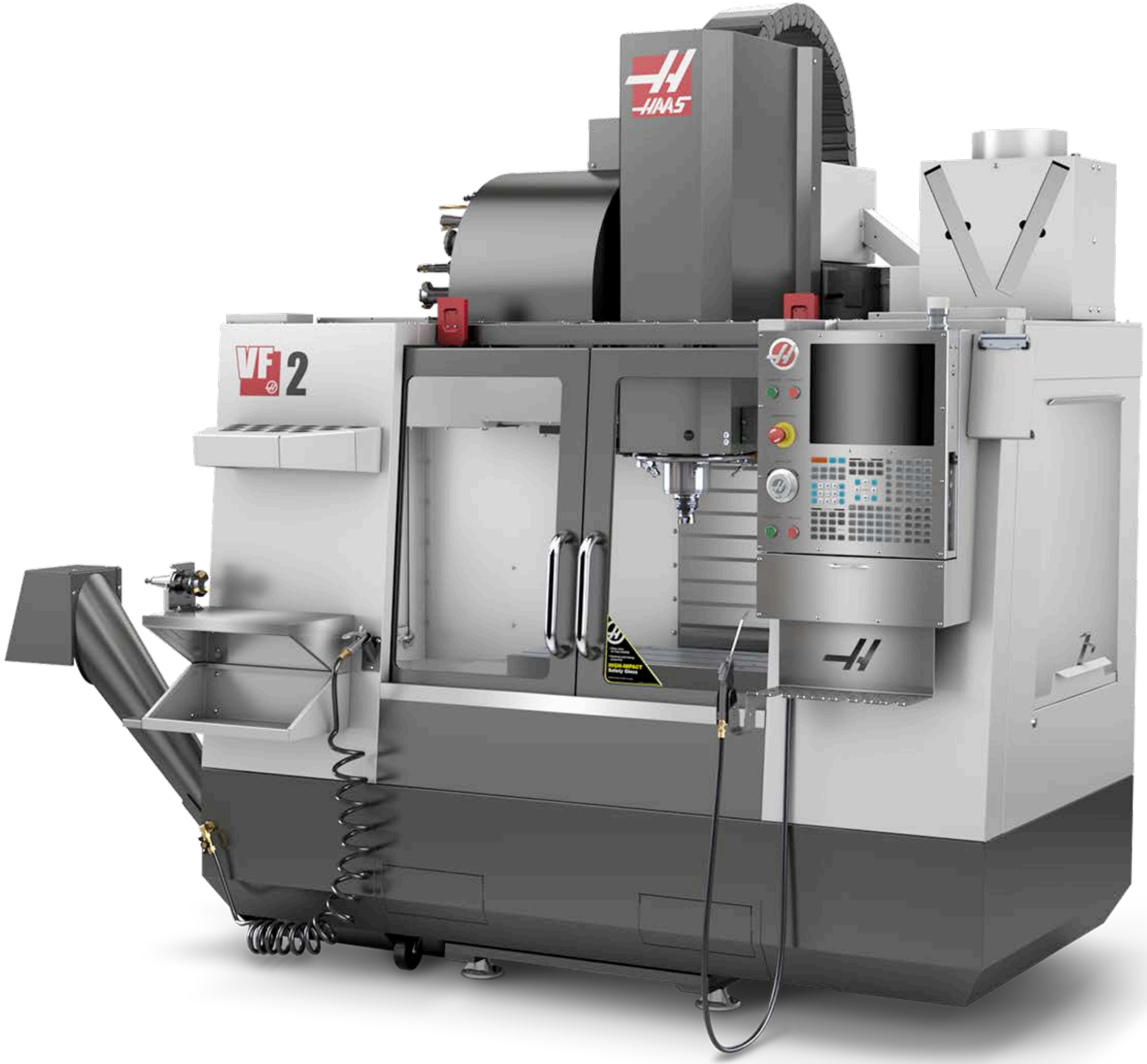
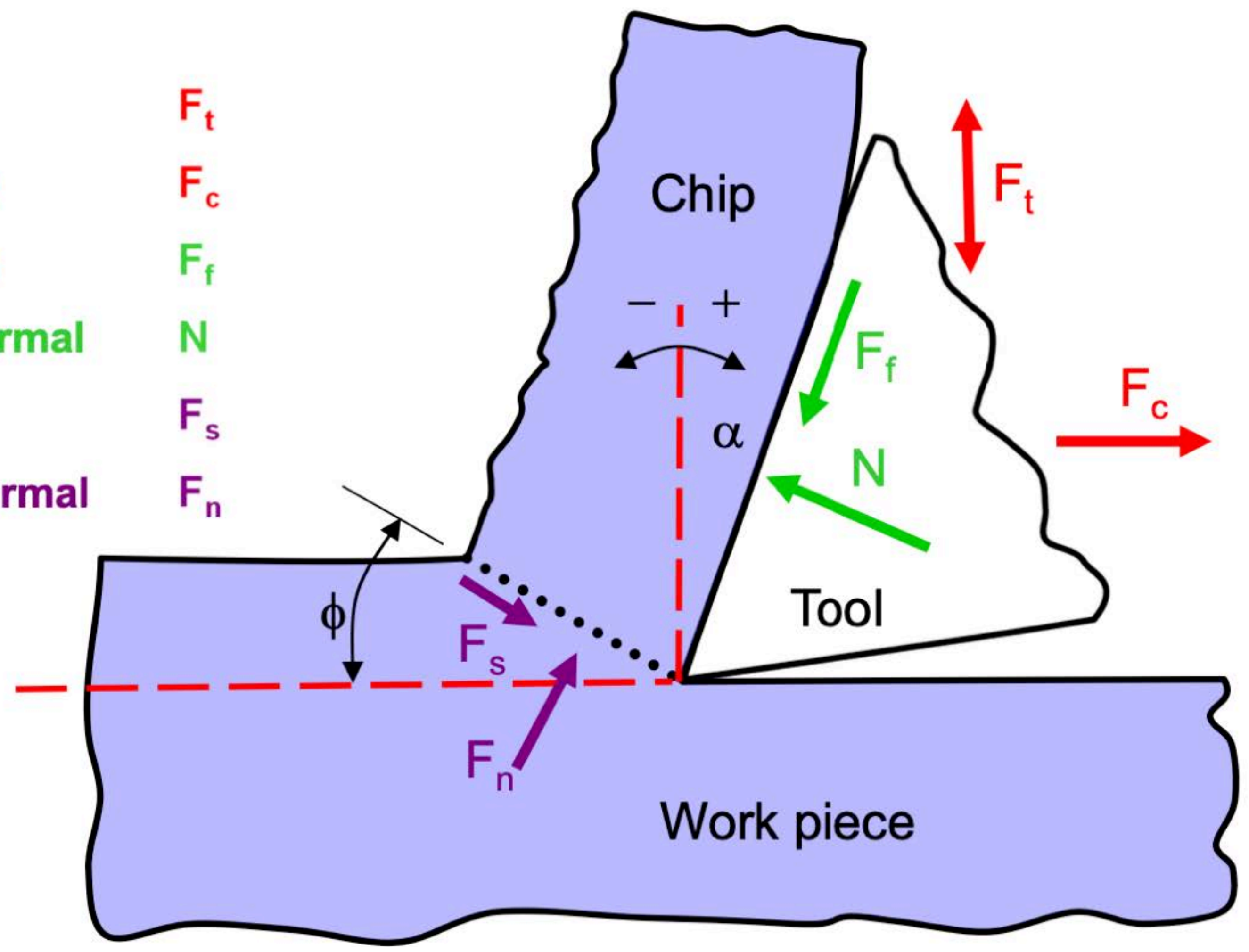
Cutting #3

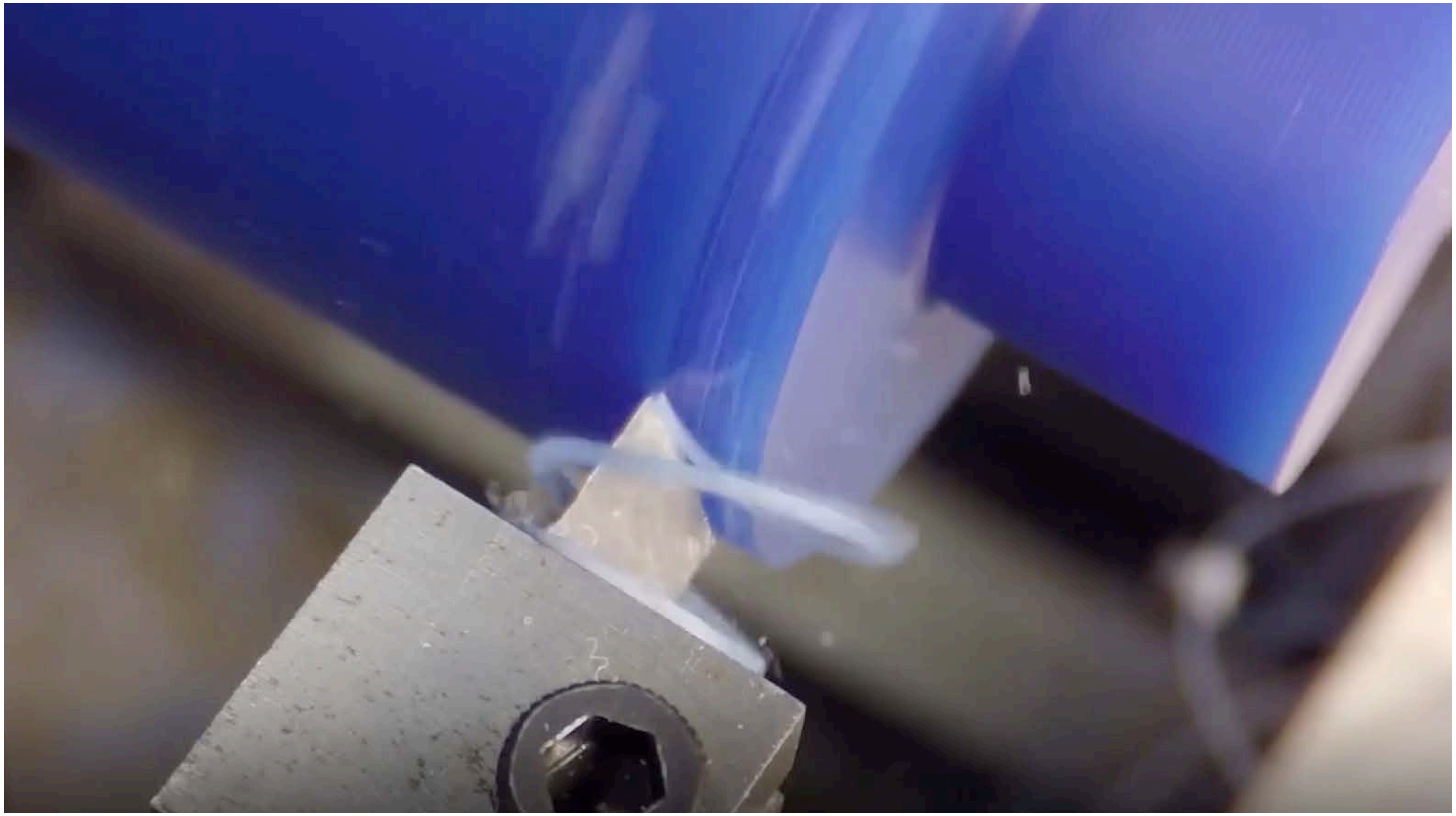
Machining in Practice



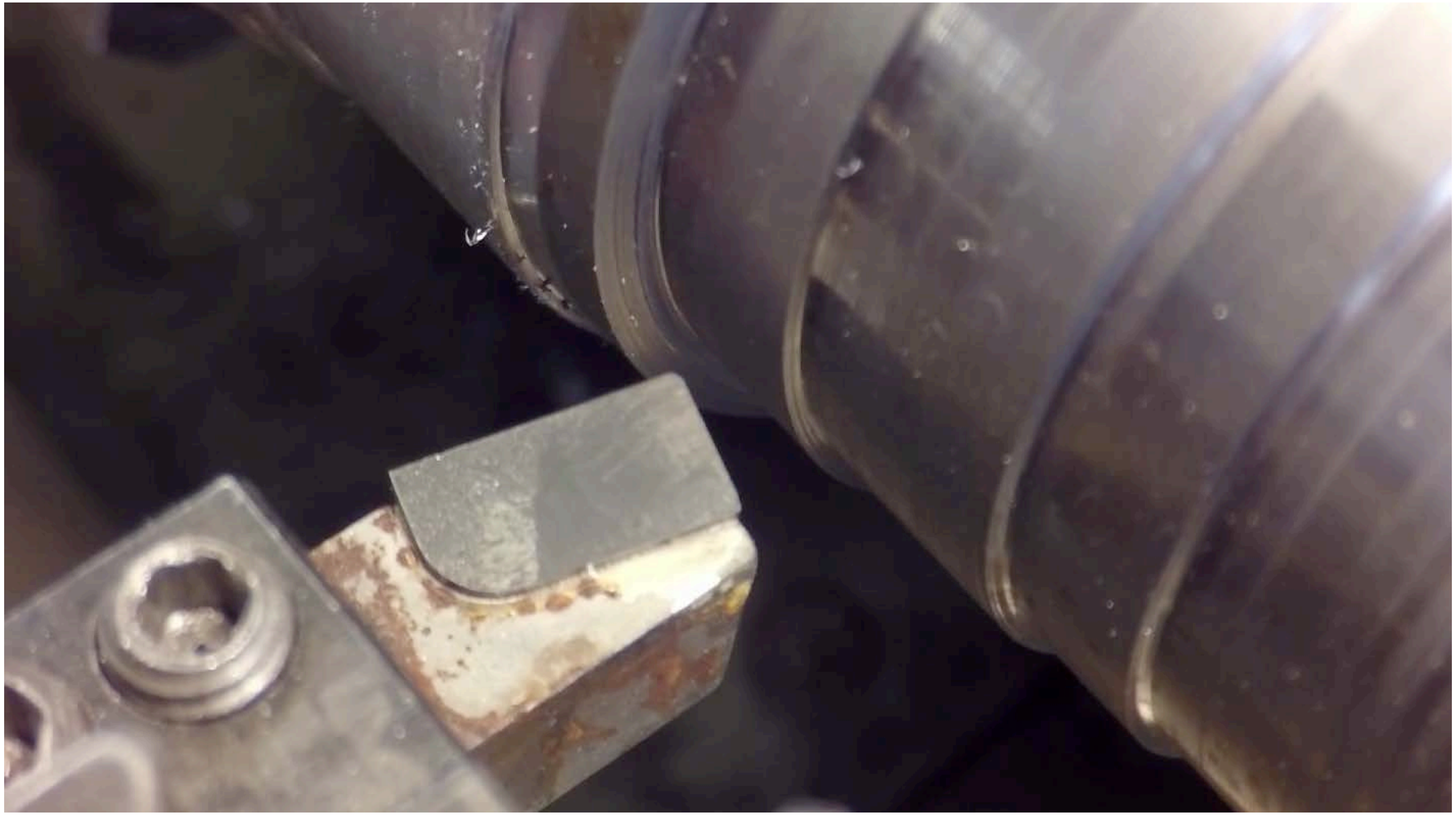
Cutting Force Demo

- Thrust F_t
- Cutting F_c
- Friction F_f
- Tool normal N
- Shear F_s
- Chip normal F_n





Cutting Power Demo



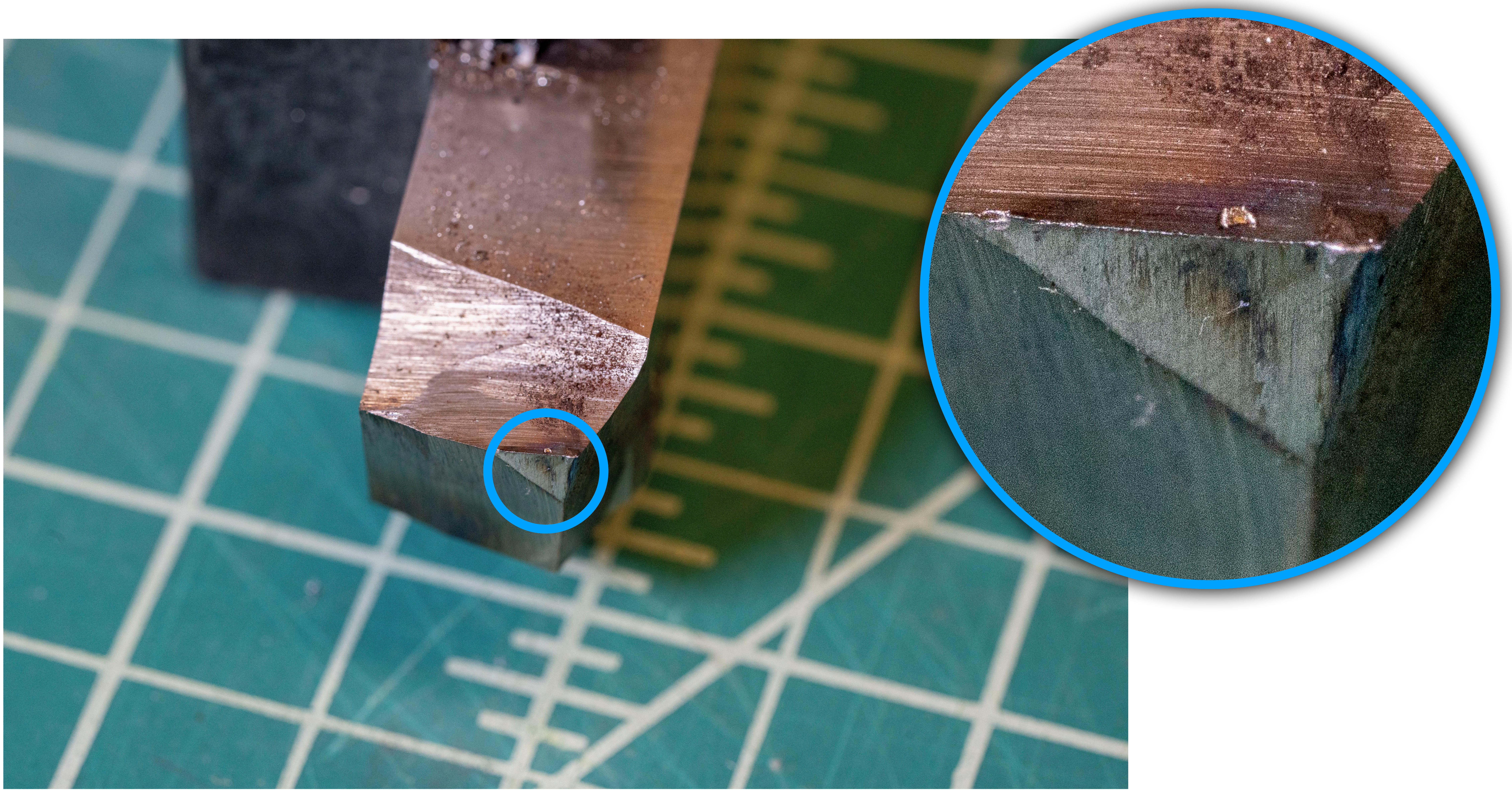
Cutting Power Demo

Rake angle (deg)	Tool	Spindle speed (RPM)	Diameter (in)	DOC (in)	Feed (in/rev)	MRR (in^3/min)	Power (hp)	Observations (chips, sounds, etc.)
7	HSS	90	3.87	0.050	0.0073			
7	HSS	140	3.87	0.050	0.0073			
7	HSS	330	3.87	0.050	0.0073			
7	Carbide	330	3.87	0.050	0.0142			
7	Carbide	385	3.87	0.050	0.0142			
7	Carbide	585	3.87	0.050	0.0142			

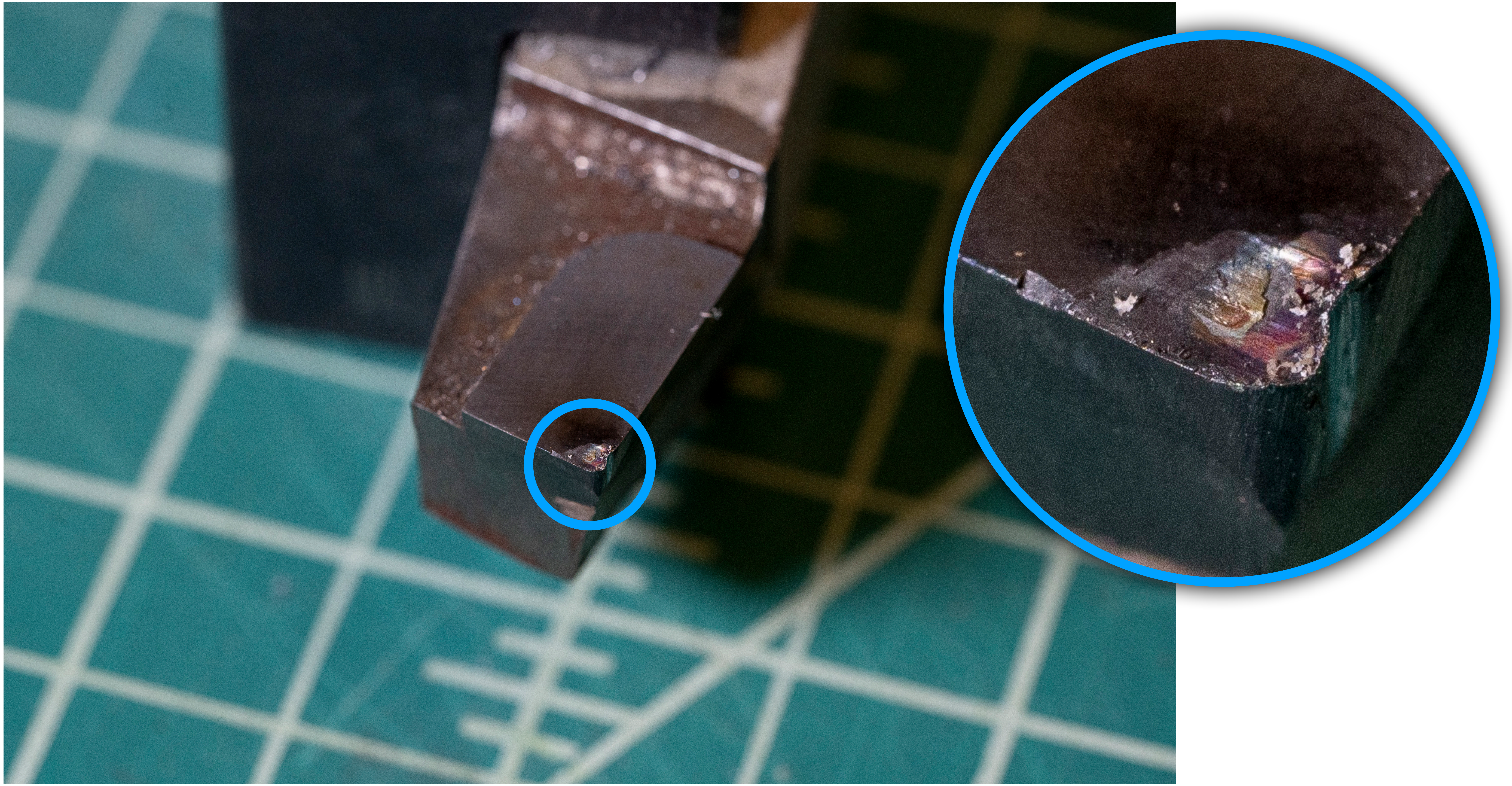
Cutting Power Demo

Rake angle (deg)	Tool	Spindle speed (RPM)	Diameter (in)	DOC (in)	Feed (in/	MRR (in^3/	Power	Observations (chips,
7	HSS	90	3.87	0.050				
7	HSS	140	3.87	0.050				
7	HSS	330	3.87	0.050				
7	Carbide	330	3.87	0.050				
7	Carbide	385	3.87	0.050	0.0142	3.32	2.33	still cutting
7	Carbide	585	3.87	0.050	0.0142	5.05	3.53	stalled machine

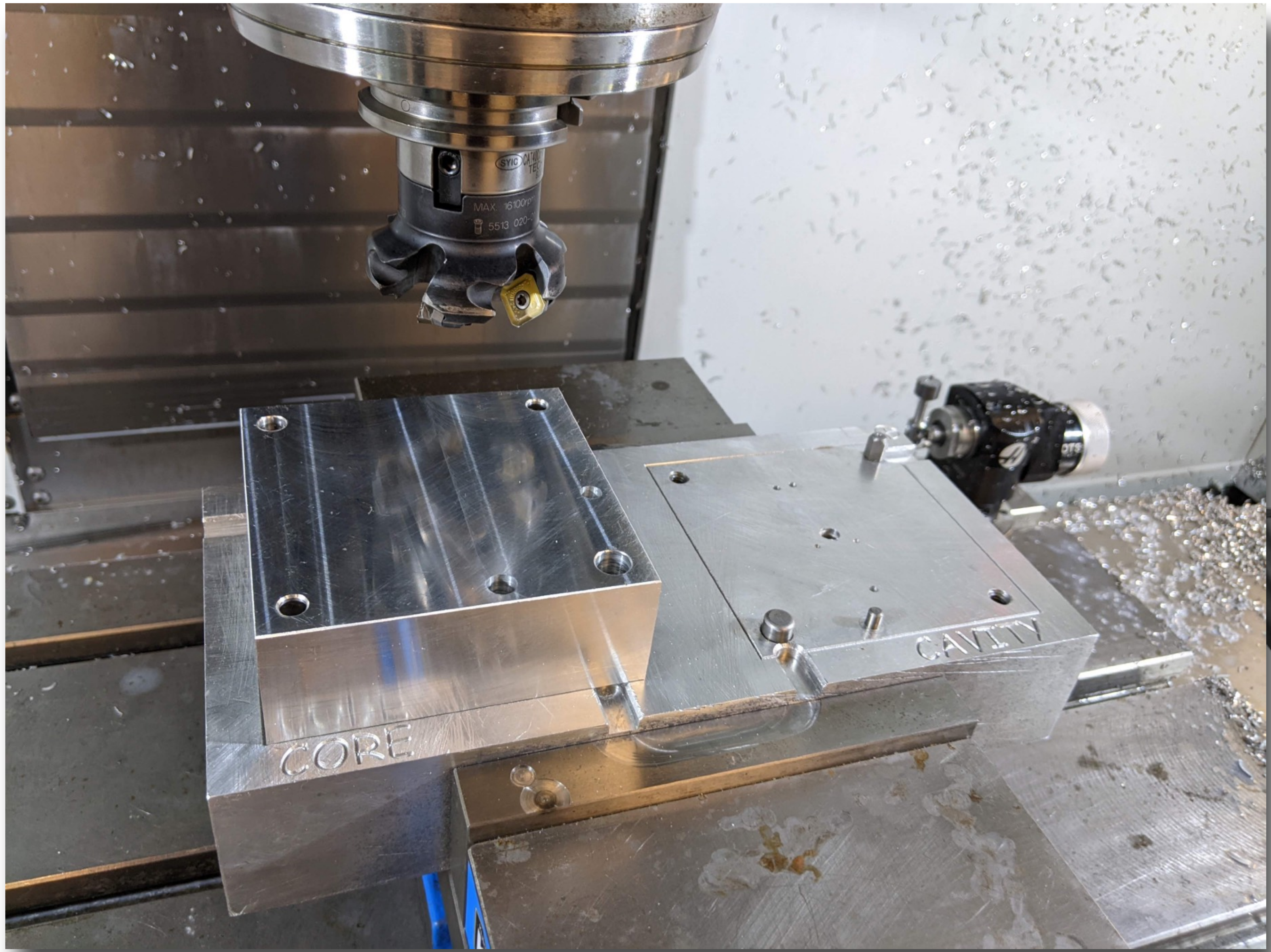
Cutting Power Demo: Results

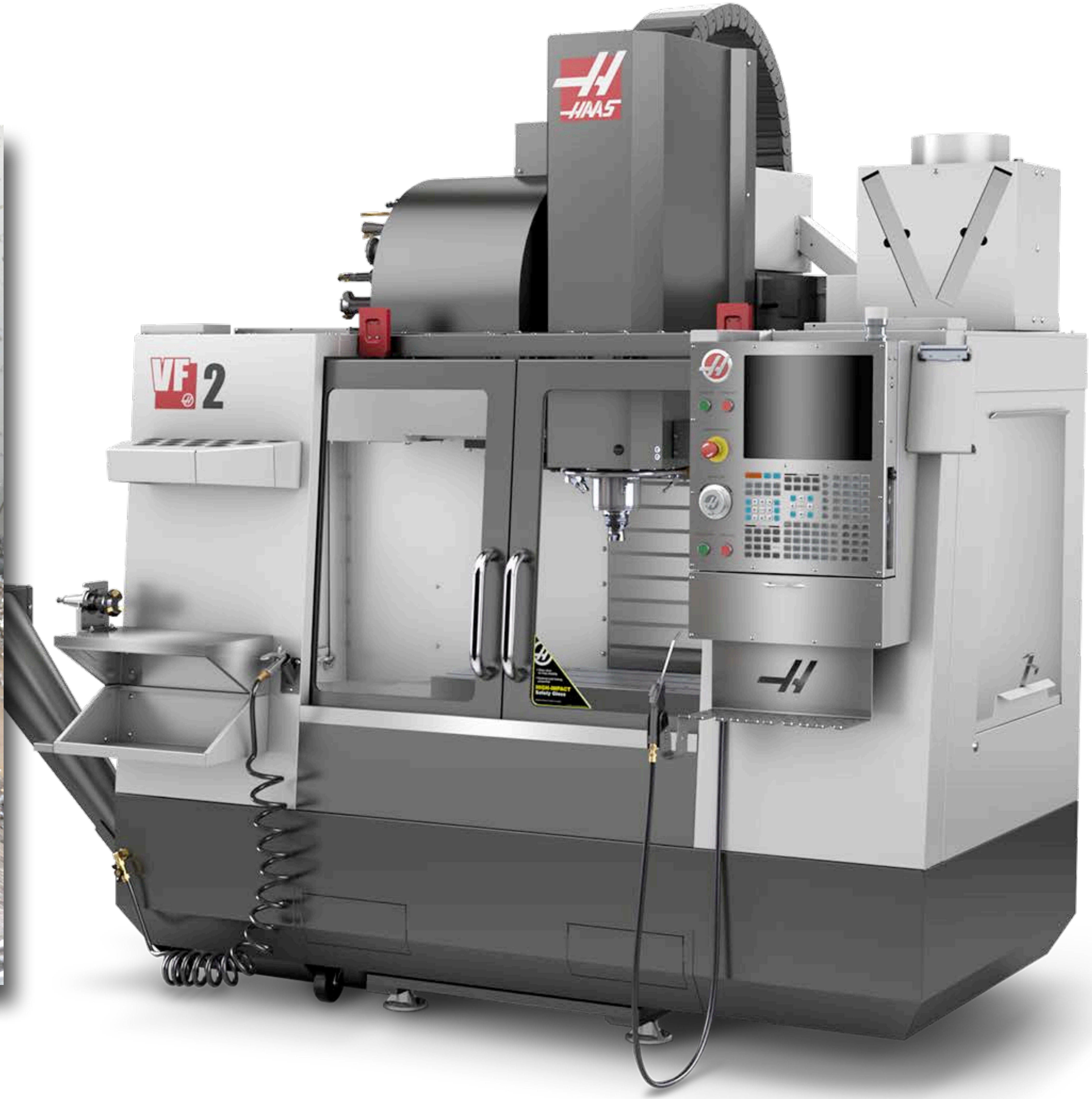


Cutting Power Demo: Results

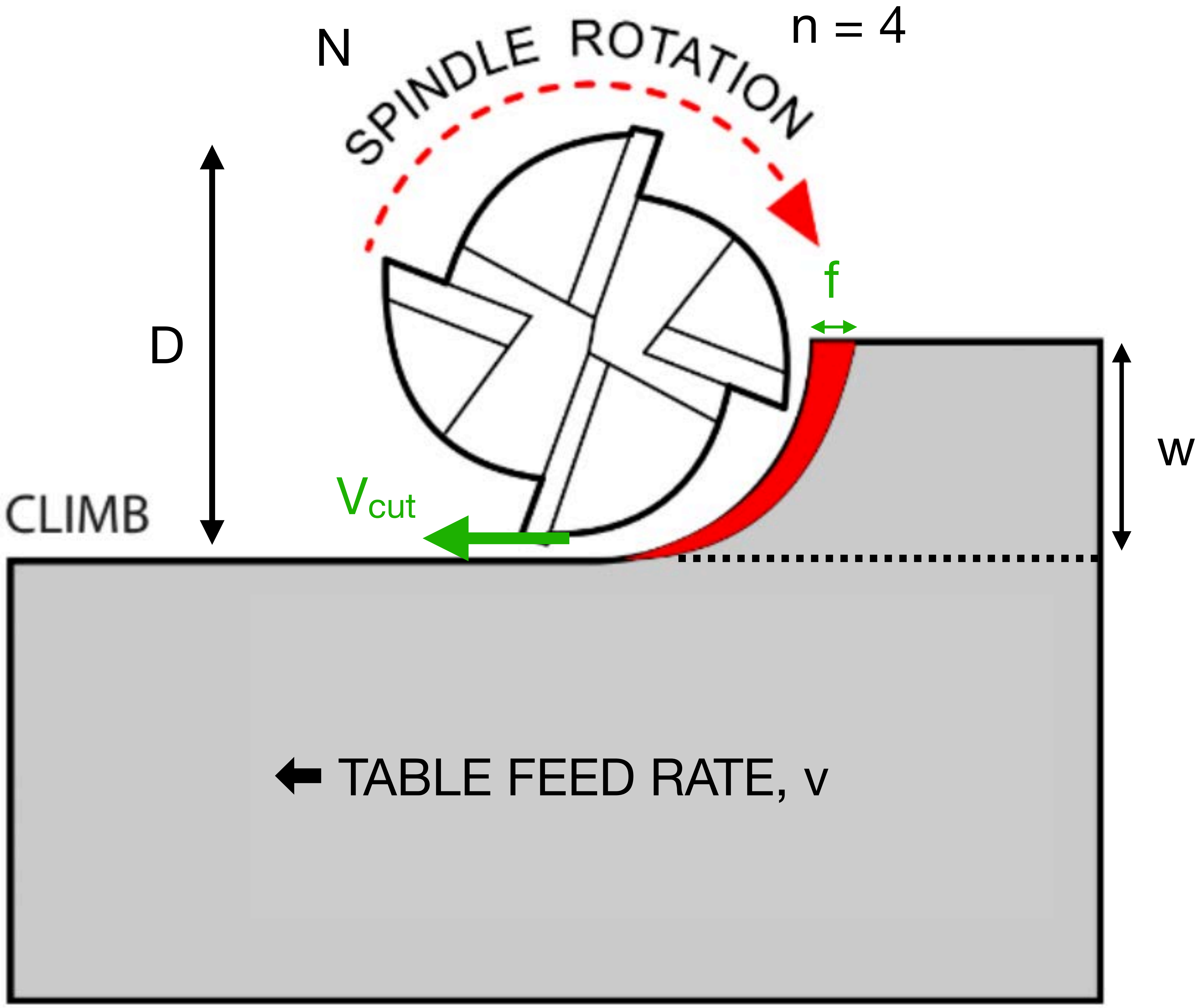


Machining in 2.008



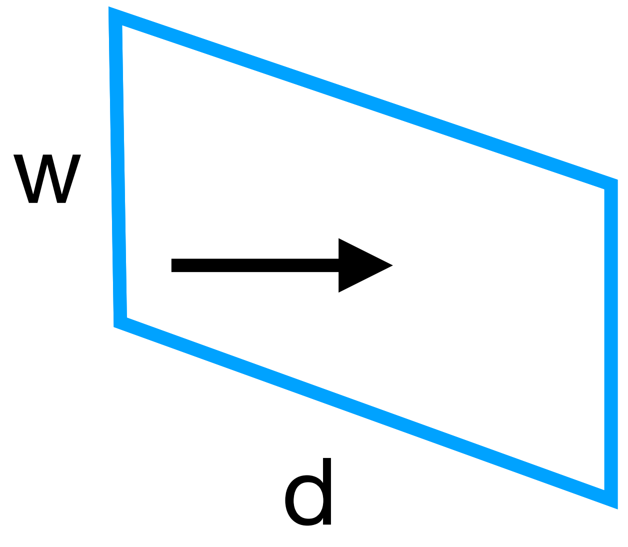


Material Removal Rate in Milling



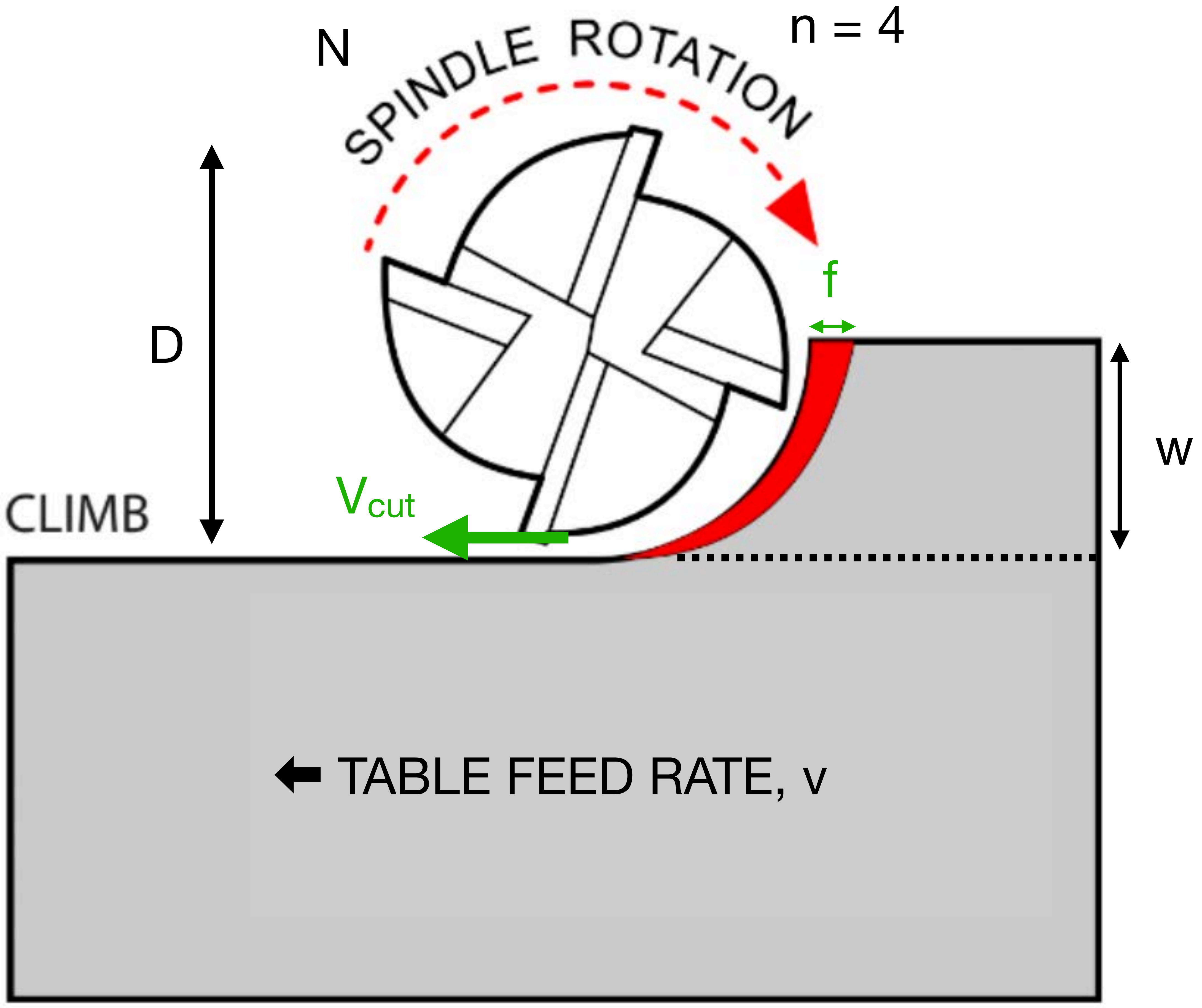
$$f = \frac{v}{Nn}$$

$$v_{cut} = \pi D N$$



- f: feed per tooth [in/tooth]
- n: number of teeth [#]
- N: spindle speed [rpm]
- v: feed rate, velocity of tool (center) relative to workpiece [in/min]
- w: width of cut [in]
- d: depth of cut [in]
- D: cutter diameter [in]

Material Removal Rate in Milling



$$f = \frac{v}{Nn}$$

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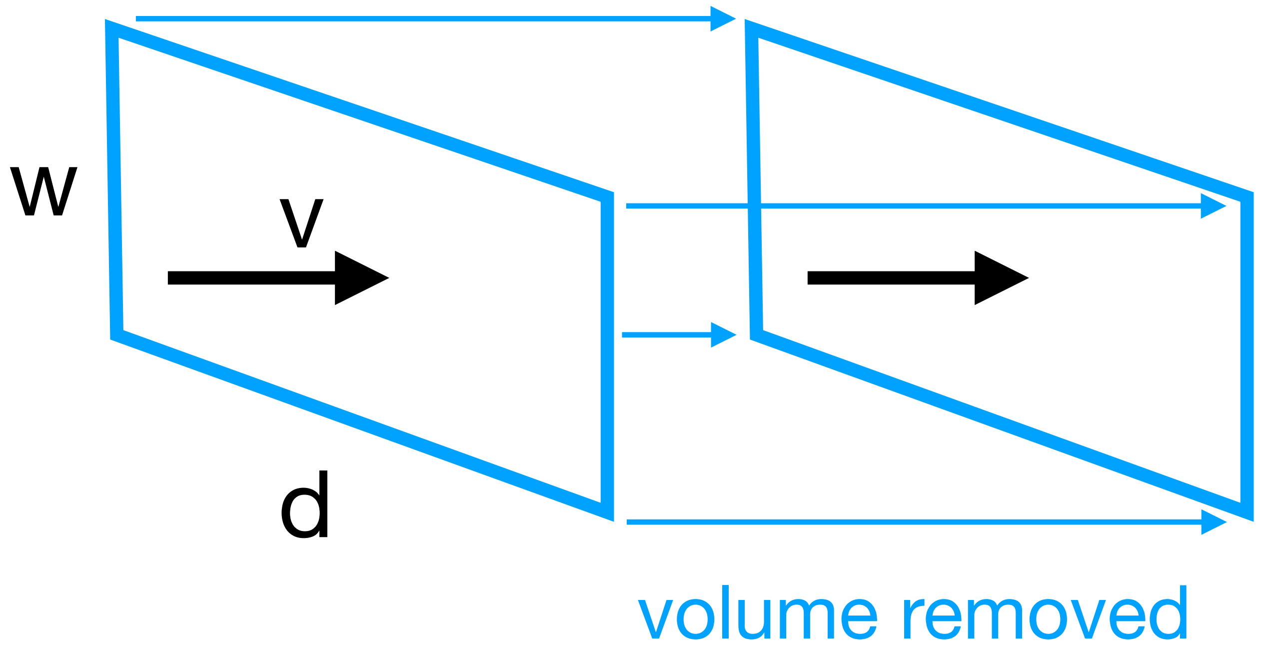


