removal rate, in mm$^3$/s;**
- ***v* is the cutting speed in mm/s;**
- ***b* is the width of cut in mm;**
- ***d* is the uncut chip thickness.**

**Material removal rate (MRR) = Cutting velocity * feed rate* depth of cut**

# Micro shaft deflection and stress in micro turning




The bending stiffness *k* of the micro shaft is determined by

$$k = \frac{F_t}{\delta}$$

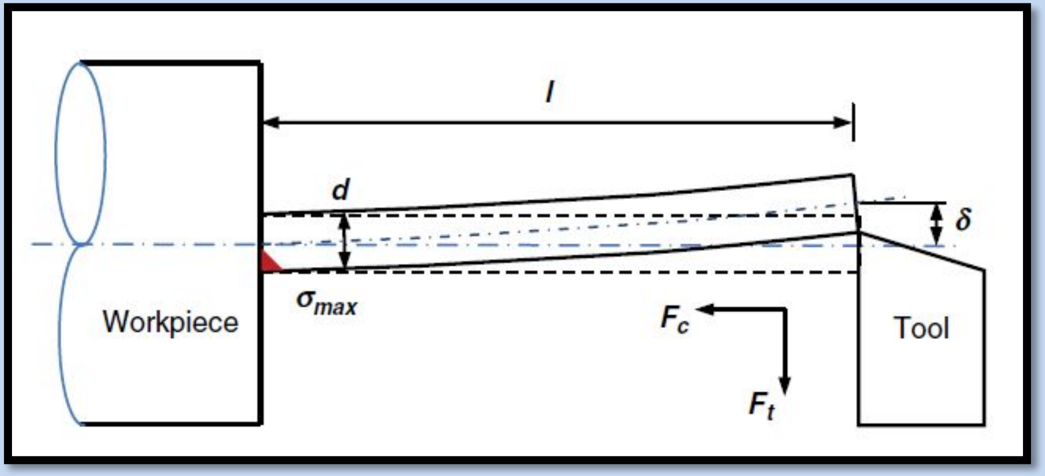
***Ft*** is the thrust force
**δ** is the bending deflection at tool-work piece contact point, which can be determined by

$$\delta = \frac{F_t l^3}{3EI} = \frac{64 F_t l^3}{3\pi E d^4}$$

*l* is the length of the shaft,
*d* is the diameter of the shaft,
*E* is Young's modulus, and
*I* is the moment of inertia.

# Find Buckling during micro turning

When axial force (here is the cutting force *Fc*) acts on the shaft, simple compression occurs for low values of the force. When *Fc* reaches a specific value, the long shaft becomes unstable and unstable bending or buckling occurs.




The critical force for the end condition as illustrated in Figure is governed by the Euler column formula

$$P_{cr} = \frac{\pi^2 EI}{4l^2}$$

Substituting $E_B = E_A,\ l_B = Sl_A,\ d_B = Sd_A,\ I_B = S^4 I_A,\ m_B = S^3 m_A$

- Here we consider a micro shaft A with a length of $l_A$ and a diameter of $d_A$, and a conventional shaft B with a length $l_B$ and a diameter of $d_B$ respectively.
- Two shafts have same aspect ratio $d/l$, and scaling factor $S$ is defined as $l_B/l_A$.

Substituting $E_B = E_A,\ l_B = Sl_A,\ d_B = Sd_A,\ I_B = S^4 I_A,\ m_B = S^3 m_A$

$$P_{crB} = \frac{\pi^2 E_B I_B}{4l_B^2} = \frac{\pi^2 E_A S^4 I_A}{4S^2 l_4^2} = S^2 P_{crA}$$

