Heat Generation

- During machining by cutting, the cutting energy is converted to heat, therefore, a considerable amount of heat is generated at the following three distinct zones:
  1. Shear zone (75%).
  2. Chip sliding on the tool face (20%).
  3. Tool sliding on the workpiece machined surface (5%) which is neglected for perfectly sharp cutting tools.
Heat Generation

- The heat produced at the shear zone is the maximum due to the plastic deformation of the metal at the shear zone.
- Most of this heat is carried away by the chips.
- Rate of energy consumption during metal cutting ($N_c$) is converted into heat (rate of heat generation) at the shear zone ($N_s$) and the tool-chip interface ($N_f$).
  $$N_c = F_v V$$
  $$N_c \approx N_s + N_f$$
- The total heat generated in the cutting zone ($Q$) is given by:
  $$N_s = F_s V_s$$
  $$N_f = F_f V_c$$
  $$Q = \frac{F_v V}{j} \text{ Cal/min}$$
- Where,
  $F_v$ : Main cutting force (Kg)
  $V$ : Cutting speed (m/min)
  $j$ : Mechanical equivalent of heat (427 Kg.m / kCal)

Heat Dissipation

- The total heat generated during machining by cutting ($Q$) dissipates to chip ($Q_{chip}$), tool ($Q_{tool}$) and workpiece ($Q_{wp}$).
- The relative amounts of heat dissipated into the chip, the tool and the workpiece change as the cutting speed $V$ changes.

$$Q = Q_{chip} + Q_{tool} + Q_{wp}$$
- $Q_{tool}$ affects the tool hardness, wear resistance, and hence its life.
- $Q_{wp}$ affects the dimensional accuracy as well as the machine tool performance.
Tool Temperature

• Maximum tool temperature occurs along tool face at some distance from cutting edge.
• Tool face heated by both the highly heated chip and the work done in overcoming the friction of chip on its face.
• Thus, tool face is heated to higher temperature than its flank.
• Temperature on tool face is higher than the average temperature of the chip.
• The thicker the chip, the greater the difference will be.
• Factors affecting tool temperature:
  - Workpiece material.
  - Coolant used.
  - Cutting Speed.
  - Feed rate.
  - Depth of cut.
  - Tool geometry.
  - Thermal conductivity of the tool.
  - Specific heat of the tool.
  - Specific cutting resistance (of WP).
• Higher cutting speeds result in greater amount of heat in the chips since there is less time to conduct that heat to the tool or the workpiece.

Cutting Fluids

Functions of cutting fluids:
1. Cool the cutting tool and workpiece (Cooling Effect).
2. Lubricate the cutting tool, thus reduce friction between the tool and the workpiece (Lubricating Effect).
3. Remove the chips (Flushing Effect).
4. Produce better surface finish.
5. Reduce the tool wear, therefore, the power consumption during cutting (cutting power).
6. Prevent corrosion of workpiece and machine.
7. Reduce thermal distortion of the workpiece which permits improved dimensional control.
8. Enable the maximum possible cutting speed to be used, thus reducing time and cost of production (Economical Effect).
9. Provide safe working environment (non-misting, non-toxic, non-flammable and non-smoking).
Types and Supply of Cutting Fluids

- **Air**: Compressed air can be used for cooling the machining zone using pure air jet or mixed with other fluid.
- **Water based cutting fluids**: Water mixed with soluble oil, chemical solutions or synthetic fluids in order to form the cutting fluid.
- **Straight (undiluted) or neat oils based cutting fluids**: Such as mineral oils, fatty oils, composed oils, extreme pressure (EP) oils and multiple use oils.
- **Liquid Nitrogen**: Liquid nitrogen having a temperature of \(-196 \, ^\circ\text{C}\) is used as a cutting fluid for difficult-to-machine materials.

Selection of Cutting Fluids

**Selection of a particular type of cutting fluid depends on:**

- Cutting speed – Feed rate – Depth of cut.
- Cutting tool material – Workpiece material.
- Velocity of cutting fluid.
- Expected cutting tool life.
- Cost of cutting fluid.
- The life of cutting fluid and the loss of cutting fluid during operation.
- Must not have negative effects on the health of the machinist or on the environment.
- Should not produce contaminants.
- Multifunction oils (for slide way lubrication and as a coolant and lubrication in machining) have to be used.
- Minimize the volume of the fluid used.
- Continuous monitoring of the cutting fluids and machine tool environment with on-line sensors is desirable.
Problems and Properties of Cutting Fluids

Problems:
• Environmental pollution (harmful gases and fumes at high temperature).
• Biological problems to operators due to physical contact with cutting fluids.
• Water pollution and soil contamination during disposal.
• Requirement of extra floor space and additional systems for pumping, storage, filtration, recycling, chilling, etc.
• The high cost of disposal of used coolants under tougher environmental laws.

