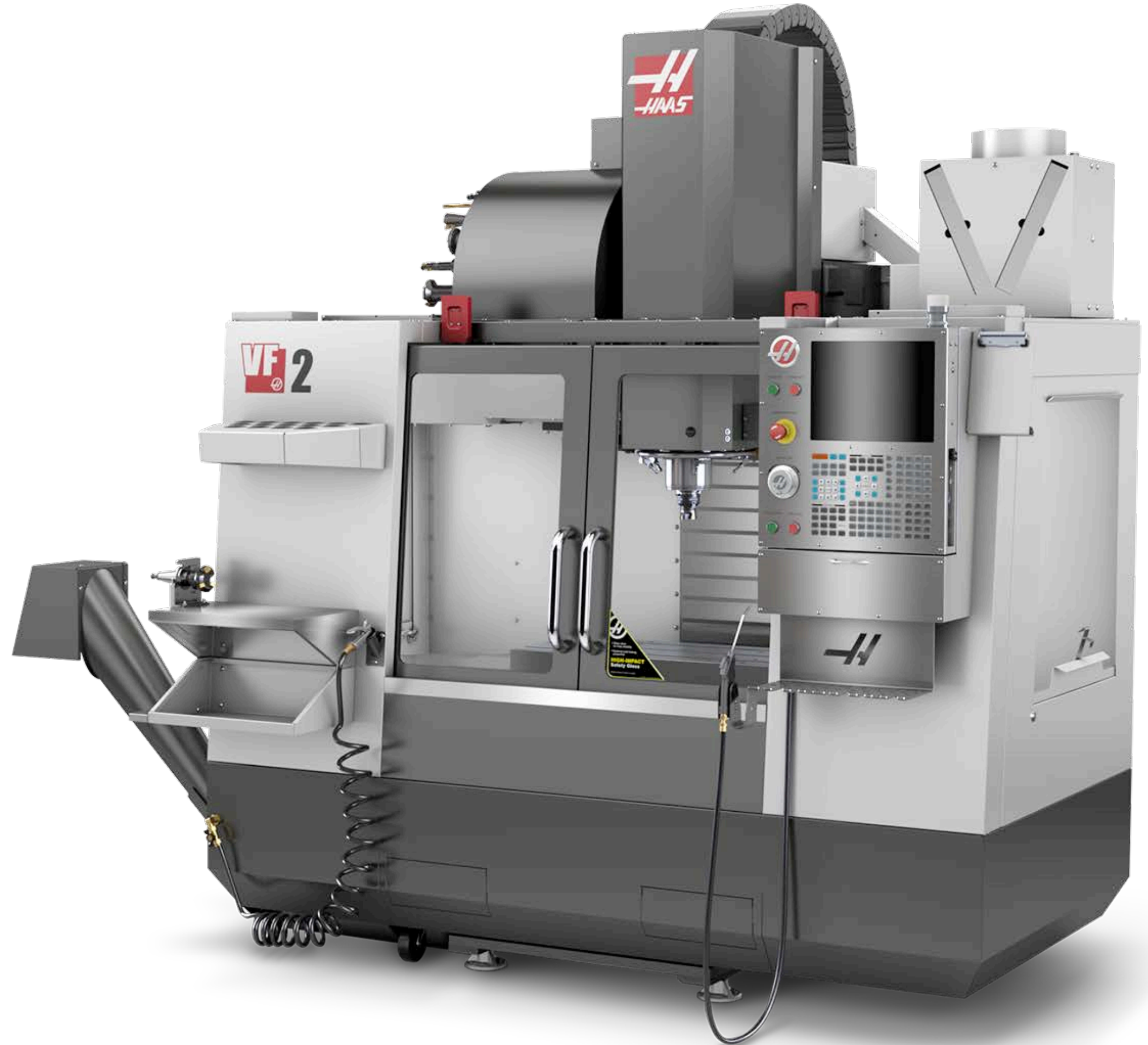


Cutting #3

Machining in Practice

1

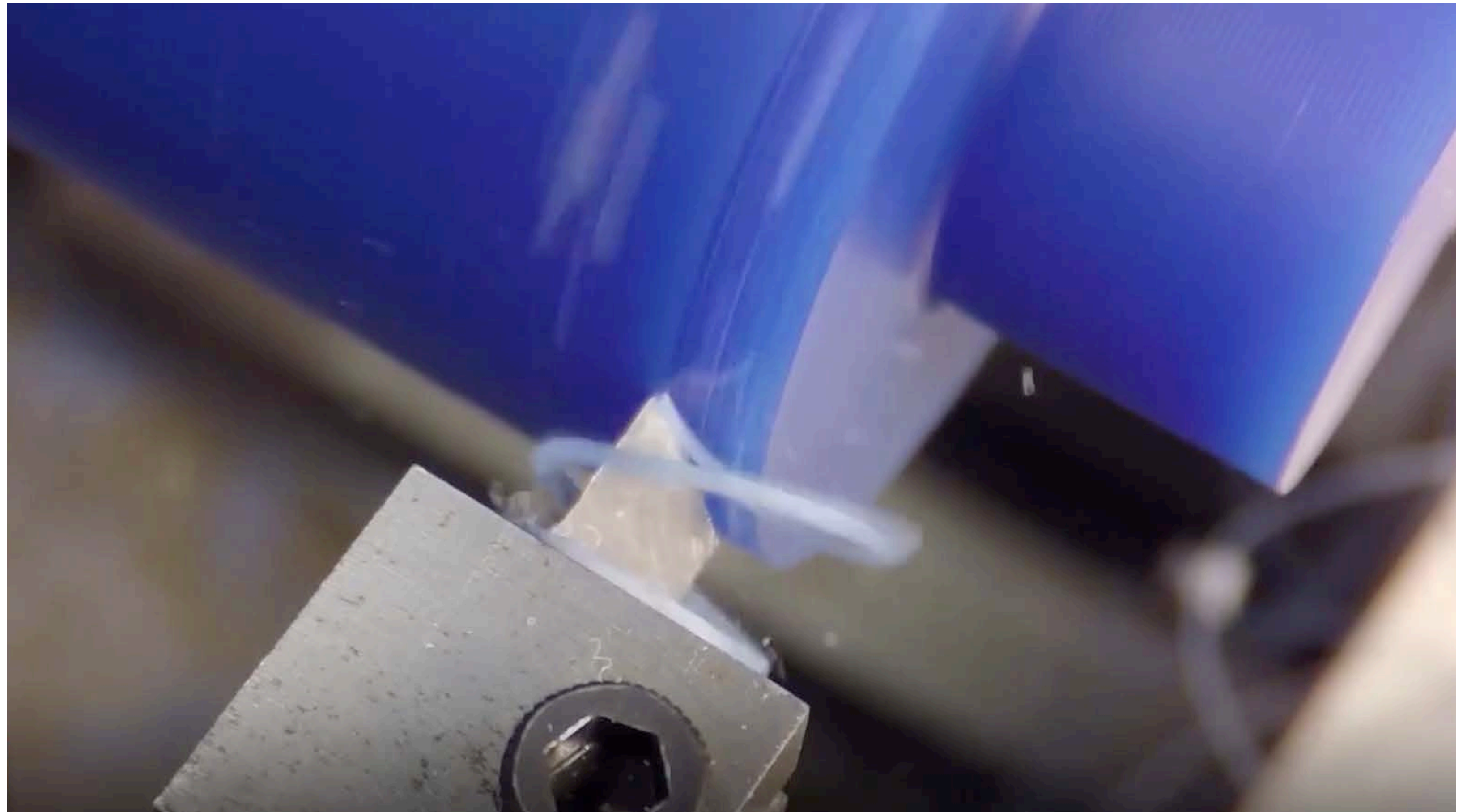
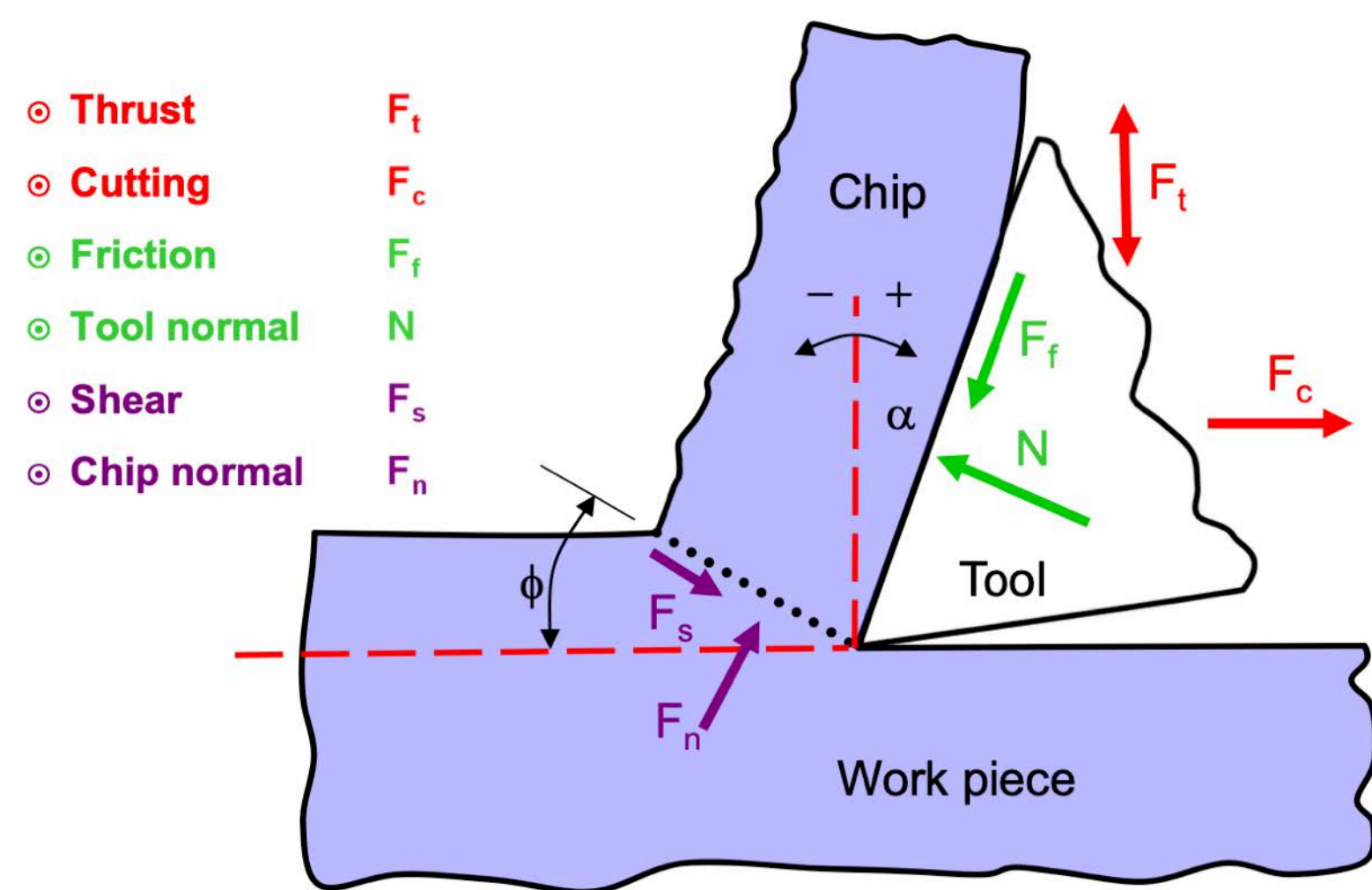


Cutting #3

Machining in Practice

2

Cutting Force Demo



Cutting #3

Machining in Practice

3

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



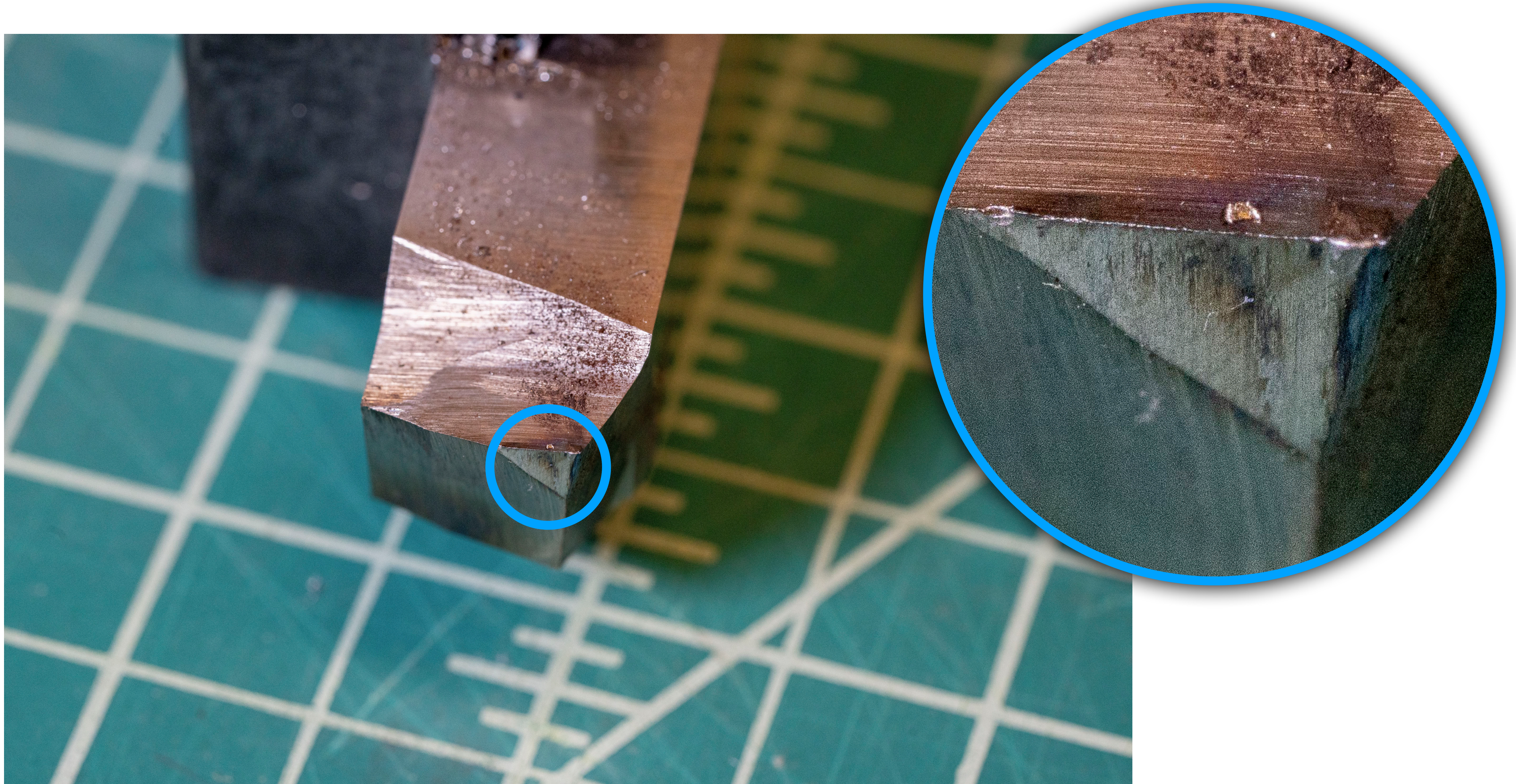
SHARP 1340F

QUANTITY IN LMP SHOP: 6

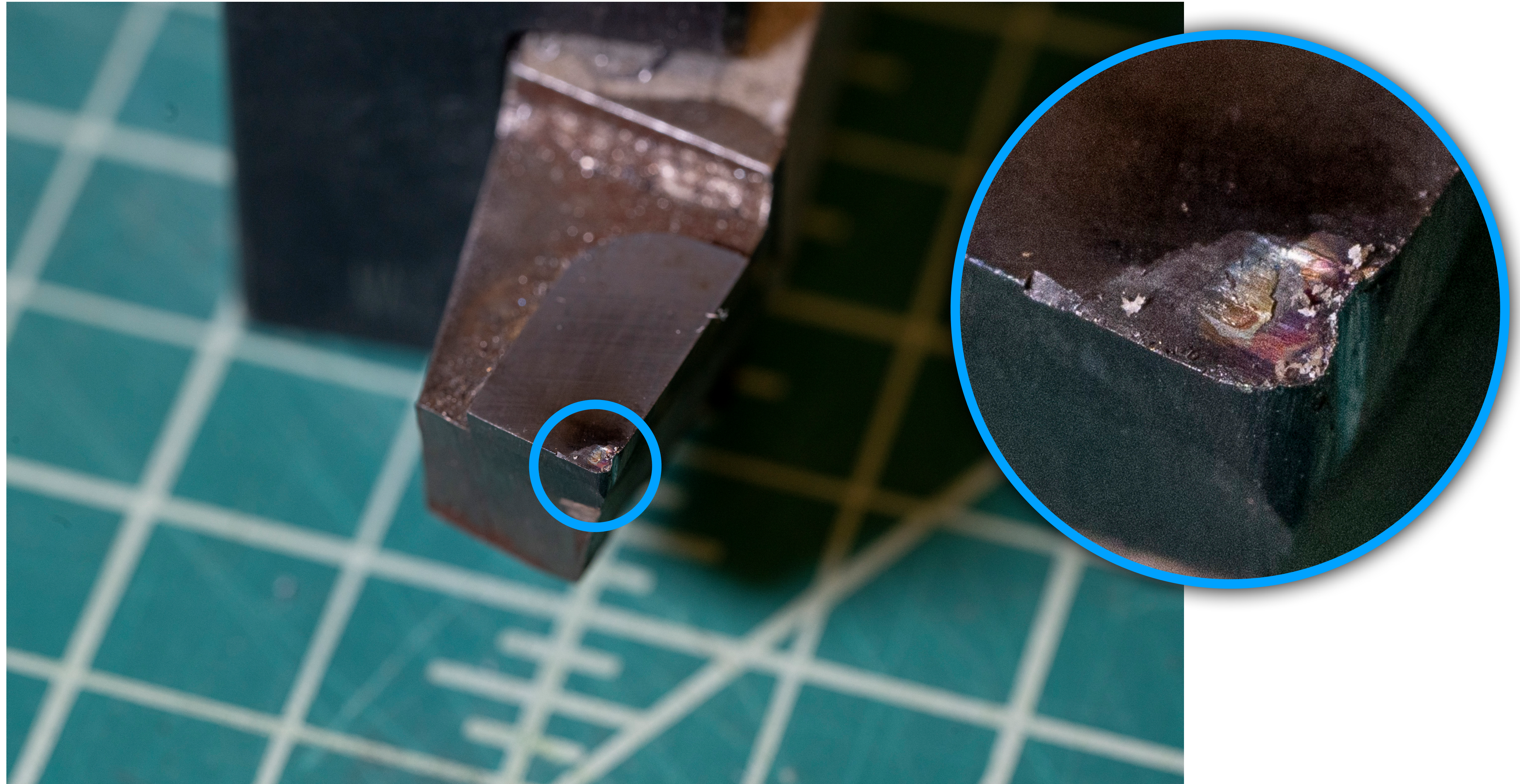
- SWING OVER BED: 13"
- SWING OVER CROSS SLIDE: 7 5/8"
- HEIGHT OF CENTER: 6 1/2"
- DISTANCE BETWEEN CENTERS: 40"
- WIDTH OF BEDWAYS: 8 1/2"
- TOTAL LENGTH OF BED: 66"
- NUMBER OF SPEEDS: 16
- RANGE OF SPEEDS: 45-1800 RPM
- TOTAL TRAVEL OF CROSS SLIDE: 6 1/2"
- TOTAL TRAVEL OF TOP SLIDE: 3 1/2"
- MAX. SIZE CUTTING TOOL: 5/8"

Motor Power: 3HP

Cutting Power Demo: Results



Cutting Power Demo: Results

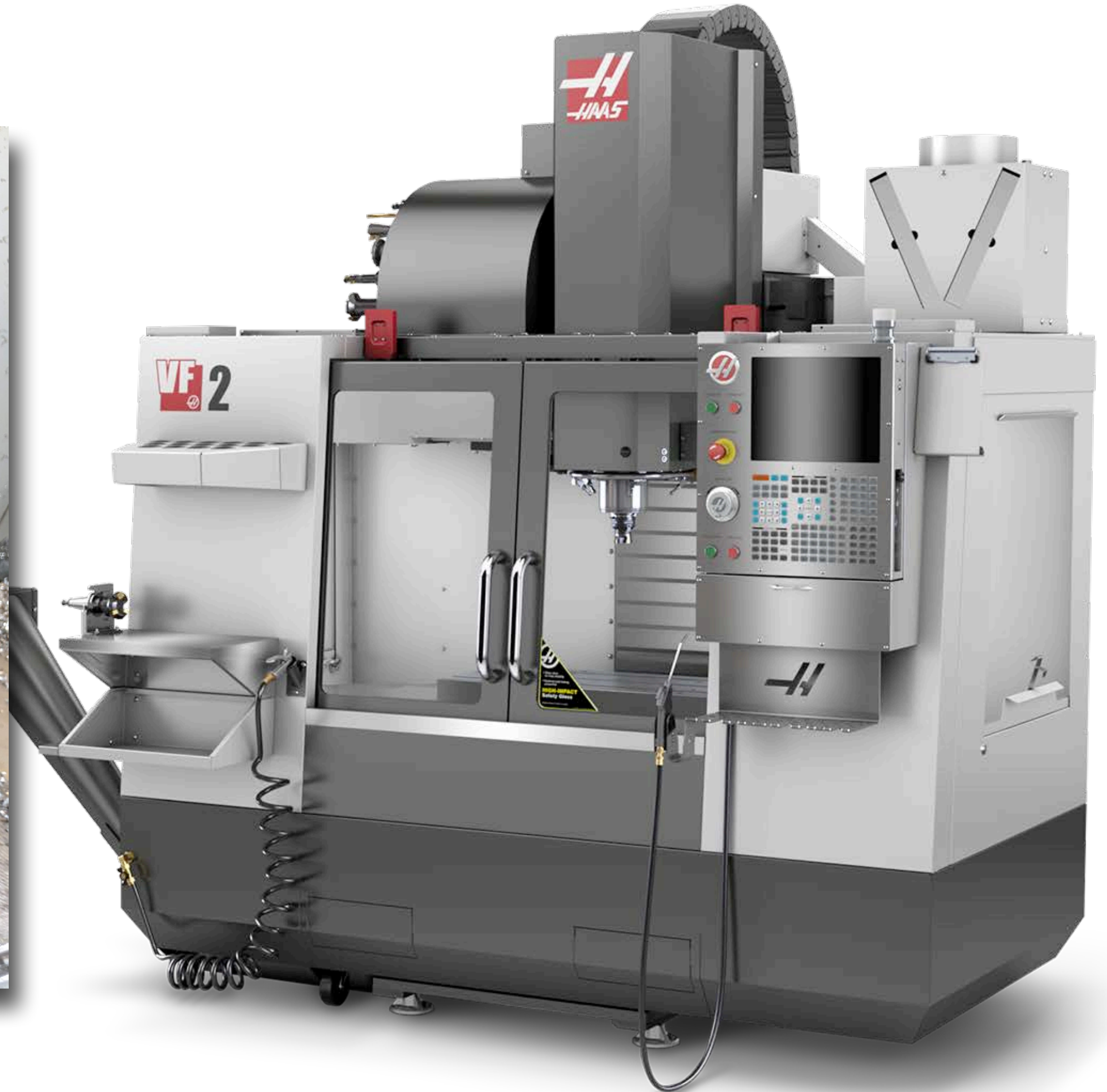
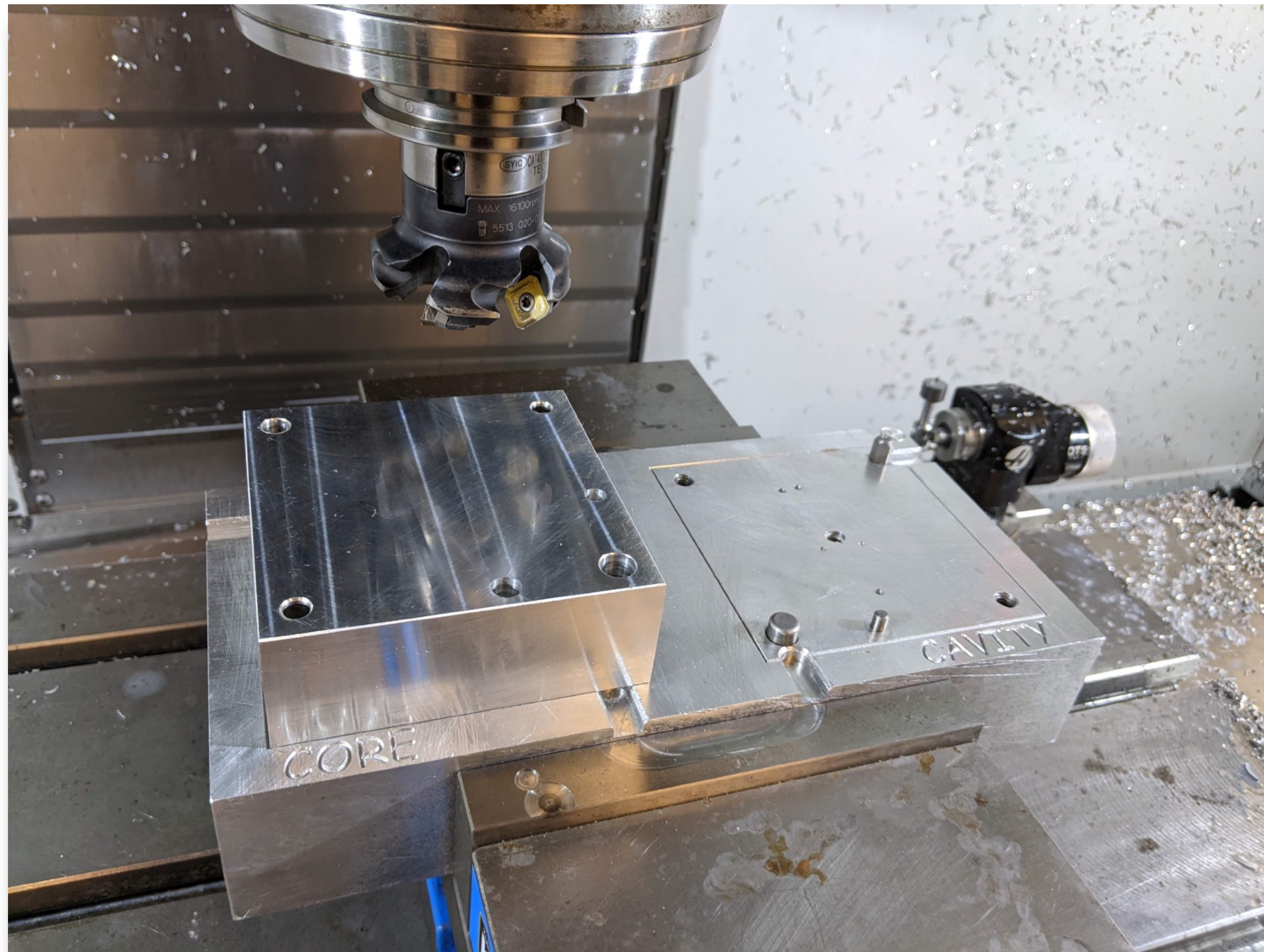