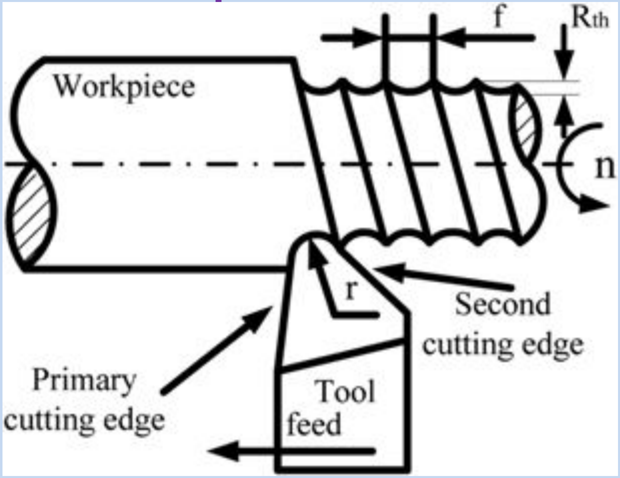
$$P_{crA} = \frac{1}{S^2} P_{crB}$$

$I_A$ and $I_B$ – Moment of inertia of shaft A and B respectively

This shows that a size reduction by a factor of $S$ results in a decrease of critical buckling force $P_{crA}$ by a factor of $1/S^2$, which means a size reduction causes micro shafts to be more sensitive to buckling.

# Size Effect on Surface Roughness in Micro Turning

- Surface quality is an important character of **micro optics and mold parts.**
- Surface roughness is predominantly considered as the most important feature of practical engineering surface due to its **crucial influence on the mechanical and physical properties of a machined part.**

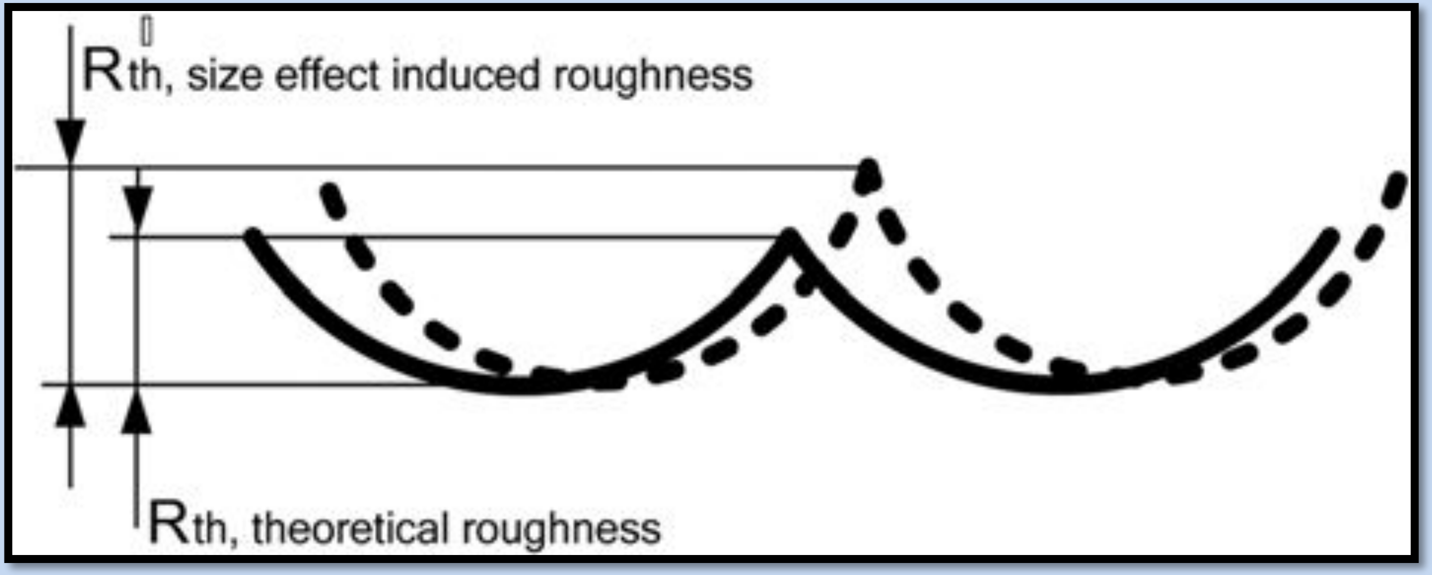



The peak-to-valley height considering **the feed per revolution (f) and cutting edge radius (r)** can be used to calculate the surface roughness , from fig

$$\boxed{R_{th} = \frac{f^2}{8r}}$$

where $R_{th}$ is the theory value of the peak-to-height,
f is the feed per revolution, and
r is the cutting edge radius.

