Cutting Processes

Simulation Techniques in Manufacturing Technology
Lecture 7

Laboratory for Machine Tools and Production Engineering
Chair of Manufacturing Technology

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Aim of the lecture

This lecture is supposed to…

- give a general understanding of selected techniques of machining with geometrically defined cutting edge.
- teach the characteristics and range of application of the principles of manufacturing technologies.
- illustrate the characterizations of the different manufacturing processes.
Outline

1 Introduction

2 Cutting processes with rotary motion

3 Cutting processes with parallel translation

4 Hard machining

5 Modeling of Machining
# Classification of manufacturing processes according to DIN 8580

## Manufacturing processes

- **Primary Shaping**
- **Forming**
- **Separation**
- **Joining**
- **Coating**
- **Change material characteristics**

### Processes with rotational primary movement
- **Severing**
- **Cutting with geometrically defined cutting edges**
- **Cutting with geometrically undefined cutting edges**
- **Removal operations**
- **Disassembling**
- **Cleaning**

### Processes with translational primary movement
- **Turning**
- **Drilling, Reaming**
- **Milling**
- **Sawing**
- **Planing, Shaping**
- **Broaching**
- **Filing, Raspining**
- **Brushlike tools**
- **Scraping, chiseling**

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Classification of processes with rotational primary movement

- **Turning**
  - Workpiece rotation
  - Tool translation

- **Milling**
  - Tool rotation
  - Workpiece translation

- **Drilling**
  - Tool rotation
  - Workpiece translation

- **Sawing**
  - Tool rotation
  - Workpiece translation

### Diagrams:

- **Primary movement**
- **Subsidiary movement**
- **Sub. movement**
Classification of processes with translational primary movement

**Broaching**
- multi teeth tool
- tool geometry implies feed
- high cutting ability
- high surface quality
- high accuracy
- high tool costs
- inflexible

**Planing**
- cutting motion by work piece
- tool feed
- stepwise, linear cutting motion
- successive feed movement
- machining of large, planar areas

**Shaping**
- cutting motion by tool
- workpiece feed
- stepwise, linear cutting motion
- successive feed movement
- machining of large, planar areas
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Turning of steel

- $v_c = 200$ m/min
- $f = 0.6$ mm
- $a_p = 5.0$ mm
- Ck 45

Source: ISCAR
High speed filming of turning process

- $\kappa_r = 102^\circ$
- $f = 0.35$ mm
- $a_p = 1.5$ mm
- Ck 45
Turning processes (DIN 8589-1)

Face Turning
Cylindrical Turning
Helical Turning
Hob Turning
Profile Turning
Form Turning

Source: Iscar, Seco, Sandvik Coromant, Lingenhöle
Face turning (Parting off)

Source: ISCAR
Rough turning

Vordrehen  CNMG 12 04 12
Geometrie -49

\[ ap = 3 - 5 \quad f = 0,45 \quad vc = 250 \]

Source: Widia
Finish turning

Source: Widia
Terms at the cutting edge

- tool shank
- minor cutting edge $S'$
- minor flank face $A_\alpha$
- minor flank face $A_\alpha'$
- rake face $A_\gamma$
- major cutting edge $S$
- major flank face $A_\alpha$
- corner radius
- cutting direction
- feed direction
Tool reference systems

Tool in hand system

Tool in use system

\[ P_r = \text{Tool reference plane} \]
\[ P_f = \text{Assumed Working plane} \]
\[ P_P = \text{Tool back plane} \]
Definition of the tool cutting edge angle $\kappa_r$
Definition of tool cutting edge angle $\kappa_r$

- Tool orthogonal plane $P_o$
- Direction of feed
- Tool cutting edge plane $P_S$
- Tool reference plane $P_r$
- Working plane $P_f$
- Workpiece
- Tool

Symbols:
- $r_\varepsilon$
- $\kappa_r$
- $f$
- $a_p$
Definition of the inclination angle $\lambda_s$

- Working plane $P_f$
- Tool cutting edge plane $P_s$
- Tool reference plane $P_r$
Definition of the inclination angle for longitudinal cylindrical turning
Definition of the tool orthogonal rake angle $\gamma$

Tool orthogonal plane $P_o$

Tool cutting edge $P_s$

Tool reference plane $P_r$
The wedge geometry is defined by the clearance angle $\alpha_0$, the wedge angle $\beta_0$ and the tool orthogonal rake angle $\gamma_0$.