Cutting #3

Machining in Practice

8

Machining in 2.008

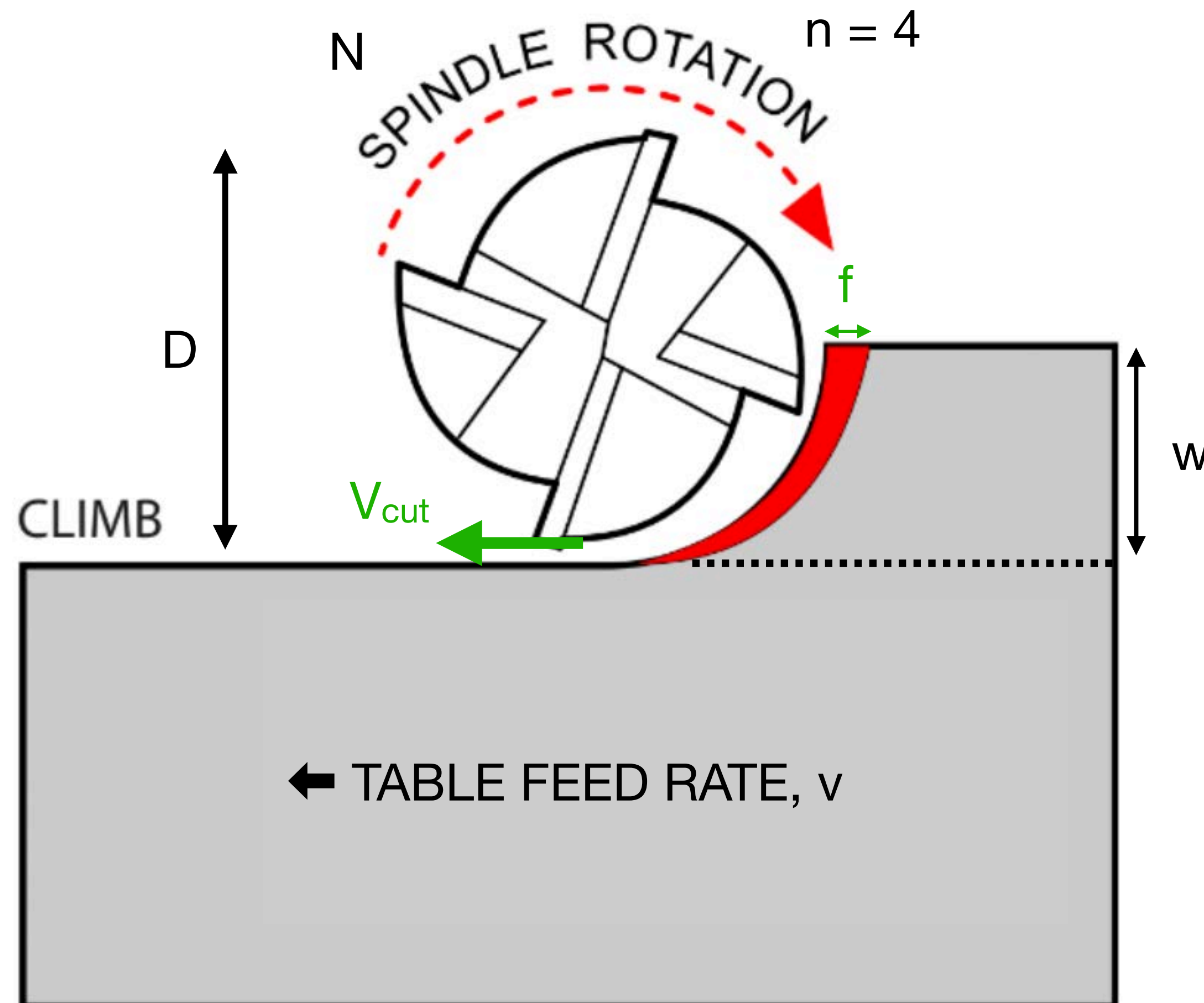


Cutting #1

Machining in Practice

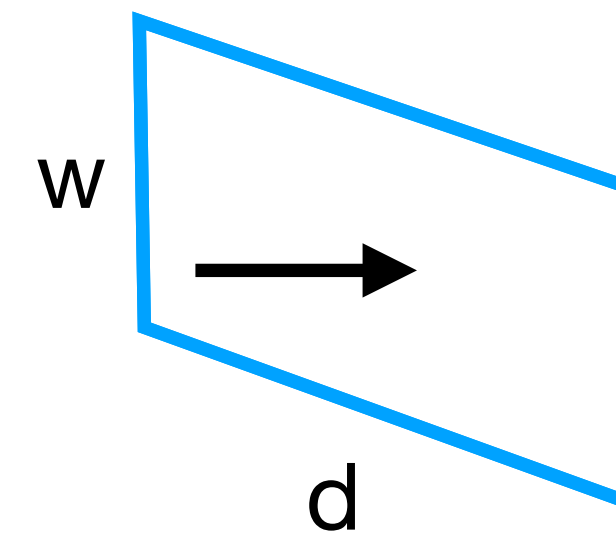
9

Material Removal Rate in Milling



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

$$v_{cut} = \pi DN$$



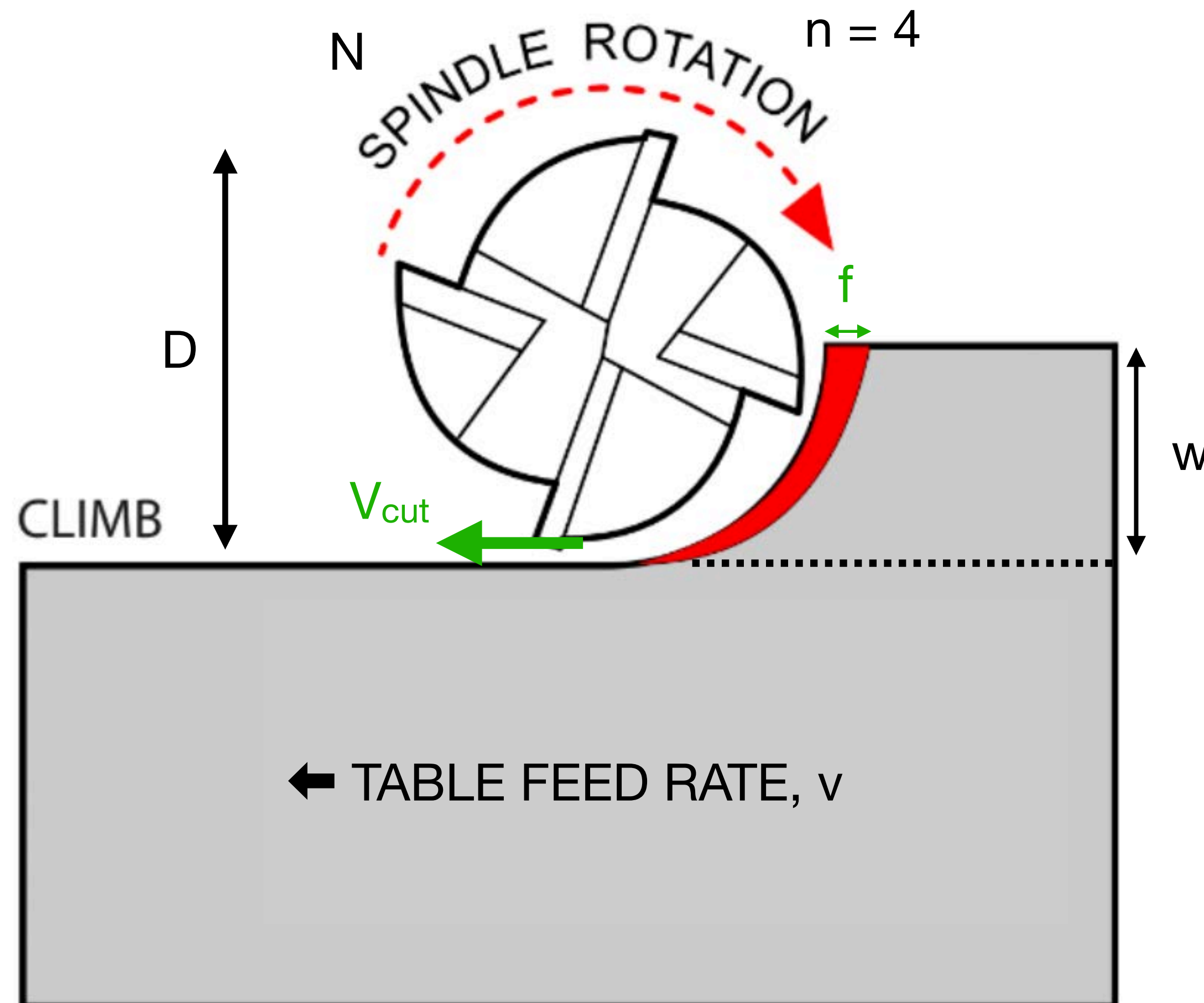
f: feed per tooth [in/tooth]
n: number of teeth [#]
N: spindle speed [rpm]
v: feed rate, velocity of tool (center) relative to workpiece [in/min]
w: width of cut [in]
d: depth of cut [in]
D: cutter diameter [in]

Cutting #1

Machining in Practice

10

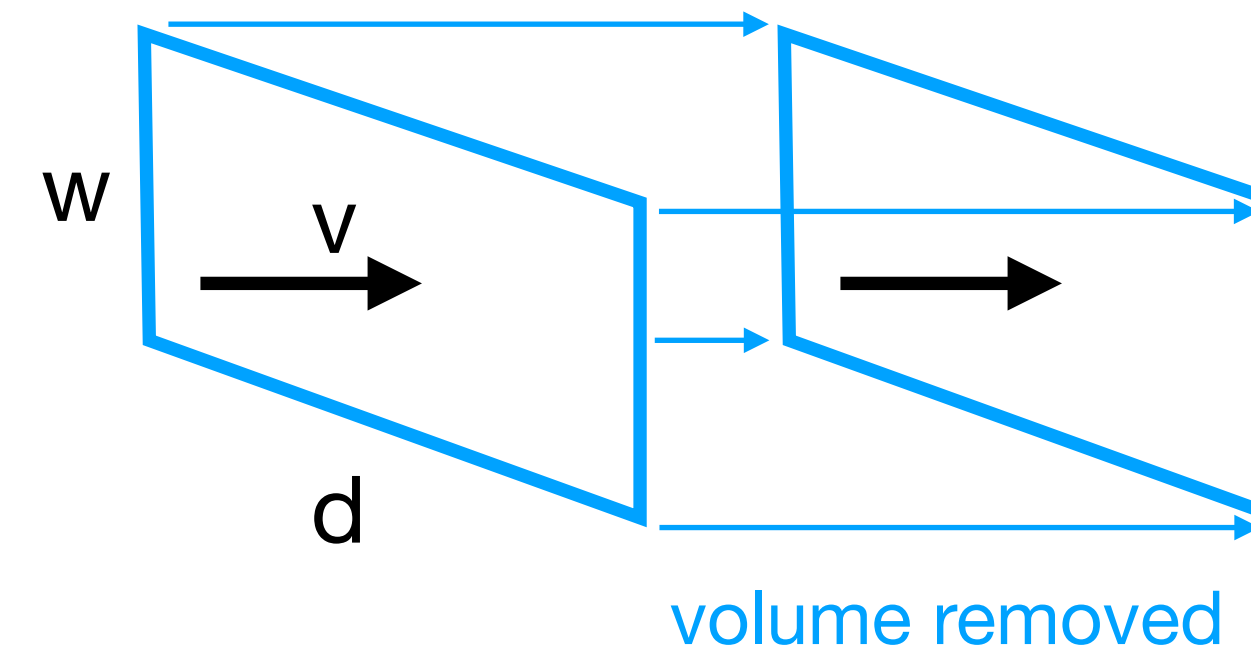
Material Removal Rate in Milling



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

$$v_{cut} = \pi DN$$

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]



$$MRR_{milling} = wdv$$

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

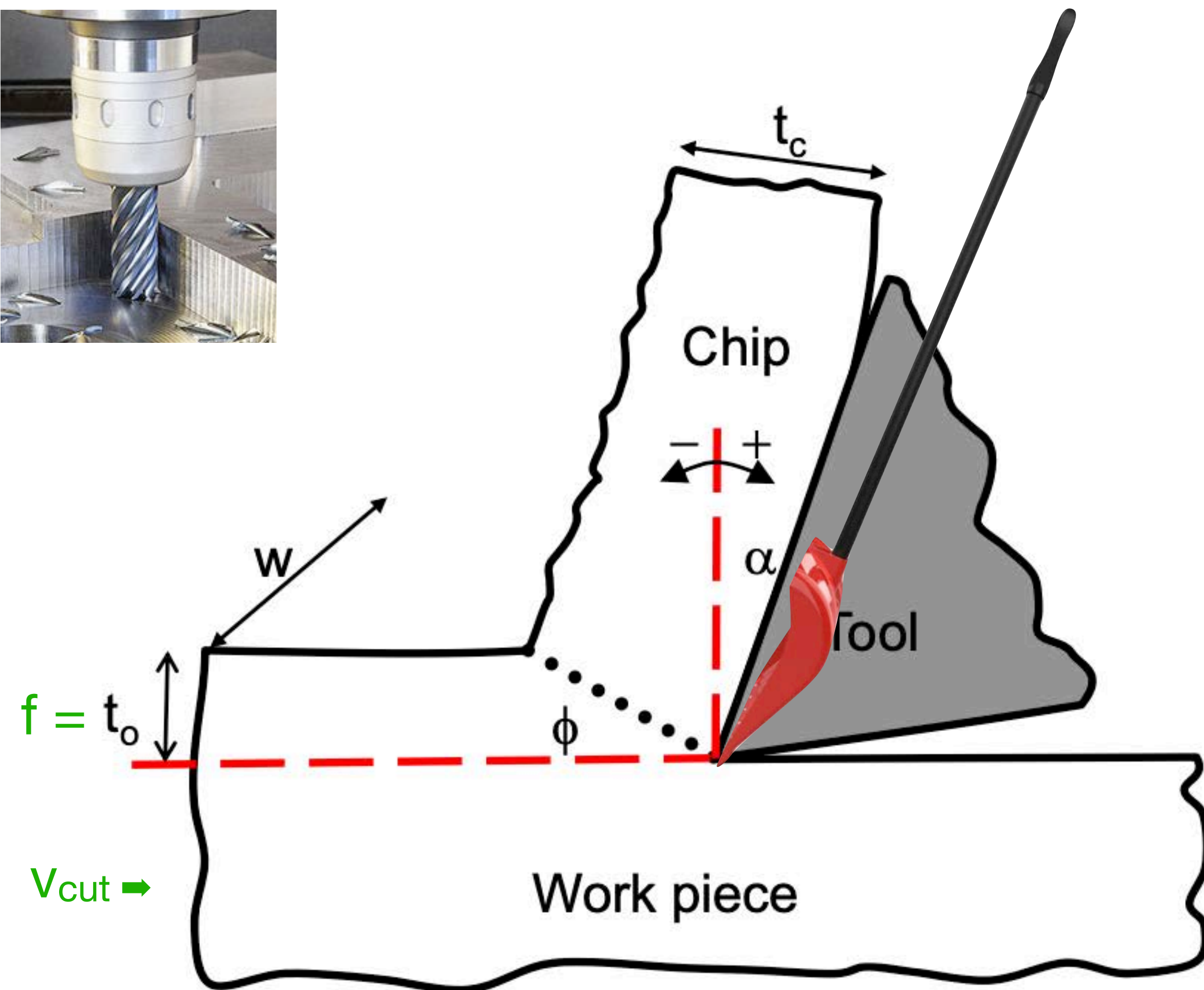
Power: total cutting power from machine [W]
u: specific energy of the material [W-s/mm³]
MRR: material removal rate [mm³/s]

Cutting #1

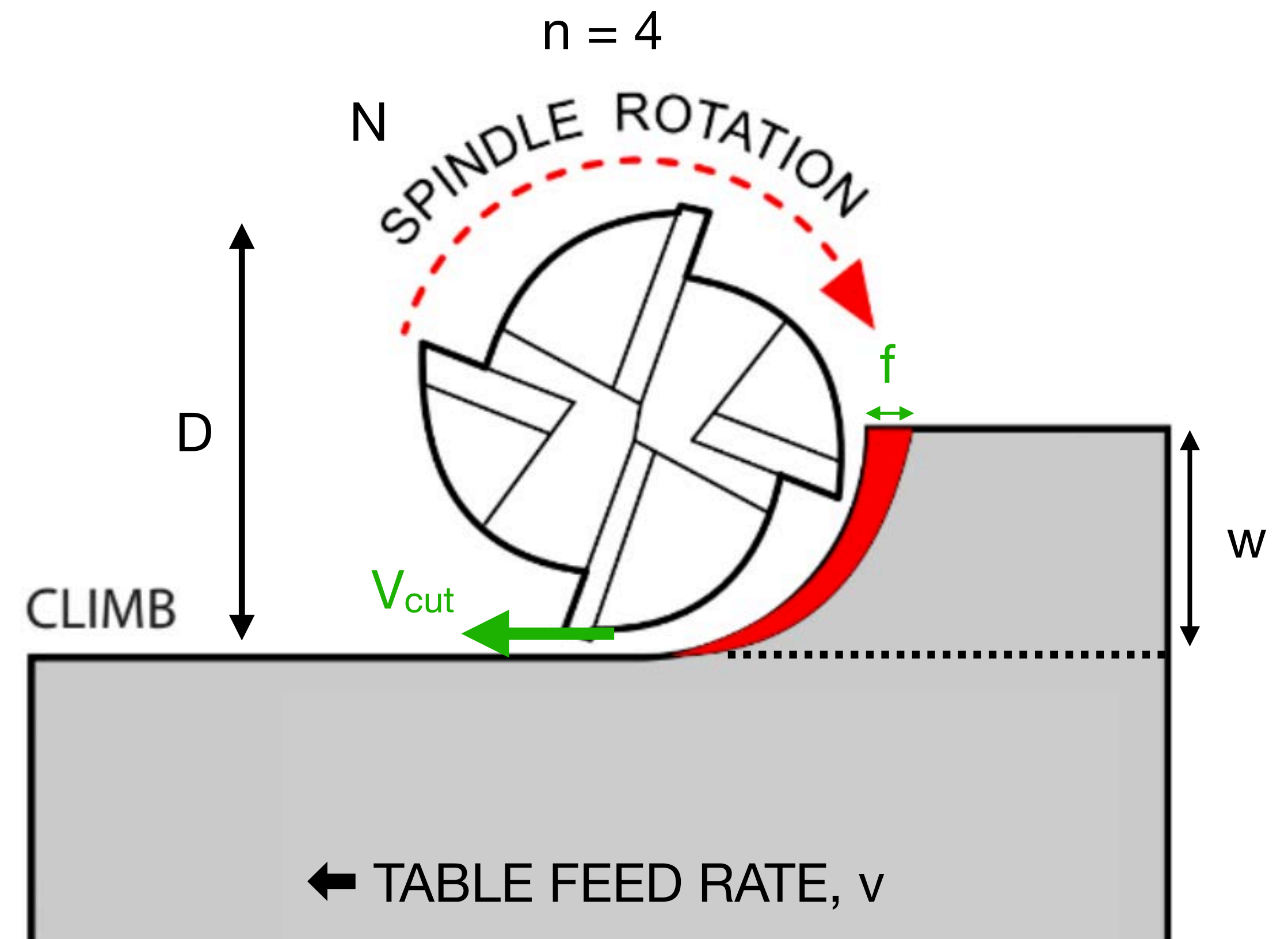
Cutting Analysis: Mechanics, Forces, and Power

11

Milling



⚠ looking down the spindle from above the machine

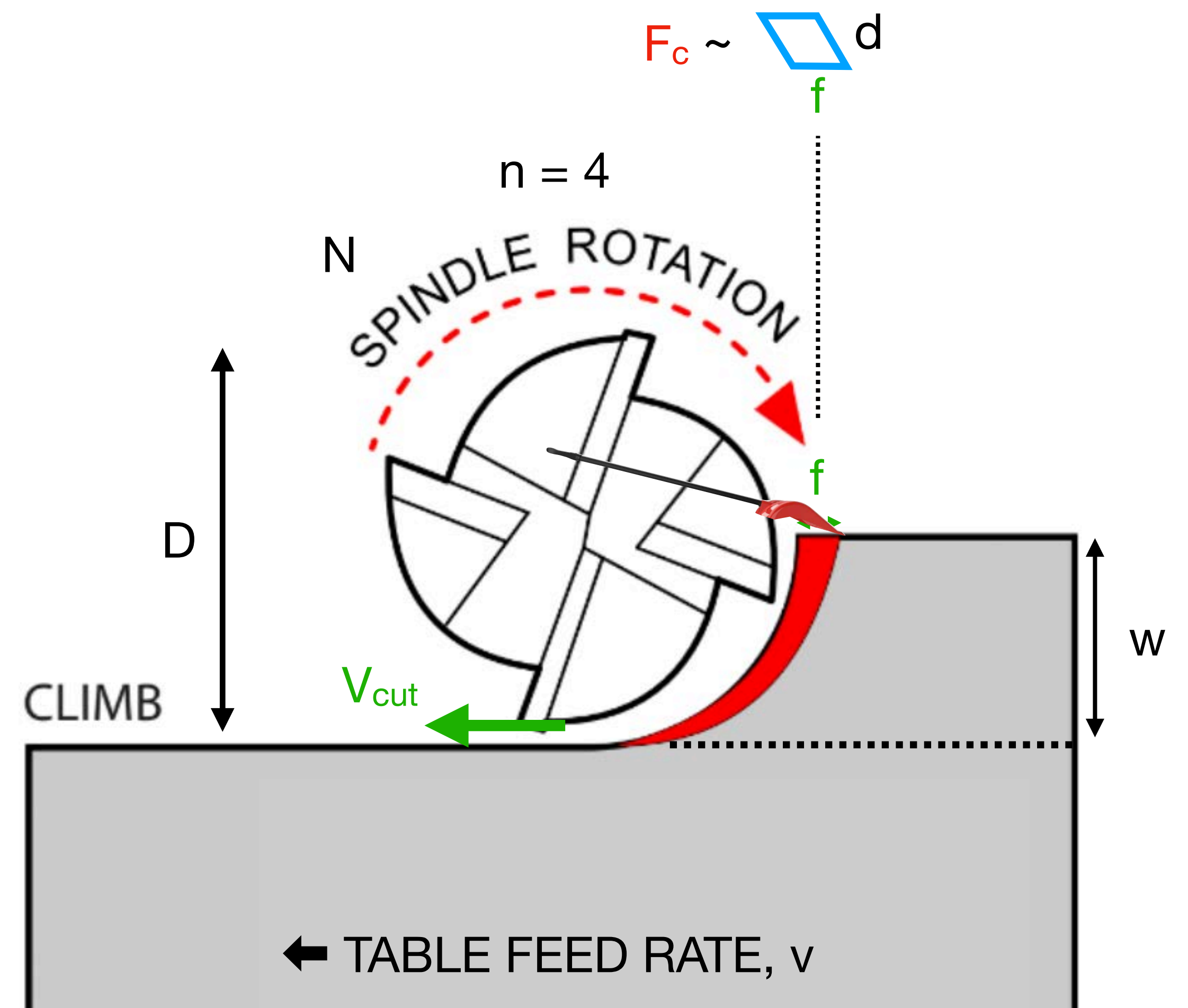
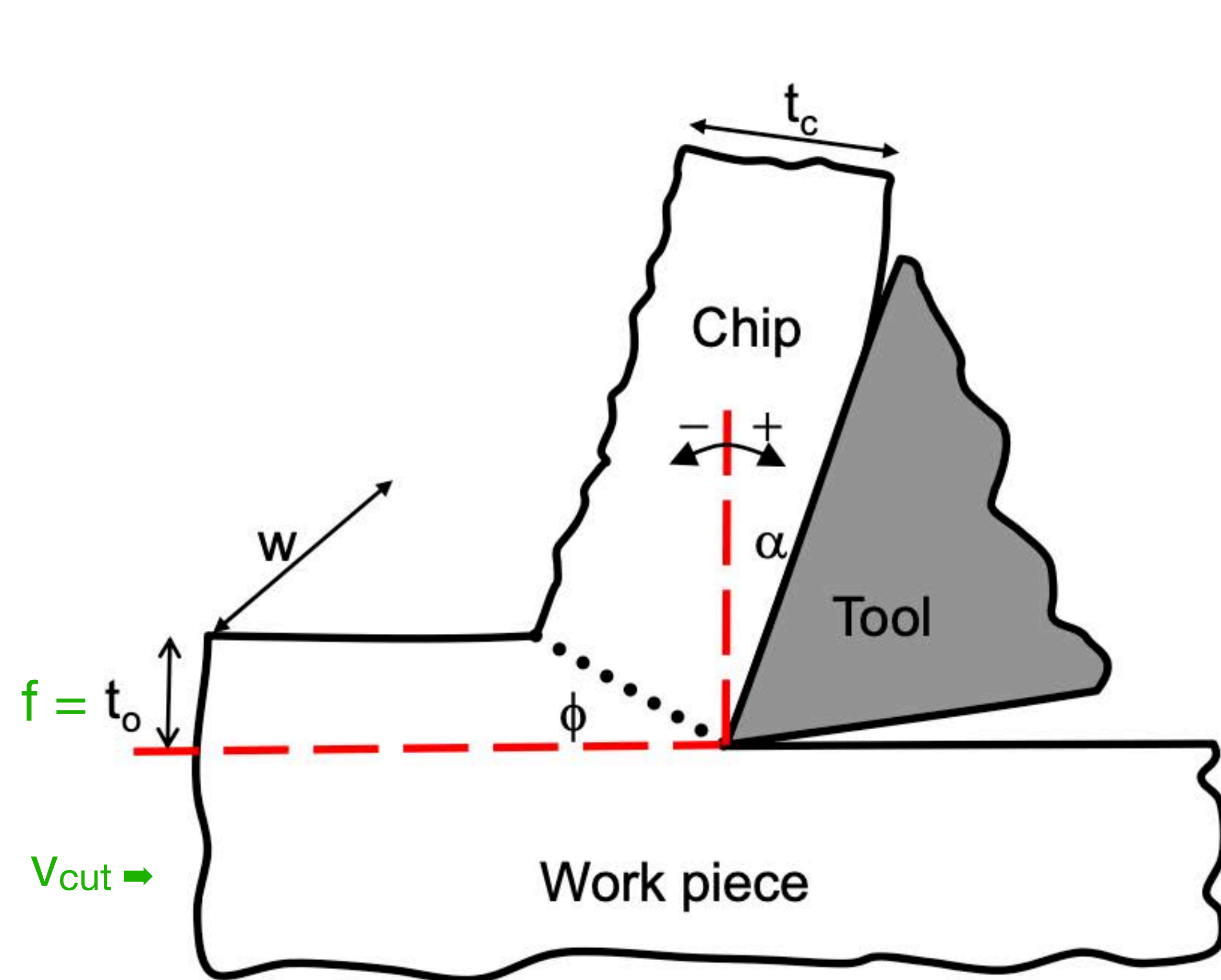


