Machining of metals

Subjects of interest

- Introduction/objectives
- Type of machining operations
- Mechanics of machining
- Three dimensional machining
- Temperature in metal cutting
- Cutting fluids
- Tool materials and tool life
- Grinding processes
- Non traditional machining processes
- Economics of machining
Objectives

• This chapter aims to provide basic backgrounds of different types of machining processes and highlights on an understanding of important parameters which affects machining of metals.

• Mechanics of machining is introduced for the calculation of power used in metal machining operation

• Finally defects occurring in the machining processes will be discussed with its solutions. Significant factors influencing economics of machining will also be included to give the optimum machining efficiency.
Introduction

- **Machining** is operated by *selectively removing the metal from the workpiece* to produce the required shape.

- Removal of metal parts is accomplished by *straining a local region of the workpiece to fracture* by the relative motion of the tool and the workpiece.

**Turning of metal**

- **Conventional methods** require mainly mechanical energy.

- **More advanced metal-removal processes** involve chemical, electrical or thermal energy.
• Produce shapes with **high dimensional tolerance, good surface finish** and often with **complex geometry** such as holes, slots or re-entrant angles.

• A **secondary processing operation** (finishing process) employed after a primary process such as hot rolling, forging or casting.

• **Tooling** must be stronger than the workpiece.
Type of machining operations

Classification of machining operations is roughly divided into:

- Single point cutting
- Multiple point cutting
- Grinding
- Electro discharge machining
- Electrochemical machining
**Single point cutting**

Removal of the metal from the workpiece by means of cutting tools which have *one major cutting edge*.
**Multiple point cutting**

Removal of the metal from the workpiece by means of cutting tools which have *more than one major cutting edge*.
Grinding

Removal of the metal from the workpiece using tool made from *abrasive particles of irregular geometry*. 
**Electrical discharge machining**

Removal of material from the workpiece by *spark discharges*, which are produced by connecting both tool (electrode) and workpiece to a power supply.

High voltage sparks between workpiece and tool erode the workpiece material. The gap between tool and workpiece kept constant by controlling the position of the tooling. The dielectric fluid cools the vaporized material into 'chips' which are then flushed away and filtered out.

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Suranaree University of Technology  
Tapany Udomphol  
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Electrochemical machining

Removal of material from the workpiece by *electrolysis*. Tool (electrode) and workpiece are immersed in an electrolyte and connected to a power supply.

Removes any electrically conductive material by the anodic dissolution of the workpiece (+ve) in a stream of electrolyte which separates the workpiece from the shaped electrode (−ve) or tool. The tool has a constant feed rate matched to the rate of dissolution of the workpiece, which is formed into a mirror image of the tool.
What happens during machining of a bar on a lathe?

A chip of material is removed from the surface of the workpiece.

**Principal parameters:**
- the cutting speed, $v$
- the depth of cut, $w$ or $d$
- the feed, $f$

**Time** requires to turn a cylindrical surface of length $L_w$,

$$t = \frac{L_w}{fn_w}$$

Where $n_w$ is the number of revolutions of the workpiece per second.

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**Geometry of single-point lathe turning**

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Tapany Udomphol

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Chip formation

- The tool removes material near the surface of the workpiece by *shearing it to form the chip*.
- Material with thickness $t$ is sheared and travels as a *chip* of thickness $t_c$ along the *rake face* of the tool.
- The chip thickness ratio (cutting ratio) $r = t / t_c$.
- *Extensive deformation* has taken place, as seen from the fibre texture of the polished and etched metal workpiece.
Two basic deformation zone:

• The entire chip is deformed as it meets the tool, known as primary shear. Shear plane angle is $\phi$.

• Localised region of intense shear occurring due to the friction at the rake face, known as secondary shear.
The shear angle $\phi$ is controlled by the cutting ratio $r$.

The relationship between rake angle, shear angle, and chip thickness ratio, $r$ can be derived as follows:

\[ r = \frac{t}{t_c} = \frac{OD \sin \phi}{OD \cos (\phi - \alpha)} \]  \hspace{1cm} \text{...Eq. 2}

and

\[ \tan \phi = \frac{r \cos \alpha}{1 - r \sin \alpha} \]  \hspace{1cm} \text{...Eq. 3}

Triangle $ODF$ has been sheared to form $ODF'$, which has the same area.

The shear strain is given by

\[ \gamma = \frac{FF'}{h} = \frac{\cos \alpha}{\sin \phi \cos (\phi - \alpha)} \]  \hspace{1cm} \text{...Eq. 4}
• The amount of primary shear is related to the rake angle $\alpha$.

(a) If $\alpha$ is a large positive value, the material is deformed less in the chip.

(b) If $\alpha$ is a negative value, the material is forced back on itself, thus requiring higher cutting forces.

(c) The tool has a negative $\alpha$ but a small area of positive rake just behind the cutting edge. → chip breaker.
Effect of rake face contact length on chip thickness and shear plane angle

- The deformed chip is flowing over a static tool, leading to frictional force similar to friction hill.
- If $\mu$ is greater than 0.5, sticky friction will result and flow will occur only within the workpiece but not at the tool-workpiece interface.
- Sticky friction is the norm in cutting due to difficulty in applying lubricant.

