Modelling and Simulation in Manufacturing Technology

„ Cutting with Undefined Cutting“

Prof. Dr.-Ing. F. Klocke

Structure

- Chip removal mechanisms
  - From geometrically defined to geometrically undefined cutting
  - Grinding paths
  - Chip thickness for single-grain
  - Chip thickness for grinding wheels (multi-grain)
  - Process factors - Correlations and influences
  - Energy balances

- Grinding tools and grinding wheel preparation
  - Structure and characteristics of grinding tools
  - Effects of grinding wheel specifications on the process
  - Wear mechanisms in grinding processes and their effects on the wheel topography
  - Preparation of grinding wheels

- Overview of grinding processes and application examples
  - Definition of parameters
  - Overview of grinding processes / procedures variants
  - Characteristics and application examples of some common grinding procedures

- Other active principles of cutting edge engagement with geom. undef. edges
**Process basics**

Milling is a chip removing process with a geometrically defined cutting tool with a rotatory cutting movement.

**correlation:**

grinding - milling?

**From milling to grinding**

Cutting edges: 4 ... 8 ... 100 ... 1000 ...
Survey of the process

The grinding process and its parameters

Process parameters

Workpiece

Grinding wheel

Process monitoring

Operator

Machine

Coolant

Process

Product
Many physical correlations are still not clear.

Input

Process = Black-Box

Output

optimisation

The "Black-Box": Grinding process

- Wear mechanisms of the grain:
  - abrasion
  - adhesion
  - tribo-chemical reaction
  - surface disorder

- Formation of machined surface:
  - formation of burrs
  - "pepper"ing
  - damage of the external zone
  - microhardness

Chip formation

questions: How are these factors linked?
Which kinematic boundary conditions exist?
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From milling to grinding

Vectoral description of grain path with position vector \( \vec{A} \)
Cycloid path of a grain

Single-grain

Multi-grain

grain 1

gain 3

gain 2

Cycloid paths of grinding grains

Cutting edges with different heights

grinding wheel

depth of cut $a_e$
Static and kinematic cutting edges

Kinematic roughness

Legend:
- $h_{cm}$: maximum chip thickness
- $l_{cu}$: chip length
- $l_{km}$: kinematic cutting edge spacing
- $l_s$: static cutting edge spacing
- $s_t$: cutting edge
- $v_c$: grinding wheel
- $v_w$: circumferential speed
- $v_w$: workpiece speed
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Chip formation in grinding

\[ h_{cu, \text{max}} \approx 2 \cdot \pi \cdot d_s \cdot \frac{v_w}{v_s} \cdot \sqrt{\frac{a_e}{d_s}} \]

\[ \sim F_c, R_z, \Delta r_s \]
Chip roots (photos taken by scanning electron microscope)

Cutting direction

25 µm

workpiece material: Ck15N

10 µm

workpiece material: Ck45N

Geometrical and kinematic contact length

\[
\begin{align*}
geq_{\text{geo}} &= \frac{d_{\text{eq}}}{2} \\
geq_{\text{eq}} &= l_g \\
\text{kinematic contact length: } l_k &= \left(1 \pm \frac{1}{|q|}\right) \cdot l_g \\
\text{with: } &l_g = \sqrt{a_e^2 + x^2} \\
x^2 &= \left(\frac{d_{\text{eq}}}{2}\right)^2 - \left(\frac{d_{\text{eq}}}{2} - a_e\right)^2 \\
q &= \frac{v_i}{v_w}
\end{align*}
\]
Contact conditions in different grinding processes

- **External cylindrical grinding**
  - Real contact conditions: \( d_{eq} = \frac{d_w - d_s}{d_w + d_s} \)
  - Transformed contact conditions: \( d_{eq} = d_s \)

- **Flat grinding**
  - Real contact conditions: \( d_{eq} = \frac{d_w}{d_w + d_s} \)
  - Transformed contact conditions: \( d_{eq} = \frac{d_w d_s}{d_w - d_s} \)

- **Internal cylindrical grinding**
  - Real contact conditions: \( d_{eq} = \frac{d_w - d_s}{d_w + d_s} \)
  - Transformed contact conditions: \( d_{eq} = \frac{d_w d_s}{d_w - d_s} \)