Cutting #1

Cutting Analysis: Mechanics, Forces, and Power

12

Milling



Cutting #1

Cutting Analysis: Mechanics, Forces, and Power

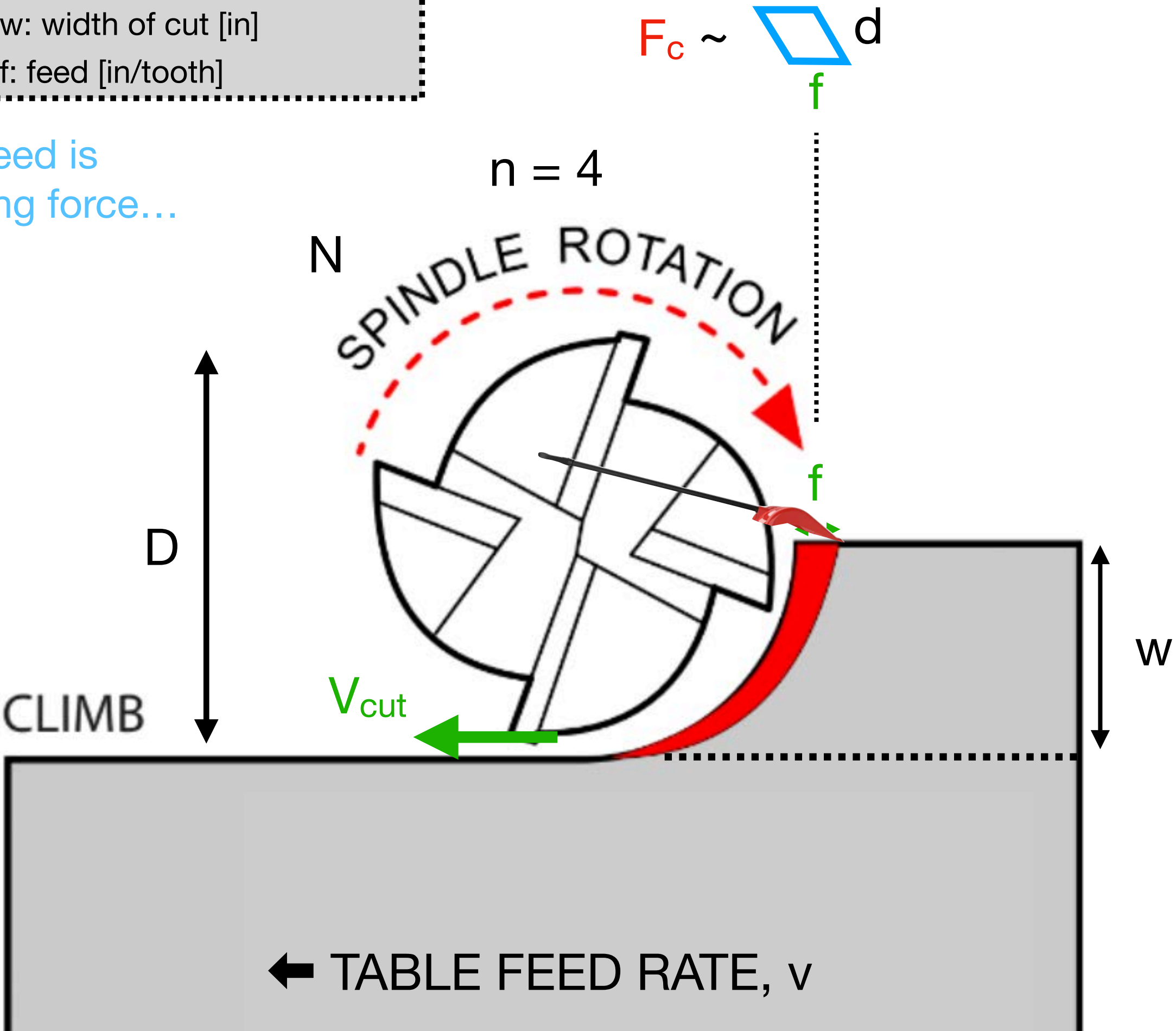
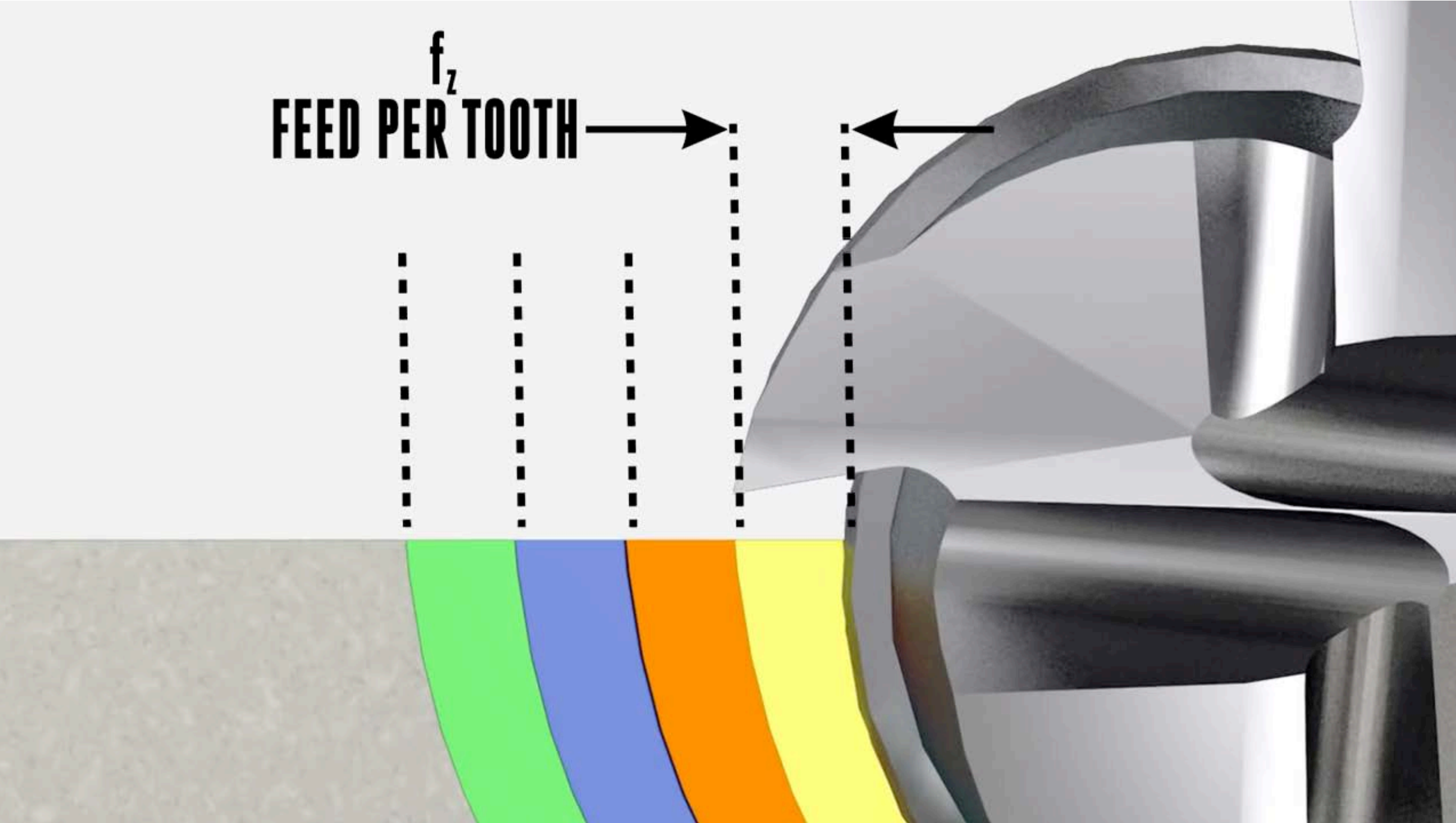
Cutting Forces in Milling

⚠ 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...

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

$F_c \sim \begin{matrix} \text{blue parallelogram} \\ f \end{matrix} d$



Specific Energy

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

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

volume → volume flow “Material Removal Rate”

energy → 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	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

Cutting #3

Forces and Power Demos

Specific Energy: Milling



ADAPTIVE : ADAPTIVE2

Tool

Select...

#6 - Ø3/8" flat (End Mill)

Coolant

Flood

Feed & Speed

Default Preset

Spindle Speed: 6000 rpm

Surface Speed: 589.049 ft/min

Ramp Spindle Speed: 6000 rpm

Cutting Feedrate: 120 in/min

Feed per Tooth: 0.00111111 in

Lead-In Feedrate: 16 in/min

Lead-Out Feedrate: 16 in/min

Transition Feedrate: 20 in/min

Ramp Feedrate: 16 in/min

Plunge Feedrate: 16 in/min

Plunge Feed per Revolution: 0.00266667 in

Shaft & Holder

OK

Cancel

ADAPTIVE : ADAPTIVE2

Passes

Tolerance: 0.004 in

Machine Shallow Areas

Optimal Load: 0.15 in

Both Ways

Minimum Cutting Radius: 0.0375 in

Machine Cavities

Use Slot Clearing

Direction: Climb

Maximum Roughing Stepdown: 0.5625 in

Fine Stepdown: 0.05625 in

Flat Area Detection

Minimum Stepdown: 3.93701e-06 in

Minimum Axial Engagement: 0 in

Order by Depth

Order By Area

Stock to Leave

Radial Stock to Leave: 0.02 in

Axial Stock to Leave: 0.02 in

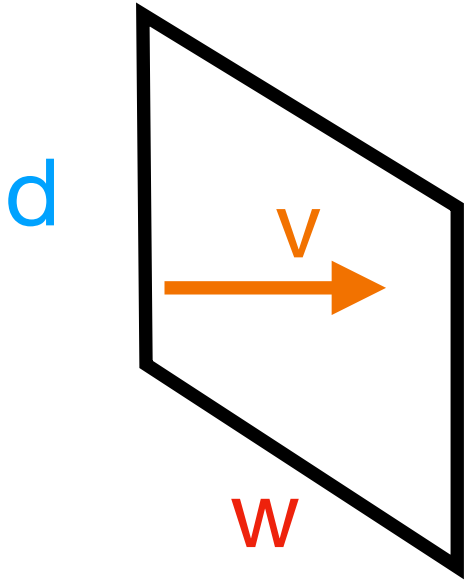
Fillets

Smoothing

Feed Optimization

OK

Cancel



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

(w)(d)(v) = (0.15)(0.5625)(120) in³/min

(w)(d)(v) = **10.1** in³/min

Material	Specific energy	
	W-s/mm³	hp-min/in³
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)

Cutting #3

Machining in Practice

17

HAAS video highlights



Cutting #3

Machining in Practice

18

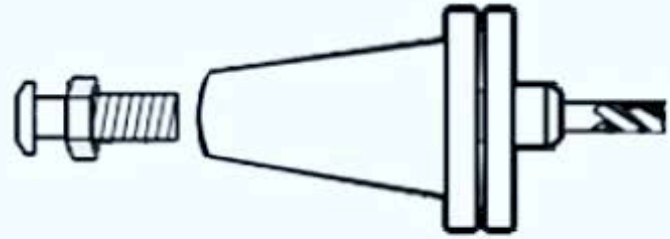
HAAS video highlights



Cutting #3

Machining in Practice

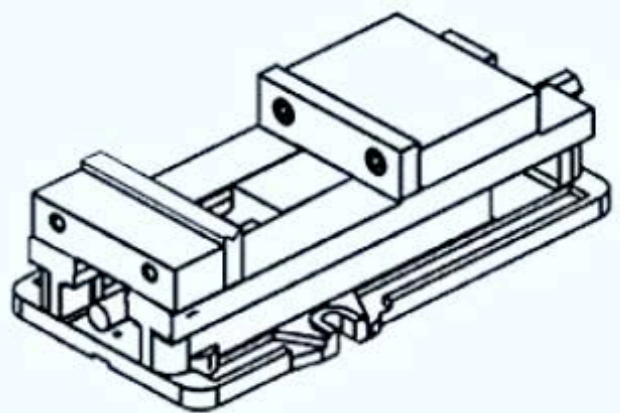
19



Tooling

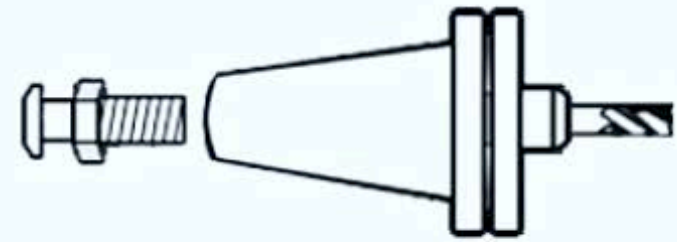


Program



Workholding

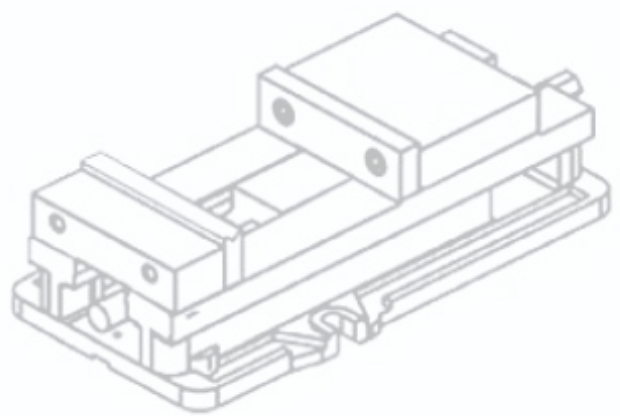
Tool Selection



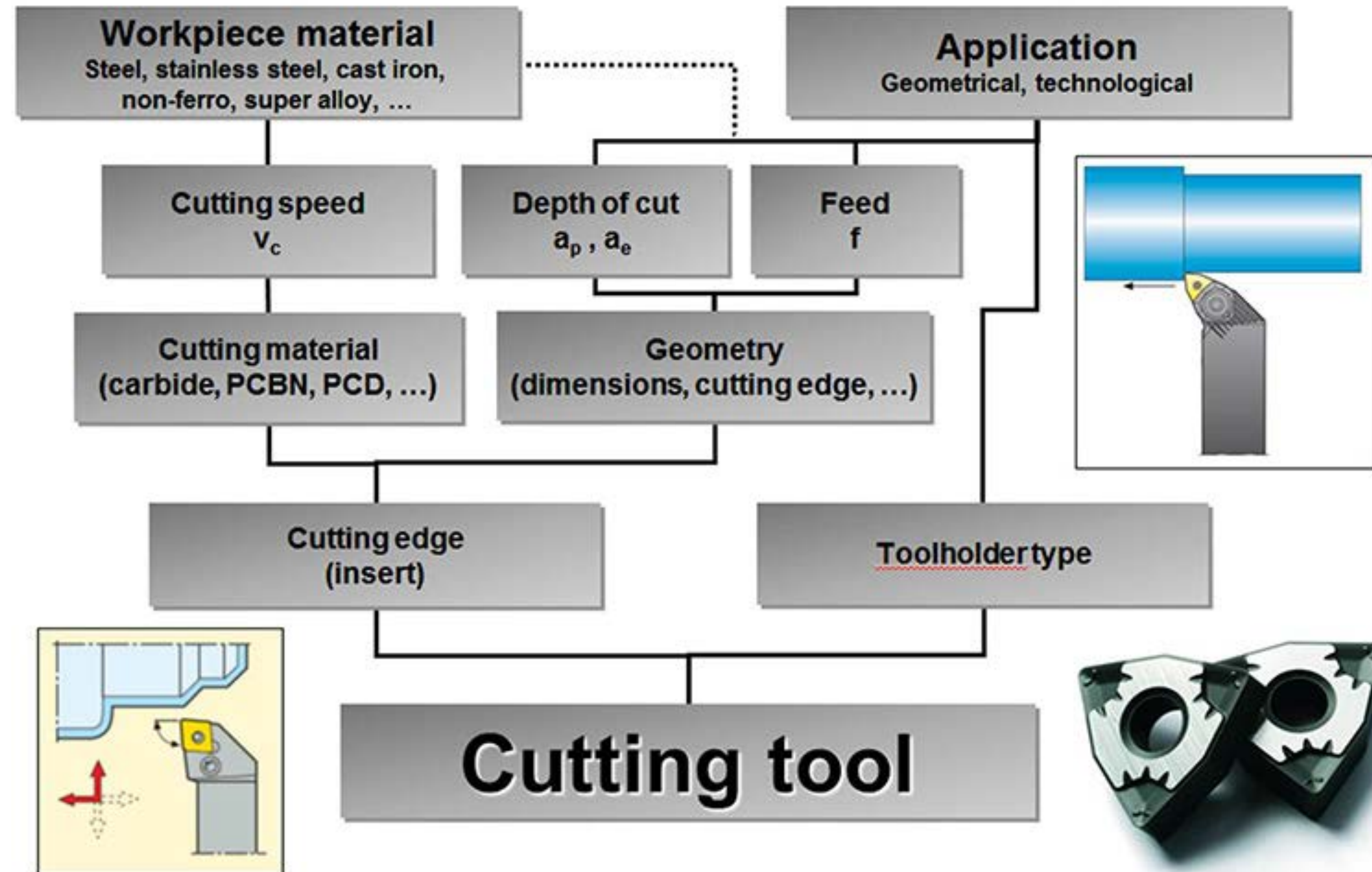
Tooling



Program



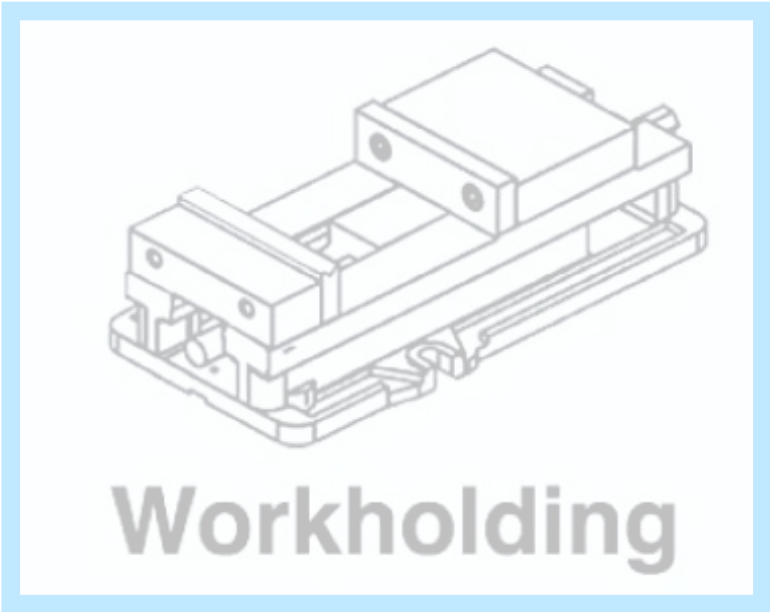
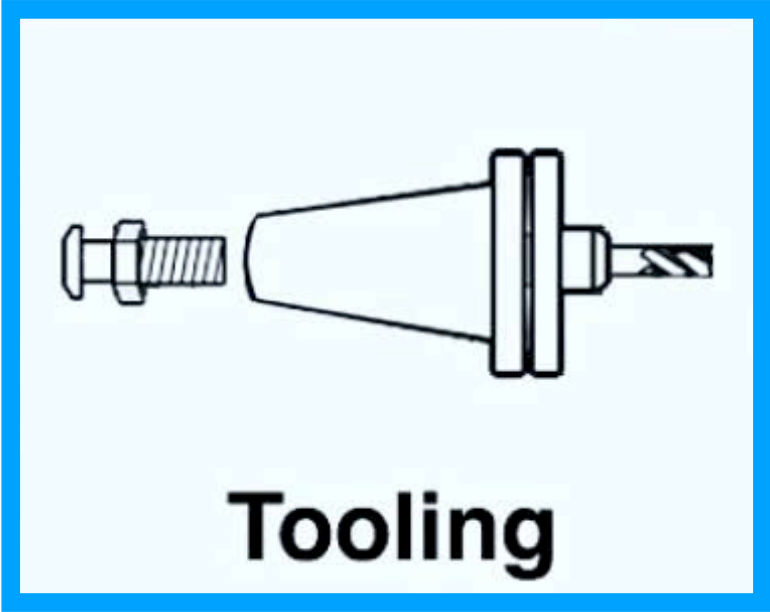
Workholding



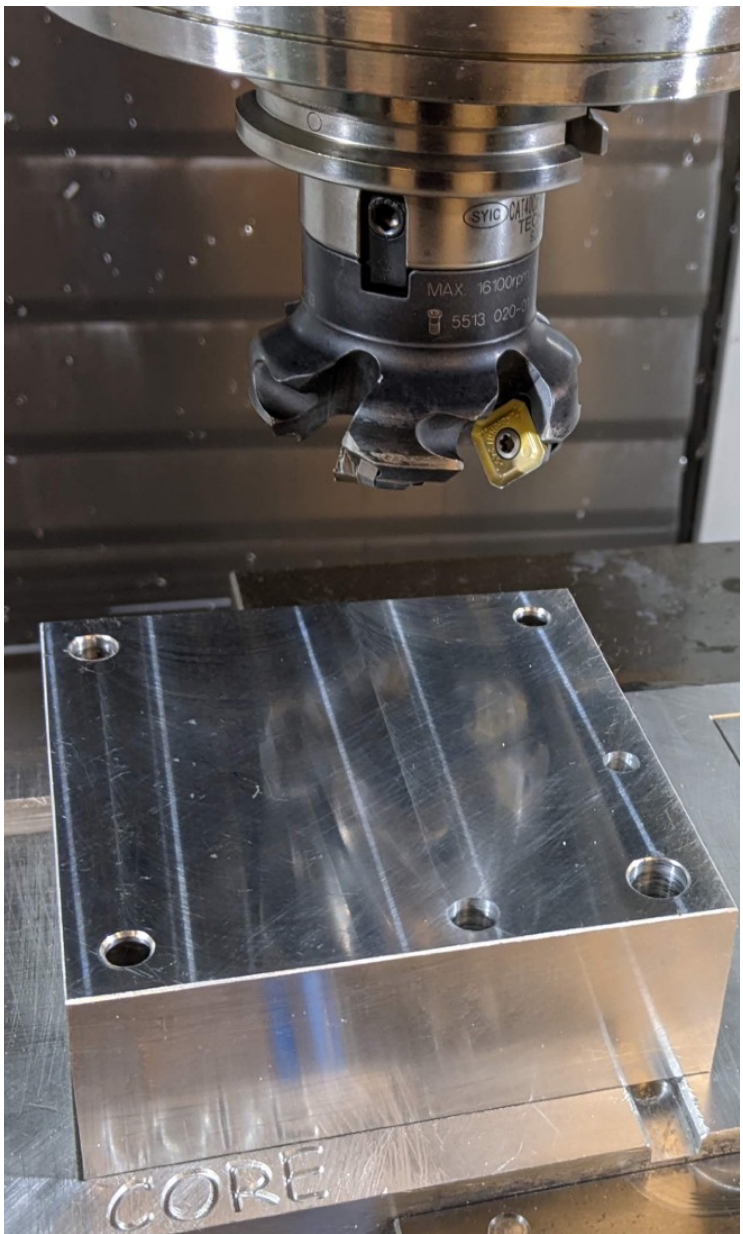
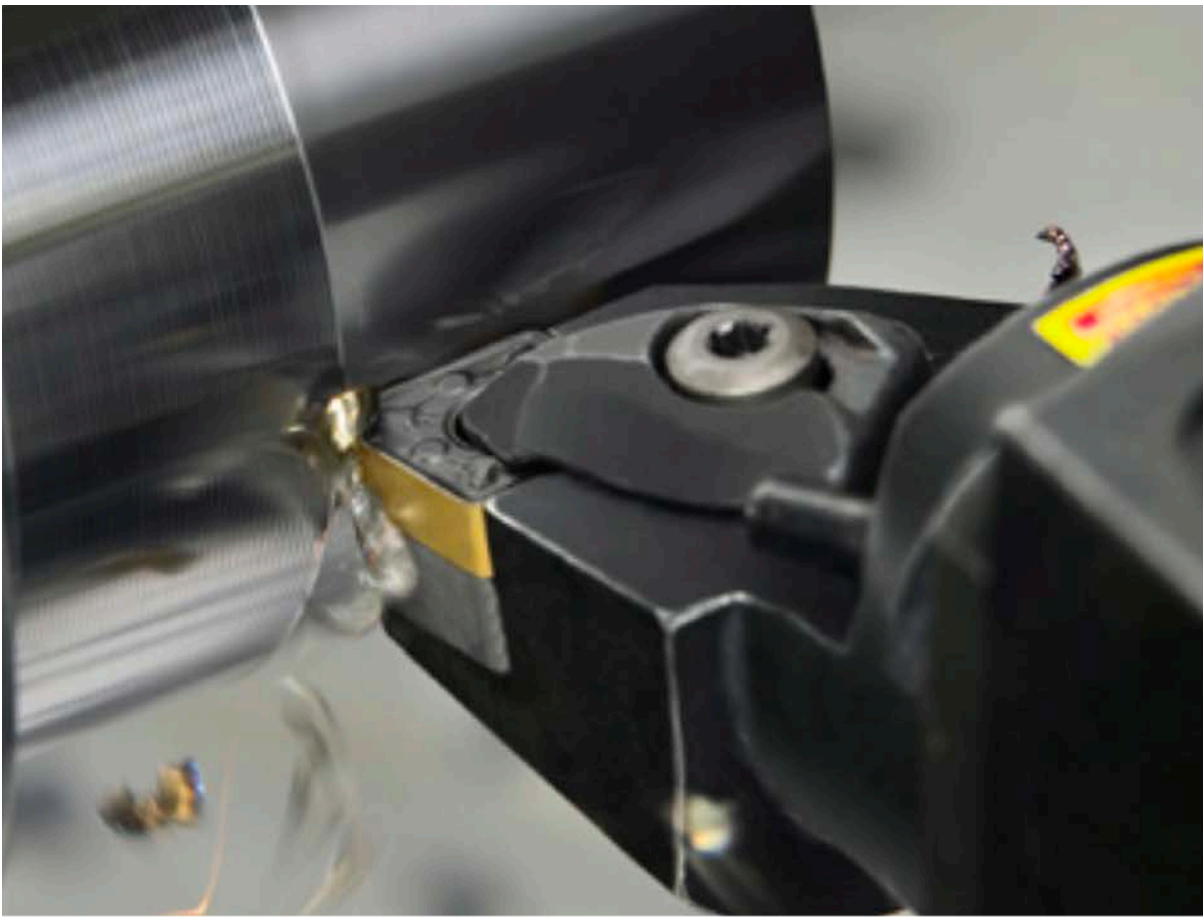
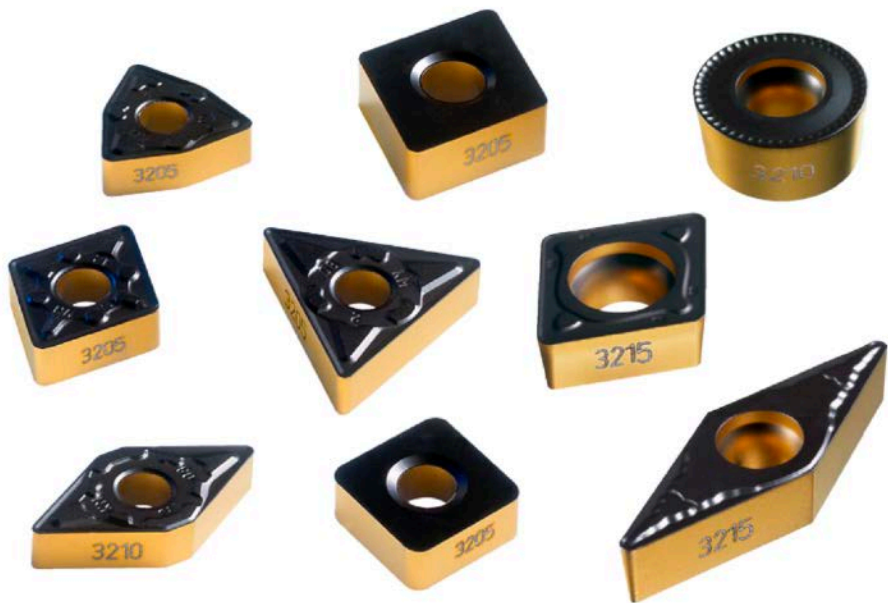
Cutting #3

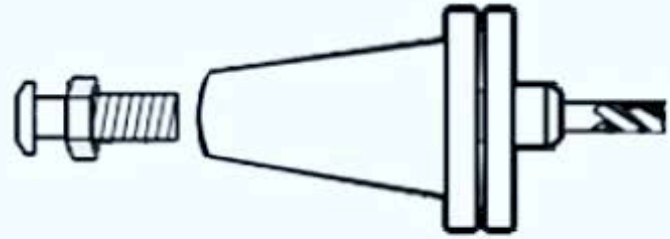
Machining in Practice

Tool Types



tool examples
can be passed
around!