Efficient cutting occurs when shear angle $\phi \sim 45^\circ$. 

force to move the chip $\uparrow$ chip thickness $\uparrow \rightarrow$ change shear angle $\phi$
**The cutting speed**

There are three velocities:
1) **Cutting speed** \( v \), is the velocity of the tool relative to the workpiece.
2) **Chip velocity** \( v_c \), is the velocity of the chip relative to the tool face.
3) **Shear velocity** \( v_s \), is the velocity of the chip relative to the work.

From continuity of mass, \( vt = v_c t_c \)  

\[ r = \frac{t}{t_c} = \frac{v_c}{v} \]  \( \ldots \text{Eq. 5} \)

From *kinematic relationship*, the vector sum of the cutting velocity and the chip velocity = the shear velocity vector.

\[ v_s = \frac{v \cos \alpha}{\cos(\phi - \alpha)} \]  \( \ldots \text{Eq. 6} \)
Since volume is constant during plastic deformation, and chip width $b$ is essentially constant,

$$
\rho \frac{L_{cw}}{W_{tcL}} = rL_t
$$

Therefore we could also obtain $r$ from the ratio of the chip length $L_c$, to the length of the workpiece from which it came, $L_w$.

If $L_c$ is unknown, it can be determined by measuring the weight of chips $W_c$ and by knowing the density of the metal $\rho$.

$$
L_{wtb} = \frac{W_c}{\rho}
$$
Shear strain rate in cutting

\[
\gamma = \frac{d\gamma}{dt} = \frac{\nu_s}{(y_s)_{\text{max}}}
\]  

...Eq. 9

Where \((y_s)_{\text{max}}\) is the estimate of the maximum value of the thickness of the shear zone, \(~\sim\) 25 mm.

**Example:** Using realistic values of \(\phi = 20\), \(\alpha = 5^\circ\), \(\nu = 3\ \text{m.s}^{-1}\) and \((y_s)_{\text{max}} \sim 25\ \text{mm}\). We calculate \(\gamma = 1.2 \times 10^5\ \text{s}^{-1}\).

This is about several orders of magnitude greater than the strain rate usually associated with high-speed metal working operation.
**Forces and stresses in metal cutting**

- \( P_R \) - the resultant force between the tool face and the chip
- \( P'_R \) - the equal resultant force between the workpiece and the chip

The **resultant force** to the rake face of the tool can be resolved into **tangential component** \( F_t \) and **normal component** \( F_n \).

- The **horizontal** (cutting) \( F_h \) and **vertical** (thrust) \( F_v \) forces in cutting can be measured independently using a strain-gauge toolpost dynamometer.

- It can be shown that
  
  \[
  F_t = F_h \sin \alpha + F_v \cos \alpha \\
  F_n = F_h \cos \alpha - F_v \sin \alpha
  \]
• If the components of the cutting force are known, then the coefficient of friction $\mu$ in the tool face is given by

$$\mu = \tan \beta = \frac{F_i}{F_n} = \frac{F_v + F_h \tan \alpha}{F_h - F_v \tan \alpha}$$

...Eq. 10

Finally, the resultant force may be resolved parallel $F_s$ and normal $F_{ns}$ to the shear plane.

...Eq. 11

$$F_s = F_h \cos \phi - F_v \sin \phi$$

...Eq. 12

$$F_{ns} = F_h \sin \phi + F_v \cos \phi$$
The **average shear stress** $\tau$ is $F_s$ divided by the area of the shear plane $A_s = bt \sin \phi$

$$\tau = \frac{F_s}{A_s} = \frac{F_s \sin \phi}{bt}$$

...Eq. 13

The **shear stress** in cutting is the main parameter affecting the energy requirement.

And the normal stress $\sigma$ is

$$\sigma = \frac{F_{ns}}{A_s} = \frac{F_{ns} \sin \phi}{bt}$$

...Eq. 14
• We need to know the **shear angle** $\phi$ in order to calculate the shear stress in cutting from force measurements.

• The **shear angle** $\phi$ can be measured experimentally by suddenly stopping the cutting process and using metallographic techniques to determine the shear zone.

• **Merchant** predicted $\phi$ by assuming that the shear plane would be at the angle which minimises the work done in cutting.

$$\phi = \frac{\pi}{4} + \frac{\alpha}{2} + \frac{\beta}{2}$$

...Eq. 15
However, in practice, the **shear plane angle** \( \phi \) is varied depending on the nature of each material (composition & heat treatment) to be machined.

Based on the **upper bound model** of the shear zone, a criterion for predicting \( \phi \) has been developed. The predicted shear plane angle \( \phi_o \) is given by

\[
\cos(\phi_o - \alpha)\sin \phi_o = \frac{k_o}{k_1} \left[ \cos \left( 45 - \frac{\alpha}{2} \right) \sin \left( 45 + \frac{\alpha}{2} \right) \right]
\]

…Eq. 16

Where
- \( \alpha \) = rake angle
- \( k_o = \sigma_o / \sqrt{3} \) and \( \sigma_o \) is the yield strength of the material
- \( k_1 = \sigma_u / \sqrt{3} \) and \( \sigma_u \) is the tensile strength of the material.
**Example:** Determine the shear plane angle in orthogonal machining with a \(6^\circ\) positive rake angle for hot-rolled AISI 1040 steel and annealed commercially pure copper.

