ME338 – Manufacturing Process II
Lecture 5: Milling/Grinding/Drilling

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http://www.mitsubishicarbide.com/en/technical_information
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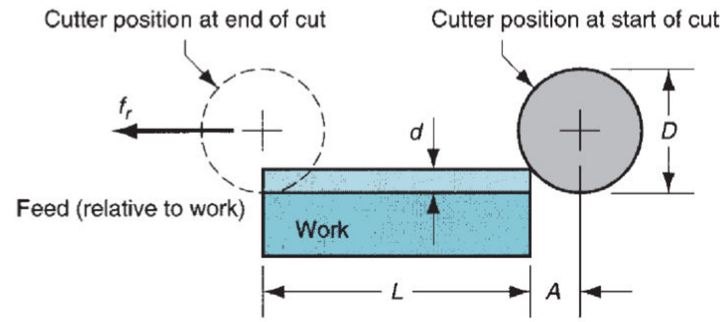
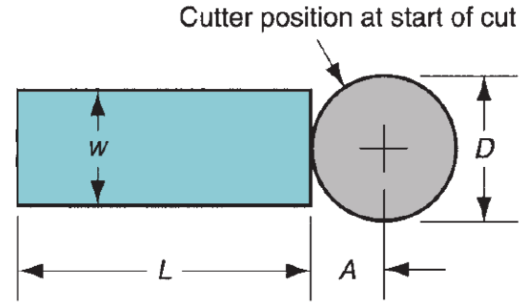
Milling process : Slab & face milling

Slab Milling

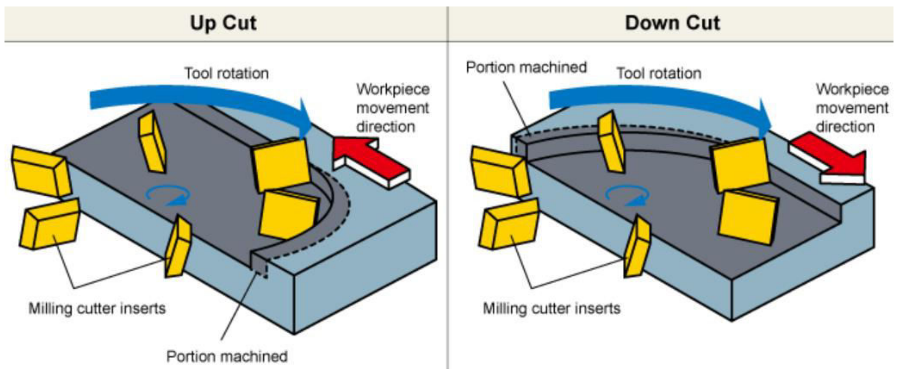


Face Milling

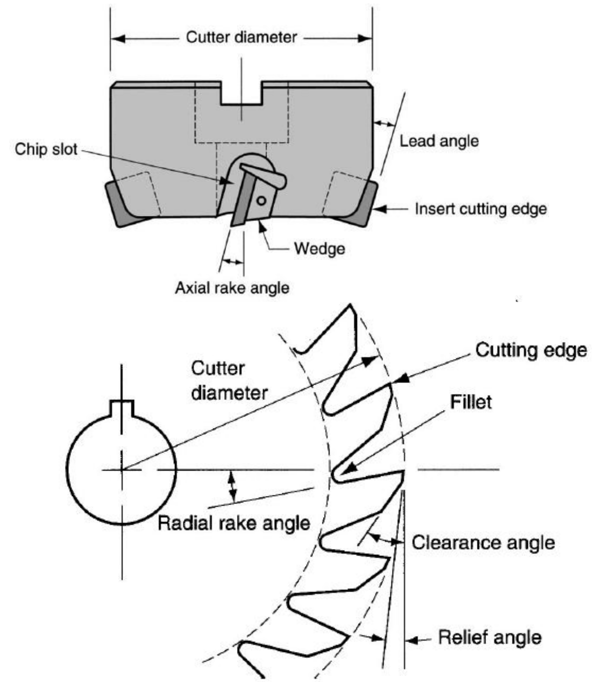


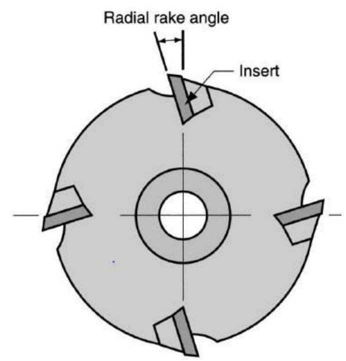
Milling techniques : Up & down

- Multiple cutting edges > higher MRR, all kinds of shapes can be generated
- Both Horizontal or vertical type : Based on the Cutter axis
- Arbor: Shaft on which milling cutter is mounted
- Up milling or down milling : decided by the conditions of the machine tool, the milling cutter and the application.
  - In terms of tool life, down cut (climb) milling is more advantageous.



