ME361 – Manufacturing Science Technology

Milling

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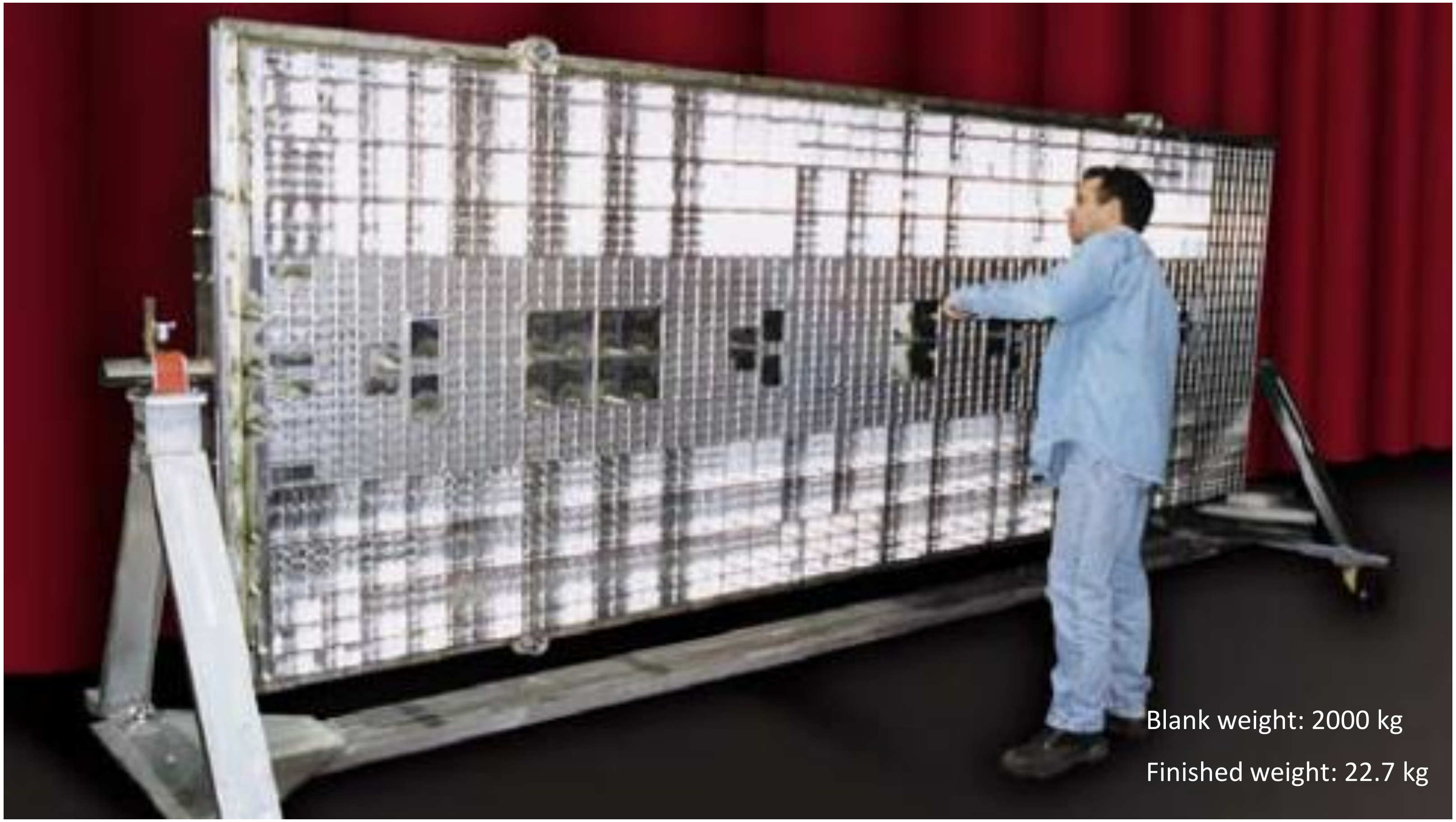
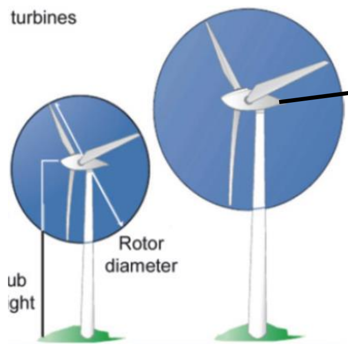
Machined (milled) parts



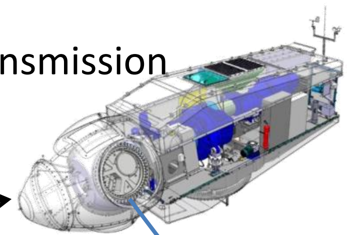
Source: He, 11th HSM, Prague

Machined (milled) parts

Large wind turbines



Transmission



Large parts

Wind turbine hub

Component cost:
~150,000 Euros

Uriarte et al. (2013), CIRP Annals Vol. 62

Machined (milled) parts

Component cost: ~800,000 Euros

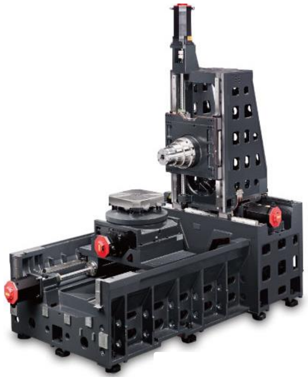
Uriarte et al. (2013), CIRP Annals Vol. 62
Nakashima (http://www.nakashima.co.jp/eng/product/index.html)