# Surface roughness profile generated by tool with radius with and without size effect

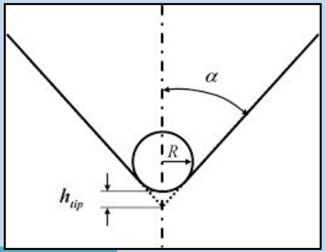



- In micro cutting, the dotted curve lines show in figure that the material in front of the primary cutting edge is piled, while the material around the second cutting edge flows back due to the high normal pressure.
- It is obvious that the value of the peak-to-valley height is larger than the theoretical result considering the side flow

# Contact depth and pile-up height in scratch test

- The micro turning is similar to the scratch test in the feeding direction.
- The material will flow to the minimum resistance direction when the pressure reaches 0.57σy, where σy is the yield strength of the material

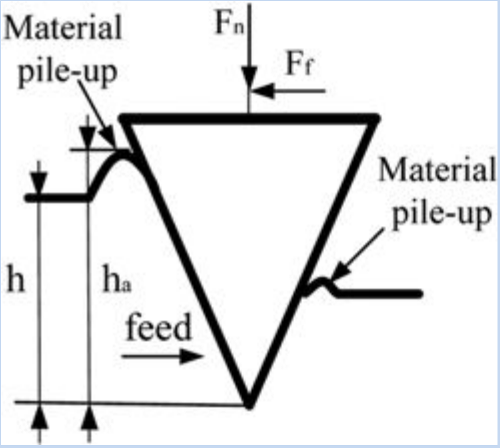
$$x = \frac{E}{\sigma_y \tan \alpha}$$




where E is the Young's modulus of work piece,
α is the actual semi apical angle of the indenter according to the geometry of the cutting edge,
**α = arcsin(1 - t/r)**
σy is the yield stress of the work piece.

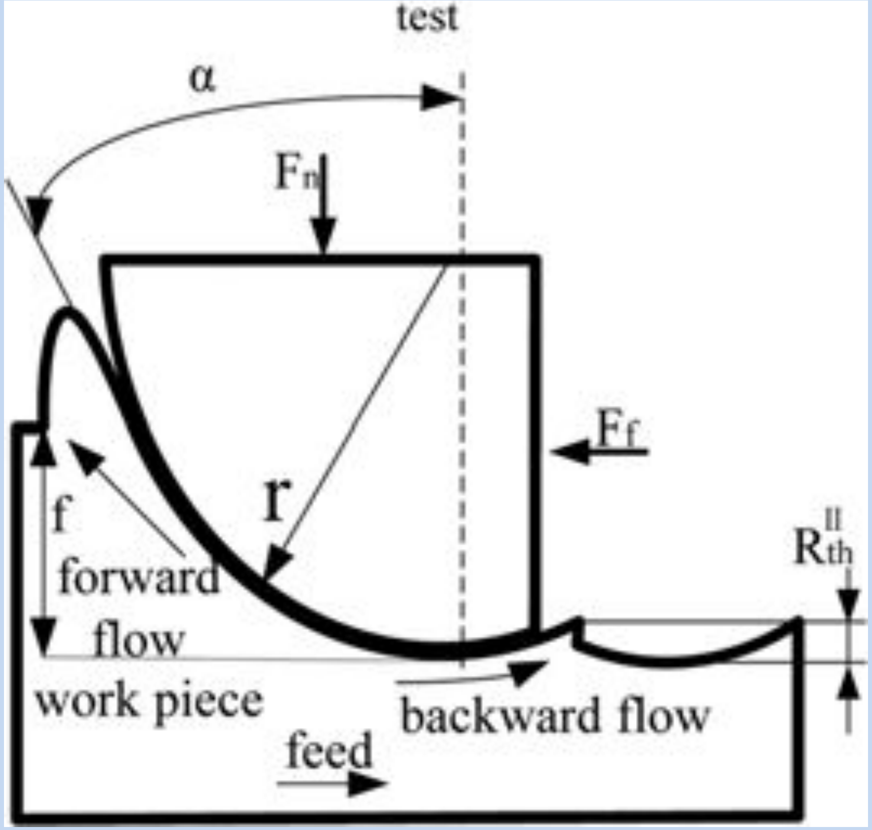
The rheological coefficient x is an important parameter to evaluate the pile-up height