---

**Up grinding**

- Kinematic contact length: \( l_k = \left( \frac{1 \pm \frac{1}{|q|}}{} \right) \cdot l_g \)
- Speed ratio: \( q = \frac{v_s}{v_w} \)
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Chip thickness

\[
\begin{align*}
\text{not deformed chip thickness for single-grain cutting} & \quad h_{\text{cu, max}} \approx 2 \cdot \pi \cdot d_s \cdot \frac{v_w}{v_s} \cdot \sqrt[\gamma]{\frac{a_e}{d_s}} \\
\text{not deformed chip thickness for multi-grain cutting} & \quad h_{\text{cu, max}} \approx k \left( \frac{1}{C_{\text{stat}}} \right)^\alpha \left( \frac{v_w}{v_s} \right)^\beta \left( \frac{a_e}{d_{\text{eq}}} \right)^\gamma 
\end{align*}
\]

with \( \alpha, \beta, \gamma \) positive

- parameters \( \alpha, \beta \) and \( \gamma \) depend on the grinding wheel specifications
- \( C_{\text{stat}} \) is the static cutting edge density
- factor \( k = \text{const.} \)
- \( d_{\text{eq}} = \) equivalent grinding wheel diameter
Structure

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**Effect of chip thickness on process parameters**

\[
 h_{cu,\text{max}} \approx k \left( \frac{1}{C_{\text{stat}}} \right)^a \left( \frac{v_w}{v_s} \right)^b \left( \frac{a_e}{d_{eq}} \right)^\gamma
\]

- Max. chip thickness \( h_{cu,\text{max}} \) increases roughness \( R_z \)
- \( h_{cu} \) is proportional to \( R_z \)
- \( h_{cu} \) is proportional to \( F_c \)
- \( h_{cu} \) is proportional to \( P_c \)
**Effect of depth of cut**

Depth of cut $a_e$ → max. chip thickness $h_{cu,max}$ → kinematic contact length $l_k$

$$h_{cu,max} \approx k \left[ \frac{1}{C_{stat}} \left( \frac{v_w}{v_s} \right)^{a} \left( \frac{a_e}{d_{eq}} \right)^{b} \right]^\gamma$$

$$l_k = \left( 1 \pm \frac{1}{|q|} \right) \cdot l_g$$

$$l_g = \sqrt{a_e \cdot d_{eq}}$$

Source: Rappold Winterthur Schleiftechnik

**Effect of cutting speed**

Grinding wheel circumferential speed $v_s$ → max. chip thickness $h_{cu,max}$

$$h_{cu,max} \approx k \left[ \frac{1}{C_{stat}} \left( \frac{v_w}{v_s} \right)^{a} \left( \frac{a_e}{d_{eq}} \right)^{b} \right]^\gamma$$

Source: Rappold Winterthur Schleiftechnik
Effect of grinding wheel diameter

\[ h_{cu, max} \approx k \left( \frac{1}{C_{stat}} \right)^{\alpha} \left( \frac{v_w}{v_s} \right)^{\beta} \left( \frac{a_e}{d_{eq}} \right)^{\gamma} \]

grinding wheel diameter \( d_s \)
→ contact area \( A_k \)
→ kinematic contact length \( l_k \)
→ max. chip thickness \( h_{cu, max} \)

Static and kinematic cutting edges in grinding

\[ F'_n = \int_{0}^{l_k} k \cdot (N_{mon})^{\nu} \cdot N_{kin}(l)dl \]

with \( N_{mon} = \) number of momentary cutting edges

Legend:
- \( h_{cu} \): maximum chip thickness
- \( l_{cu} \): chip length
- \( l_{kin} \): kinematic cutting edge spacing
- \( l_{stat} \): static cutting edge spacing
- \( S_i \): cutting edge
- \( V_w \): circumferential speed
- \( v_w \): workpiece speed
Cutting speed

- Cutting speed $v_c$ → Chip thickness $h_{cu}$ → Number of kinematic cutting edges $N_{kin}$