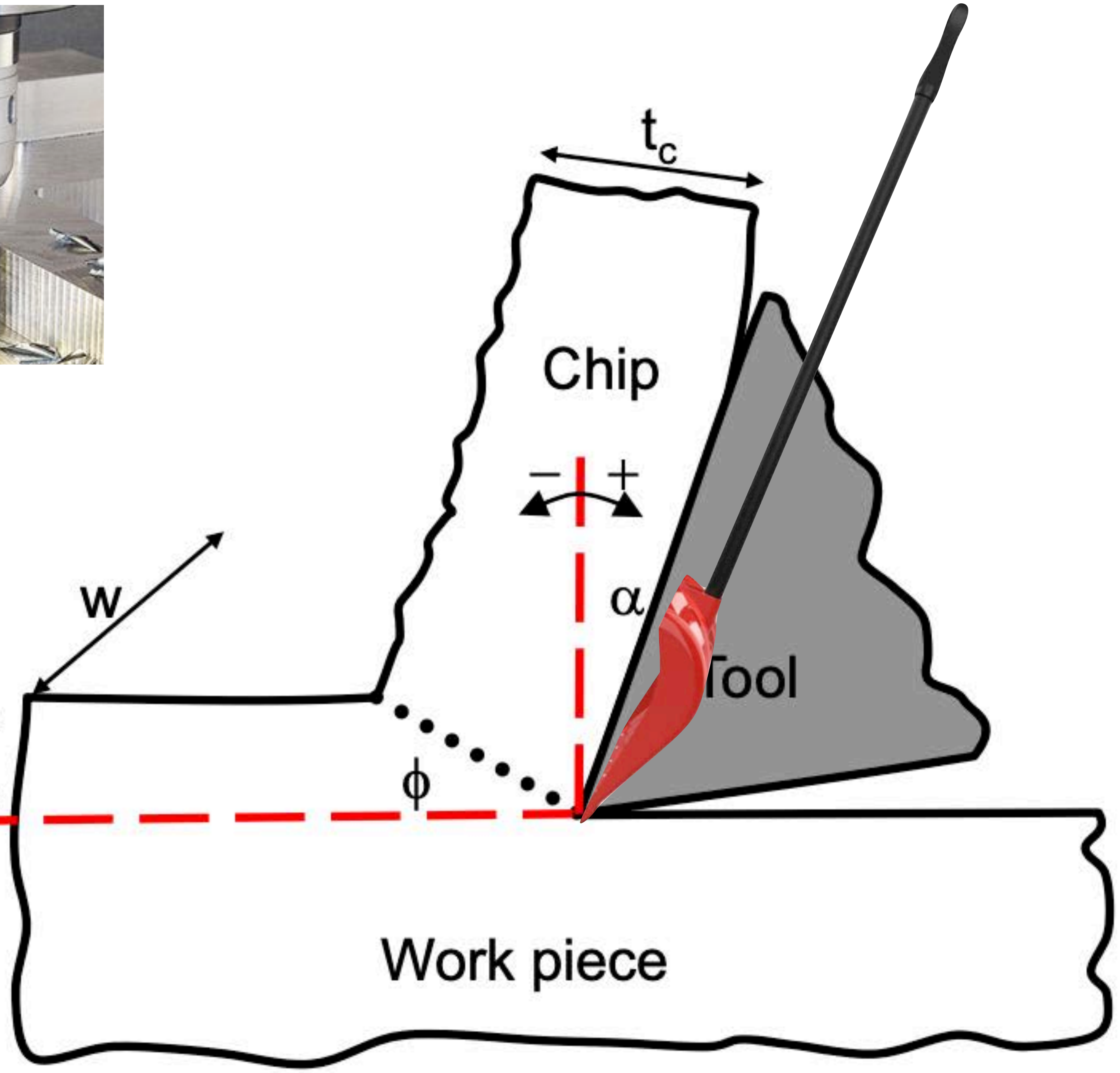
$$MRR_{milling} = wdv$$

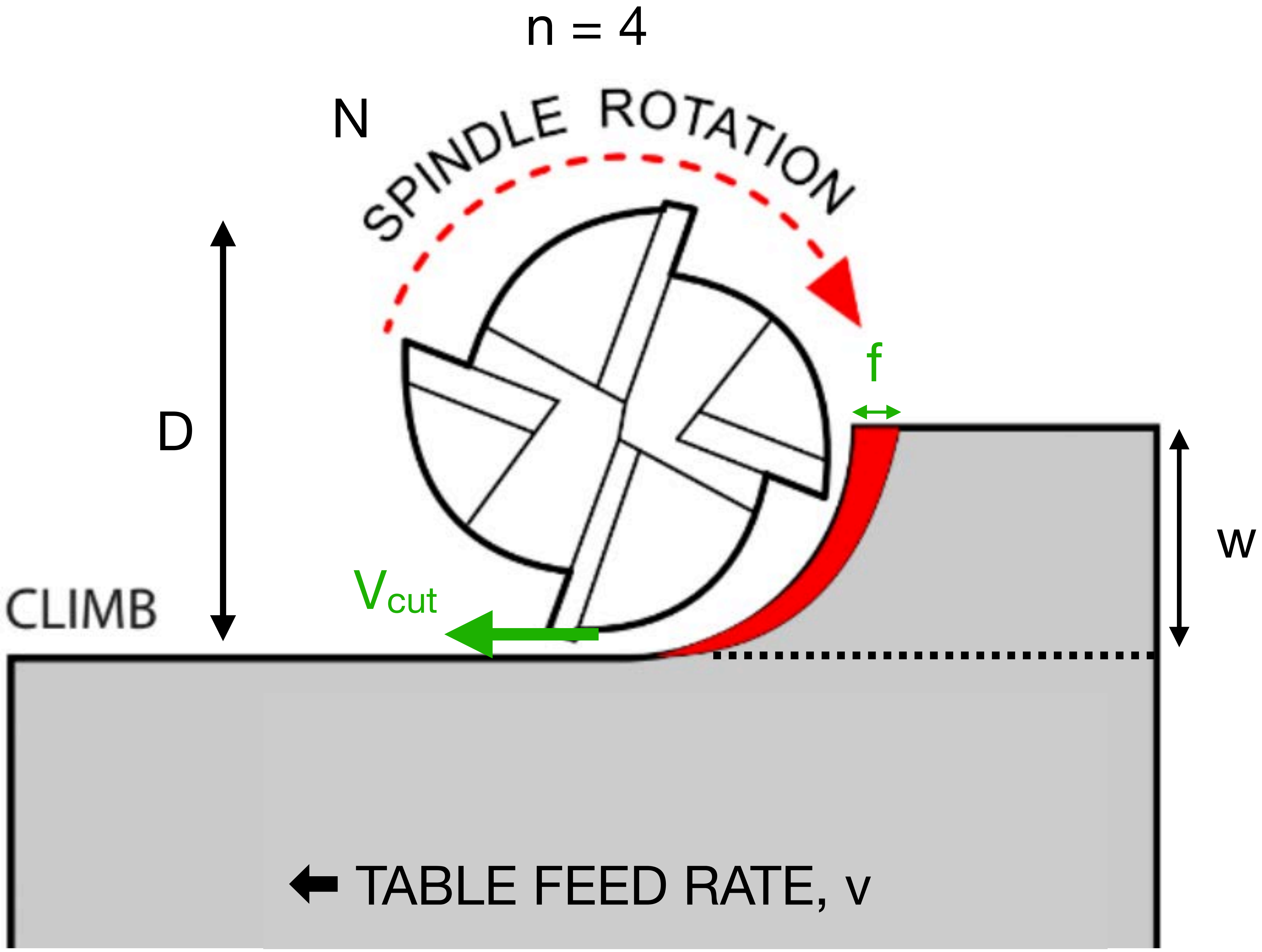
$$Power = u \cdot MRR_{milling}$$

Power: total cutting power from machine [W]
u: specific energy of the material [W-s/mm^3]
MRR: material removal rate [mm^3/s]

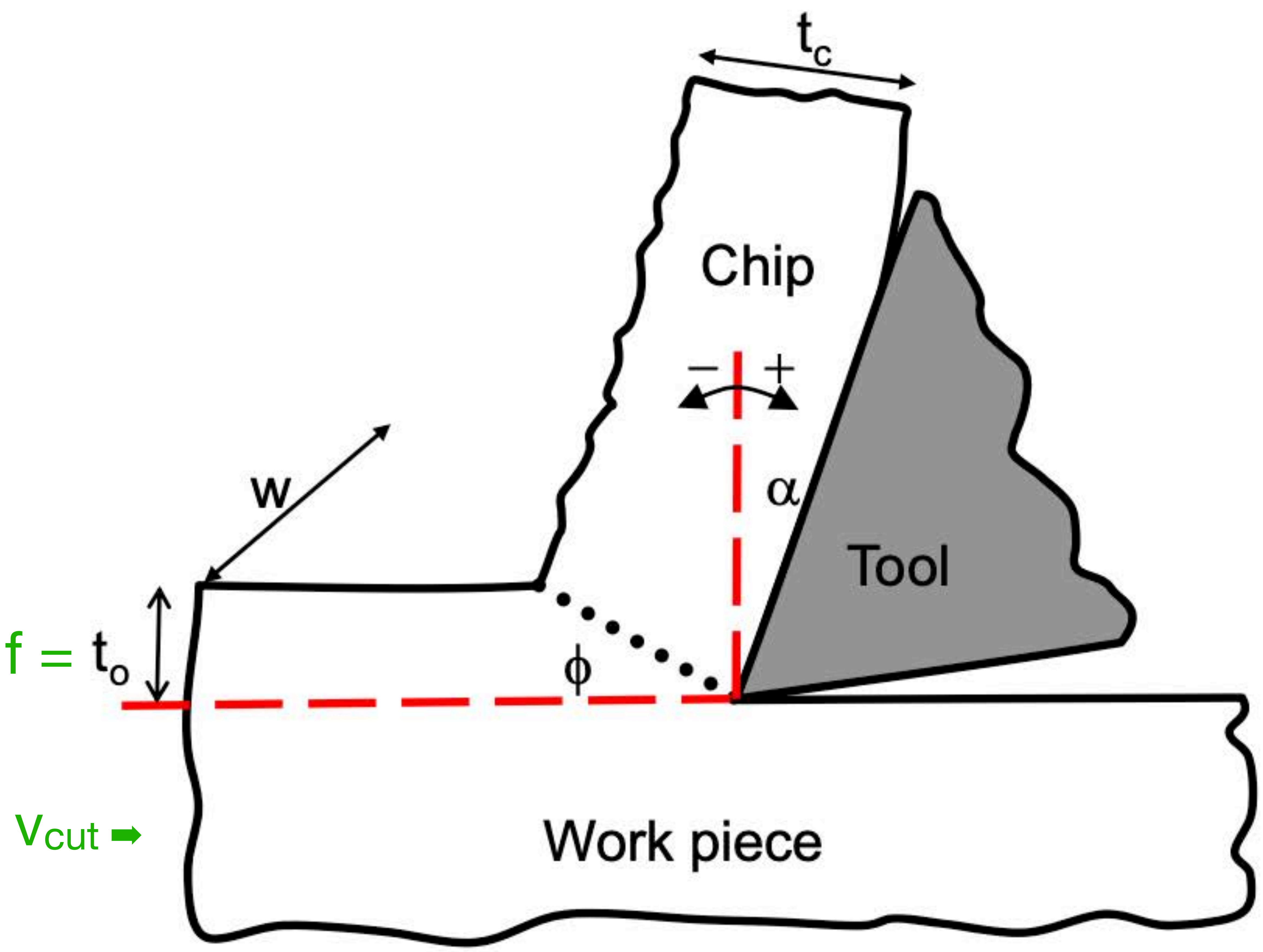
Milling

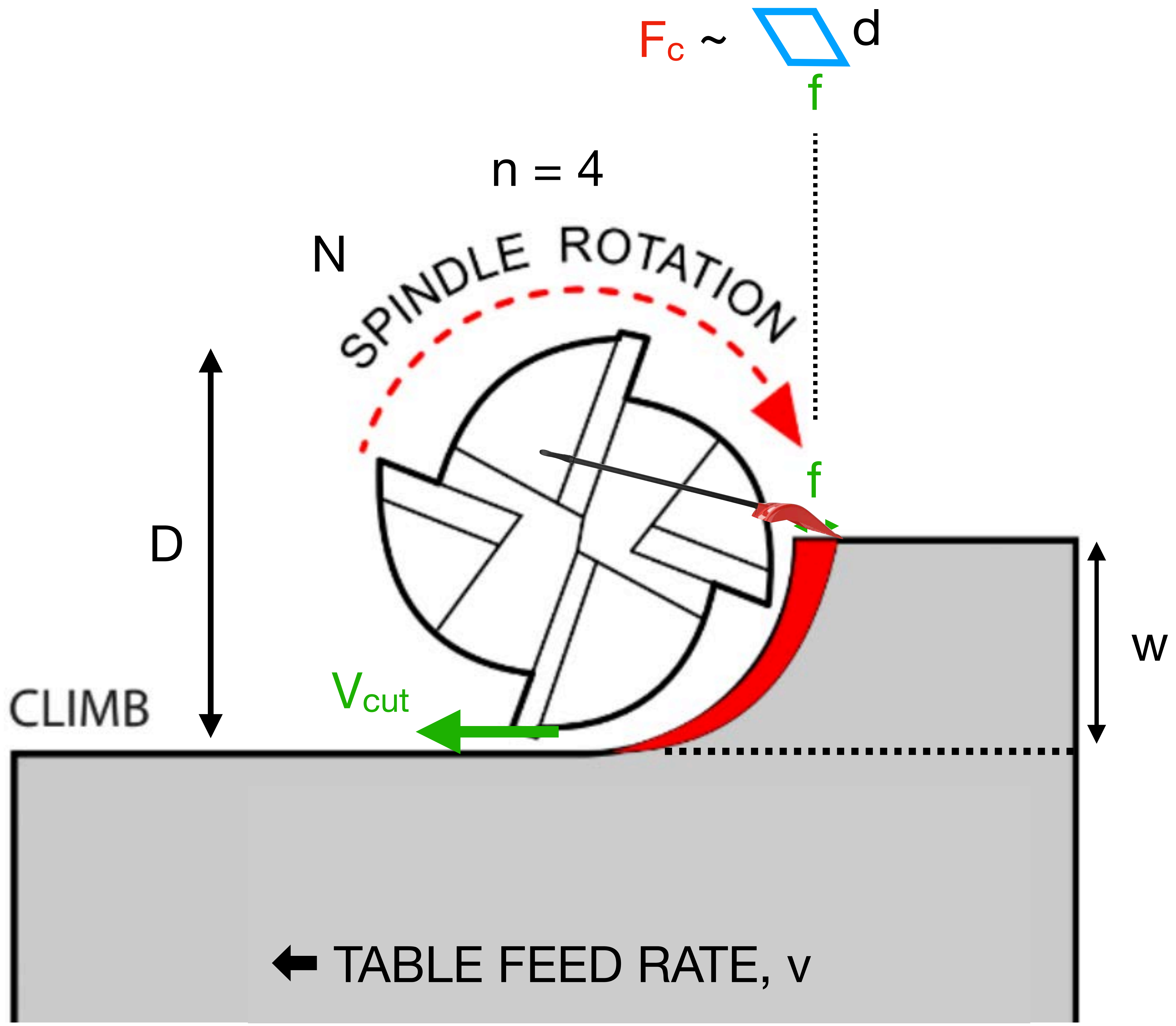
⚠️ looking down the spindle from above the machine





Milling


t_c
Chip
− +
α
w
Tool
f = t_o
ϕ
Vcut ➡
Work piece


F_c ~ d
f
n = 4
N
SPINDLE ROTATION
f
D
w
CLIMB
V_{cut}
⬅ TABLE FEED RATE, v

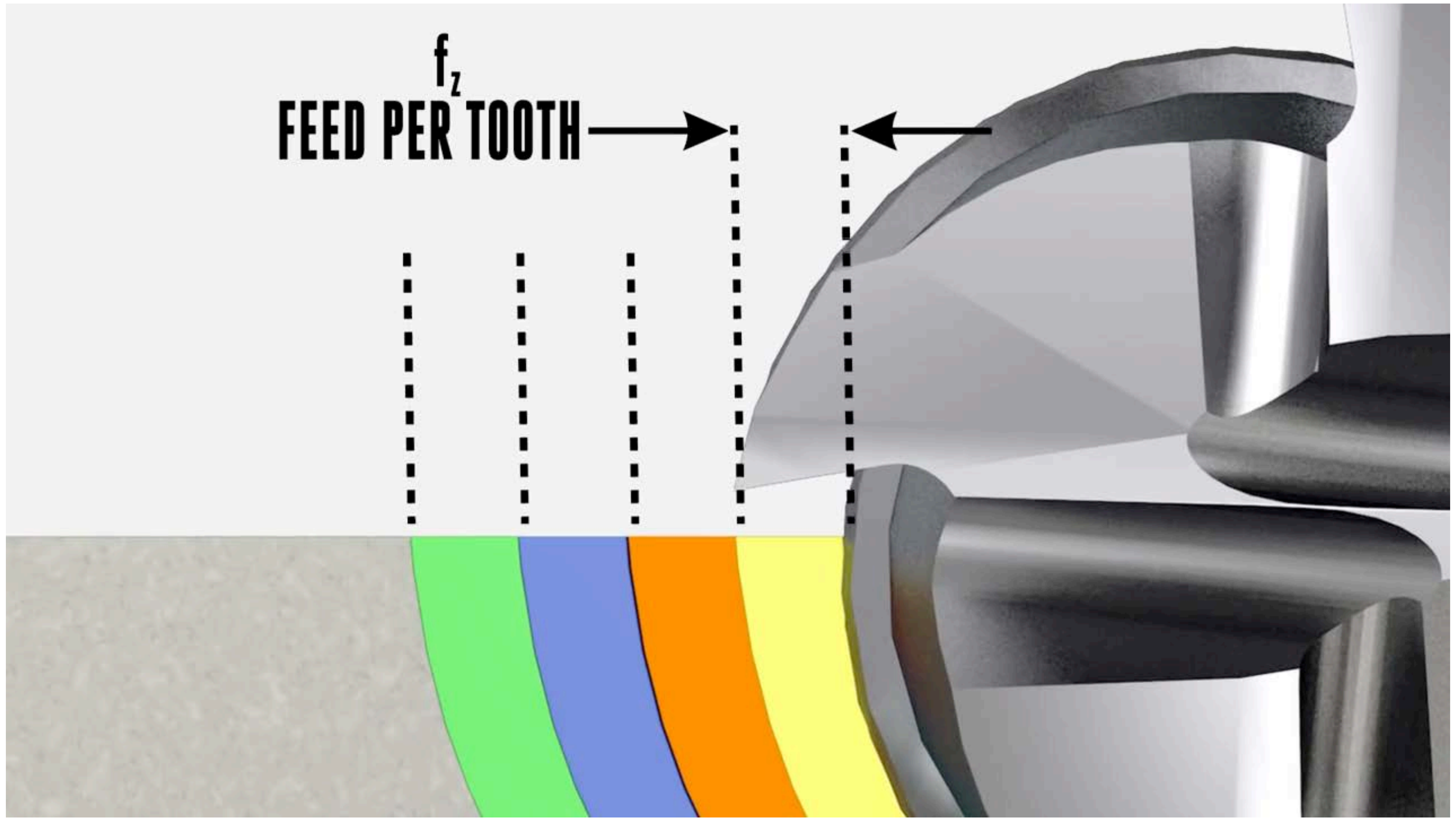
Cutting Forces in Milling

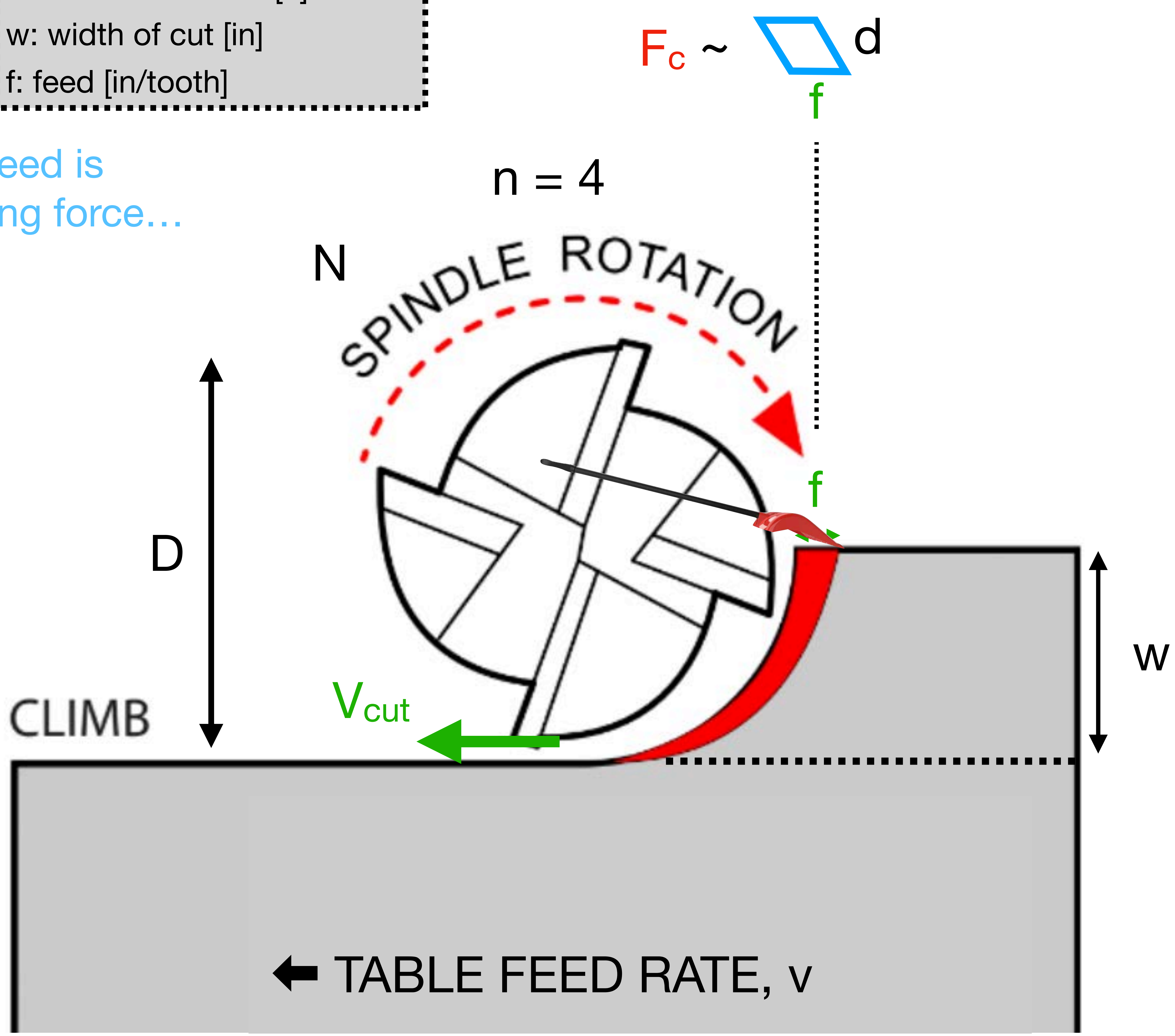
D: cutting tool diameter [in]
N: spindle speed [rev/min]
n: number of teeth [#]
w: width of cut [in]
f: feed [in/tooth]

⚠️ connection between spindle speed and feed makes this confusing

adjust N with v constant: f changes (v_{cut} also changes)

seems like speed is affecting cutting force…





Specific Energy

how much energy does it take to cut different materials? there's an empirical chart for that!

$$u = \frac{Enegry}{Volume}\Big|_{certain\ conditions}$$

$volume \rightarrow volume\ flow$ "Material Removal Rate"

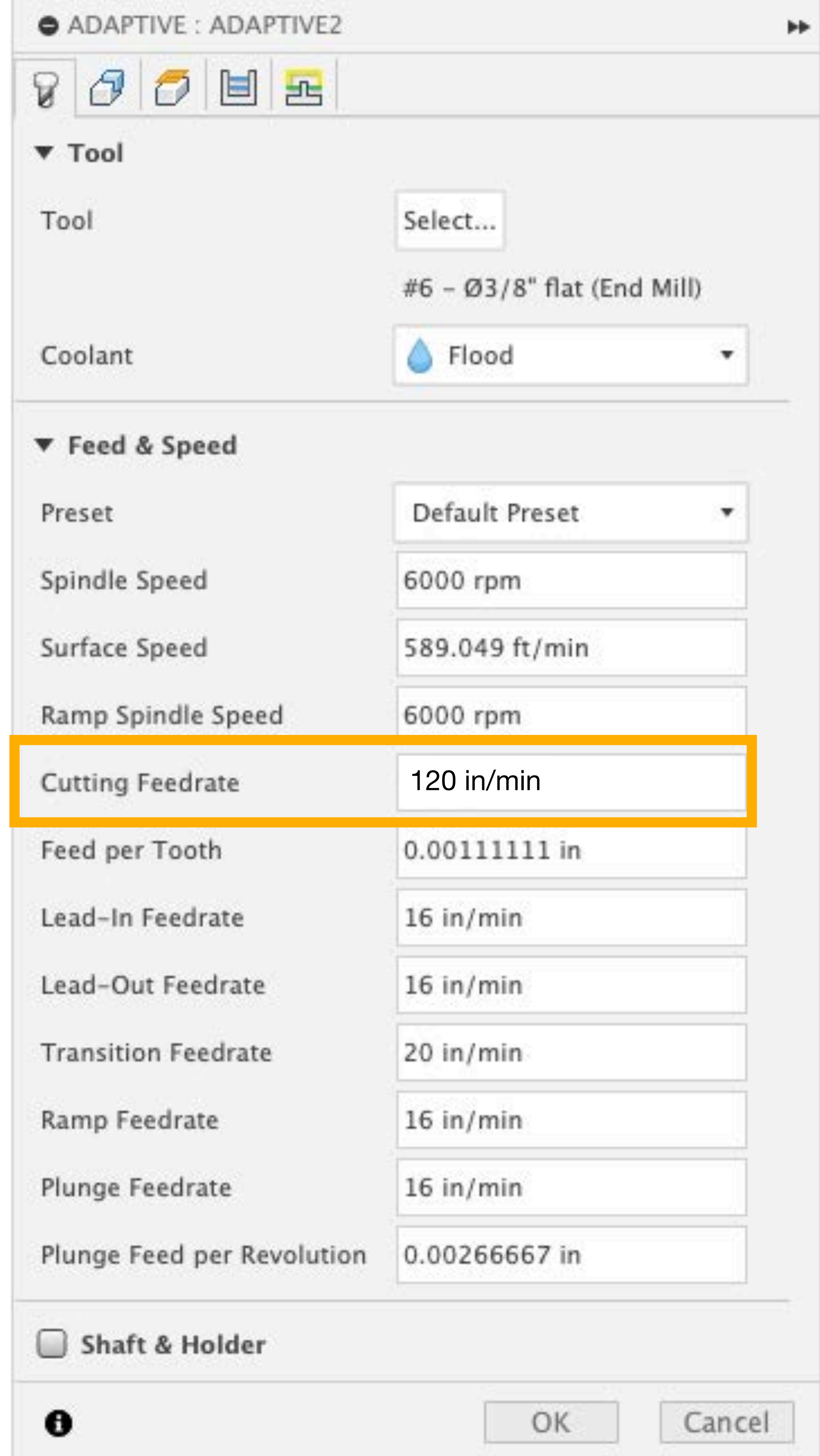
$energy \rightarrow power$ how much power is needed?

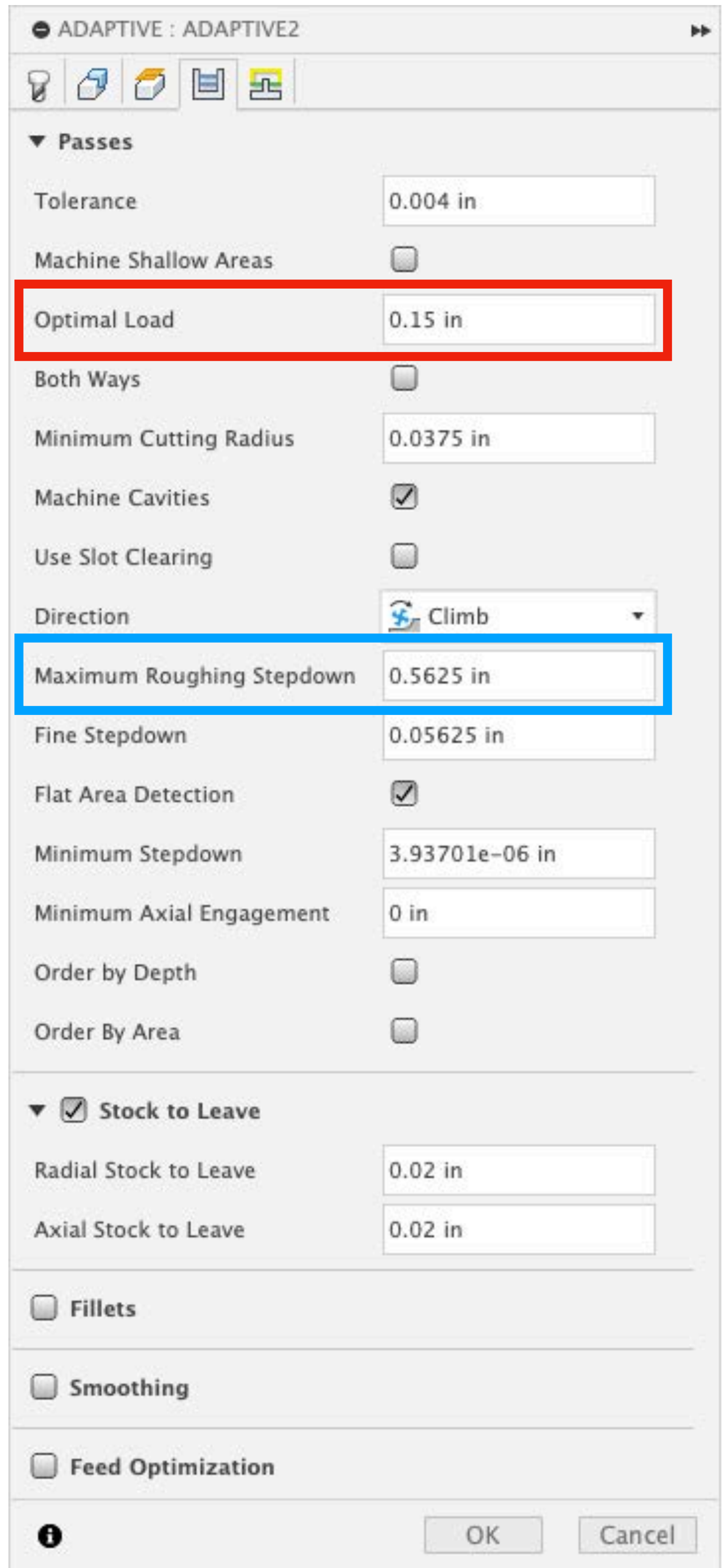
TABLE 21.2

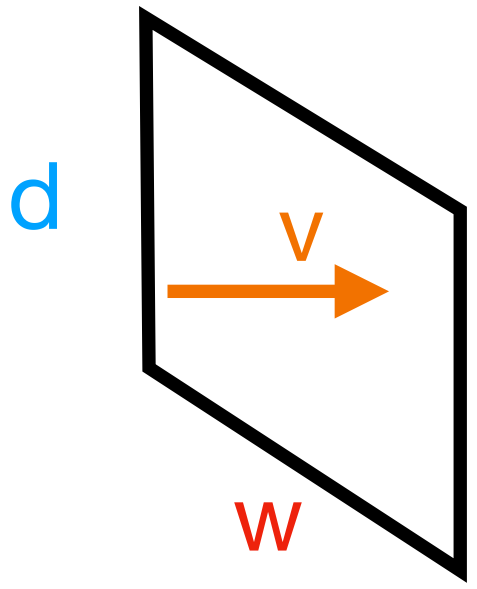
Approximate Range of Energy Requirements in Cutting Operations at the Drive Motor of the Machine Tool (for Dull Tools, Multiply by 1.25)

Material	Specific energy W-s/mm^3	Specific energy hp-min/in^3
Aluminum alloys	0.4–1	0.15–0.4
Cast irons	1.1–5.4	0.4–2
Copper alloys	1.4–3.2	0.5–1.2
High-temperature alloys	3.2–8	1.2–3
Magnesium alloys	0.3–0.6	0.1–0.2
Nickel alloys	4.8–6.7	1.8–2.5
Refractory alloys	3–9	1.1–3.5
Stainless steels	2–5	0.8–1.9
Steels	2–9	0.7–3.4
Titanium alloys	2–5	0.7–2

Specific Energy: Milling







$$MRR_{milling} = wdv$$

$$Power = u \cdot MRR_{milling}$$

(w)(d)(v) = (0.15)(0.5625)(120) in^3/min

(w)(d)(v) = **10.1** in^3/min

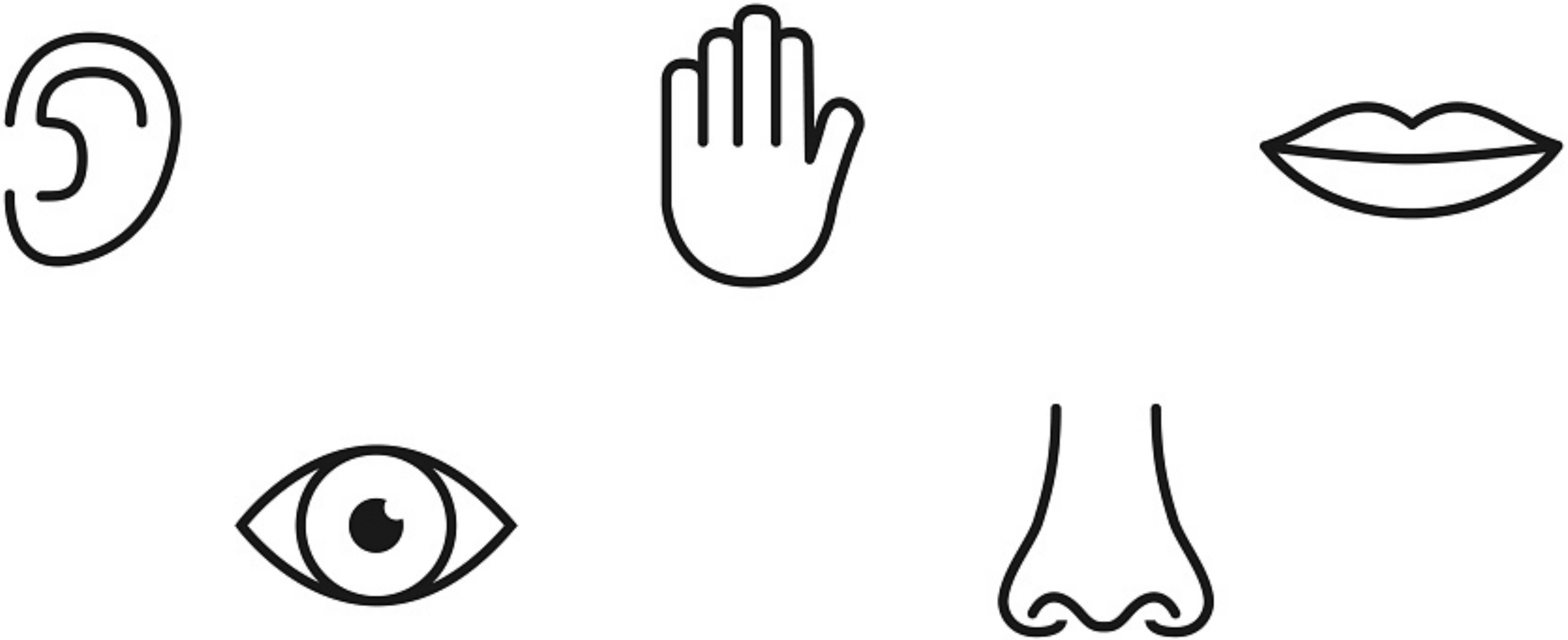
Material	Specific energy W-s/mm^3	Specific energy hp-min/in^3
Aluminum alloys	0.4–1	0.15–0.4

power = [1.5, 4] HP

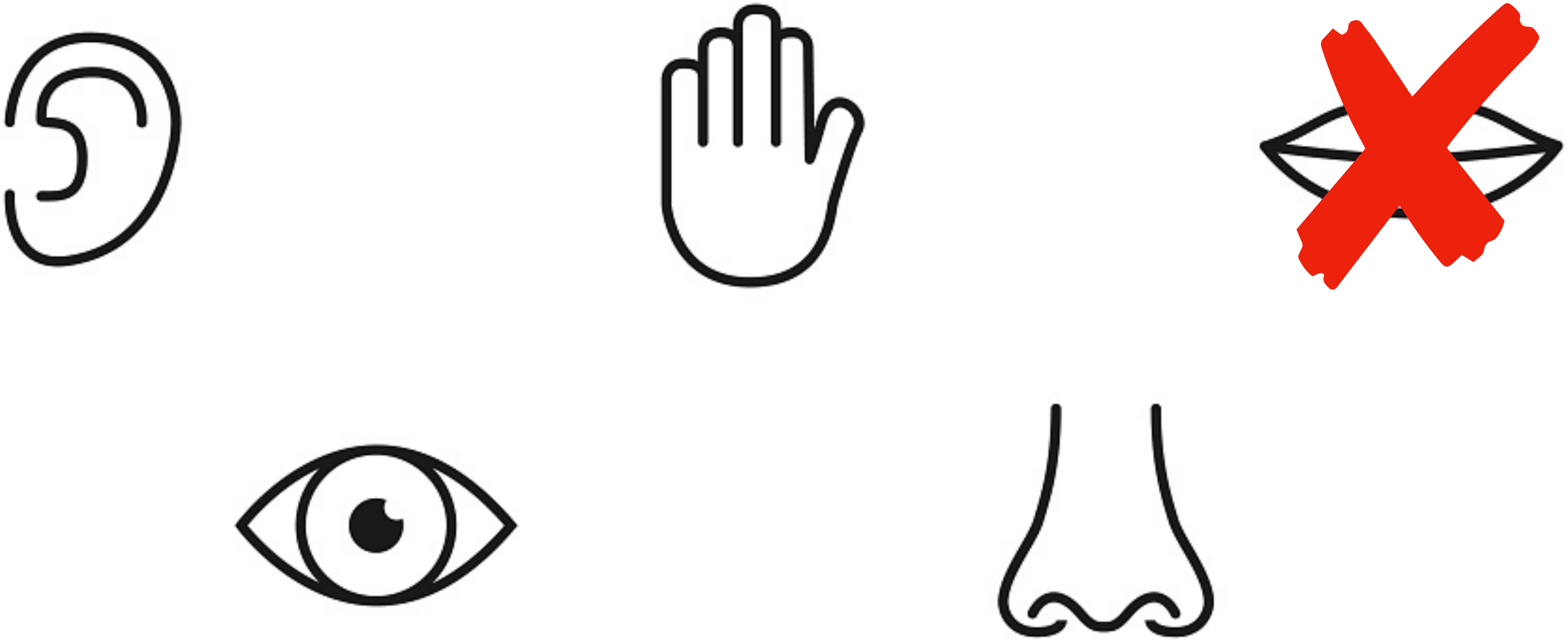
power = [1.1, 2.9] kW

- Bridgeport Milling Machine: 2 HP (1.5kW)
- HAAS: 30HP (22 kW)