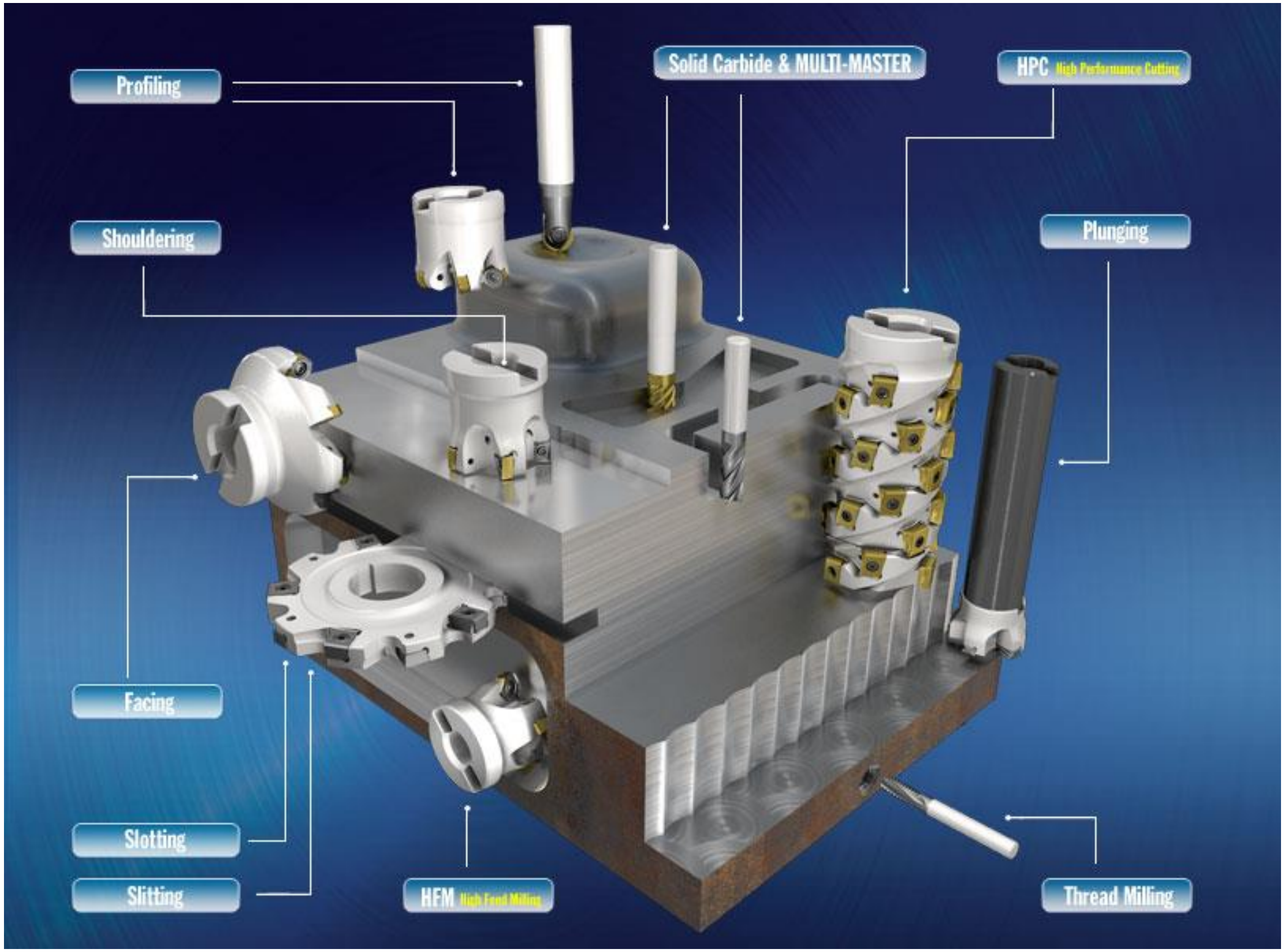
Objectives of machining models for milling

Milling makes up about ~85% of all the material removal (machining) processes

- Process planning
  - Predict forces, torque and power
    - Identify cutting force coefficients – give us a sense of machinability
    - Simulate manufactured part surface quality
  - Size tools and machines
  - Design NC tool path
  - Process planning
- Diagnostics
  - Identify causes of process/tool/system failure
- Product design