"Number of chips" increases

- Higher damage of external zone by higher temperature due to friction
- Grinding forces decrease because $N_{kin}$ and $h_{cu}$ decrease
- Roughness decreases $h_{cu} \sim R_z$

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Energy distribution and heat flow during grinding process

Effect of different contact lengths

e.g. creep grinding with low table speeds

\[ h_{cu, max} \approx k \left( \frac{1}{C_{stat}} \right)^{\alpha} \left( \frac{v_w}{v_s} \right)^{\beta} \left( \frac{a_e}{d_{eq}} \right)^{\gamma} \]

- temperature rises \( l_k \sim T \)
- high influence on external zone \( l_k \)
- normal force rises \( l_k \sim F_{n,S} \)
- roughness decreases \( l_k \sim \frac{1}{R_z} \)

\[ l_g = \sqrt{a_e \cdot d_{eq}} \]

\[ F'_{n} = \int_{0}^{l_k} k \cdot (N_{mon})^\nu \cdot N_{kin}(l)dl \]
Tools for cutting with geometrical undefined cutting edge
Chip formation with undefined cutting edges

Composition of grinding wheels
Structure of grinding wheels

![Diagram of grinding wheel structure]

**Specification of conventional grinding wheels**

<table>
<thead>
<tr>
<th>Example</th>
<th>Abrasive</th>
<th>Grain size</th>
<th>Hardness</th>
<th>Texture</th>
<th>Bonding Type</th>
<th>Special Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>A</td>
<td>60</td>
<td>L</td>
<td>S</td>
<td>B</td>
<td>P</td>
</tr>
<tr>
<td>Corundum</td>
<td>A</td>
<td>60</td>
<td>L</td>
<td>S</td>
<td>B</td>
<td>P</td>
</tr>
<tr>
<td>Silicon Carbide</td>
<td>A</td>
<td>60</td>
<td>L</td>
<td>S</td>
<td>B</td>
<td>P</td>
</tr>
</tbody>
</table>

<table>
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<tr>
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<th>Hardness</th>
<th>Texture</th>
<th>Bonding Type</th>
<th>Special Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>coarse</td>
<td>medium</td>
<td>fine</td>
<td>very fine</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>30</td>
<td>70</td>
<td>220</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>36</td>
<td>80</td>
<td>240</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>46</td>
<td>90</td>
<td>280</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>54</td>
<td>100</td>
<td>320</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>60</td>
<td>120</td>
<td>400</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>80</td>
<td>150</td>
<td>500</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>180</td>
<td>600</td>
<td>800</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>240</td>
<td>900</td>
<td>1200</td>
<td></td>
</tr>
</tbody>
</table>

| Volume: | \( V = V_a + V_b + V_p \) [cm³] |
| Mass:   | \( m = m_a + m_b + \rho_V V_a + \rho_V V_b \) [g] |
| Density:| \( \rho = \frac{\rho_V V_a + \rho_V V_b}{V_a + V_b + V_p} \) [g/cm³] |

- Example: 60 L 5 B
- Corundum A V vitrified bonding
- Silicon Carbide C S silicate bonding
- Rubber bonding R
- Resin bonding B
- Shellac bonding Mg
- Magnesit bonding E

A B C D extremely soft
E F G H very soft
I J K L soft
M N O medium
O R S hard
T U V W very hard
X Y Z extremely hard
### Specification of high-hardness grinding wheels

<table>
<thead>
<tr>
<th>Example</th>
<th>Abrasive</th>
<th>Grain Size</th>
<th>Bonding</th>
<th>Hardness</th>
<th>Body Material</th>
<th>Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diamond</td>
<td>D</td>
<td>126</td>
<td>K</td>
<td>J</td>
<td>A</td>
<td>C 50</td>
</tr>
<tr>
<td>CBN</td>
<td>B</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Carbide</th>
<th>Carat/cm³</th>
<th>Term</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>1.7</td>
<td>C-25</td>
</tr>
<tr>
<td>2.2</td>
<td>3.3</td>
<td>C-35</td>
</tr>
<tr>
<td>4.4</td>
<td>5.5</td>
<td>C-100</td>
</tr>
<tr>
<td>6.6</td>
<td>6.6</td>
<td>C-150</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Vol.%</th>
<th>Term</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.0</td>
<td>V-120</td>
</tr>
<tr>
<td>18</td>
<td>V-180</td>
</tr>
<tr>
<td>24</td>
<td>V-240</td>
</tr>
</tbody>
</table>