Geometry of milling cutter

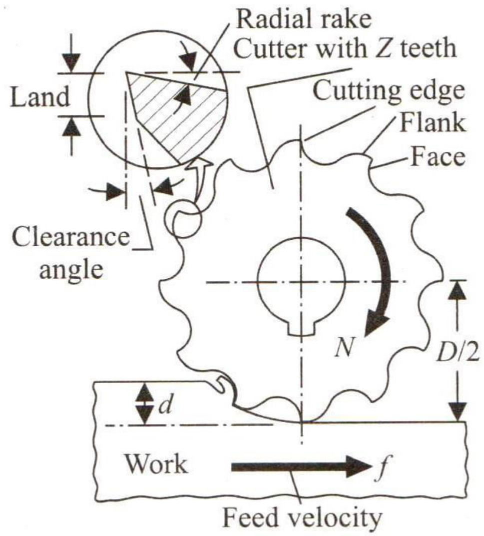




Images from M. Groover text book

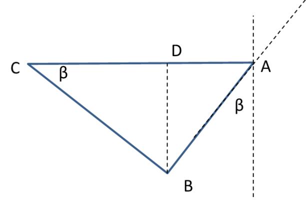
Basic mechanics of slab milling process

- Milling has straight cut teeth
- Orthogonal machining
- Given feed f (mm/min),
- All teeth are participating in cutting action
- No of teeth: Z,
- Rotation speed: N
- Effective feed/tooth: f/NZ
- Material removal rate per unit width of the job: f.d

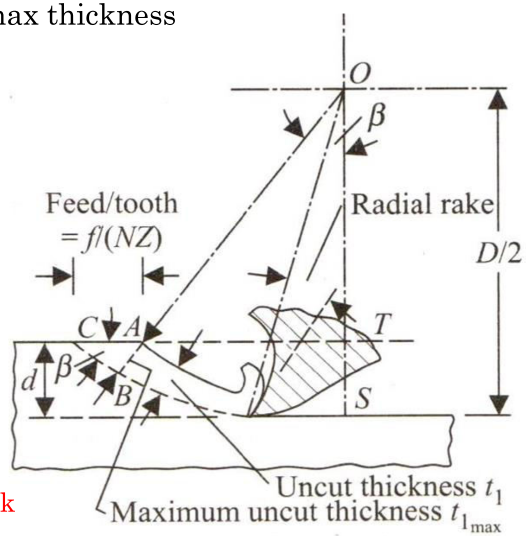


Basic mechanics of slab milling process

- Feed/tooth = AC = f/NZ
- Uncut chip thickness is not uniform (due to radial action of cutting), starts with zero and ends with max thickness
- Max uncut chip thickness = AB



β is not friction angle here
Symbol used in Ghosh/mallick text book

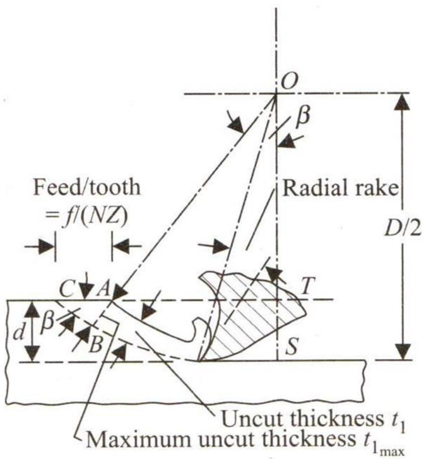


Basic mechanics of slab milling process

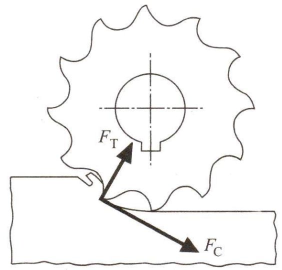
- AB ~ AC. Sin β
  - β angle included by the contact arc at the center
- $t_{1\max} = AC.Sin\,\beta$
- From triangle OAT: Cos β = OT/OA
- OT = D/2 – d, OA = D/2
- $Sin\,\beta \;=\; 2(d/D)1/2$

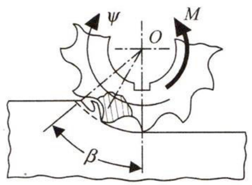
$$t_{0\,max} = \frac{2f}{NZ}\sqrt{\frac{d}{D}} \qquad t_{0avg} = \frac{f}{NZ}\sqrt{\frac{d}{D}}$$

- Since, uncut chip thickness varies, F_c and F_t also changes as the cutting edge moves along the cut surface