$$\frac{h_a}{h} = 0.3084 \ln x + 0.3233$$



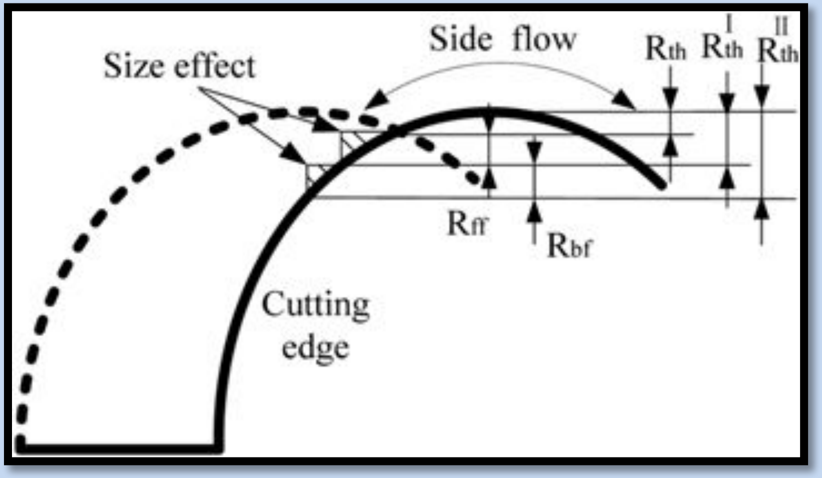

**Sketch of contact depth and pile-up height in scratch**

The pile-up height consists of two processes in the feeding direction of micro turning. First, the material piles in front of the primary cutting edge, then the material flows along the rear face and piles up as shown in fig below




**Side flow around the cutting edge in micro turning**

The pile-up height can be divided into two components;
$R_{ff}$ is the forward side flow pile-up height,
while $R_{bf}$ is the backward side flow pile-up height.




**Sketch of pile-up surface roughness**

The peak-to-valley height due to side flow can be given in

$$\frac{R_{th}^{\mathrm{I}}}{R_{th}} = k_1 \ln x + k_2$$

$$\frac{R_{th}^{\mathrm{II}}}{R_{th}^{\mathrm{I}}} = k_3 \ln x + k_4$$

where ki is the fitting coefficients, i is from 1 to 4

$$\frac{R_{th}^{\mathrm{II}}}{R_{th}} = g_1 \ln^2 x + g_2 \ln x + g_3$$

The coefficients gi can be calibrated via micro turning tests performed over a wide range of cutting conditions.

**Therefore the bending stiffness can be expressed as**

$$\boxed{k = \frac{3EI}{l^3} = \frac{3\pi E d^4}{64 l^3}} \quad \text{....Eqn A}$$

## Bending stress at the end of the shaft

$$\boxed{\sigma = \frac{32 F_t l}{\pi d^3}}$$

- Here we consider a micro shaft A with a length of *la* and a diameter of *da*, and a conventional shaft B with a length *lb* and a diameter of *db* respectively.
- Two shafts have same aspect ratio *d/l*, and scaling factor *S* is defined as *lb/la*.

$$\boxed{E_B = E_A,\ l_B = S l_A,\ d_B = S d_A,\ I_B = S^4 I_A,\ m_B = S^3 m_A} \quad \text{....Eqn B}$$

Substituting Equation B into Equation A gives:

$$k_B = \frac{3E_B I_B}{l_B^3} = \frac{3E_A S^4 I_A}{S^3 l_A^3} = Sk_A$$

**This shows that a size scaling down gives a reduction on the bending stiffness by the same factor.**

Consider that the same thrust force is loaded on shaft A and B, and this is likely the case for the same cutting conditions, that is, uncut chip thickness and feed rate might be used for cutting micro shaft A and shaft B, which will result in the same cutting forces

