Theory of cutting – Surface integrity

Technology II – Jan Tomíček
Why?

Why are we so much concerned about the influence of $T$, $Vc$, $Q$ and others?

All parameters have great influence on final surface.

What is the surface?

Surface layer
## Surface layer properties

<table>
<thead>
<tr>
<th>Level</th>
<th>Product</th>
<th>Surface</th>
<th>Surface layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>Tool marks</td>
<td>Residual stress</td>
<td></td>
</tr>
<tr>
<td>Weight</td>
<td>Texture</td>
<td>hardness</td>
<td></td>
</tr>
<tr>
<td>tollerances</td>
<td>roughness</td>
<td></td>
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</tr>
</tbody>
</table>
Main factors

• Primary deformation zone

Effect of stress on material.
Small rakes $\rightarrow$ small effect
Big(negative)rakes $\rightarrow$ great influence

• Built-up edge
Change of tool form $\rightarrow$ precision, dimensions, tolerances
Main factors

- Cutting edge radius

Material going under edge is work hardened. → hardened layer

A – slowly going down +
B – Very steep drop down -
C – cracks of surface.
Main factors

• Tool wear (tool sharpness)
  - Shrap becomes worn
  - Radius, smoothness, straightness

Residual stress

Nitrogen Gas Environment
Tool Chip Contact Length 0.33mm

Compressed Air Gas Environment
Tool Chip Contact Length 0.33 to 0.53mm

Depth of Cut 1.5mm, Cutting Speed 600m/min, 80sec cut
Residual stress

- remain in a solid material after the original cause of the stresses has been removed
- desirable x undesirable
  (aircraft parts, toughened glass, smartphones)
- plastic deformation, phase transformation, temperature gradient

- Prince rupert’s drop
- https://www.youtube.com/watch?v=xe-f4gokRBs
Main factors

• Tool geometry
  Corner radius, feed marks
  Clearance angle, cutting edge angle
Factors...

- Vibration – toughness of the system MTPE (Machine-Tool-Piece-Environment)
- Cutting liquids
- Material isotrophy
TOOL MATERIALS

• carbon and low alloy steel
• **high-speed steel** (HSS) – highly alloyed steel – alloying ingredients: W, Mo, Cr, V + Co
• **sintered** (cemented) **carbide** – powder metalurgy: WC, TiC, TaC + Co (as the binder)
• **coated sintered carbide** - thin layer of wear resistant material (TiC, TiN or Al₂O₃)
• **ceramics** – pure (Al₂O₃) or mixed (+ TiC, TiN)
• diamond (synthetic)
• cubic boron nitride (cBN)
## TOOL MATERIALS

<table>
<thead>
<tr>
<th>Material</th>
<th>Introduced in practice (approx.)</th>
<th>Hardness</th>
<th>Limiting temperature $[^\circ C]$</th>
<th>Strength flexural [Mpa]</th>
<th>Strength compressive [Mpa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>carbon steel</td>
<td>1780</td>
<td>60 HRC</td>
<td>250</td>
<td>2000 - 3000</td>
<td>2500 - 3500</td>
</tr>
<tr>
<td>high speed steel (HSS)</td>
<td>1900</td>
<td>65 HRC</td>
<td>600</td>
<td>3000 - 4500</td>
<td>3200 - 5500</td>
</tr>
<tr>
<td>sintered (cemented) carbide</td>
<td>1930 (1940)</td>
<td>80 HRC; 1500 HV</td>
<td>900</td>
<td>900 - 2200</td>
<td>4000 - 5600</td>
</tr>
<tr>
<td>coated carbide</td>
<td>1970</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>ceramics</td>
<td>1950 (1970)</td>
<td>2500 HV</td>
<td>1100</td>
<td>400 - 700</td>
<td>3500 - 4500</td>
</tr>
<tr>
<td>diamond (synthetic)</td>
<td>1960</td>
<td>7000 HV</td>
<td>700</td>
<td>300</td>
<td>3000</td>
</tr>
<tr>
<td>cubic boron nitride (cBN)</td>
<td>1970</td>
<td>4000 HV</td>
<td>1500</td>
<td>600</td>
<td>4000</td>
</tr>
</tbody>
</table>
Steel tool materials

- Carbon content 0.7-1.5%
- Hardenable – quenching
- Hand tools - axes, pickaxes, qarrying tools
- Stamping dies (punch+die), metal cutting tools
- Hand tools (file, chisel...)
Tool materials hardness

Fig. 2.26. Hardness of tool materials decreasing with increasing temperature.
## Typical HSS tool materials