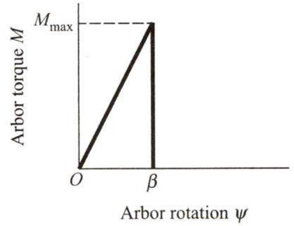


Forces & Torque in slab milling



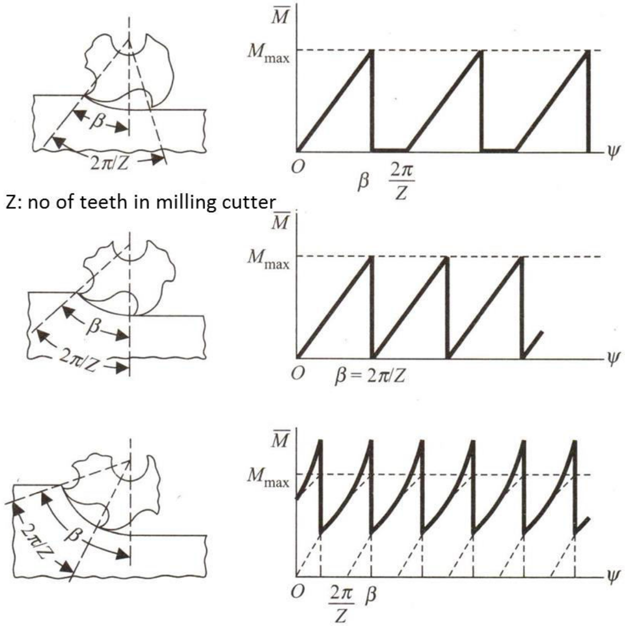


β – angle of contact



- Average uncut chip thickness (t_1) is known. Width w of cutter is known, so F_c and F_t can be calculated
- F_t acts in radial direction, so no torque due to F_t
- Torque is only generated due to cutting force F_c.
- Maximum torque $M_{max} \;=\; (Fc\ x\ D/2)$
- Avg Torque M_{avg} = 0.5 x M_{max} x (angle of contact β)/(max angle allowed)
- Max angle allowed = 2π/ No of teeth

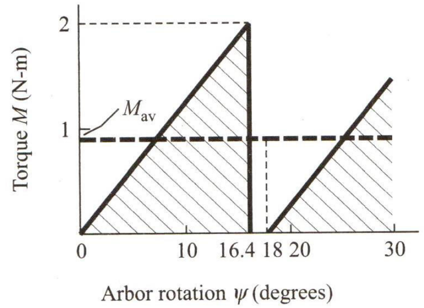
Milling torque fluctuations



(a) Types of tooth engagements

(b) Nature of torque fluctuation

Milling torque : example



- Torque is only generated due to cutting force Fc.
- Maximum torque $M_{max} = (Fc\ x\ D/2)$
- Avg Torque M_{avg} = 0.5 x M_{max} x (angle of contact ß)/(max angle allowed)
- Max angle allowed = 2π/Z, where Z no of teeth in milling cutter
- Total power consumption $P = T\omega \quad \omega = 2\pi N$

Problem

A mild steel (ms) block of 20 mm width is being milled using a straight slab milling cutter with 20 teeth, 50 mm diameter, and 10° radial rake. The feed velocity of the table is 15 mm/min and the cutter rotates at 60 rpm. If a depth of cut of 1 mm is used, what will be the power consumption?

- Assume coefficient of friction and shear strength
- Depth of cut d and cutter diameter D is known
- Angle of contact (ß) can be found, ß=16.4°
- Total no of teeth N = 20, Angle per tooth = 18°
- Max uncut chip thickness t_{0max} can be found
- Shear strength τ, width w, depth of cut is known
- Cutting force Fc, Ft can be calculated

$$Sin\beta = 2\sqrt{\frac{d}{D}}$$

$$t_{1max} = \frac{2f}{NZ}\sqrt{\frac{d}{D}}$$

Problem

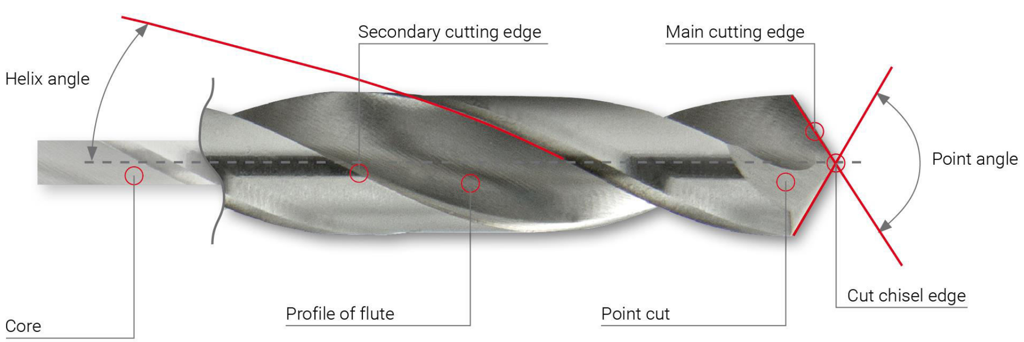
Estimate the power required during the up milling of a mild steel block of 20 mm width using a straight slab milling cutter with 10 teeth, 75 mm diameter, and 10° radial rake. The feed velocity of the table is 100 mm/min, the cutter rotates at 60 rpm, and the depth of cut is 5 mm.