Substituting Equation (B) into Equation

$$\sigma = \frac{32F_t l}{\pi d^3}$$

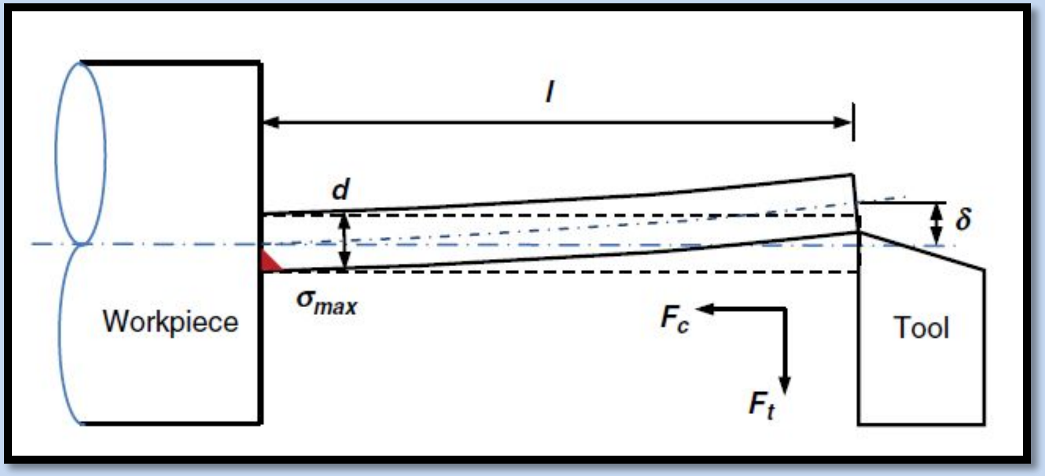
$$\sigma_B = \frac{32F_t l_B}{\pi d_B^3} = \frac{32F_t S l_A}{\pi S^3 d_A^3} = \frac{1}{S^2}\sigma_A$$

$$\sigma_A = S^2 \sigma_B$$

This indicates that under the same load maximum stress of shaft A is *S*2 times that of shaft B. That means the micro shaft in the micro turning process is more likely to reach the maximum material strength.

# Find Buckling during micro turning

When axial force (here is the cutting force *Fc*) acts on the shaft, simple compression occurs for low values of the force. When *Fc* reaches a specific value, the long shaft becomes unstable and unstable bending or buckling occurs.

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$$P_{crB} = \frac{\pi^2 E_B I_B}{4 l_B^2} = \frac{\pi^2 E_A S^4 I_A}{4 S^2 l_4^2} = S^2 P_{crA}$$

$$P_{crA} = \frac{1}{S^2} P_{\mathrm{crB}}$$

This shows that a size reduction by a factor of $S$ results in a decrease of critical buckling force $P_{crA}$ by a factor of $1/S^2$, which means a size reduction causes micro shafts to be more sensitive to buckling.

# Flow stress and strain rate

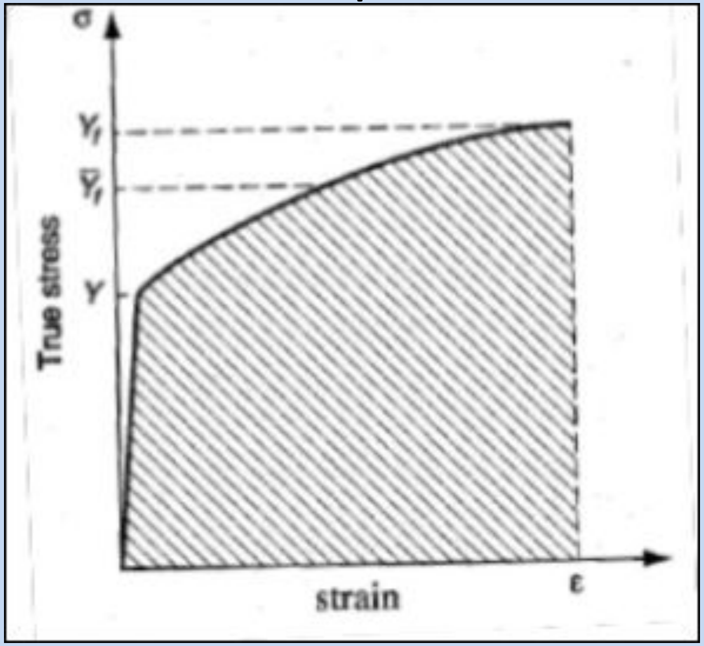
# Flow stress

## Definition

- Flow stress is the instantaneous value of stress required to continue deforming the material plastically - to keep the metal flowing.