<table>
<thead>
<tr>
<th></th>
<th>Standard</th>
<th>Mark</th>
<th>C</th>
<th>W</th>
<th>V</th>
<th>Mo</th>
<th>Cr</th>
<th>Co</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cz</td>
<td>19 824</td>
<td>Poldi Maximum Special</td>
<td>0,75</td>
<td>18</td>
<td>1,3</td>
<td>max. 0,4</td>
<td>4,2</td>
<td></td>
</tr>
<tr>
<td>Cz</td>
<td>19 830</td>
<td>Poldi Maximum Special Mo 5</td>
<td>0,85</td>
<td>6,2</td>
<td>1,8</td>
<td>5</td>
<td>4,2</td>
<td></td>
</tr>
<tr>
<td>US</td>
<td>18-4-1</td>
<td>T 1 (tungsten)</td>
<td>0,8</td>
<td>18</td>
<td>1</td>
<td>-</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>M2 (Molybdenum) &quot;standard&quot;</td>
<td>0,95</td>
<td>6</td>
<td>2</td>
<td>5</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>M35</td>
<td>0,92</td>
<td>6,4</td>
<td>1,8</td>
<td>5</td>
<td>4,3</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>M42</td>
<td>1,1</td>
<td>1,5</td>
<td>1,15</td>
<td>9,5</td>
<td>3,75</td>
<td>8</td>
</tr>
</tbody>
</table>

W – just increased hot hardness
Mo,W,Cr increases hardness significantly (63-65 HRC)
Co – increases „hot“ hardness (67HRC)
+ coatings TiN (less friction, lower temperature)
Sintered carbide

• homogenous mixture of carbide grains in a tough cobalt binder matrix.
• Sintering – thermal process of bonding
• Different ratio → different properties
Sintered carbides (ISO grades)

- **K** = WC + Co
  
  tough → non-steel cutting (non-ferrous metals, cast iron) – discontinuous chip

- **P** = WC + TiC + TaC + Co
  
  hard, wear resistant, brittle → steel cutting – continuous chip

- **M** = WC + TiC + TaC + Cr₂O₃ + Co → for materials difficult to machine or universal use

Cobalt content influence:

hardness ← low ... Co... high → toughness
Coated sintered carbide

FIGURE 7.33 Multiple layer CVD coating on cemented carbide tool
Increase of productivity

tool steel → HSS → SC → coated → multicoated
Coated sintered carbide insert

Titanium carbide remains as the basic material covering the substrate for strength and wear resistance. The second layer is aluminum oxide which has proven chemical stability at high temperatures and resists abrasive wear. The third layer is a thin coating of titanium nitride to give the insert a lower coefficient of friction and to reduce edge build-up.

Fig. 3.2. An example of a triple-coated sintered carbide insert.
Coatings

• PVD – Physical Vapour Deposition
  – Cathodic arc deposition
  – Electron beam
  – PLD – Pulse laser deposition
  – Sputter deposition
  Low temp – 550-700°C

• CVD – chemical Vapour deposition
  – Many processes
  – High temp – 700-1050°C
Coating

• PVD
   – Titanium Nitride, Carbide (TiN, TiC, TiCN)
   – Zirconium Nitride (ZrN)
   – Chromium nitride (CrN)
   – Titanium Aluminium Nitride (TiAlN)

• CVD
   – Titanium Carbide (TiC)
   – Aluminum Oxide (Al$_2$O$_3$)
   – Diamond (DLC) Diamond like carbon
<table>
<thead>
<tr>
<th>Layer</th>
<th>colour characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZrN</td>
<td>brass-colored</td>
</tr>
<tr>
<td>TiZrN</td>
<td>brass-colored</td>
</tr>
<tr>
<td>ZrCN</td>
<td>gold colours</td>
</tr>
<tr>
<td>TiCN</td>
<td>gold-yellow</td>
</tr>
<tr>
<td>TiN</td>
<td>reddish yellow to violet</td>
</tr>
<tr>
<td>CrN</td>
<td>metallic grey</td>
</tr>
<tr>
<td>TiC</td>
<td>grey to anthracite</td>
</tr>
<tr>
<td>TiCrN</td>
<td>anthracite grey</td>
</tr>
<tr>
<td>AlTiN</td>
<td>bluish-violet-black</td>
</tr>
<tr>
<td>TiAlN</td>
<td>reddish-violet</td>
</tr>
</tbody>
</table>
Cermets