- Assume coefficient of friction and shear strength
- Depth of cut d and cutter diameter D is known
- Angle of contact (ß) can be found, ß=16.4°
- Total no of teeth N = 20, Angle per tooth = 18°
- Max uncut chip thickness t_{0max} can be found
- Shear strength τ, width w, depth of cut is known
- Cutting force Fc can be calculated
- Maximum torque M_{Max} = (Fc x D/2)
- Avg Torque M_{avg}= 0.5xM_{max} x (angle of contact ß)/(max angle allowed)

$$Sin\beta = 2\sqrt{\frac{d}{D}}$$

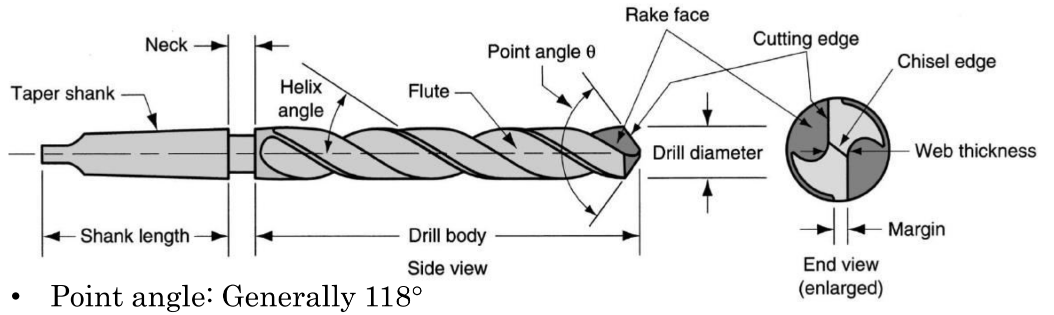
$$t_{1max} = \frac{2f}{NZ}\sqrt{\frac{d}{D}}$$

Drilling process : Twist drill



- Drill has two cutting edges, each 180° ahead of other edge
- Chip/coolant flows through the flutes

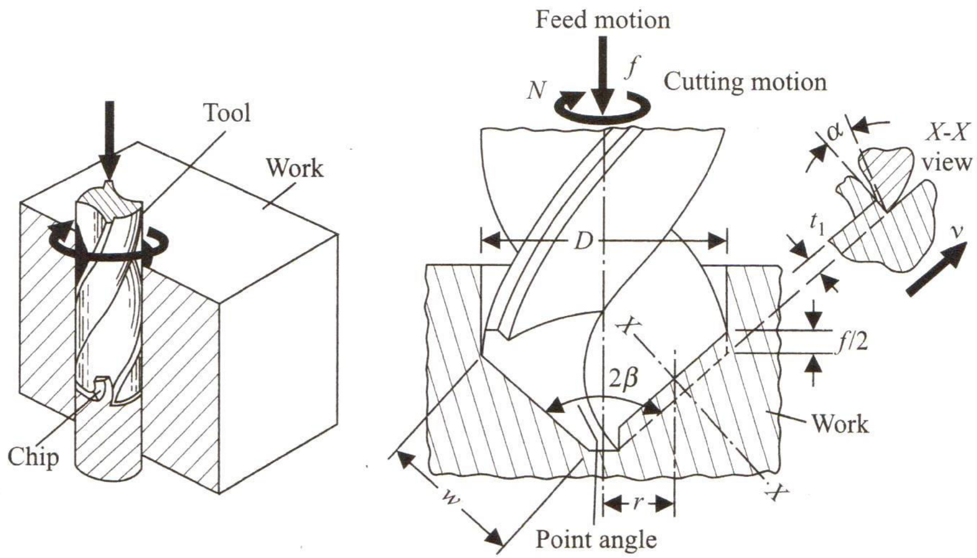
Geometry of Drill



- Point angle: Generally 118°
  - Smaller for soft / easy to machine materials
- Helix angle: determines the rake angle
  - Larger for soft materials
  - Rake angle decreases from circumference to the center
  - Chisel edge has a negative rake angle
- Web thickness: Rigidity of the tool
- Thicker for high-hardness materials

