Principles of Cutting
Simulation Techniques in Manufacturing Technology
Lecture 6

Laboratory for Machine Tools and Production Engineering
Chair of Manufacturing Technology

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Intention of the lecture

This lecture is supposed to …

- … describe the fundamental mechanisms of cutting.
- … convey mechanical, thermal and chemical loads affecting the cutting wedge.
- … illustrate the resultant wear phenomena.
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Cutting: Machining with geometrically defined cutting edge

Definition (DIN 8589):
Machining is cutting, in which layers of materials are mechanically separated from a workpiece in the form of chips by means of a cutting tool.
Nomenclature at the wedge

- **Rake face** $A_\gamma$
- **Minor cutting edge** $S'$
- **Minor flank** $A_\alpha'$
- **Major cutting edge** $S$
- **Major flank** $A_\alpha$
- **Corner radius**
- **Tool shank**

Direction of primary motion

Direction of feed motion
Tool-in-hand system (ISO 3002)

assumed working plane $P_f$

tool cutting edge plane $P_s$

machine coordinate system

tool reference plane $P_r$

Fix with the machine by turning, if the cutting edge is positioned in the centre of the spindle.

Fix with the tool!

Variable with the process!

Plane of the rake face $A_\gamma$

$k_r$ Tool cutting edge angle

$\lambda_s$ Tool cutting edge inclination angle
Tool references systems (ISO 3002/1)

- **Tool-in-hand system**
  - Tool back plane $P_r$
  - Working plane $P_f$
  - Assumed working plane
  - Tool reference plane

- **Tool-in-used system**
  - Working plane $P_{fe}$
  - Working back plane $P_{pe}$
  - Working reference plane
Definition of the tool cutting edge inclination during external cylindrical turning

\[ \kappa_y = 90^\circ \]

Working plane \( P_f \)

Cutting insert

Tool holder

Tool reference plane \( P_r \)

Feed direction

Direction of primary motion

Tool cutting edge plane \( P_S \)

Workpiece

Shoulder

\[ \lambda_s \]
Process kinematics at the wedge

Idealised wedge in the assumed working plane

The geometry of the idealised cutting wedge is defined by the rake angle $\gamma_o$, the wedge angle $\beta_o$ and the clearance angle $\alpha_o$.
Cutting edge angle and inclination angle

- Tool cutting edge angle $\kappa_r$
- Tool cutting edge inclination $\lambda_s$
Orientation of the cutting edge: process kinematics

- **Free orthogonal cut**
  - Tool cutting edge inclination \( \lambda_s = 0^\circ \) and \( \kappa_0 = 90^\circ \)

- **Free oblique cut**
  - Tool cutting edge inclination \( \lambda_s \)
  - Not equal to \( 0^\circ \)

- **Non-free oblique cut**
Process kinematics at the idealised wedge

- The wedge geometry is defined by the clearance angle $\alpha_O$, the wedge angle $\beta_O$ and the tool orthogonal rake angle $\gamma_O$.

- The wedge penetrates the material and causes elastic and plastic deformations.

- Due to the given geometry the deformed material is forming a chip which flows across the rake face.

![Diagram of process kinematics at the idealised wedge](image)
Process kinematics and rounded cutting edge radius

- In reality there are only rounded cutting edges
- The cutting edge radius is usually measured in the tool orthogonal plane $P_O$
- Feed direction and cutting direction are enclosing the feed motion angle $\varphi$
- The directions of effective cutting speed and cutting speed are enclosing the effective cutting speed angle $\eta$

**Diagram:**
- Effective cutting speed $v_{re}$
- Cutting speed $v_c$
- Feed velocity $v_f$
- Workpiece
- Chip
- Rounded cutting edge
- Tool orthogonal plane $P_O$
Shearing zones in cutting processes

- Shearing is very essential in cutting.
- So-called shearing zones might be formed.
- The most important shearing zone is called primary shearing zone.
- The zones where shearing is caused by friction are called secondary shearing zones.
- Under a wearless consideration the secondary shearing zone of the flank drops out.
Chip formation

1. Primary shearing zone
2. Secondary shearing zone of the rake face
3. Separative zone (stagnation point)
4. Secondary shearing zone of the flank
5. Preliminary deformation zone

Workpiece material: C53E
Cutting edge material: HW-P30
Cutting speed: \( v_c = 100 \text{ m/min} \)
Cross-section area of cut: \( a_p \times f = 2 \times 0.315 \text{ mm}^2 \)
Penetration of tool and work piece, cross-sectional area

The cross-sectional area is determined by the tool cutting edge angle $\kappa_r$, the feed $f$ and the depth of cut $a_p$.