- 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

\[ \alpha_0 + \beta_0 + \gamma_0 = 90^\circ \]
Penetration of tool and workpiece: Cross-sectional area

- Tool cutting edge angle: $\kappa_r$
- Depth of cut: $a_p$
- Feed: $f$
- Width of undeformed chip: $b$
- Undeformed chip thickness: $h$
- Cross section of undeformed chip: $A$

\[
A = a_p \cdot f = b \cdot h
\]
Tool variants in longitudinal cylindrical turning

right hand side cutting

left hand side cutting

neutral

Feed direction

Source: ISCAR
Facing (DIN 8589-1: ON 3.2.1.1)

Cross face turning

Cross parting off

Longitudinal face turning

Source: Sandvik Coromant
Facing (DIN 8589-1: ON 3.2.1.1): cross / longitudinal face turning
Facing (DIN 8589-1: ON 3.2.1.1): cross parting off

WALTER CUT

vc = 140 m/min
f = 0.08 mm/rev.
ap = 2.0 mm

XLDEL1616K-GX16-1
GX16-1E200N020-CF4 WSP43

1.7225
42CrMo4
Rm = 900 N/mm²
Cylindrical turning (DIN 8589-1: ON 3.2.1.2)

### Longitudinal-cylindrical turning

- **Tool**
- **Workpiece**

### Centreless rough turning

- **Tool**
- **Workpiece**

### Cross-cylindrical turning

- **Tool**
- **Workpiece**

Source: Iscar, Ceratizit
Helical turning (DIN 8589-1: ON 3.2.1.3)

Thread turning

Thread chasing

Source: ISCAR Sandvik

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Profile turning (DIN 8589-1: ON 3.2.1.5)

Trepanning

Grooving

Cross-profile turning

Source:

© WZL/Fraunhofer IPT
Contour turning (DIN 8589-1: ON 3.2.1.6)

NC contour turning

Copy turning

Kinematic contour turning

Source: Sandvik Coromant
Internal turning

Skimming

workpiece

tool

f

n

Undercut

workpiece

tool

f

n

Cut in

workpiece

tool

f

n

Source: Lach-Diamant, Iscar, Boehlerit
Internal turning tools

Source: Sandvik
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Face milling (DIN 8589-3: ON 3.2.3.1)
Face milling (DIN 8589-3: ON 3.2.3.1)

Xtra-tec

\[ \begin{align*}
\phi &= 63 \text{ mm} \\
z &= 6 \\
v_c &= 240 \text{ m/min} \\
n &= 1213 \text{ 1/min} \\
f_z &= 0.2 \text{ mm} \\
v_f &= 1455 \text{ mm/min} \\
ap &= 2 \text{ mm} \\
ae &= 43 \text{ mm} \\
1.7225 \\
42\text{CrMo4}
\end{align*} \]
Milling processes (DIN 8589-3)

- **Face milling**
- **Circular milling**
- **Helical milling**
- **Hob milling**
- **Profile milling**
- **Form milling**

Source: Sandvik Coromant, Walter, Fette, Milltech, Seco, Gleason

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Slab milling: face and peripheral milling

- **Face milling**
  - Workpiece surface is created with the face plane

- **Peripheral milling**
  - Workpiece surface is created with the peripheral plane