**Given**
- Hot-rolled 1040 steel: \(\sigma_o = 415\) MPa, \(\sigma_u = 630\) MPa
- Annealed copper: \(\sigma_o = 70\) MPa, \(\sigma_u = 207\) MPa

\[
\cos(\phi_o - 6)\sin \phi_o = \frac{k_o}{k_1} \left[ \cos \left(45 - \frac{6}{2}\right) \sin \left(45 + \frac{6}{2}\right) \right]
\]

\[
\cos(\phi_o - 6)\sin \phi_o = \frac{k_o}{k_1} (0.552)
\]

\[
\frac{1}{2} \left[ \sin 6^\circ + \sin (2\phi_o - 6) \right] = \frac{k_o}{k_1} (0.552)
\]

\[
2\phi_o = \left[ \sin^{-1} \left( 1.104 \frac{k_o}{k_1} - 0.1045 \right) \right] + 6^\circ
\]

For hot-roll 1040 steel:

\[
2\phi_o = \left[ \sin^{-1} \left( 1.104 \times \frac{415}{630} - 0.1045 \right) \right] + 6^\circ
\]

\[
2\phi_o = \sin^{-1} (0.6227) + 6^\circ = 44.5^\circ
\]

\[
\phi_o = 22.3^\circ \text{ Experimental range is 23 to 29}\text{o}
\]

For annealed copper:

\[
2\phi_o = \left[ \sin^{-1} \left( 1.104 \times \frac{70}{207} - 0.1045 \right) \right] + 6^\circ
\]

\[
2\phi_o = \sin^{-1} (0.2688) + 6^\circ = 21.6^\circ
\]

\[
\phi_o = 10.8^\circ \text{ Experimental range is 11 to 13.5}\text{o}
\]

Note that \(k_o/k_1\) is a fraction, then we can use **tensile values** directly in the above equations.
**Specific cutting energy**

- **Power** required for cutting is $F_h v$
- The volume of metal removed per unit time (metal removal rate) is $Z_w = btv$
- Therefore the energy per unit volume $U$ is given by

$$U = \frac{F_h v}{Z_w} = \frac{F_h v}{btv} = \frac{F_h}{bt}$$

...Eq. 17

Where $b$ is the width of the chip
$t$ is the undeformed chip thickness

*Force values of specific cutting energy for various materials and machining operations*
The specific cutting energy $U$ depends on the material being machined and also on the cutting speed, feed, rake angle, and other machining parameters.

(at cutting speed $> 3 \text{ m.s}^{-1}$, $U$ is independent of speed)

The total energy for cutting can be divided into a number of components:

1. The total energy required to produce the gross deformation in the shear zone.
2. The frictional energy resulting from the chip sliding over the tool face.
3. Energy required to curl the chip.
4. Momentum energy associated with the momentum change as the metal crosses the shear plane.
5. The energy required to produce the new surface area.
**Example:** In an orthogonal cutting process $v = 2.5 \text{ m.s}^{-1}$, $\alpha = 6^\circ$, and the width of cut is $b = 10 \text{ mm}$. The underformed chip thickness is $200 \mu\text{m}$. If $13.36$ g of steel chips with a total length of $500 \text{ mm}$ are obtained, what is the slip plane angle? density $= 7830 \text{ kg.m}^{-3}$.

From *Eq. 8*, thickness of chip

$$t_c = \frac{W_c}{\rho b L} = \frac{0.01336\text{kg}}{(7830\text{kg.m}^{-3}) \times (0.010\text{m})(0.500\text{m})}$$

$t_c = 0.341\text{mm}$

From *Eq. 3*

$$\tan \phi = \frac{r \cos \alpha}{1 - r \sin \alpha} = \frac{0.586 \cos 6^\circ}{1 - 0.586 \sin 6^\circ} = 0.621$$

$\phi = 32^\circ$

Chip thickness ratio

$$r = \frac{t}{t_c} = \frac{0.200}{0.341} = 0.586$$

$\beta = ?$, from *Eq. 10*

$$\mu = \tan \beta = \frac{F_t}{F_n} = \frac{F_v + F_h \tan \alpha}{F_h - F_v \tan \alpha}$$

$$\tan \beta = \frac{440 + 1100 \tan 6^\circ}{1100 - 440 \tan 6^\circ} = 0.527$$

$\beta = 27.8^\circ$
If a toolpost dynamometer gives cutting and thrust forces of $F_h = 1100$ N and $F_v = 440$ N, determine the percentage of the total energy that goes into overcoming friction at the tool-chip interface and the percentage that is required for cutting along the shear plane. (Density $\rho = 7830$ kg.m$^{-3}$.)