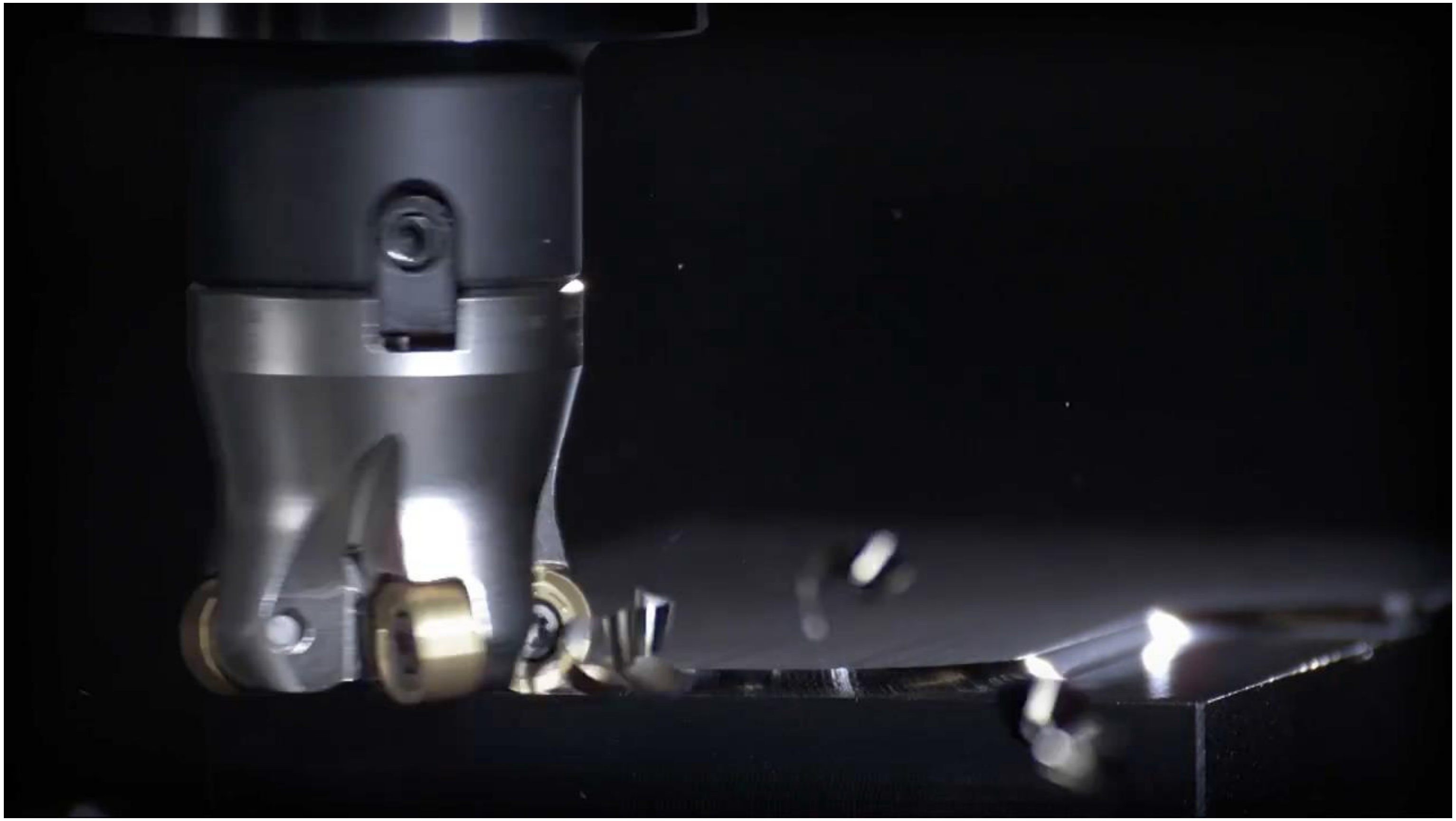
Milling machines, cutters and operations



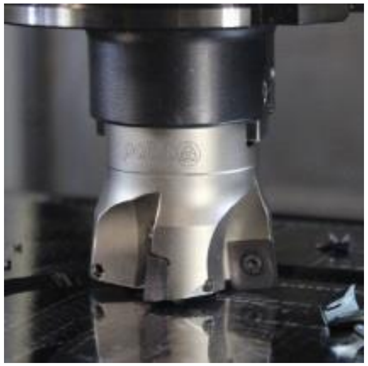


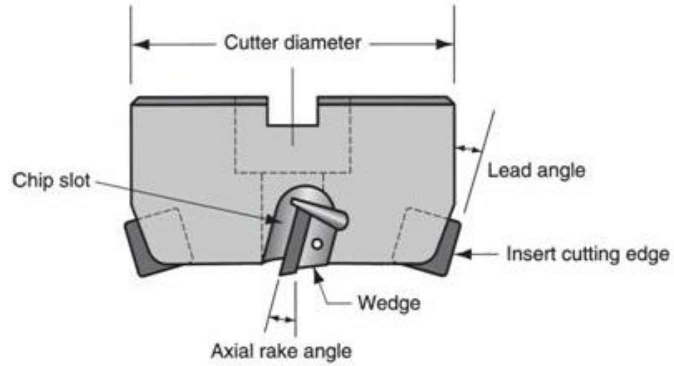
Images sourced from: Iscar, Awea machines, and T Schmitz