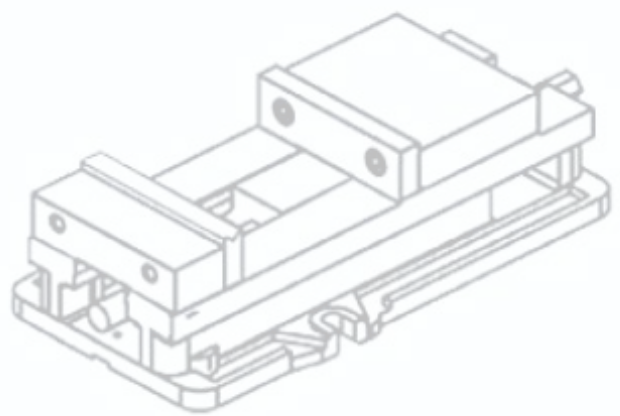




Tooling



















Program



Workholding

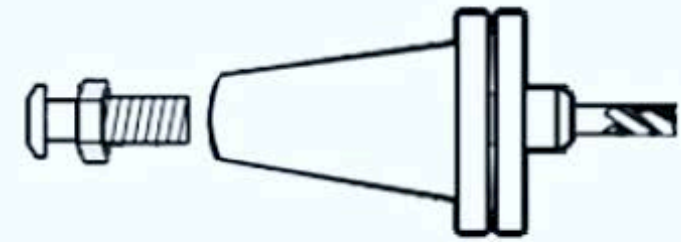
Tool Restrictions

	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

Cutting #3

Machining in Practice

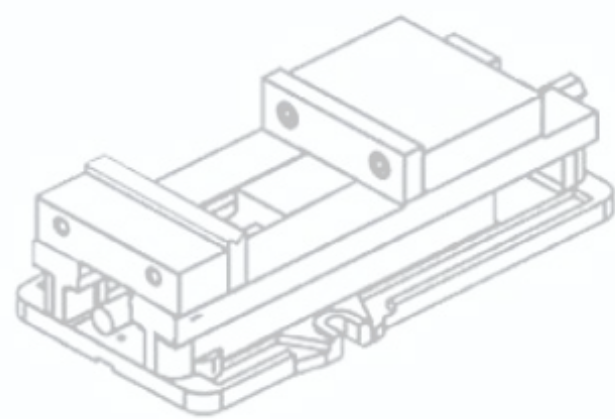
23



Tooling

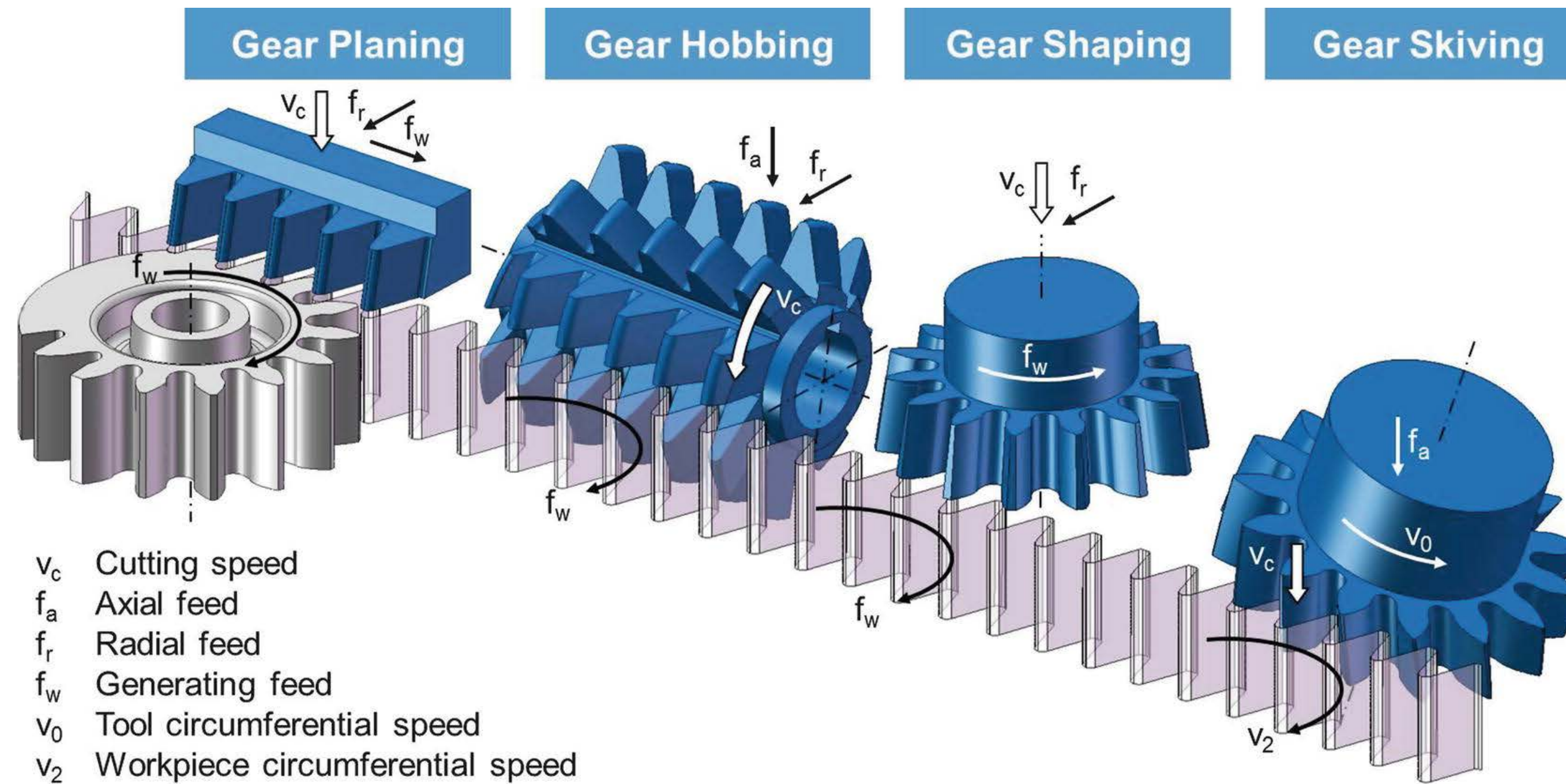


Program



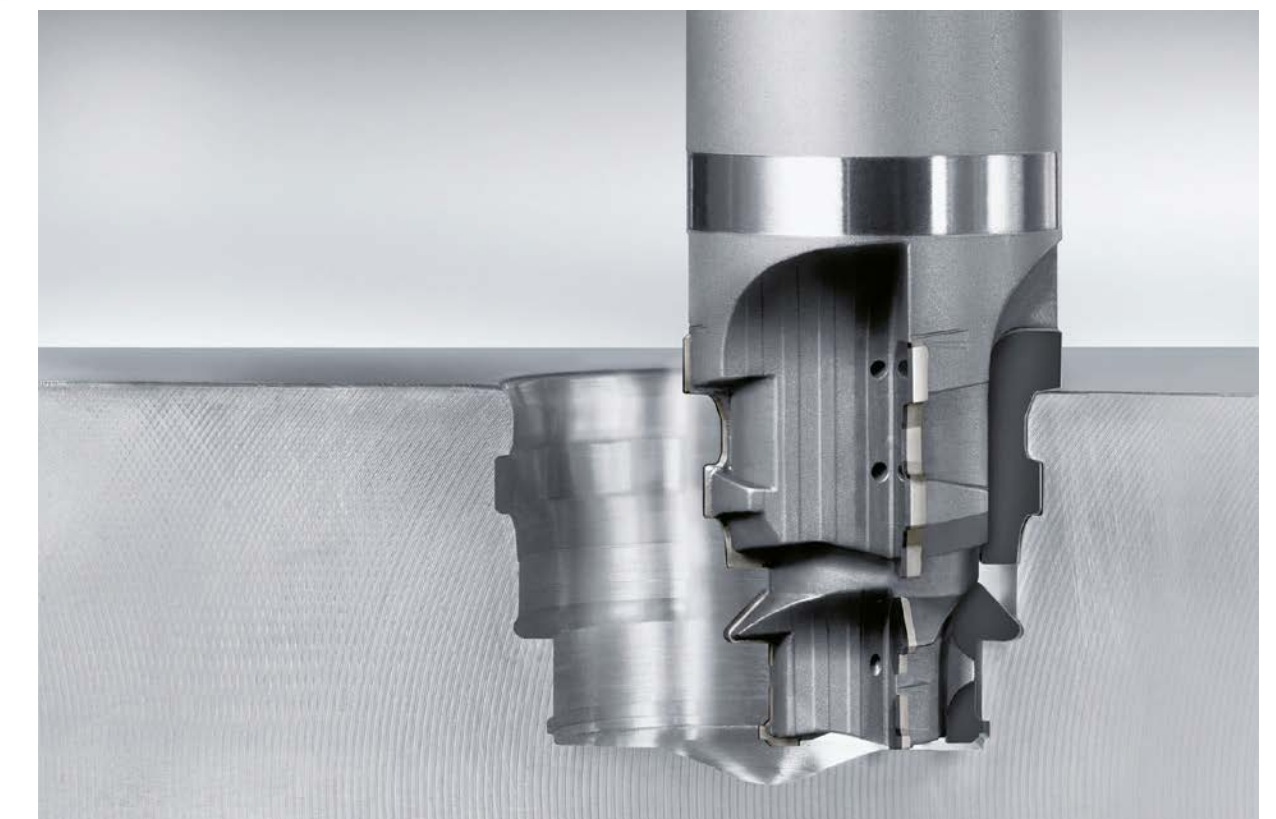
Workholding

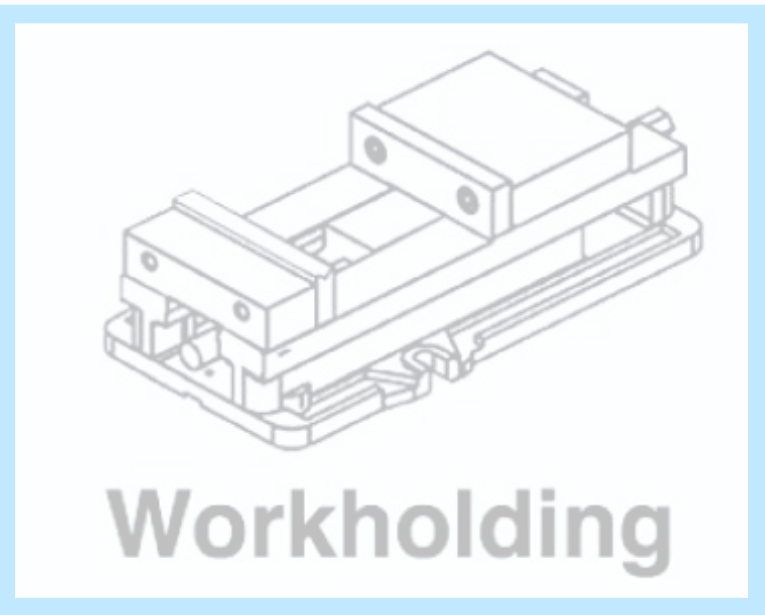
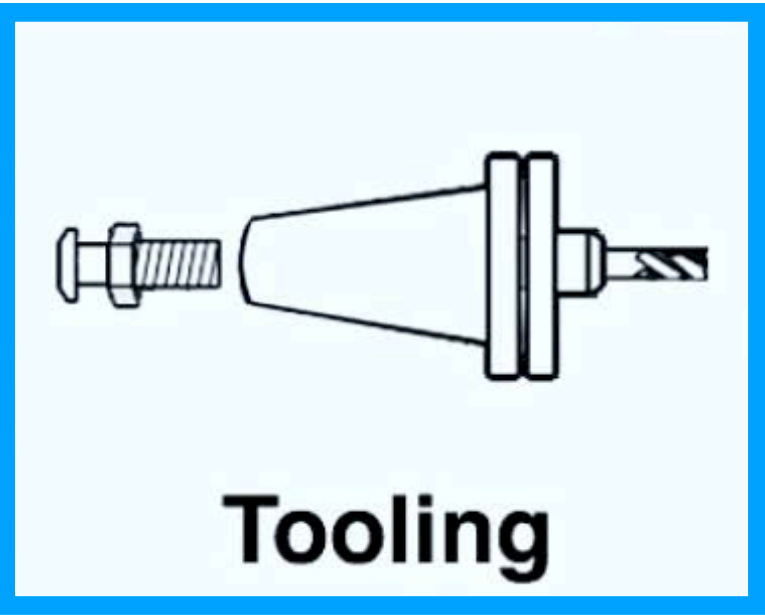
Dedicated Tools



form tools: match the job you want to do

↓ flexibility, but ↑ rate





Tool Materials

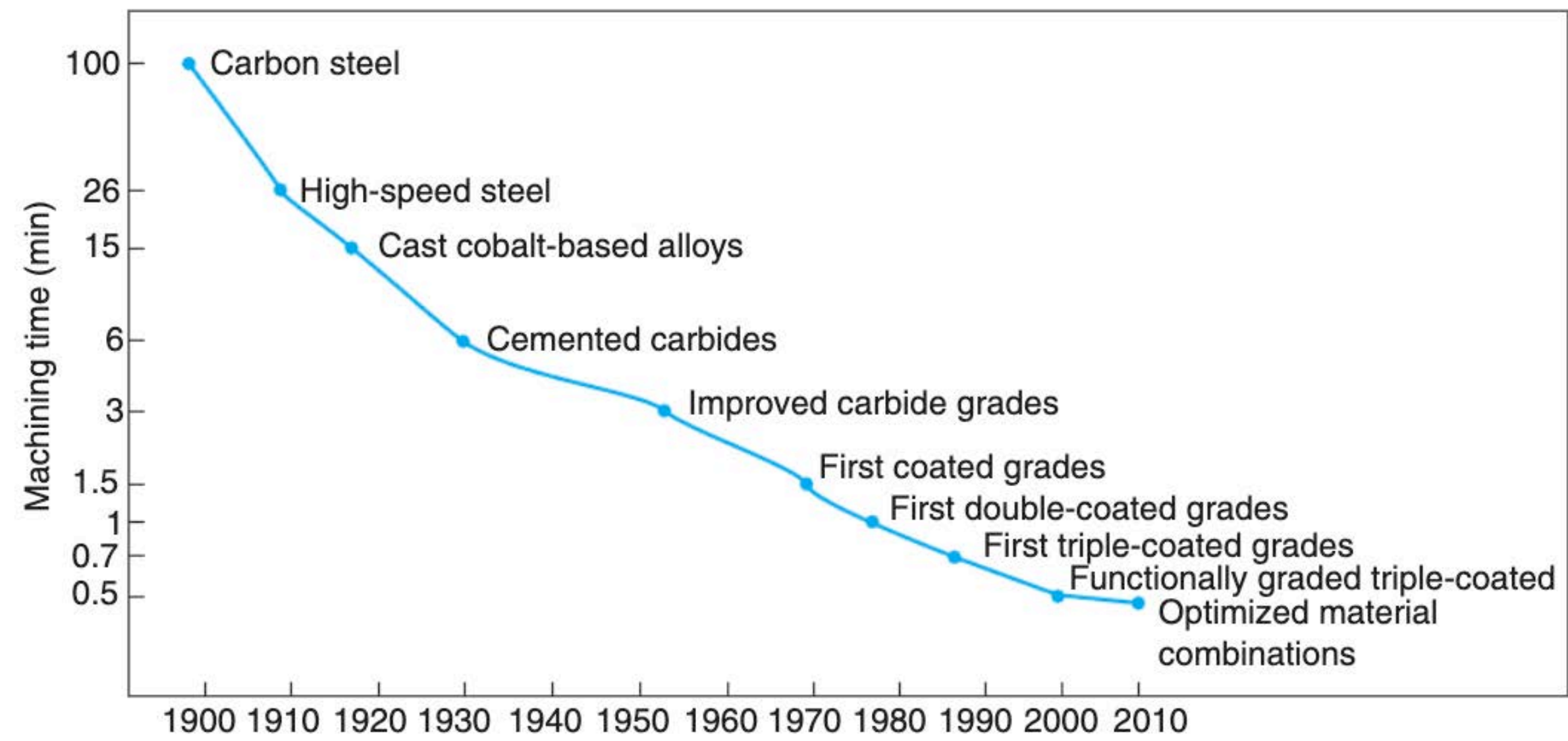


FIGURE 22.6 Relative time required to machine with various cutting-tool materials, indicating the year the tool materials were first introduced; note that machining time has been reduced by two orders of magnitude within a 100 years. *Source:* Courtesy of Sandvik.

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

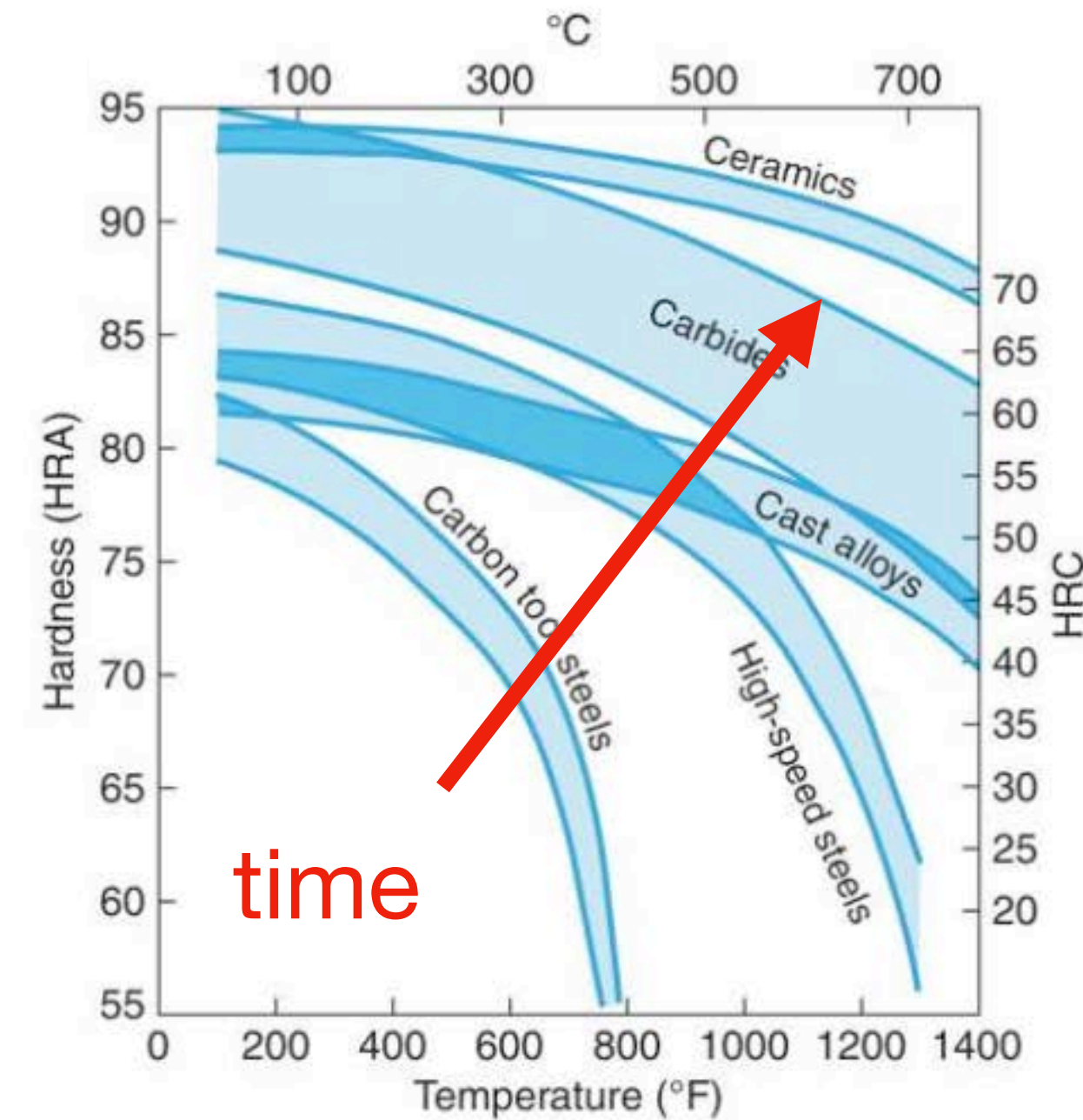
1868- 2% [carbon](#), 2.5% [manganese](#), and 7% [tungsten](#) "**Mushet**" **steel**, lose hardness at 200 degrees C

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.

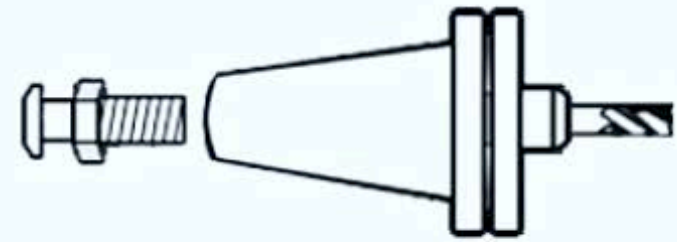


Cutting #3

Machining in Practice

25

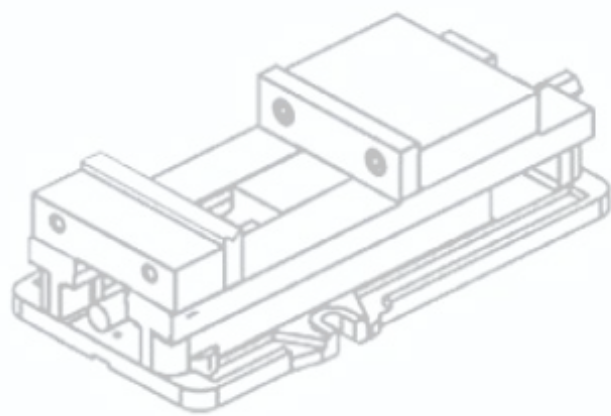
Tool Wear



Tooling



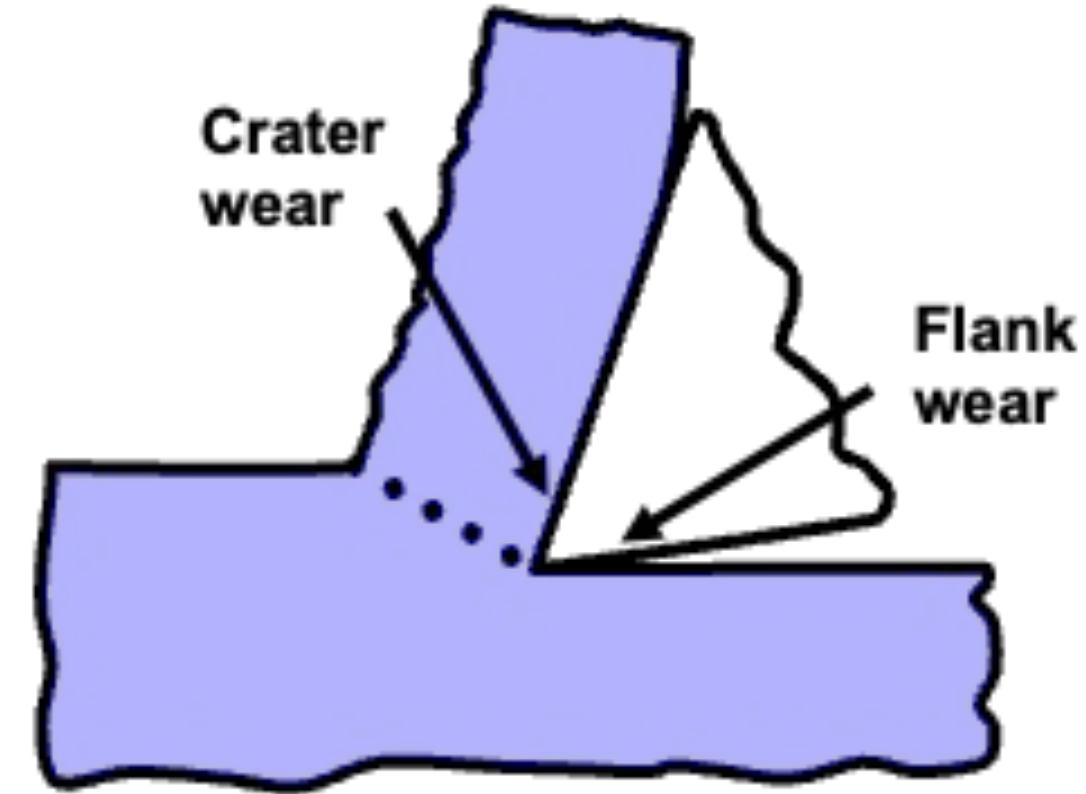
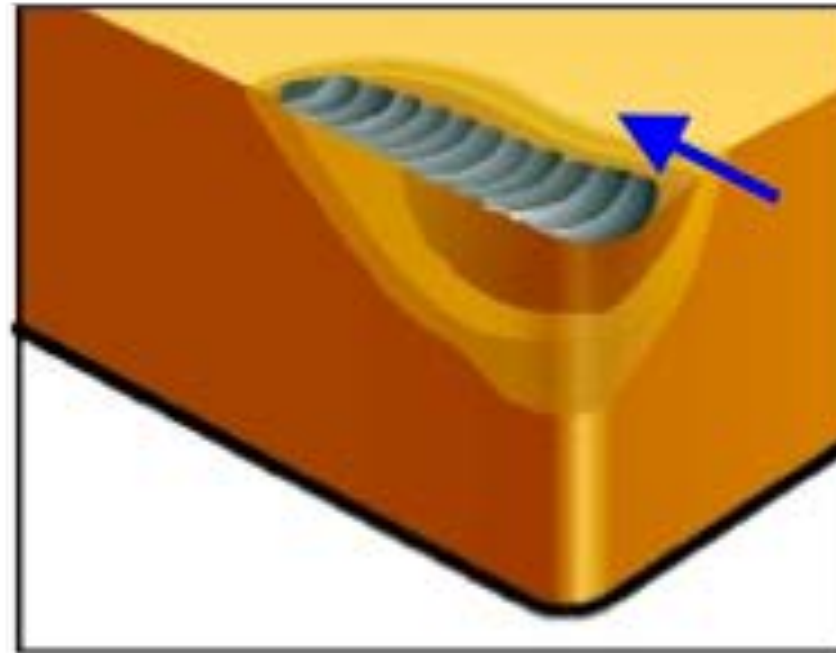
Program