The total specific energy is

$$U = U_f + U_s$$

From Eq. 17

$$U = \frac{F_h}{bt}$$

The frictional specific energy at the tool-chip interface $U_f$ and along the shear plane $U_s$ is

$$U_f = \frac{F_t v_c}{btv} = \frac{F_t r}{bt} \quad \text{and,} \quad U_s = \frac{F_s v_s}{btv}$$

Thus

$$\frac{\text{Friction energy}}{\text{Total energy}} = \frac{U_f}{U} = \frac{F_t v_c}{F_h v} = \frac{F_t r}{F_h}$$

$$F_t = P_R \sin \beta, \quad \text{and} \quad P_R = P_R' = \sqrt{F_v^2 + F_h^2}$$

$$P_R = \sqrt{(440)^2 + (1100)^2} = 1185N$$

$$F_t = 1185 \sin(27.8^\circ) = 553N$$

$$\%\text{friction energy} = \frac{553(0.586)}{1100} \times 100 = 29.5\%$$
From Eq.17, \[ \frac{\text{Shearing energy}}{\text{Total energy}} = \frac{F_s v_s}{F_h v} \]

From Eq.11, \[ F_s = F_h \cos \phi - F_v \sin \phi \]
\[ F_s = 1100 \cos 32^\circ - 440 \sin 32^\circ \]
\[ F_s = 700N \]

\[ v_s = \frac{\nu \cos \alpha}{\cos(\phi - \alpha)} = \frac{2.5 \cos 6^\circ}{\cos(32 - 6)} = 2.77\text{m.s}^{-1} \]

\[ \%\text{shearing energy} = \frac{700 \times 2.77}{1100 \times 2.5} \times 100 = 70.5\% \]

\[ U = \frac{F_h v}{b t v} = \frac{1100 \times 2.5}{0.010 \times (200 \times 10^{-6}) \times 2.5} N.m^{-2} = 550M.J.m^{-3} \]

This analysis of energy distribution neglects two other energy requirements in cutting:

- **Surface energy** required to produce new surfaces.
- **Momentum change** as the metal crosses the shear plane

(significant in high-speed machining at cutting speeds above 120 m.s\(^{-1}\).)
Type of machining chips

Three general classifications of chips are formed in the machining process.

(a) Continuous chip  
(b) Chip with a built up edge, BUE  
(c) Discontinuous chip
Continuous chips

Continuous chip is characteristic of cutting ductile materials under steady stage conditions.

However, long continuous chips present handling and removal problems in practical operation.

→ required chipbreaker.

Discontinuous chips

Discontinuous chip is formed in brittle materials which cannot withstand the high shear strains imposed in the machining process without fracture.

Ex: cast iron and cast brass, may occur in ductile materials machined at very low speeds and high feed.
**Chip with a built-up edge (BUE)**

- Under conditions where the **friction** between the chip and the rake face of the tool is high, the chip may weld to the tool face.
- The accumulation of the chip material is known as a **built-up edge (BUE)**.
- The formation of **BUE** is due to **work hardening** in the secondary shear zone at low speed (since heat is transferred to the tool).
- The **BUE** act as a **substitute cutting edge** (blunt tool with a low rake angle).

*Chip formation with a built-up edge.*

*Poor texture on the surface*
**Machining force**

Due to complexity of practical machining operations, the machining force $F_h$ often is related empirically to the machining parameters by equation of the type

$$F_h = kd^af^b$$  \[\text{Eq. 18}\]

Where

- $d$ is the depth of cut
- $f$ is the feed
- $k$ is a function of rake angle, decreasing about 1% per degree increase in rake angle.

*Effect of cutting speed on cutting force.*

Due to low temperature at low speed $\rightarrow$ work hardening

Tapany Udomphol

Suranaree University of Technology

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Three-dimensional machining

- Orthogonal machining such as surface broaching, lathe cutoff operations, and plain milling are two dimensional where the cutting edge is perpendicular to the cutting velocity vector.
- Most practical machining operations are three dimensional.
- Ex: drilling and milling.

- Rotating the tool around **x** axis → change the **width** of the cut.
- Rotating the tool around **y** axis → change the **rake angle** \( \alpha \).
- Rotating the tool around **z** axis (by an **inclination angle** \( i \)) → change the cutting process to three dimensional.
Three dimensional cutting tool

- has two cutting edges, which cut simultaneously.
- primary cutting edge is the side-cutting edge.
- secondary cutting edge is the end-cutting edge.
Multiple-edge cutting tools

Drilling

• Used to created round *holes* in a workpiece and/or for further operations.

• *Twist drills* are usually suitable for holes which a length less than five times their diameter.
**Multiple-edge cutting tools**

**Milling**

- Used to produce flat surfaces, angles, gear teeth and slotting.
- The tool consists of *multiple cutting edges* arranged around an axis.
- The *primary cutting action* is produced by rotation of the tool and the feed by motion of the workpiece.

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**Tool-workpiece arrangement typical for milling.**

**Three common milling cutters.**
Temperature in metal cutting

- A significant temperature rise is due to large plastic strain and very high strain rate although the process is normally carried out at ambient temperature.

- Strain rate is high in cutting and almost all the plastic work is converted into heat.

- Very high temperature is created in the secondary deformation zone.

- At very high strain rate → no time for heat dissipation → temperature rise.

Temperature in metal cutting is therefore an important factor affecting the choice of tool materials, tool life, type of lubricant,
If all the heat generated goes into the chip, the adiabatic temperature is given by

\[ T_{ad} = \frac{U}{\rho c} \]  

...Eq. 19

Where \( U \) = specific cutting energy  
\( \rho \) = the density of the workpiece material  
\( c \) = specific heat of workpiece.

For lower velocities, the temperature will be less than in Eq. 19. The approximate chip-tool interface temperature is given by

\[ \frac{T}{T_{ad}} = C \left( \frac{1}{R_t} \right)^p \]  

...Eq. 20

Where \( C \sim 0.4 \) and \( p \sim 1/3 \) to \( 1/2 \).  
\( R_t \) is thermal number.