The undeformed chip thickness $h$ and the width of cut $b$ can be calculated from the feed $f$ and the depth of cut $a_p$ respectively, using the cutting edge angle $\kappa_r$.

$h = f \cdot \sin \kappa_r$

$b = \frac{a_p}{\sin \kappa_r}$
Outline

1 The Cutting Part
2 Chip Formation
3 Shear Plane Model
4 Machinability
5 Force Components
6 Tool Life
7 Surface Integrity
8 Chip Form
Chip formation depending on the material behaviour

1. Continuous chip
2. Segmented chip
3. Shearing chip
4. Discontinuous chip

Range of lamellar-segmented and discontinuous chip

Range of continuous chips

Shear strength $\tau$

Degree of deformation $\varepsilon$

$\varepsilon_0$

Elastic region
Plastic region
Yield range

$E_0$: Degree of deformation in the shear plane
E: Elastic limit
B: Breaking limit
Z: Fraction point

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Chip formation for brittle material behaviour

1. Bring up gathering
2. Split up, crack segment formation
3. Shearing and next bring up
4. Second segment formation and bring up
5. Shearing and next crack
6. Third segment formation and bring up
7. Shearing and next crack... Dynamic cutting force

source: Codron 1906
Outline

1. The Cutting Part
2. Chip Formation
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The shear plane model

Accounts:
- plastic deformation only in the shear plane
- plane strain deformation
- ideal sharpness of the cutting edge

Realisation: The orthogonal cut

- tool cutting edge angle $k_r = 90^\circ$
- tool cutting edge inclination $\lambda_s = 0^\circ$

All the force components are in the tool orthogonal plane $P_o$. 

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Krystoff 1939: Shear angle determination

\[ (\rho - \gamma_o) + \Phi = 45^\circ \]

\[ \rho \quad \Phi \]

trace of the shear plane

major axis system

machine coordinate system

principle of maximum shear stress

\[ \Phi = \frac{\pi}{4} + \gamma_o - \rho \]

workpiece

tool

\[ P_o \quad P_f \quad P_n \]
Ernst and Merchant 1941: Force equilibrium and shear angle

shear plane location is determined by the minimum for cutting energy

\[
\frac{\partial E_c}{\partial \phi} = 0 \quad \text{suff.:} \quad \frac{\partial^2 E_c}{\partial \phi^2} \neq 0
\]

\[
\frac{\partial |F_c|}{\partial \phi} = 0 \quad \text{suff.:} \quad \frac{\partial^2 |F_c|}{\partial \phi^2} \neq 0
\]

\[
\Phi = \frac{\pi}{4} + \frac{1}{2} \times (\gamma_0 - \rho)
\]

\[
tan \rho = \frac{F_\gamma}{F_{\gamma n}} = \frac{F_f \cos \gamma + F_c \sin \alpha}{F_c \cos \gamma - F_f \sin \alpha}
\]
Shear plane model: force calculation

Demonstration of the total force as a function of the shear stress with consideration of:

- shear work
- friction work at the face

\[
F_z = \frac{\tau_\phi \cdot b \cdot h}{\sin \phi \cdot \cos(\phi + \rho - \gamma_0)}
\]

By using the circle of Thales, the total force can be substitute with the two force components cutting force and feed force. (in the orthogonal cut)

\[
F_c = \frac{\cos(\rho - \gamma_0)}{\sin \phi \cdot \cos(\phi + \rho - \gamma_0)} \cdot \tau_\phi \cdot b \cdot h
\]
\[
F_f = \frac{\sin(\rho - \gamma_0)}{\sin \phi \cdot \cos(\phi + \rho - \gamma_0)} \cdot \tau_\phi \cdot b \cdot h
\]

Calculation of the force components with a physical and theoretical background!