HAAS video highlights

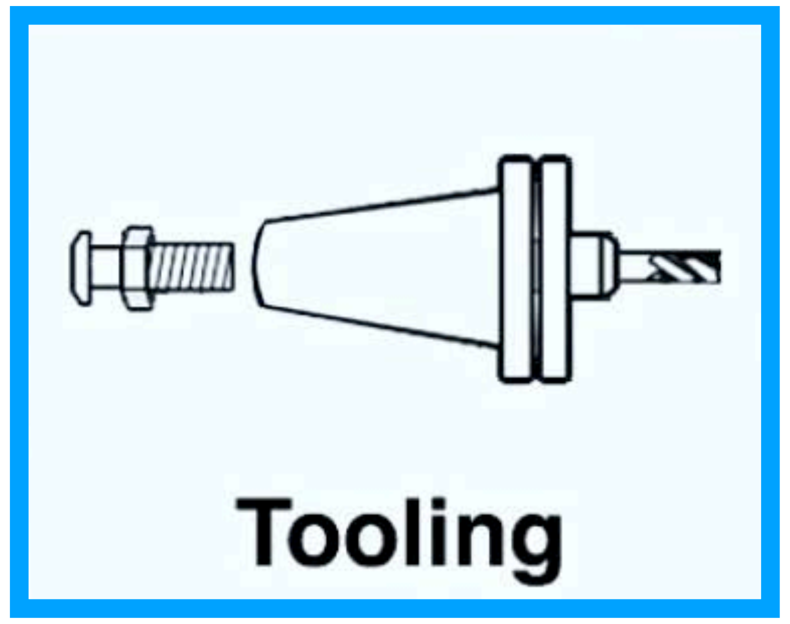


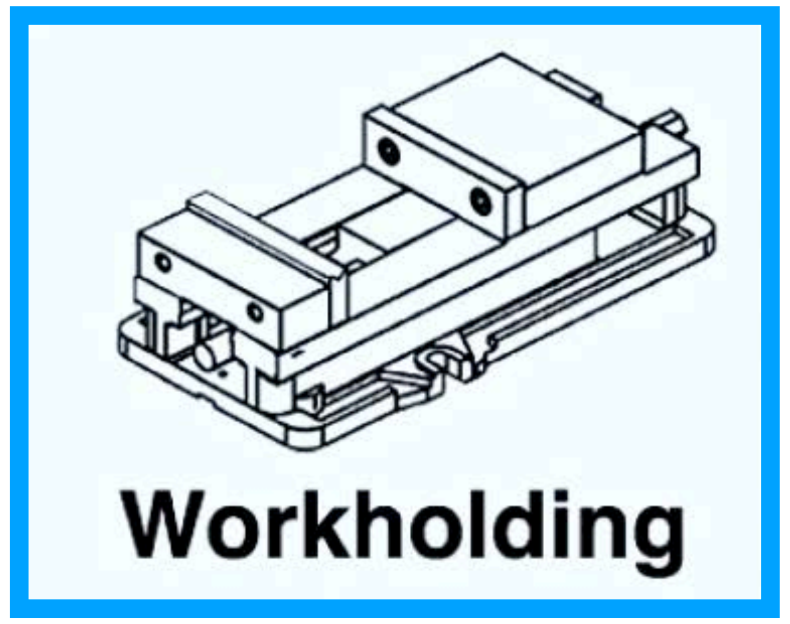
HAAS video highlights

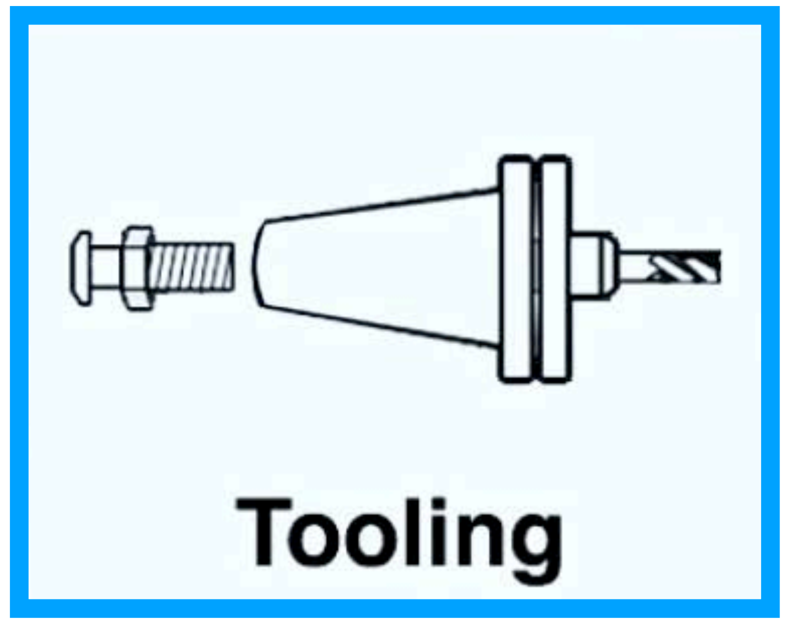


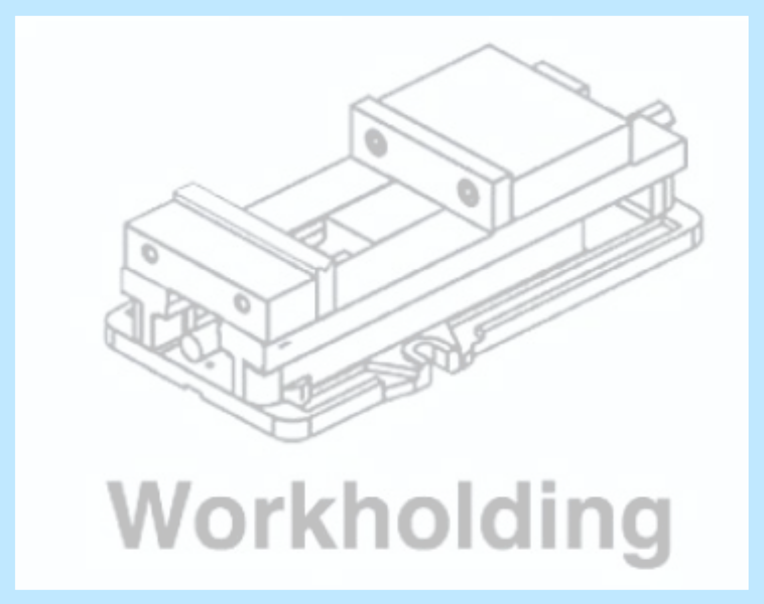
Cutting #3

Machining in Practice

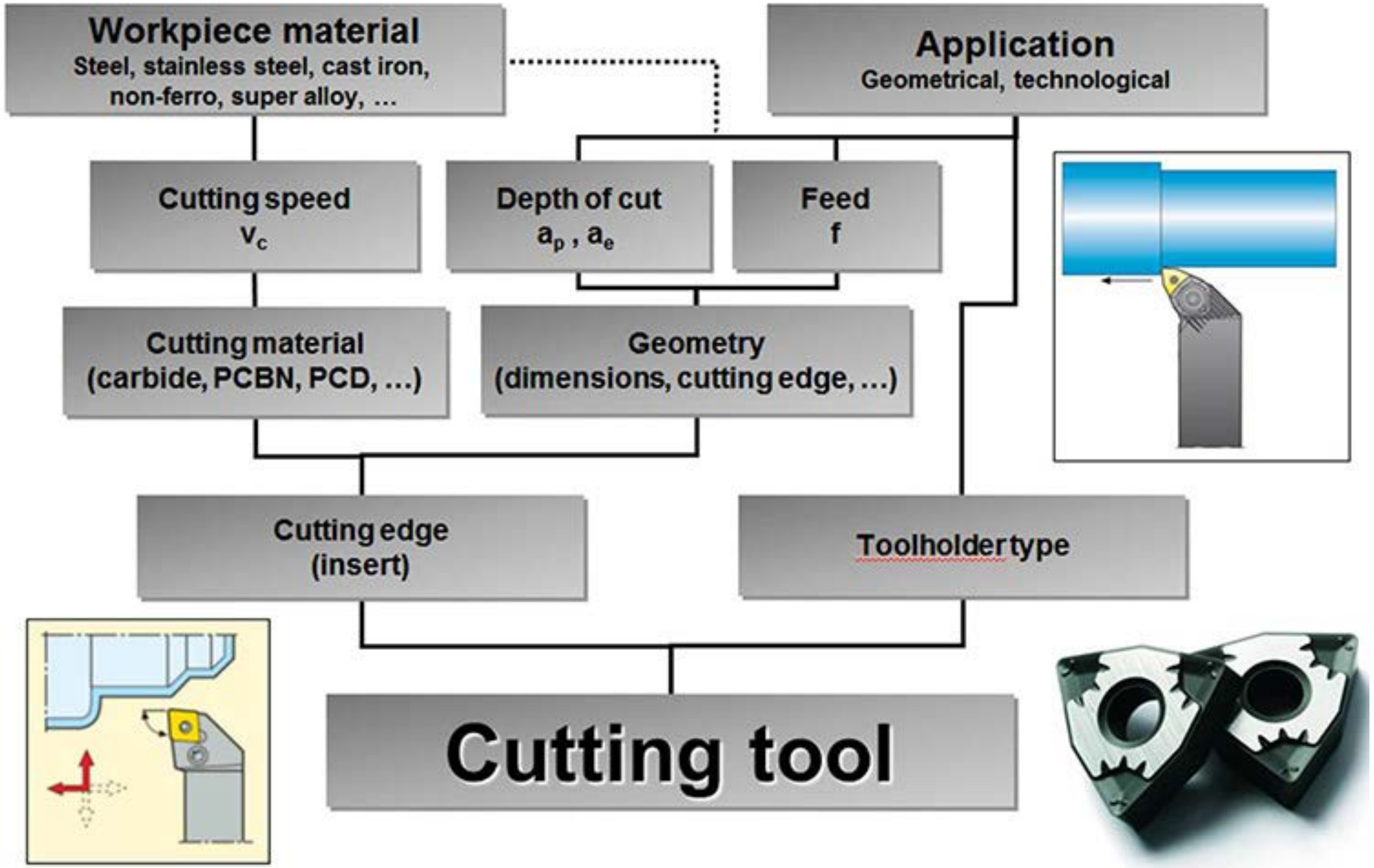


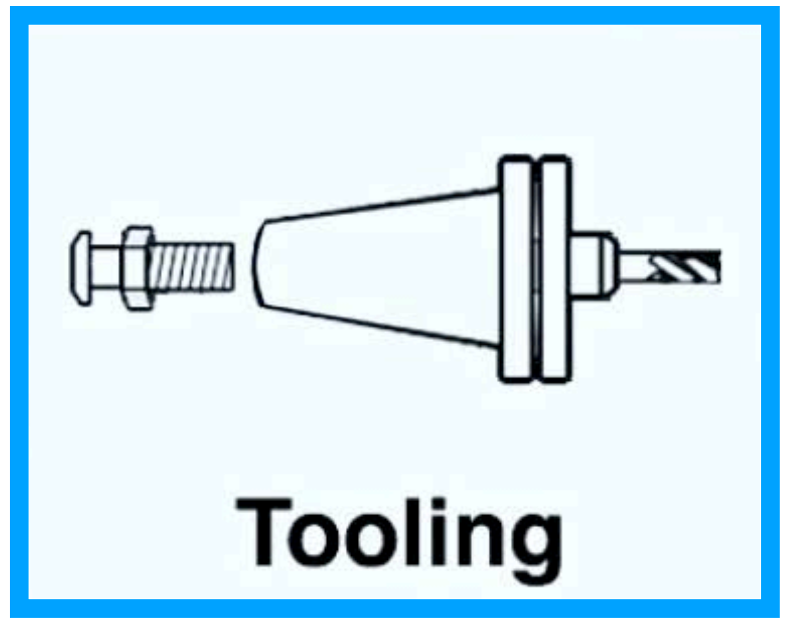


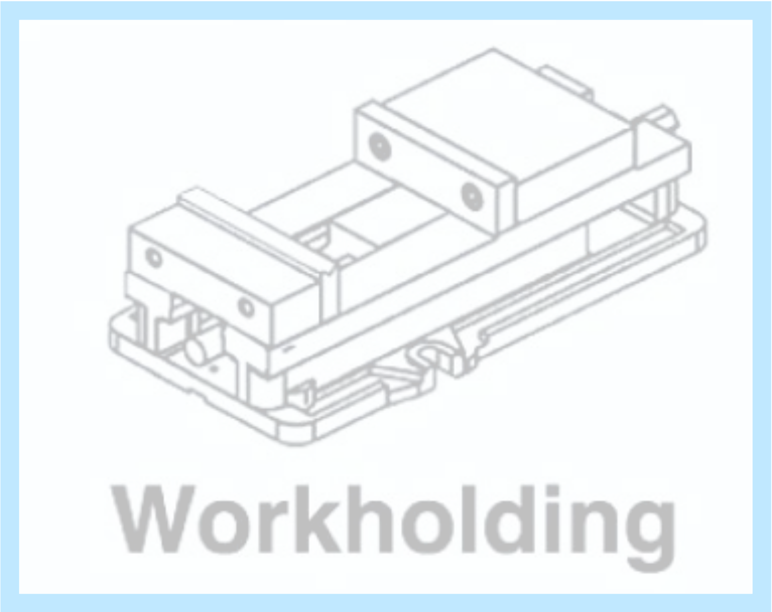




Tool Selection

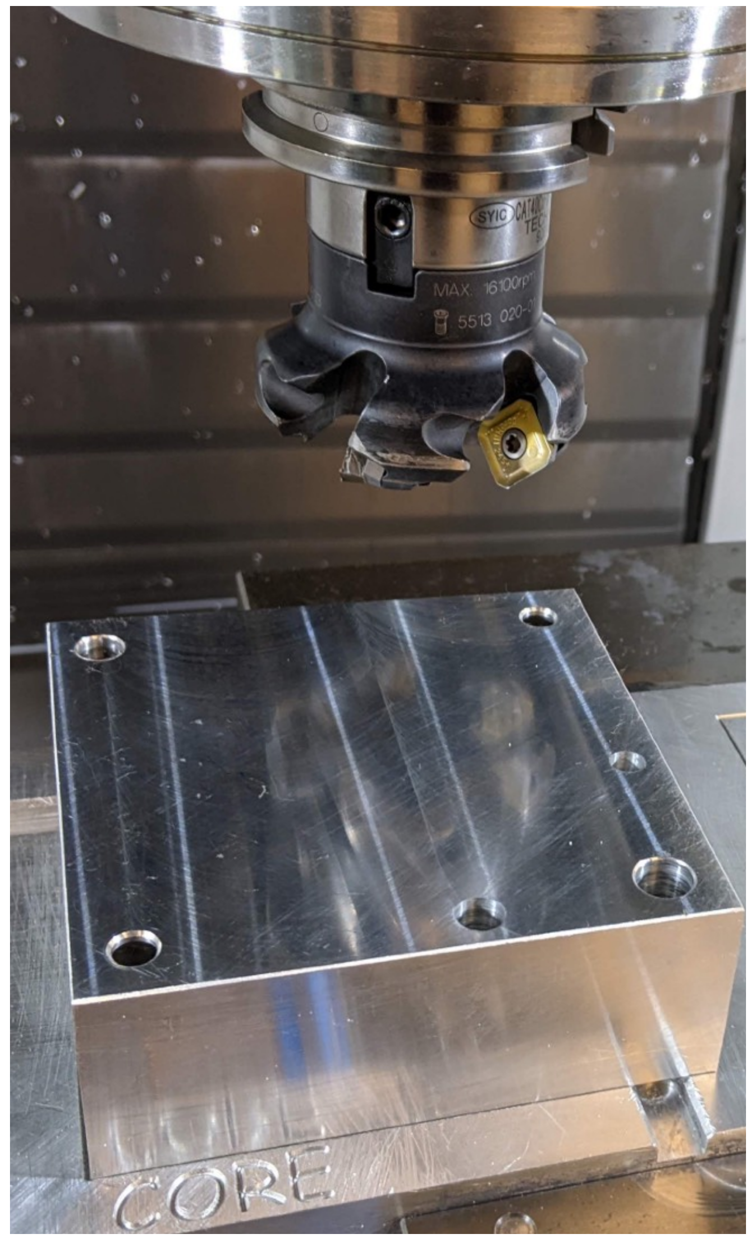


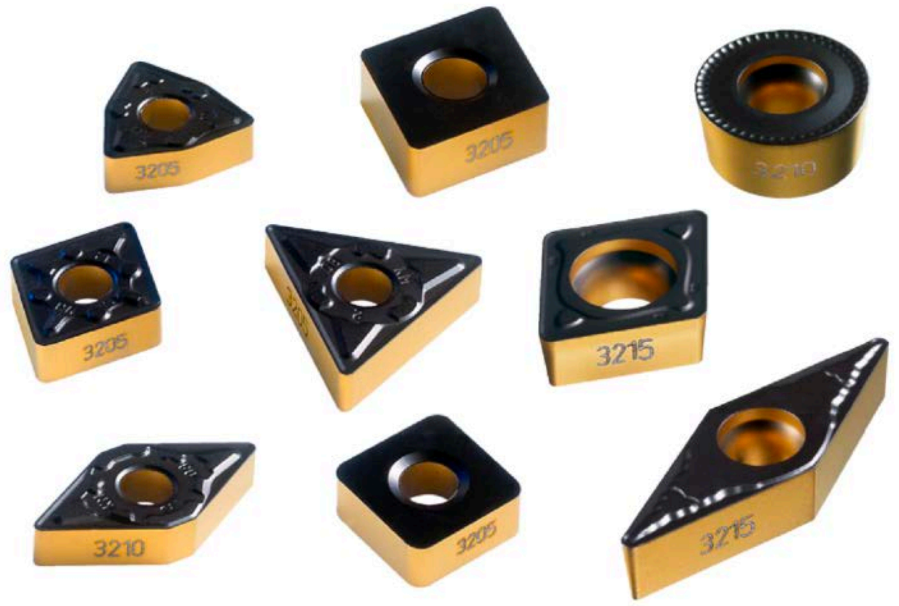


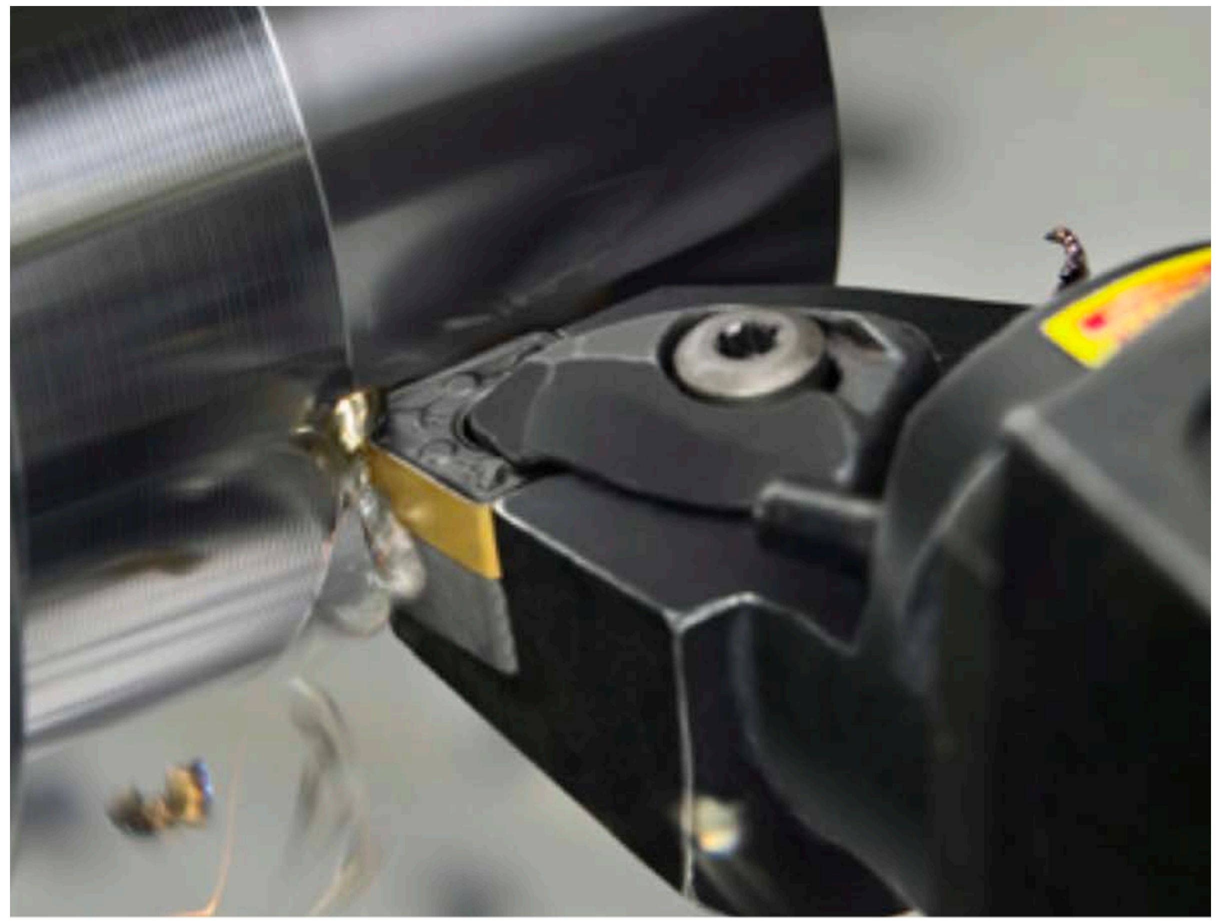


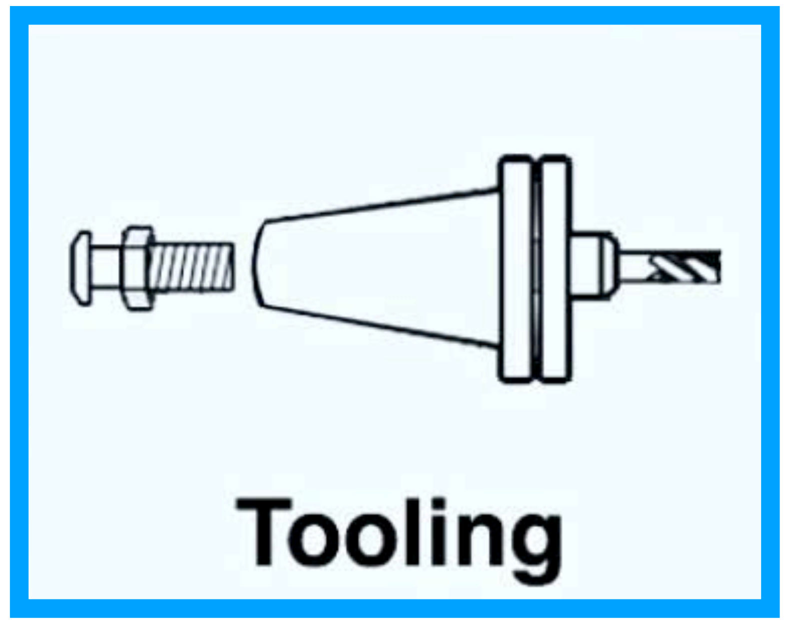
Tool Types

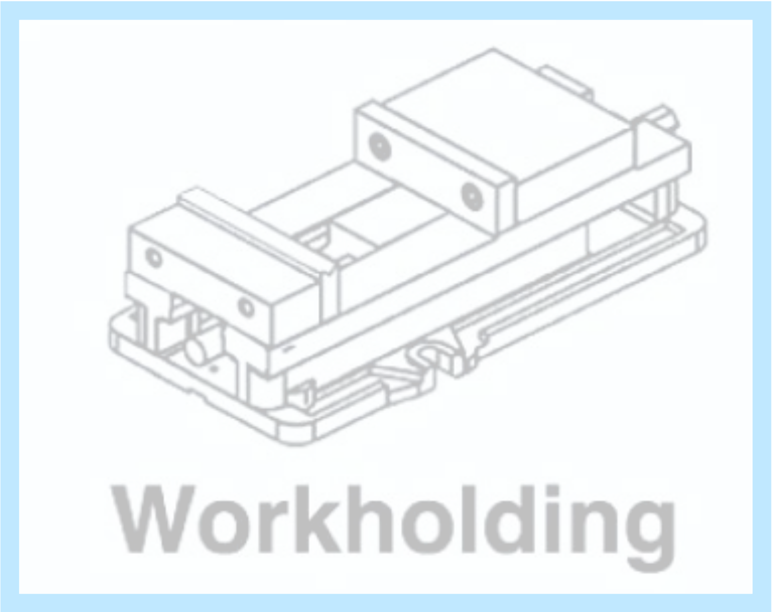
tool examples can be passed around!





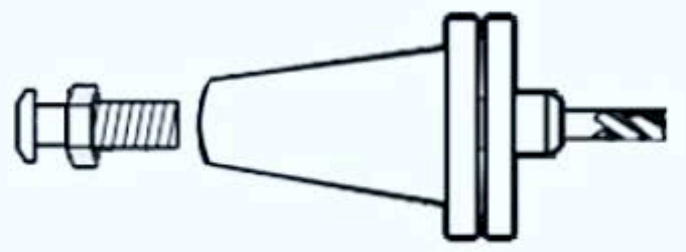






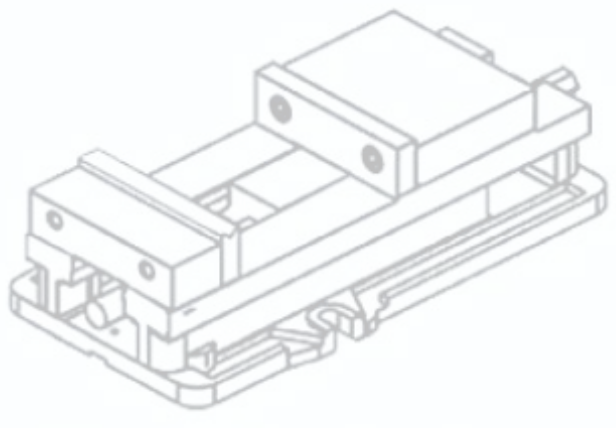
Tool Restrictions

Name ^	Corner radius	Diameter	Flute length	Overall length	Type
2008 TOOL LIBRARY REVISED					
1 - Ø1/16" (End Mill)		0.0625 in	0.125 in	2.5 in	Flat end mill
2 - Ø3/32" (End Mill)		0.09375 in	0.125 in	1 in	Flat end mill
3 - Ø1/8" (End Mill)		0.125 in	0.2 in	2.5 in	Flat end mill
4 - Ø3/16" (End Mill)		0.1875 in	0.45 in	2 in	Flat end mill
5 - Ø1/4" (End Mill)		0.25 in	0.969 in	2.5 in	Flat end mill
6 - Ø3/8" (End Mill)		0.375 in	0.75 in	3 in	Flat end mill
7 - Ø1/16" (End Mill)		0.0625 in	0.08 in	2 in	Ball end mill
8 - Ø1/8" (End Mill)		0.125 in	0.08 in	1.5 in	Ball end mill
9 - Ø1/4" (End Mill)		0.25 in	0.54 in	2 in	Ball end mill
10 - Ø1/16" 2° (2 Degree Tapered End Mill)	0 in	0.0625 in	0.577 in	2 in	Tapered mill
11 - Ø1/4" 130° (SPOT DRILL)		0.25 in	0.08 in	1.5 in	Spot drill
12 - Ø0.12" 118° (Ejector Pin Drill)		0.12 in	1.48 in	4 in	Drill
13 - Ø0.234" 118° (Nut Shaft Drill)		0.234 in	1.1 in	3.042 in	Drill
14 - Ø2" 45° (Face mill)	0 in	2 in	0.317 in	5.6 in	Face mill
15 - Probe/Edge Finder		5 mm			Probe



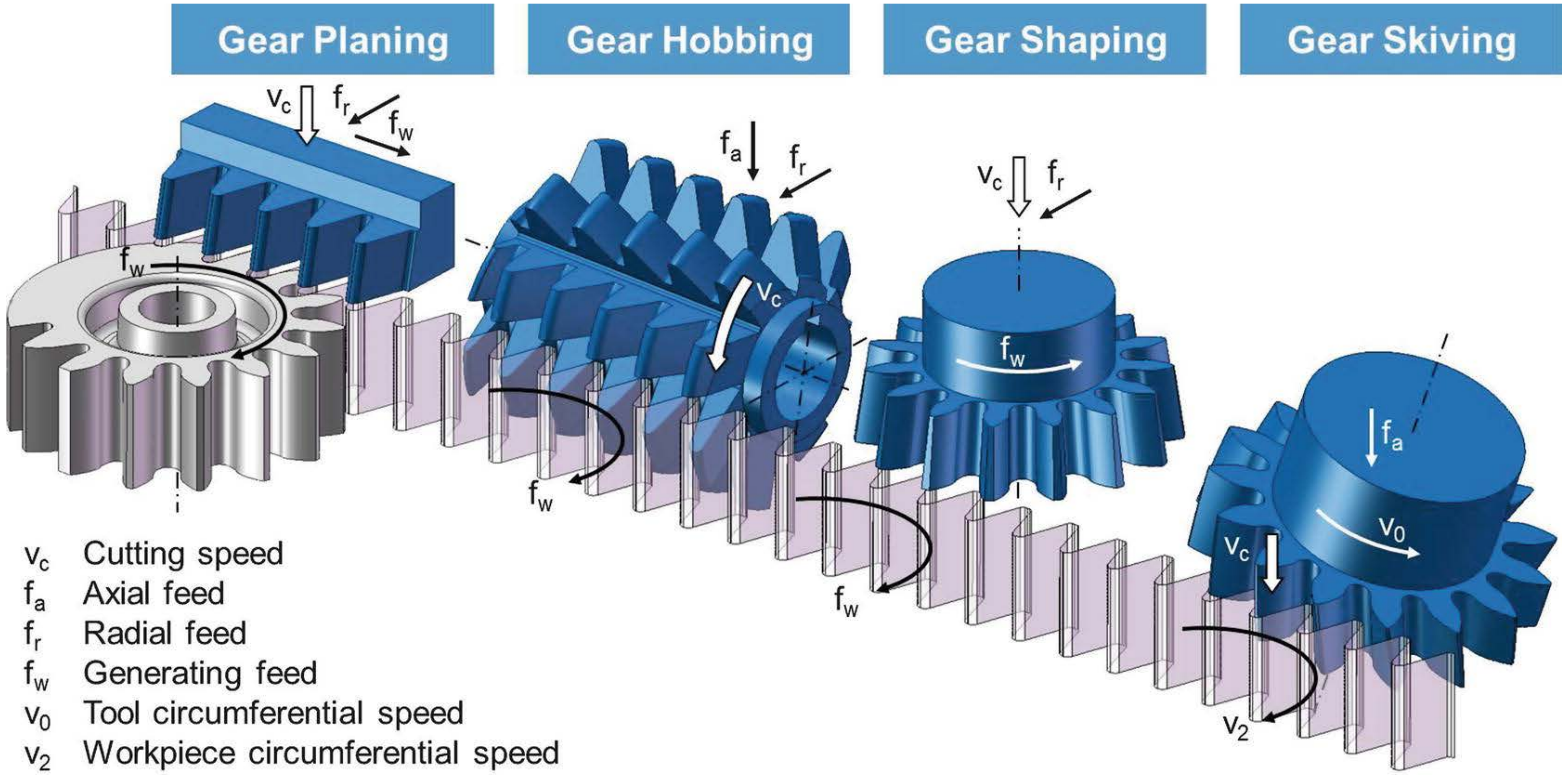
Tooling

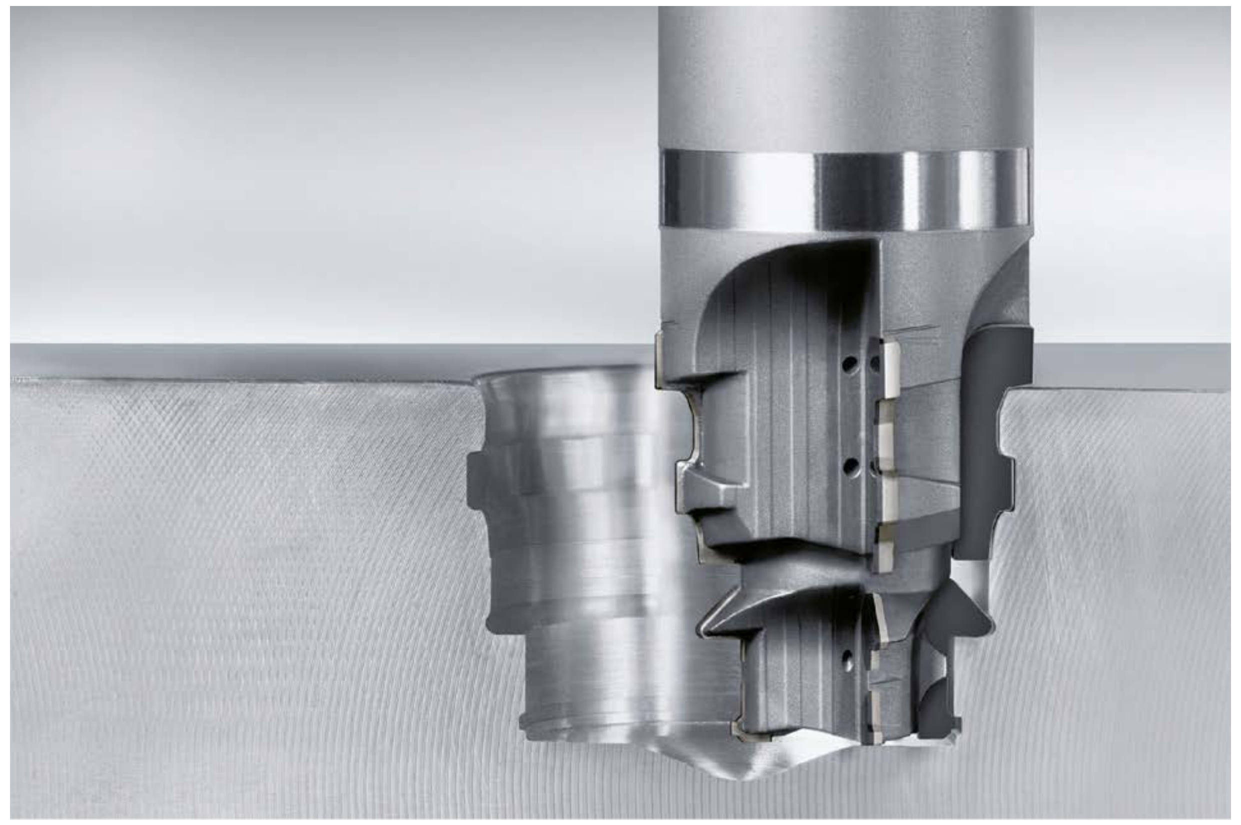
Program



Workholding

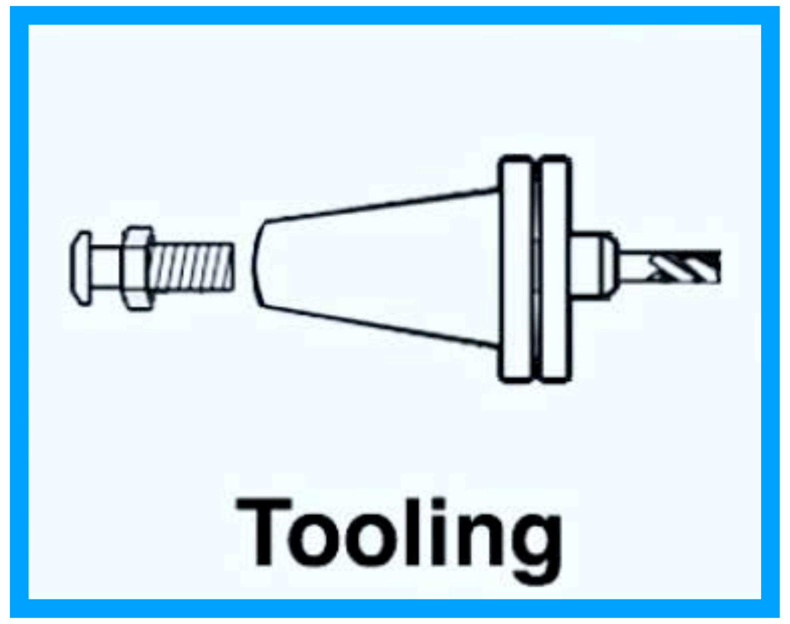
Dedicated Tools

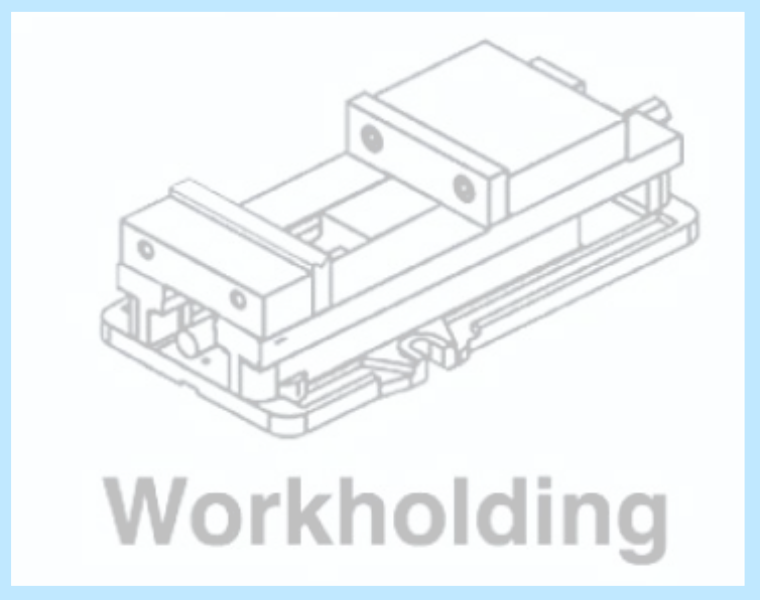




form tools: match the job you want to do

⬇flexibility, but ⬆rate





Tool Materials

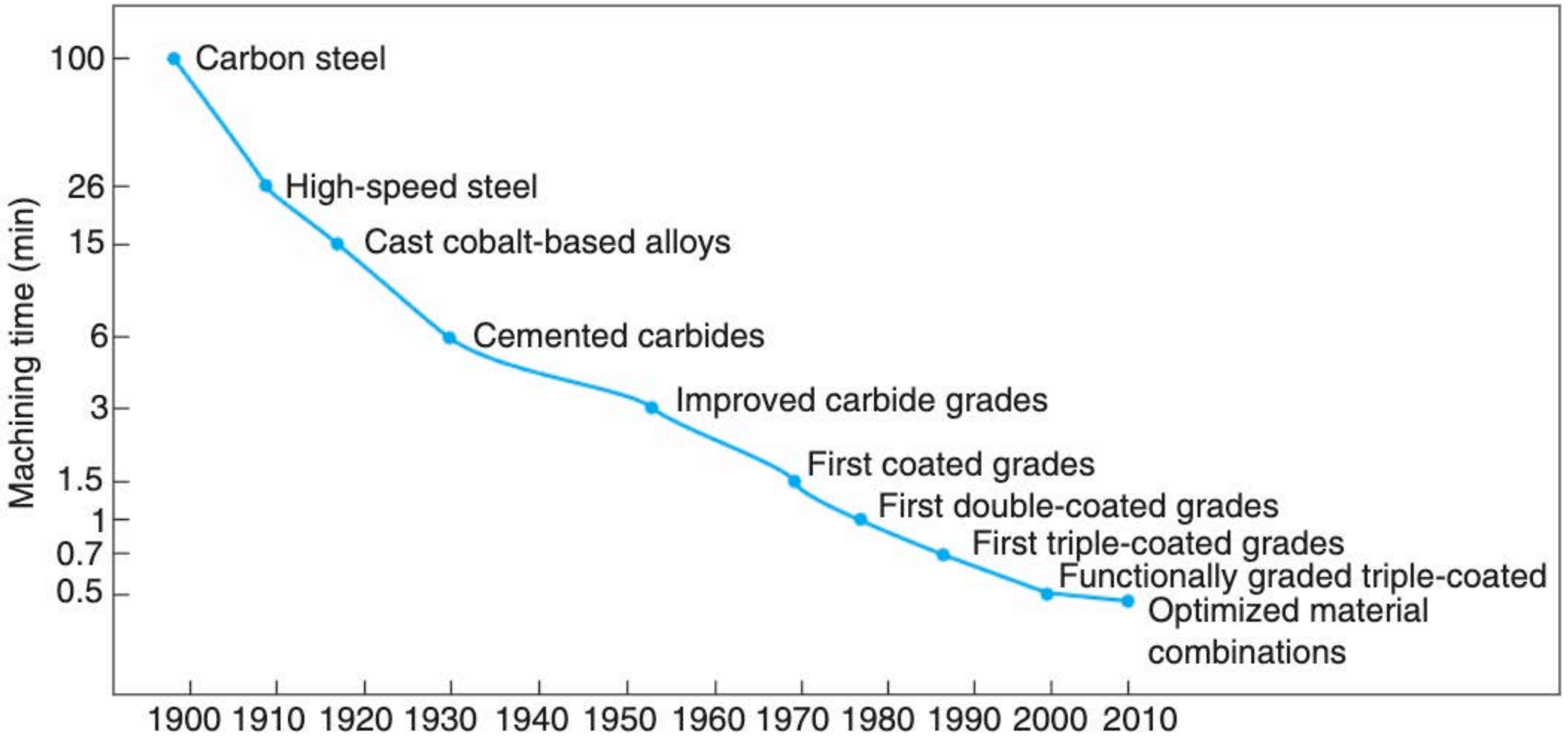
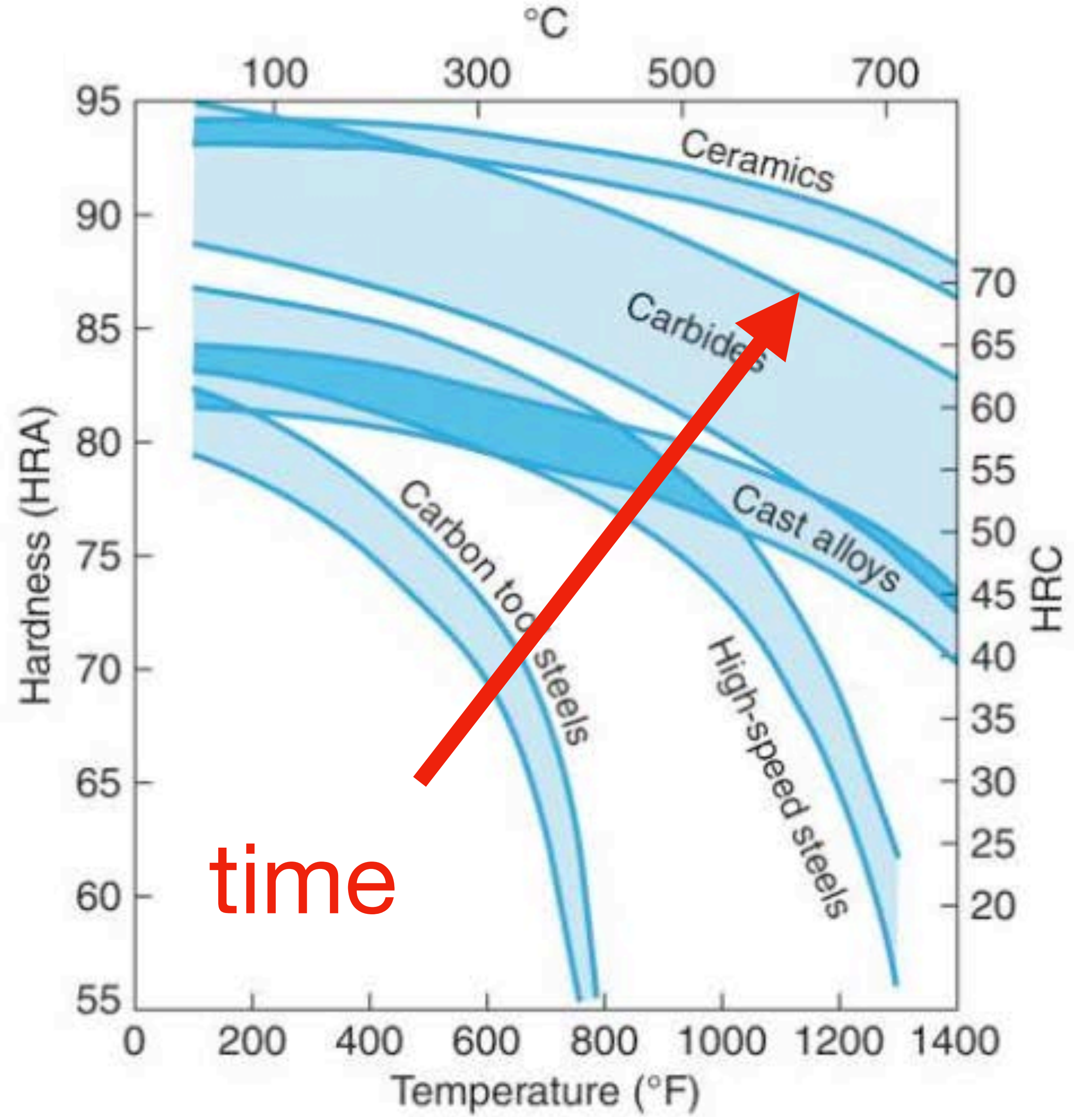


FIGURE 22.6 Relative time required to machine with various cutting-tool materials, indicating the year the tool materials were first introduced; note that machining time has been reduced by two orders of magnitude within a 100 years. *Source:* Courtesy of Sandvik.