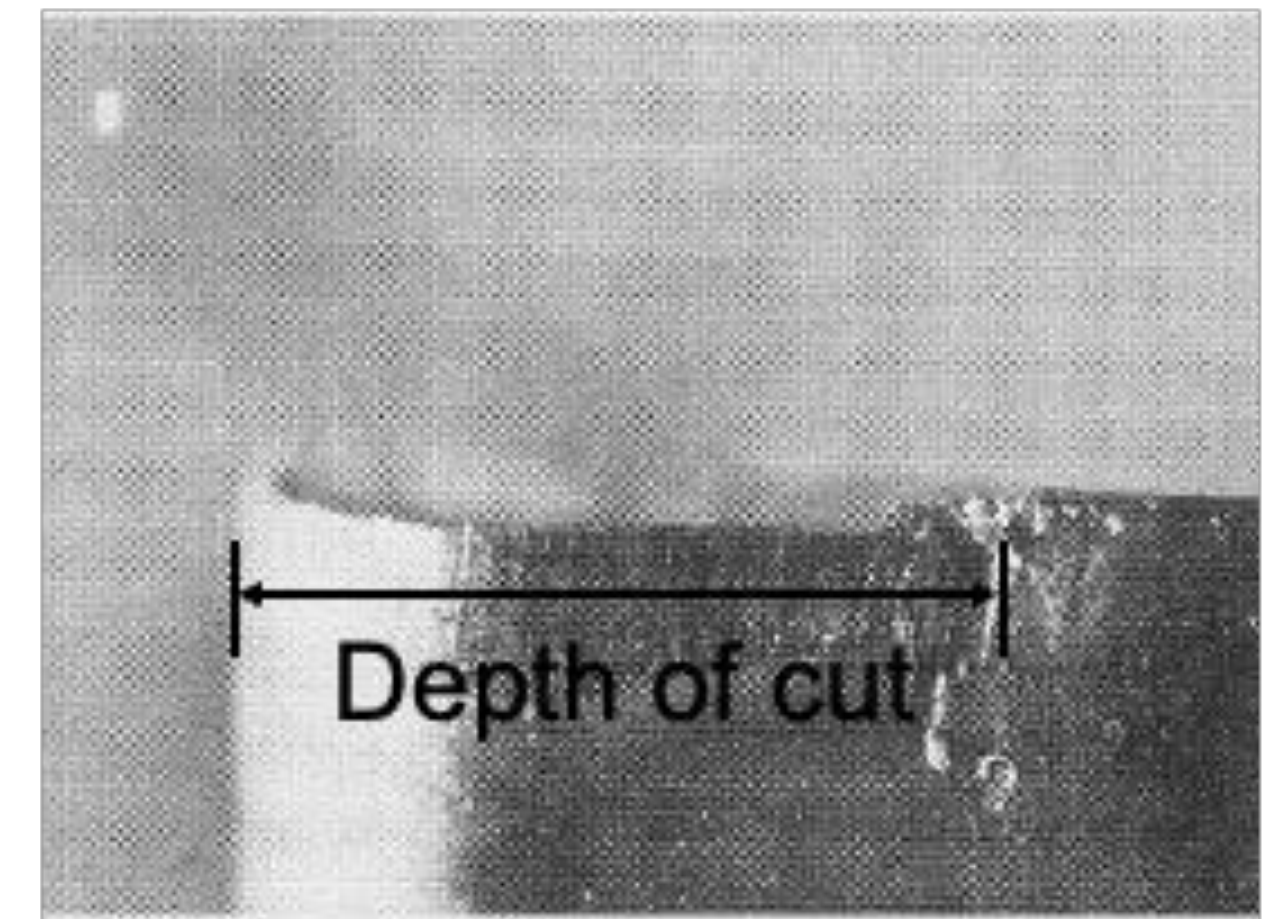
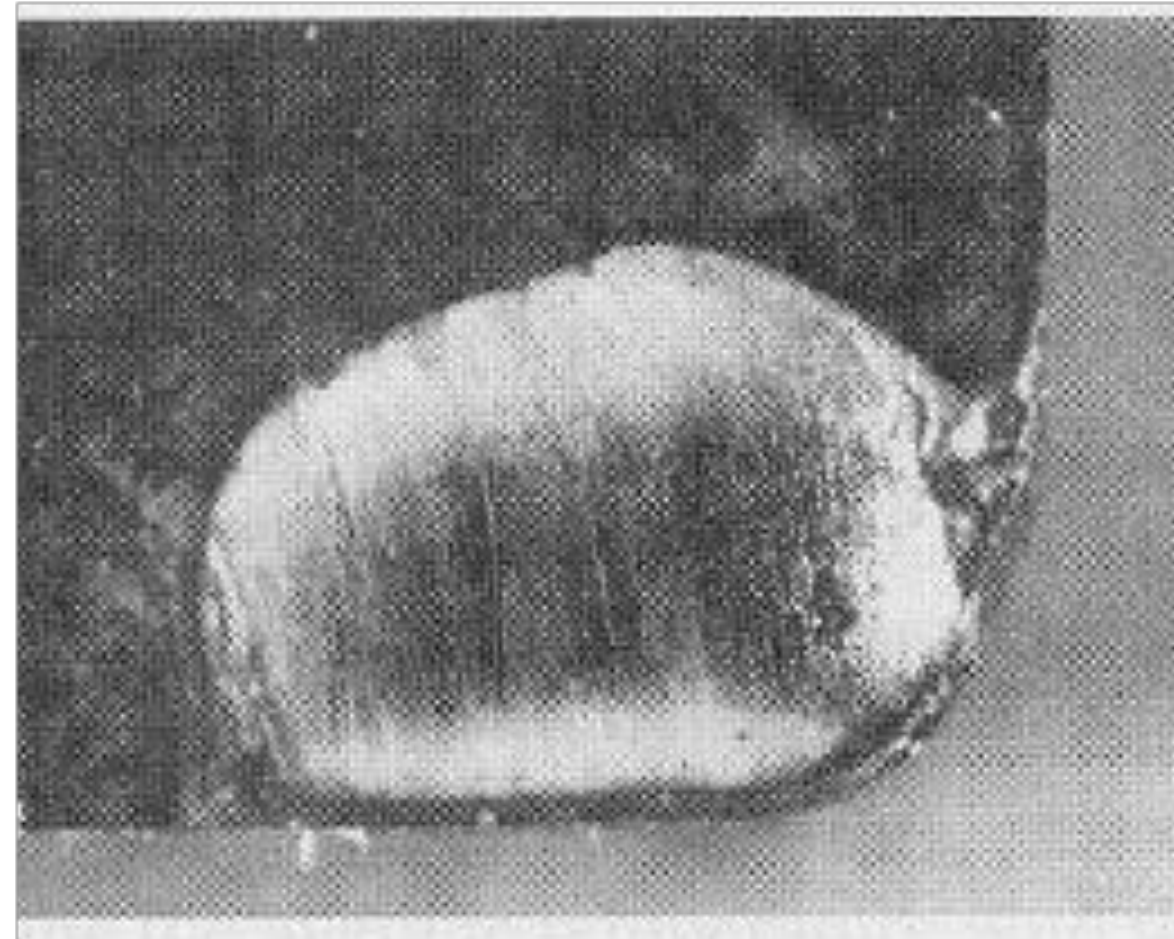
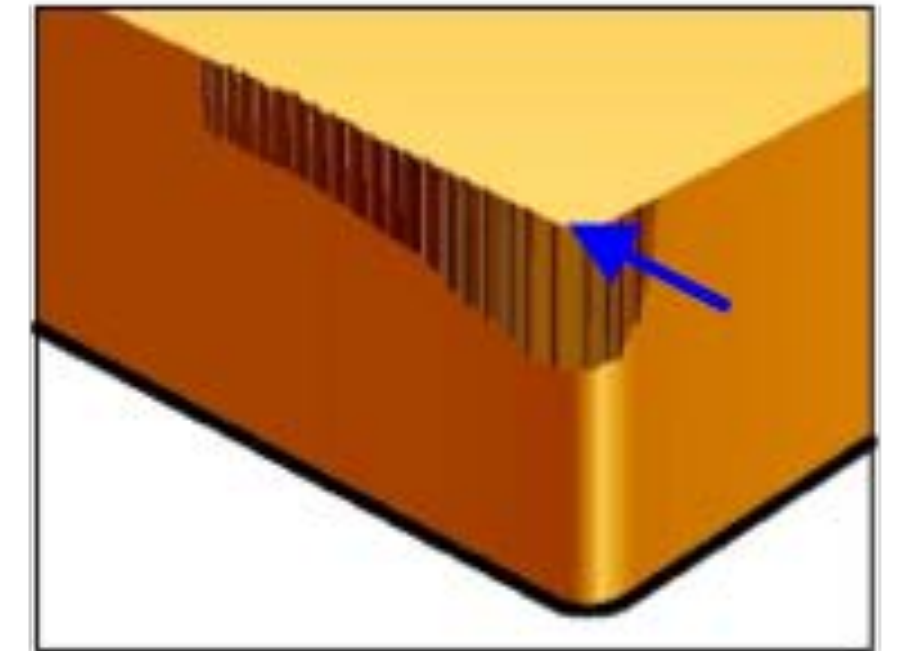
Workholding



Crater wear

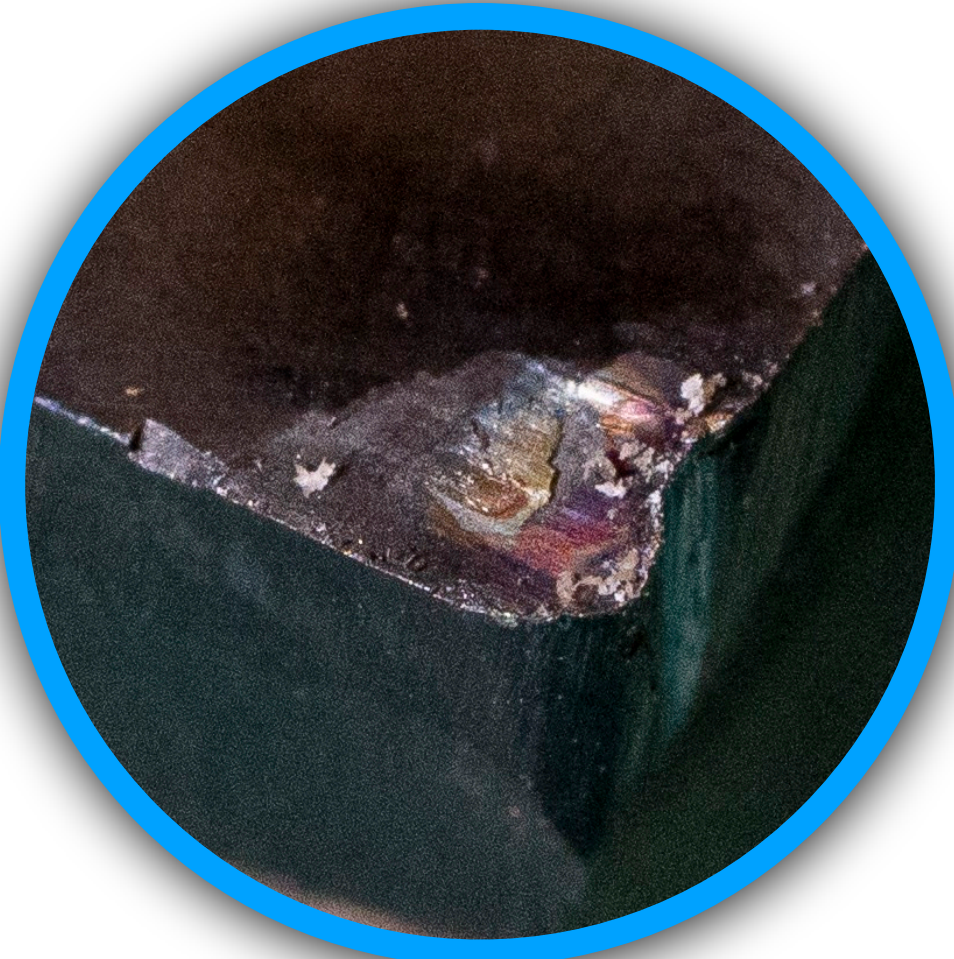
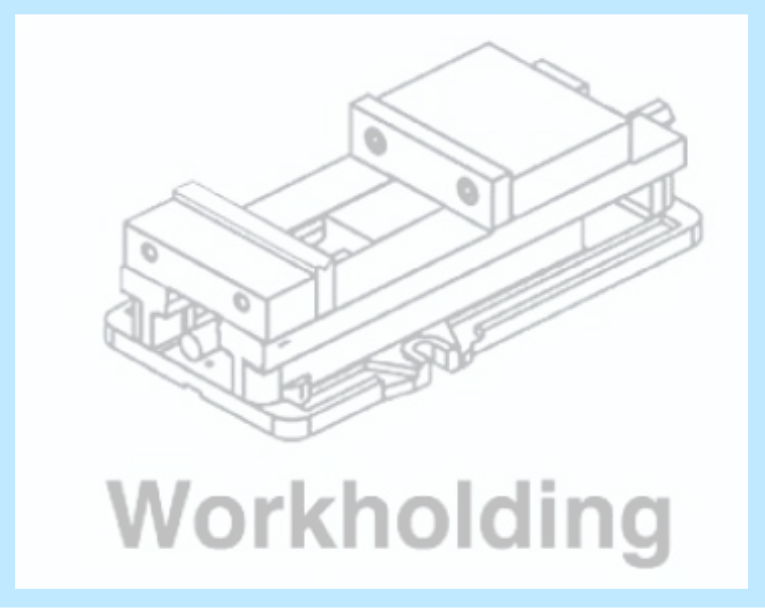
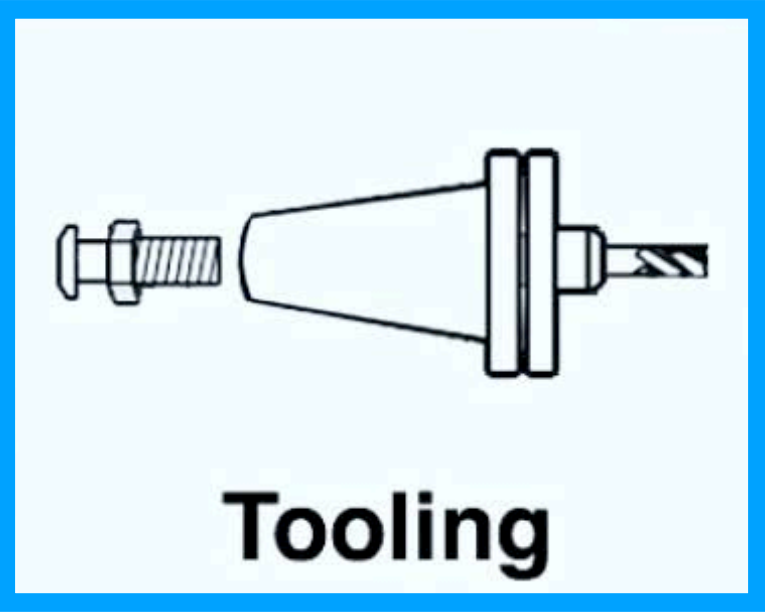










Flank wear

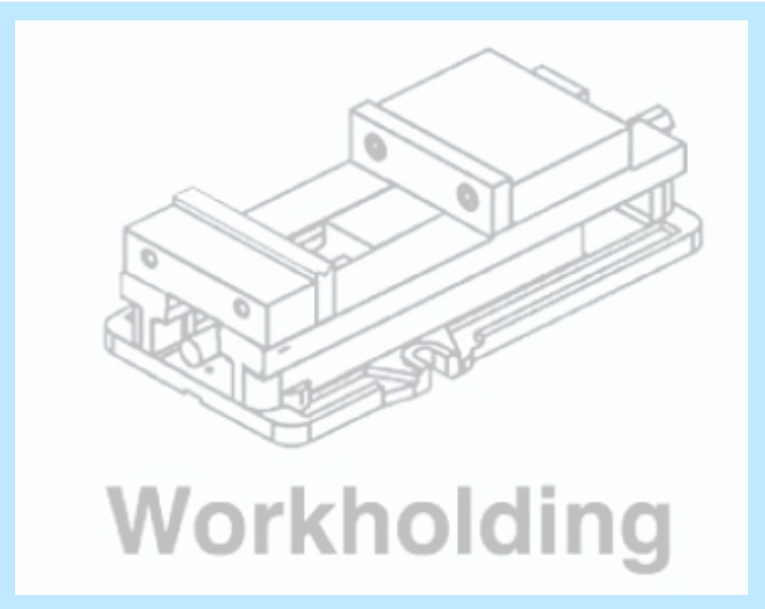
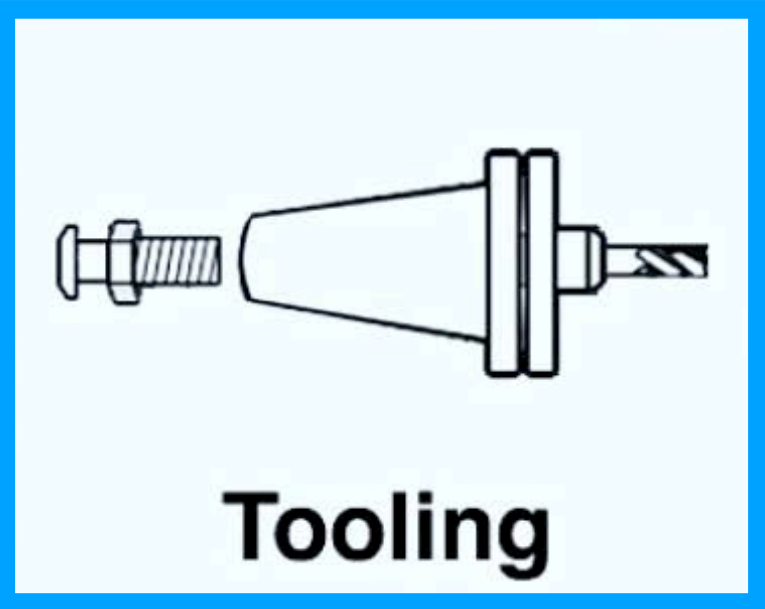


Images from Figure 23.2 Fundamentals of Modern Manufacturing (4th Edition) by Groover. (c) Wiley (2010).
Wear schematics from: http://www.sandvik.coromant.com/en-us/knowledge/milling/troubleshooting/tool_wear

Tool Wear



Tool Damage Form	Cause	Countermeasure
Flank Wear	 <ul style="list-style-type: none">• Tool grade is too soft.• Cutting speed is too high.• Flank angle is too small.• Feed rate is extremely low.	<ul style="list-style-type: none">• Tool grade with high wear resistance.• Lower cutting speed.• Increase flank angle.• Increase feed rate.
Crater Wear	 <ul style="list-style-type: none">• Tool grade is too soft.• Cutting speed is too high.• Feed rate is too high.	<ul style="list-style-type: none">• Tool grade with high wear resistance.• Lower cutting speed.• Lower feed rate.
Chipping	 <ul style="list-style-type: none">• Tool grade is too hard.• Feed rate is too high.• Lack of cutting edge strength.	<ul style="list-style-type: none">• Tool grade with high toughness.• Lower feed rate.• Increase honing. (Round honing is to be changed to chamfer honing.)• Use large shank size.
Fracture	 <ul style="list-style-type: none">• Tool grade is too hard.• Feed rate is too high.• Lack of cutting edge strength.	<ul style="list-style-type: none">• 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	 <ul style="list-style-type: none">• Tool grade is too soft.• Cutting speed is too high.• Depth of cut and feed rate are too large.• Cutting temperature is high.	<ul style="list-style-type: none">• Tool grade with high wear resistance.• Lower cutting speed.• Decrease depth of cut and feed rate.• Tool grade with high thermal conductivity.
Welding	 <ul style="list-style-type: none">• Cutting speed is low.• Poor sharpness.• Unsuitable grade.	<ul style="list-style-type: none">• Increase cutting speed. (For JIS S45C, cutting speed 80m/min.)• Increase rake angle.• Tool grade with low affinity. (Coated grade, cermet grade)
Thermal Cracks	 <ul style="list-style-type: none">• Expansion or shrinkage due to cutting heat.• Tool grade is too hard.• *Especially in milling.	<ul style="list-style-type: none">• Dry cutting. (For wet cutting, flood workpiece with cutting fluid)• Tool grade with high toughness.
Notching	 <ul style="list-style-type: none">• Hard surfaces such as uncut surfaces, chilled parts and machining hardened layer.• Friction caused by jagged shape chips. (Caused by small vibration)	<ul style="list-style-type: none">• Tool grade with high wear resistance.• Increase rake angle to improve sharpness.
Flaking	 <ul style="list-style-type: none">• Cutting edge welding and adhesion.• Poor chip disposal.	<ul style="list-style-type: none">• Increase rake angle to improve sharpness.• Enlarge chip pocket.

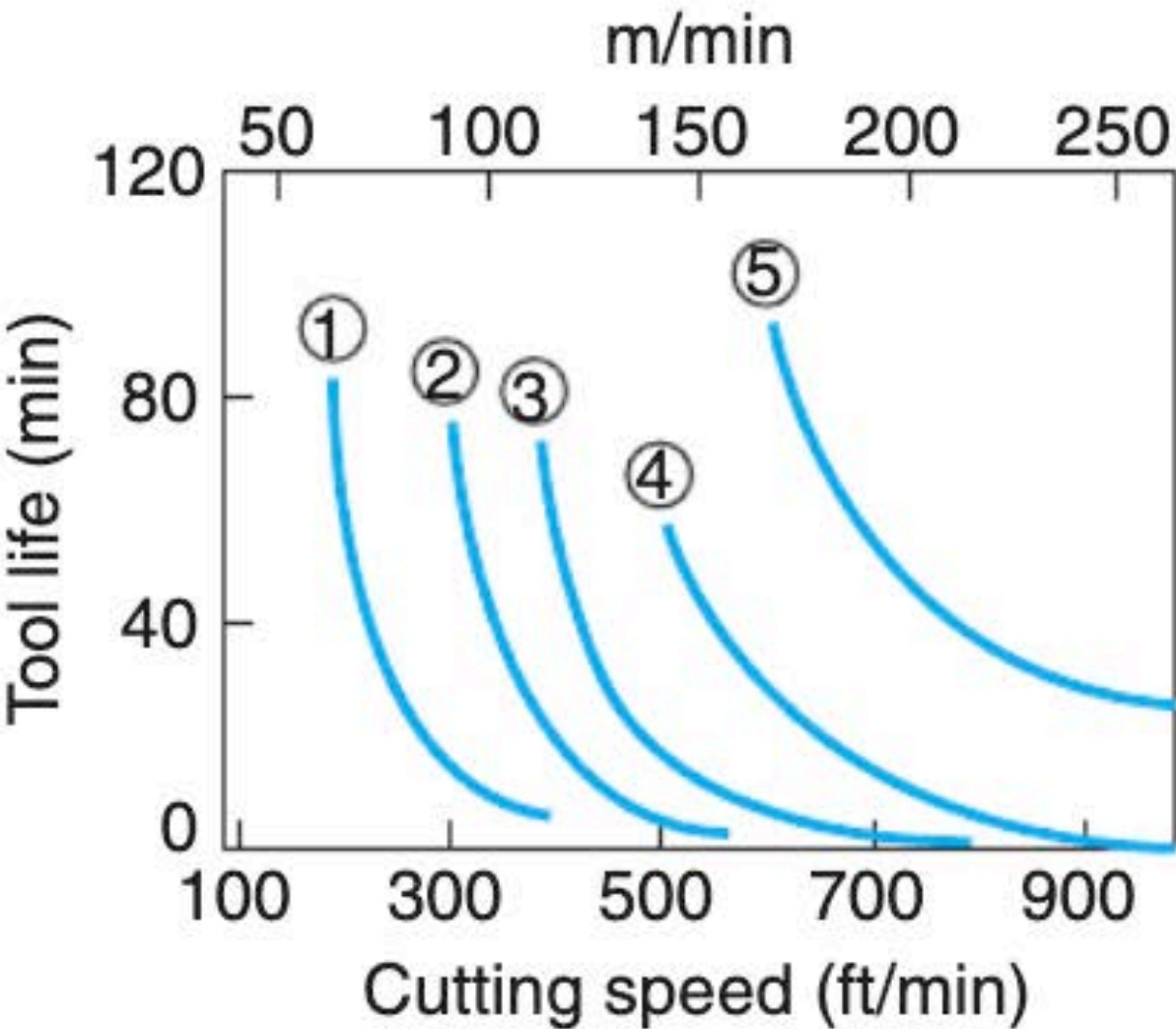
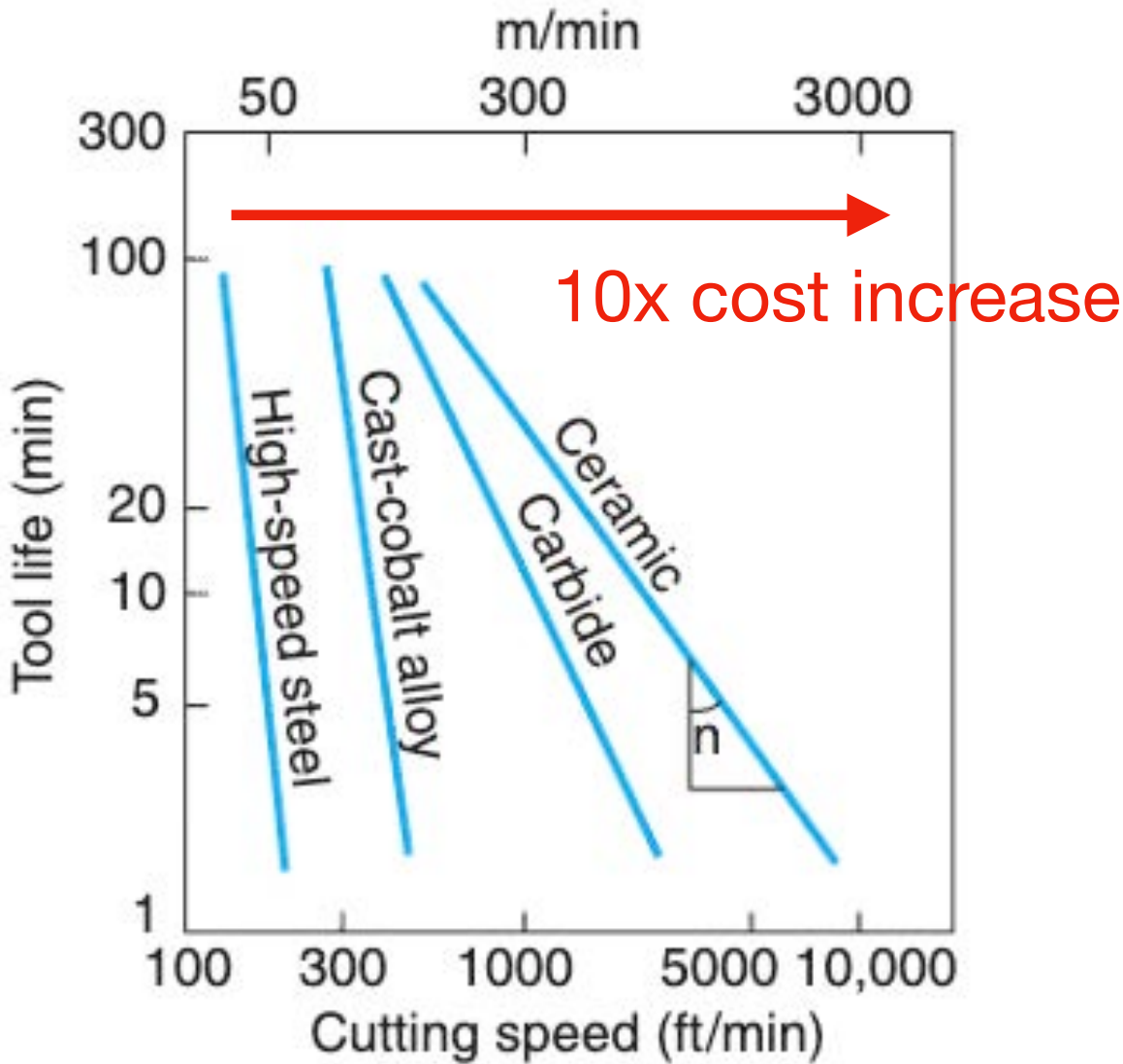