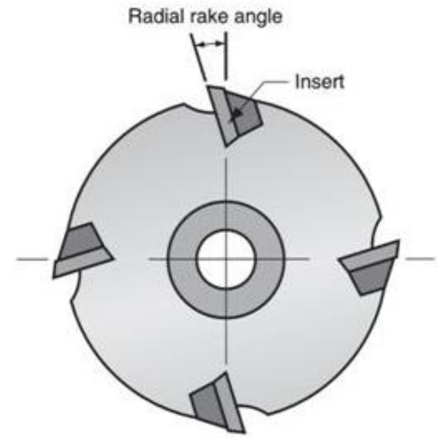
Face milling

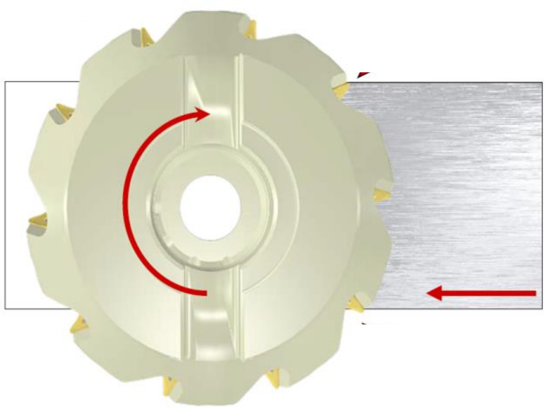


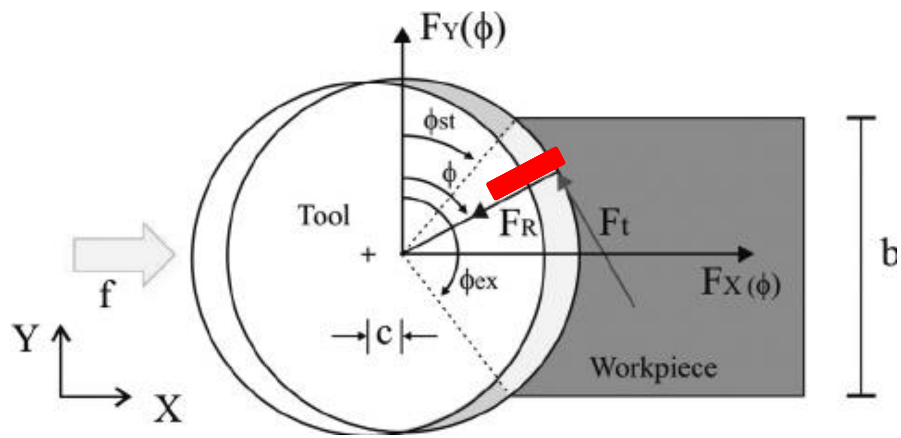
Face milling



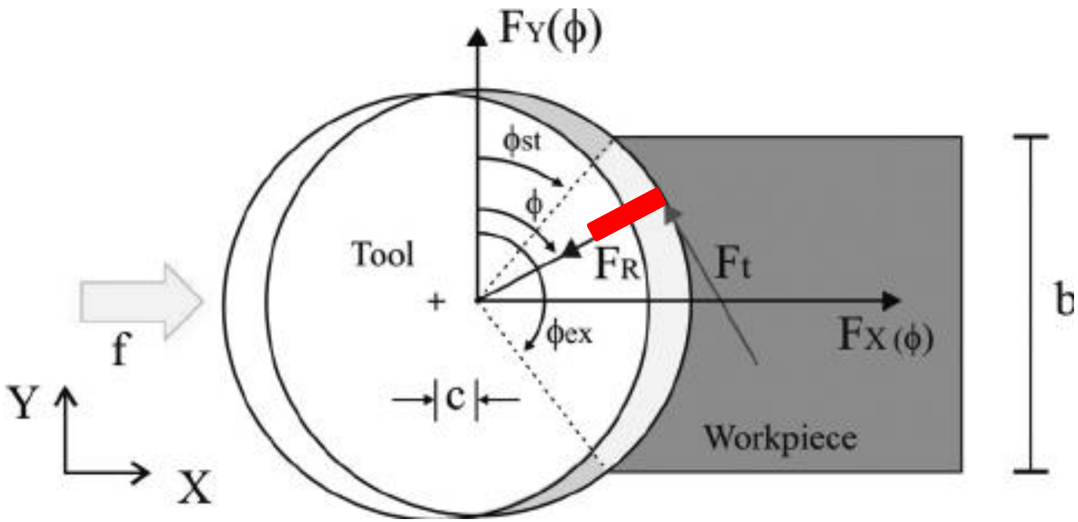








Face milling process mechanics



c – feed rate [mm/rev-tooth]
ϕ – engagement angle
ϕ_{st} - entry angle
ϕ_{ex} - exit angle
F_t - tangential force
F_r - radial force
b – width of cut
Helix angle = 0°

Instantaneous chip thickness - varies periodically as a function of time-varying immersion:

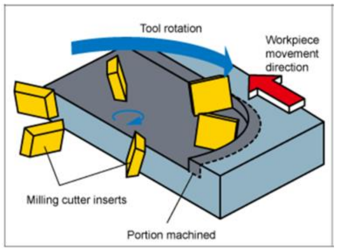
$$h(\phi) = c \sin \phi$$

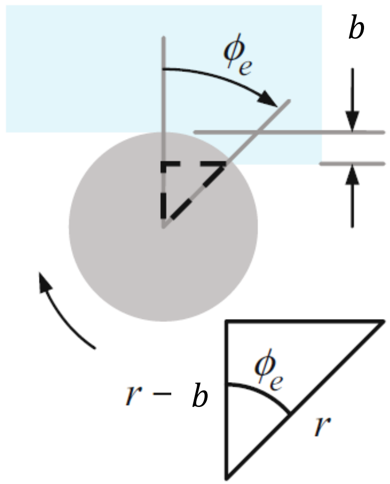
Average chip thickness per revolution from the swept zone:

$$h_a = \frac{\int_{\phi_{st}}^{\phi_{ex}} c \sin \phi \, d\phi}{\phi_{ex} - \phi_{st}}$$

Up/down milling

Up milling

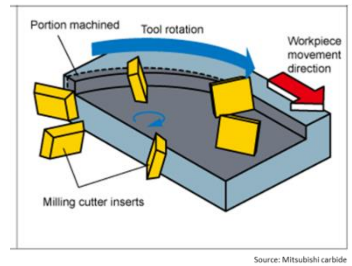


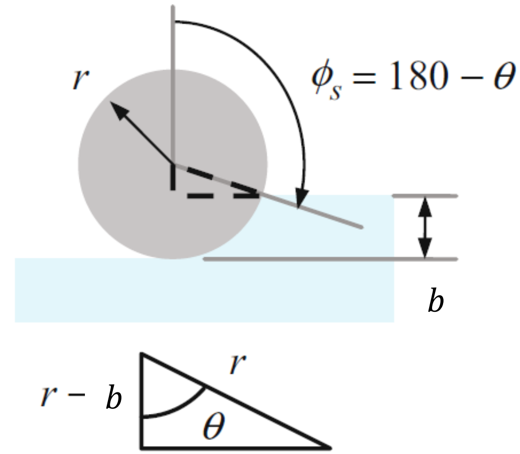


$$\phi_{st} = 0$$

$$\phi_{ex} = cos^{-1}\left(\frac{r-b}{r}\right)$$

Down milling

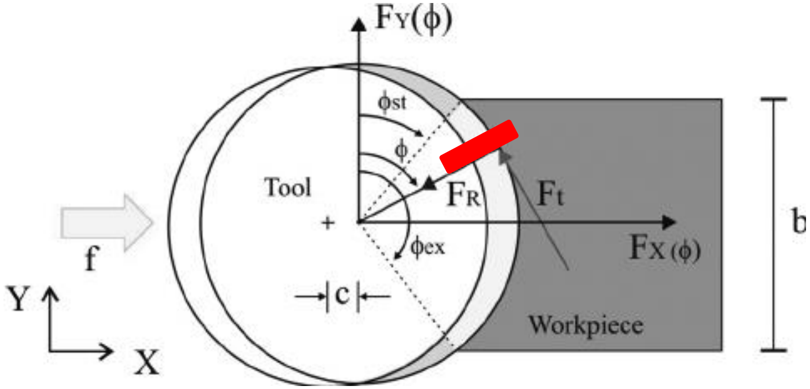




$$\phi_{st} = 180 - cos^{-1}\left(\frac{r-b}{r}\right)$$

$$\phi_{ex} = 180$$

Milling process mechanics



Resolve cutting forces to horizontal (feed), normal and axial components:

$$F_x(\phi) = F_t \cos\phi - F_r \sin\phi\,;$$
$$F_y(\phi) = F_t \sin\phi - F_r \cos\phi\,;$$
$$F_z(\phi) = F_a$$

Tangential, radial and axial forces:

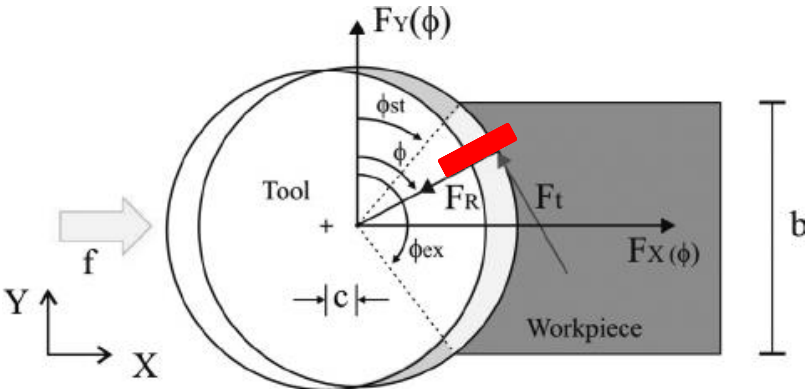
$$F_t(\phi) = K_{tc} a h(\phi) + K_{te} a;$$
$$F_r(\phi) = K_{rc} a h(\phi) + K_{re} a;$$
$$F_a(\phi) = K_{ac} a h(\phi) + K_{ae} a;$$

K_{tc} - tangential, K_{rc} - radial and K_{ac} - axial cutting force coefficient; K_{te}, K_{re}, K_{ae} - edge coefficients (mechanistically identify these, or transform to oblique from orthogonal database)
$ah(\phi)$ - uncut chip area
a – edge contact length (depth of cut)

Condition for cutting forces being active:

$$F_x(\phi), F_y(\phi), F_z(\phi) > 0 \quad \text{when } \phi_{st} \le \phi \le \phi_{ex}$$

Milling process mechanics



Multiple teeth in cut:
when swept angle $\phi_s >$ cutter pitch angle ϕ_p

$$\phi_s = \phi_{ex} - \phi_{st} > \phi_p$$

$$\phi_p = \frac{2\pi}{N_t}$$

$$F_q = \sum_{j=1}^{N_t} F_{qj}(\phi_j); \quad q = x, y, z$$

Resultant force, instantaneous:

$$F = \sqrt{{F_x}^2 + {F_y}^2 + {F_z}^2}$$

Instantaneous torque on spindle:

$$T_c = \frac{D}{2}\sum_{j=1}^{N_t} F_{tj}(\phi_j); \quad \text{when } \phi_{st} \le \phi \le \phi_{ex}$$

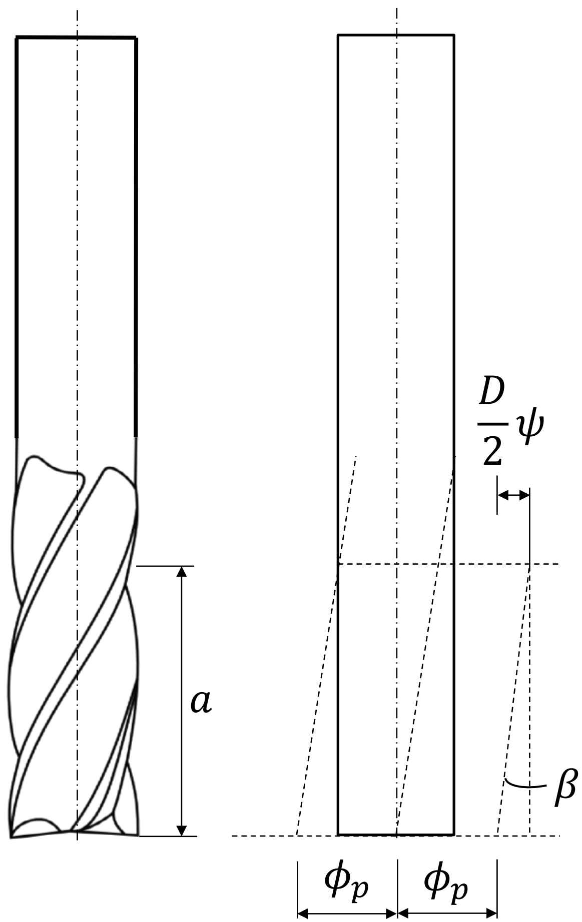
Cutting power drawn from motor:

$$P_t = V\sum_{j=1}^{N_t} F_{tj}(\phi_j); \quad \text{when } \phi_{st} \le \phi \le \phi_{ex}$$

$$V = \pi D N$$

End milling

Mechanics of end mills



- Helix (β) provides a gradually increasing chip load
- Because of the helix, a point (z) on the axis of the cutting edge lags the end point of the tool:

$$\boxed{\psi = \frac{2ztan\beta}{D}}$$

- When bottom point of a flute is at immersion angle ϕ, , a point (z) on the axis of the cutting edge will have immersion angle of $\phi - \psi$
- Bottom points of remaining flutes are at angles:

$$\boxed{\phi_j(z) = \phi + j\phi_p}$$

- Immersion angle for flute j at a point (z) on the axis

$$\boxed{\phi_j(z) = \phi + j\phi_p - \frac{2\tan\beta}{D}z}$$

- Chip thickness different at each point:

$$\boxed{h_j(\phi) = c\sin\phi_j(z)}$$

Mechanics of end mills

Chip thickness different at each point along the axis:

$$h_j(\phi) = c \sin \phi_j(z) \quad \text{(a)}$$

Hence the tangential, radial and axial forces acting on a differential flute element with height dz, are:

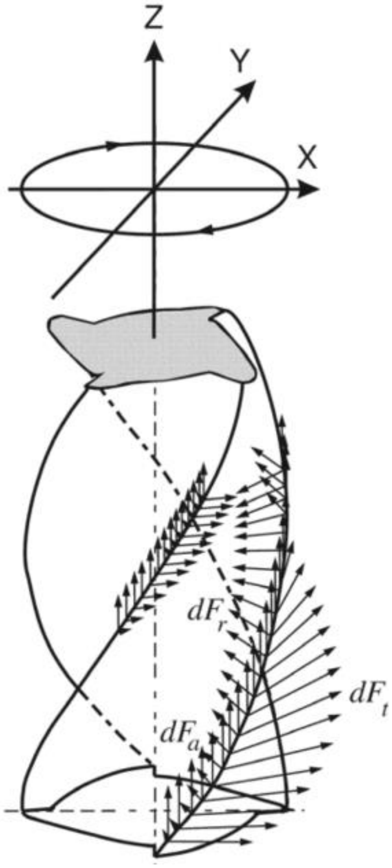
$$\begin{aligned} dF_{t,j}(\phi, z) &= \left[K_{tc} h\left(\phi_j(z)\right) + K_{te}\right] dz; \\ dF_{r,j}(\phi, z) &= \left[K_{rc} h\left(\phi_j(z)\right) + K_{re}\right] dz; \\ dF_{a,j}(\phi, z) &= \left[K_{ac} h\left(\phi_j(z)\right) + K_{ae}\right] dz; \end{aligned} \quad \text{(b)}$$

Immersion angle for flute j at a point (z) on the axis

$$\phi_j(z) = \phi + j\phi_p - \frac{2 \tan \beta}{D} z$$

Resolve cutting forces to horizontal (feed), normal and axial components:

$$\begin{aligned} dF_{x,j}\left(\phi_j(z)\right) &= -dF_{t,j} \cos \phi_j(z) - dF_{r,j} \sin \phi_j(z); \\ dF_{y,j}\left(\phi_j(z)\right) &= dF_{t,j} \sin \phi_j(z) - dF_{r,j} \cos \phi_j(z); \\ dF_{z,j}\left(\phi_j(z)\right) &= dF_{a,j} \end{aligned} \quad \text{(c)}$$



Mechanics of end mills

Chip thickness different at each point along the axis:

$$\boxed{h_j(\phi) = c \sin \phi_j(z)} \quad \text{(a)}$$

Tangential, radial and axial forces :

$$\begin{aligned} dF_{t,j}(\phi, z) &= \left[K_{tc} h\left(\phi_j(z)\right) + K_{te}\right] dz; \\ dF_{r,j}(\phi, z) &= \left[K_{rc} h\left(\phi_j(z)\right) + K_{re}\right] dz; \\ dF_{a,j}(\phi, z) &= \left[K_{ac} h\left(\phi_j(z)\right) + K_{ae}\right] dz; \end{aligned}$$

(b)

Horizontal (feed), normal and axial components:

$$\begin{aligned} dF_{x,j}\left(\phi_j(z)\right) &= -dF_{t,j} \cos \phi_j(z) - dF_{r,j} \sin \phi_j(z)\,; \\ dF_{y,j}\left(\phi_j(z)\right) &= dF_{t,j} \sin \phi_j(z) - dF_{r,j} \cos \phi_j(z)\,; \\ dF_{z,j}\left(\phi_j(z)\right) &= dF_{a,j} \end{aligned}$$

(c)

Substitute (a) and (b) into (c)

$$dF_{x,j}\left(\phi_j(z)\right) = \left\{\frac{c}{2}\left[-K_{tc} \sin 2\phi_j(z) - K_{rc}\left(1 - \cos 2\phi_j(z)\right)\right] + \left[-K_{te} \cos \phi_j(z) - K_{re} \sin \phi_j(z)\right]\right\} dz$$

$$dF_{y,j}\left(\phi_j(z)\right) = \left\{\frac{c}{2}\left[K_{tc}\left(1 - \cos 2\phi_j(z)\right) - K_{rc} \sin 2\phi_j(z) -\right] + \left[K_{te} \sin \phi_j(z) - K_{re} \cos \phi_j(z)\right]\right\} dz$$

$$dF_{z,j}\left(\phi_j(z)\right) = \left[K_{ac} \sin \phi_j(z) + K_{ae}\right] dz$$

Total cutting force per flute, analytically:

$$F_q = \int_{z_{j1}}^{z_{j2}} dF_{qj}\left(\phi_j(z)\right) dz;$$

Total cutting force, numerically:

$$F_q = \sum_{z_{j1}=1}^{z} \Delta F_{qj}\left(\phi_j(z)\right) \Delta z; \; q = x, y, z$$

Cutting coefficients - identification in milling

Conduct a dedicated series of tests at different feed rates and identify coefficients directly for the tool-workpiece-cutting parameter combination of interest