(advantage of analytical models)
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Overview: Influencing Variables on Machinability

**Machine tool**
- machine tool
- machine condition

**Production conditions**
- production processes
- engagement parameter
- cooling

**Workpiece**
- geometry
- surface integrity
- clamping

**Material**
- type of the material
- chemical configuration
- microstructure
- strength property
- heat treatment

**Cutting material**
- type of the material
- chemical configuration
- microstructure
- strength property
- surface treatment

**Tool**
- tool type
- geometry of the cutting edge
- clamping

**Machinability**
- tool life
- surface integrity
- total force
- chip form
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Resultant force and ist components in the cutting process

The information about the absolute values and the directions of the force components provide a basis:

- For the construction of machine tools
- For the definition of the cutting conditions
- For the evaluation of the cutting edge stresses and the explanations of the wear process
- For the evaluation of the material's machinability

F_z: Resultant force
F_c: Cutting force
F_f: Feed force
F_p: Passive force
F_a: Active force
F_D: Thrust force

v_c: Cutting speed
v_f: Feed velocity
v_e: Effective cutting speed
Dependencies of the force components

- The peaks in the cutting speed chart are traced back to the fact of built-up edge growth.
- The decrease in force along with increasing cutting speed is a result of the material softening.
- The force curves $F_p$ and $F_f$ have opposing trends with increasing tool cutting edge angle $\kappa_r$, which is the angle between the main cutting edge and the direction of feed.
- The increase of the resultant force components dependent on the depth $a_p$ can be traced back to the higher stock removal volume.
Cutting force measuring during the turning process

3-component-cutting-force-measuring-platform
Measurement $F_c$, $F_f$, $F_p$
Force approximation: Empirical models

Linear approximation:

\[
F_i = A \cdot b \cdot h + B \cdot b
\]

- result of a curve fit
- first part is based on the shear plane theory
- very easy function
- not very precise
- calculations are not sufficiently verified (method is not commonly used)

Potential approximation:

\[
F_i = k_i \cdot b \cdot h^{(1-m)}
\]

- result of a curve fit
- calculation of the cutting force is statistically verified
- very precise
- no theoretical basis
- calculation of the other force components is not sufficiently verified

- Schlesinger (1931)
- Pohl (1934)
- Klein (1938)
- Richter (1954)
- Hucks (1956)
- Thomson (1962)
- Altintas (1998)

- Taylor (1883/1902)
- Fischer (1897)
- Friedrich (1909)
- Hippler (1923)
- Salomon (1924)
- Kronenberg (1927)
- Klopstock (1932)
- Kienzle (1952)
Correlation between the force and the undeformed chip thickness

Today you describe the problem by curve fitting on your computer!
KIENZLE Equation to calculate the static cutting forces

Linear equation:
\[ y_i = a \cdot x + b \]

\[ \Rightarrow \log F'_i = a \cdot \log h + \log F'_i \]

\[ \log \left( \frac{F_i}{b} \right) = a \cdot \log h + \log F'_i \]

\[ F_i = (h)^{1-m_i} \cdot F'_i \]

KIENZLE equation:
\[ F_i = k_{i1.1} \cdot b \cdot h^{1-m_i} \]

\[ \tan \varepsilon = 1 - m_i = \frac{\log F'_i(B) - \log F'_i(A)}{\log h(B) - \log h(A)} \]
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Tool wear

is influenced by high contact stresses, high cutting temperatures and relative sliding velocities

These process values depend on:

- tool and workpiece materials
- tool geometry
- interface conditions
- machining parameters
Thermic stress – segmenting the effective work during machining

- The work transformed during the machining relates with the chip width.
- Especially the shearing energy increases with wider chips.
- Friction of flank face and cutting energy are in independent of the chip width h.
- The energy dedicated during the machining process is nearly completely transformed into heat.
- The heat emerges in the primary shearing zone and the friction zone at the tool (secondary shearing zone).

Effective Energy

\[ W_E = F_e \times l_e \]

Deformation energy

Shear energy

Cutting energy

Friction energy

Friction of flank face

Friction of rake face

Latent energy and heat

Quelle: Vieregge
Distribution of heat and temperature in workpiece, chip and tool

Allocation of heat in the machining zone

Heat flows emerging from the machining zone

Material: steel
Yield stress: \( k_t = 850 \text{ N/mm}^2 \)
Cutting material: HW-P20
Primary speed: \( v_c = 60 \text{ m/min} \)
Chip width: \( h = 0.32 \text{ mm} \)
Chip angle: \( \gamma_o = 10^\circ \)

\[ Q_{air} = \text{Heat flow to environment} \]
\[ Q_{chip} = \text{Heat flow to chip} \]
\[ Q_{Wp} = \text{Heat flow to workpiece} \]
\[ Q_{tool} = \text{Heat flow to tool} \]