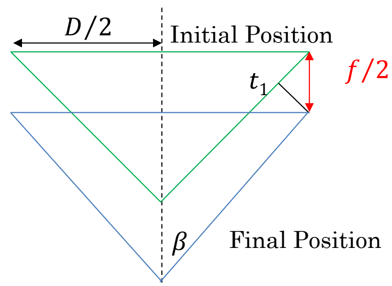
Workpiece material	Point angle	Helix angle
Aluminum	90 to 135	32 to 48
Brass	90 to 118	0 to 20
Cast iron	90 to 118	24 to 32
Mild steel	118 to 135	24 to 32
Stainless steel	118 to 135	24 to 32
Plastics	60 to 90	0 to 20

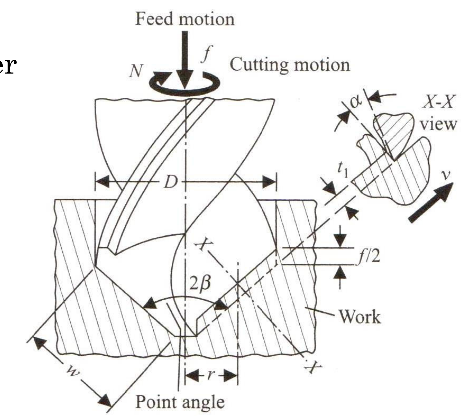
Analysis of drilling



Analysis of drilling

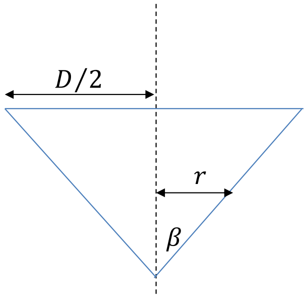
- Drill has two cutting edges, each 180° ahead of other edge
- In drilling, feed motion is given to drill (into the workpiece)
- If total advancement of the drill per revolution or feed is f, half of the feed motion ($f/2$) is shared by each cutting edge
  – Therefore, depth of cut is half of the feed motion
- Uncut chip thickness t_1, width of cut w are:
  – $t_0 = (f/2)\,Sin\,\beta, w = (D/2)/Sin\,\beta$
  – β: half point angle, D: drill diameter





Analysis of drilling

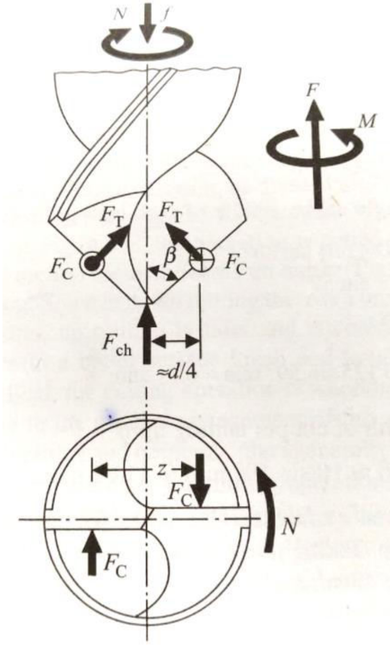
- Normal rake angle depends upon the radial location of the sectioning plane.
- Normal rake angle depends upon the <u>helix angle (ψ)</u> and <u>half-point angle (β)</u> of the drill
- Approximate value of normal rake angle at a radial distance (r) is
  - $\alpha \approx \tan^{-1}\left[\dfrac{\frac{2r}{D}\tan\psi}{\sin\beta}\right]$
  - r radius of the point on the cutting edge, where the normal rake angle is measured, ψ helix angle



Torque and thrust in drilling

- Total thrust force F
  - $F = 2F_T sin\beta + F_{ch} + F_{friction}$
  - F_{ch} force from chisel edge (60% of the total thrust force $\approx 0.60F$)
  - $F_{friction}$ friction force ($\approx 0.03F$)
- $2F_T sin\beta \approx 0.37F$, $F = 5.4F_T \sin\beta$

- Total Moment
  - $M = F_c z + M_{ch} + M_{friction}$
  - M_{ch} moment from chisel edge ($\approx 0.08M$)
  - $M_{friction}$ moment due to friction ($\approx 0.12M$)
  - $\approx$ 80% contribution of moment comes from the cutting action of the lips (i.e.,)
  - $F_c z = 0.8M$, $M = 1.25F_c z$
  - At $z = \frac{D}{2}$, $M = 0.625F_c D$