Taylor’s Tool Life Equation

cutting velocity significantly affects rate of tool wear

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

Taylor tool life equation



	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	—

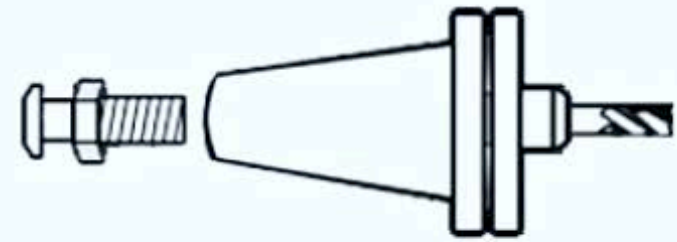
softer workpiece

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

Cutting #3

Machining in Practice

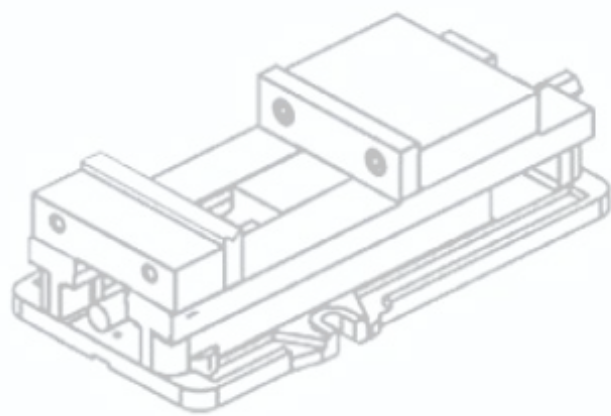
28



Tooling

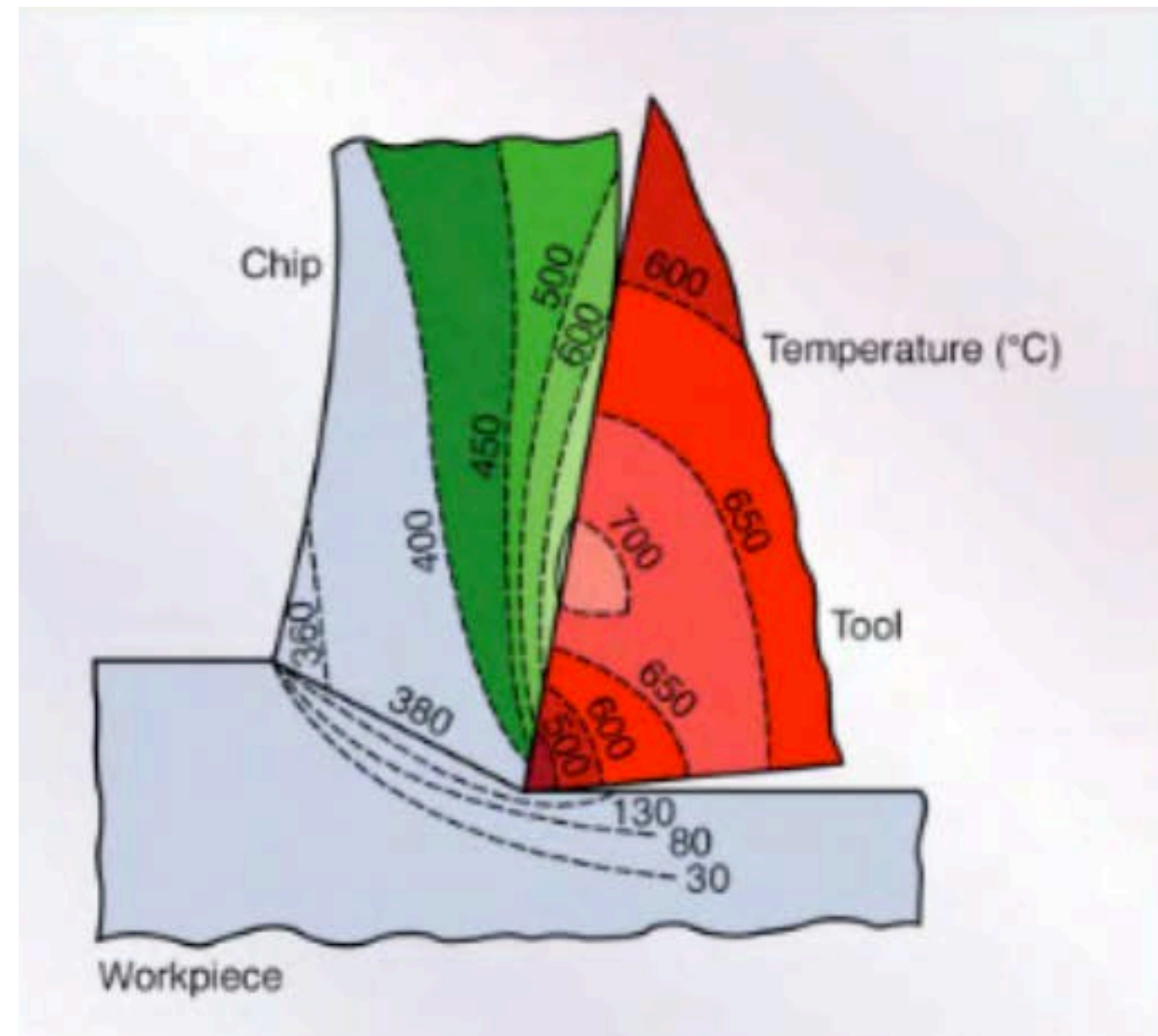


Program



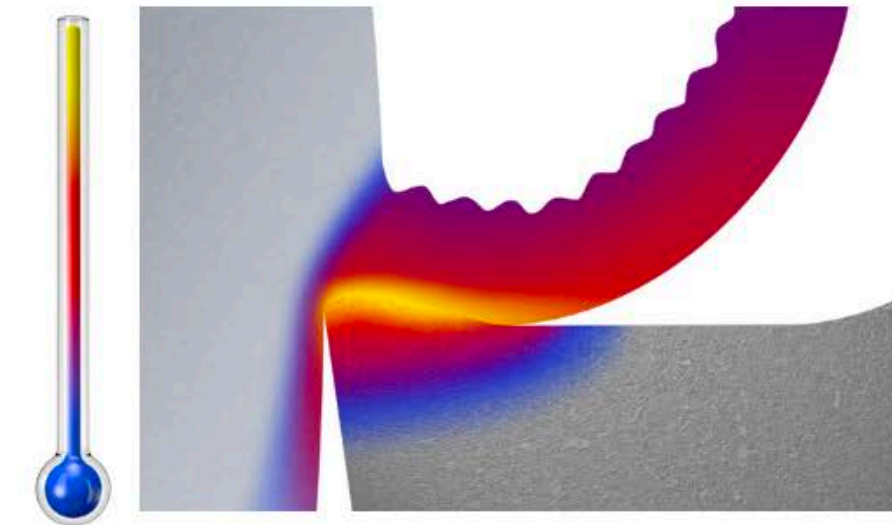
Workholding

Tool Materials

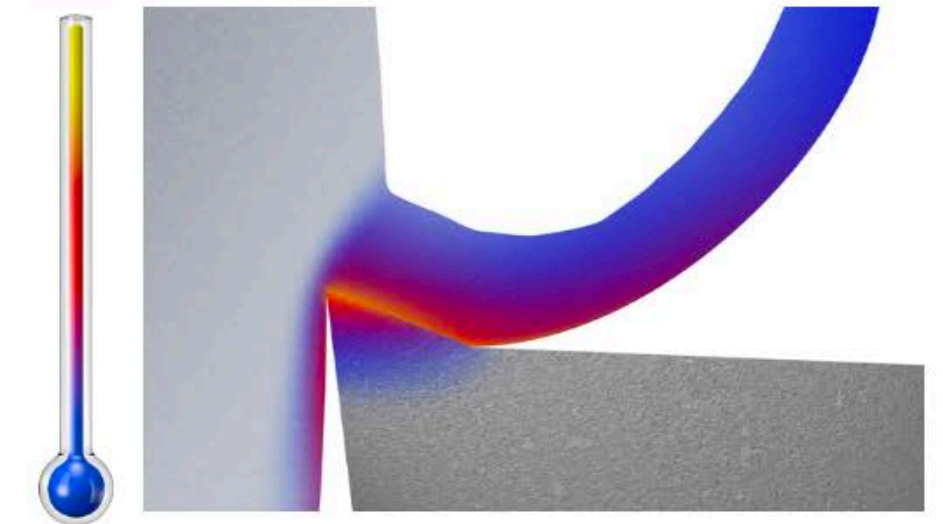


- temperature: sensitive to cutting speed
heat is generated rapidly and cannot dissipate
- work done in shearing
 - friction: tool + chip and tool + workpiece rubbing
- get info from tool manufacturers

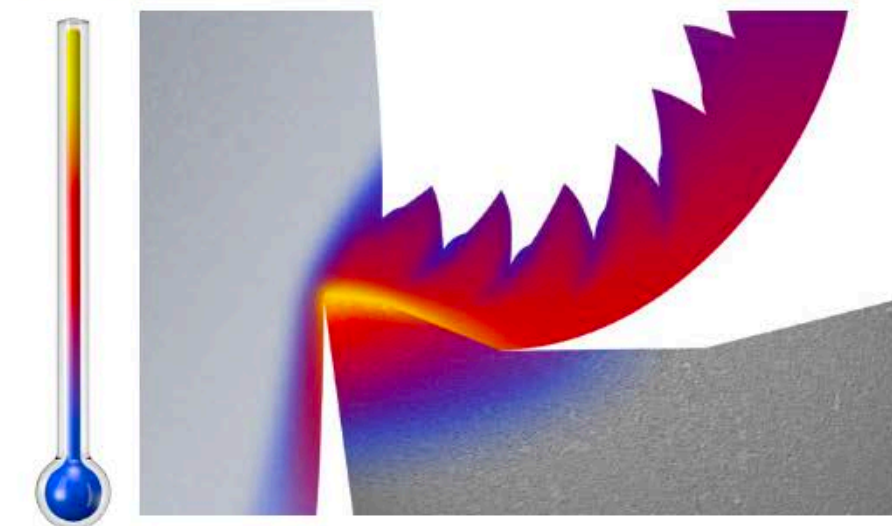
P Steel



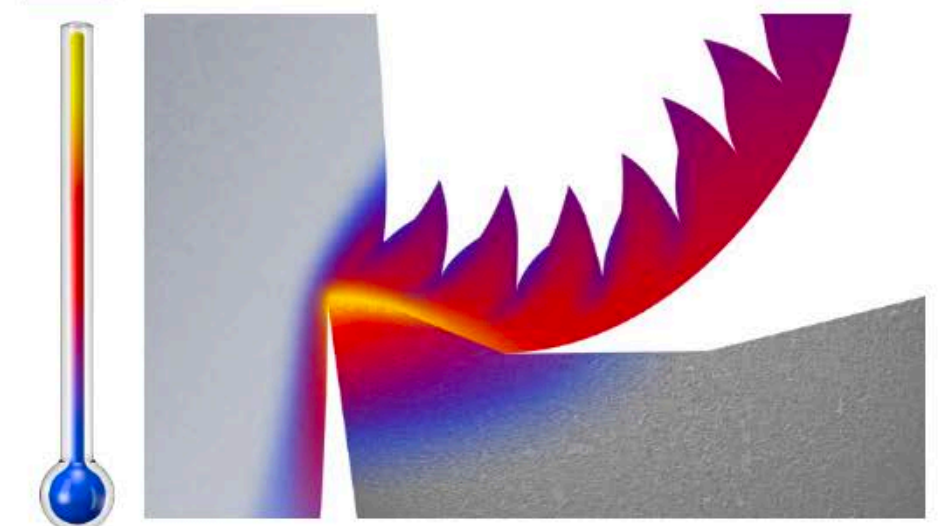
N Aluminum



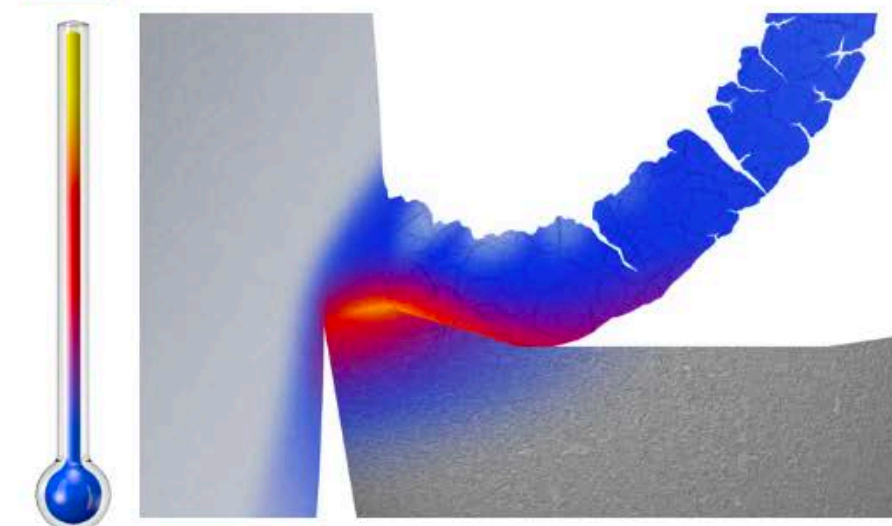
M Stainless steel



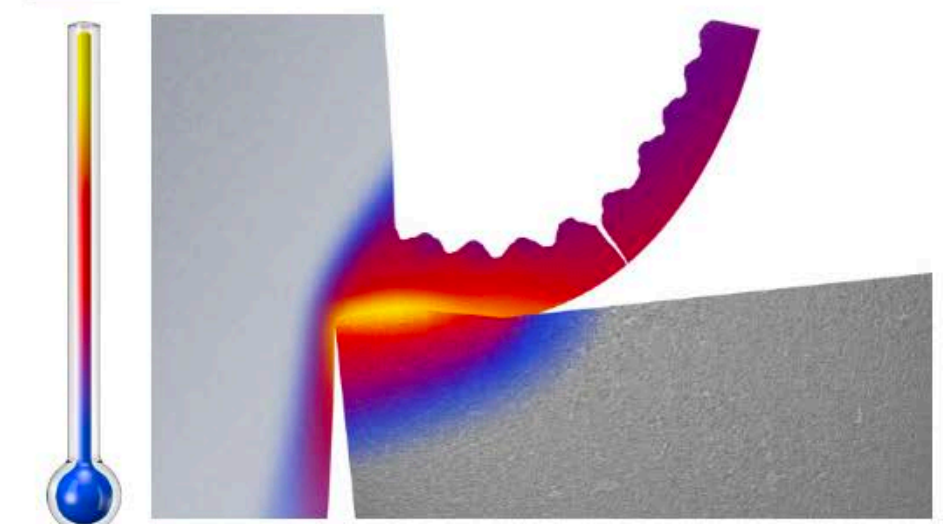
S Heat resistant super alloys

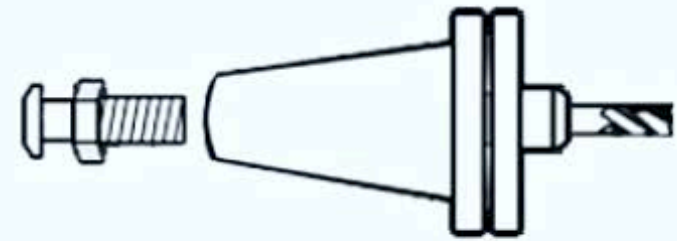


K Cast iron



H Hardened steel

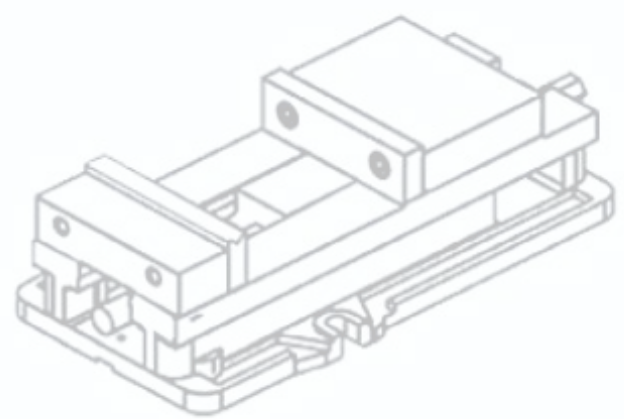




Tooling



Program



Workholding

Tool Coatings

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

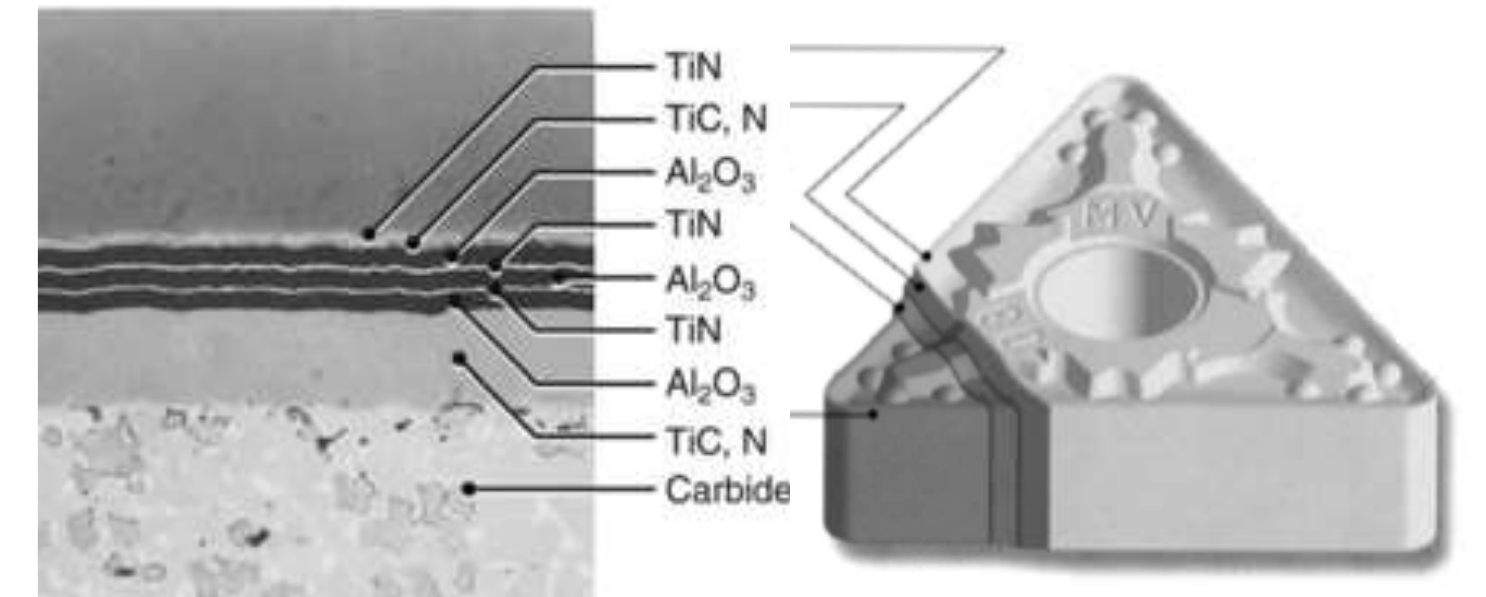
Layers: 2-20 μm thick

TiN: low friction

TiCN: wear resistance

Al_2O_3 : high thermal stability

Carbide: hardness and fracture toughness



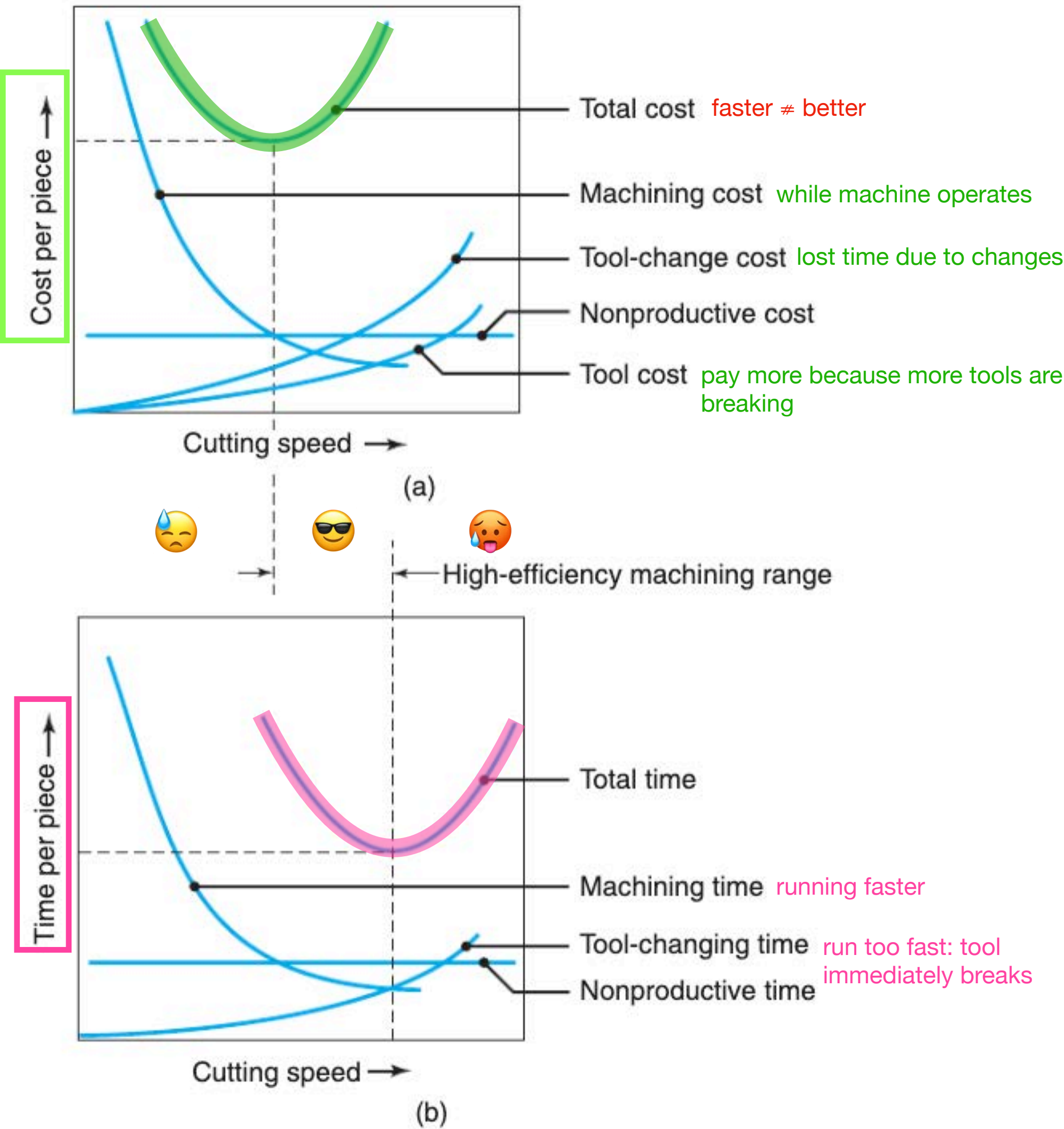
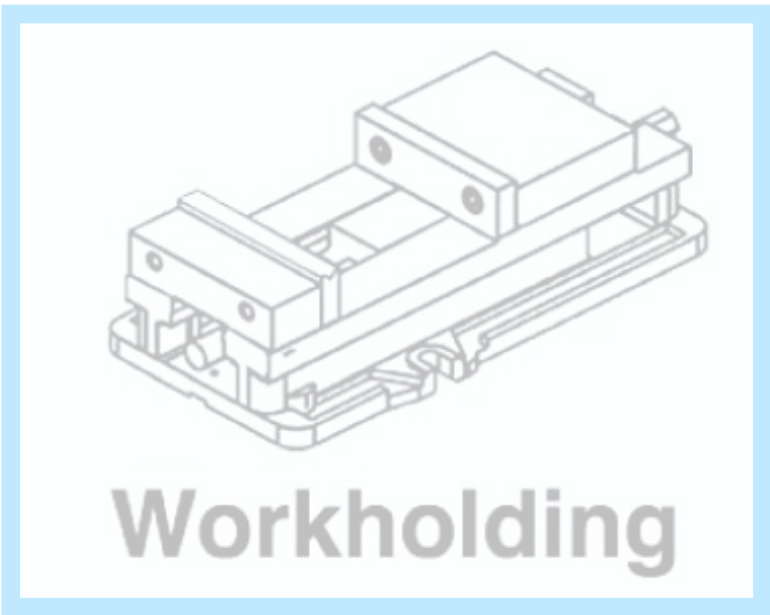
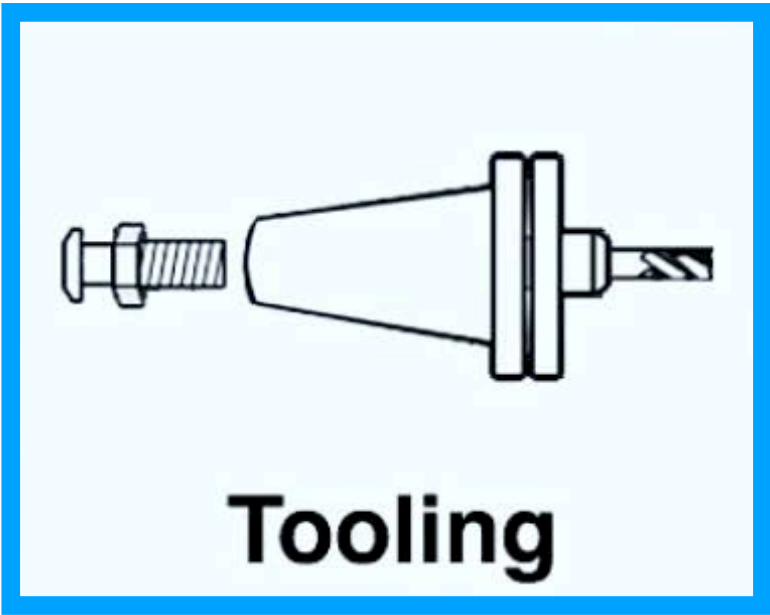
Kalpajian and Schmid, *Manufacturing Engineering and Technology*.
from *DeGarmo's Materials & Processes in Manufacturing* (10th Edition) by Black and Kohser, © Wiley (2008).



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

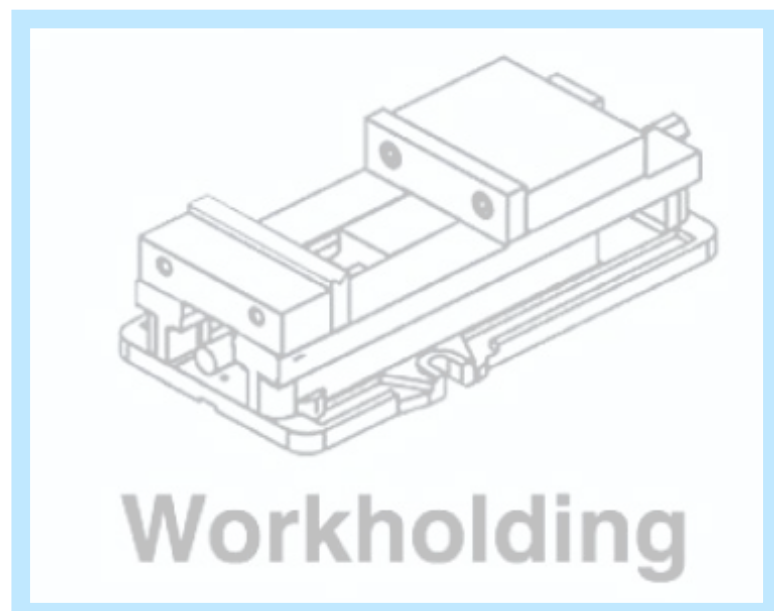
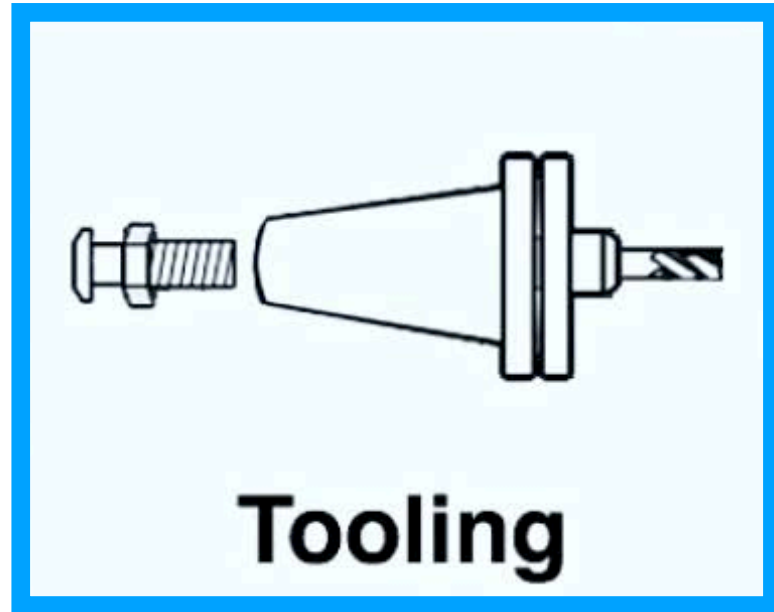
Machining Cost



Cutting #3

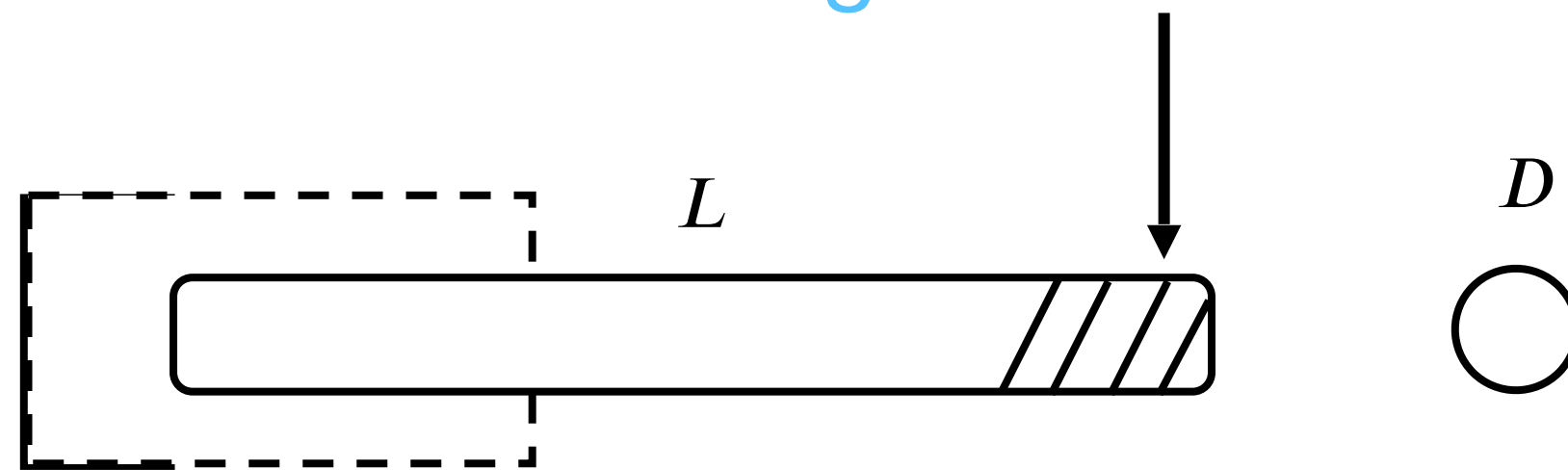
Machining in Practice

31



Tool Stiffness

beam bending!