Properties:
1. High specific heat – High heat conductivity.
2. Good lubricating properties.
3. Odorless and non-flammable.
5. Stable – Low Viscosity.
6. Permit clear view of the workpiece.

Mechanisms of Tool Wear

• The tool wears due to the interaction between chip and tool occurring at high thermal and mechanical stresses.
• Tool wear mechanism depends on:
  - Tool material.
  - Workpiece material.
  - Cutting variables (speed, chip cross sectional area, type of coolant, tool geometry, and machine tool condition and rigidity).
• Basic Mechanisms of tool wear:
  - Diffusion.
  - Adhesion.
  - Abrasion.
  - Electrochemical.
• The four basic mechanisms operate singly or in various combinations.
• Tool wear in metal cutting processes is mainly due to adhesion and abrasion.
Mechanisms of Tool Wear

**Diffusion Wear:**
- Fusion of tool material to the chip and the workpiece.
- Occurs when atoms in a metallic crystal lattice move from an area of high atomic concentration of that particular metallic group to an area of low concentration.
- The rate of diffusion increases exponentially with temperature.
- Caused by the high temperature generated at tool-workpiece and chip-tool interfaces.

**Adhesion Wear:**
- Caused by fracture of welds that are formed as a part of the tool/chip friction mechanism
- When these minute particles are fractured, small bits of the tool material are torn out and carried away to the underside of the chip or by the machined workpiece surface.

**Abrasion Wear:**
- When hard particles on the underside of the chip pass over the tool face, they remove the tool material by the mechanical abrasion action, these particles could be: (a) Abrasive inclusions in the workpiece, (b) Fragments of the built-up-edges, or (c) Particles of tool material which have been removed by adhesion

**Electrochemical Wear:**
- Occurs when ions are passed between the tool and the workpiece causing oxidation of the tool surface.

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Forms of Tool Wear

The progressive wear of the cutting tool takes many forms:

a) Crater wear. Tool wears on the tool face.

b) Flank wear which is in the form of wear land generated as the newly cut surface of the workpiece rubs against the cutting tool.

c) Notch wear occurs locally in the area of the main cutting edge where it contacts the workpiece surface.

d) Thermal cracks occurring in the form of small running cracks across the cutting edge that are caused by thermal shock loads.
**Forms of Tool Wear**

- When machining at high cutting speeds and feed rates, the tool wear occurs mainly in the tool face.
- At medium cutting speeds, tool wear occurs simultaneously in its flank and its face.
- At low cutting speeds, a substantial tool wear occurs, mainly, at the tool flank.
- Crater wear occurs when machining ductile materials.
- Flank wear occurs when machining brittle materials such as cast iron and bronze.

**Crater Wear**

- Crater wear occurs in the tool face at a short distance from the cutting edge while machining ductile materials like steel and its alloys.
- Crater wear weakens the tool strength and increases the cutting temperature and the friction between the tool face and the chip.
- Crater wear can increase rake angle and reduce cutting force.

\[
C_w = 2(K_m - B_c) \\
q = \frac{K_l}{K_m}
\]

Where:
- \( K_m \) is the distance between centre of crater and cutting edge,
- \( K_l \) is the crater depth and \( B_c \) is the width of the land.
- The allowable values of the wear index \( q \) should not exceed 0.4 and 0.6 for carbide and high speed steel tools respectively.
- The measurement of the crater wear is not as simple as that of the flank wear.
- For this reason the tool life is usually determined in terms of the flank wear.
Flank Wear

- Flank wear occurs mainly on the nose part, main flank and the auxiliary flank.
- Maximum amount of heat is at tool nose due to the more severe heating at the nose since heat also passes over it from the end (auxiliary) cutting edge.
- It is mainly caused by the abrasive action of the hard inclusions in the workpiece, fragments of the built-up-edge or particles of tool material which have been removed by adhesion.
- This type of wear depends, mainly, on the hardness of the cutting tool and workpiece at the high working temperatures, the amount and distribution of hard constituents in the workpiece.

\[ V_f = \text{mean width of flank wear} \]
\[ V_{f_{\text{max}}} = \text{maximum wear of nose radius} \]

Flank Wear

- If a sharp tool is used to cut at given speed for a specific period of time, the flank wear \( (V_f) \) will develop with time and passes through 3 stages:

**I: Initial wear period** where the sharp cutting edge is quickly broken down by the heavy abrasion action, hence a finite land is formed.

**II: Uniform wear period** is characterized by the gradual increase of the flank wear. The slope of the line in this period depends on the cutting conditions (speed, feed rate and depth of cut), tool geometry, type of coolant, work material and tool material.

