Manufacturing Technology I
Lecture 3
„Fundamentals of Cutting“

Prof. Dr.-Ing. F. Klocke

Structure of the lecture

- Examples: turning of steel
- The cutting part - Terms and symbols
- The cutting operation
- Loads of the cutting part
  - Influences exerted by the geometry of a cutting part on its characteristics under load
- Too wear
  - Types of tool wear and tool wear measurements
  - Wear mechanisms of the cutting process
- Summary
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Example: turning of steel, roughing

source: Wida
Example: turning of steel, finishing

source: Widia

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Terms at a simple cutting part

- $h$: thickness of cut (before deformation)
- $h_{in}$: chip thickness (after deformation)
- $\alpha$: tool orthogonal clearance
- $\beta$: tool orthogonal wedge angle
- $\gamma$: tool orthogonal rake

Cutting edges and surfaces on the cutting part of a turning tool

source: ISO 3002/1
**Tool-in-hand system**

- Assumed working plane $P_t$
- Assumed direction of primary motion
- Tool back plane $P_b$
- Tool cutting edge normal plane $P_n$
- Tool orthogonal plane $P_o$
- Tool plane of reference $P_r$
- Assumed direction of feed motion
- Selected point on the cutting edge
- Tool reference plane $P_r$

**Tool-in-use system**

- Direction of primary motion
- Resultant cutting direction
- Resultant cutting direction
- Direction of feed motion
- Wirk-Rückebene $P_{rw}$
- Working plane $P_{we}$
- Working cutting edge plane $P_{re}$
- Working orthogonal plane $P_{ro}$
- Working cutting edge normal plane $P_{re} = P_{ro}$
- Selected point on the cutting edge
- Working reference plane $P_{rw}$
- Plane containing base of tool

Source: ISO 3002/1
Engagement in longitudinal cylindrical turning

Angles at a selected point on the cutting edge
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Chip formation

<table>
<thead>
<tr>
<th>material</th>
<th>cutting material</th>
<th>cutting speed</th>
<th>cross-sectional area</th>
<th>CK53</th>
<th>HW-P30</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>v_c  = 100 m/min</td>
<td>a_v = 2·0,315 mm²</td>
</tr>
</tbody>
</table>
### Strain rates of different manufacturing processes

#### Process:
- Superplastic Forming
- Deep Drawing
- Hot Rolling
- Cold Rolling
- Bar- and Tube-Drawing
- High Speed Forging
- Wire-Drawing
- Explosive Forming
- Split-Hopkinson-Bar-Test
- Cutting

![Strain rate chart](chart.png)

**strain tensor:**

\[
\begin{bmatrix}
2 \cdot \varepsilon_x \\
2 \cdot \varepsilon_y \\
\gamma_{xy} \\
\gamma_{yx} \\
2 \cdot \varepsilon_z
\end{bmatrix}
\]

### Calculation of the strain rate

#### Strain rate

\[
\dot{\varepsilon}_x = \frac{\partial v_x}{\partial x}, \quad \dot{\varepsilon}_y = \frac{\partial v_y}{\partial y}, \quad \dot{\varepsilon}_z = \frac{\partial v_z}{\partial z}
\]

#### Shearing strain rate

\[
\dot{\gamma}_{xy} = \frac{\partial v_y}{\partial x} + \frac{\partial v_x}{\partial y}, \quad \dot{\gamma}_{yx} = \frac{\partial v_x}{\partial y} + \frac{\partial v_y}{\partial x}, \quad \dot{\gamma}_{xz} = \frac{\partial v_x}{\partial z} + \frac{\partial v_z}{\partial x}, \quad \dot{\gamma}_{zx} = \frac{\partial v_z}{\partial x} + \frac{\partial v_x}{\partial z}
\]

**strain tensor:**

\[
\begin{bmatrix}
2 \cdot \ln \frac{h_0}{h} & \Phi - \psi - \gamma_c & 0 \\
\Phi + \psi - \gamma_c & 2 \cdot \ln \frac{h_0}{h} & 0 \\
0 & 0 & \frac{h_0}{h} \Phi - \psi
\end{bmatrix}
\]

The outcome of the time derivation is the strain rate!

\[
\dot{\gamma}_c = 2 \cdot \frac{\partial}{\partial t} \ln \frac{h_0}{h}, \quad \dot{\psi} = 2 \cdot \frac{\partial}{\partial t} \left( \frac{h_0}{h} \right)
\]

**strain:**

\[
\dot{\gamma}_c = \frac{h_0}{h} \dot{\psi} = \dot{\psi}, \quad \dot{\psi} = \arctan \left( \frac{w_1}{w_0} \right)
\]

\[
\dot{\xi} = 0
\]
Types of chip formation

- **continuous chip**
  - very equal metallographic structure

- **segmented chip**
  - local hard deformed metallographical structure
  - local nearly no deformed metallographic structure

- **shearing chip**
  - local hard deformed metallographic structure
  - local nearly no deformed metallographic structure
  - fractional separation of segments

Which type of chip formation is existent, is generally affected by the friction on the face.