- Flow stress is the stress required to sustain a certain plastic strain on the material.

- The average flow stress is the average value of stress over the stress strain curve from the beginning of strain to the final maximum value that occurs during deformation



# Estimation of flow stress

- ✔ Flow stress can be determined form simple uniaxial tensile test, homogeneous compression test, plane strain compression test or torsion test, split Hopkinson bar.

- ✔ The most commonly used model for prediction of flow stress are **Johnson cook model.**

- ✔ **Assumption:** Flow stress depends on the strain, strain rate and temperature can be multiplicatively decomposed into three separate functions.

# Strain rate

- ✔ Rate of change in strain of a material with respect to time.
- ✔ The strain rate involved in machining process are in the range of $10^3$ to $10^6$ $s^{-1}$

$$\dot{\varepsilon} = \frac{2V\cos(\gamma_n)}{\sqrt{3}h\cos(\varphi_n-\gamma_n)}$$

- ✔ where $\gamma_n$ is the normal rake angle

  $\phi_n$ is the shear angle,

  V is the cutting speed in mm/min

  h is the thickness of primary shear zone

# Johnson cook model

$$\sigma = [\mathrm{A} + \mathrm{B} \in^n] \left[1 + C \ln \frac{\dot{\in}}{\dot{\in}_0}\right] \left[1 - \left(\frac{T - T_{Room}}{T_{Melt} - T_{Room}}\right)^m\right]$$

Where

| | |
|---|---|
| A | Yield strength of work material (MPa) |
| B | Strain Hardening modulus (MPa) |
| C | Strain rate sensitivity coefficient |
| m | Thermal softening coefficient |
| n | Hardening coefficient |
| $\dot{\in}$ | Strain rate (/s) |
| $\dot{\in}_0$ | Reference strain rate (/s) |
| $\in$ | Plastic Strain |
| $T_{room}$ | Room temperature (K) |
| $T_{melt}$ | Melting temperature of workpiece (K) |
| T | Workpiece temperature (K) |
| $T_0$ | Ambient temperature (K) |

# Modified Johnson cook model

$$\sigma_{micro} = \sigma\sqrt{1 + \left(\frac{18a^2bG^2\eta}{\sigma^2}\right)^{\chi}}$$

$\sigma_{micro}$ is the flow stress during micro turning

a is the empirical constant

b is the magnitude of burger vector

G is the shear modulus

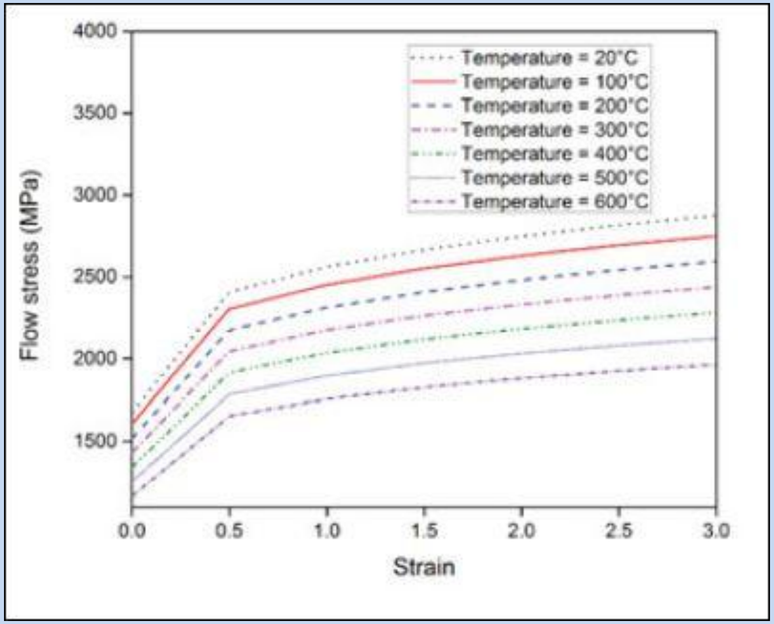
$\chi$ is the geometric dislocation density