300 BC- First recorded use of diamond engraving tools, ~1700's- **Diamond** rock drills, Today- many applications, but not suitable for steels

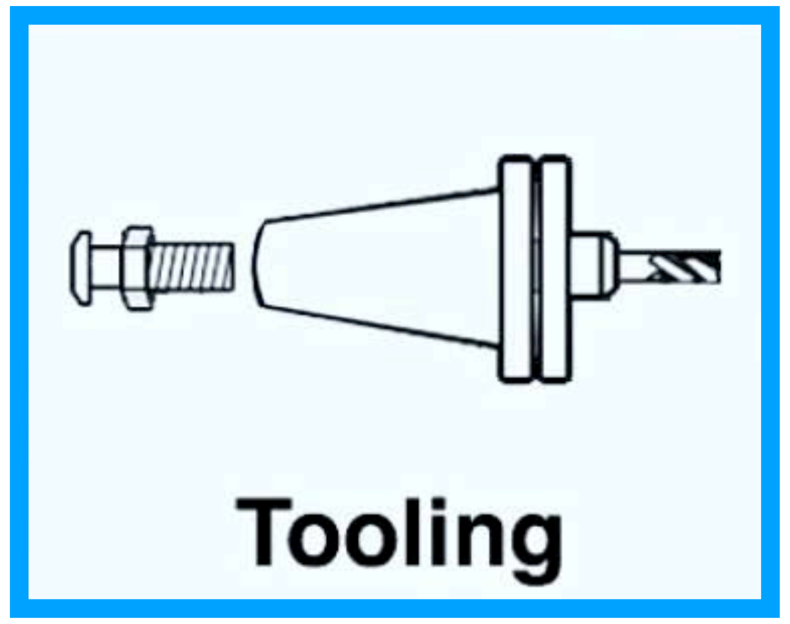
1868- 2% carbon, 2.5% manganese, and 7% tungsten **"Mushet" steel,** lose hardness at 200 degrees C

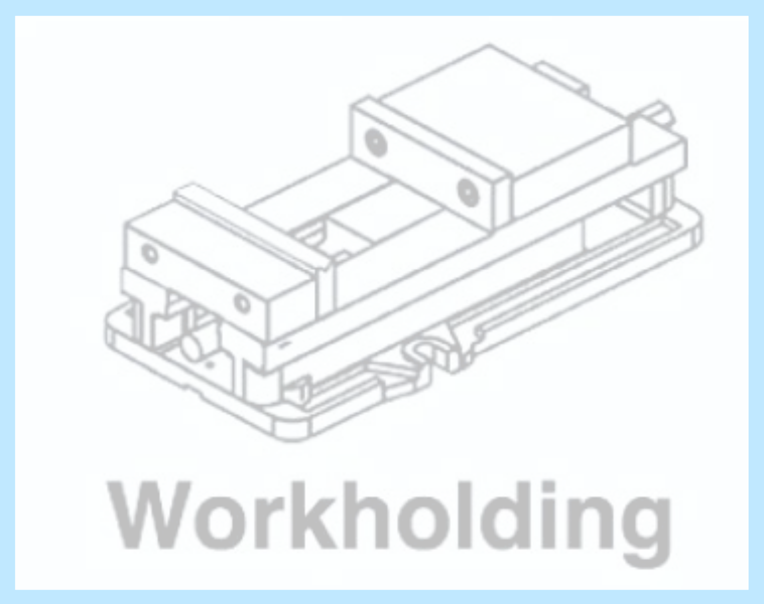
1899- Scientific empiricism results in 0.65-0.80% carbon, 0.1-0.4% manganese, 18% tungsten, 4% chromium, 1% vanadium, 0.2-0.4% silicon, **early "High Speed Steel"**, lose hardness at 600 degrees C, machine tools get redesigned

1920- Fine particles of carbide cemented in cobalt, tungsten, titanium or tantalum binders. **"Cemented carbide",** lose hardness at 900 C

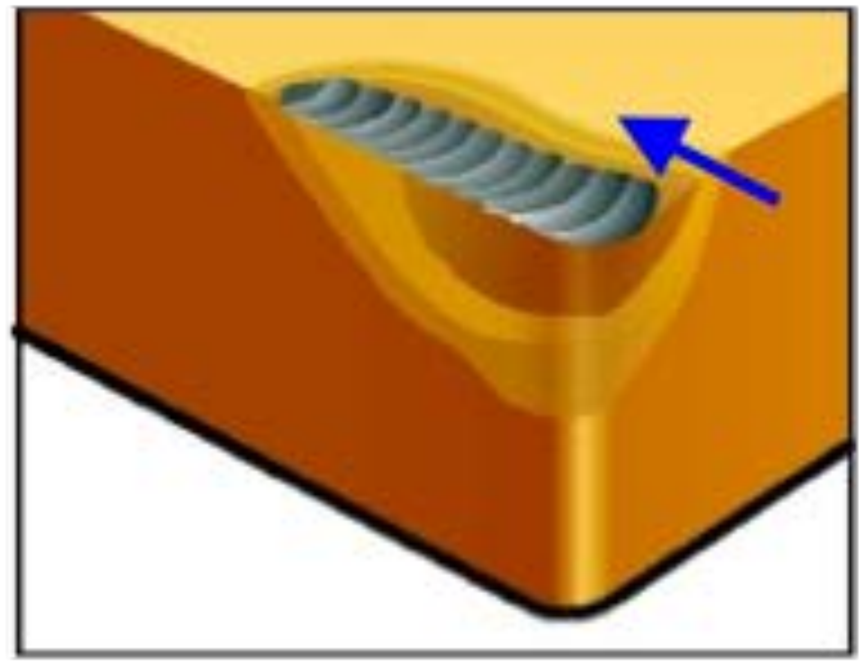
1957- Cubic Boron Nitride (cBN), withstands temperatures greater than 2000 C, used for machining ferrous metals,

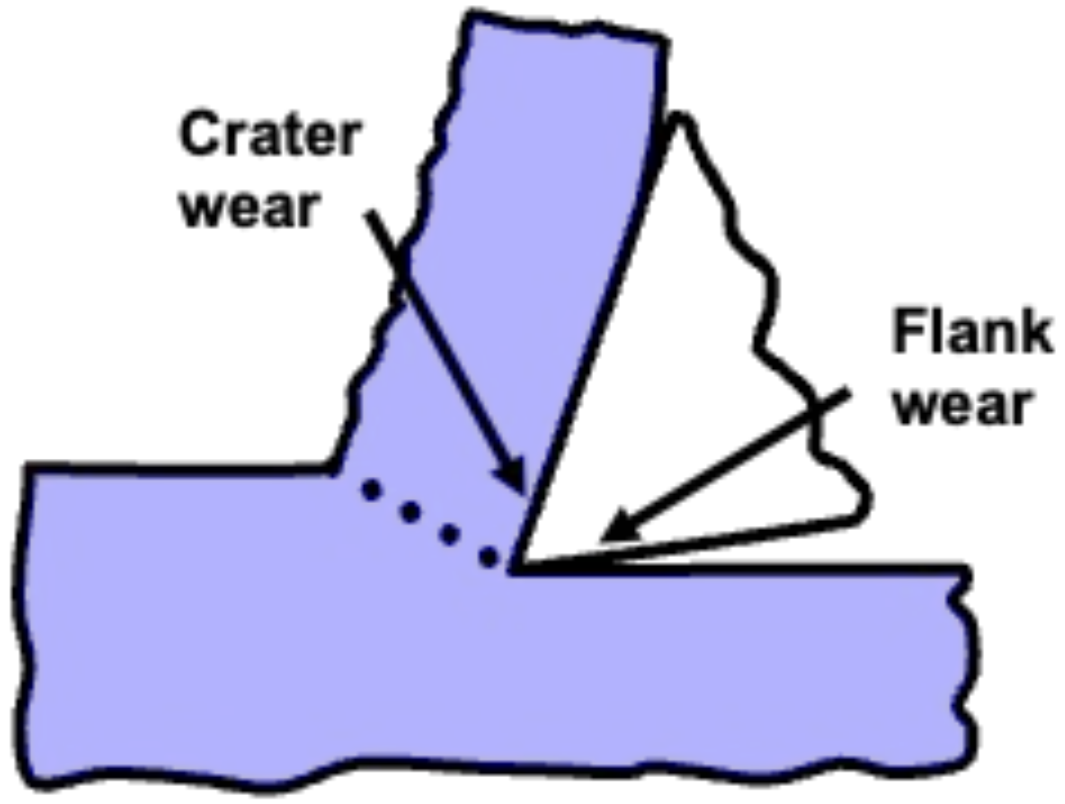
2011- 2 to 20% aluminum, 1 to 12% oxygen, 2 to 12% total of one or more rare earth elements, a balance of silicon and nitrogen. **"Ceramic"** end mill operate above 800 C, where Ni-based alloys soften.

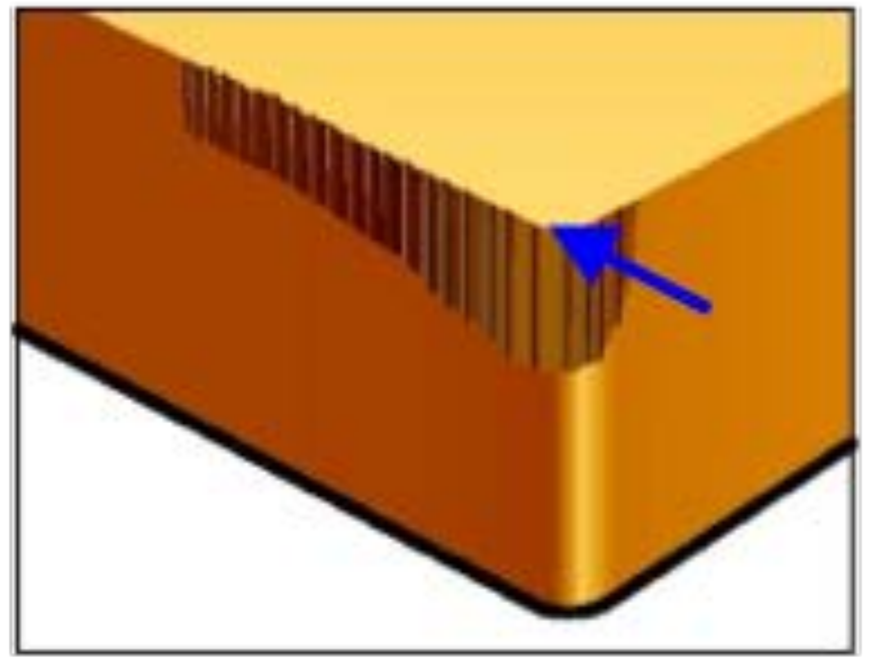


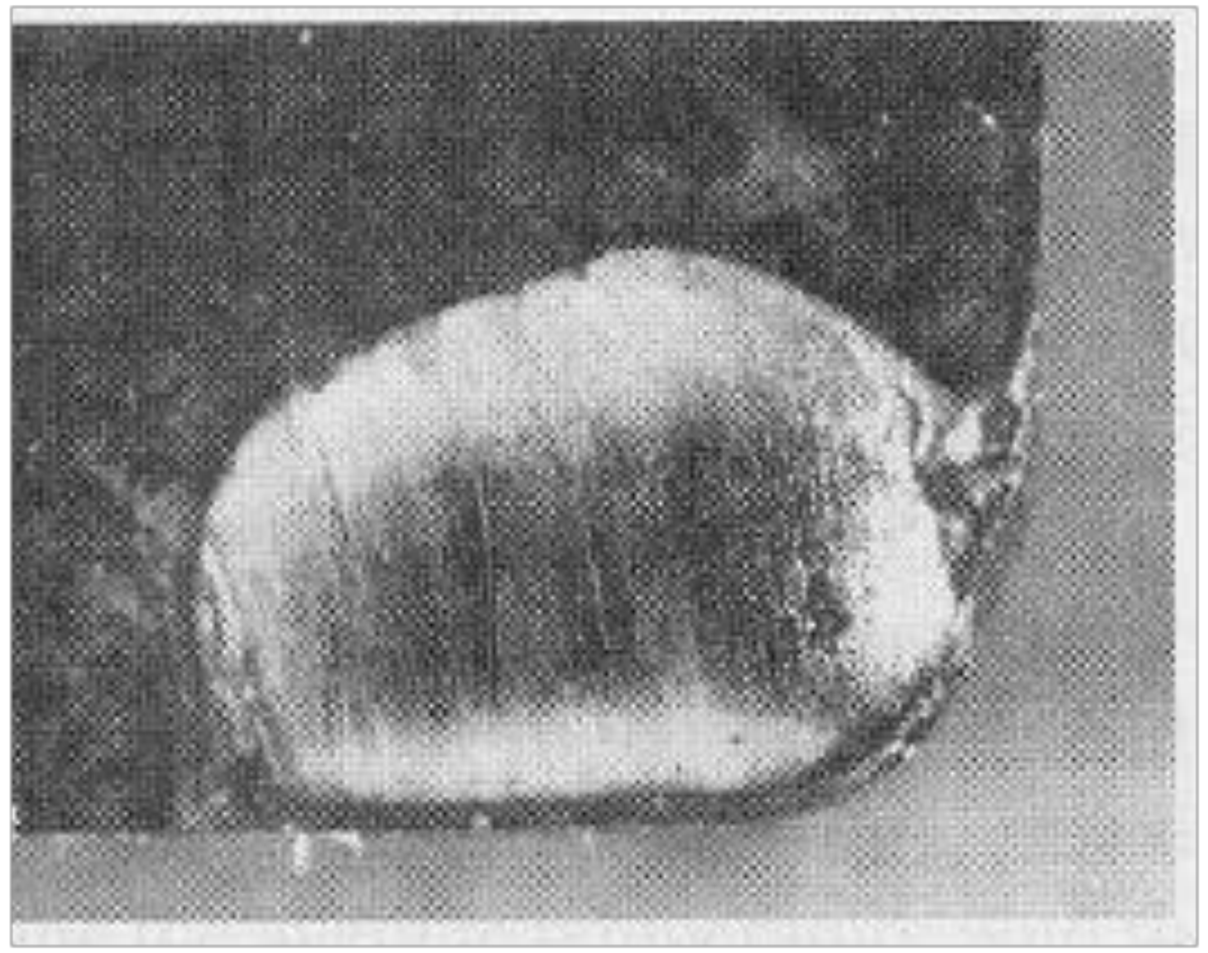


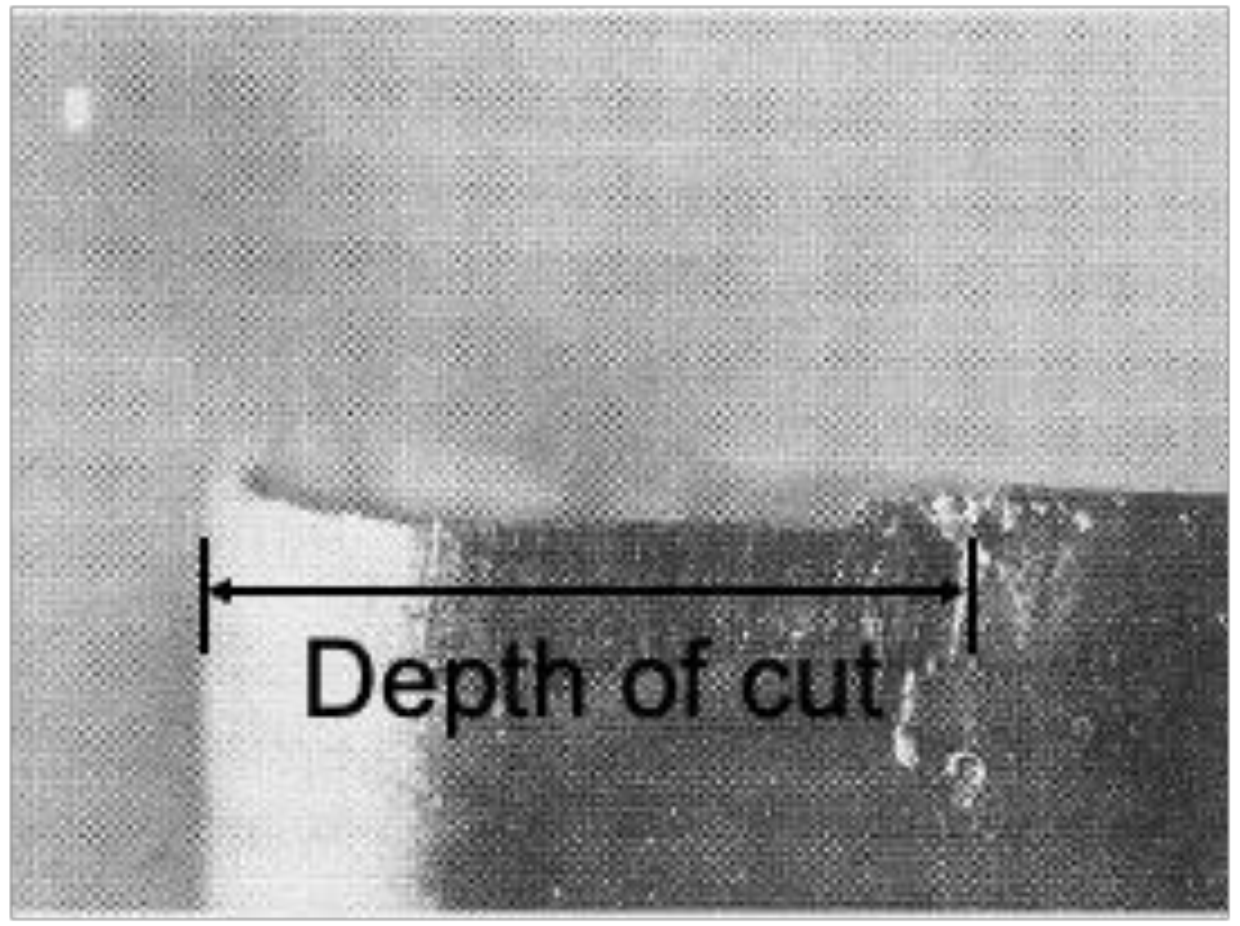
Tool Wear



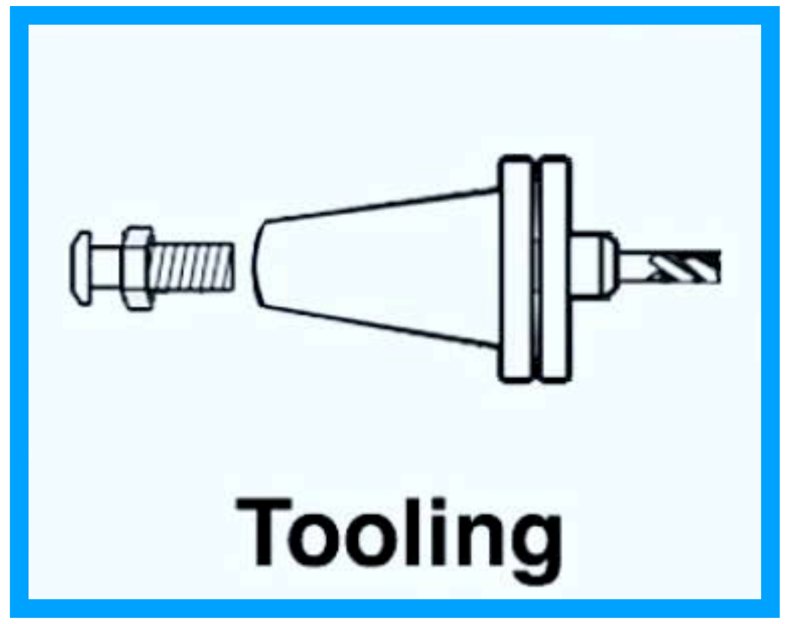


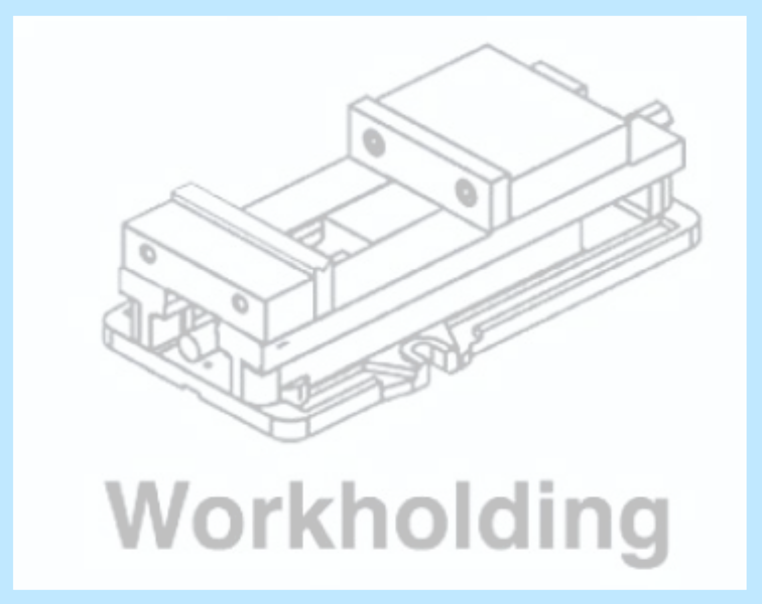




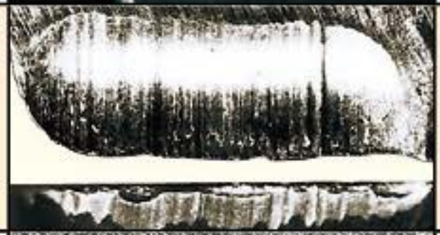
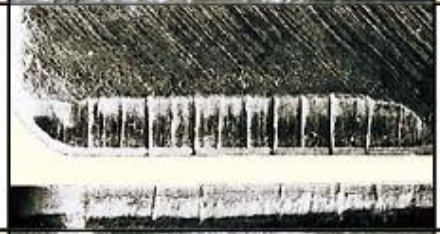


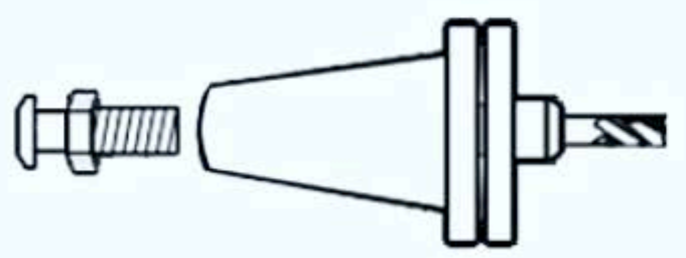
Images from Figure 23.2 Fundamentals of Modern Manufacturing (4th Edition) by Groover. (c) Wiley (2010).
Wear schematics from: http://www.sandvik.coromant.com/en-us/knowledge/milling/troubleshooting/tool_wear

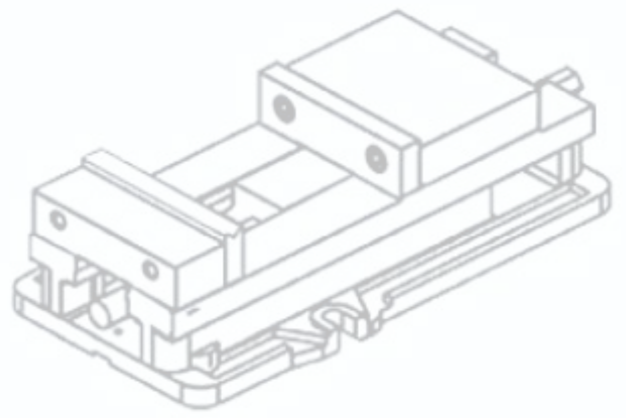




Tool Wear

Tool Damage Form		Cause	Countermeasure
Flank Wear		• Tool grade is too soft. • Cutting speed is too high. • Flank angle is too small. • Feed rate is extremely low.	• Tool grade with high wear resistance. • Lower cutting speed. • Increase flank angle. • Increase feed rate.
Crater Wear		• Tool grade is too soft. • Cutting speed is too high. • Feed rate is too high.	• Tool grade with high wear resistance. • Lower cutting speed. • Lower feed rate.
Chipping		• Tool grade is too hard. • Feed rate is too high. • Lack of cutting edge strength. • Lack of shank or holder rigidity.	• Tool grade with high toughness. • Lower feed rate. • Increase honing. (Round honing is to be changed to chamfer honing.) • Use large shank size.
Fracture		• Tool grade is too hard. • Feed rate is too high. • Lack of cutting edge strength. • Lack of shank or holder rigidity.	• Tool grade with high toughness. • Lower feed rate. • Increase honing. (Round honing is to be changed to chamfer honing.) • Use large shank size.
Plastic Deformation		• Tool grade is too soft. • Cutting speed is too high. • Depth of cut and feed rate are too large. • Cutting temperature is high.	• Tool grade with high wear resistance. • Lower cutting speed. • Decrease depth of cut and feed rate. • Tool grade with high thermal conductivity.
Welding		• Cutting speed is low. • Poor sharpness. • Unsuitable grade.	• Increase cutting speed. (For JIS S45C, cutting speed 80m/min.) • Increase rake angle. • Tool grade with low affinity. (Coated grade, cermet grade)
Thermal Cracks		• Expansion or shrinkage due to cutting heat. • Tool grade is too hard. *Especially in milling.	• Dry cutting. (For wet cutting, flood workpiece with cutting fluid) • Tool grade with high toughness.
Notching		• Hard surfaces such as uncut surfaces, chilled parts and machining hardened layer. • Friction caused by jagged shape chips. (Caused by small vibration)	• Tool grade with high wear resistance. • Increase rake angle to improve sharpness.
Flaking		• Cutting edge welding and adhesion. • Poor chip disposal.	• Increase rake angle to improve sharpness. • Enlarge chip pocket.



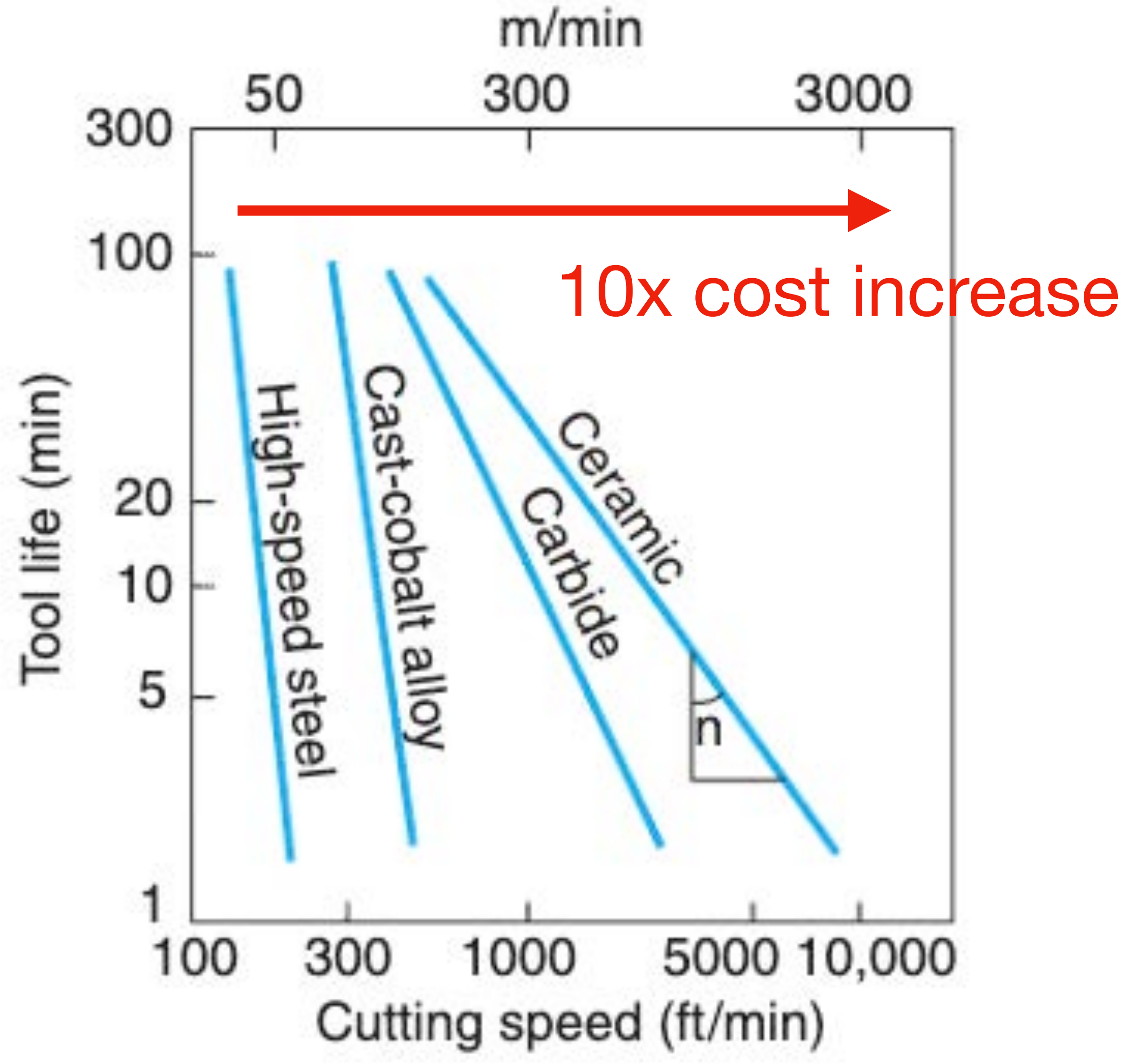


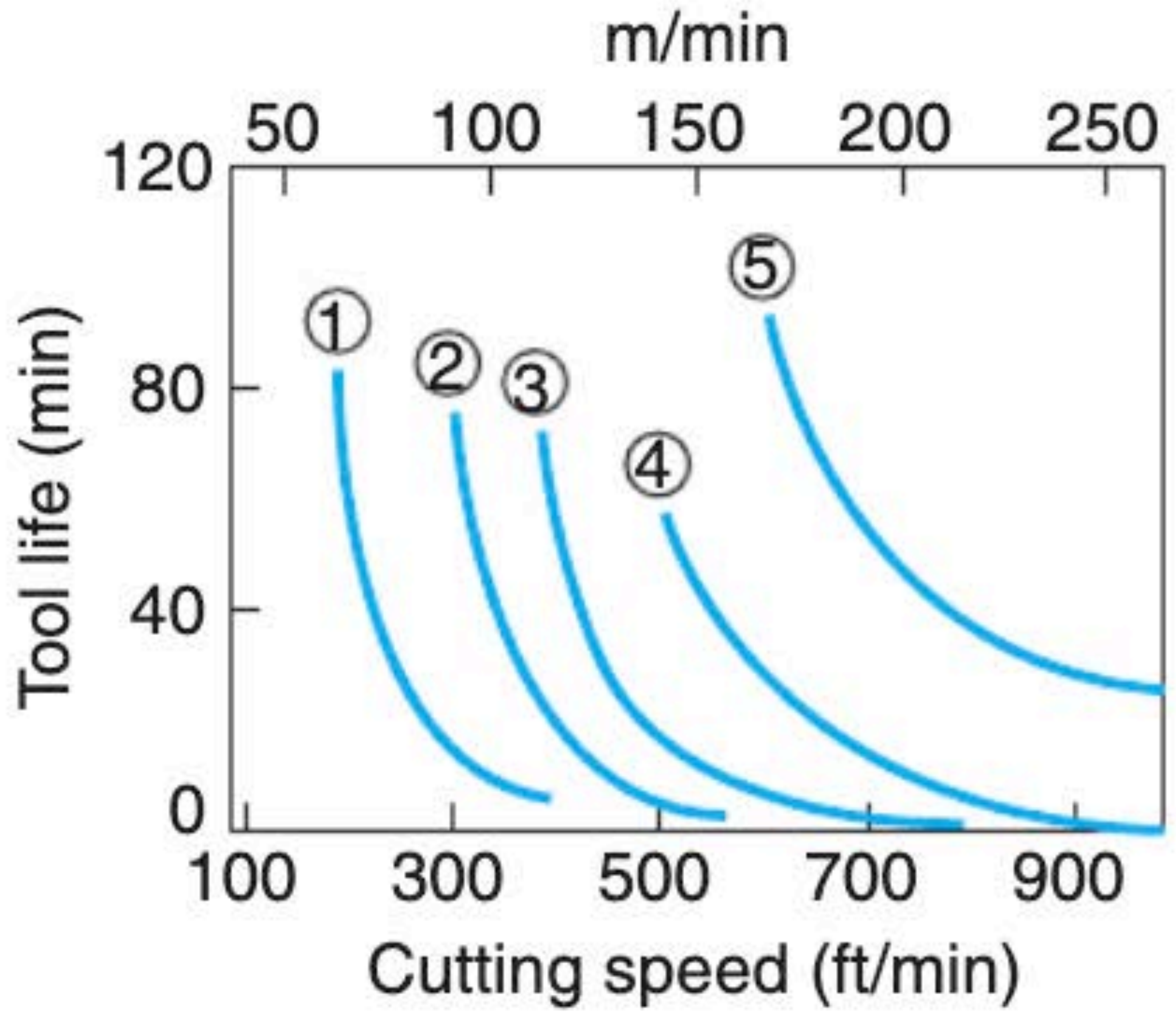
Taylor's Tool Life Equation

cutting velocity significantly affects rate of tool wear

$$v_{cut} \cdot t^n = C$$

Taylor tool life equation



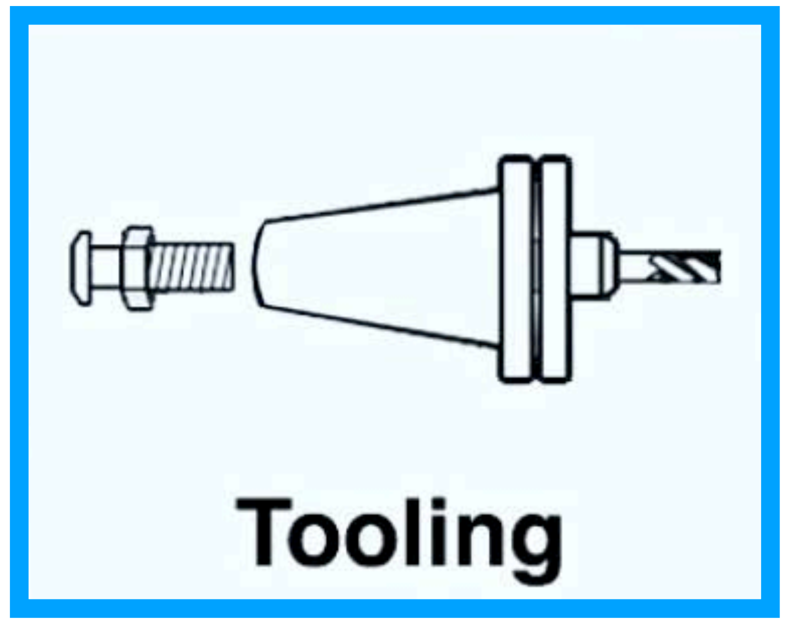


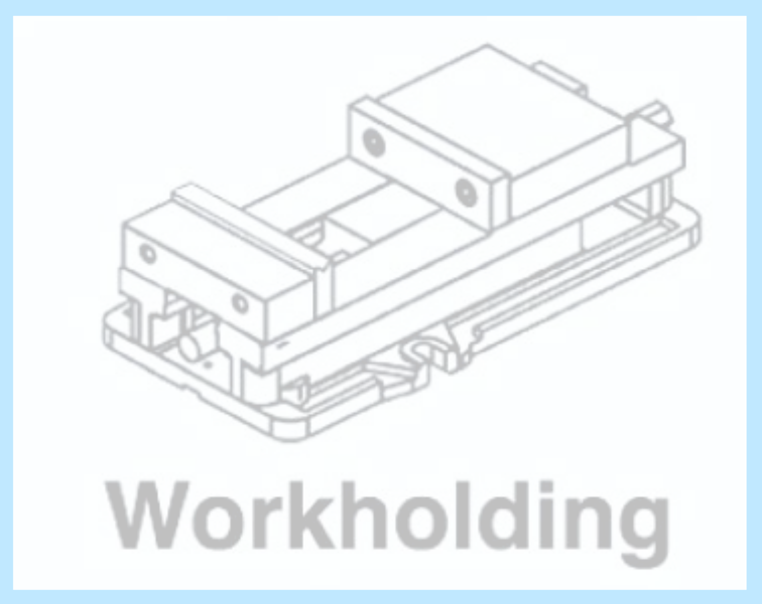
harder workpiece

	Hardness (HB)	Ferrite	Pearlite
① As cast	265	20%	80%
② As cast	215	40	60
③ As cast	207	60	40
④ Annealed	183	97	3
⑤ Annealed	170	100	—

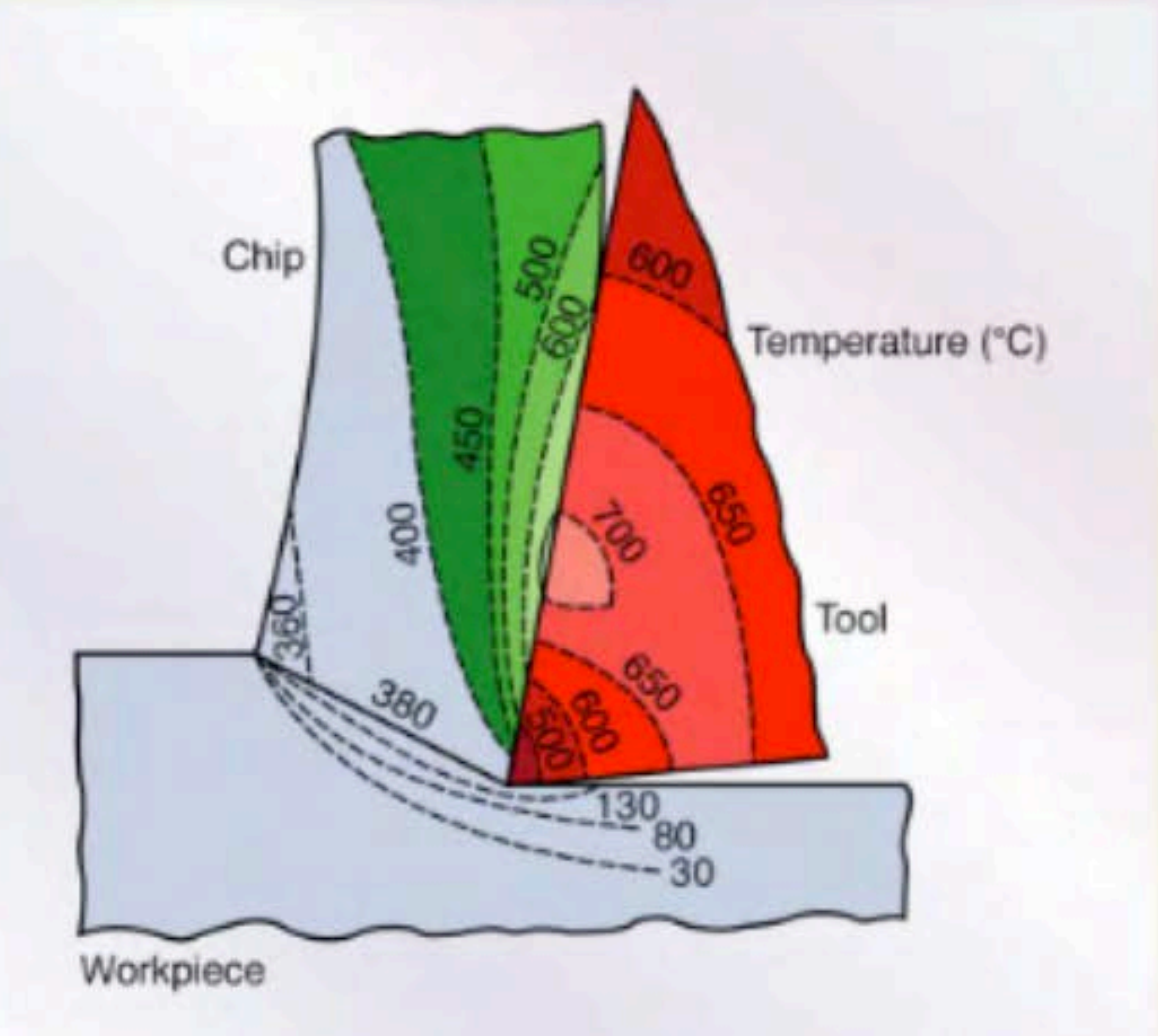
softer workpiece

C: empirical constant
(cutting speed at t = 1min)
n: empirical constant
t: tool life (time to failure)
v_{cut}: cutting velocity