**Note:** The finite element method has been used for calculating the temperature distributions in the chip and the tool.
Cutting fluids

• The cutting fluids are designed to ameliorate the effects of high local temperatures and high friction at the chip-tool interface.

Primary functions of cutting fluid:

• To decrease friction and wear.
• To reduce temperature generation in the cutting area.
• To wash away the chips from the cutting area.
• To protect the newly machined surface against corrosion.

Also, cutting fluids help to

• Increase tool life,
• Improve surface finish
• Reduce cutting force
• Reduce power consumption
• Reduce thermal distortion of the workpiece.
Cutting fluids are normally *liquids*, but can be *gases*.

There are two basic types of liquid cutting fluids:

1) **Petroleum-based nonsoluble fluids** (straight cutting oils). May contain mineral oil, fatting oils, sulphur or chlorine.

2) **Water-miscible fluids** (soluble oils). May contain some contamination of fatty oils, fatty acids, wetting agents, emulsifiers, sulphur, chlorine, rust inhibitors and germicides.

- **Sulphur and chloride** react with fresh metal surfaces (active sites for chemical reaction) to form compounds with lower shear strength → reduce friction.

- **Chlorinated fluids** work well at low speeds and light loads due to slower reaction of chlorine and metal whereas **sulphur compounds** work well at severe conditions.

- **Combination of both** → more effective.

Vegetable-based cutting fluid
Tool materials and tool life

Properties of cutting tool materials:

- **Hardness**, particularly at high temperature
- **Toughness** to resist failure or chipping
- **Chemical inertness** with respect to the workpiece
- **Thermal shock resistance**
- **Wear resistance**, to maximise the lifetime of the tool.

Tool materials:

- **Carbon and low alloy steels**
- **High speed steels (HSS)**
- **Cemented carbide**
- **Ceramic or oxide tools**
- **Diamond like structure**
Three main forms of wear in metal cutting

1) **Adhesive wear**: the tool and the chip weld together at local asperities, and wear occurs by the fracture of the welded junctions.

2) **Abrasive wear**: occurs as a result of hard particles on the underside of the chip abrading the tool face by mechanical action as the chip passes over the rake face.

3) **Wear from solid-state diffusion** from the tool materials to the workpiece at high temperature and intimate contact at the interface between the chip and the rake face.
Two main types of wear in cutting tool:

1) **Flank wear** is the development of a wear land on the tool due to **abrasive rubbing** between the tool flank and the newly generated surface.

2) **Crater wear** is the formation of a circular crater in the rake face of the tool, as a result of **diffusion wear** due to high temperature developed at the interface between the chip and the rake face of the tool.

The predominant wear process depends on **cutting speed**.

- **Flank wear** dominates at low speed.
- **Crater wear** predominates at higher speeds.
The higher temperatures that occur at high cutting speeds, which results in increased tool wear.
**Tool materials**

**Carbon and low alloy steels**

- High carbon tool steel is the oldest cutting tool materials, having C content ranging from 0.7 – 1.5% carbon.

- Shaped easily in the annealed condition and subsequently hardened by quenching and tempering.

- Due to insufficient hardenability, martensite only obtained on the surface whereas a tough interior provides the final tool very shock resistant.

- $H_v \sim 700$ after quenching and tempering. However the tool will be soften and becomes less and less wear resistance due to coarsening of fine iron carbide particles – that provide strength.

- For low cutting speed due to a drop in hardness above $150^\circ$C.
High speed steels (HSS)

- Retain their **hot hardness** up to 500°C.
- **Cutting speed** ~ 2 times higher than carbon tool steels.
- Very stable secondary carbide dispersions (between 500-650°C), giving rise to a tempering curves.

- **Carbon content** in each steel is balanced against the major alloying elements to form the appropriate stable mix of carbides with \( W, Mo, Cr \) and \( V \).

- **Cobalt** is added to slow down the rate of carbide coarsening → material can withstand higher temperatures.

- **M series** have higher abrasive resistance and cheaper.

- Cannot stand very high speed cutting.

**Tempering curve for M2 high speed steel**

<table>
<thead>
<tr>
<th>Carbide</th>
<th>Approximate hardness ( H_v )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( X_2C )</td>
<td>1900</td>
</tr>
<tr>
<td>( X_2C_3 )</td>
<td>1700</td>
</tr>
<tr>
<td>( X_23C_6 )</td>
<td>1400</td>
</tr>
<tr>
<td>( X_6C )</td>
<td>1200</td>
</tr>
<tr>
<td>( X_3C )</td>
<td>800</td>
</tr>
</tbody>
</table>

**Typical HSS compositions**

<table>
<thead>
<tr>
<th>Type</th>
<th>Alloying elements/wt%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C</td>
</tr>
<tr>
<td>M2</td>
<td>0.85</td>
</tr>
<tr>
<td>M42</td>
<td>1.1</td>
</tr>
<tr>
<td>T2</td>
<td>0.85</td>
</tr>
<tr>
<td>T15</td>
<td>1.5</td>
</tr>
</tbody>
</table>
Cemented carbides

• Consist of heat-resistant refractory carbides (hardness) embedded in a ductile metal matrix (toughness).

• Normally made by powder processing using liquid phase sintering.