Source: Sandvik Coromant

© WZL/Fraunhofer IPT
Up and down milling

### Down milling
- **Ploughing**: ▼
- **Surface quality**: ▲
- **Chatter**: ▼
- **Clamping forces**: ▼

### Up milling
- **Ploughing**: ▲
- **Surface quality**: ▼
- **Chatter**: ▲
- **Clamping forces**: ▲

<table>
<thead>
<tr>
<th>Ploughing</th>
<th>Down milling</th>
<th>Up milling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface quality</td>
<td>▲</td>
<td>▼</td>
</tr>
<tr>
<td>Chatter</td>
<td>▼</td>
<td>▲</td>
</tr>
<tr>
<td>Clamping forces</td>
<td>▼</td>
<td>▲</td>
</tr>
</tbody>
</table>
Tool-in-hand system: Face milling
Tool-in-hand system: Peripheral milling

\[ \omega_E = 0^\circ \]
\[ \omega_c = \omega_A - \omega_E \]

trace of \( P_s \equiv P_p \)

trace of \( P_r \)
Contact conditions and cutting edge geometry in face milling

- Entry plane: $\phi = 0$
- Tangential plane
- Cutting C-C
- Tool cutting edge
- Plane B-B

**Contact types:**
- $b = \frac{a_p}{\sin \kappa}$
- $h(\phi) = f_z \cdot \sin \phi \cdot \sin \kappa_r$
- $\phi_i = \arccos \frac{a_{el}}{D/2}$
- ($f_z << D$)
Precision milling operations

Finish milling
- no. of teeth: 10 to 60
- $a_p = 0.3$ bis 1 mm
- $f_z = 0.3$ bis 0.5 mm

Wide finish milling
- no. of teeth: 1 to 6
- $a_p = 0.05$ to 0.2 mm
- $f_z = 0.5$ bis 6 mm

Finish milling with planing knives and wide finishing cutting edge
- no. of planing knives: 20 to 30
- no. of wide finishing cutting edges: 1 to 2
- finishing $a_p1 = 0.5$ to 2 mm
- cutting edges $f_{z1} = 0.1$ to 0.3 mm
- wide finishing $a_p2 = 0.03$ to 0.05 mm
- cutting edges $f_{z2} = 2$ to 5 mm
Indexable end mills

Source: Coromant Sandvik, Seco
Inserted tooth milling cutter

Source: Coromant Sandvik, Seco-Tools
Example of use: Blisk (Blade Integrated Disk)
Circular milling (DIN 8589-3: ON 3.2.3.2)

![Diagram of circular milling](image)

- Additional axial cutting edges
- Radial cutting edges

Source: Walter
Helical milling (DIN 8589-3: ON 3.2.3.3)
Hob milling

- $v_c$: Cutting speed
- $f_a$: Axial feed
- $f_w$: Hob feed

Rotation of hub, radial feed, axial feed, rotation of workpiece.
Different hob types

- **Solid steel hob**
  - High rotational speeds
  - Short milling times
  - Short setting distance

- **Inserted blade hob**
  - High material removal rates
  - Roughing and Finishing
  - Easy regrinding
  - Large gear diameters and modules

- **Indexable cutter**
  - No regrinding
  - Relatively low accuracy
  - Roughing
  - Large gear diameters and modules

Source: Fette, Saazor, Saacke
Profile milling (DIN 8589-3: ON 3.2.3.5)

Profile milling cutter

Gang milling cutter

Source: Sandvik Coromant, Ingersoll, Alesa, Seco
Form milling (DIN 8589-3: ON 3.2.3.6)

Form profile milling

Source: Milltech, Dalscheid
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Example of gun drilling

Source: Widia
Example of gun drilling

Xtra-tec® DRILL

- Ø = 21 mm
- z = 1
- vc = 220 m/min
- n = 3335 1/min
- fz = 0.12 mm
- vf = 400 mm/min
- t = 25 mm