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Conditions of the cutting process

- **Material**: Ck45; Cutting material HM-P20; 
  \[ a_p \times f = 2 \times 0.25 \text{ mm}^2; \quad v_c = 160 \text{ m/min} \]
- **Cutting temperature**: \( T_c \sim 1030 \, ^\circ\text{C} \)
- **Chip velocity**: \( v_w = 67 \text{ m/min} \)
- **Heating rate**: \( 10^5 \, ^\circ\text{C/s} \)
- **Average compressive stress**: \( \sigma_c \leq 350 \, \text{N/mm}^2 \)
- **Average shearing stress**: \( \tau_s \leq 250 \, \text{N/mm}^2 \)

Shear strain:
- Tensile test: \( \varepsilon \sim 0.2 \)
- Cutting: \( 0.8 < \varepsilon < 4.0 \)

Strain rate:
- Tensile test: \( \dot{\varepsilon} \sim 10^3 \, \text{1/s} \)
- Cutting: \( \dot{\varepsilon} \sim 10^2 \, \text{1/s} \)

Components of the total force

- **Primary motion** (workpiece)
- **Direction of feed motion** (tool)
- **Total force** \( F \)
- **Cutting force** \( F_c \)
- **Feed force** \( F_f \)
- **Back force** \( F_b \)
Influence of parameters on the components of the total force

Graphical determination of the parameters $F_{c1,1}'$ and $(1-m_c)$
Distribution of effective work during the cutting process

\[
W_e = F_x \cdot l_x = W_d + W_f = F_r \cdot l_r + F_f \cdot l_f
\]

source: Vieregge

<table>
<thead>
<tr>
<th>Work W (Nm)</th>
<th>Chip thickness h (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1000</td>
<td>0.01</td>
</tr>
<tr>
<td>2000</td>
<td>0.02</td>
</tr>
<tr>
<td>3000</td>
<td>0.03</td>
</tr>
<tr>
<td>4000</td>
<td>0.04</td>
</tr>
<tr>
<td>5000</td>
<td>0.05</td>
</tr>
<tr>
<td>6000</td>
<td>0.06</td>
</tr>
<tr>
<td>7000</td>
<td>0.07</td>
</tr>
</tbody>
</table>

- shear work
- friction work
- cutting work
- friction at flank
- friction at face
- total work

source: Vieregge

Distribution of heat and temperature in workpiece, chip and tool

\[
\Delta L = \alpha \cdot L_{max} \cdot \Delta T
\]

for steel

- cutting material
- cutting speed
- thickness of cut
- tool orthogonal rake

<table>
<thead>
<tr>
<th>Workpiece</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>380°</td>
<td>500</td>
</tr>
<tr>
<td>300°</td>
<td>450</td>
</tr>
<tr>
<td>130°</td>
<td>400</td>
</tr>
<tr>
<td>80°</td>
<td>600</td>
</tr>
<tr>
<td>30°</td>
<td>650</td>
</tr>
<tr>
<td>10°</td>
<td>700</td>
</tr>
</tbody>
</table>

source: Vieregge
Force components and chip temperatures in turning

![Graph showing temperature vs. cutting speed and cutting force vs. cutting speed.]