Soft | Hardness | Bonding Type |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>Medium</td>
<td>Resin Bonding</td>
</tr>
<tr>
<td>R</td>
<td>Hard</td>
<td>Metal Bonding</td>
</tr>
<tr>
<td>T</td>
<td>Very Hard</td>
<td>Vitrified Bonding</td>
</tr>
</tbody>
</table>

- **K** = Resin Bonding
- **B** = Metal Bonding
- **M** = Resin Bonding
- **G** = Galvanic Bonding
- **S** = Sinter Metal Bonding
- **V** = Vitrified Bonding

### Tasks and characteristics of grinding tools

**Task**

While cutting with geometrical undefined cutting edges the effect of material removal is caused by grains penetrating the workpiece material.

**Required properties**

- **Hardness and Toughness**
  - Material removal from the workpiece
  - Maintaining the sharpness
- **Thermal Stability**
  - Withstanding high machining temperatures
  - Withstanding rapid temperature changes
- **Chemical Stability**
  - Avoiding chemical reactions at high temperatures and high pressures
### Grouping of conventional grinding wheels

<table>
<thead>
<tr>
<th>symbol</th>
<th>abrasive</th>
<th>Knoop hardness [N/mm²]</th>
<th>thermal stability [°C]</th>
<th>thermal conductivity [W/(m°C)]</th>
<th>fields of application</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>corundum</td>
<td>1950 to 2200</td>
<td>2000</td>
<td>6</td>
<td>medium-tough to hard materials below 60 HRC ( R_m &lt; 500 \text{ N/mm}^2 ) such as:</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• steel</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• malleable cast iron</td>
</tr>
<tr>
<td></td>
<td>Sol-Gel-corundum</td>
<td>&gt; corundum</td>
<td>-</td>
<td>6</td>
<td>tough-hard steels over 60HRC, such as tool-steel</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• grinding and polishing of glas</td>
</tr>
<tr>
<td>C</td>
<td>silican carbide</td>
<td>3000</td>
<td>1300</td>
<td>55</td>
<td>• surface grinding of HM, GG, ceramics, non-ferrous metals</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• dressing</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• manual grinding</td>
</tr>
</tbody>
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</thead>
<tbody>
<tr>
<td>B</td>
<td>cubic boron nitride (CBN)</td>
<td>4700</td>
<td>1370</td>
<td>200-700</td>
<td>• hardened steel</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• low alloy steel</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• HSS</td>
</tr>
<tr>
<td>D</td>
<td>diamond</td>
<td>8000</td>
<td>900</td>
<td>600 - 2100</td>
<td>• carbon saturated steel</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• glas, stone, ceramics</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• tungsten carbide, cermets</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• glass-fibre re-inforced plastics (GRP)</td>
</tr>
</tbody>
</table>

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[Image of RWT Aachen logo]
Tasks and characteristics of bonds

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<th>Required properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>The purpose of the bond is to retain the grinding grit in place until it is blunted by the cutting operation. The bond should then release the grain so that the next sharp grain can be used.</td>
<td>the bonding material must be firm enough. formation of bond bridges with sufficiently large cross-sections. a durable joint must be formed between bond and grit.</td>
</tr>
</tbody>
</table>

Grouping of bonds

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<thead>
<tr>
<th>symbol</th>
<th>bonding type</th>
<th>characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>V</td>
<td>vitrified bond</td>
<td>• brittle and thus sensitive to impact load&lt;br&gt;• high modulus of elasticity&lt;br&gt;• high thermal stability, low resistance to thermal shock&lt;br&gt;• chemical resistance against oil and water</td>
</tr>
<tr>
<td>D</td>
<td>resin bond</td>
<td>• high impact and shock resistance as well as side pressure&lt;br&gt;• application in parting-off and roughing wheels&lt;br&gt;• high elasticity in fine-grinding wheels enables high surface qualities</td>
</tr>
<tr>
<td>M G</td>
<td>metal bond galvanic bond</td>
<td>• high wear resistance&lt;br&gt;• difficult to dress&lt;br&gt;• high thermal conductivity</td>
</tr>
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Other active principles of cutting edge engagement with geom. undef. edges