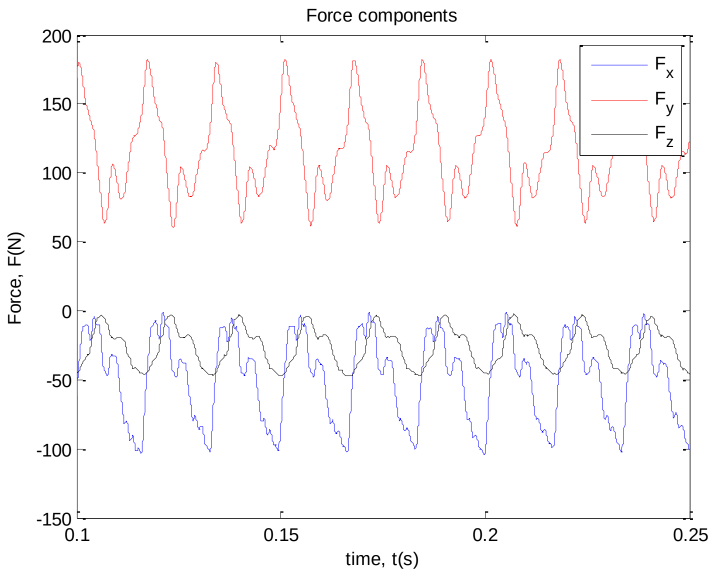
- Use a small workpiece
- Ensure dynamometer is clamped rigidly to the table
- Measure cutting forces at stable DOC and at low cutting speed
- Collect cutting forces for a full number of revolutions
- Conduct set of milling tests at different feeds but constant axial DOC and immersion (preferably slotting)

Run	Axial DOC [mm]	Radial engagement [% of D]	Feed/tooth [mm/tooth]	Cutting speed [m/min]	Spindle speed [RPM]	Feed [mm/min]
1	1	100	0.1	180	3570	1428
2	1	100	0.125	180	3570	1785
3	1	100	0.15	180	3570	2142
4	1	100	0.175	180	3570	2500

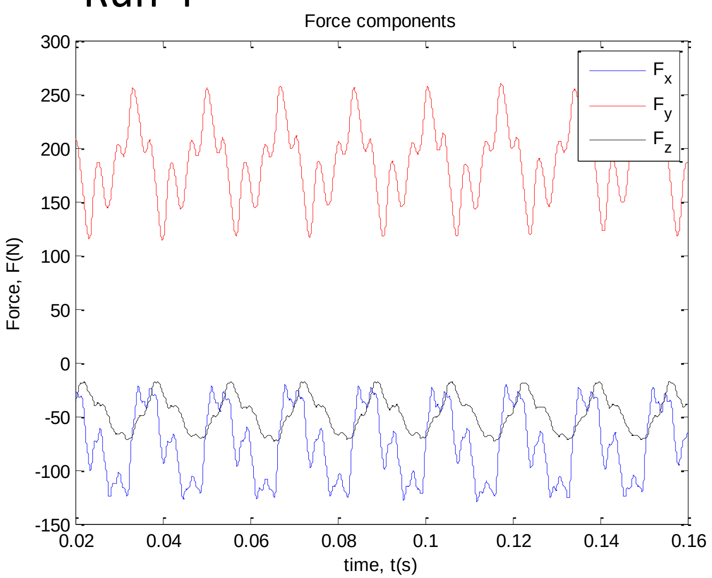
Cutting force measurements in milling

Run	Axial DOC [mm]	Radial engagement [% of D]	Feed/tooth [mm/tooth]	Cutting speed [m/min]	Spindle speed [RPM]	Feed [mm/min]
1	1	100	0.1	180	3570	1428
2	1	100	0.125	180	3570	1785
3	1	100	0.15	180	3570	2142
4	1	100	0.175	180	3570	2500

Run 1



Run 4



Identification in milling (slotting)

Average milling force per tooth period

$$\bar{F}_q = \frac{1}{\phi_p}\int_{\phi_{st}}^{\phi_{ex}} F_q(\phi_j)\,d\phi; \quad q = x, y, z$$

when $\phi_{st} \leq \phi \leq \phi_{ex}$

For full immersion slotting, $\phi_{st} = 0; \phi_{ex} = \pi$

$$\bar{F}_x = \left\{\frac{N_{ac}}{8\pi}\left[K_{tc}\cos 2\emptyset - K_{rc}[2\emptyset - \sin 2\emptyset]\right] + \frac{N_a}{2\pi}\left[-K_{te}\sin\emptyset + K_{re}\cos\emptyset\right]\right\}_{\emptyset_{et}}^{\emptyset_{ex}}$$

$$\bar{F}_y = \left\{\frac{N_{ac}}{8\pi}\left[K_{tc}(2\emptyset - \sin 2\emptyset) + K_{rc}\cos 2\emptyset\right] - \frac{N_a}{2\pi}\left[K_{te}\cos\emptyset + K_{re}\sin\emptyset\right]\right\}_{\emptyset_{et}}^{\emptyset_{ex}}$$

$$\bar{F}_z = \frac{N_a}{2\pi}\left[K_{te}\cos\emptyset + K_{re}\sin\emptyset\right]_{\emptyset_{et}}^{\emptyset_{ex}}$$

Identification in milling (slotting)