Source: Kronenberg, Vieregge

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Cutting forces and chip temperatures in turning

- **Temperature vs. Cutting Speed**
  - TiAl6V4
  - Ck45N
  - AlZnMgCu1,5

- **Cutting Force $F_c$ vs. Cutting Speed**

- **Material Comparison**
  - **Aluminium**
    - Feed: 0.25 mm
    - Depth of cut: 2 mm
  - **Steel/Titanium**
    - Feed: 0.1 mm
    - Depth of cut: 1 mm

- **Image of Cutting Setup**
  - Workpiece
  - Insert
  - Quartz-fiber
  - Clamping
Tool wear locations

**Crater Wear**
Area of high level of stress and temperature, i.e. of the order of 1200°C.

**Built-Up Edge**
Observable for ductile materials. Not stable, breaks off frequently.

**Flank Wear**
Mainly responsible for the resulting surface quality => used as failure criteria.

*Tool Wear appears at three locations at the cutting tool*
Wear mechanisms

- The total wear at the wedge is a superposition of distinct wear mechanisms.
- During cutting all distinct wear mechanisms occur simultaneously.
- Diffusion and oxidation are dependent on the temperature level and occur mainly at high cutting speeds.

source: Vieregge
Wear mechanisms at the wedge: adhesion

- Low cutting speeds cause low contact temperatures between chip and tool. This goes along with high contact pressure.

- Low contact temperatures, high contact pressure and material affinity lead to adhesion.

- Adhesion at the wedge may cause built-up edges.

- Built-up edges are unstable. They peel away off the edge and slide over the flank and the face periodically.
Wear mechanisms at the wedge: abrasion

- Abrasion at the wedge is caused by hard particles in the chip, which penetrate into the tool material and slide and scratch over the face.

- As a result on the face a crater is generated.

- As a result on the flank a wear land is generated.
Catastrophic failure of the wedge

If the mechanical load at the wedge surpasses the resistance of the cutting material, the cutting edge fails.

- Chipping and break outs at the cutting edge
- Little disruptions at the cutting edge
The cutting edge influenced by thermic overload

- The cutting material may heat massively through thermic load which reduces its resistance towards mechanical stress; the cutting edge may deform plastically.
- The plastic deformation appears basically with high speed steel.
- Thermic alternating load may cause comb cracks at the wedge.
- They appear mainly during discontinuous cuts whereas the cutting edge heats in circuit and cools down in the disruption.
- In order to avoid comb cracks in discontinuous cutting (e.g. during milling) the use of coolant can often be avoided.
Formation of comb cracks and parallel cracks during milling

Comb cracks

Comb and parallel cracks

GJS70 $v_c = 200 \text{ m/min}$

42CrMo4+QT $v_c = 275 \text{ m/min}$

Heating during the cut

Cooling down

Temperature

Tension ten. $+ 0 - \text{ comp.}$

Source: Lehwald, Vieregge
Wear mechanisms at the wedge: diffusion

- If the temperature level of the contact area reaches a limit and affinity of material is given diffusion can be activated.
- The diffusion is shown by an analogue experiment. Here a cemented carbide tool works on quenched steel.
- During cutting only a very short time is available for diffusion to occur.
Types of wear and values for the tool wear characterization

- **Flank Wear**
- **Crater Wear**

**Dimensions and Values**:

- **VB**: Flank wear width
- **KM**: Crater center distance
- **KF**: Distance from crater to edge
- **KB**: Crater width
- **KT**: Crater depth

Image: A-A section with annotations for measurements.
Evaluation of crater wear

Measured indicators for the evaluation of crater wear are the crater depth KT, the crater centre distance KM, the crater width KB and the displacement of the cutting edge SV in face flank direction.

Weakening of the cutting edge is a result of massive crater wear → Danger of a cutting edge fraction (crater edge fracture).
A distinction is drawn between the measured indicators flank wear width $VB$ and the displacement of the cutting edge in flank direction $SV_\alpha$.