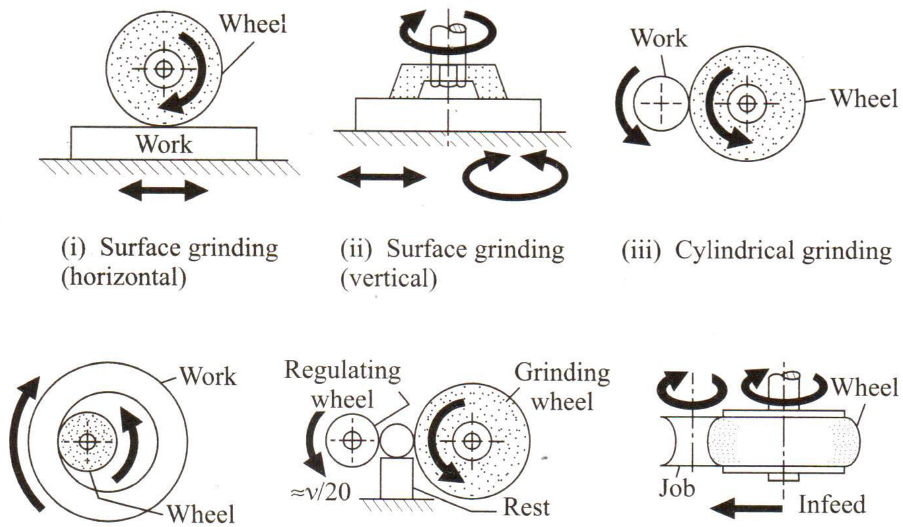


Example : Drilling

- Estimate the torque and the thrust force when drilling a solid block of <u>mild steel</u> with a normal twist drill made of <u>HSS</u> (point angle 118°, Helix angle: 30°). Drill diameter: 20 mm, Shear strength of mild steel: 400N/mm2. Drill rotational speed: 240 rpm. Feed: 0.25 mm/rev. Friction coefficient between HSS and mild steel is 0.6.

- Solution:
  - First find normal rake angle $\alpha \approx \tan^{-1}\left[\dfrac{\frac{2r}{D}\tan\psi}{\sin\beta}\right]$
  - Find uncut chip thickness (t_0) and width of cut (w) $t_0 = (f/2)\,Sin\,\beta$, $w = (D/2)/Sin\,\beta$
  - Find the friction angle (λ): $\lambda = \tan^{-1}\mu$
  - Use lee-Shaffer theory (or any given theory) and find shear plane angle ϕ
  - Find shear force $F_s = \tau A_s = \tau w \dfrac{t_0}{\sin\phi}$
  - Find cutting force (F_c) and thurst force (F_t)
  - Total moment $M \approx 0.625\,F_c D$
  - Total thurst force $F \approx 5.4F_t \sin\beta$

Grinding Process : various kinds

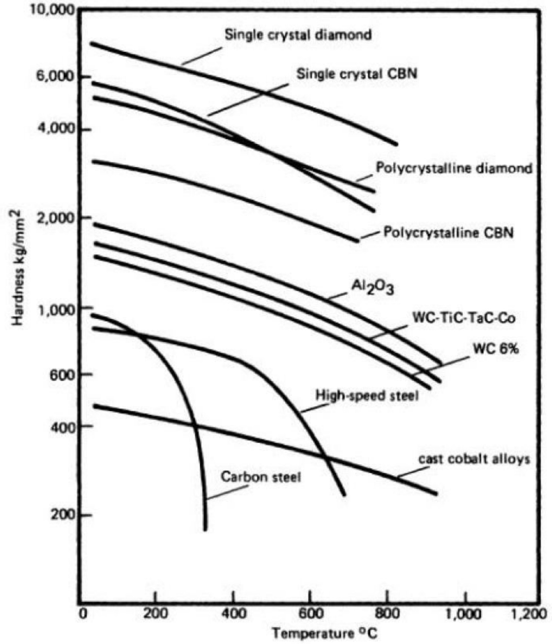


(i) Surface grinding (horizontal)
(ii) Surface grinding (vertical)
(iii) Cylindrical grinding
(iv) Internal cylindrical grinding
(v) Centreless grinding
(vi) Form cylindrical grinding

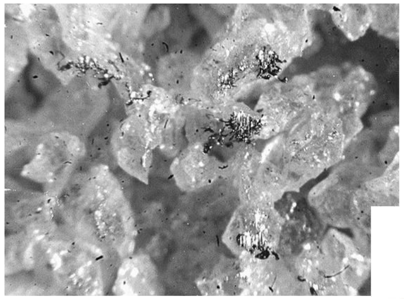
Grinding wheels

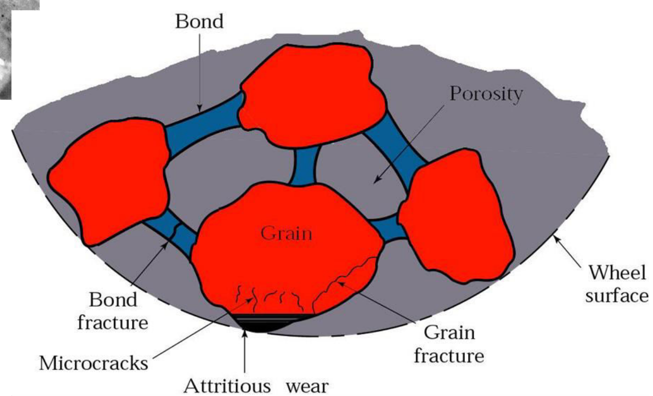
Hardness of common abrasives used in Grinding