Tool Materials

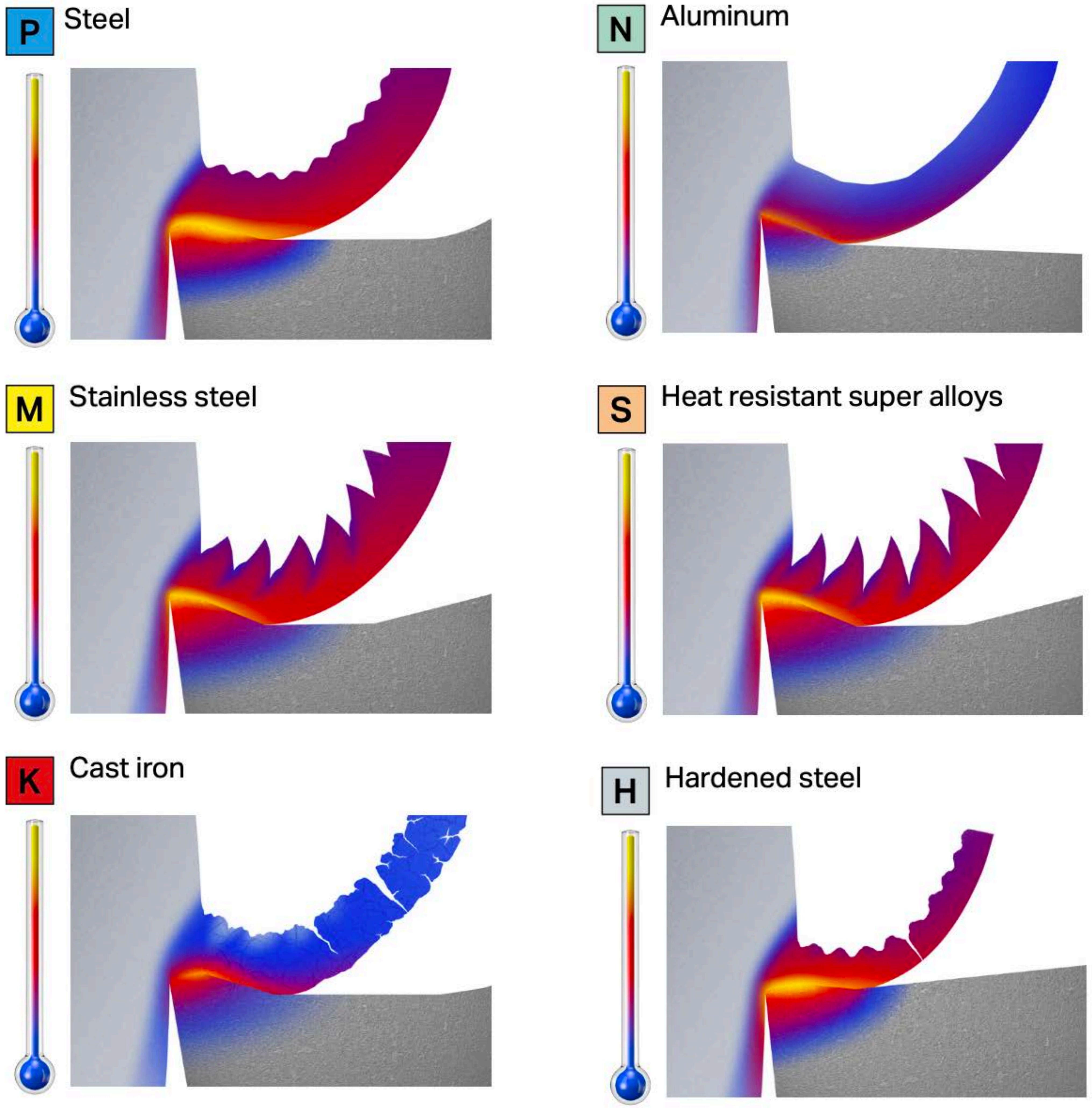


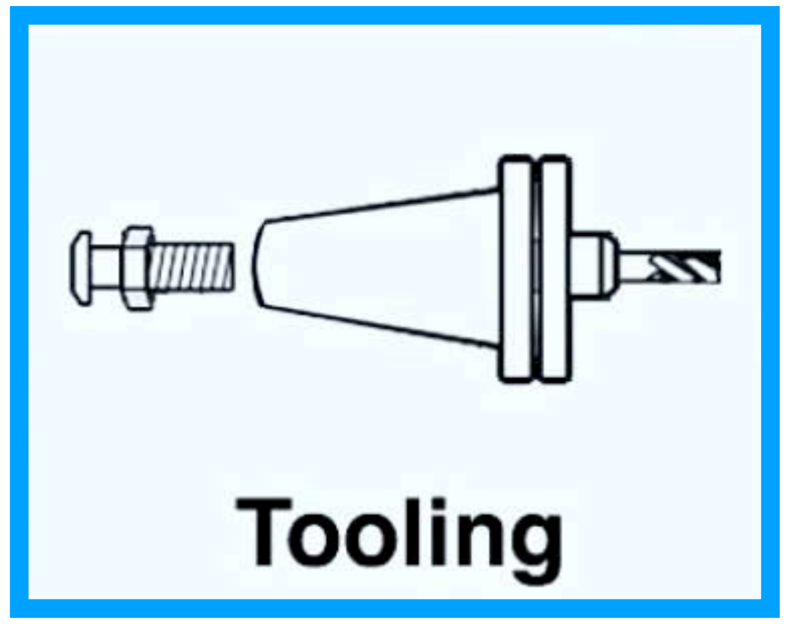
temperature: sensitive to cutting speed

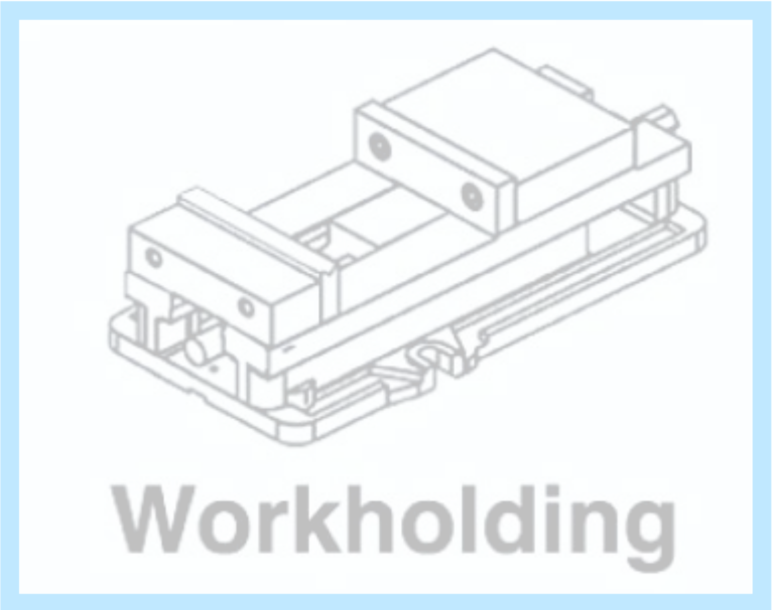
heat is generated rapidly and cannot dissipate

- work done in shearing
- friction: tool + chip and tool + workpiece rubbing

get info from tool manufacturers







Tool Coatings

- increase wear resistance
- increase oxidation resistance
- reduce friction
- increase resistance to metal fatigue
- increase resistance to thermal shock

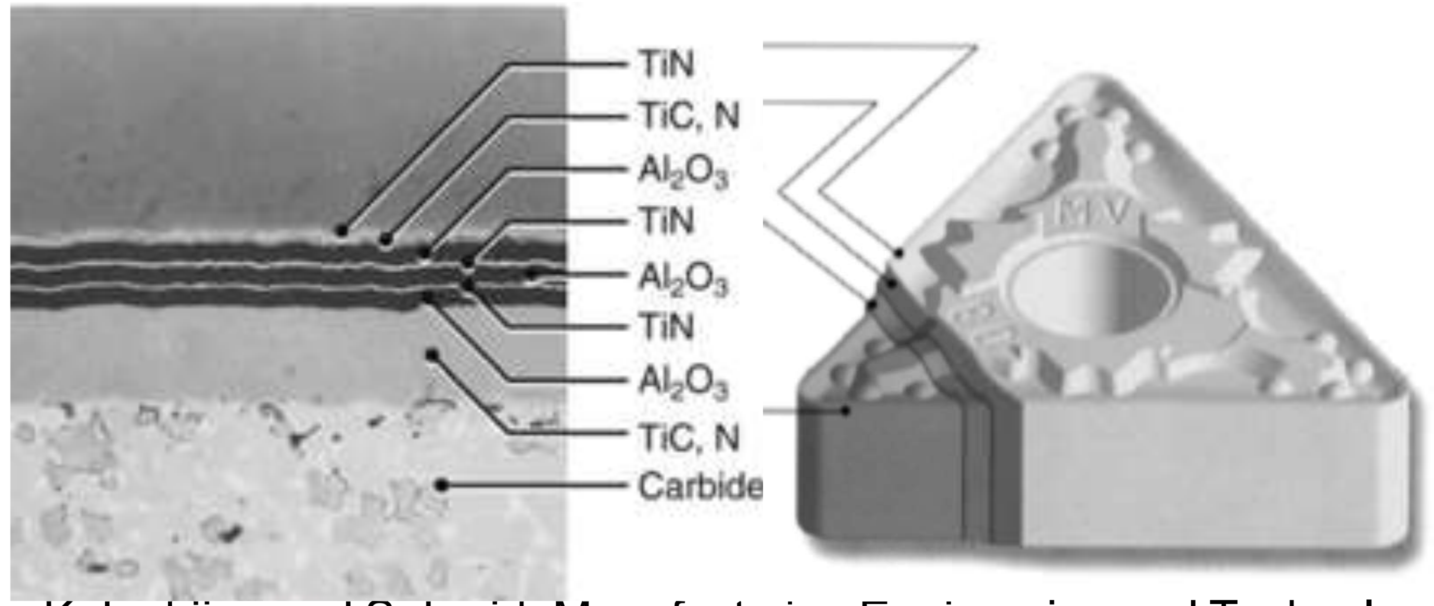
Layers: 2-20 µm thick

TiN: low friction

TiCN: wear resistance

Al_2O_3: high thermal stability

Carbide: hardness and fracture toughness

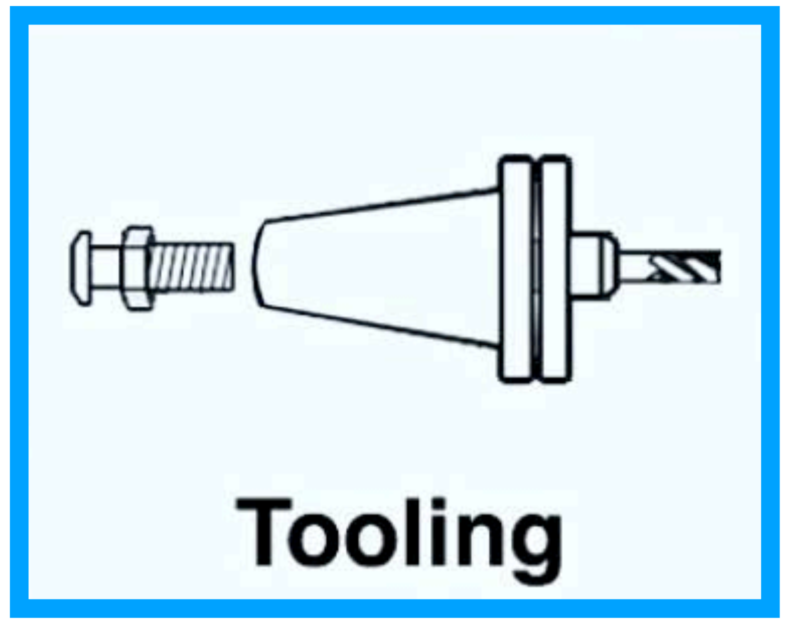


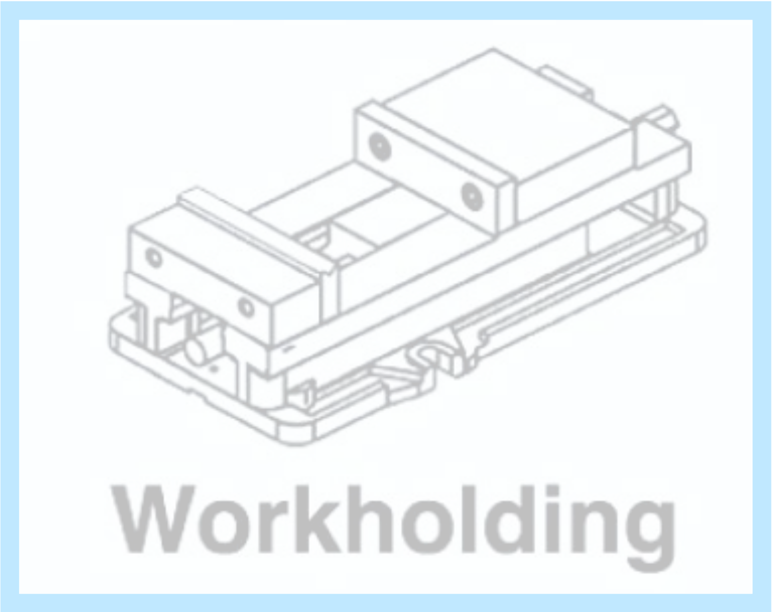
Kalpakjian and Schmid, Manufacturing Engineering and Technology.

from DeGarmo's Materials & Processes in Manufacturing (10th Edition) by Black and Kohser, © Wiley (2008).

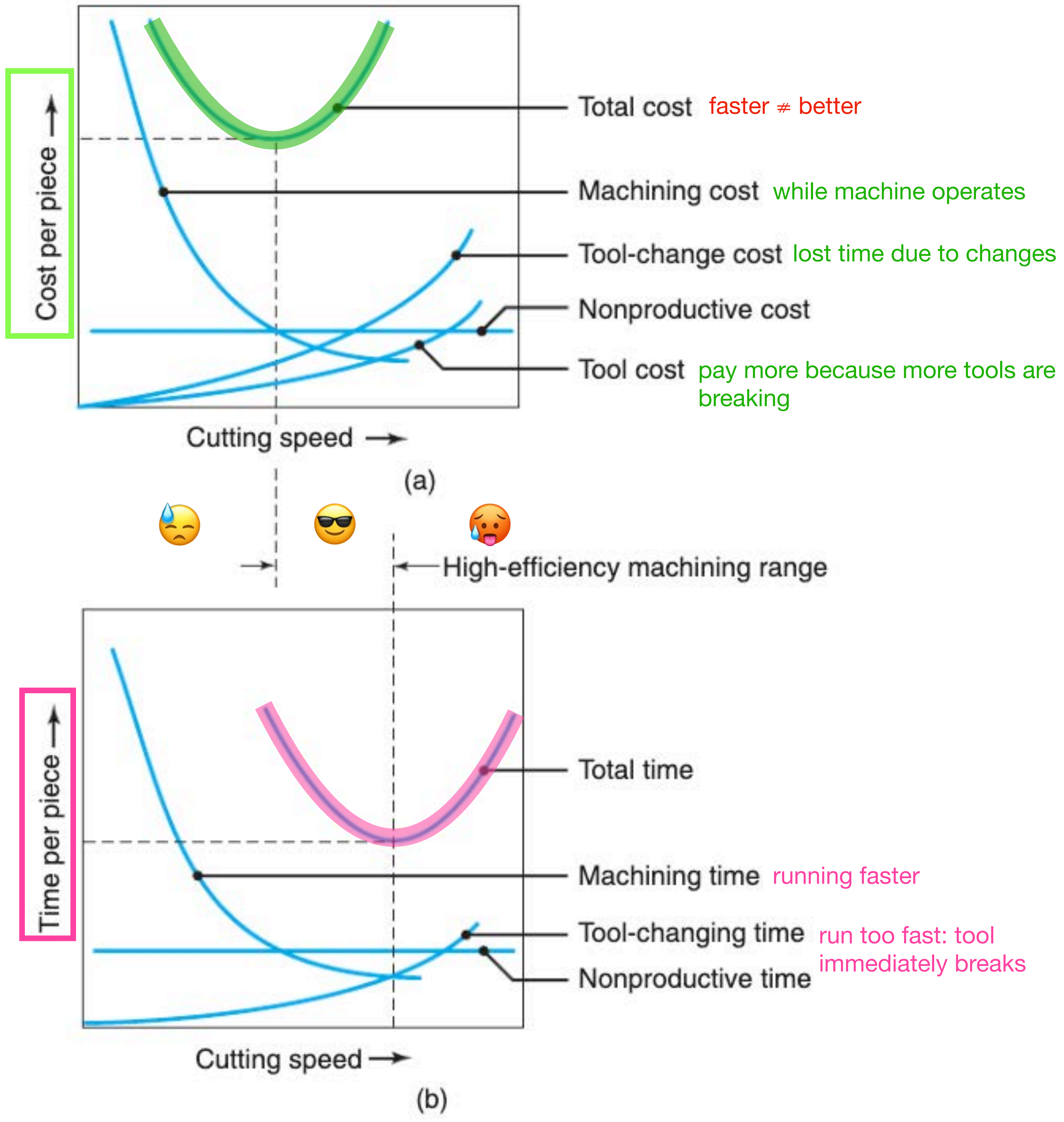
Examples:

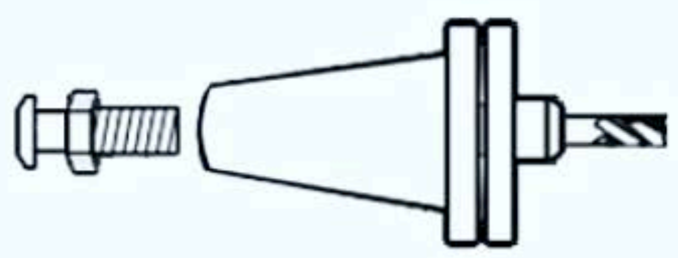
- TiN (a basic yellowish coating that has fallen out of wide use)
- TiCN (a popular bluish-grey coating)
- TiAlN and AlTiN (an extremely popular dark purple coating)
- TiAlCrN, AlTiCrN and AlCrTiN (PVD coating)
- PCD: polycrystalline diamond





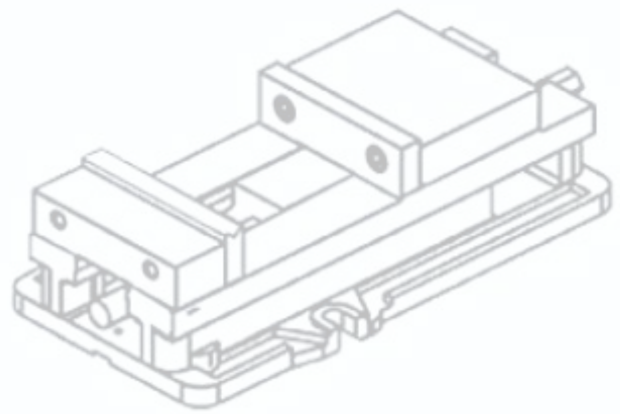
Machining Cost





Tooling

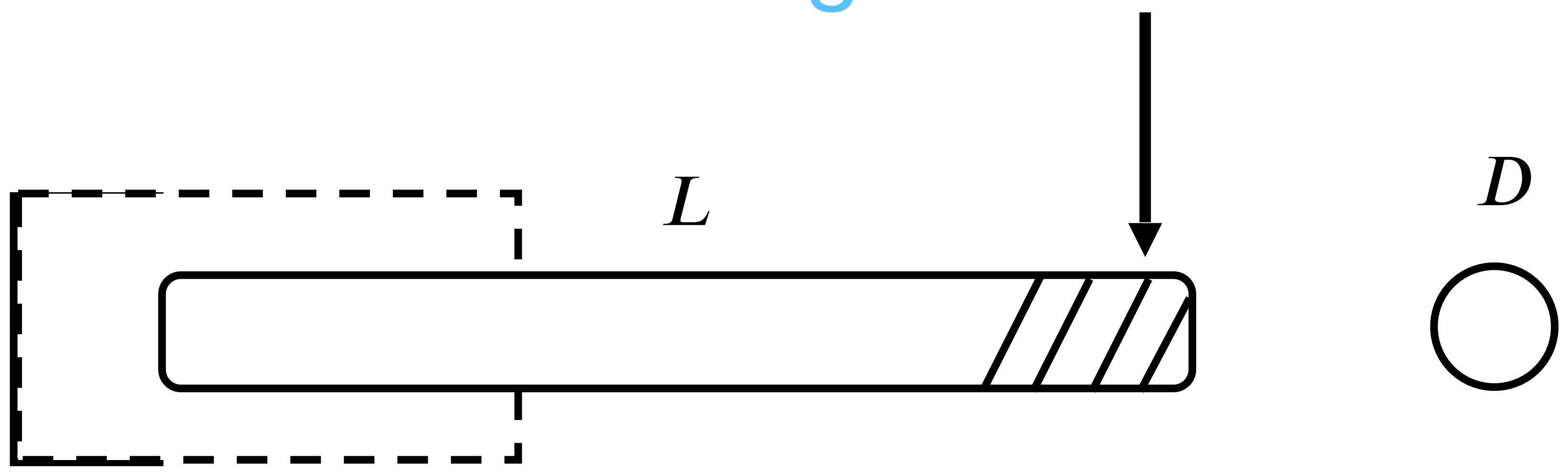
Program

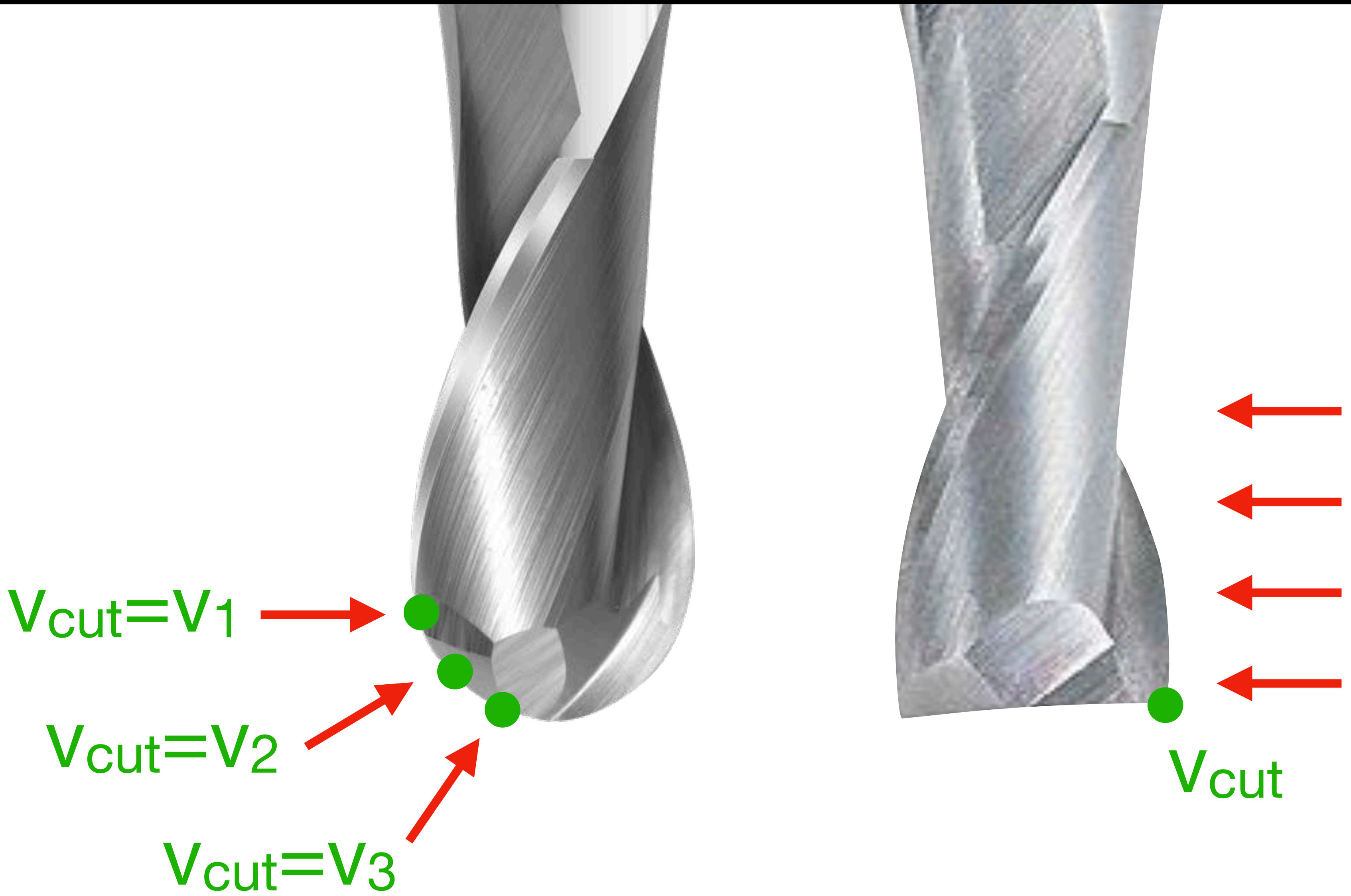


Workholding

Tool Stiffness

beam bending!





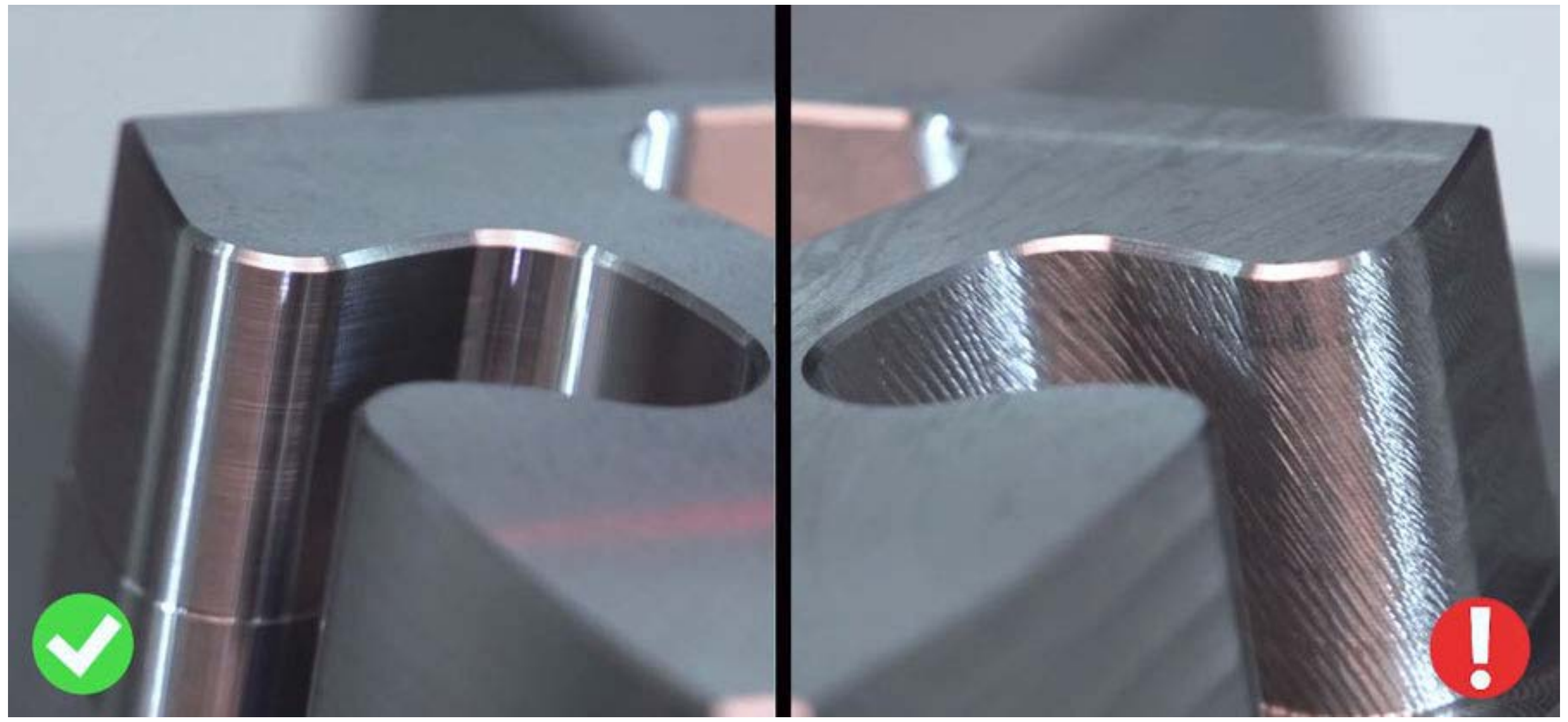
beam bending:

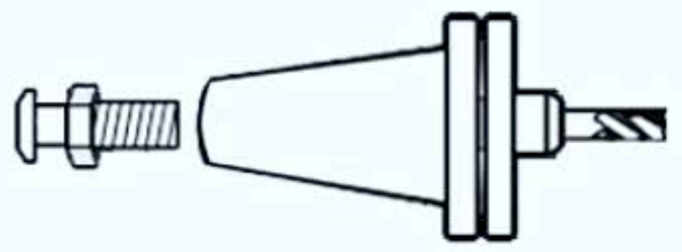
$$\delta = \frac{FL^3}{3EI} \qquad F = \frac{3\delta EI}{L^3}$$

$$k = \frac{\partial F}{\partial \delta} = \frac{3\pi}{64}\boxed{\frac{D^4}{L^3}}E$$

δ: amount of deflection
F: force
L: length
E: elastic modulus of the tool material
I: area moment of inertia
k: stiffness

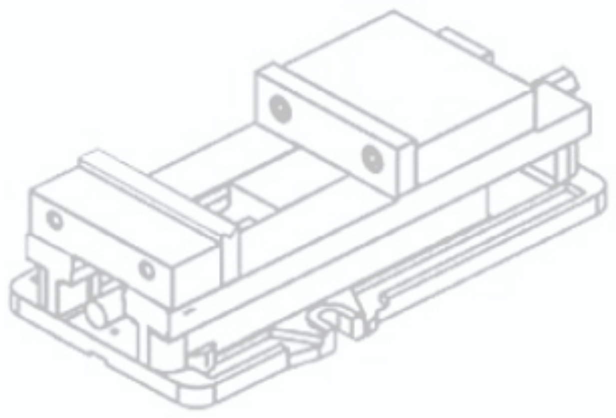
chatter:





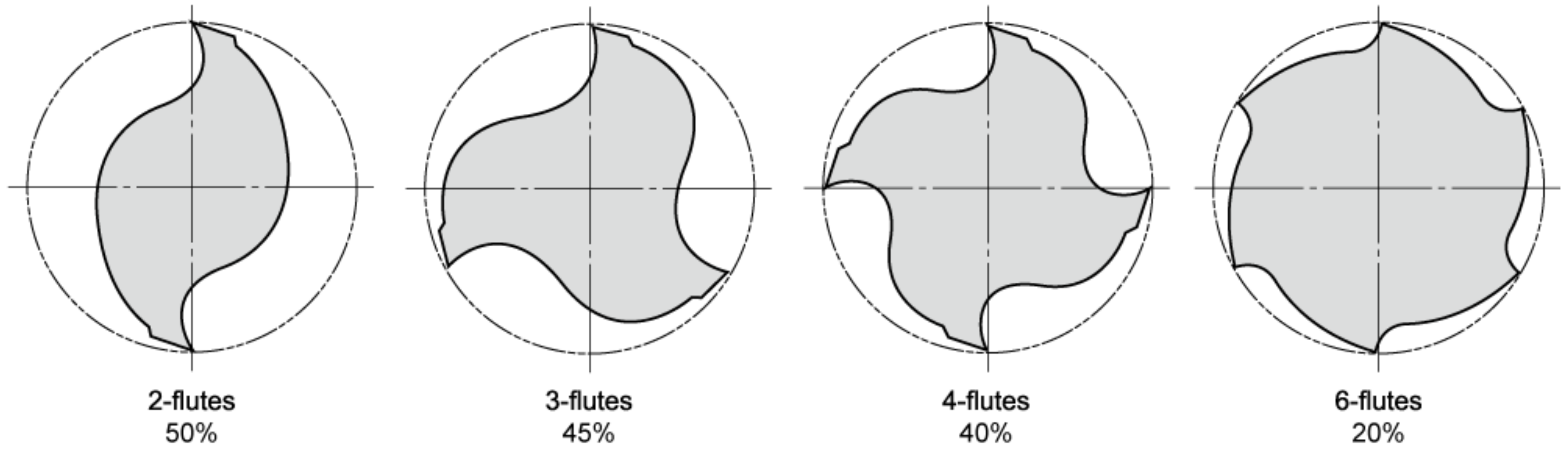
Tooling

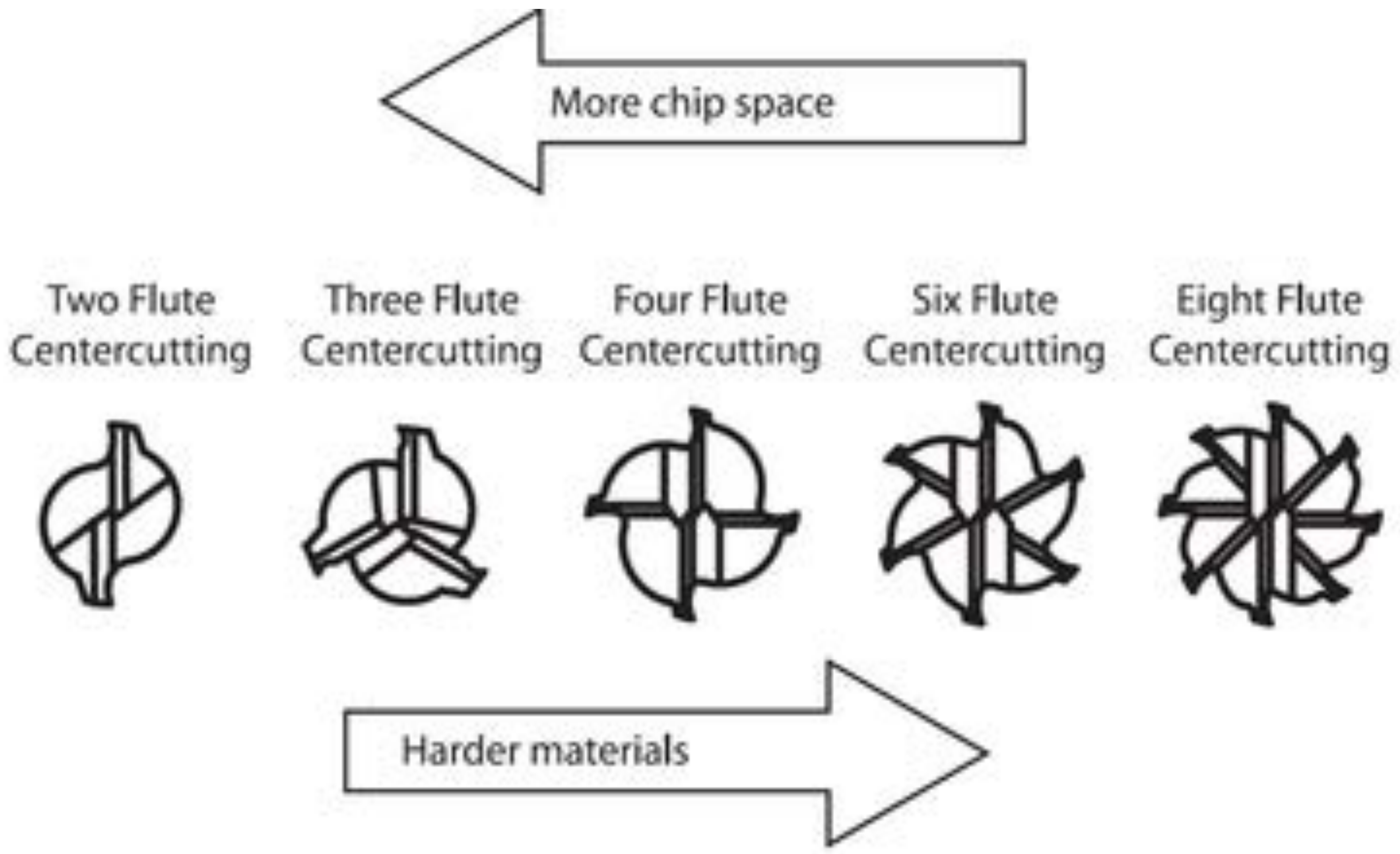
Program

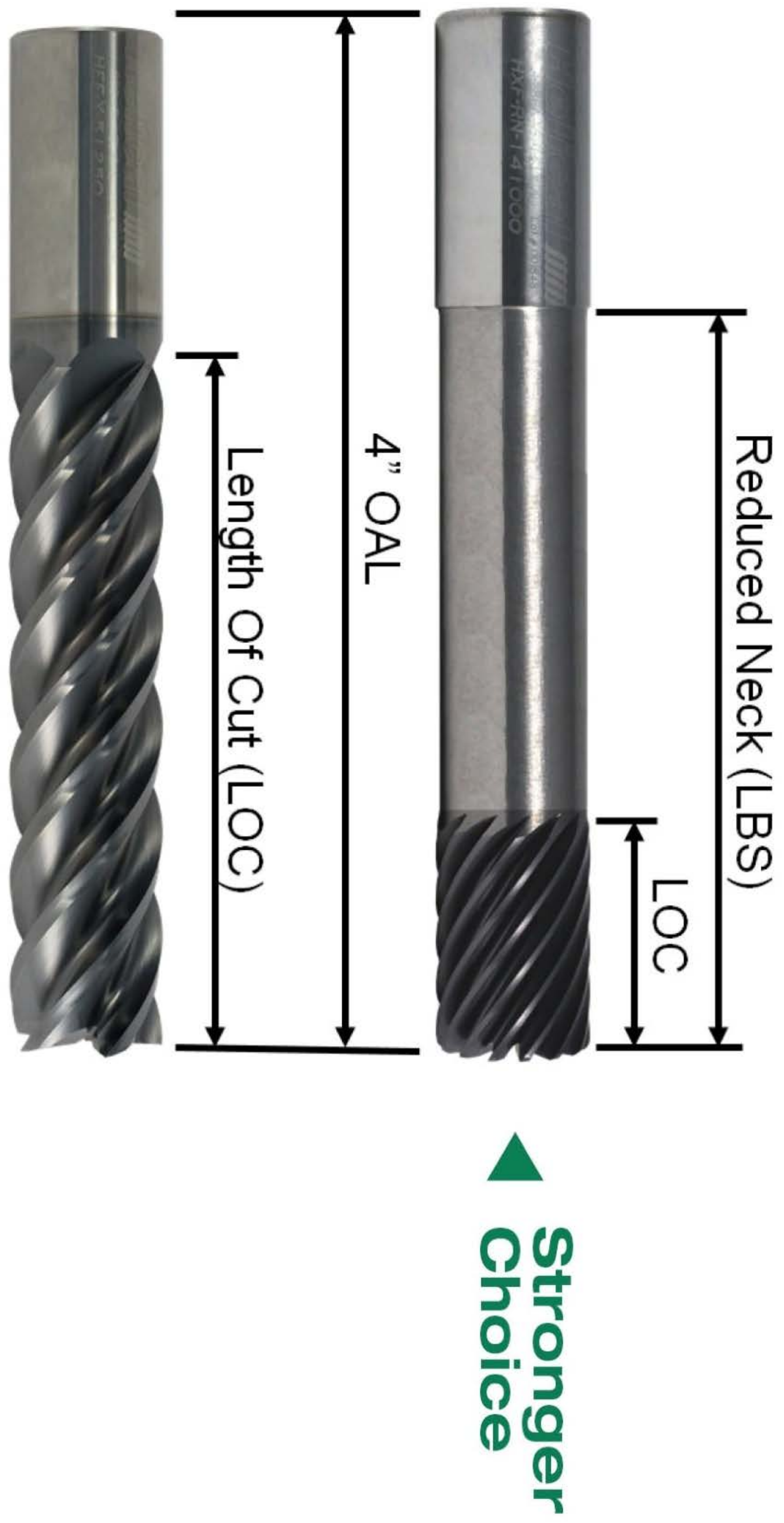


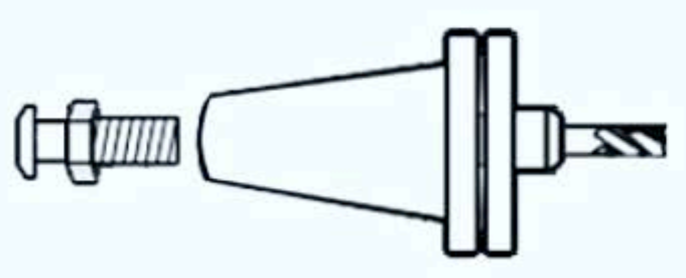
Workholding

Tool Stiffness



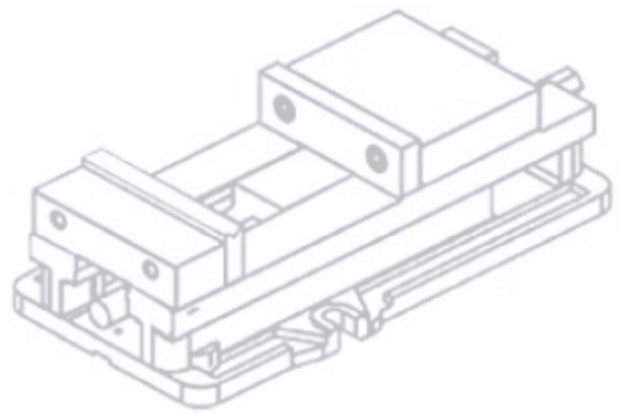






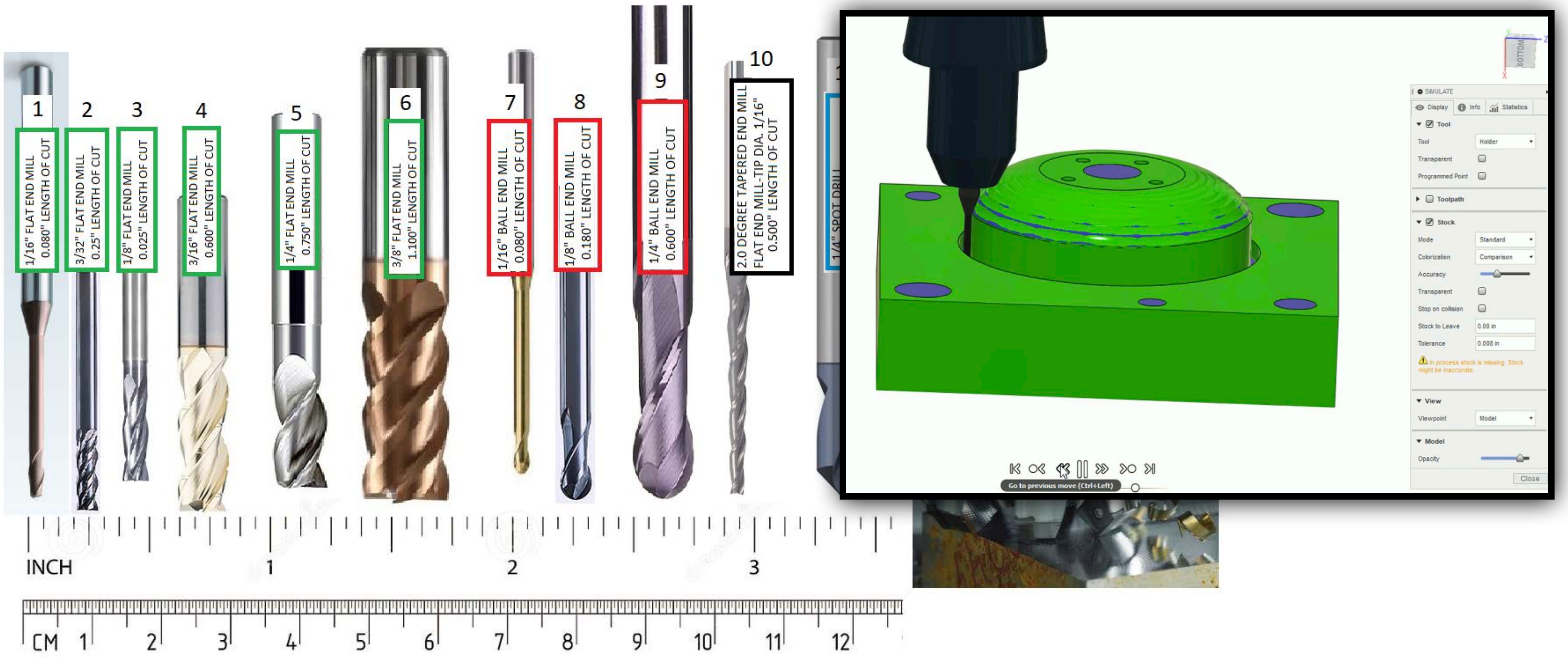
Tooling

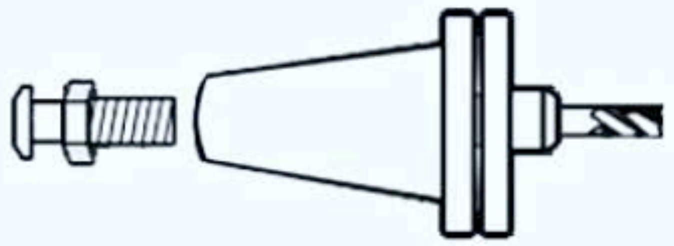
Program



Workholding

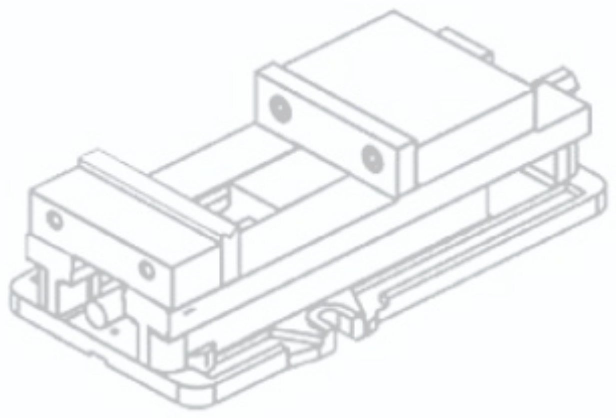
Design for Manufacturing: Machining





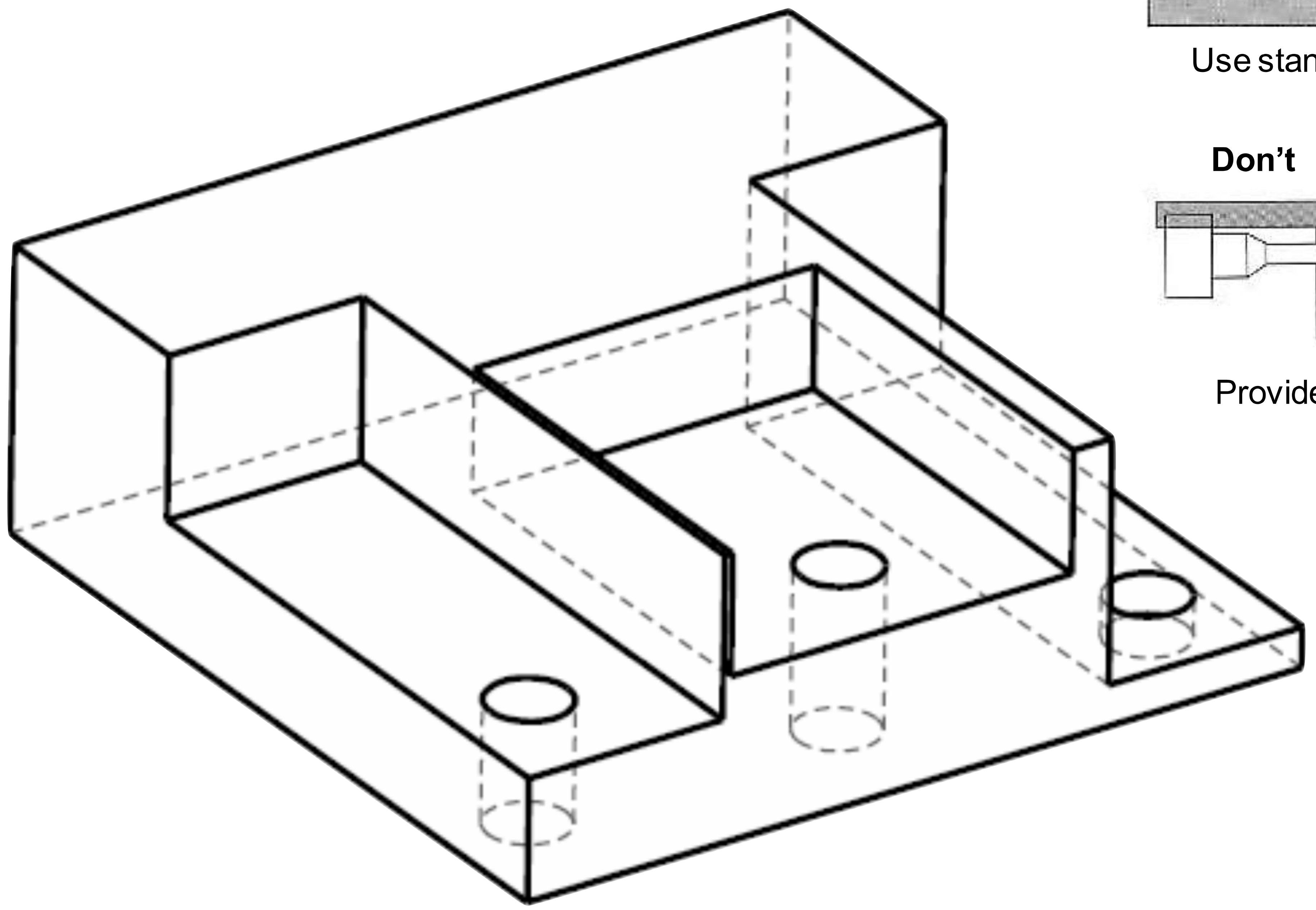
Tooling

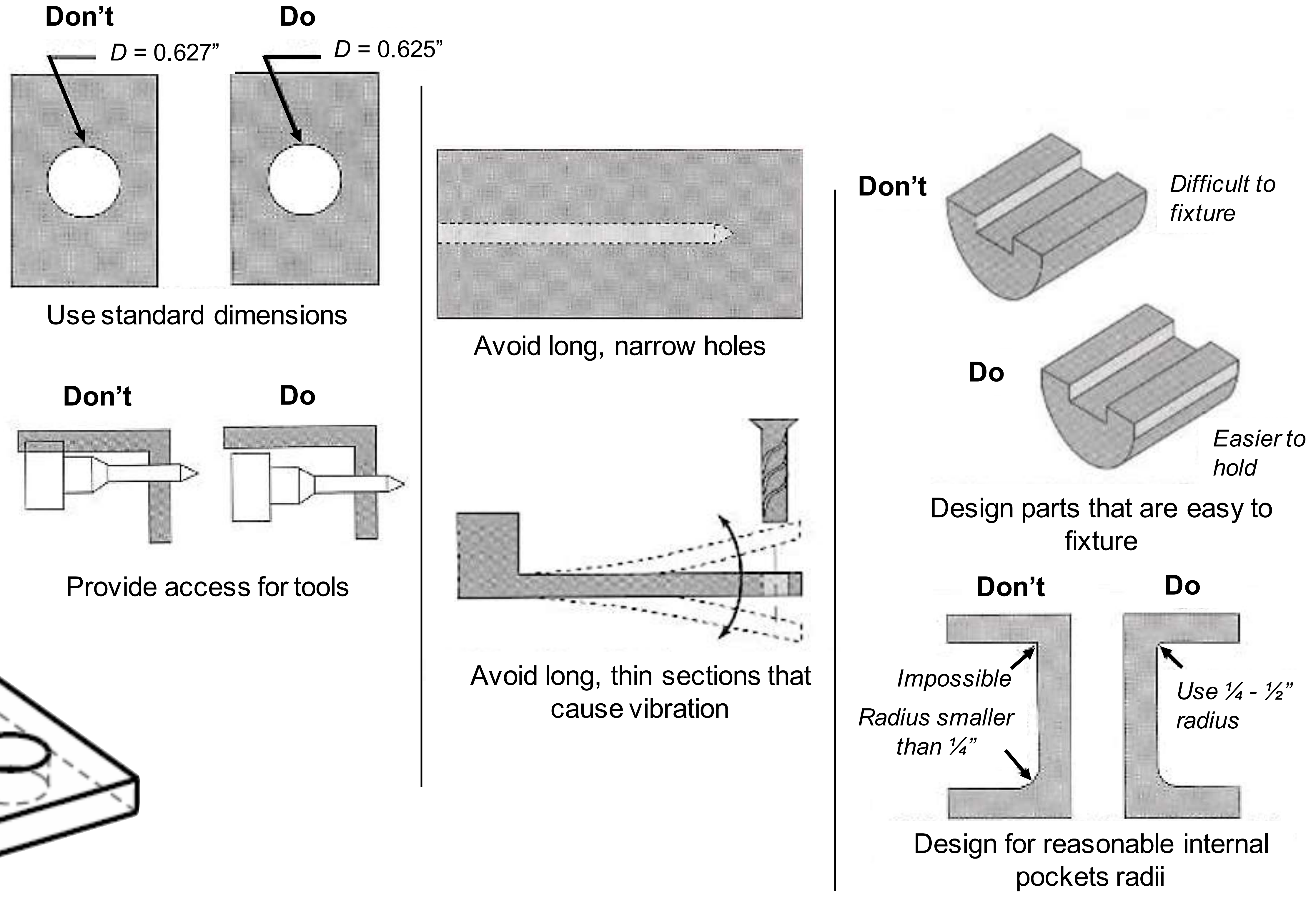
Program



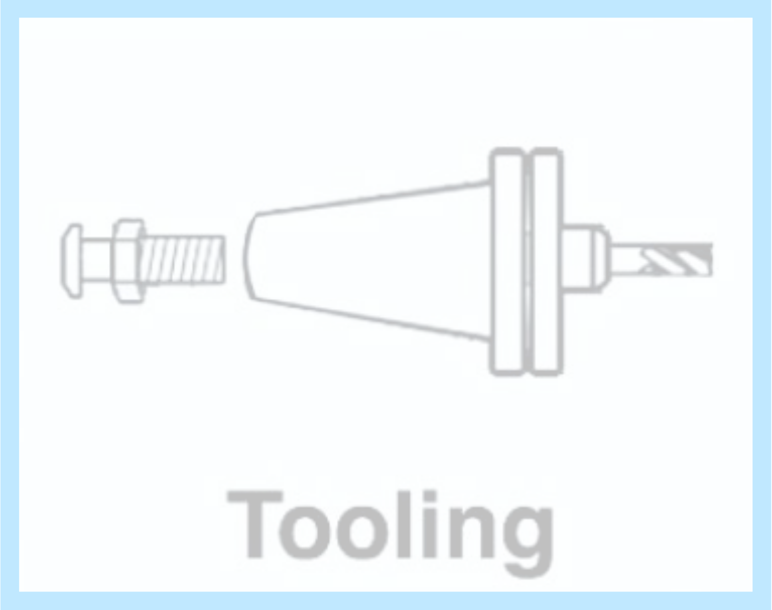
Workholding

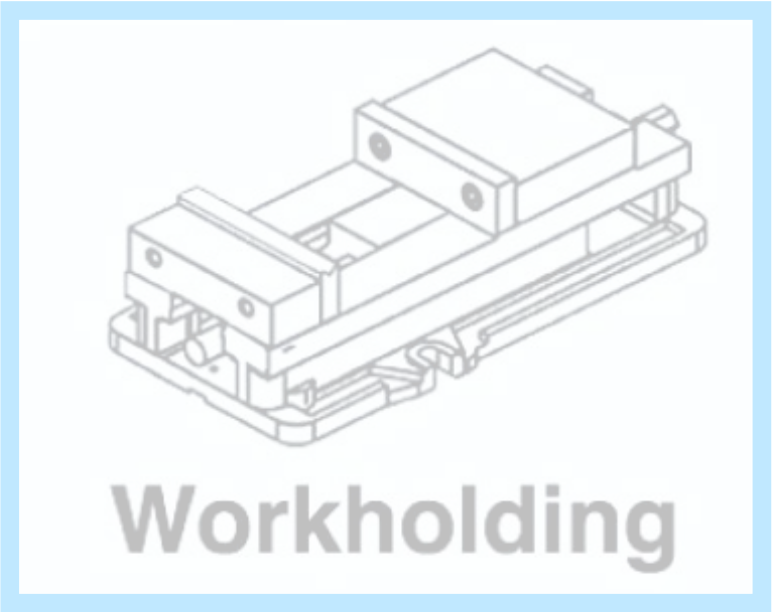
Design for Manufacturing: Machining



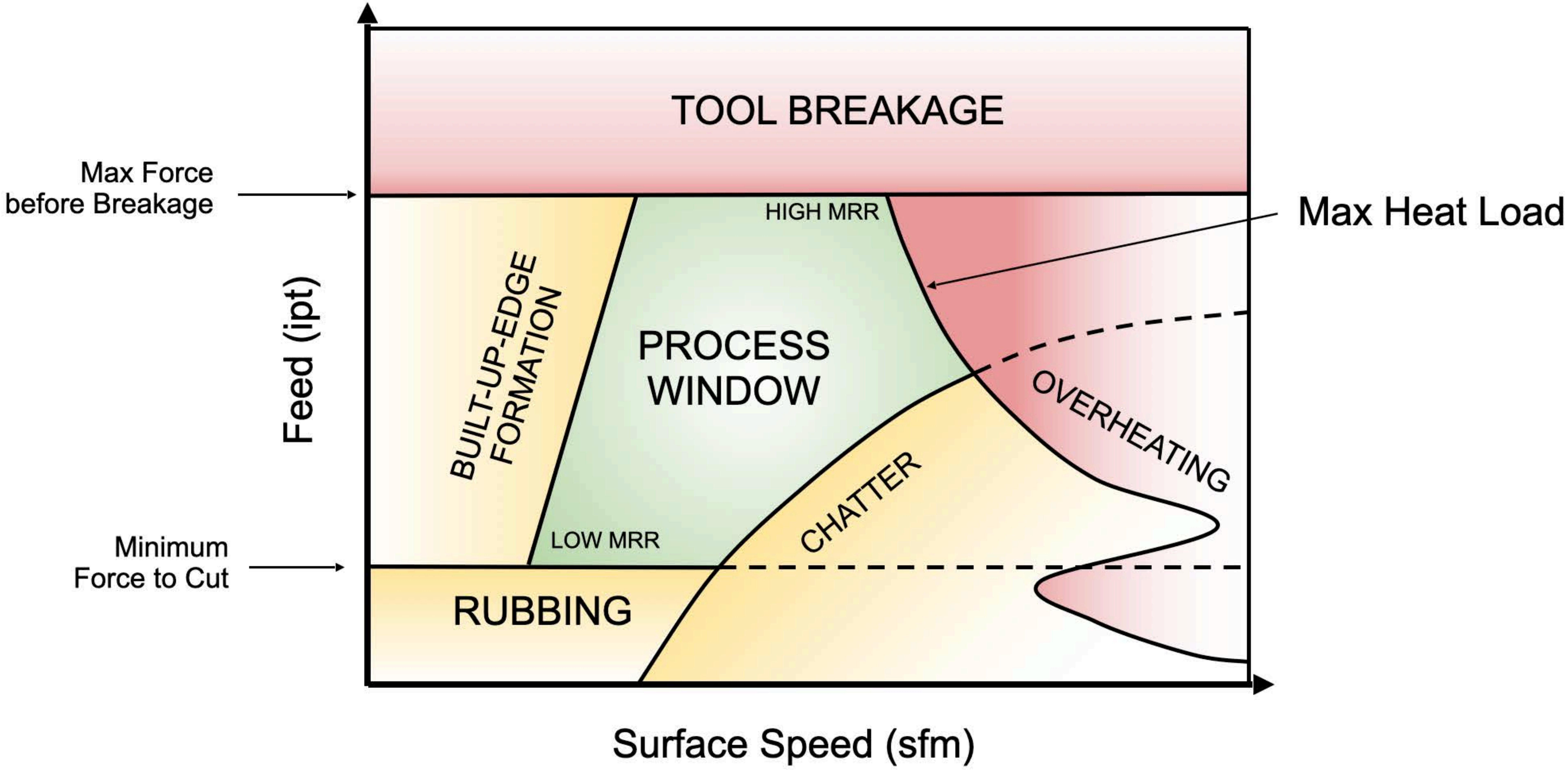


From Otto and Wood, Product Design: Techniques in Reverse Engineering and New Product Development



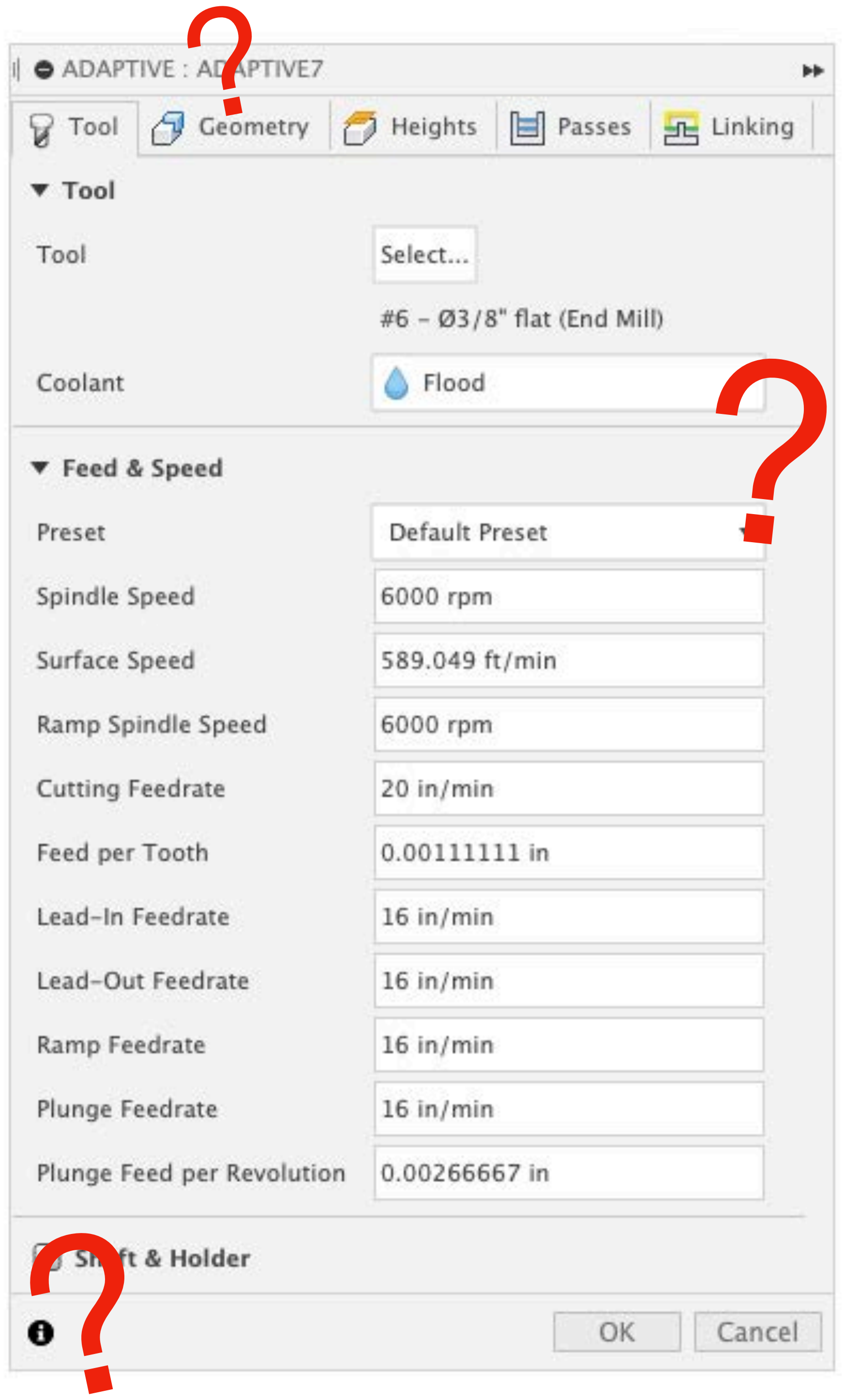


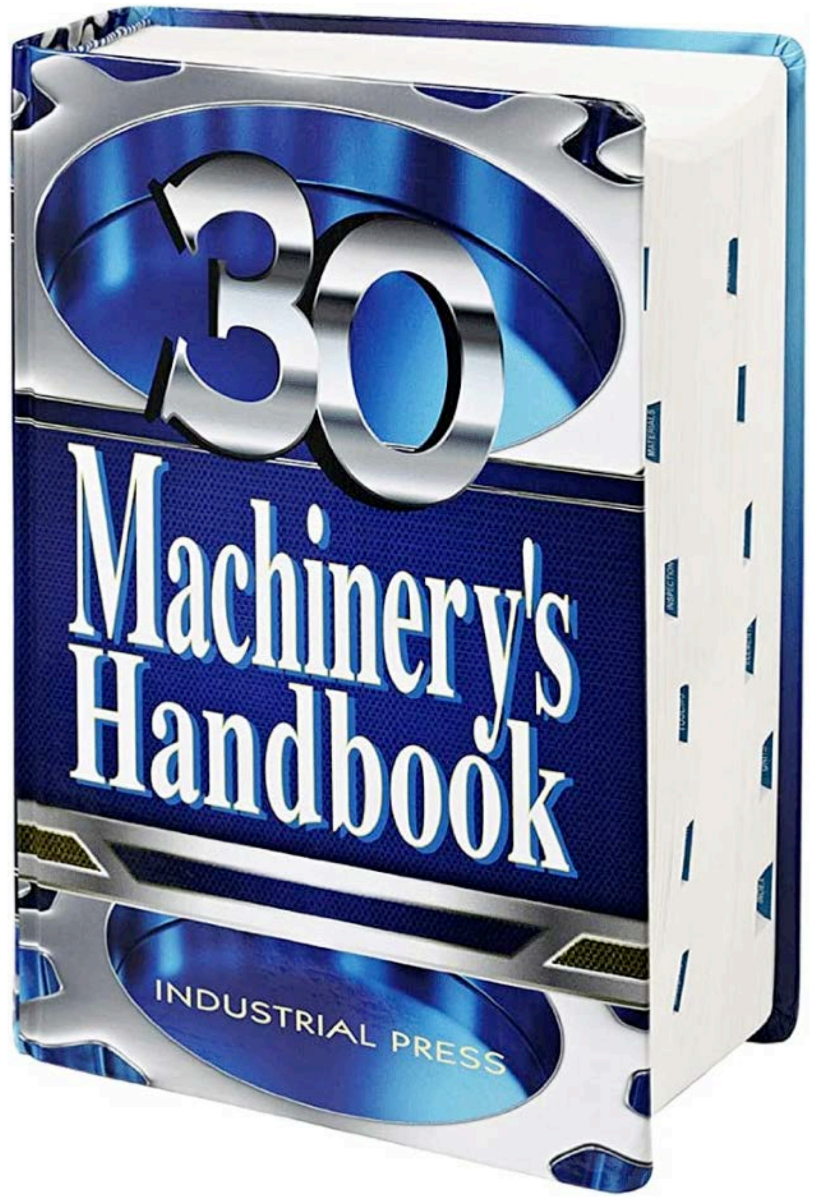
Design for Manufacturing: Machining

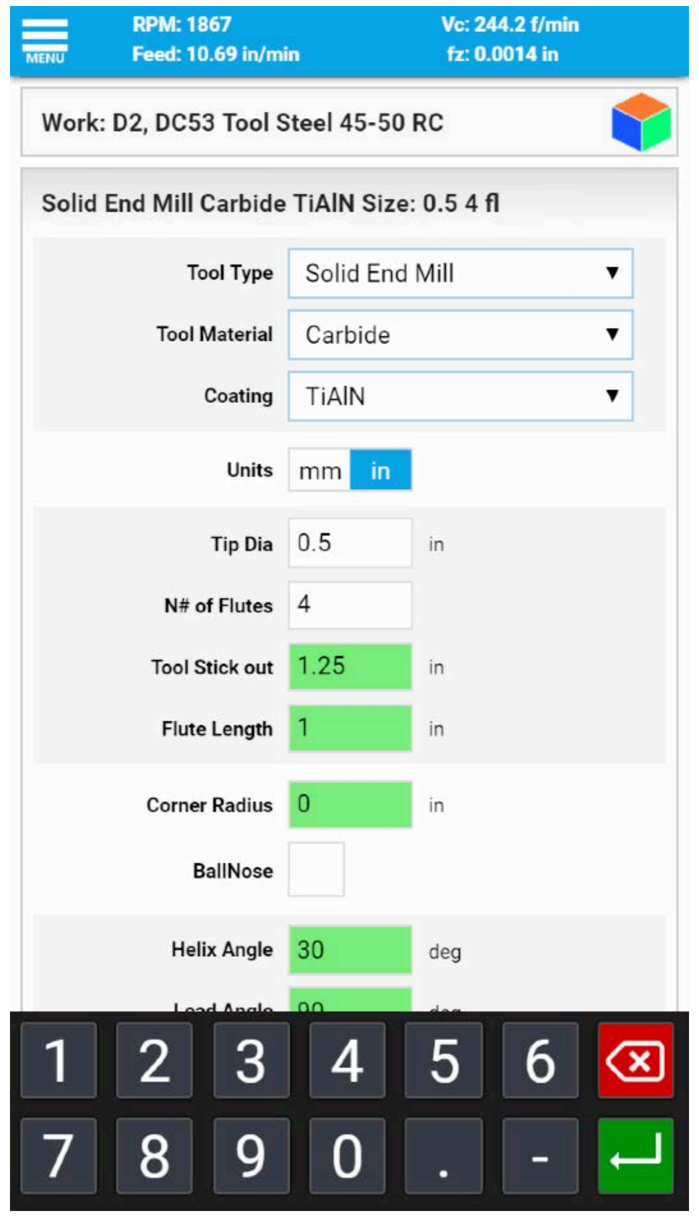


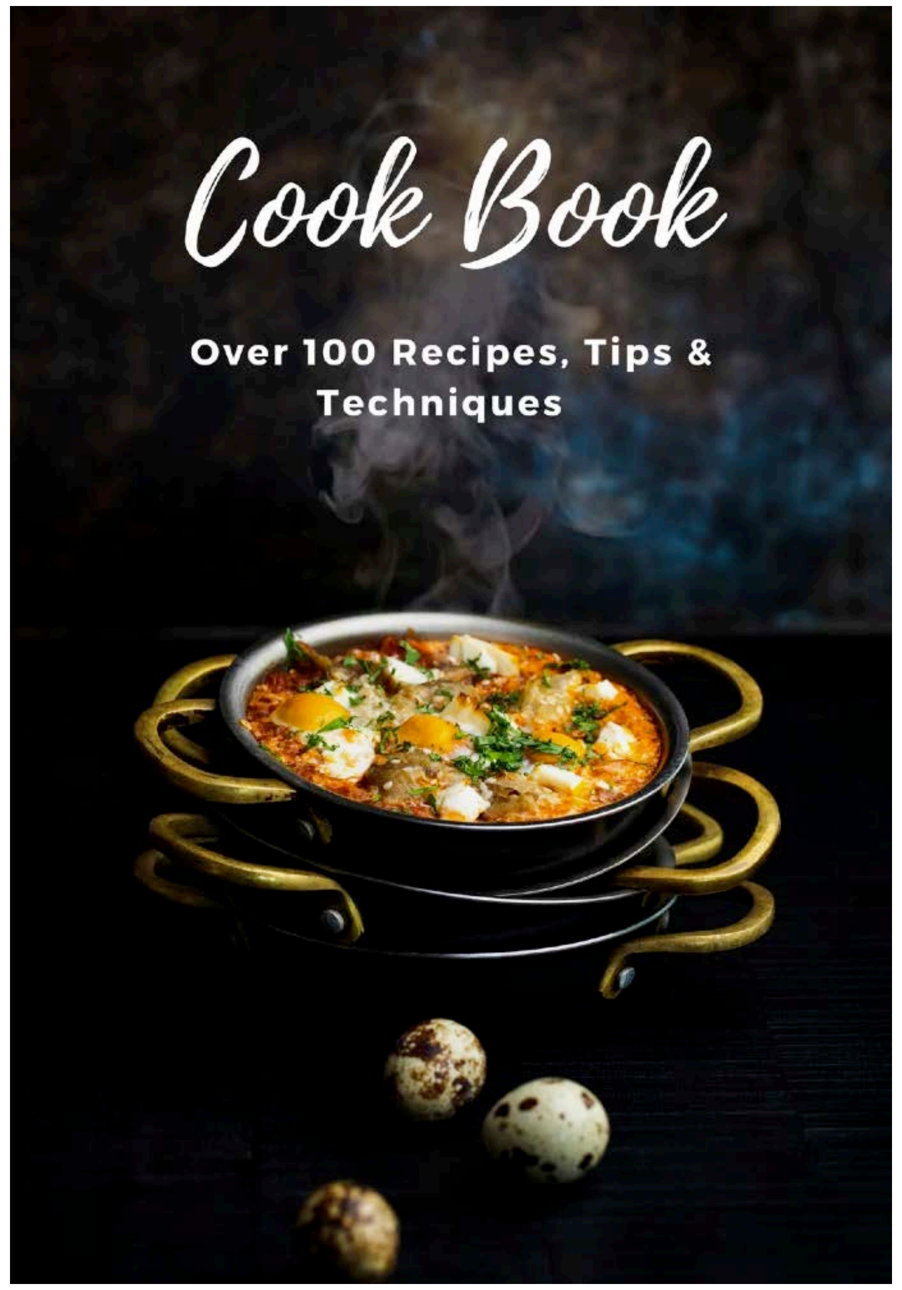
Feed and Speeds

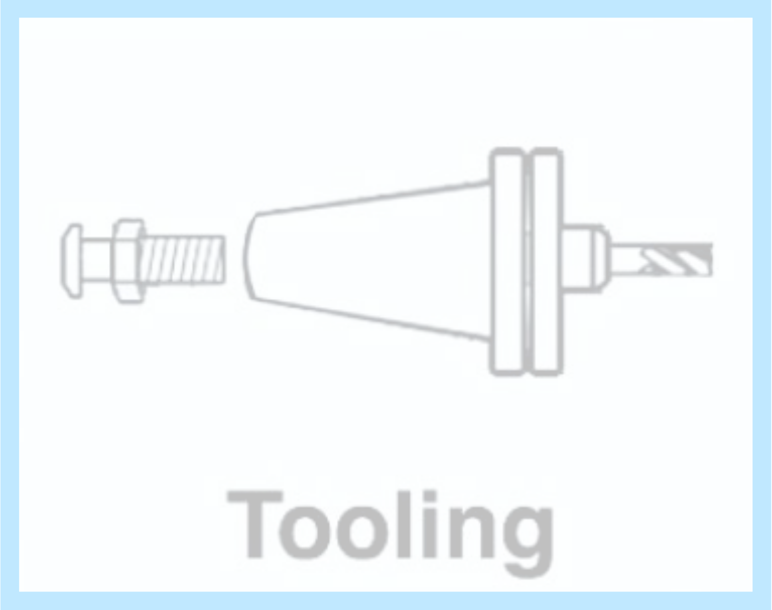
where do you start?

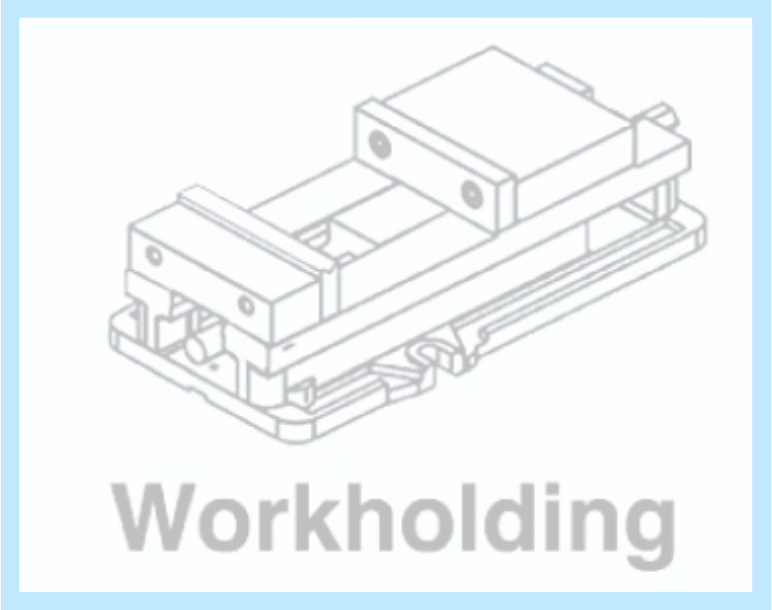












Design for Manufacturing: Machining

Roughing of steel
CMC 02.1

P R

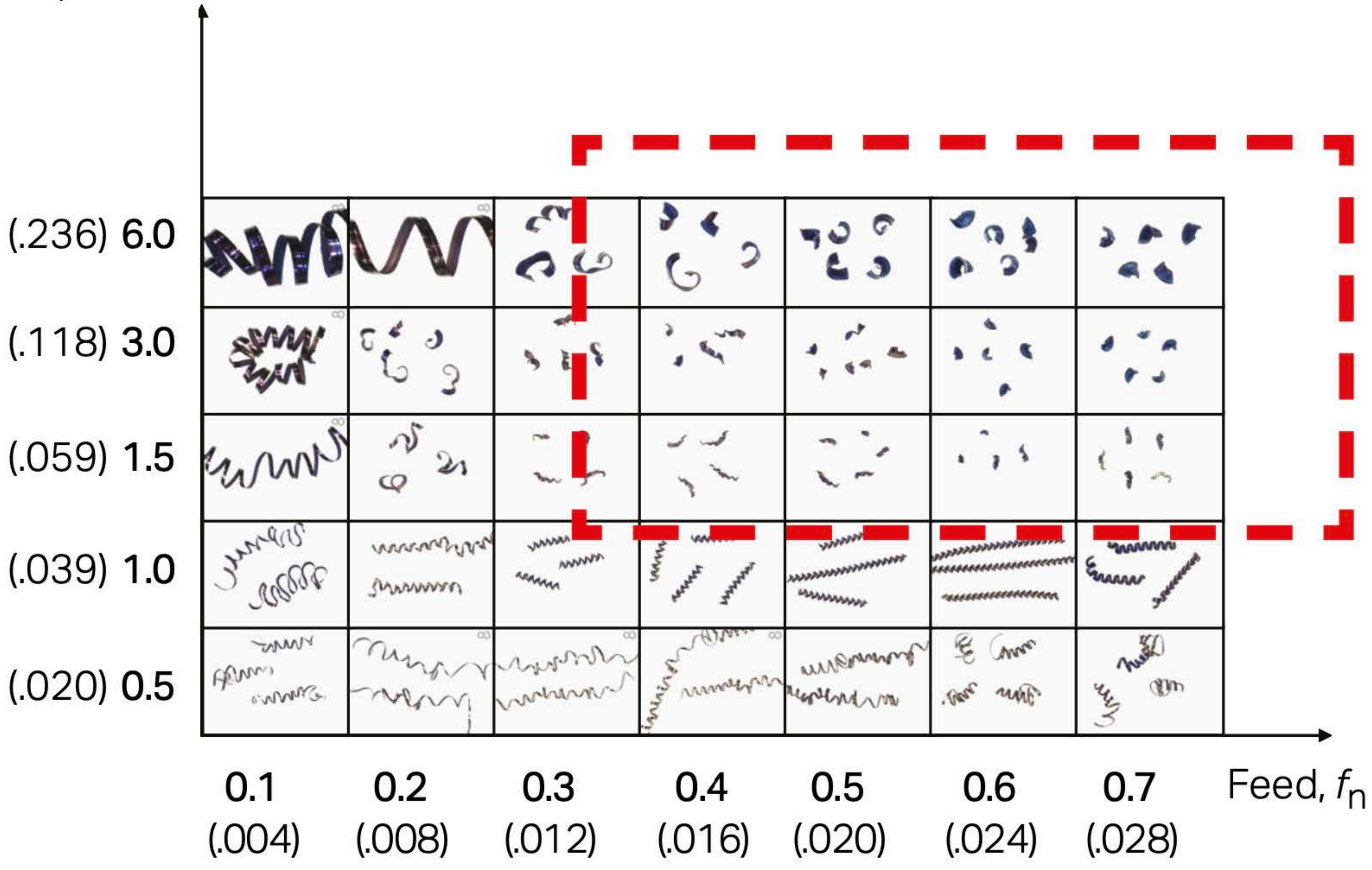
CNMM 120412-PR
(CNMM 432-PR)

Chip breaking area:

a_p = 5.0 (1.0 - 7.5) mm
f_n = 0.5 (0.25 - 0.7) mm/r

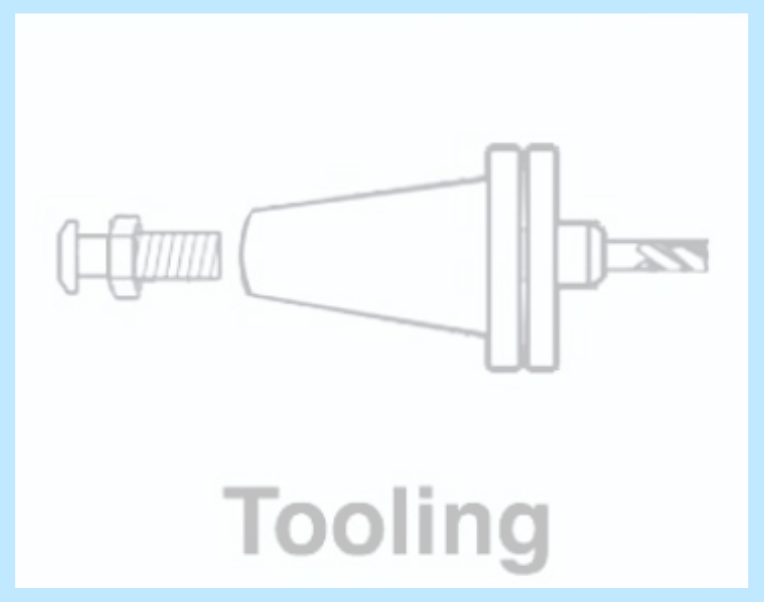
a_p = .197 (.039 - .295) inch
f_n = .020 (.010 - .028) inch/r

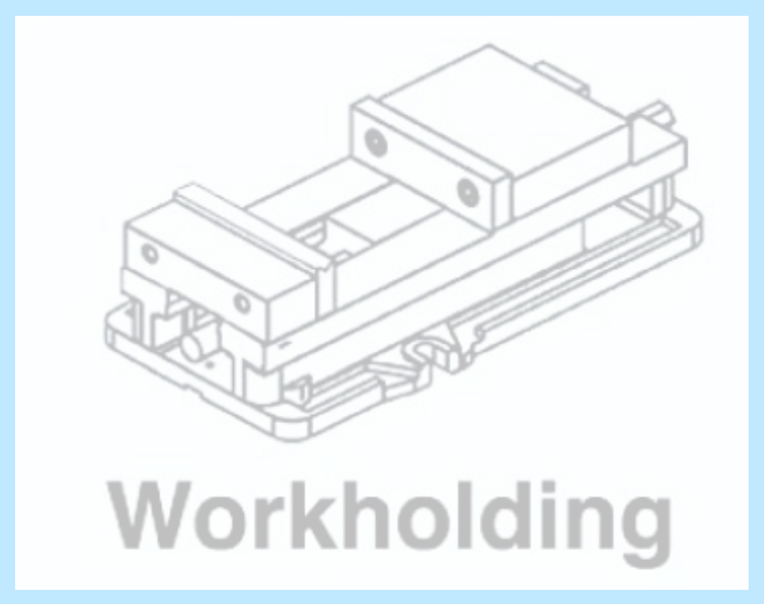
Cutting depth,
a_p mm (inch)



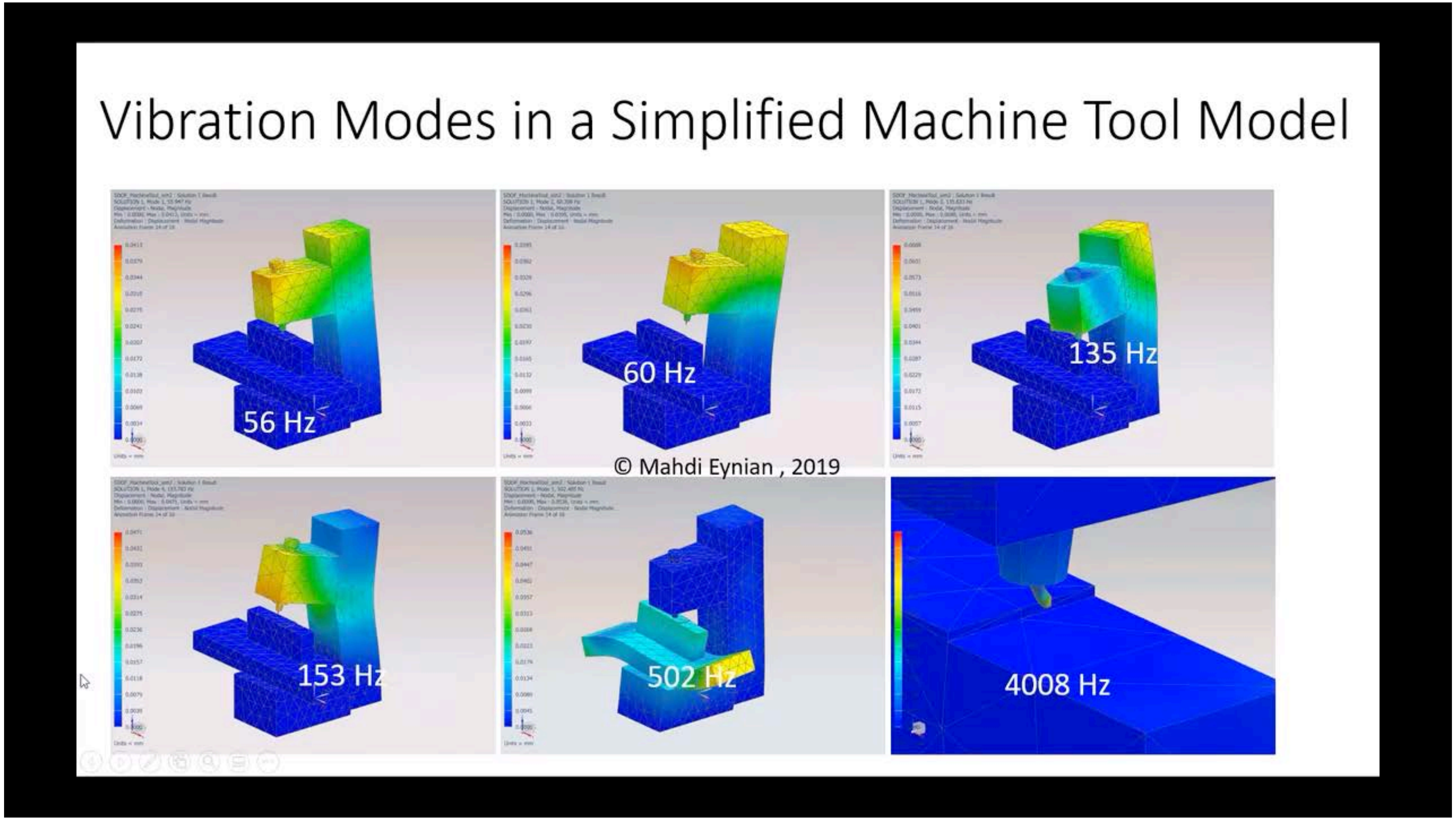
Feed, f_n mm/r (inch/r)

The area marked in red indicates the area which gives acceptable chip breaking.