$\eta$ is the effective strain gradient

$$\sigma_{micro} = \sigma\sqrt{1 + l\eta}$$

l = material length scale

$\eta$ = strain gradient

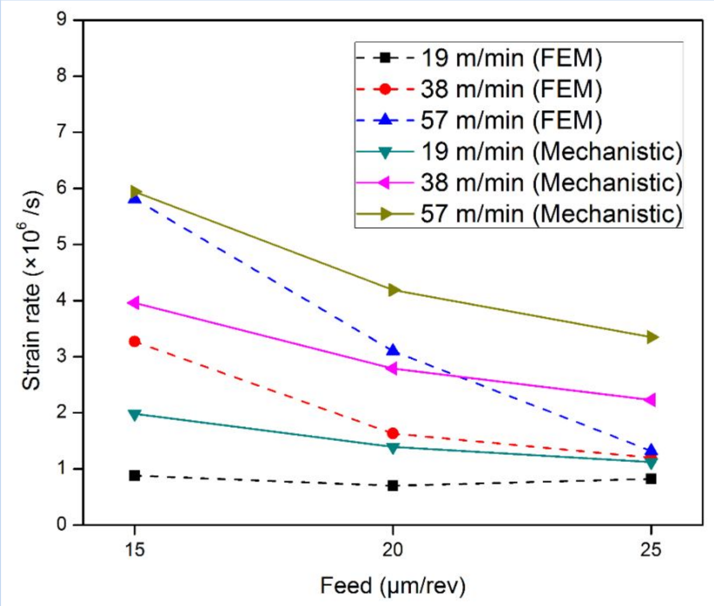



Variation of flow stress with strain at various temperatures with $10^5$ strain rate

- ✔ When the temperature increases, there is a decrease in flow stress observed mainly due to thermal softening.
- ✔ When temperature increases there is decrease in the density and multiplication rate of dislocations, resulting in a loss of resistance to plastic flow, and therefore, the material becomes softer and more ductile.

# Strain rate variation with cutting speed and feed rate

- During micro turning of titanium alloy, when cutting speed increases, there is an increase in strain rate because of severe plastic deformation.
- On the other hand, strain rate decreases by increasing the feed rate due to increase in adiabatic shear band spacing.



# Eccentric force in Micro turning

- In order to increase linear cutting speed, spindles for micro cutting normally have higher rotational speed than that used in conventional cutting processes
- In fact miniaturized high speed spindles might have a higher level of errors than conventional spindles. Therefore it is necessary to analyze the size effect on deflection of micro shafts under eccentric force.

Consider two shafts (the same as the above analysis) are mounted in two spindles which are subjected to radial run out $\varepsilon A$ and $\varepsilon B$ respectively. We assume two spindles have the same radial run out. The rotational speed of the miniaturized spindle A is S times that of conventional spindle B,

$$\boxed{\varepsilon_A = \varepsilon_B \quad \text{and} \quad \omega_A = S\omega_B}$$

The eccentric force is given by

$$\boxed{F_e = m\omega^2 \varepsilon}$$

Substituting $E_B = E_A,\ l_B = Sl_A,\ d_B = Sd_A,\ I_B = S^4 I_A,\ m_B = S^3 m_A$

and

$$\boxed{\varepsilon_A = \varepsilon_B \quad \text{and} \quad \omega_A = S\omega_B}$$

We get $$\boxed{F_{eB} = m_B \omega_B^2 \varepsilon_B = S^3 m_A S^{-2} \omega_A^2 \varepsilon_A = SF_{eA}}$$

Substituting Equation $E_B = E_A,\ l_B = Sl_A,\ d_B = Sd_A,\ I_B = S^4 I_A,\ m_B = S^3 m_A$ and

$$F_{eB} = m_B \omega_B^2 \varepsilon_B = S^3 m_A S^{-2} \omega_A^2 \varepsilon_A = SF_{eA}$$

in

$$\boxed{\delta = \frac{F_t l^3}{3EI} = \frac{64 F_t l^3}{3\pi E d^4}}$$

$$\delta_B = \frac{F_{eB} l_B^3}{3E_B I_B} = \frac{S F_{eA} S^3 l_A^3}{3E_A S^4 I_A} = \delta_A$$