1.7225
42CrMo4
Drilling processes DIN 8589-2

Drilling, Countersinking, Reaming

- Spot facing
- Centre drilling
- Tapping
- Profile drilling
- Form drilling

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Criteria for drilling

- Material separation and reaming at the major cutting edge
- Plastic deformation at the chisel edge
- Cutting speed drops down to zero in the centre of the drill
- Chips are difficult to remove
- Unfavourable heat distribution at the interface
- Increased wear at the sharp-edged corner
- Reaming between leading lands and drilling wall

Source:
Geometry of the cutting part of a twist drill (DIN 8589-2)

- cutting part
- plunge (lettering point)
- flat tang
- tapered shaft
- drill diameter d
- point length
- cutting length
- flute length
- total length
- cone length
- plunge length
Geometry at the cutting edge of a twist drill

Construction dimensions DIN 6539
Type: N
Diameter: $d = 1$ mm
Drill-point angle: $\sigma = 118^\circ$

Major clearance angle: $\alpha = 10^\circ$
Twist angle: $\delta = 35^\circ$
Cutting material: HW-K20
Grain size: $D_k = 0.5 - 0.7 \mu m$
Cutting conditions dependent on drill diameter

![Graph showing cutting speed (v_c) and rake angle (g) and clearance angle (a) for different drill radii (r) and rake angles (γ) and clearance angles (α).]
Fundamental kinematics: Centre drilling

- Cutting direction
- Effective direction
- Feed direction
- Cutting edge 1
- Cutting edge 2
- \( \frac{f}{2} \)
- \( \alpha \)
- \( \alpha_{xe} \)
- \( \beta \)
- \( \eta \)
Fundamental kinematics: Centre drilling

![Diagram of centre drilling process with annotations for tool, workpiece, and kinematic traces.](image)
## Twist drill for various materials

<table>
<thead>
<tr>
<th>Type</th>
<th>Point angle $\sigma$ / °</th>
<th>Twist angle $\delta$ / °</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>118</td>
<td>18 to 30</td>
<td>e.g. steel</td>
</tr>
<tr>
<td>H</td>
<td>118</td>
<td>10 to 15</td>
<td>e.g. grey cast iron</td>
</tr>
<tr>
<td>W</td>
<td>130</td>
<td>35 to 45</td>
<td>e.g. Aluminum</td>
</tr>
</tbody>
</table>

Source: DIN 1414
Specific geometries of twist drills

- **Form A**: Cone shaped drill (basic polish for form A-D)
- **Form B**: Pointed transverse cutting edge
- **Form C**: Pointed cutting edge with corrected major cutting edge
- **Form D**: Cross-wise polish
- **Form E**: Pointed transverse cutting edge with facetted cutting edge corners
- **Form E**: Point angle 180° with centre tip
Drilling processes I (DIN 8589-2)

<table>
<thead>
<tr>
<th>Centre drilling</th>
<th>Gun drilling</th>
<th>Tapping</th>
<th>Profile drilling</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>primary motion</strong></td>
<td><strong>tool</strong></td>
<td><strong>primary motion</strong></td>
<td><strong>tool</strong></td>
</tr>
<tr>
<td><strong>feed motion</strong></td>
<td><strong>feed motion</strong></td>
<td><strong>feed motion</strong></td>
<td><strong>feed motion</strong></td>
</tr>
<tr>
<td>workpiece</td>
<td>workpiece</td>
<td>workpiece</td>
<td>workpiece</td>
</tr>
</tbody>
</table>

**Drilling:** Cutting with circular primary motion. The axis of rotation of the tool and of the produced internal area are identical. The direction of the feed has the direction of this axis of rotation.
Gun drilling

Source: Sandvik
Deep hole drilling

Single lip drilling

Diameter range
0,8 to 40 mm

BTA-Method

Diameter range
6 to 300 mm

Ejector-Method

Diameter range
18 to 250 mm

Source: Sandvik
Example of use: Micro deep hole drilling

Source: TITEX
## Drilling processes II (DIN 8589-2)

### Sinking:
Drilling for producing planes which are orthogonal to the axis of rotation or rotationally symmetric cone and form planes.