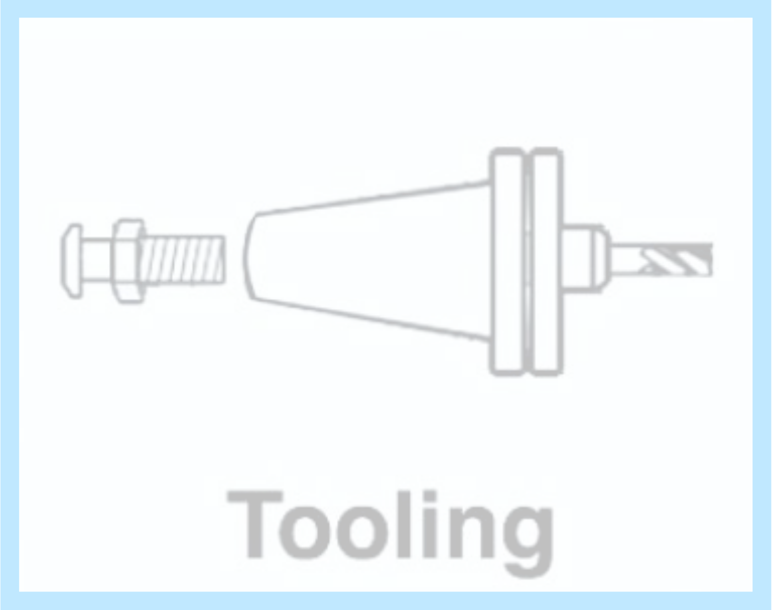


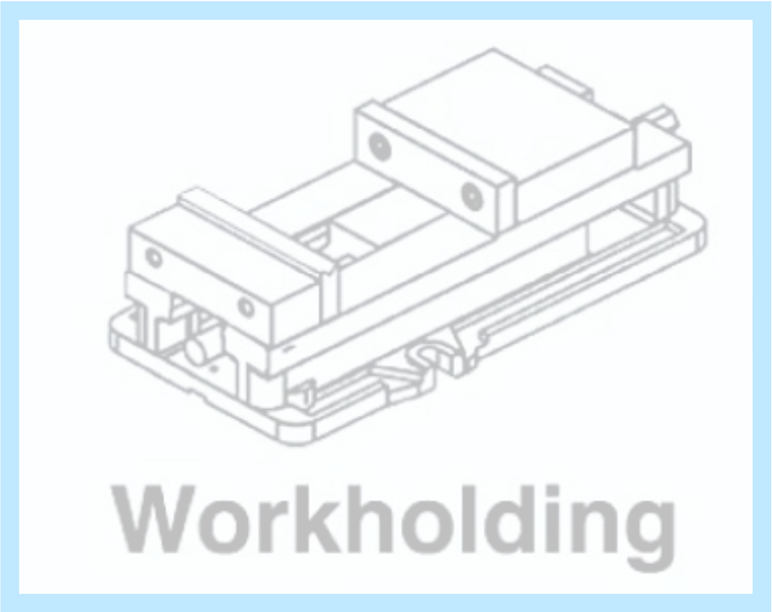


Vibration and Chatter

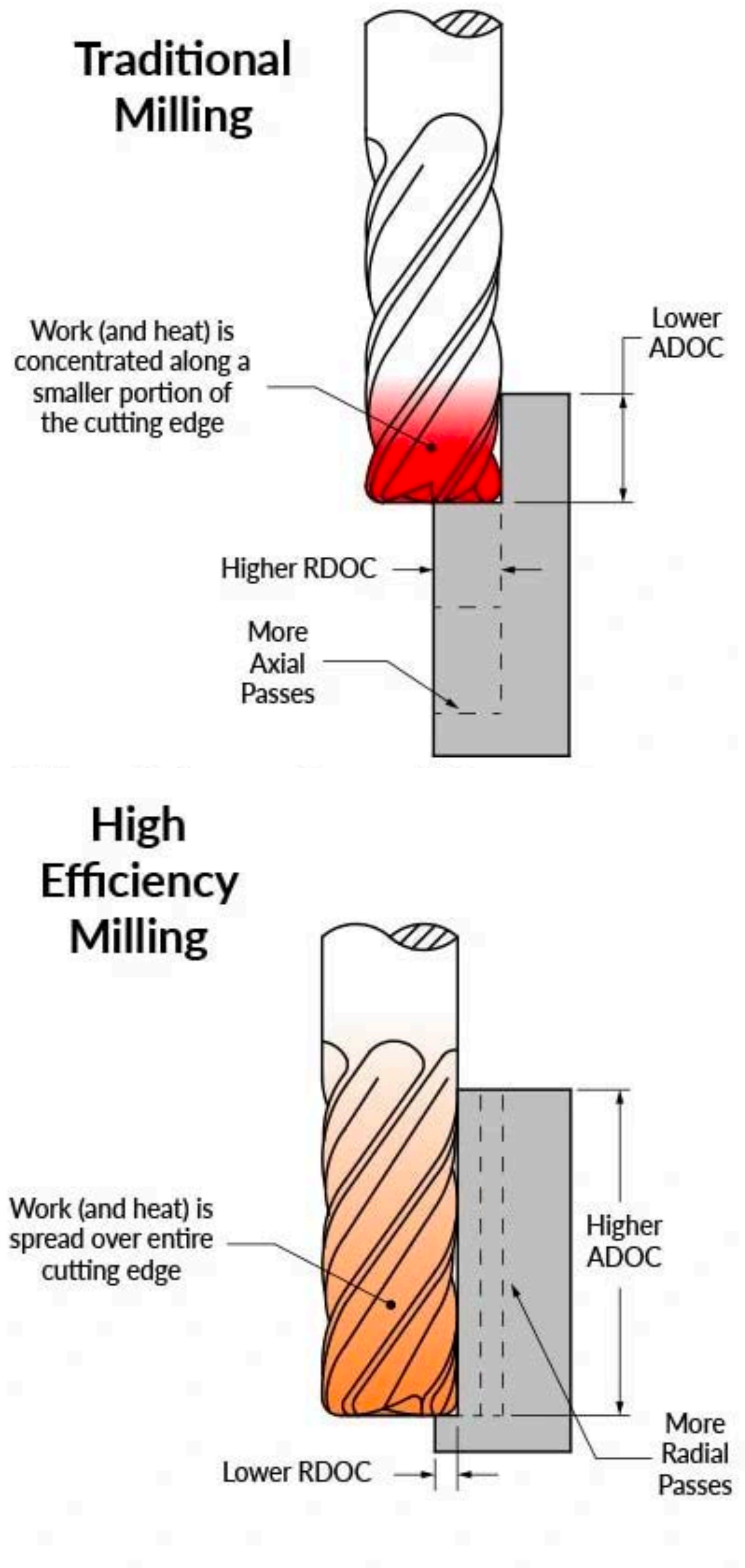


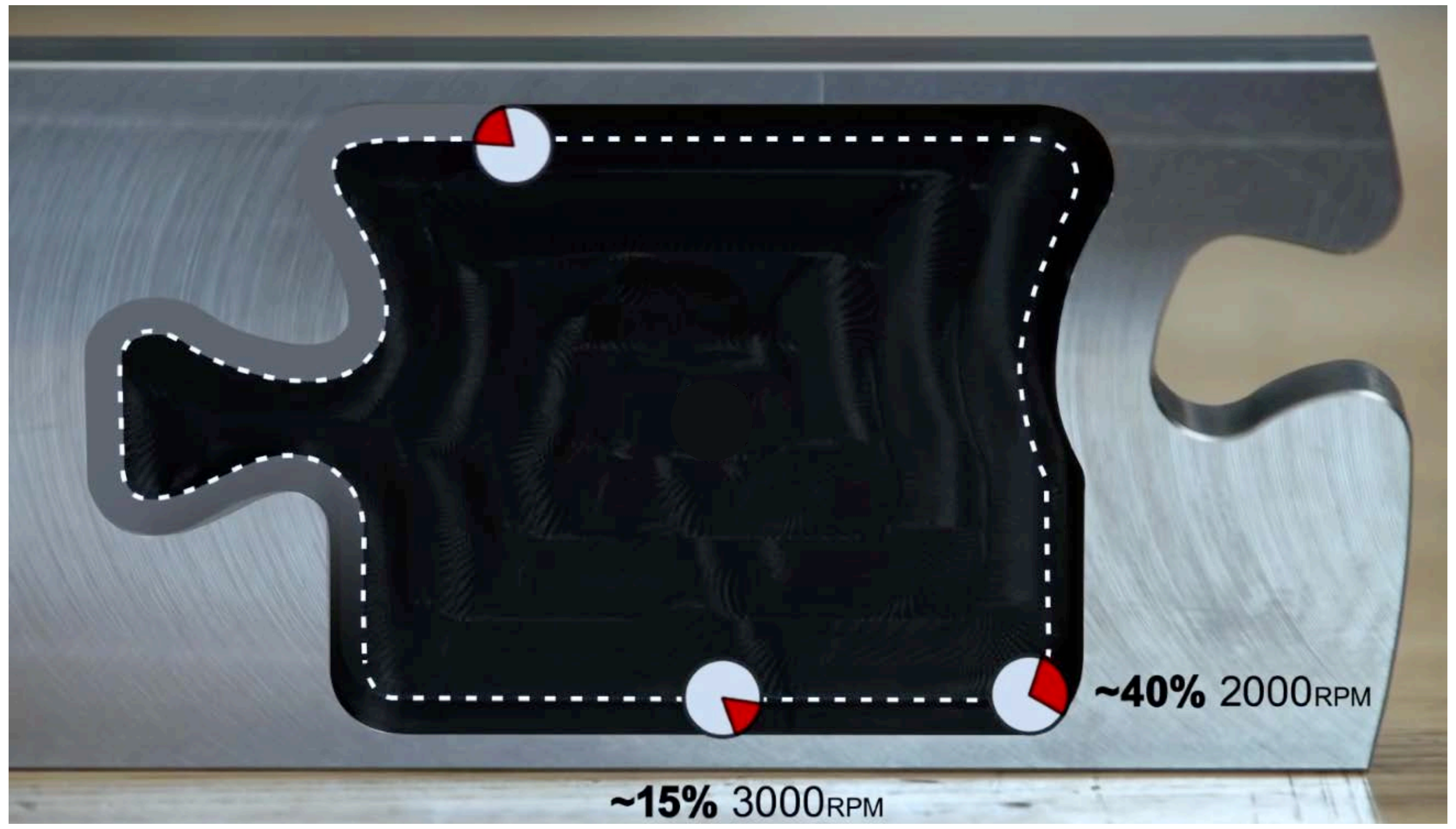
18,000 FPS | 24K RPM | 0.5" DOC | 0.0125" WOC | 200 IPM



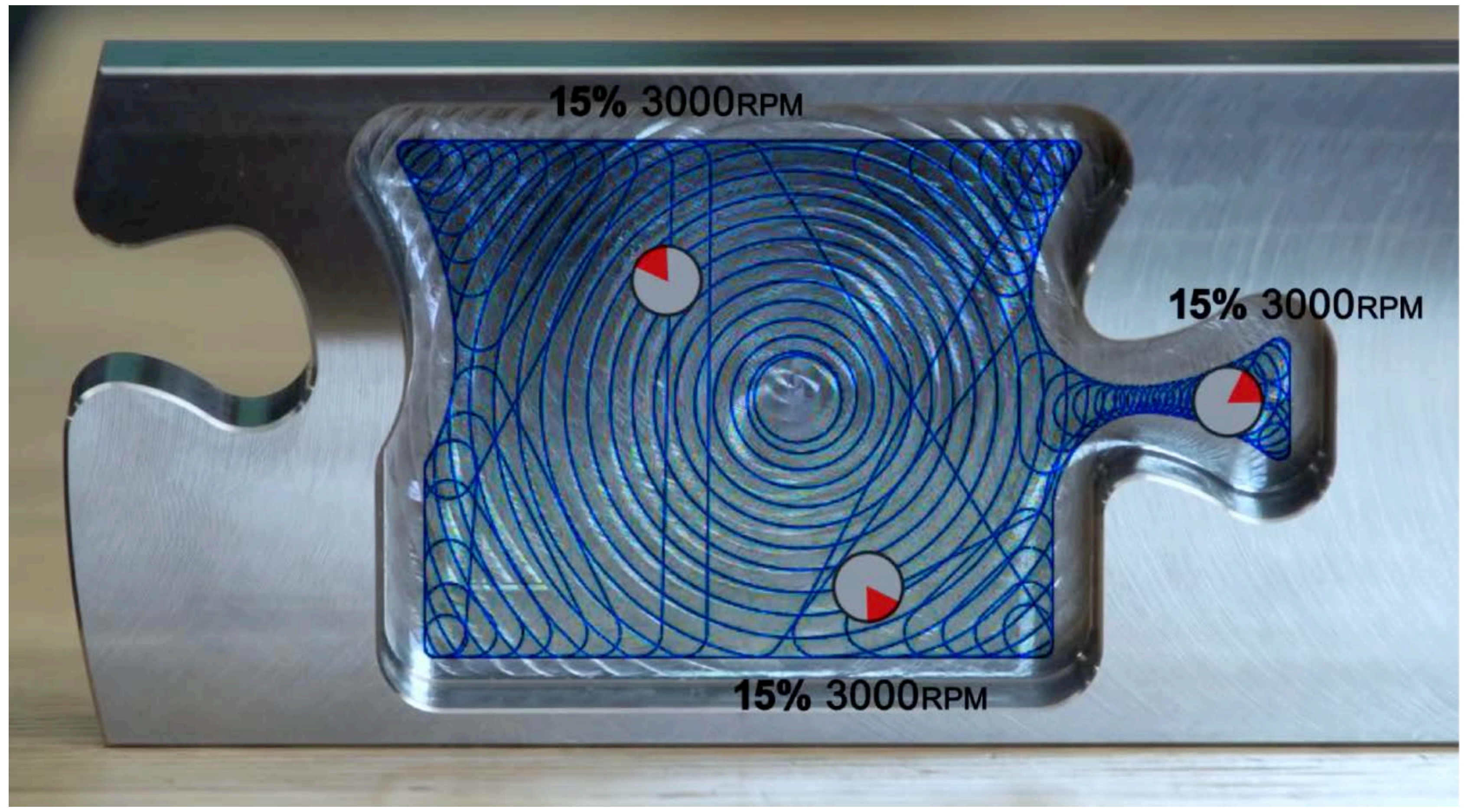


Adaptive Toolpaths





simple program and machine



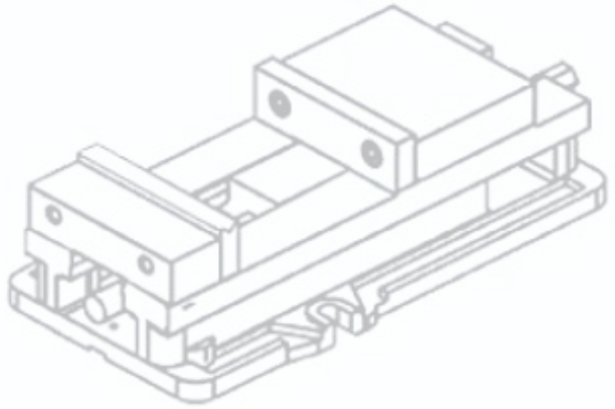
needs fast computers and machines

Cutting #3

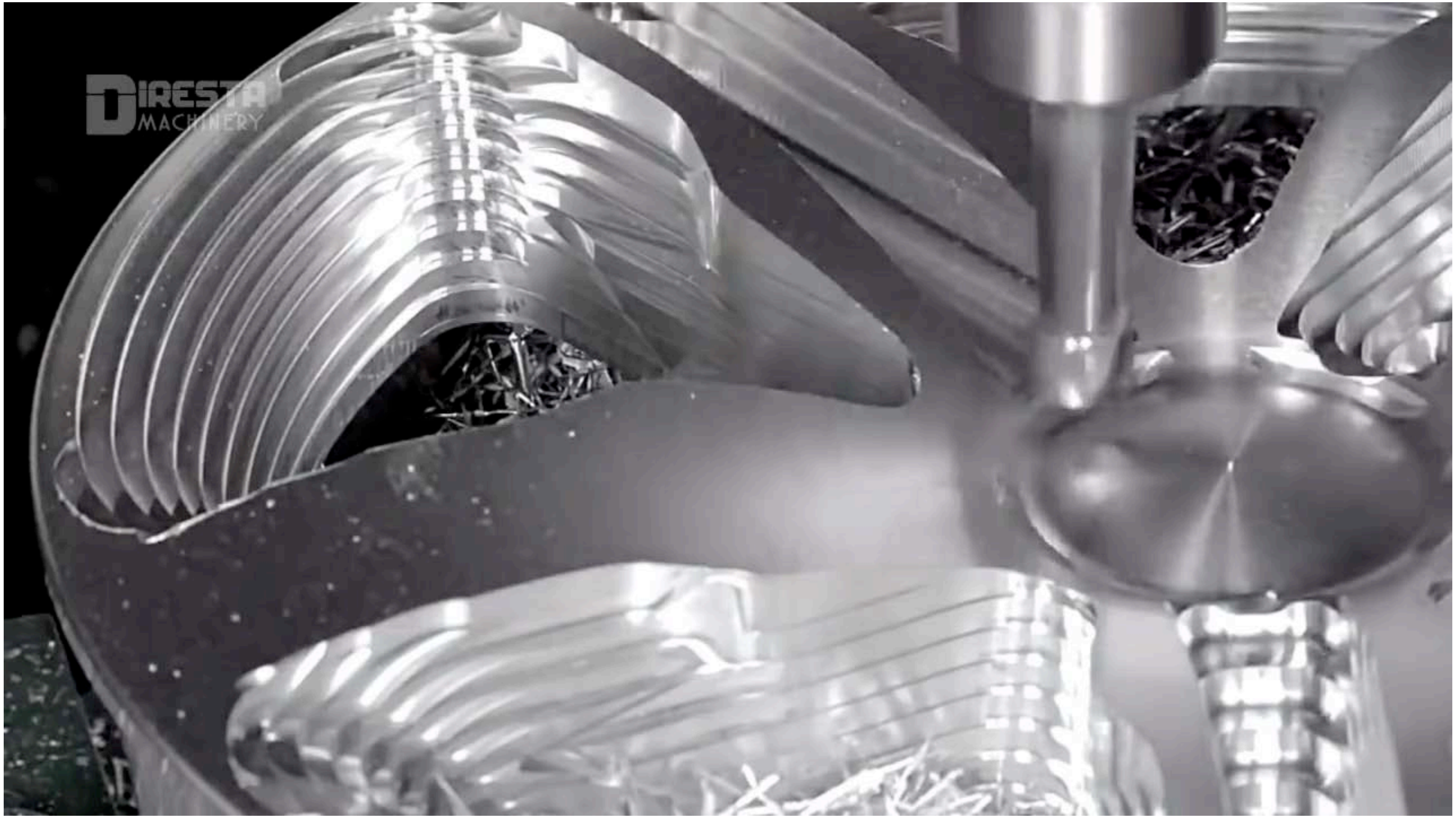
Machining in Practice

Tooling

Program

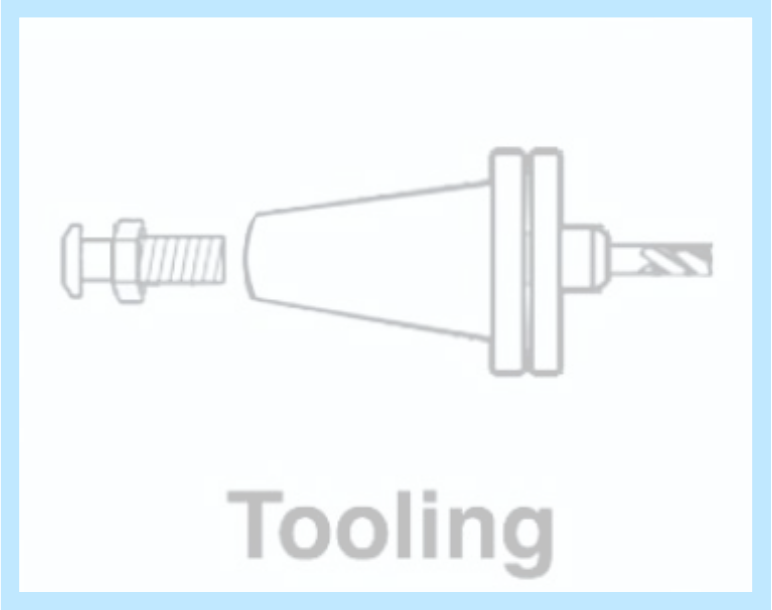


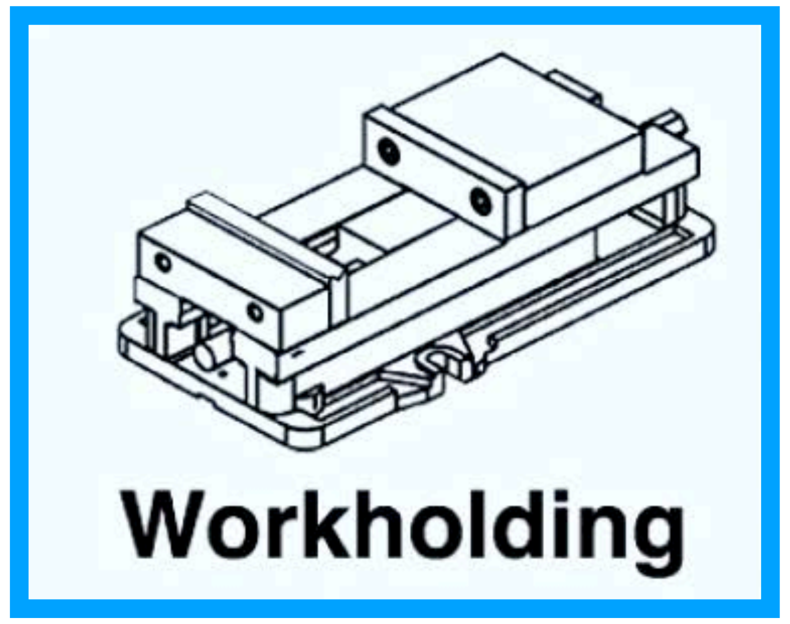
Workholding



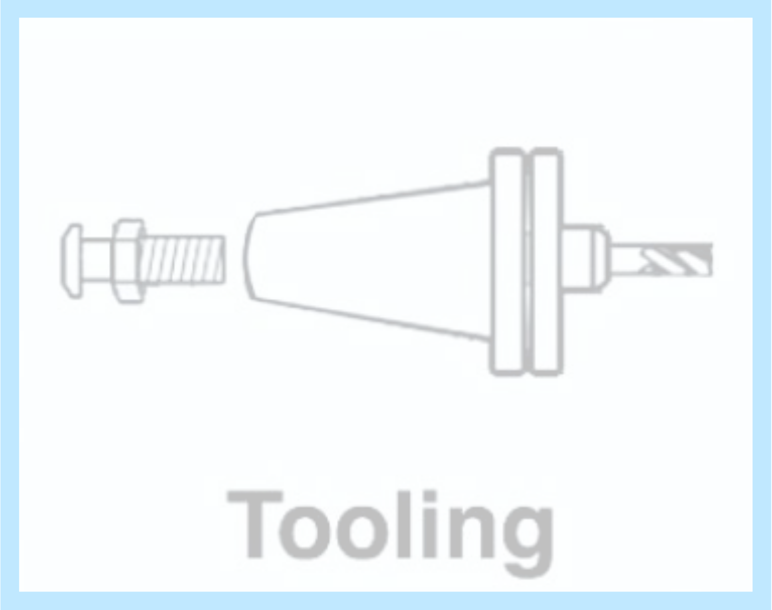
Cutting #3

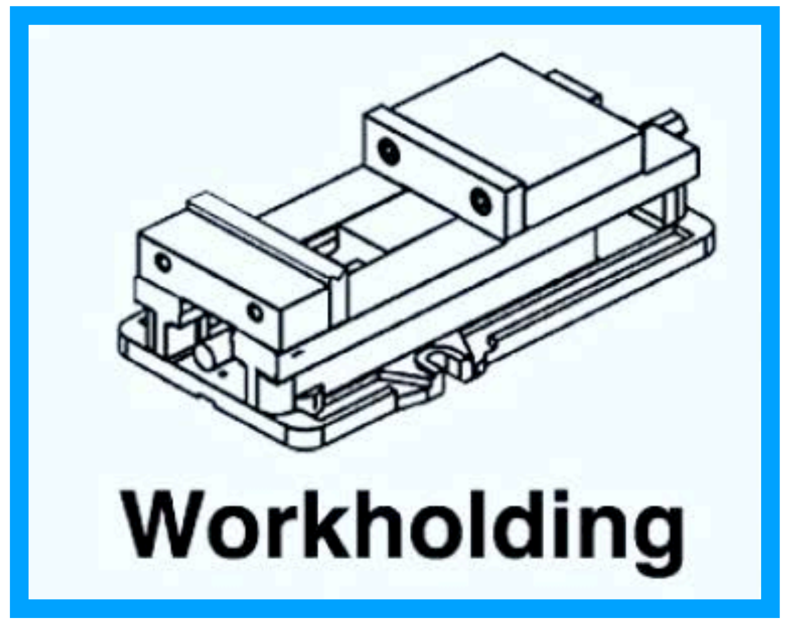
Machining in Practice



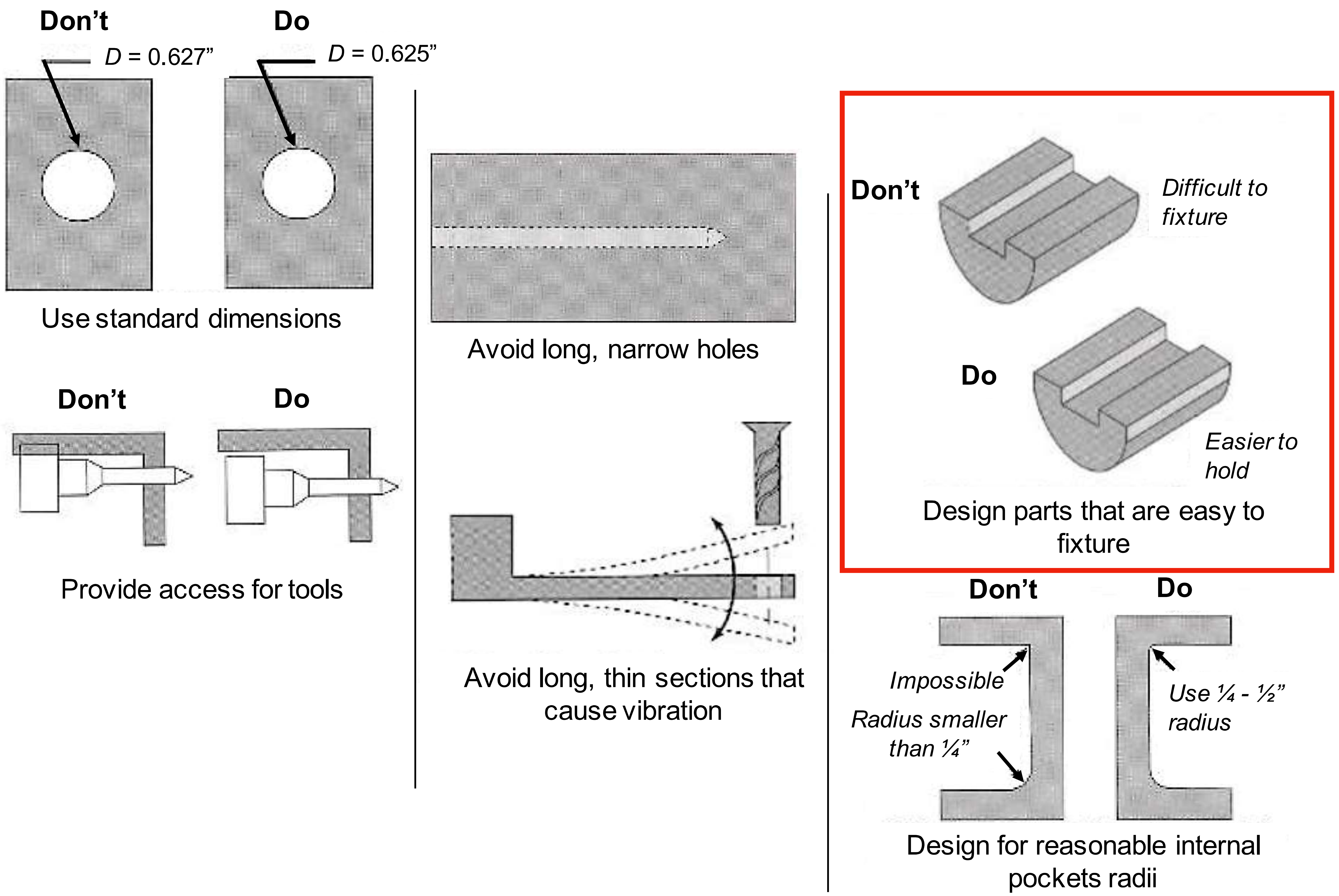


Stiffness Returns!





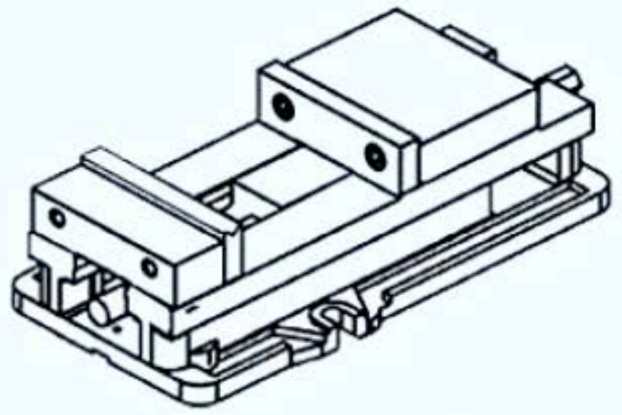
Strategies



From Otto and Wood, Product Design: Techniques in Reverse Engineering and New Product Development