Material	N/mm^2
Common glass	300–5000
Quartz	8000
Hardened steel	7000–13,000
Emery	14,000
Tungsten carbide	18,000–24,000
Aluminium oxide	20,000–30,000
Titanium carbide	18,000–32,000
Silicon carbide	21,000–30,000
Boron carbide	28,000
Diamond	70,000–80,000

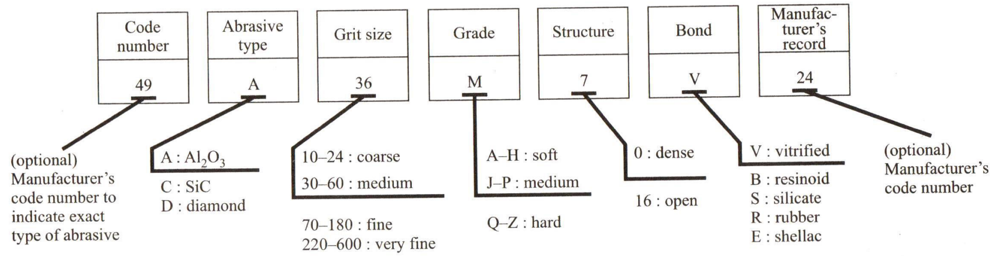


Grinding wheel surface



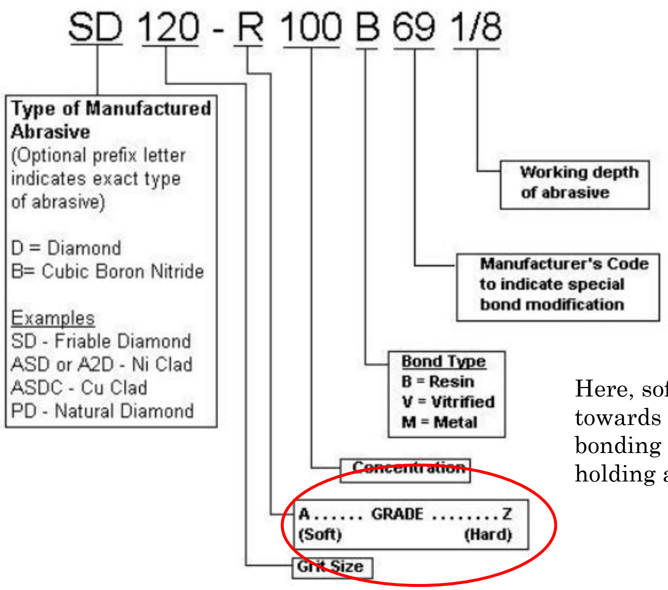


Grinding wheels - specification



- Abrasive type:
  - A (Al2O3), B (cubic boran nitride), C (SiC), D (diamond). For ferrous material, Al2O3 used
- Grit size: higher grit number for fine polishing
  - 10-24 (coarse), 30-60 (medium), 70-180 (fine), 220-600 (super fine)
- Grade: strength of bonding materials to keep abrasive grains
  - A-I(Soft), J-P (Medium), Q-Z (Hard)
  - For harder work materials, soft bonding material, For softer work, hard bonding material
- Structure: voids/porosity in grinding wheel : 0 (dense), 16 (open)
  - Ductile material produces larger chips so open structure is recommended
  - For harder, brittle material, dense structure should be used
- Bond: V (Vitrified), B (resinoid), S (Silicate), R (Rubber), E (Shellac)
  - Vitrified bond material is the most common

Grinding wheels - specification

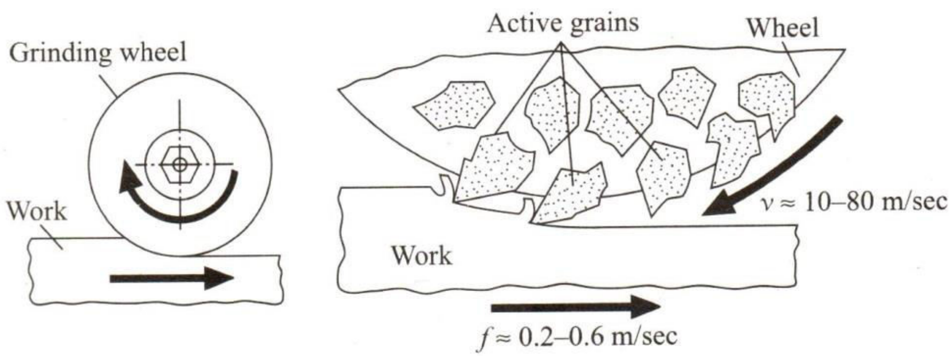


Here, soft/hard does not indicate towards hardness, but represent bonding strength of material used for holding abrasive grains together