### Reaming:
Bore up with a low undeformed chip thickness for producing better qualities of the surface.

<table>
<thead>
<tr>
<th>Countersinking</th>
<th>Cylinder sinking</th>
<th>Reaming</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Countersinking Diagram" /></td>
<td><img src="image2" alt="Cylinder Sinking Diagram" /></td>
<td><img src="image3" alt="Reaming Diagram" /></td>
</tr>
</tbody>
</table>

**Countersinking**: primary motion, feed motion, tool, workpiece

**Cylinder Sinking**: primary motion, feed motion, tool, workpiece

**Reaming**: primary motion, feed motion, tool, workpiece
Round reaming

Boring with small uncut chip thickness with a reamer in order to produce a high precision cylindrical inner surface with excellent surface quality.
Solid-carbide reamer

Source: Iscar, Rübig, Gühring
Construction principle of a reamer with guide rail

Mounting plate
Mounting screw
Cutting insert
Adjusting screw

Source: MAPAL
Reamer with two PCD-cutting edges and PCD-guide rail

EN-GJL-250, $v_c = 120$ m/min, $v_f = 675$ mm/min

Source: MAPAL
Construction types of multibladed reamers

Source: SECO, DIHART, MAPAL
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   3.3 Sawing

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## Definitions and kinematics

**Planing/shaping:** Cutting with repeated parallel translation as primary motion and successive feed motion which is orientated orthogonal to the primary motion. The kinematics of planing and shaping are identical. When the primary motion comes from the workpiece the process is called **planing**, when the primary motion comes from the tool the process is called **shaping**.

<table>
<thead>
<tr>
<th>Planing</th>
<th>Shaping</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Planing Diagram" /></td>
<td><img src="image2" alt="Shaping Diagram" /></td>
</tr>
</tbody>
</table>

- **Planing Diagram**:
  - Main movement
  - Subsidiary movement
  - Primary motion at the workpiece

- **Shaping Diagram**:
  - Primary motion at the tool
  - Subscripts: \( v_R \), \( v_c \), \( f \), \( a_p \)
Planing processes (DIN 8589-4)

<table>
<thead>
<tr>
<th>Finish planing</th>
<th>Contour planing</th>
<th>Profile planing</th>
<th>Circular planing</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>primary motion</strong></td>
<td><strong>feed motion</strong></td>
<td><strong>feed motion</strong></td>
<td><strong>feed motion</strong></td>
</tr>
<tr>
<td><strong>workpiece</strong></td>
<td><strong>tool</strong></td>
<td><strong>tool</strong></td>
<td><strong>tool</strong></td>
</tr>
<tr>
<td><strong>feed motion</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Contour planing**: The tool moves along the contour of the workpiece, while the workpiece moves in a primary motion.
- **Profile planing**: Similar to contour planing, but focuses on creating profiles rather than just contours.
- **Circular planing**: The tool moves in a circular motion around the workpiece, while the workpiece moves in a primary motion.
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Broaching processes I

Broaching: Cutting with a tool with more than one flute. The flutes are orientated one after another with the stepping of the undeformed chip thickness. The feed motion is substituted by the stepping. The last flutes of the tool produces the desired profile of the workpiece. After one run, the workpiece is ready and the surface finished.