• Has advantage over high speed steel in that the obtained carbides are much more stable, see Table.

• They are brittle so should run without vibration or chatter.

• Cobalt is used as a binder.

• \( \sigma_0 \approx 1500 - 2500 \) MPa, depending on \( V_f \) and size distribution of carbides.

• Cutting temperature up to \( 1100^\circ \)C.

• Cutting speed \( \approx 5 \times \) that used with high speed steel.

<table>
<thead>
<tr>
<th>Carbide</th>
<th>Melting temperature ( T_m/K )</th>
<th>Hardness ( H_C )</th>
</tr>
</thead>
<tbody>
<tr>
<td>TiC</td>
<td>3338</td>
<td>3200</td>
</tr>
<tr>
<td>NbC</td>
<td>3773</td>
<td>2400</td>
</tr>
<tr>
<td>WC</td>
<td>3073</td>
<td>2000</td>
</tr>
</tbody>
</table>

Microstructure of a K grade (WC-Co) cemented carbide.
Tool coatings

- Changing the tool surface properties. \( \rightarrow \) surface engineering
- Coating can improve the performance of both high speed steel and cemented carbide tool materials. \( \rightarrow \) increased materials removal rates, time taken to change the tool.
- Coating a very thin layer of TiC or TiN over the WC-Co tool reduces the effects of adhesion and diffusion and reduces the crater wear.

- Chemical and physical vapour deposition (CVD, PVD) are two methods of depositing thin carbide layers onto materials.
- TiN layer (golden colour) is hard and has low dissolution rate and friction coefficient in steel.
- TiC binds well with the matrix, has good abrasion and solution wear resistance.
Ceramics or oxide tools

There are three categories:

1) Alumina (\( \text{Al}_2\text{O}_3 \))

2) A combination of alumina and titanium carbide

3) Silicon nitride (\( \text{Si}_3\text{N}_4 \)), less thermal expansion than \( \text{Al}_2\text{O}_3 \) → minimise thermal stress

- For machining cast irons at high speeds.
- Better wear resistance and less tendency for the tool to weld to the chip.
- Cutting speed at 2-3 times > cemented carbides in uninterrupted cuts where shock and vibration are minimised (due to poor thermal shock and brittleness of ceramics).
- Required rigid tool mounts and rigid machine tools.
- Inherent unreliability of ceramic tooling limits its use to specialist cutting operation.

### Table 4 Ceramic properties

<table>
<thead>
<tr>
<th>Ceramic</th>
<th>Melting temperature ( T_m/\text{K} )</th>
<th>Hardness ( H_V )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{Al}_2\text{O}_3 )</td>
<td>2323</td>
<td>2100</td>
</tr>
<tr>
<td>( \text{Si}_3\text{N}_4 )</td>
<td>2173</td>
<td>2700</td>
</tr>
</tbody>
</table>
‘Diamond like’ structure

- Diamond provides the highest **hot hardness** of any material.
- **Synthetic diamonds** (1950s) and **cubic boron nitride CBN** (1970s), made by high pressure, high temperature pressing. The latter possesses $H_v = 4000$.
- Highest thermal conductivity $\rightarrow$ ideal for cutting tool, but has two disadvantages; **cost** and **diamond – graphite reversion** at 650°C.
- Made by depositing a layer of small crystals on a carbide backing and sintering them with a binder $\rightarrow$ **polycrystalline diamond tooling** (**PCD)**.
- Used for cutting **low temperature materials**, i.e., aluminium or copper alloys.
- Used at very low **cutting speed** for very hard materials, i.e., ceramics.
Tool performance

- Tool performance has been improved by the development of tool coatings.

Minimum time required to surface machine a hot rolled mild steel bar

Suranaree University of Technology
Tapany Udomphol
Jan-Mar 2007
Tool life determination

*Tool life* can be determined based on different criteria;

1) The point at which the tool no longer makes economically *satisfactory parts*, *or*

2) Defined in terms of an average or maximum allowable *wear land*.

3) The point at which the tool has a *complete destruction* when it ceases to cut, *or*

4) The *degradation of the surface finish* below some specified limit, or the increase in the cutting force above some value, *or*

5) When the *vibrational amplitude* reaches a limiting value.
Taylor equation

- **Cutting speed** is the most important operating variable influencing **tool temperature**, and hence, **tool life**.

_Taylor_ has established the empirical relationship between cutting speed $v$ and the time $t$ to reach a **wear land** of certain dimension as

$$vt^n = \text{constant} \quad \ldots\text{Eq. 21}$$

Where typical values of the exponent $n$ are:
- 0.1 for high-speed steel
- 0.2 for cemented carbide
- 0.4 for ceramic tool

**Note:** this is the machining time between regrinding the tool not the total life before it is discarded.
Modified Taylor equation

*Taylor equation* has been extended by including parameters such as *feed* $f$ and *depth of cut* $w$ as follows:

$$vt^nw^f = \text{constant}$$  …Eq. 22

**Note:** *Taylor equation* is completely empirical and as with other empirical relationships, it is dangerous to extrapolate outside of the limits over which the data extend.

However, tool life can be conservatively estimated by using wear curves and the replacement of the tool should be made before they have used up their economical life.
Machinability

**Definition:** The ability of a material to be machined.

*Machinability depends of a number of factors:*

1) **Hardness** – soft materials are easily sheared and require low cutting forces.