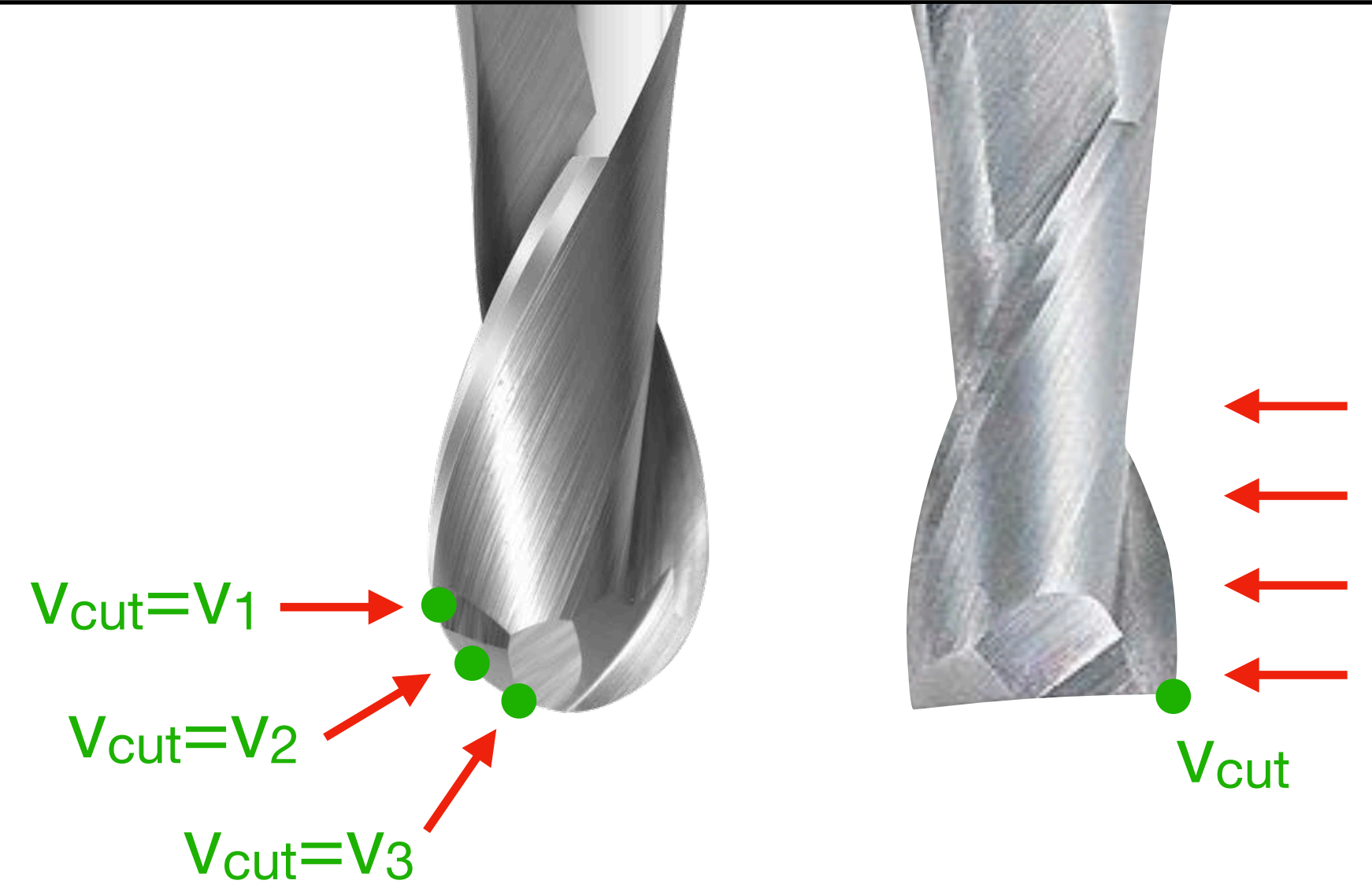


beam bending:

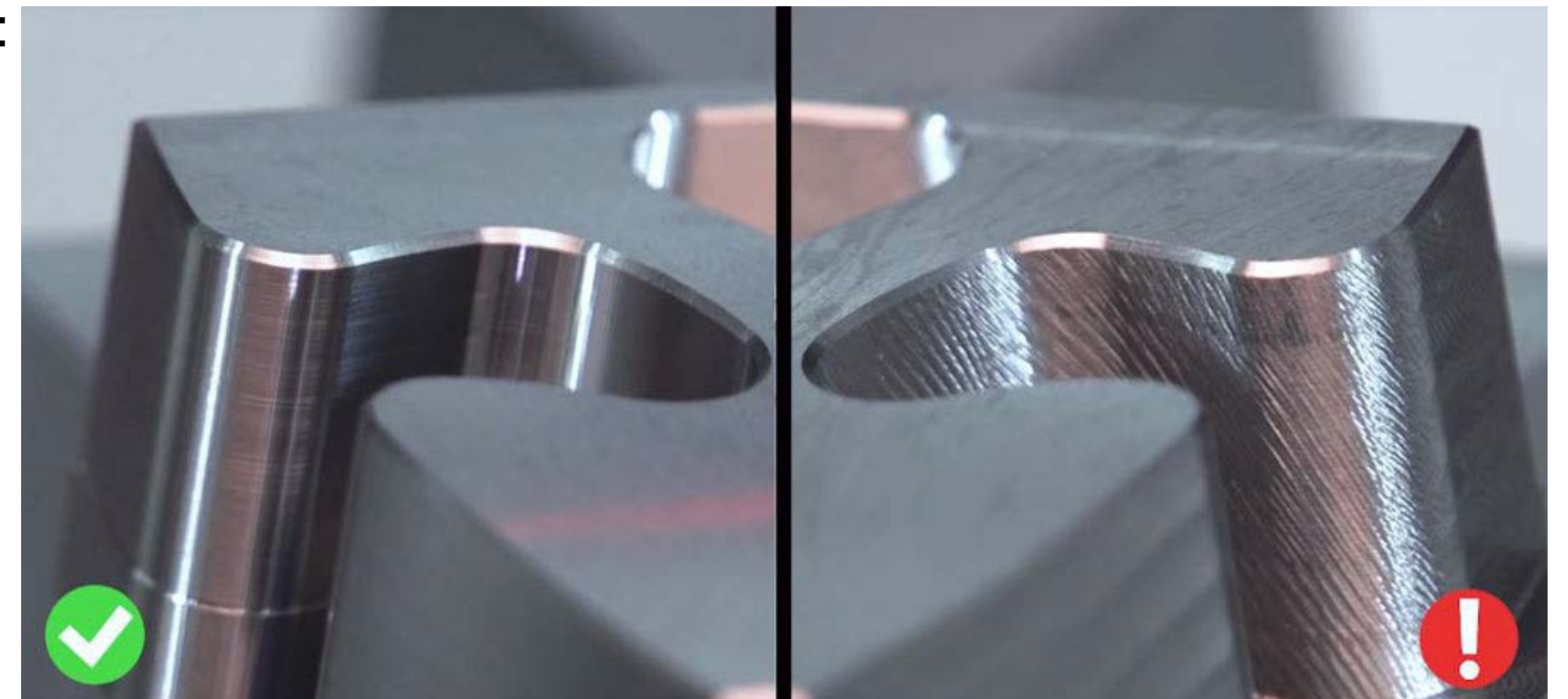
$$\delta = \frac{FL^3}{3EI} \quad F = \frac{3\delta EI}{L^3}$$

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

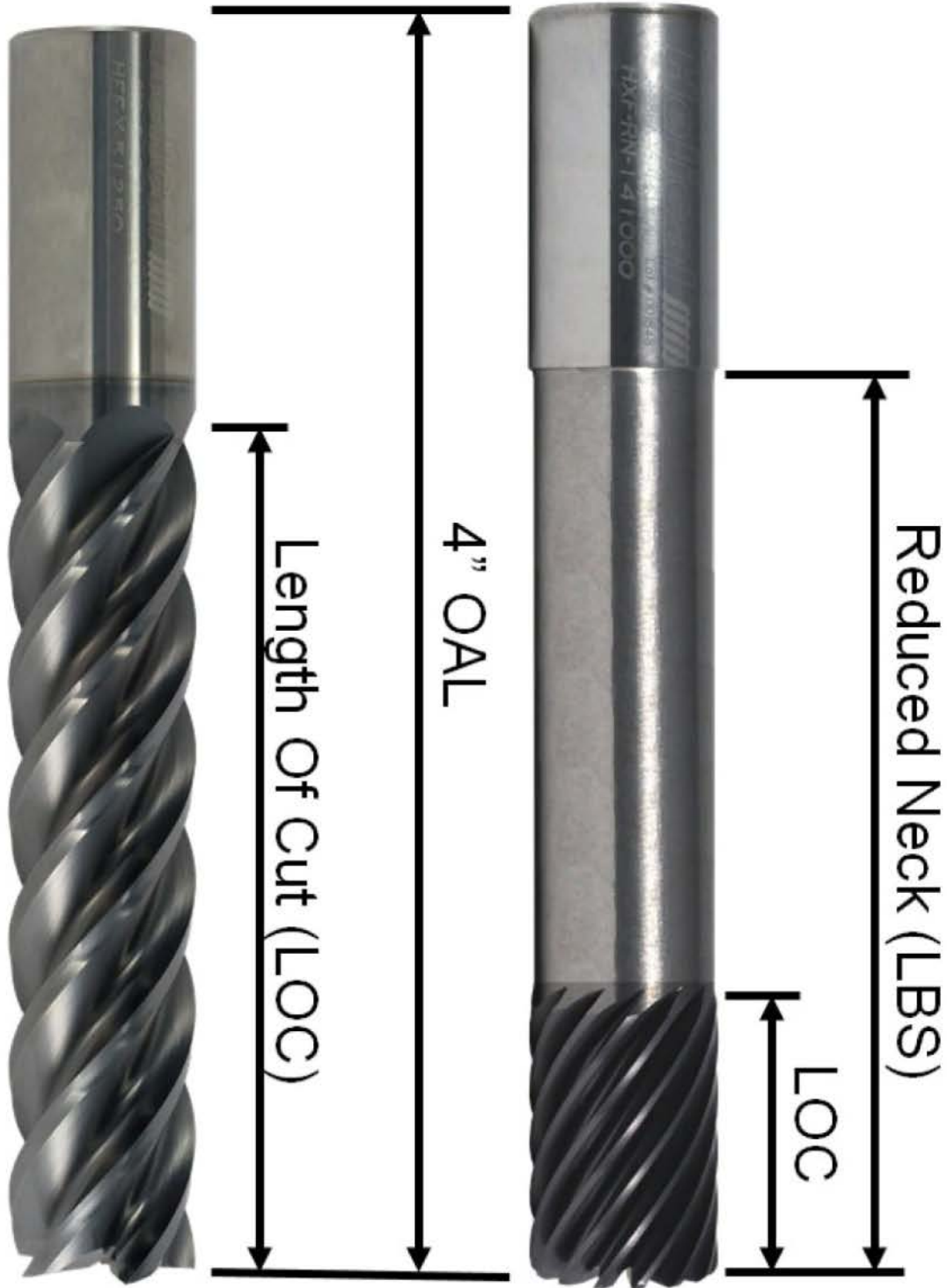
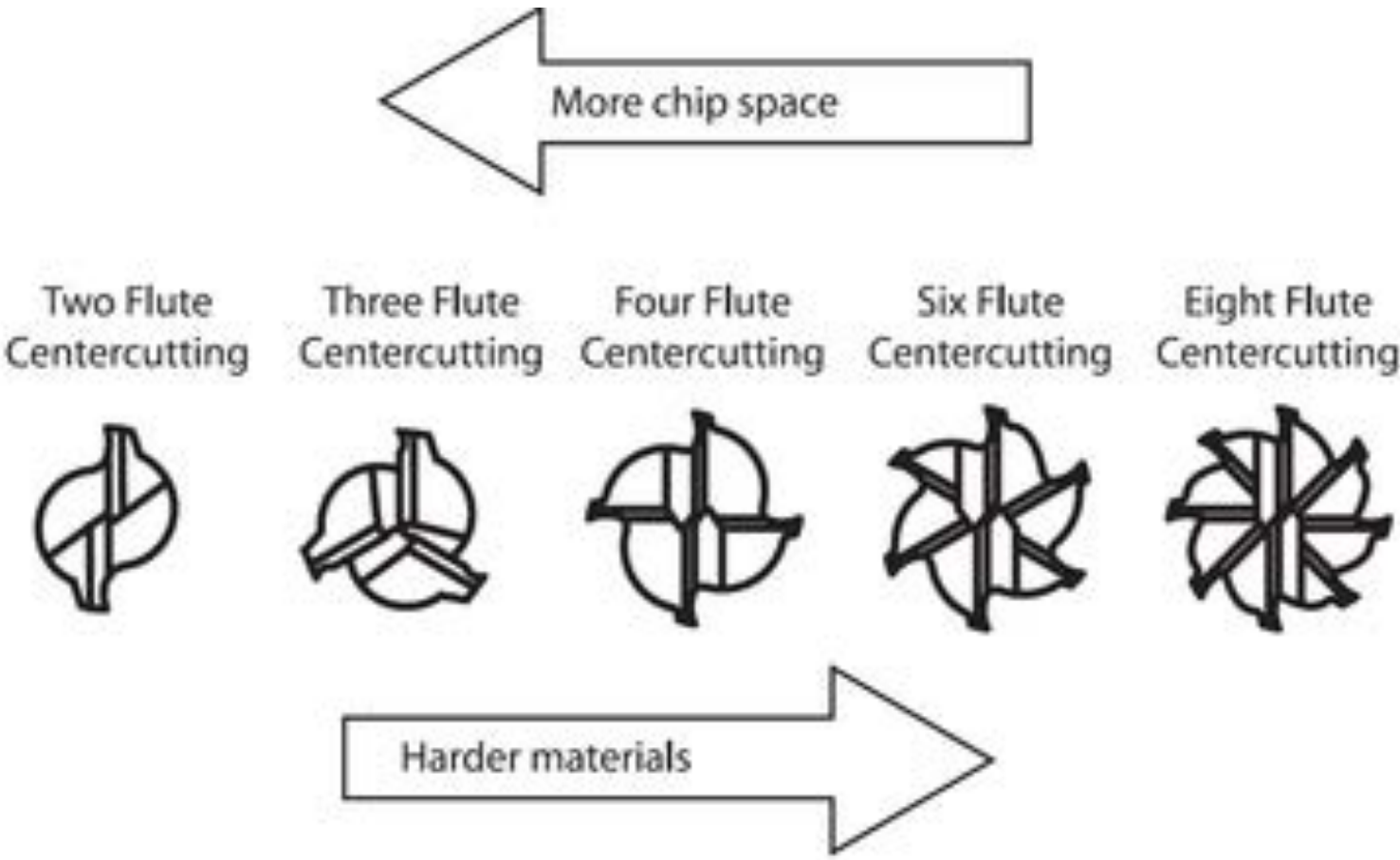
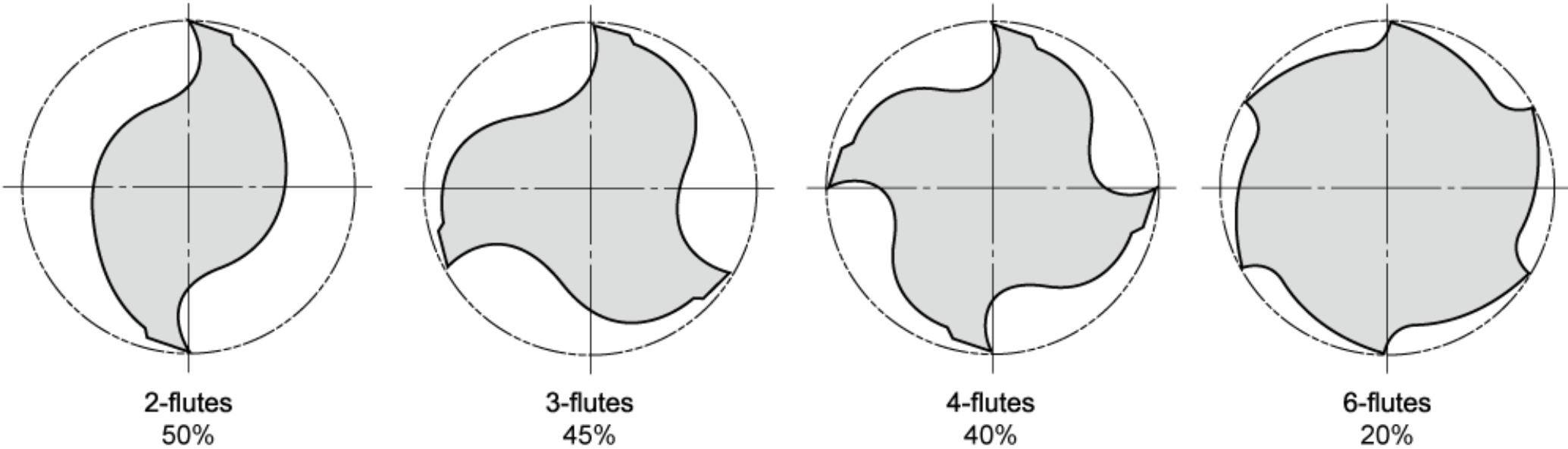
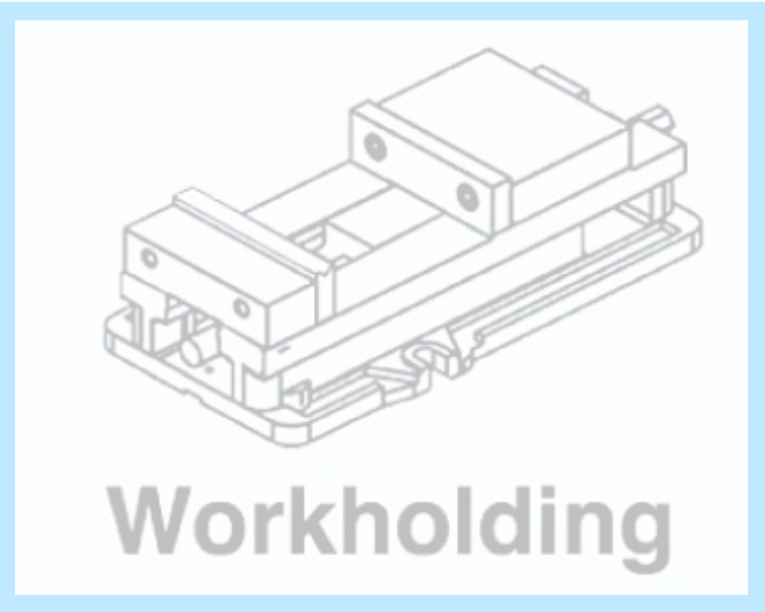
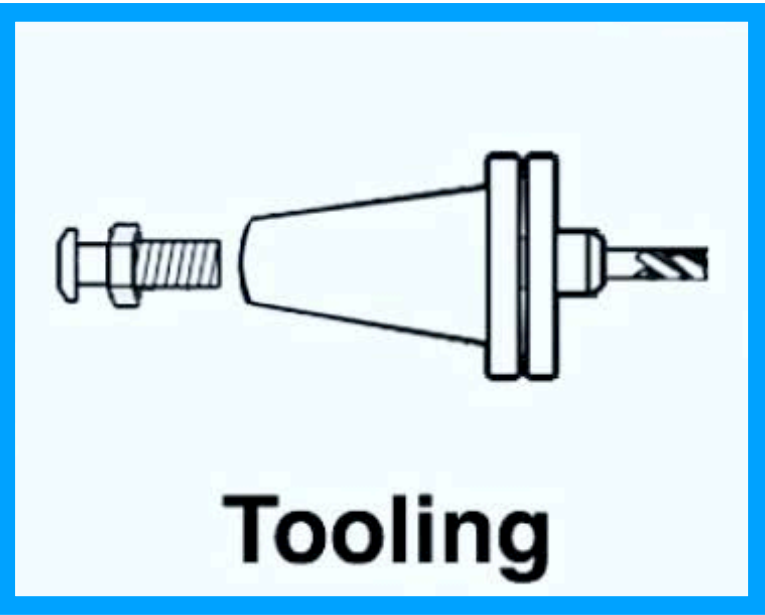
δ : amount of deflection
 F : force
 L : length
 E : elastic modulus of the tool material
 I : area moment of inertia
 k : stiffness



chatter:

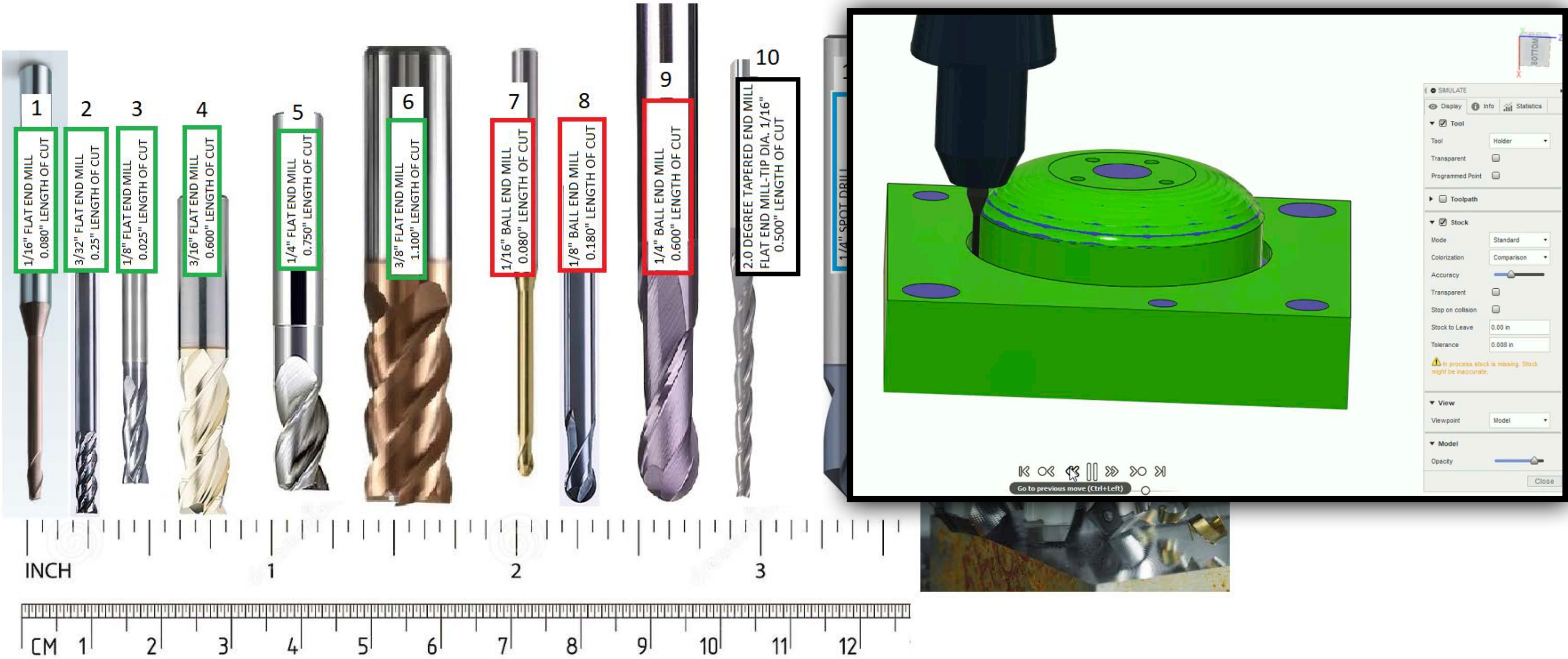
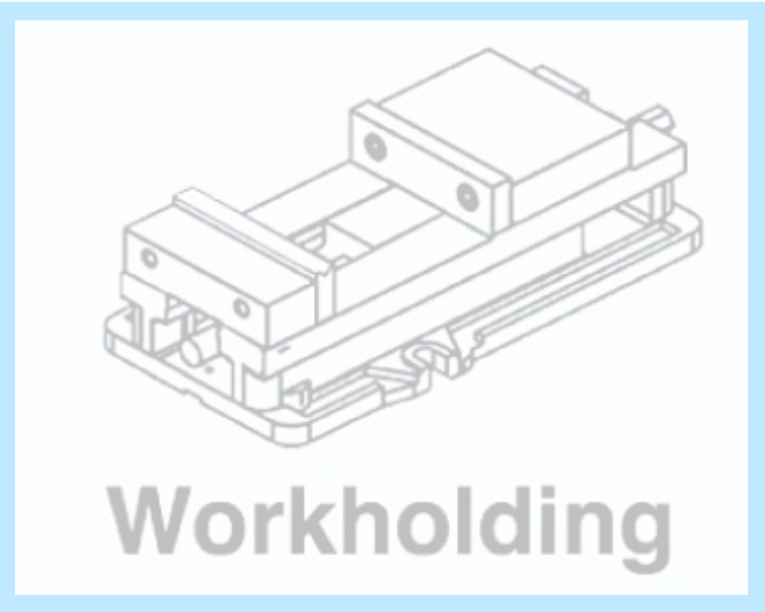
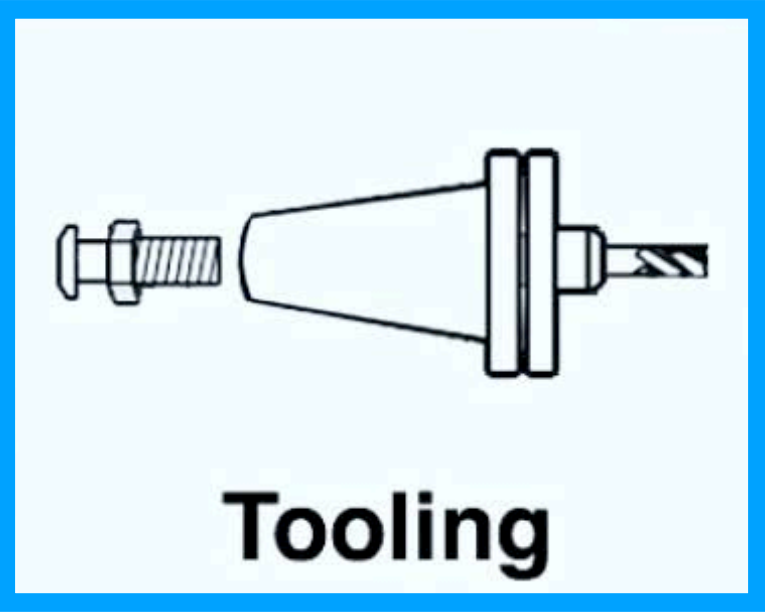