- This equation implies that if a size reduction by a factor of *S* and a speed increase by the same factor of *S*, which is close to some micro cutting applications.
- The deflection of shaft caused by eccentric force remains the same as that of conventional cutting before scaling down.
- In terms of maximum stress shaft A is *S* times that of shaft B. That means micro shaft would be more sensitive to eccentric force induced deflection, and the micro shaft in the micro turning process is more likely to reach material strength.
- We should take these into consideration when we choose spindle speed for micro cutting process.

Substituting Equation $E_B = E_A,\ l_B = Sl_A,\ d_B = Sd_A,\ I_B = S^4 I_A,\ m_B = S^3 m_A$ and

$$F_{eB} = m_B \omega_B^2 \varepsilon_B = S^3 m_A S^{-2} \omega_A^2 \varepsilon_A = SF_{eA}$$

in

$$\boxed{\sigma = \frac{32F_t l}{\pi d^3}}$$

Will give

$$\boxed{\sigma_B = \frac{32F_{eB} l_B}{\pi d_B^3} = \frac{32SF_{eA} Sl_A}{\pi S^3 d_B^3} = \frac{1}{S}\sigma_A}$$

# Cutting force in orthogonal machining

$$P_Z = \frac{t s_0 \tau_s \cos(\eta_0 - \gamma_0)}{\sin \beta_0 \cos(\beta_0 + \eta_0 - \gamma_0)}$$

t = depth of cut

$S_0$ = Uncut chip thickness

$\Upsilon_0$ = Rake angle

$\eta_0$ = Friction angle

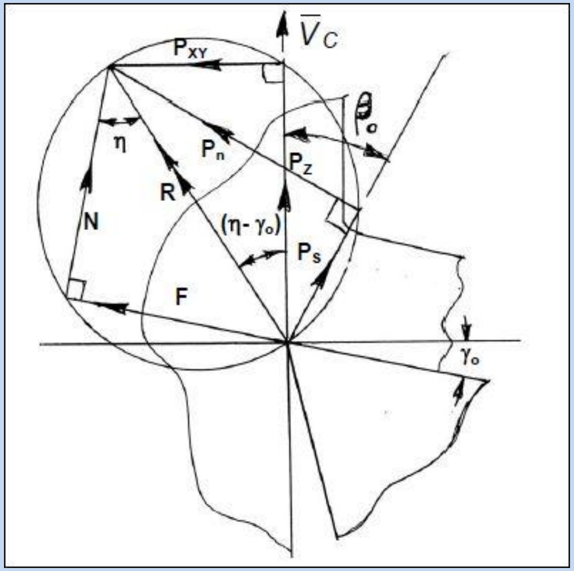
$\beta_0$ = Shear angle

$\tau_s$ = Shear stress

$$\sigma_{Ref}(\varepsilon, \dot{\varepsilon}, T) = \left[A + B\varepsilon^n\right]\left[1 + C \ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right]\left[1 - \left(\frac{T - T_{room}}{T_m - T_{room}}\right)^m\right]$$

$$\tau = \sigma / \sqrt{3}$$

Acc. To Von Mises criteria)




**Merchant circle diagram**

**For micro machining**

$$\sigma = \sigma_{Ref}\left(\sqrt{1 + \ell\eta}\right)$$

l = material length scale

η = strain gradient

Material removal rate = Cutting velocity * feed rate* depth of cut

1. Calculate the cutting force during micromachining process, if depth of cut = 6 μm, Uncut chip thickness = 3 μm, material length scale = 5 μm, strain gradient = (1/3 μm), Rake angle, Friction angle and Shear angle are 5, 10, 30° respectively. Evaluate at strain rate 0.5 $s^{-1}$ and temperature 600℃. Assume Johnson cook material constants for mild steel.

2. Calculate the material removal rate during micro turning process if cutting velocity = 100 m/min, depth of cut = 5 μm, and feed rate 3 μm/rev.