2) **Surface texture** – how easy it is to produce the required surface finish. Materials with high work hardening exponent \( n \) tend to form built-up edge (BUE).

3) **The maximum rate of metal removal** – allow low cycle times.

4) **Tool life** – abrasive particles can increase tool wear.

5) **Chip formation** – uniform discrete chips suggest good machinability.
To improve machinability

- **Change the microstructure of the materials.** Soft particles are often deliberately added to improve machinability.

- **Reducing the cutting temperature** by using cutting fluid – can effectively act as coolant and lubricant. Maximum tool surface temperature remains the same but the volume of the tool that reached the high temperature is reduced.

- **Control surface texture** – reduce the formation of built-up edge.

- **Increase rate of material removal** – modern cutting machines, effective toolings.

*Effect of coolant on tool temperatures.*
Grinding processes employ an abrasive wheel containing grains of hard material bonded in a matrix.

- Similar to multiple edge cutting but with irregularly shaped grain (tool).
- Each grain removes a short chip of gradually increasing thickness. After a while sharp edges become dull.

Geometry of chip formation in grinding

- Large negative rake angle $\alpha$. Grains could slide over the workpiece than cut.
- The depth of cut $d$ in grinding is very small (a few $\mu$m).
Grinding wheel

• Employ aluminium oxide $\text{Al}_2\text{O}_3$ or silicon carbide $\text{SiC}$ as abrasive grain, which are often alloyed with oxides of $\text{Ti}$, $\text{Cr}$, $\text{V}$, $\text{Zr}$, etc, to impart special properties.

• Since $\text{SiC}$ is harder than $\text{Al}_2\text{O}_3$, it finds applications for the grinding of harder materials.

• **Diamond wheels** are used for fine finishing.

• **Soft grade alumina wheel** has a large $V_f$ of pores and low glass content → surprisingly used for cutting hard materials and fast material removal, where as **hard grade alumina wheel** (denser) is used for soft materials and for large area grinding.
Wheel performance is controlled by the **strength of the bond**. Binders used are depending on application, i.e., *glass*, *rubber* or *organic resin*.

**Interconnected porosity** provides the **space** to which the **chips** can go and provides a **path** for the **coolant** to be delivered to the cutting surface.

**Specific cutting energy** is 10 times > other cutting process since not all of particles can cut but **rub** on the surface, and also the **rake angle** is not optimised.

**70% of energy** goes to the finished surface → very high temp, residual stresses.
**Grain depth of cut**

The grain depth of cut, \( t \), is given by

\[
t = 2 \sqrt{\frac{v_w}{Crv_g}} \sqrt{\frac{d}{D}}
\]

...Eq. 23

Where:
- \( C \) = the number of active grains on the wheel per unit area (~1 – 5 mm\(^{-2}\))
- \( D \) = diameter of the wheel, and
- \( r = b'/t \)
- \( v_w \) = velocity of the workpiece
- \( v_g \) = velocity of the grinding wheel

\( d = \) wheel depth of cut and \( t << d \)
**Specific cutting energy**

The *specific cutting energy* $U$ in grinding is

$$U = \frac{F_h v_g}{v_w b d}$$

...Eq. 24

Where
- $F_h$ is the tangential force on the wheel
- $v_g$ is the velocity of grinding wheel
- $v_w$ is the velocity of the workpiece.

And $U$ is strongly dependent on $t$

$$U \propto \frac{1}{t}$$

$t$ is the thickness.

, $b$ is the chip width
, $d$ is the wheel depth of cut

If the grain cross section is assumed *triangular*, the *force on a single abrasive grain* $F_g$ will be

$$F_g \propto rt \propto \sqrt{\frac{rv_w}{C v_g}} \sqrt{\frac{d}{D}}$$

...Eq. 25
Surface temperature

Large portion of energy in grinding process goes to raising the temperature. The surface temperature $T_w$, strongly dependent on the energy per unit surface area, is given by

$$T_w \propto \frac{F_g v_g}{v_w b} \propto Ud$$  
...Eq. 25

- **Ground surface temperature** can be $> 1600^\circ$C, which can lead to melting or metallurgical changes, i.e., untempered martensite, grinding cracks, surface oxidation (grinding burn).

- **Improper grinding** can also lead to residual tensile stresses in the ground surface $\rightarrow$ using proper grinding fluid and softer wheel at lower wheel speeds.
**Grindability**

Grindability is measured by using *grinding ratio* or *G ratio*, which is the volume of material removed from the work per unit volume of wheel wear.

- The *G ratio* depends on the grinding process and grinding conditions (wheel, fluid, speed and feed) as well as the material.
- The values of *G ratio* can vary from 2 to over 200.
**Example:** A horizontal spindle surface grinder is cutting with \( t = 5 \) mm and \( U = 40 \) GPa. Estimate the tangential force on the wheel if the wheel speed is \( 30 \) m.s\(^{-1} \), the cross-feed per stroke is \( 1.2 \) mm, the work speed is \( 0.3 \) m.s\(^{-1} \), and the wheel depth of cut is \( 0.05 \) mm.