Effect of the specification on $h_{cu}$ - grain size

- Grain size
- Grain concentration
- Bonding hardness
- Texture
- Number of kinematic cutting edges $N_{kin}$
- Number of current cutting edges $N_{mom}$
- Distance between kinematic cutting edges $l_{kin}$
- Chip thickness $h_{cu}$
Effect of the specification on $h_{cu}$ - grain concentration

- Grain size
- Grain concentration
- Bonding hardness
- Texture

\begin{align*}
\text{number of kinematic cutting edges } N_{kin} & \quad \downarrow \\
\text{number of current cutting edges } N_{mom} & \quad \uparrow \\
\text{distance between kinematic cutting edges } l_{kin} & \quad \downarrow \\
\text{Chip thickness } h_{cu} & \quad \uparrow \\
\end{align*}

Effect of the specification on $h_{cu}$ - bonding hardness

- Grain size
- Grain concentration
- Bonding hardness
- Texture

\begin{align*}
\text{number of kinematic cutting edges } N_{kin} & \quad \downarrow \\
\text{number of current cutting edges } N_{mom} & \quad \uparrow \\
\text{distance between kinematic cutting edges } l_{kin} & \quad \downarrow \\
\text{Chip thickness } h_{cu} & \quad \uparrow \\
\end{align*}
Effect of the specification on $h_{cu}$ - texture

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  - Characteristics and application examples of some common grinding procedures

- Other active principles of cutting edge engagement with geom. undef. edges
### Variation of grinding wheel topography with material removal rate

<table>
<thead>
<tr>
<th>Process Start</th>
<th>Material Removal Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="#" alt="Graph 1" /></td>
<td>$Q_{w} = 4 \text{ mm}^3/\text{mm} $ $V_{w} = 500 \text{ mm}^2/\text{mm}$</td>
</tr>
<tr>
<td><img src="#" alt="Graph 2" /></td>
<td>$Q_{w} = 4 \text{ mm}^3/\text{mm} $ $V_{w} = 1000 \text{ mm}^2/\text{mm}$</td>
</tr>
</tbody>
</table>

### Wear types at grain and bonding

- Chemical and thermal wear of bond
- Bond breakage
- Grain breakage
- Pressure softening
- Chemical wear
- Abrasive wear

![Scanning - electron microscope - pictures of single grains](#)

**a:** before engagement  
**b:** after engagement time
Examples of grain wear

- abrasion and small grain breakage
- crack initiation
- adhesion
- adherence of chips
- grain breakage
- micro breakage

The chip thickness $h_{cu}$ determines wear behaviour and wear speed.
Motivation for grinding wheel dressing

<table>
<thead>
<tr>
<th>Macroscopic wear</th>
<th>Microscopic wear</th>
</tr>
</thead>
<tbody>
<tr>
<td>radial wear</td>
<td></td>
</tr>
<tr>
<td>edge wear</td>
<td></td>
</tr>
</tbody>
</table>

Consequence

- Profile lost
- Off-size condition
- Blunted grit-cutting-edges
- Increase of grinding forces
- Damage of the workpiece structure in the external zone

Tool conditioning

Structure

- Chip removal mechanisms
  - From geometrically defined to geometrically undefined cutting
  - Grinding paths
  - Chip thickness for single-grain
  - Chip thickness for grinding wheels (multi-grain)
  - Process factors - Correlations and influences
  - Energy balances
- Grinding tools and grinding wheel preparation
  - Structure and characteristics of grinding tools
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### Kinematics of common dressing processes

<table>
<thead>
<tr>
<th>Standing Dressing Tools</th>
<th>Rotating Dressing Tools</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single-grit dressing tool</td>
<td>Profile dressing roll</td>
</tr>
<tr>
<td>Dressing tile</td>
<td>Form dressing roll</td>
</tr>
<tr>
<td>Multi-grit dressing tool</td>
<td>Pot dressing wheel</td>
</tr>
</tbody>
</table>