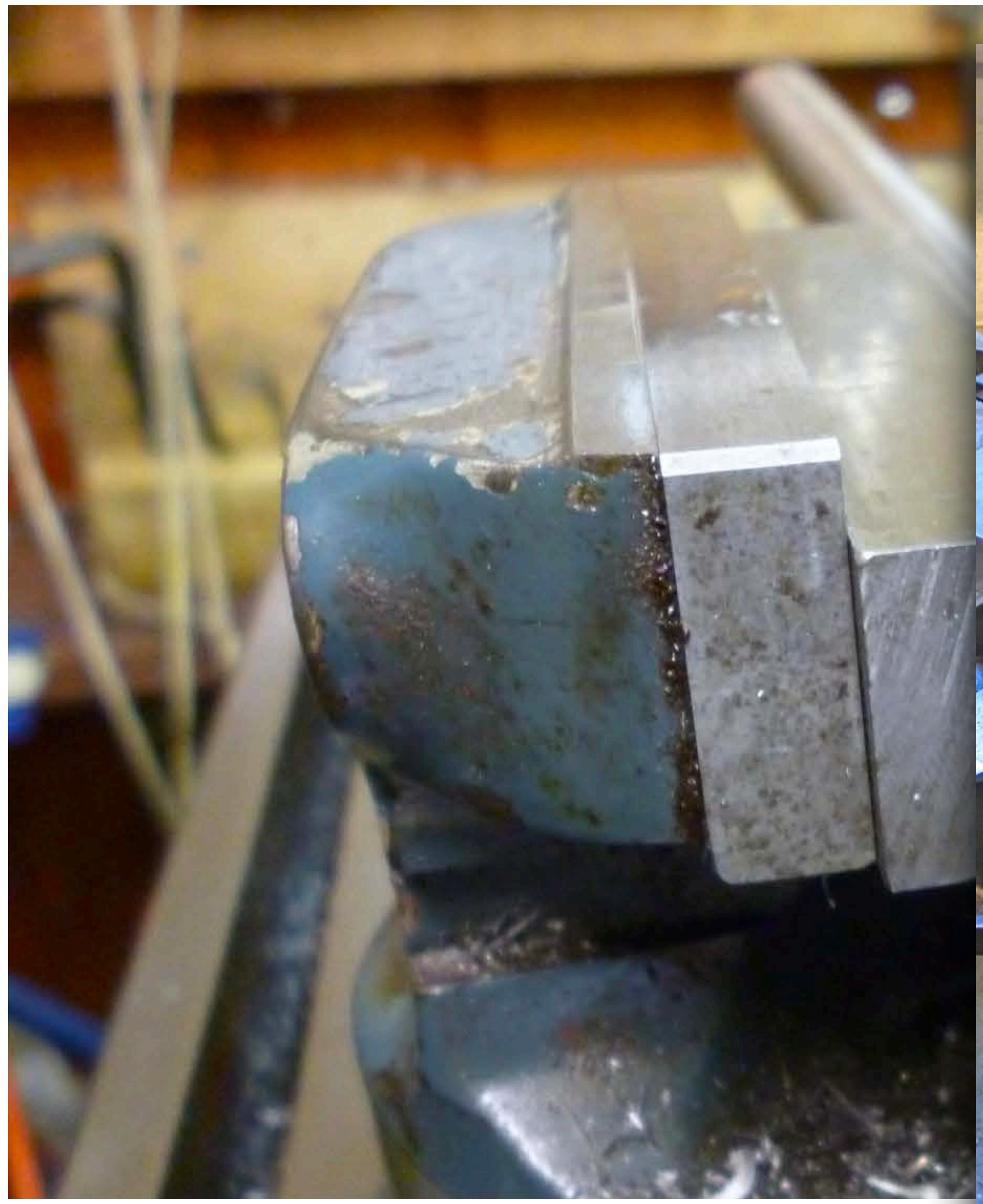
Tooling

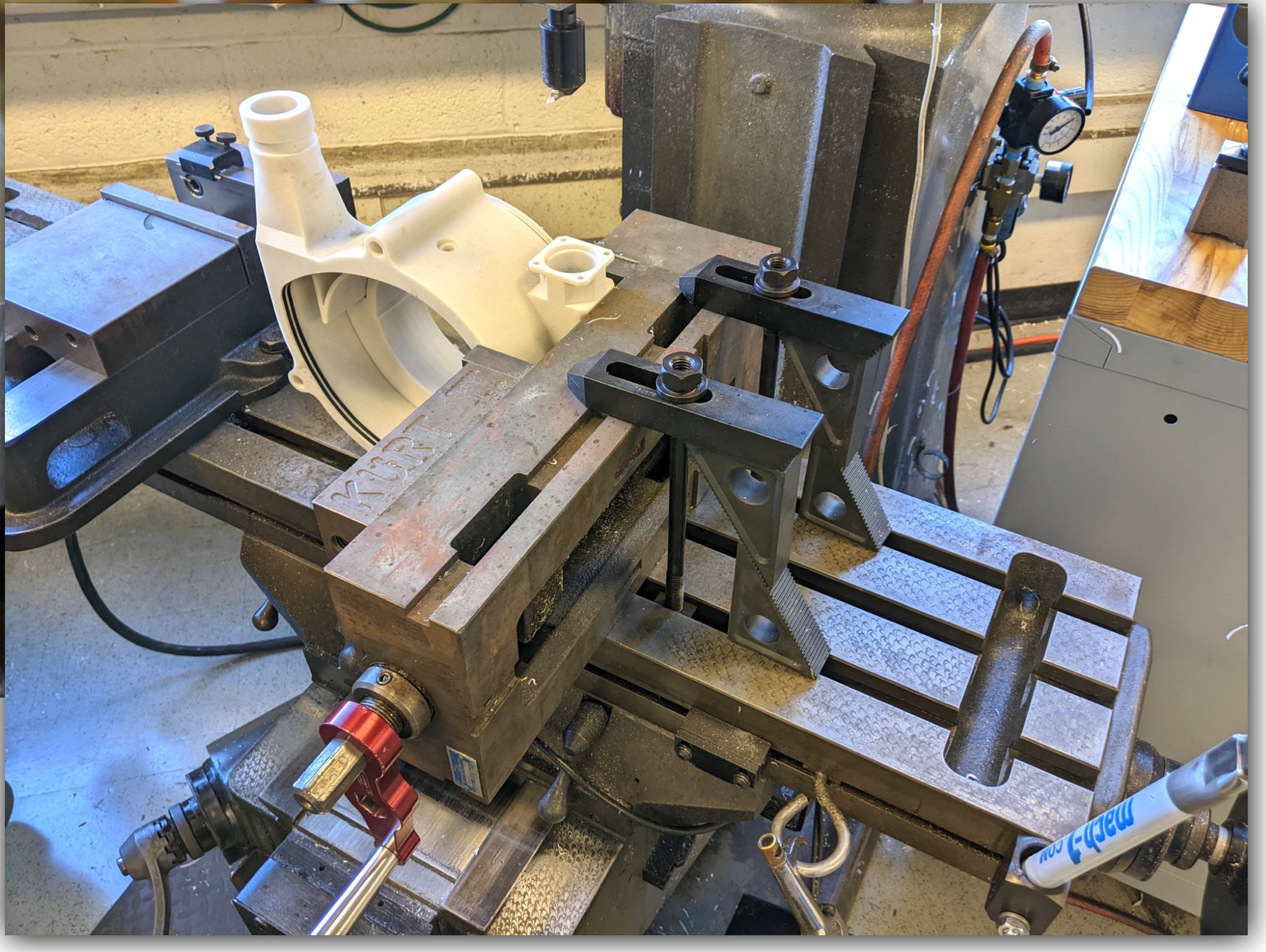
Program

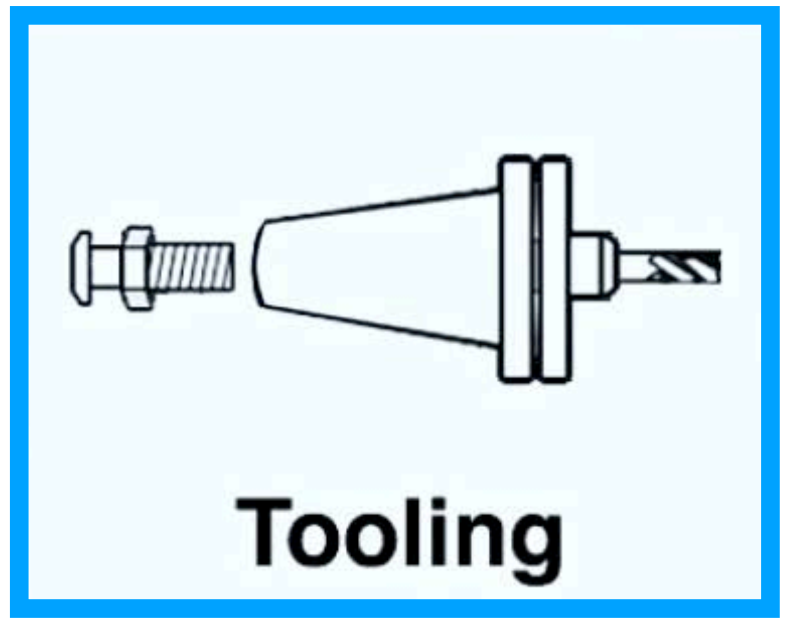


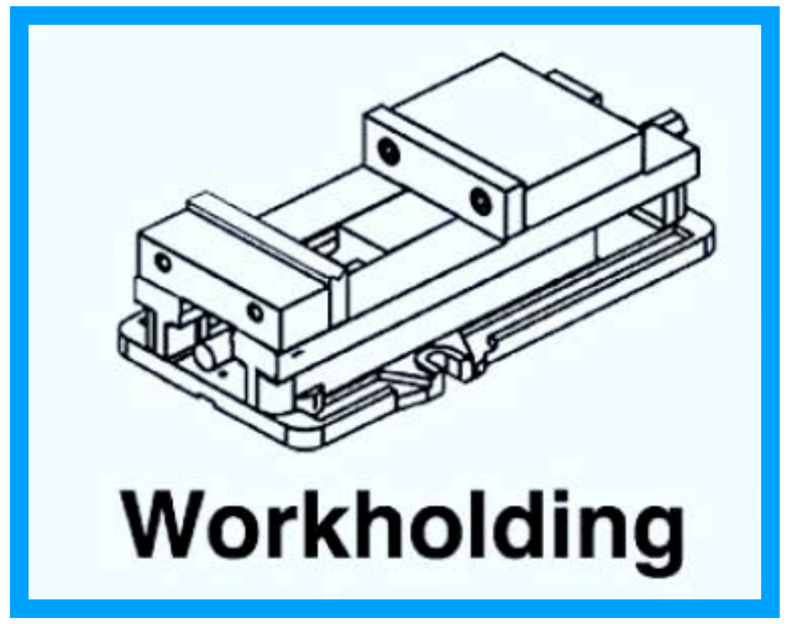
Workholding

Strategies

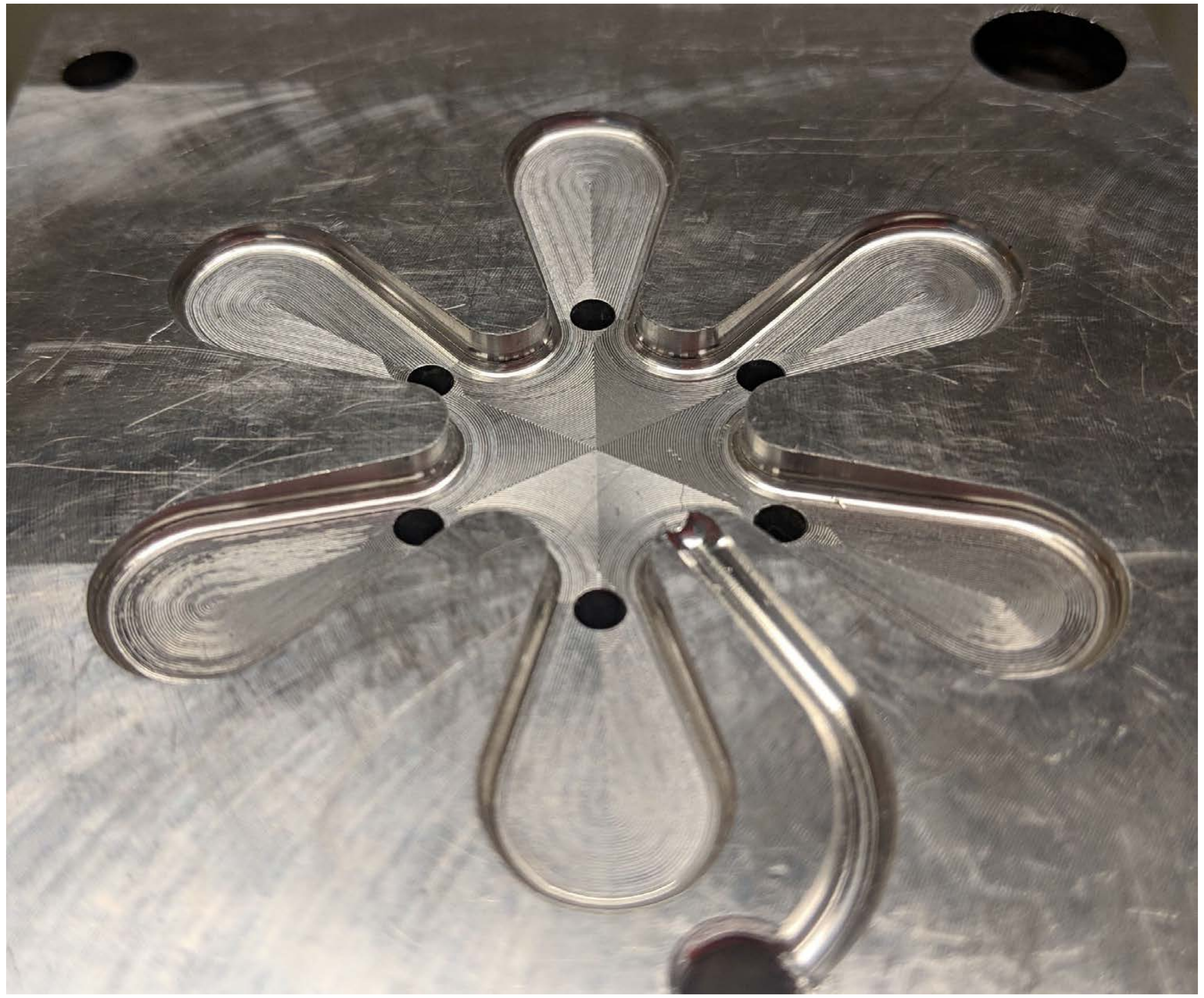


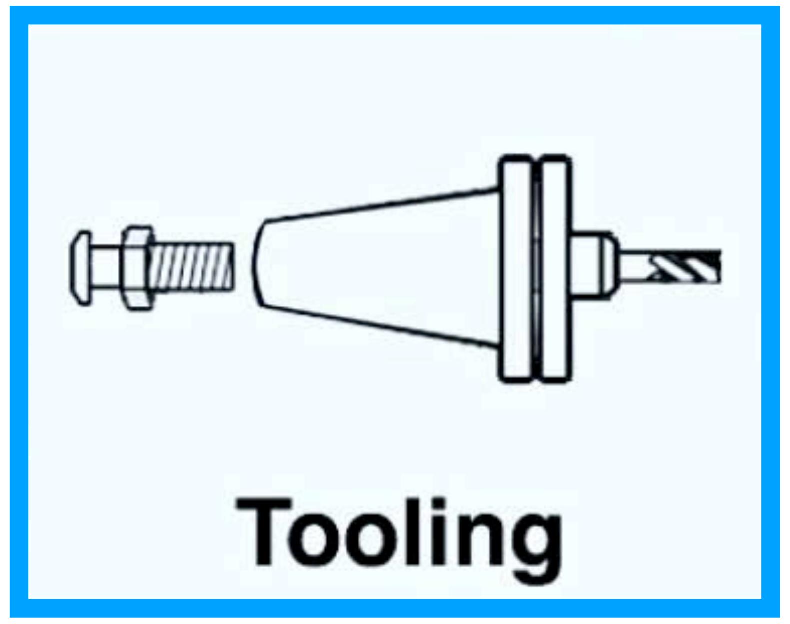


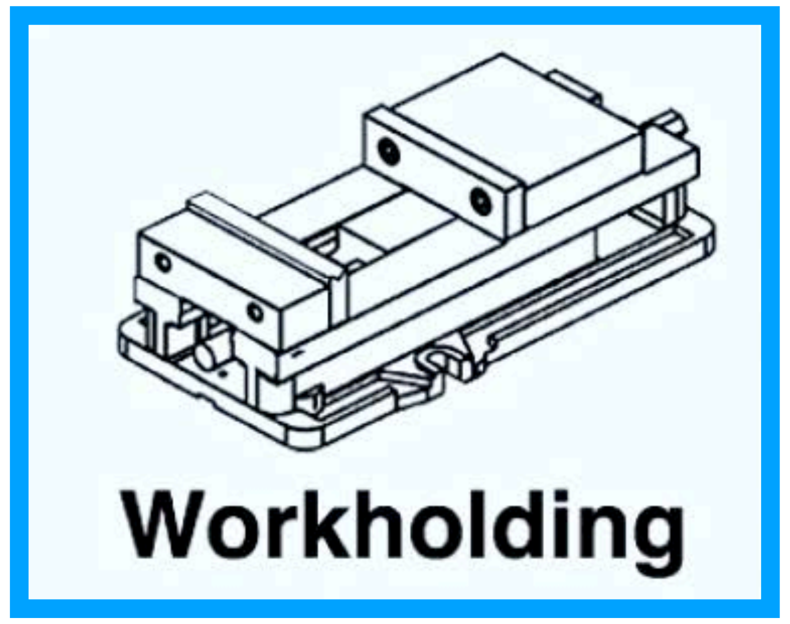




Surface Finish







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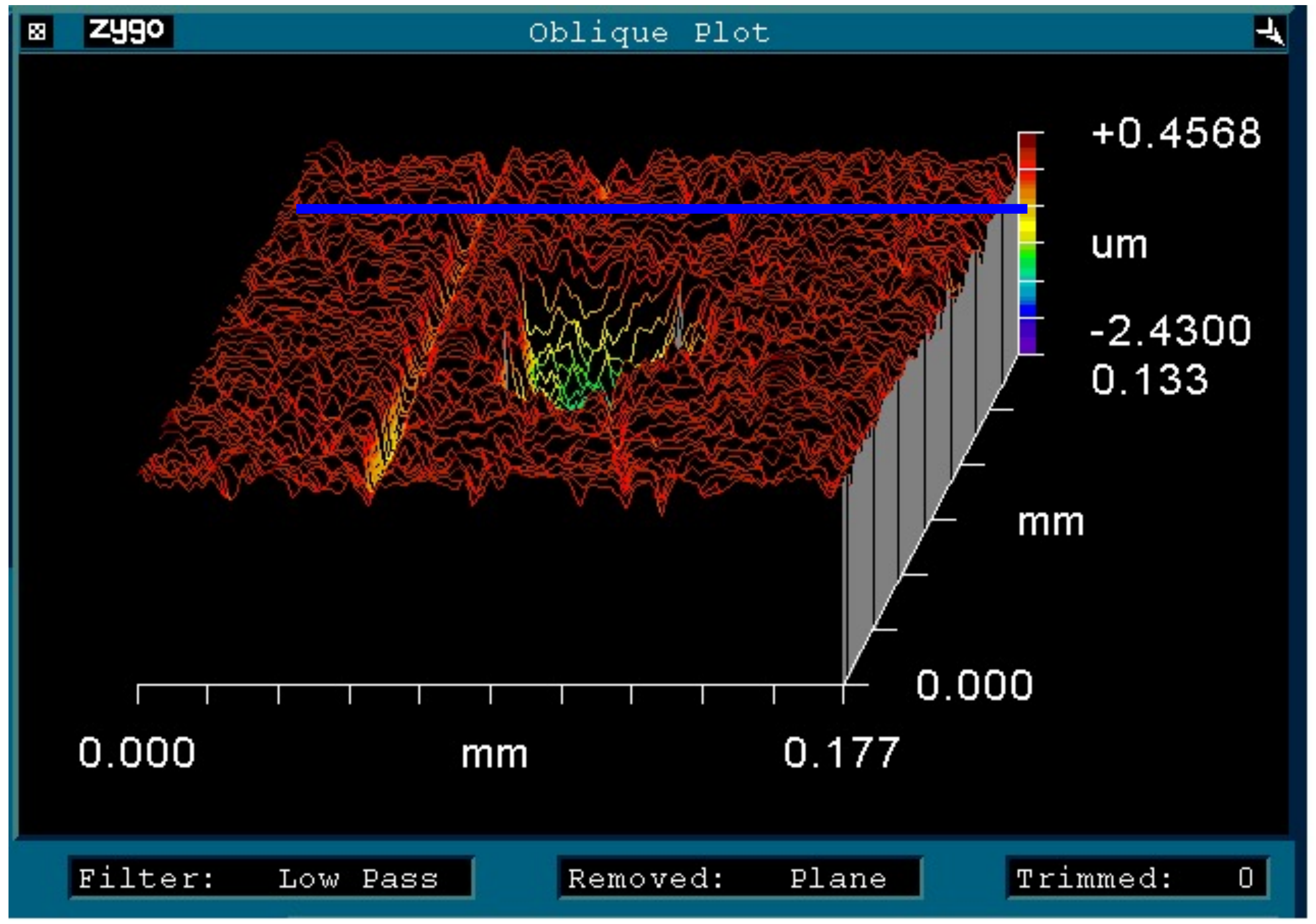
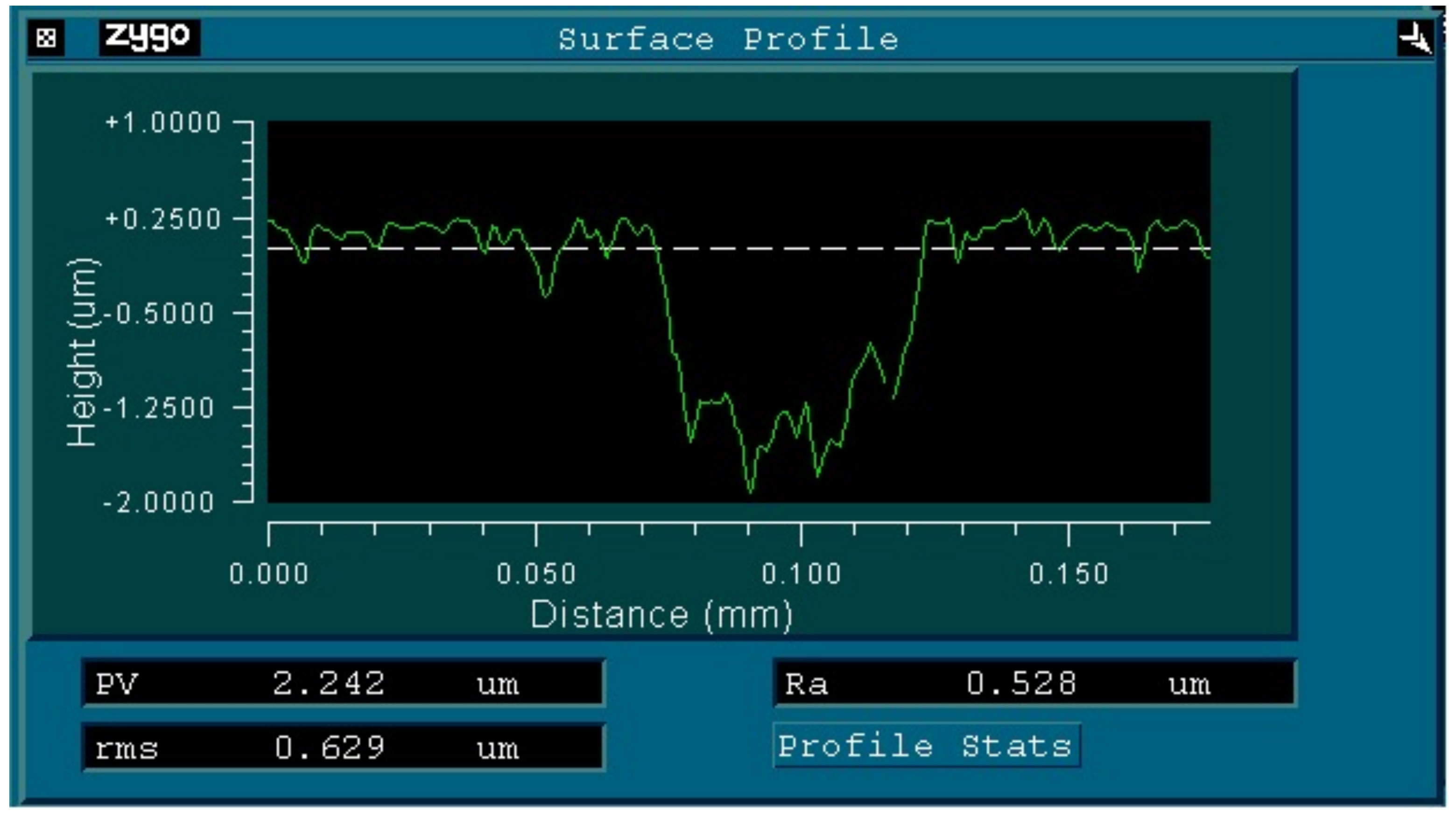
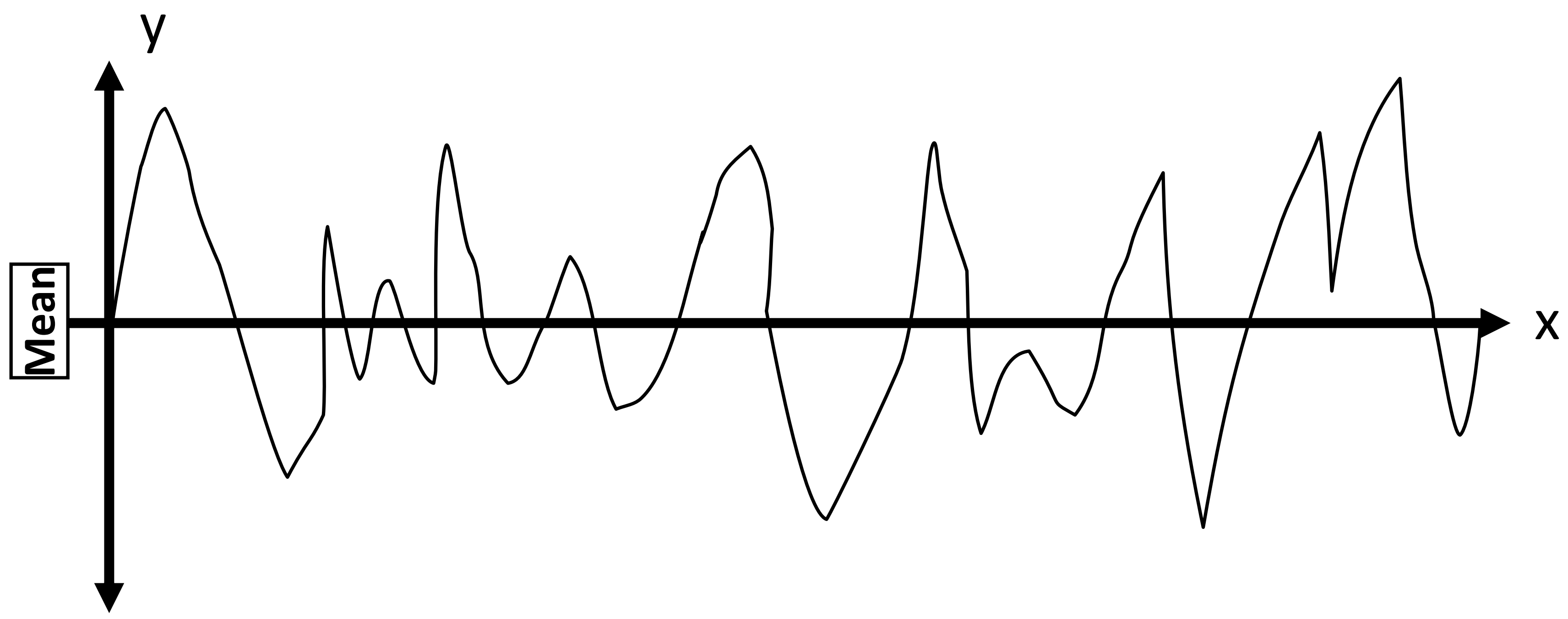






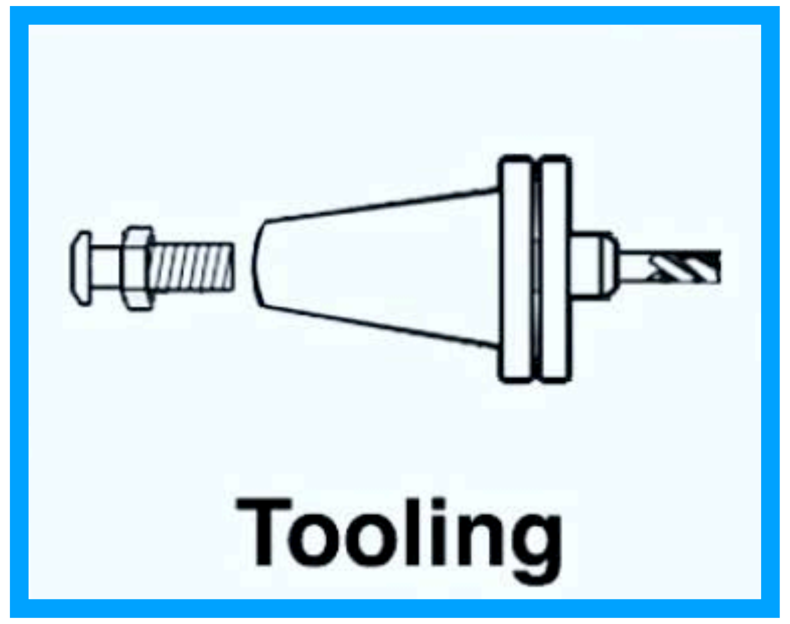
$$R_a = \frac{1}{L}\int_0^L |y|\, dx$$

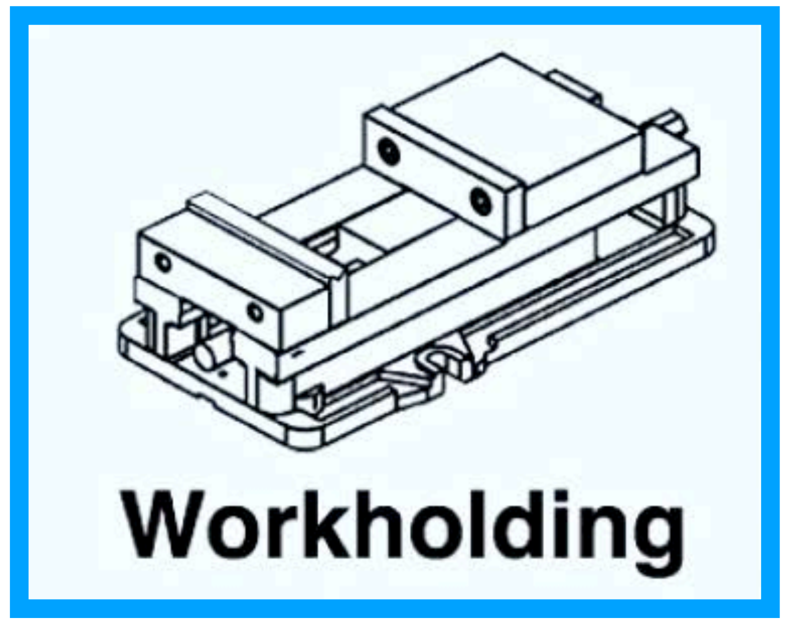
$$Roughness\ Height = \frac{f^2}{8R}$$

R_a: average roughness

f: feed

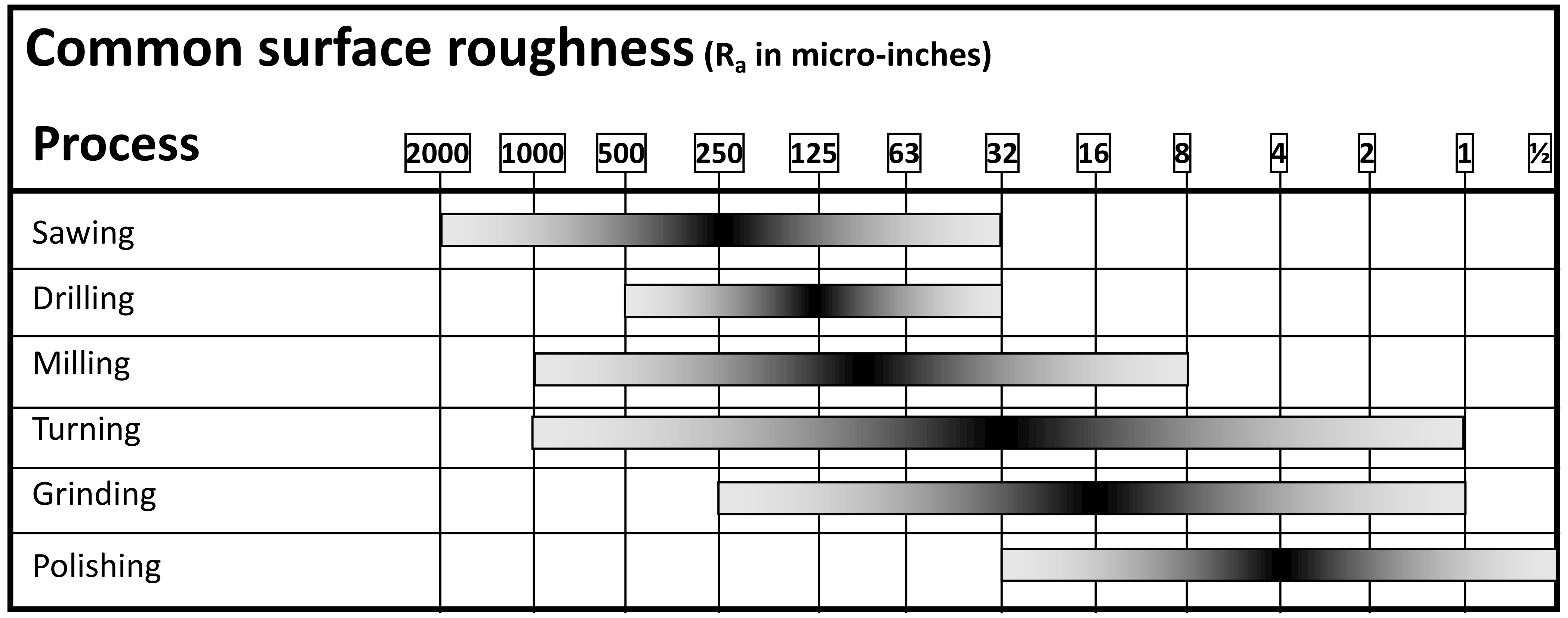
R: tool nose radius

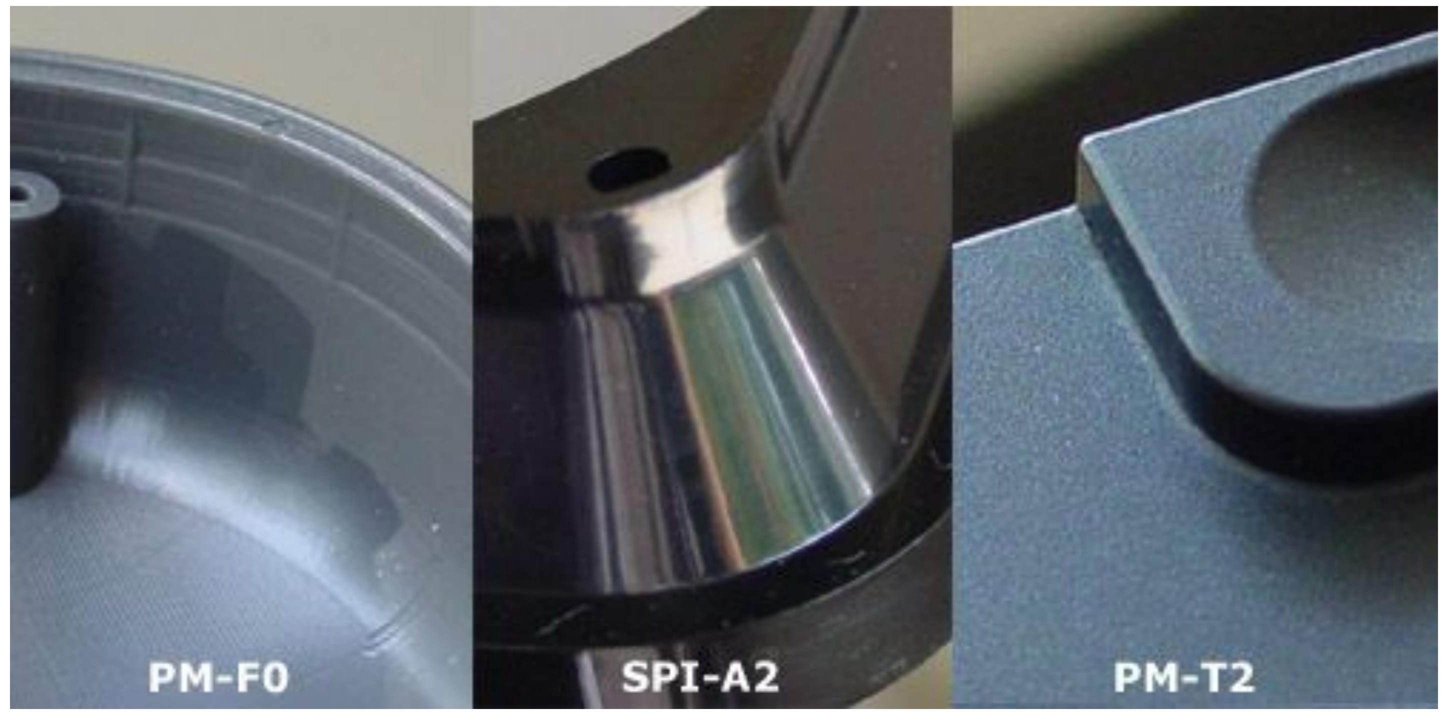


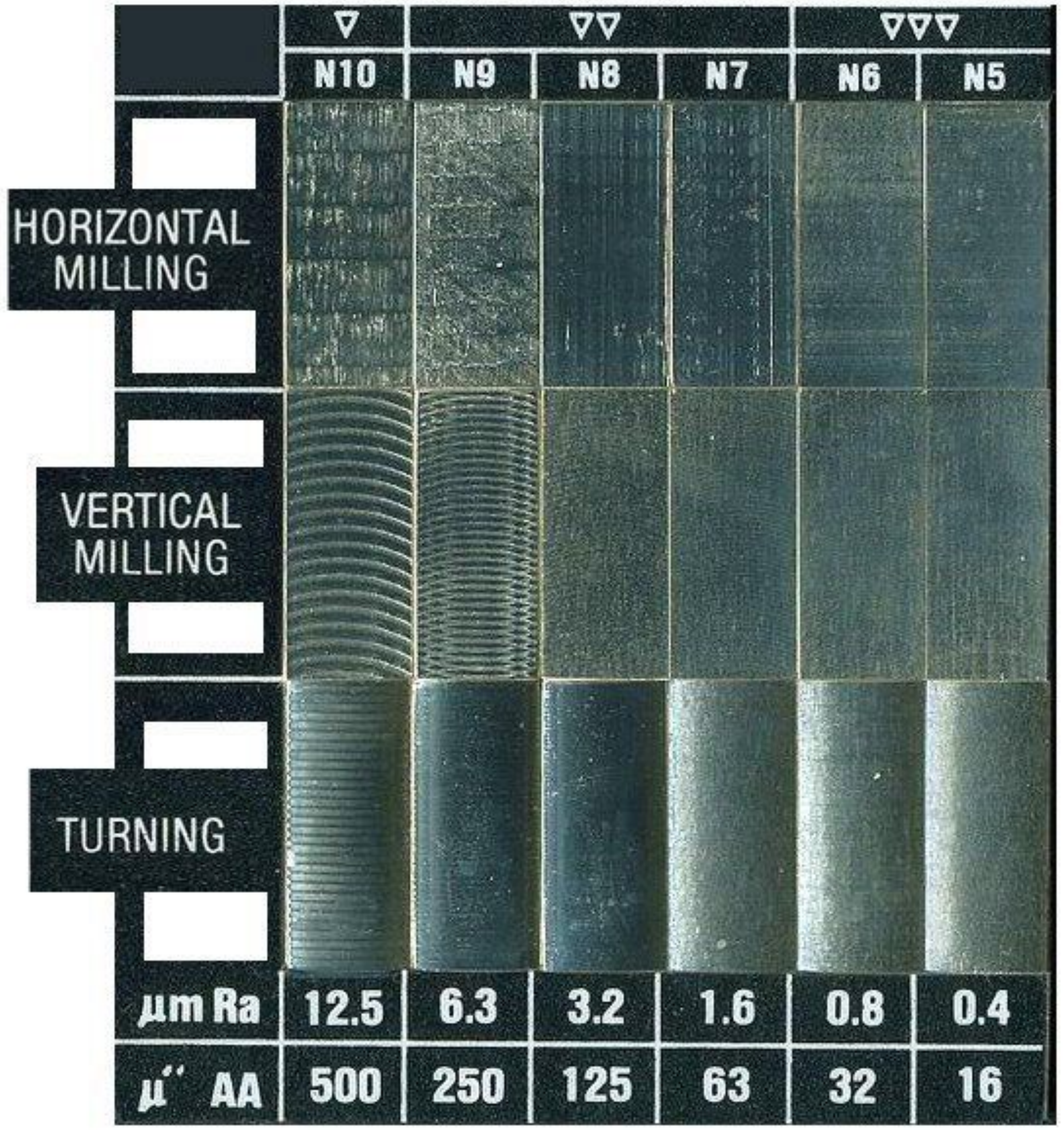


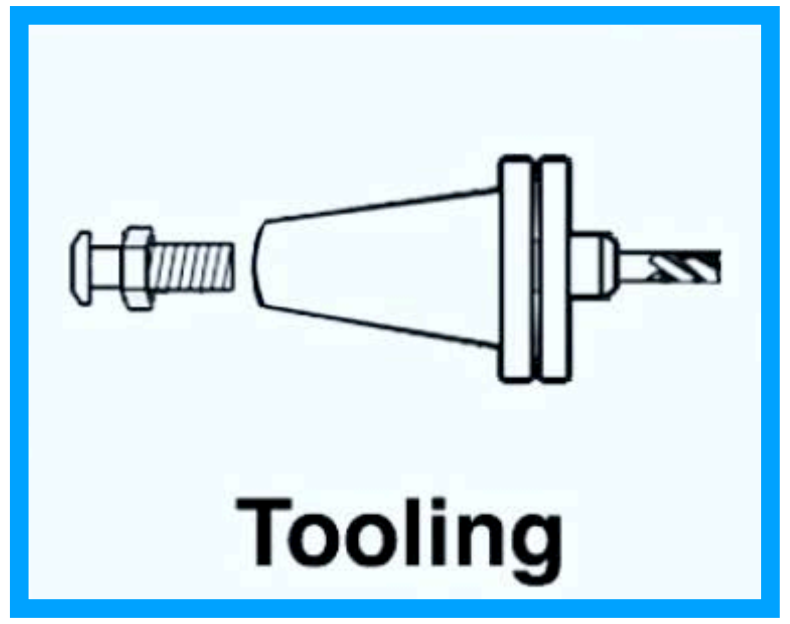
Surface Finish

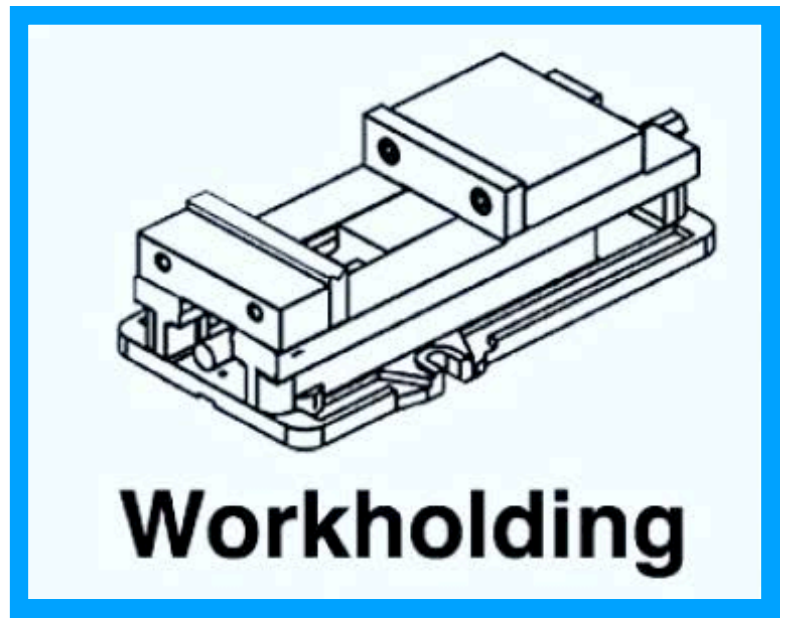
specify what you need, considering time and cost!











Manufacturing Attributes (vs Injection Molding)

Rate	Quality	Flexibility	Cost
low-medium	good!	high	wide range: depends on design, material, volume

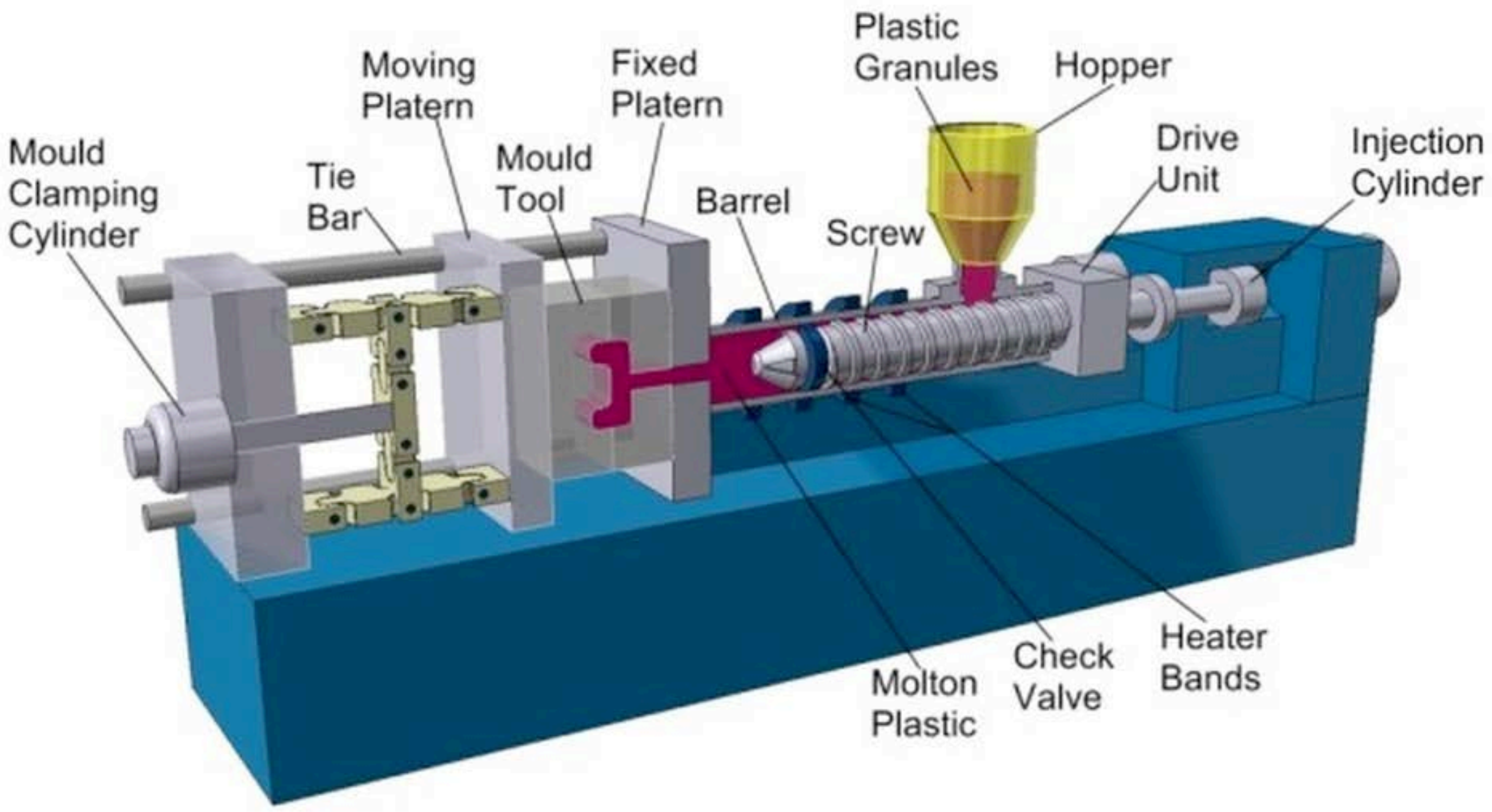


Image Credits

Slide 1:

Slide 8:

Slide 14:

Slide 15:

Slide 20:

Image Credits (cont.)

Image Credits (cont.)

Slide 25:

Slide 28:

Slide 30:

Slide 33:

Image Credits (cont.)

Slide 35:

Slide 37:

Slide 38:

Image Credits (cont.)