Grinding wheel dressing

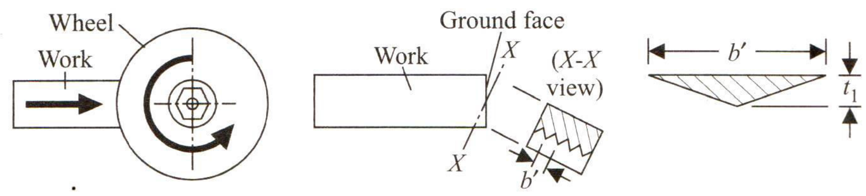
- Normally grinding wheel have self-sharpening characteristics
- Dull abrasive grains automatically removed due to fracture, and new sharpen grains are exposed
- In dense structure, chips clogg the voids between the abrasive grains
- This reduces the metal removal rate
- To avoid it, wheels are 'dressed'. It removes the clogged chips and expose the fresh abrasive grains.

Analysis of surface grinding



- Grinding: Rectangular cross-section is being fed radially at a rate f (mm/min)
- Assumed that <u>active grains</u> are uniformly distributed,
- If Z = total no of active grains, N = rpm of grinding wheel, effective feed per active grain = f/NZ
- Uncut chip thickness (t_1) is almost equal to ~ f/NZ

Grinding - mechanics



(a) Scheme of plunge grinding

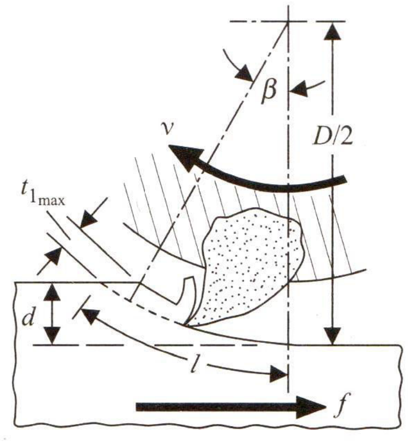
(b) Nature of ground face

(c) Cross-section of typical chip

- If grinding wheel diameter is D and rotation speed is N rpm, then cutting speed v = πDN
- Material removal rate in grinding (MRR) = vfd,
  - where f – feed, d – depth of cut
- Chips produced in grinding have a <u>triangular cross-section</u>
- Ratio (r_g) of chip thickness (t_1) to chip width (b') is about 10-20,
- $b'=r_g.t_1$
- No of grains/revolution Z = πDCb' , C: surface density of active grains

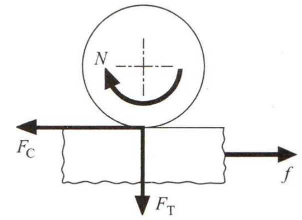
Chip formation during grinding

- $Cos\ \beta = \frac{\left(\frac{D}{2} - d\right)}{\frac{D}{2}} = 1 - 2\frac{d}{D}$
- $Cos\ \beta = 1 - \frac{\beta^2}{2}, \beta = 2\sqrt{\frac{d}{D}}$
- The chip length $l = \sqrt{Dd}$
- Total volume of material removed per unit time $= f.d.b$
- Where b is width of the cut in mm
- The chips produced during grinding have a triangular cross-section,
- and ratio (r) of chip thickness (t) to chip width (w) is about 10-20
- $t_{1max} = \sqrt{\frac{6f}{\pi DNCr_g}\sqrt{\frac{d}{D}}}$



Grinding - mechanics

- No of grains/revolution Z = πDCb',
  - C: surface density of active grains
- Uncut chip thickness $t_0 = \sqrt{\frac{f}{\pi DNCr_g}}$
- Once t_0 is known, specific energy U_c can be determined as $U_c = U_0 t_0^{-0.4}$
- Power required to grind $W = \frac{AfU_c}{60}$,
  - A = cross-sectional area of job (mm^2)
- Force per single grit $Fc = \frac{60000W}{\pi DACN}$
- or $Fc = \frac{1000fU_c}{\pi DCN}$



Material	U_0 (J/mm³)
Steel	1.4 – 4.0
Stainless steel	1.4 - 1.6
Al alloys	0.35
Copper	1.2