<table>
<thead>
<tr>
<th>Material</th>
<th>Feed (mm)</th>
<th>Depth of Cut (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium</td>
<td>0.25</td>
<td>2</td>
</tr>
<tr>
<td>Steel</td>
<td>0.1</td>
<td>1</td>
</tr>
<tr>
<td>Titanium</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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Influence exerted by cutting edge geometry on machining parameters

- Low minimum thickness of cut ($r_e$ low)
- Increasing cutting part stability
- $\alpha_n = 6^\circ$ to $12^\circ$
- Decreasing wear
- Increased cutting part stability
- Major first face ($r_i = 0.4$ to $2$ mm)
- Increasing back force and cutting part stability
- $\lambda_e = +8^\circ$ to $-6^\circ$
- Controlled chip flow
- Better surface integrity
- Reduced the probability of chatter vibrations
- Lower cutting force

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Types of tool wear and tool wear measurements

- Flank wear land
- Crater wear
- Tool orthogonal rake
- Tool orthogonal clearance
- Width of flank wear land
- Crater front distance
- Crater depth
- Cutting edge offset in face direction
- Cutting edge offset in flank direction
- Crater centre distance i.e. distance between the deepest point in the crater and the cutting edge concerned

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- Examples: turning of steel
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- Loads to which the cutting part is exposed
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Wear mechanisms in cutting processes

source: Vieregge

Comb and transverse crack formation in milling operations

source: Lehwald, Vieregge
Plastic deformation of the cutting edge

- Work material: Ti Al 6V 4
- Tool material: HS18 - 1 - 2 - 10
- Cutting speed: \( v_c = 8 \text{ m/min} \)
- Cross-sectional area: \( a_p = 1.5 \times 0.25 \text{ mm}^2 \)
- Cutting part geometry:
  - \( \gamma_0 \)
  - \( \lambda_0 \)
  - \( \alpha_0 \)
  - \( \kappa_0 \)
- Cutting time: \( t_c = 1 \text{ min}, \) cycles-to-failure: \( N = 33 \times 10^3 \)

Flank wear and formation of build-up cutting edge

- Cutting speeds: \( v_c = 2, 10, 20, 30, 40 \text{ m/min} \)
- Flank wear:
  - \( v_c = 2 \text{ m/min} \)
  - \( v_c = 10 \text{ m/min} \)
  - \( v_c = 20 \text{ m/min} \)
  - \( v_c = 30 \text{ m/min} \)
  - \( v_c = 40 \text{ m/min} \)
- Cutting part geometry:
  - \( \alpha_0 \)
  - \( \gamma_0 \)
  - \( \lambda_0 \)
  - \( \kappa_0 \)
  - \( r_c \)
- Cutting time: \( t_c = 30 \text{ min} \)
Flank wear at turning tools

- Cutting part geometry
- Cutting time $t_c = 30$ min
- Cutting speed $v_c$
- Width of flank wear land $VB$
- Materials:
  - Ck53N
  - HS12-1-4-5
- Depth of cut $a_p = 2$ mm
- Cutting speed $v_c$
- Feed $f = 0.4$, $0.25$, $0.1$ mm

Simplified representation of diffusion process in cemented carbide tools

- Case hardened steel C10
- Quenched and tempered steel Ck53
- Cemented carbide P30
- TiC - WC (TaC/NbC)
- Co - WC: solid solution
- Solution of WC to:
  - $Fe_2W_C\_C\_C; (FeW)_C; (FeW)_{12}C_6$
- Zones:
  - Zone A: Fe-Co-MK
  - Zone B: Co-Fe-MK
Oxidation zones of a cemented carbide turning tool

Material: Ck53N
Cutting material: HC-P30
Cutting speed: \( v_c = 125 \text{ m/min} \)
Cross-sectional area: \( a_p \cdot f = 3 \cdot 0.25 \text{ mm}^2 \)
Cutting time: \( t_c = 20 \text{ min} \)

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List of questions I

- Identify the different cutting edges and areas of a turning tool!
- Specify and explain the angles for determination of the orientation and shape of the cutting part!
- Specify the types of chip formation and explain their development!
- In which plane do you measure the tool angles?
- List the orthogonal components of the total force!
- Illustrate qualitatively the dependence of feed, cutting speed, cutting depth and tool cutting edge angle on the total force components! Explain the dependence!
- Specify an empirical force equation and explain the characteristic parameters!
- Where can you identify heat sources during chip formation and how dissipates the major heat? Please identify the place of the highest cutting temperature?

List of questions II

- Specify the influencing factors for choosing the geometry of the cutting part!
- How to increase the stability of the cutting edge?
- Specify the influencing variables to reduce the probability for chatter vibrations!
- Identify and explain the types of tool wear at the cutting part!
- Signify the major tool wear measurements!
- Specify the wear mechanisms and indicate their dependence of the cutting speed.
- Explain comb and transverse crack formation!
- Illustrate the term „built-up edge formation“ and explain the progression of the flank wear land and the surface roughness dependent on the cutting speed!