The rate of metal removal \( M = \text{speed} \times \text{feed} \times \text{depth of cut} \)

\[
M = v_wbd = 0.3(1.2 \times 10^{-3})(0.05 \times 10^{-3}) = 0.018 \times 10^{-6} \ m^3s^{-1}
\]

From Eq. 24, **required power**

\[
\text{Power} = U \times M = (40 \times 10^9 \ Nm^{-2})(0.018 \times 10^{-6} \ m^3s^{-1})
\]

\[
\text{Power} = 720 \ Nm.s^{-1} = 720W
\]

But \( \text{Power} = F_h v_g \)

\[
F_h = \frac{720}{30} \frac{Nm.s^{-1}}{m.s^{-1}} = 24 \ N
\]
Non-traditional machining processes

• The search for better ways of machining complex shapes in hard materials.

• Use forms of energy other than mechanical energy.

<table>
<thead>
<tr>
<th>Source of energy</th>
<th>Name of process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal energy processes</td>
<td>Electrical discharge machine, EDM</td>
</tr>
<tr>
<td></td>
<td>Laser-beam machining, LBM</td>
</tr>
<tr>
<td></td>
<td>Plasma-arc machining, ECM</td>
</tr>
<tr>
<td>Electrical energy processes</td>
<td>Electrochemical machining, ECM</td>
</tr>
<tr>
<td></td>
<td>Electrochemical grinding, ECG</td>
</tr>
<tr>
<td>Chemical process</td>
<td>Chemical machining process</td>
</tr>
<tr>
<td>Mechanical process</td>
<td>Ultrasonic machining, USM</td>
</tr>
</tbody>
</table>
**Electrical discharge machining (EDM)**


- Removal of material through *melting* or *vaporisation* caused by a high-frequency spark discharge. *EDM* machined surface may be deleterious to *fatigue* properties due to the recast layer.

- Good selection of the proper electrode material for the workpiece

- Produce deep holes, slots, cavities in hard materials without drifting or can do *irregular contour*.
**Electrochemical machining (ECM)**

- Metal is removed by anodic dissolution in an electrolytic cell. **Workpiece** – *anode*, **tool** – *cathode*.
- *Rate of metal removal* depends upon the amount of **current** passing between the tool and the workpiece, independent of material hardness.
- **ECM** is a cold process which results in *no thermal damage* to the workpiece, hence, giving a **smooth burr-free surface**.
- Not suited for producing sharp corners or cavities with flat bottoms.
Electrochemical grinding (ECG)

- A combination of ECM and abrasive grinding in which most of the metal is removed by electrolytic action.
- It is used with hard carbides or difficult-to-grind alloys where wheel wear or surface damage must be minimised.
Chemical machining (CHM)

- Metal is removed by controlling chemical attack with chemical reagents.

**Process**

1. Surface cleaning
2. Masking areas not to be dissolved
3. Attacking chemicals
4. Cleaning

Chemical machining of microscopic holes and grooves in glass.

Photo chemical machining product
**Ultrasonic machining (USM)**

- The tool is excited around 20,000 Hz with a *magnetostrictive transducer* while a *slurry of fine abrasive particles* is introduced between the tool and the workpiece.

- Each cycle of vibration removes minute pieces of pieces of the workpiece by *fracture* or *erosion*.

- Used mostly for machining *brittle hard materials* such as semiconductors, ceramics, or glass.
Economics of machining

- Optimum speed which balances these opposing factors and results in minimum cost per piece.

Total cost

\[ C_u = C_m + C_n + C_c + C_t \]  …Eq. 26

Where

- \( C_u \) = the total unit (per piece) cost
- \( C_m \) = the machining cost
- \( C_n \) = the cost associated with non-machining time, i.e., setup cost, preparation, time for loading & unloading, idle machine time.
- \( C_c \) = the cost of tool changing
- \( C_t \) = the tool cost per piece.
1) Machining cost

Machining cost \( C_m \) can be expressed by

\[
C_m = t_m (L_m + O_m)
\]

Where

- \( t_m \) = the machining time per piece (including the time the feed is engaged whether or not the tool is cutting).
- \( L_m \) = the labour cost of a production operator per unit time.
- \( O_m \) = the overhead charge for the machine, including depreciation, indirect labour, maintenance, etc.

…Eq. 27

2) Cost of non-machining time

The cost of non-machining time \( C_n \) is usually expressed as a fixed cost in dollars per piece.
3) Cost of tool changing

The cost of tool changing $C_c$ can be expressed by.

$$C_c = t_g \left( \frac{t_{ac}}{t} \right) \left( L_g + O_g \right)$$

...Eq. 28

Where

- $t_g$ = the time required to grind and change a cutting edge
- $t_{ac}$ = the actual cutting time per piece
- $t$ = the tool life for a cutting edge
- $L_g$ = the labour rate for a toolroom operator
- $O_g$ = the overhead rate for the tool room operation.

The Taylor equation for tool life can be written

$$t = \left( \frac{K}{v} \right)^{\frac{1}{n}}$$

...Eq. 29

$$t_{ac} = \frac{\pi L_a D}{f v}$$

...Eq. 30
4) Tool cost per piece

The tool cost per piece can be expressed by

\[ C_t = C_e \frac{t_{ac}}{t} \]  

…Eq. 31

Where \( C_e \) is the cost of a cutting edge, and \( t_{ac}/t \) is the number of tool changes required per piece.
Variation of machining costs with cutting speed

\[ C_u = C_m + C_n + C_c + C_t \]
References