- Collective name
Materials where hard particles are:
TiC, TiCN, TiN instead of WC
Ceramic bonding material:
MgO, BeO(beryllium)Al₂O₃

CERamic/METal
Ceramics

- Two basic groups
  - Aluminium oxide based
    - Pure (low strength, toughness, fracture and chipping)
    - Mixed (up to 20-45% of TiC or TiN – thermal conductivity)
    - Re-inforced (whisker) – crystal fibres made of SiC

- Silicon nitride based
  - Twice the fracture resistance as Al based
• Aluminium
  – White (oxidic)
  – Black (TiC, TiCN)
  – Whisker
• Silicon Nitride based
  – Their fracture toughness is nearly some carbide grades.
  – including milling cast iron and interrupted cutting with scale.

• SiAlON
  – combined with "Al" and "O".
  – excellent heat resistance
  – mechanical strength under high temperature
Diamond

- Monocrystalline – natural – highest hardness
- Polycrystalline diamond (PCD)

- MONO – fine machining – precision (glass making) dressing of grinding wheels
- PCD – thin layer (0,5-1,5 mm) of grains bonded to a basic SC material.

!!! High temperature (600°C)
Cubic boron nitride (CBN)

- Synthetic material (not natural)
- Very hard (next to diamond)
- Best known abrasive
- Cheaper than diamond for large pieces
- Composite (CBN + ceramics)
  - 40-60% - cheap
  - Up to 100%
CBN

- High cutting speeds
- Finish turn. of hardened steels, with a hardness over 45 HRc.
- Above 55 HRc, CBN can replace grinding
- Not used for less then 45 HRC (ferrite)
- High speed roughing of grey cast irons in both turning and milling operations.
TOOL MATERIALS USE

- HSS: 46%
- Carbides: 30%
- Coated carbides: 15%
- Ceramics: 7%
- Others: 2%
### Cutting materials properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Steel</th>
<th>HSS Steel</th>
<th>SC</th>
<th>Coated HSS</th>
<th>Coated SC</th>
<th>Ceramics</th>
<th>PCBN</th>
<th>Diamond</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toughness</td>
<td></td>
<td></td>
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<tr>
<td>Hot hardness</td>
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<tr>
<td>Impact strength</td>
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<tr>
<td>Wear resistance</td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>Chipping resistance</td>
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<td></td>
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<tr>
<td>Cutting speed</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Finish obtainable</td>
<td>rough</td>
<td>rough</td>
<td>good</td>
<td>good</td>
<td>good</td>
<td>Very good</td>
<td>Very good</td>
<td>excellent</td>
</tr>
</tbody>
</table>

The arrows indicate the relative performance of each material type in each property.
Machinability denotes the relative ease with which a material can be machined using appropriate tooling and cutting conditions.

Influencing factors:

• tool wear and tool life;
• chip formation;
• cutting forces and power;
• surface finish
Machinability testing and rating

**Testing** – a comparison of work materials

**Measuring** – the machining performance of a test material is measured relative to that of a base (standard) material

**Criterion used**: varying **cutting speed** by identical other cutting conditions:
- cutting speed \( v_c \) of tested vs. standard (etalon) material

**Rating** – **machinability index** (machinability rating):

\[
MR = \frac{V_c T}{V_c T_{et}}
\]
Machinability testing and rating

- **Tool life method**
  - same condition measuring the tool life

- **Tool forces and power consumption method**
  - higher specific energies (spec. Cut. Force i.e.)
  - equal lower machinability

- **Surface finish method**
  - easy (roughness test) but quite irrelevant (al vs. Steel, vs stainless steel)

*This rating method also doesn't always agree with other methods. For instance titanium alloys would rate well by the surface finish method, low by the tool life method, and intermediate by the power consumption method.*
CUTTING FLUIDS

Functions:
• **removing heat generation** at the shear and friction zone – the *cooling* effect;
• **reducing friction** at the tool – chip and tool – workpiece interfaces – the *lubricating* effect;
• **washing away chips** – the *cleaning* effect.

Fluid types:
• **cutting oils** – mineral oils - *lubricants*;
• **emulsified oils** – oil droplets suspended in water (1:30), the cheapest, both *cooling and lubricating*;
• **chemical fluids** – chemicals (eg. S, Cl, P) in a water solution – good *coolants*, mostly for high cutting speeds and high cutting temperatures (grinding).
Cutting fluids – the lubricant effect

Two forms of tool – workpiece contact:
• roughness peaks contact
• surface contact

Fig. 5.1. Roughness peaks contact.

Fig. 5.2. Surface contact.