**III: Destructive wear** occurs intensively due to the formation of thermal cracks and plastic deformation of the tool material.
Flank Wear

- Once the tool wear enters zone III, it is uneconomical to grind the tool and the accuracy of the machined parts are drastically affected.
- In order to avoid the sudden breakdown of the cutting tools, they should be reground when the average flank wear \((V_{B_{III}})\) reaches a certain allowable value \((V_{Ball})\).
- The value of \(V_{Ball}\) depends on: Workpiece material, tool material and the type of the machining operation.

<table>
<thead>
<tr>
<th>Operation</th>
<th>Allowable Average Flank Wear Land ((V_{Ball}))</th>
<th>mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-Speed Steels</td>
<td>Carbides</td>
<td></td>
</tr>
<tr>
<td>Turning</td>
<td>1.50</td>
<td>0.40</td>
</tr>
<tr>
<td>Face Milling</td>
<td>1.50</td>
<td>0.40</td>
</tr>
<tr>
<td>End Milling</td>
<td>0.30</td>
<td>0.30</td>
</tr>
<tr>
<td>Drilling</td>
<td>0.40</td>
<td>0.40</td>
</tr>
<tr>
<td>Reaming</td>
<td>0.15</td>
<td>0.15</td>
</tr>
</tbody>
</table>

Tool Life

- The **tool life (cutting edge durability)** is the time a newly sharpened tool cuts satisfactorily before it becomes necessary to remove it to reground it or replace it.
- The tool life can be expressed, quantitatively, using the length of work cut, the volume of metal removed, the number of components produced and the cutting speed for a given tool life \((V_{T}:\) Cutting speed for a tool life of \(T\) in minutes).
- The tool life is the most widely used criterion for the evaluation of the **machinability** of the different materials because of its direct impact on the total machining cost.

- Effect of increasing the cutting speed from \(V_1\) to \(V_4\) (using four newly sharpened tools of identical geometry operating under identical cutting conditions of feed and depth of cut) is a decrease of the tool life \((T)\).
Tool Life

- Effect of Increasing the cutting speed from \( V_1 \) to \( V_4 \) (using four newly sharpened tools of identical geometry operating under identical cutting conditions of feed and depth of cut) is a decrease of the tool life (T).
- The corresponding cutting times \( T_1, T_2, T_3 \), and \( T_4 \) for reaching the allowable flank wear (\( V_{B\text{-all}} \)) for each cutting speed are plotted.

Tool Life Equation

- Plots of log T against log V.
- Taylor produced the empirical tool life equation: \( VT^n = C \)

Where:
- \( V = \) Cutting Speed (m/min)
- \( T = \) Tool Life – Durability (min)
- \( n = \) Taylor Exponent
- \( C = \) Taylor Constant

\( C = V \) when \( T = 1 \) minute

\[ n = \frac{b}{a} = \cot \alpha \]
Taylor Exponent and V-T Diagram for Different Tool Materials

<table>
<thead>
<tr>
<th>Tool Material</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-speed steels</td>
<td>0.08 – 0.20</td>
</tr>
<tr>
<td>Cast alloys</td>
<td>0.10 – 0.15</td>
</tr>
<tr>
<td>Carbides</td>
<td>0.20 – 0.50</td>
</tr>
<tr>
<td>Ceramics</td>
<td>0.50 – 0.70</td>
</tr>
</tbody>
</table>

### End of Tool Life
- Tool Flank wear frequently used in terms of the allowable value of the flank wear ($V_{\text{allow}}$).
- Radial force component increases suddenly from its original value by 10%.
- Surface roughness during finishing operations exceeds a certain predetermined level.
- Bright bands appear on the machined surface of steels.
- Dark spots appear on the machined surface of cast iron.
- Noise occurs in drilling operations.

### Tool life, solved example

The durability of a cutting tool is 40 min at a cutting speed 140 m/min and 100 min at a cutting speed of 60 m/min. Calculate:

a) Taylor’s constant,

b) tool life for $V=1$ m/min,

c) cutting speed for a tool life $T=1$ min,

d) tool life for $V=70$ m/min,

e) Cutting speed for durability of 120 min

#### Solution

a) $VT^n = C$. Thus, $140(40)^n = 60(100)^n = C$

$\therefore 2.33(40)^n = (100)^n \Rightarrow \log 2.33 + n \log 40 = n \log 100 \Rightarrow n = 0.923$ and $C = 4215.3$

b) For $V=1$ m/min: $T^{0.923} = 4215.3 \Rightarrow T = 8457.3$ min

c) For $T=1$ min: $V = C = 4215.3$ m/min

d) For $V=70$ m/min: $(70)^{0.923} = 4215.3 \Rightarrow T = 84.76$ min

e) For $T=120$ min: $V(120)^{0.923} = 4215.3 \Rightarrow V = 50.78$ m/min