<table>
<thead>
<tr>
<th>Plane broaching</th>
<th>External broaching</th>
<th>Internal broaching</th>
</tr>
</thead>
<tbody>
<tr>
<td>primary motion</td>
<td>feed motion</td>
<td>primary motion</td>
</tr>
<tr>
<td>tool</td>
<td>tool</td>
<td>tool</td>
</tr>
<tr>
<td>workpiece</td>
<td>workpiece</td>
<td>workpiece</td>
</tr>
</tbody>
</table>

source: DIN 8589-5
# Broaching processes II

<table>
<thead>
<tr>
<th>Profile broaching</th>
<th>Helical broaching</th>
<th>Cylindrical broaching</th>
</tr>
</thead>
<tbody>
<tr>
<td>feed motion</td>
<td>tool</td>
<td>tool</td>
</tr>
<tr>
<td>primary motion</td>
<td>workpiece</td>
<td>workpiece</td>
</tr>
</tbody>
</table>

- **Profile broaching**: The tool moves along the workpiece, with feed motion and primary motion.
- **Helical broaching**: The tool rotates along the workpiece, with feed motion and primary motions.
- **Cylindrical broaching**: The tool moves along the workpiece in a cylindrical manner, with feed motion and primary motions.

### Source: DIN 8589-5

- Initial shape of the workpiece
- End shape of the workpiece
Internal broaching tools (schematic)

- Shank
- Way
- Roughing
- Finishing
- Calibrating part ($f_z=0$)

**Detail A**
- $f_z$
- $t$

- $\alpha_{02}$: clearance angle
- $\alpha_{01}$: chamfer inclination
- $\gamma_{0}$: rake angle

**Detail B**
- $b_{\alpha_{01}}$
- $\alpha_{01}$
- $\alpha_{02}$

- $t$: division
- $f_z$: inclination
Broaching tools

Source: Forst
Example of use for internal broaching

Source: Forst
Used proceedings for the production of turbine discs

Source: MTU
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# Sawing processes

**sawing:** Cutting with circular motion or parallel translation as primary motion. The tools have more than one flute. The depth of cut is low and the primary motion comes from the tool.

<table>
<thead>
<tr>
<th>Hack sawing</th>
<th>Band sawing</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Hack sawing diagram" /></td>
<td><img src="image2" alt="Band sawing diagram" /></td>
</tr>
</tbody>
</table>

**Circular sawing**

![Circular sawing diagram](image3)

- **Tool**
- **Primary motion**
- **Workpiece**
- **Feed motion**

Source: DIN 8589-6

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Nomenclature and tool geometry of the saw band

Tooth point

Width

Tooth root

R

Back of blade

Cutting part

Tooth space (chip space)

Band saw

Working plane

Workpiece

Width

γ₀

β₀

α₀

H

t

Tooth pitch

R Base radius

H Tooth height

v_c cutting speed

v_e Effective cutting speed

f_z Tooth feed

a_e Intervention width
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# Hard machining with geometrically defined cutting edges

## Techniques
- turning
- milling
- broaching

## Cutting materials
- ultra fine grained carbides
- ceramics
- PCBN

## Technological specialties
- cutting process is conducted by a single or a few cutting edges
- strong relation between the condition of single cutting edges and the surface rim zone of the workpiece, because the materials are hard and thus the tools possess a high wear risk
- risk of white layers
Mechanically strong steel parts need to be hardened / tempered

Hardening steel leads to mechanically strong parts

<table>
<thead>
<tr>
<th>Soft</th>
<th>Hardening / Tempering</th>
<th>Hard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Micro structure: Ferrite</td>
<td></td>
<td>Micro structure: Martensite</td>
</tr>
<tr>
<td>Hardness: 20 - 35 HRC</td>
<td></td>
<td>Hardness: 55 - 65 HRC</td>
</tr>
<tr>
<td>Material volume: 100 %</td>
<td></td>
<td>Material volume: Approx. 103 % non-uniform strain and distortion</td>
</tr>
</tbody>
</table>

=> Final cut necessary to achieve high accuracy in form and size, small and medium parts need to be oversized by approx. 0.3 - 0.5 mm
Typical parts for hard machining

- **Cams shaft**: Slipping load (e.g. contact with bucket tappet)
- **Bearing rings**: Rolling load (contact with rollers), Micro slipping (Contact with shaft)
- **Gears**: Rolling load (Contact with partner gear), Bending load (at tooth ground), Slipping load (Contact with synchronising ring)
Hard machining, turning and grinding

- Hard machining can be realised by defined and undefined machining principles.