### Dressing tools

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<tr>
<td>Multi-grit dressing tool</td>
<td>Pot dressing wheel</td>
</tr>
</tbody>
</table>
Creation of tool-topography with dressing processes

- **Standing dressing tool**
  - Similar to: turning
  - Creation of a “thread”

- **Rotating dressing tool**
  - Profile-roll
  - Form-roll
  - Similar to external cylindrical grinding
  - Overlapping of grit engagement paths
  - “thread” + Overlapping of grit engagement paths

Process preparation of CBN-grinding wheels

- **Dressing of CBN grinding wheels**
  - **Profiling**
    - Generating the grinding wheel shape
  - **Sharpening**
    - Generation of the cutting edge space structure
By sharpening the grinding wheel layer becomes ready for use

| Grinding wheel: B 252 KSS 10JA V240 | q_d: Dressing speed ratio |
| Dressing tool: Diamond roller | a_d: Dressing feed |
| Sharpening block height: h_Sb = 25 mm | Q'_Sb: spec. sharpening mat. removal |
| Cutting speed: v_c = 90 m/s | a_Sb: Sharpening block feed |

View 1 2
Grinding wheel

qd = -0.375
a_d = 50 µm
Q'_Sb = 400 mm³/mms
a_Sb = 70 mm

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**Definition of parameters - e.g. surface grinding**

Parameters for the characterisation of the grinding process

Legend:

\[ V_w \]: removed workpiece volume mm³
\[ a_e \]: engagement (infeed) mm
\[ v_w \]: workpiece speed m/s

**Definition of parameters - e.g. face grinding**

Legend:

\[ a_p \]: contact width mm
\[ b_s \]: grinding wheel width mm
\[ v_s \]: grinding wheel speed m/s
Parameters for the grinding process

V\textsubscript{w} = a\textsubscript{e} \cdot a\textsubscript{p} \cdot l

V\textsubscript{w} = \frac{l}{t}

Q'\textsubscript{w} = \frac{Q\textsubscript{w}}{b\textsubscript{seff}}

Q_{w} = \frac{dV_{w}}{dt} = const = \frac{a_{e} \cdot a_{p} \cdot l}{t} = a_{e} \cdot a_{p} \cdot v_{w}

Legend:

V\textsubscript{w}: removed workpiece volume mm\textsuperscript{3}
Q\textsubscript{w}: material removal rate mm\textsuperscript{3}/s
Q'\textsubscript{w}: specific material removal rate mm\textsuperscript{3}/mms

Structure

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Overview of different grinding processes

<table>
<thead>
<tr>
<th>Cylindrical</th>
<th>Surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>external cylindrical</td>
<td>internal cylindrical</td>
</tr>
<tr>
<td>peripheral-plunge-grinding</td>
<td>surface</td>
</tr>
<tr>
<td>peripheral-traverse-grinding</td>
<td>turn</td>
</tr>
<tr>
<td>Side grinding</td>
<td></td>
</tr>
<tr>
<td>side-plunge-grinding</td>
<td></td>
</tr>
<tr>
<td>side-traverse-grinding</td>
<td></td>
</tr>
</tbody>
</table>

Surface grinding

Surface - peripheral - grinding

\[
Q_w = a_e \cdot a_p \cdot v_w
\]

\[
a_p = b_s = b_{seff}
\]

\[
Q'_w = \frac{a_e \cdot a_p \cdot v_w}{b_{seff}} = a_e \cdot v_w
\]
External - cylindrical - grinding

\[ Q_w = \pi \cdot d_w \cdot a_p \cdot v_w \]
\[ = \pi \cdot d_w \cdot a_p \cdot v_{fr} \]
\[ v_w = v_{fr} \]

mit
\[ d_{wa} \geq d_w \geq d_{we} \]
\[ v_{fr} = a_e \cdot n_w \]
\[ a_p = b_s = b_{seff} \]

\[ \Rightarrow Q'_w = \pi \cdot d_w \cdot a_p \cdot a_e \cdot n_w \]
\[ = \pi \cdot d_w \cdot a_e \cdot n_w \]