Average milling force per tooth period

$$\overline{F_q} = \frac{1}{\phi_p}\int_{\phi_{st}}^{\phi_{ex}} F_q(\phi_j)\,d\phi; \quad q = x, y, z$$

when $\phi_{st} \leq \phi \leq \phi_{ex}$

For full immersion slotting, $\phi_{st} = 0; \phi_{ex} = \pi$

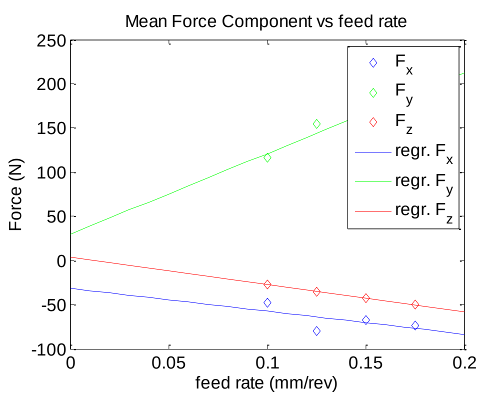
Average milling force per tooth period, simplified:

$$\overline{F_x} = -\frac{N_t a}{4}K_{rc}c - \frac{N_t a}{\pi}K_{re}$$

$$\overline{F_y} = \frac{N_t a}{4}K_{tc}c + \frac{N_t a}{\pi}K_{te}$$

$$\overline{F_z} = \frac{N_t a}{4}K_{ac}c + \frac{N_t a}{\pi}K_{ae}$$

$$\overline{F_q} = \overline{F_{qc}}c + \overline{F_q}; \quad q = x, y, z$$



Cutting coefficients

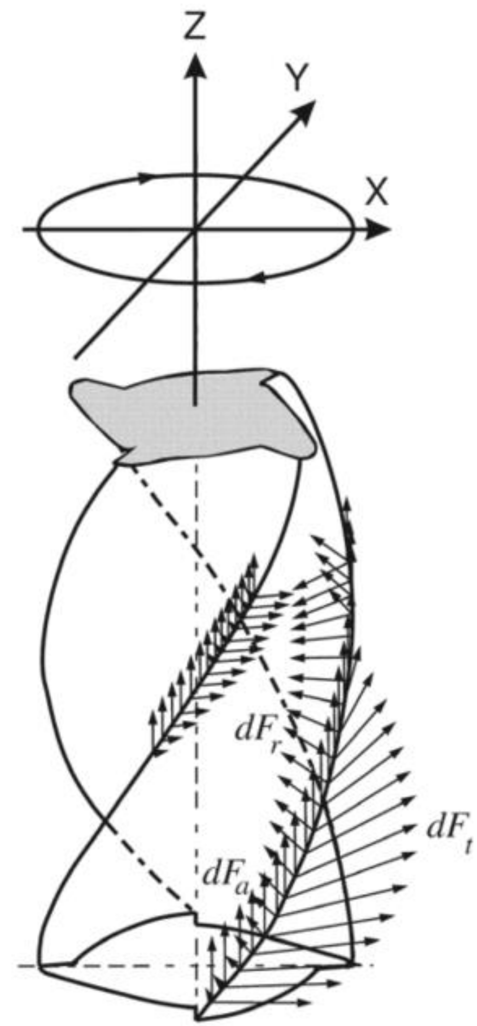
$$K_{tc} = \frac{4\overline{F_{yc}}}{N_t a} \qquad K_{te} = \frac{\pi\overline{F_{ye}}}{N_t a}$$

$$K_{rc} = -\frac{4\overline{F_{xc}}}{N_t a} \qquad K_{re} = -\frac{\pi\overline{F_{xe}}}{N_t a}$$

$$K_{ac} = -\frac{\pi\overline{F_{zc}}}{N_t a} \qquad K_{ae} = \frac{2\overline{F_{ze}}}{N_t a}$$

TABLE 2.2. Pseudocode for Milling Force Simulation Algorithm

Inputs	
Cutting conditions	$a, c, n, \phi_{st}, \phi_{ex}$
Tool geometry	D, N, β
Cutting constants	$K_{tc}, K_{rc}, K_{te}, K_{re}$
Integration angle	$\Delta\phi$
Integration height	Δa
Outputs	
Cutting force history	$F_x(\phi), F_y(\phi), F(\phi)$
Cutting torque and power history	$T_c(\phi), P_c(\phi)$
Variables	
$\phi_p = \frac{2\pi}{N}$	Cutter pitch angle
$K = \frac{2\pi}{\Delta\phi}$	Number of angular integration steps
$L = \frac{a}{\Delta a}$	Number of axial integration steps
$i = 1$ to K	Angular integration loop
$\phi(i) = \phi_{st} + i\Delta\phi$	Immersion angle of flute's bottom edge
$F_x(i) = F_y(i) = F_t(i) = 0.0$	Initialize the force integration registers
$k = 1$ to N	Calculate the force contributions of all teeth
$\phi_1 = \phi(i) + (k-1)\phi_p$	Immersion angle for tooth k
$\phi_2 = \phi_1$	Memorize the present immersion
$j = 1$ to L	Integrate along the axial depth of cut
$a(j) = j \cdot \Delta a$	Axial position
$\phi_2 = \phi_1 - \frac{2\tan\beta}{D} a(j)$	Update the immersion angle due helix
if $\phi_{st} \le \phi_2 \le \phi_{ex}$	If the edge is cutting, then
$h = c\sin\phi_2$	Chip thickness at this point
$\Delta F_t = \Delta a(K_{tc}h + K_{te})$	Differential tangential force
$\Delta F_r = \Delta a(K_{rc}h + K_{re})$	Differential radial force
$\Delta F_x = -\Delta F_t\cos\phi_2 - \Delta F_r\sin\phi_2$	Differential feed force
$\Delta F_y = \Delta F_t\sin\phi_2 - \Delta F_r\cos\phi_2$	Differential normal force
$F_x(i) = F_x(i) + \Delta F_x$	Sum the cutting forces
$F_y(i) = F_y(i) + \Delta F_y$	contributed by the all
$F_t(i) = F_t(i) + \Delta F_t$	'active edges
else	
next j	
next k	
Resulting cutting force values at immersion angle $\phi(i)$	
$F(i) = \sqrt{F_x^2(i) + F_y^2(i)}$	Resultant cutting force
$T_c(i) = \frac{D}{2}F_t(i)$	Cutting torque
next i	
Plot $F_x(i), F_y(i), F_i, T_c(i)$ with varying immersion $\phi(i)$	
stop	
end	



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