The flank wear width is referred to the cutting edge without wear.
The typical course of wear

16MnCr5 (62 HRC)  
CBN20  
$v_c = 200 \text{ m/min}$  
$f = 0.08 \text{ mm}$  
$a_p = 0.2 \text{ mm}$
Taylor Function

Tool-life function in a double logarithmic system has the shape of a straight line

\[ y = m \cdot x + b \]

\[ \log T = k \cdot \log v_c + \log C_v \]

with \( k = \tan \delta_{vc} = -\frac{\log C_v}{\log C_T} \)

**Taylor-equation (simple)**

\[ T = v_c^k \cdot C_v \]

\[ v_c = T^{1/k} \cdot C_T \]

**Taylor-equation (extended)**

\[ T = C_{vfa} \cdot v_c^{k_{vc}} \cdot f_z^{k_f} \cdot a_p^{k_ap} \]

Frederick Winslow Taylor (USA, 1856-1915)
Wear diagram: Flank wear

the choice of the tool life criterion

under fixed cutting edge geometries and cutting conditions

determination of the tool life

consideration of the boundary conditions
Determination of the cutting speed for a tool life of 15 minutes

\[ v_{15\text{B}0.3} = 170 \frac{m}{\text{min}} \]
Tool wear modelling

Tool life equations

Tool life by Taylor:

\[ T = v_c^k \cdot C_v \]

Tool life by Hasting:

\[ T = \frac{A}{g^B} \]

T = Tool life
k, A, B = Constants
C_v = T for v_c = 1 m/min

v = Temperature

Empirical tool wear model

Physical tool wear model

Abhesion

Abrasition + Diffusion

Adhesion / Abrasion

Model by Archard:

\[ \frac{dV}{dt} = K \frac{F \cdot S}{3H} \]

Model by Usui:

\[ \frac{dV}{dt} = \sigma_n \cdot v_{ch} \cdot C_1 \cdot e^{-\frac{C_2}{T}} \]

Model by Takeyama:

\[ \frac{dV}{dt} = G \cdot v_c + D \cdot e^{-\frac{E}{R^g}} \]

dV/dt = Wear volume per time
K, C1, C2, G, D = Constants
H = Hardness
σ_n = Normal pressure
F = Mechanical load
v_{ch} = Sliding velocity
S = Cutting path
\nu = Temperature

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## Factors influencing surface quality in metal cutting

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### Kinematic roughness
- Tool motion

### Cutting roughness
- Chip formation mechanisms, BUE
- Alteration of cut surface

### Additional factors
- Vibrations, chips, deformation of feed tracks
- Dynamic stiffness of the system tool-work-machine tool, cutting forces, chip formation, tool micro geometry, work material, cutting parameter

### Influences on surface quality in metal cutting

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### Influenced by
- Cutting speed, feed
- Wear on minor flank, overall wear
- Tool geometry, work material, temperature, tool material
- Corner and flank wear, friction and welds, cooling

Source: F. Betz
Kinematic (theoretical) depth of roughness

The theoretical depth of roughness $R_t$ can be derived from the geometrical engagement specifications and is a function of the feed and the corner radius $r_\varepsilon$

$$R_t = r_\varepsilon - \sqrt{r_\varepsilon^2 - \frac{f^2}{4}}$$

or

$$R_t = \frac{f^2}{8 \cdot r_\varepsilon}$$
Theoretical and measured depths of roughness

- The illustration demonstrates a comparison of theoretical and measured depths of roughness.

- The divergency between the results in the low feed area can be traced back to the low chip width which grows with increasing rounded cutting edge radius.

Source: Moll und Brammertz
Chip tip theory

- The geometrical ideal surface profile is determined by the kinematic depths of roughness $R_{\text{kin}}$.

- Due to the material resilience and the cutting edge wear, material of the work piece is being displaced which partially springs back afterwards.

- Chip tips are created because of this process.

- Due to the creation of chip tips the real depth of roughness is higher than the theoretical kinematic depth of roughness $R_{\text{kin}}$.

Source: Brammertz, 1961
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### Evaluation criterion: Chip Formation

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<th>Acceptable</th>
<th>Good</th>
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1. Ribbon chip
2. Snarled chip
3. Flat helical chip
4. Angular helical chip
5. Helical chip

6. Helical chip segment
7. Cylindrical helical chip
8. Spiral chips
9. Spiral chip segment
10. Discontinuous chip
Thanks for your attention!