Structure

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Overview of processes - Examples

<table>
<thead>
<tr>
<th>Cylindrical</th>
<th>Surface</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Peripheral-plunge-grinding</strong></td>
<td><img src="image1.png" alt="Diagram" /></td>
</tr>
<tr>
<td><strong>Peripheral-traverse-grinding</strong></td>
<td><img src="image2.png" alt="Diagram" /></td>
</tr>
</tbody>
</table>

**Characteristics of external - cylindrical - grinding**

- generation of rotationally symmetric workpiece geometries
- frontal centering processing at up-grinding (usually)
- use of back-rests, to avoid high workpiece deflection

**Difficulties:**
- workpiece fitting: centering has to guarantee a true running
- deflection because of high stress resultants at long and thin workpieces
- chattering
Application area of external cylindrical grinding

Machining of:

- bearing carriers, shaft-steps, notches
- Printing rolls, rolls of paper producers
- steel rolling mills

source: Effesis

Characteristics of internal cylindrical grinding

- kinematically identic to centreless external cylindrical grinding
- bigger contact arc in comparison to external cylindrical grinding

- disadvantages
  - problems with chip transport and supply of coolant
  - deformation of the workpiece when the workpiece is long
    ⇒ conicity,
    upvaluation of end of hole
  - high wear

source: Effesis
Application area of internal cylindrical grinding

Machining of:

- gear-wheels
- bearing rings
- retainer of spindles

Source: Daimler Chrysler

Characteristics of surface grinding

- Many procedure variants
- Machining of notches and profiles, big flat surfaces
- Machining by deep- and pendular grinding
- Disadvantages
  - high heat insertion in deep grinding
  - according to geometry bad chip transport
Application area of surface grinding

Machining of:
• guidelines
• sealing-surfaces of motors
• profile of turbine blades for aircraft engines

Characteristics of centreless grinding

• Creation of rotationally symmetrical workpieces
• supported on the periphery
  (linear support of the workpiece)
• restricted on cylindrical, conic or convex machining surfaces
• no sources of error in clamping / centering
• easy workpiece change
• problems:
  • dynamically instable
  • compensation of deviation of circle form
Application area of centreless grinding

Main application area: line production

- bolts, shafts, bearing elements
- bearing carrier of camshafts, cam followers
- pin of a nozzle, rotor axes, ball pivot
- rods, pipes, platens, billiard balls

Structure

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Other active principles

Basic principles of cutting edge engagement

<table>
<thead>
<tr>
<th>Bound by energy</th>
<th>Bound by virtue</th>
<th>Bound by path</th>
<th>Bound by range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blast chipping</td>
<td>Free abrasive gr.</td>
<td>Grinding</td>
<td>Honing</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lapping</td>
<td></td>
</tr>
</tbody>
</table>

Active principle - bound by energy

balst chipping
Active principle - bound by virtue

Gleitschleifen

Active principle - bound by path

Grinding  Honing

cutting edge

grinding / honing
Questions I

1. Of which components a grinding wheel is built of?
2. Which tasks have the components of a grinding wheel?
3. Which grain types and bonding types do exist?
4. Name diverse wear types that could occur on grinding wheels.
5. Why must grinding wheels get sharpened?
6. What is the material removal-rate a quantum for?
7. How do you assign the material removal volume?
8. What is the difference between down-grinding / up-grinding?
9. Name four common grinding procedures!
10. What are the advantages and disadvantages in deep- and pendulum-grinding?
Questions I

1) What is the material removal-rate a quantum for?

2) How do you assign the material removal volume?

3) In which procedures for generating a rationally symmetric geometry is the tool feed a) radial b) axial?

4) What is the difference between down-grinding / up-grinding?

5) Name four common grinding procedures!

6) How can you avoid workpiece deflection in the process of external cylindrical grinding?

7) What problems can occur in the internal cylindrical grinding process and how are they caused?

8) What are the advantages and disadvantages in deep- and pendulum-grinding?

9) What are the typical devices, which are machined in centreless grinding?

10) What are the four active principles of the cutting edge engagement in machining with geometrically undefined cutting edges?