- Hardened steel can only be cut defined if the material in front of the cutting tip is heated and softened by the process itself.

- This leads to special requirements for the cutting material and the press design.
## Application for Precision Hard Turning

<table>
<thead>
<tr>
<th>Part:</th>
<th>Precision profile roller Ø 150 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material:</td>
<td>X210CrW12 hardened (63 HRC)</td>
</tr>
<tr>
<td>Machining:</td>
<td>Hard turning of the profile</td>
</tr>
</tbody>
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<table>
<thead>
<tr>
<th>Machining time [%]</th>
<th>Machining Cost [%]</th>
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</thead>
<tbody>
<tr>
<td>100</td>
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</tbody>
</table>

- **Grinding**
- **Hard Turning**

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Outline

1. Introduction
2. Cutting processes with rotary motion
3. Cutting processes with parallel translation
4. Hard machining
5. Modeling of Machining
Force calculation: Time function

Substitution of the empirical force equation proposed by *Kienzle* with the technical terms:

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

\[
F_i \approx k_{i1.1} \cdot \frac{a_p}{\sin \kappa_r} \cdot \left[ \frac{\pi \cdot D \cdot v_f}{z \cdot v_c} \cdot \sin \omega \cdot \sin \kappa_r \right]^{(1-m_i)}
\]

- Diameter of the tool
- Number of teeth
- Polar coordinate

*Source: Diss. Rehse*

\[
h_{\text{max}} \approx f_z \cdot \sin \kappa_r \cdot \sin \omega
\]

\[
b = \frac{a_p}{\sin \kappa_r}
\]

Question: What is the angle \(\omega\)?

\[
\omega = \frac{2 \cdot \hat{b}}{D} \quad \hat{b} = v_c \cdot t
\]

Discretisation of the equation

\[
dF_i \approx k_{i1.1} \cdot \frac{a_p}{\sin \kappa_r} \cdot \left[ \frac{\pi \cdot D \cdot v_f}{z \cdot v_c} \cdot \sin \left( \frac{2 \cdot v_c \cdot dt}{D} \right) \cdot \sin \kappa_r \right]^{(1-m_i)}
\]
The same procedure for the other flutes!

**Force calculation: Technical terms**

**discretisation of the equation:**

\[
dF_i \approx k_{i1.1} \cdot \frac{a_p}{\sin \kappa_r} \cdot \left[ \frac{\pi \cdot D \cdot v_f}{z \cdot v_c} \cdot \sin \left( \frac{2 \cdot v_c \cdot dt}{D} \right) \cdot \sin \kappa_r \right]^{(1-m_i)}
\]

- **Discrete time function**
- **Discrete force components** \(dF_i(dt)\)
- **Solving the equation for discrete times**
- **Transformation of the force components into the x- and y-direction**
- **Addition of the force components in x- and y-direction separately**
- **The same procedure for the other flutes!**
Penetration calculation: Peripheral milling

Matrix model for the penetration calculation

- Feed velocity
- Vector field for representation of the tool
- Vector field for the representation of the workpiece
- Thickness of cut $h$
- Width of cut $b$

Data of the machine tool
Data of the tool
Data of the workpiece
Thank you for your attention!!
Questions

- How can one differ the manufacturing processes by their primary movement?
- Which contact conditions exist in external circular cylindrical turning?
- Why is there a necessity to have both a tool in hand and tool in use system?
- Describe the most important angles at the cutting wedge.
- Name the benefits and disadvantages of up- and down milling.
- List different process variants for drilling.
- Why is reaming used?
- Which correlation exists between the helix angle and the hardness of the workpiece material in drilling?
- Please name the different sawing processes and their process characteristics.
- Which characteristics distinguish the different methods of planing and shaping?
- How is broaching characterized?
- Which are the most important processes to manufacture involute gear profiles?