Tool Stiffness

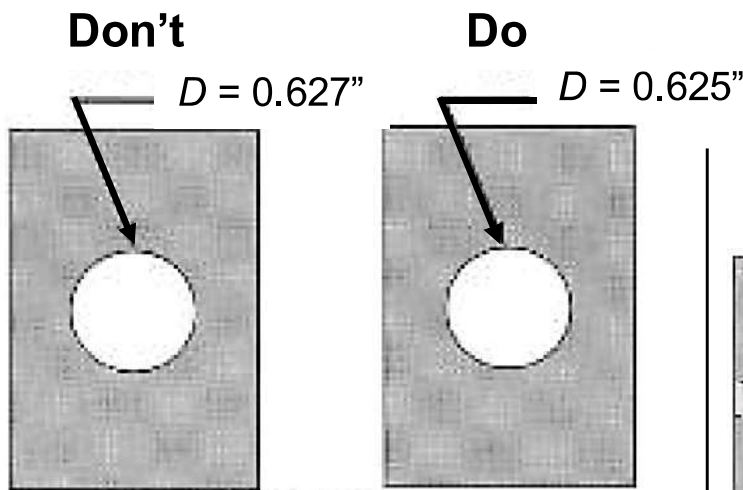
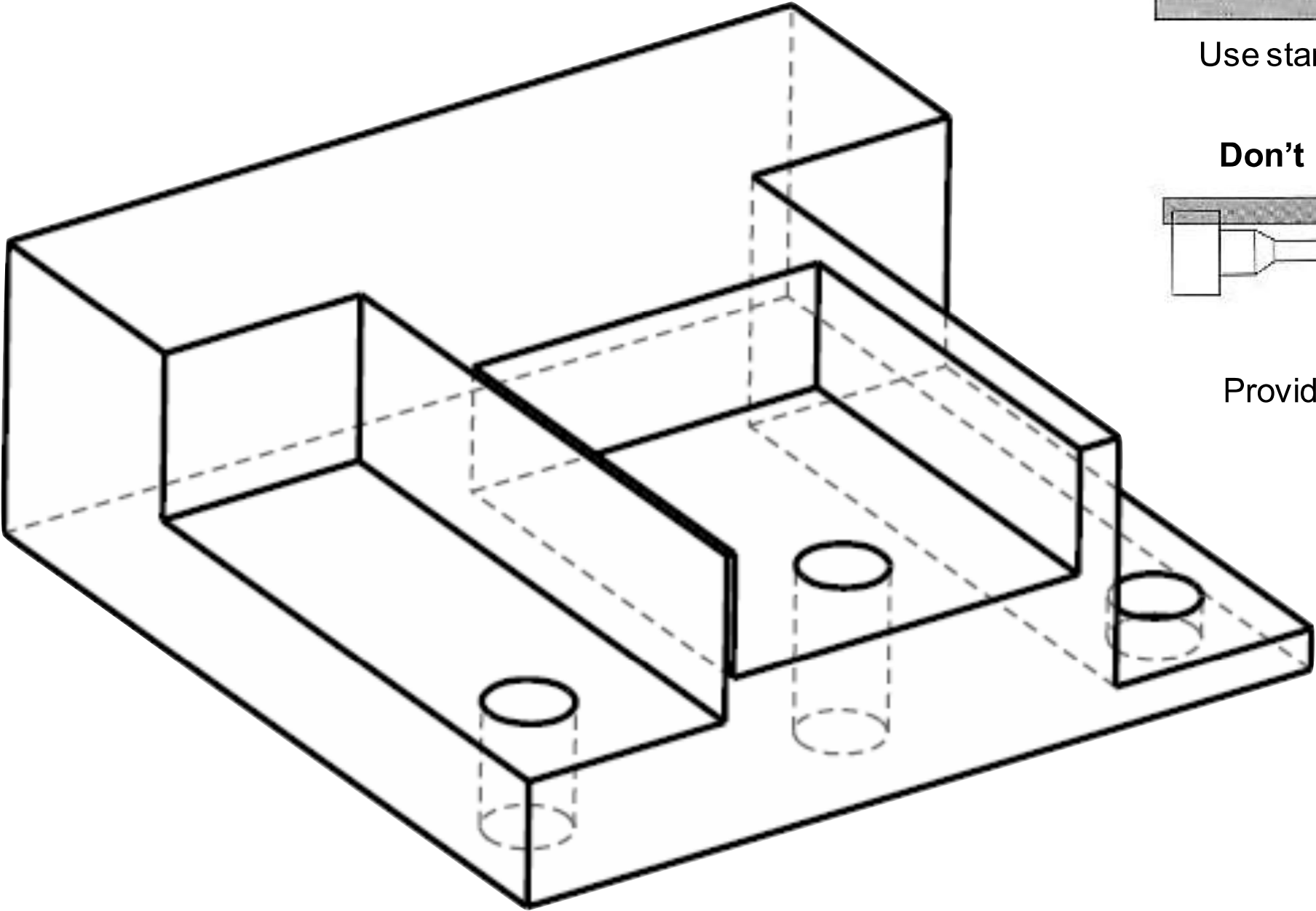
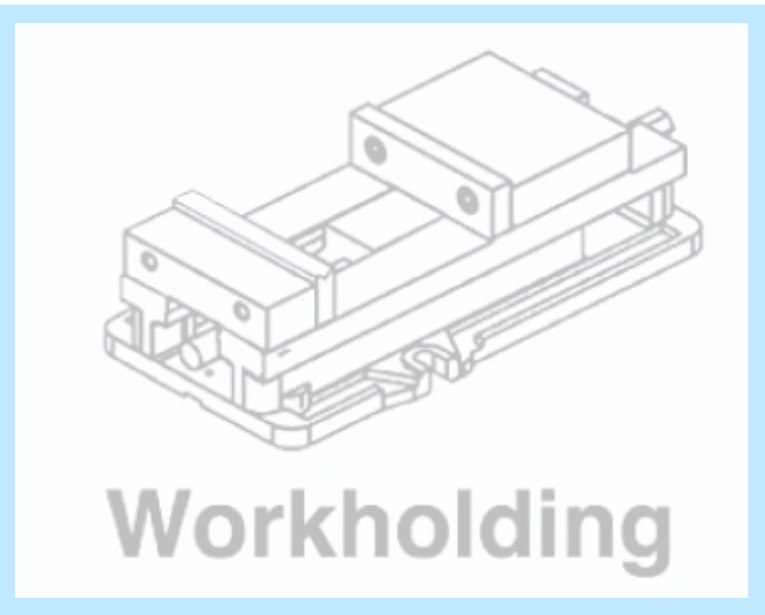
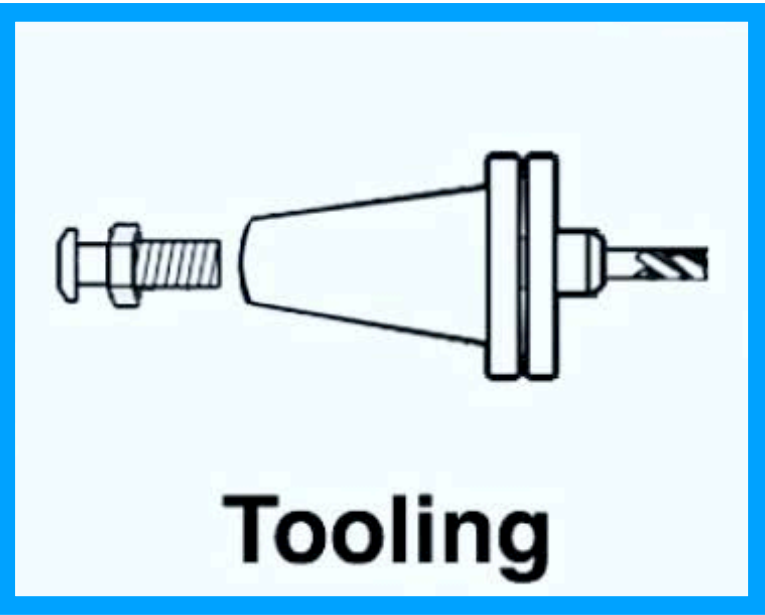


Stronger Choice

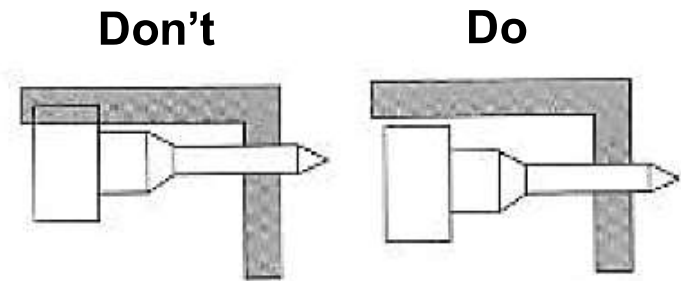
Design for Manufacturing: Machining



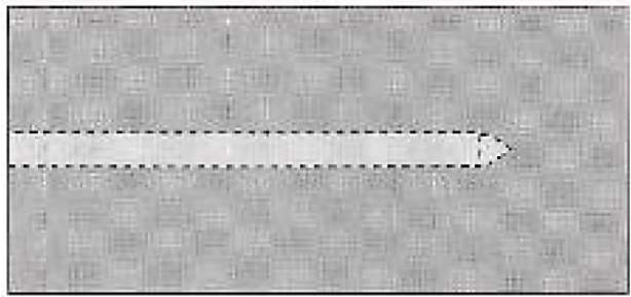
Design for Manufacturing: Machining



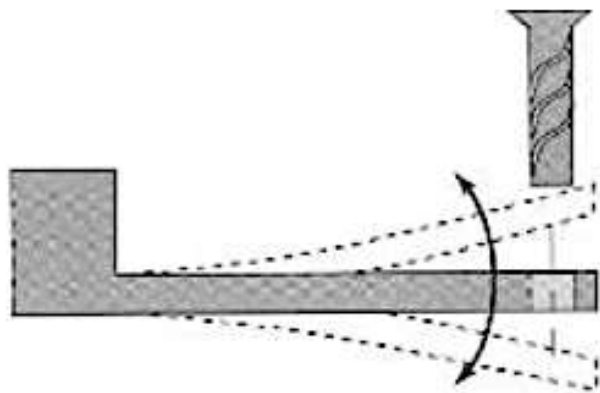
Use standard dimensions



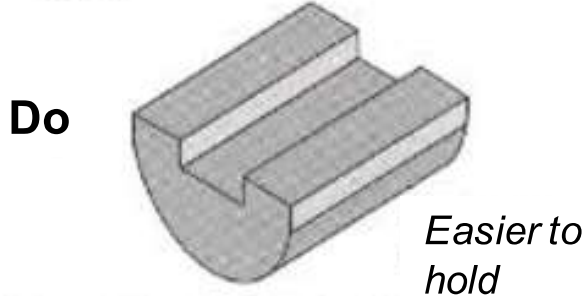
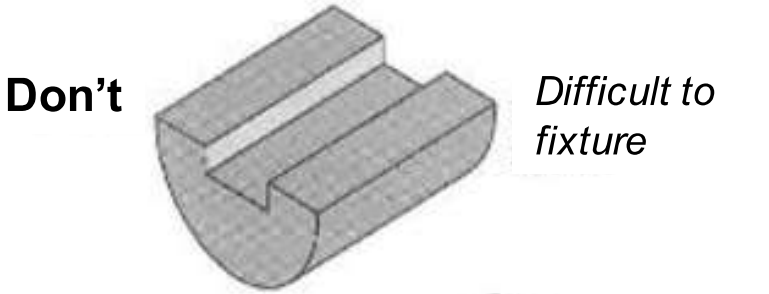
Provide access for tools



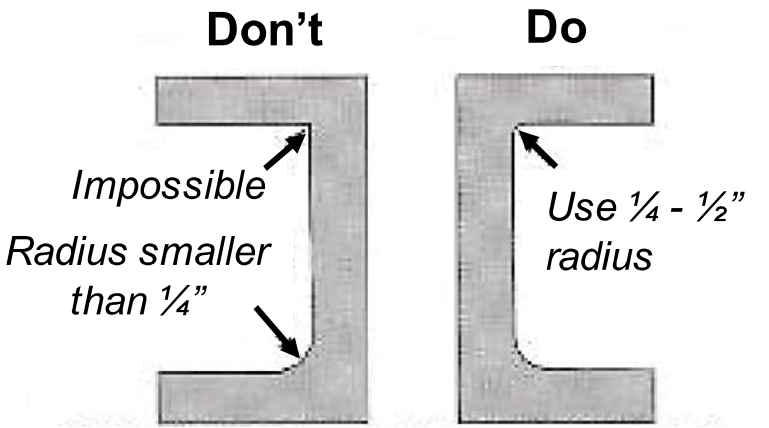
Avoid long, narrow holes



Avoid long, thin sections that cause vibration



Design parts that are easy to fixture



Design for reasonable internal pockets radii

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

Cutting #3

Machining in Practice

35

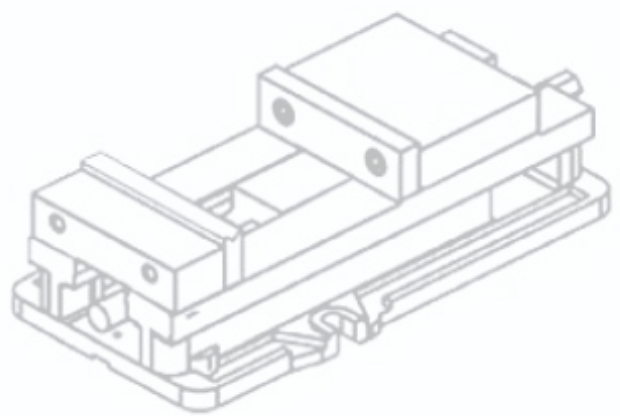
Design for Manufacturing: Machining



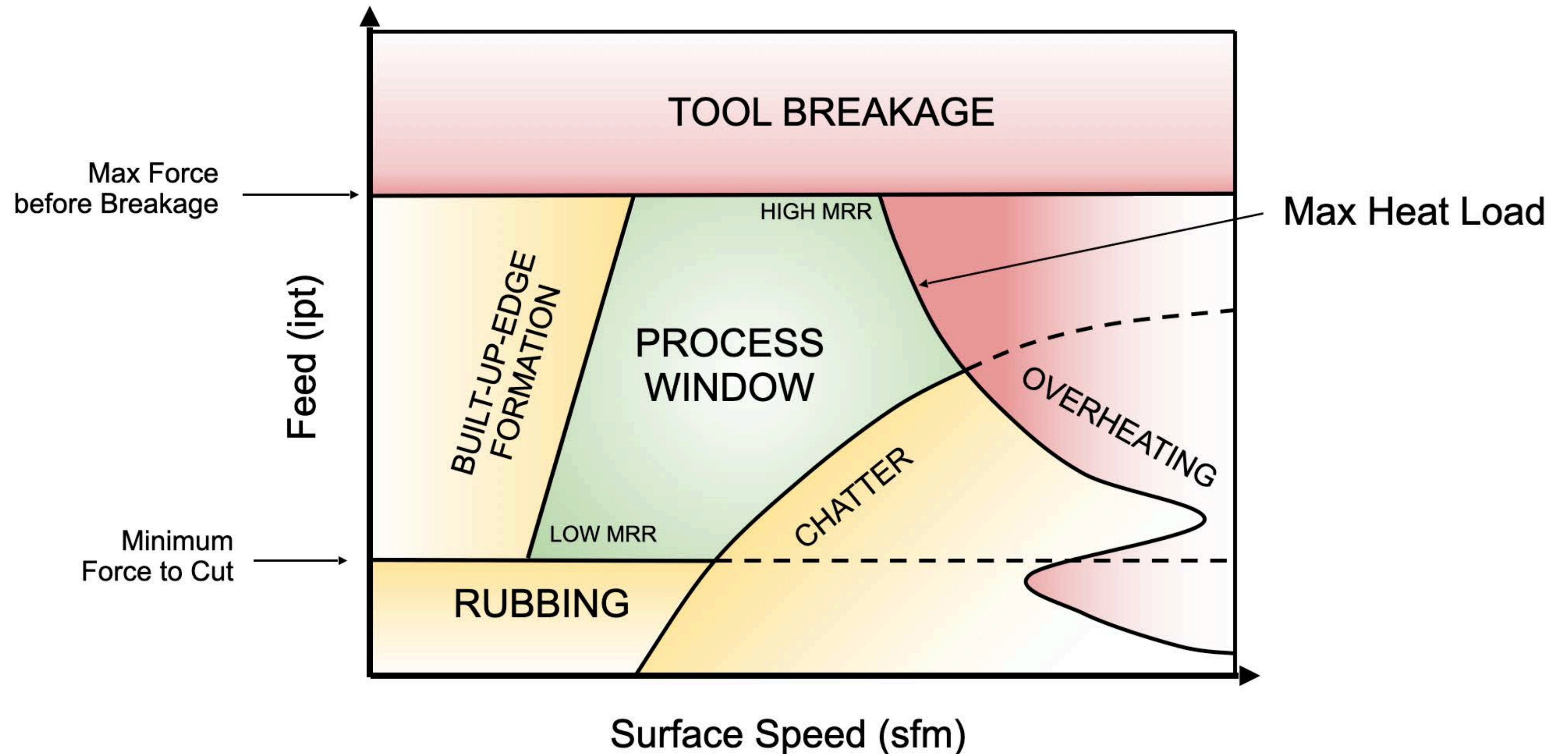
Tooling



Program



Workholding

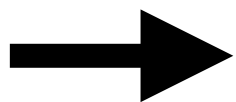
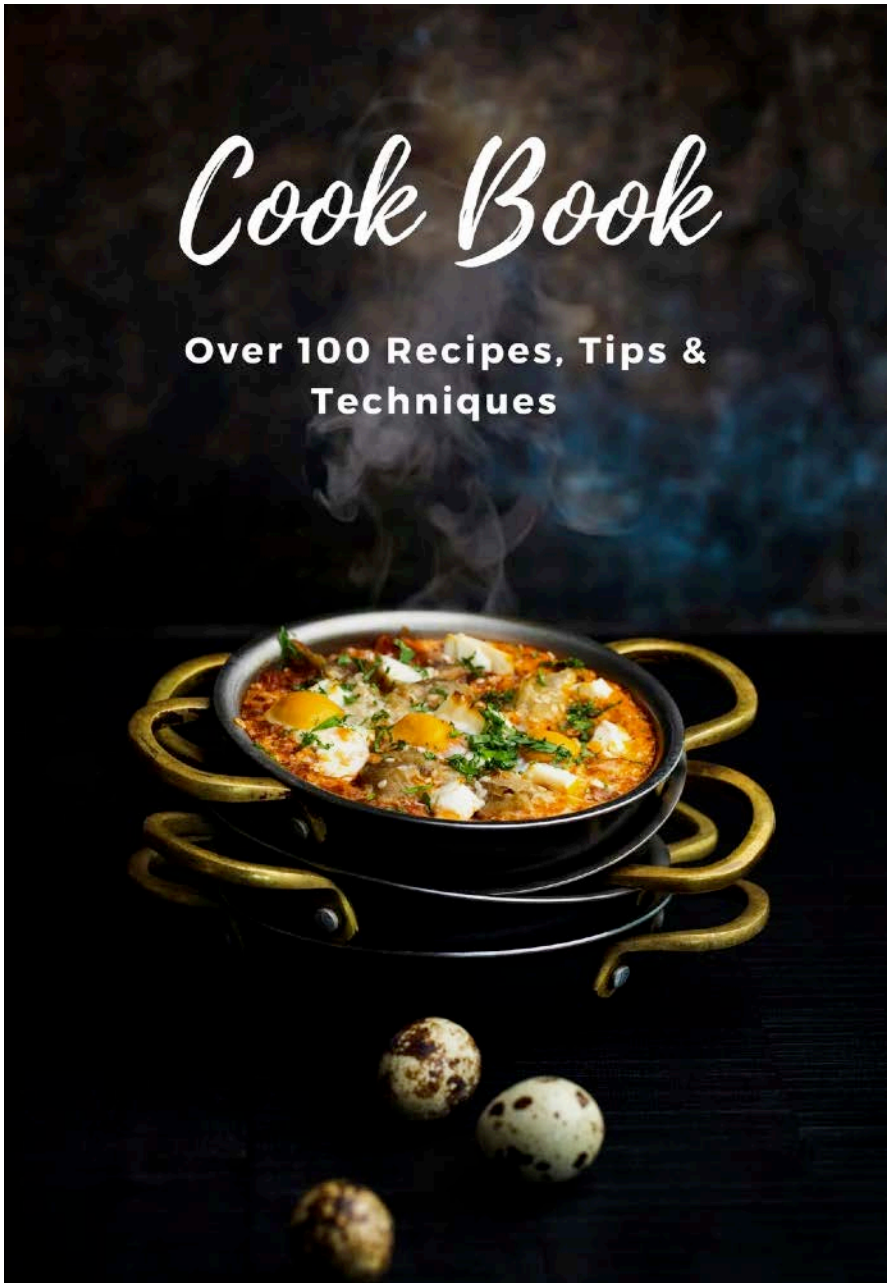
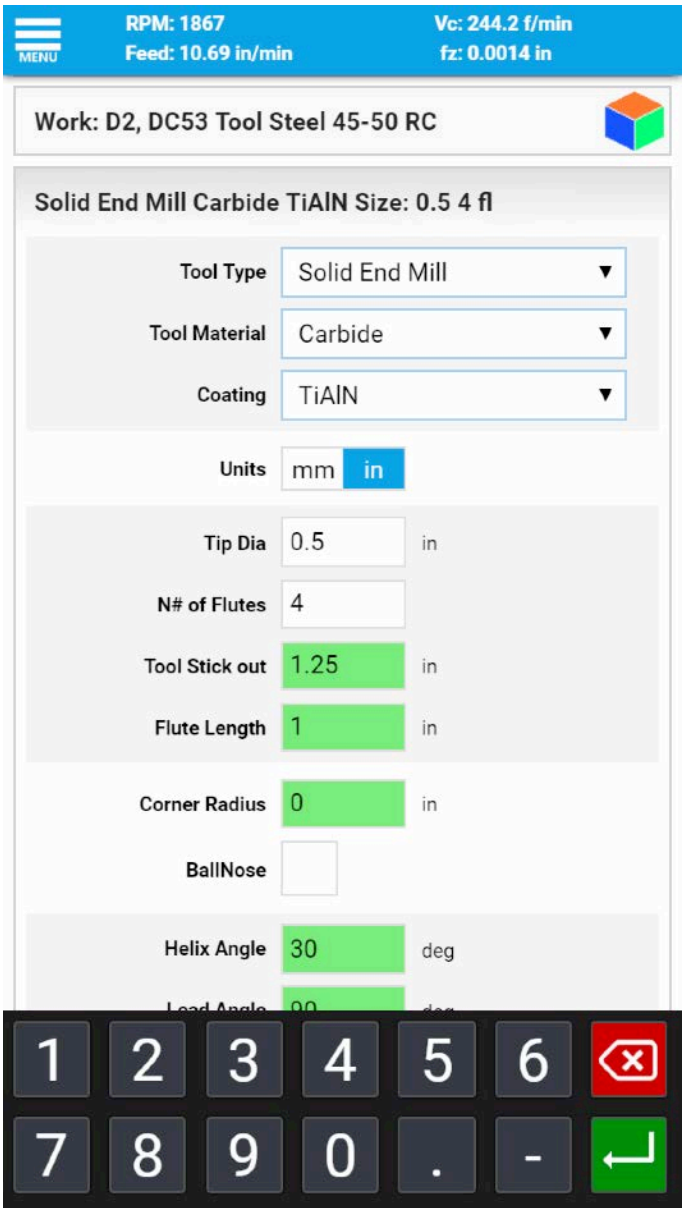
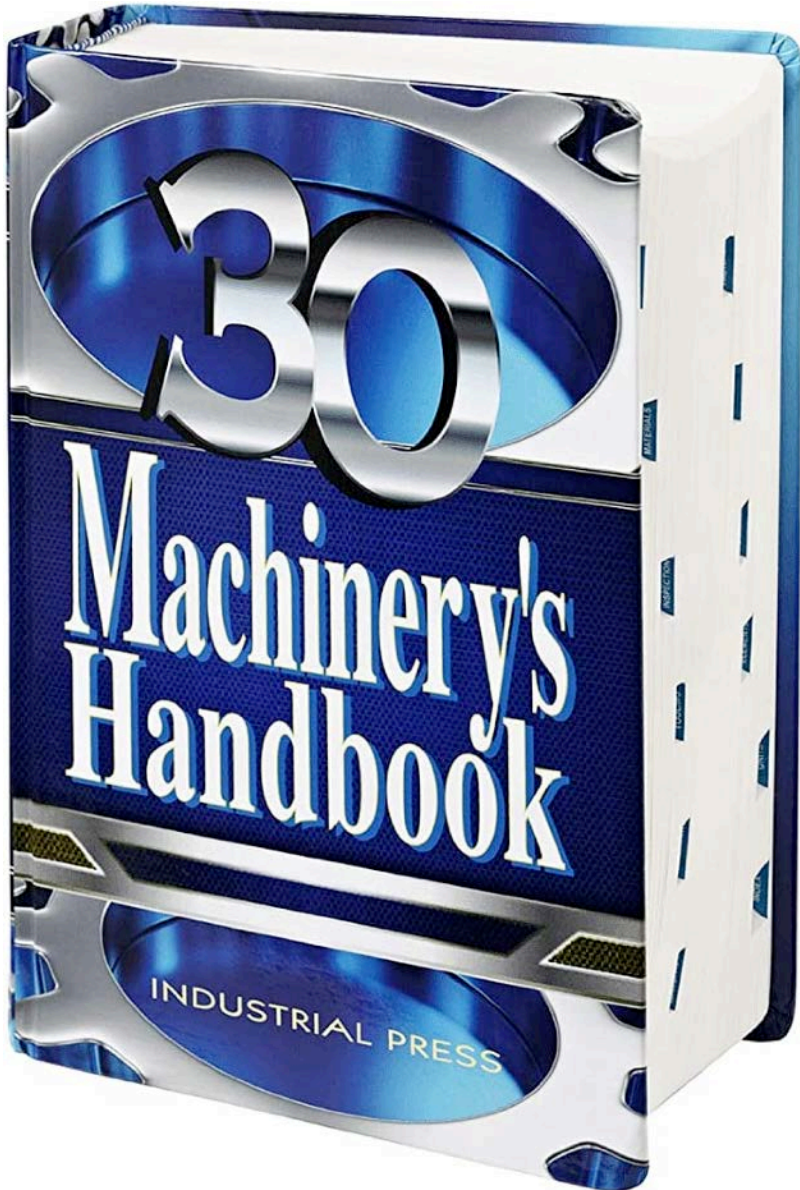
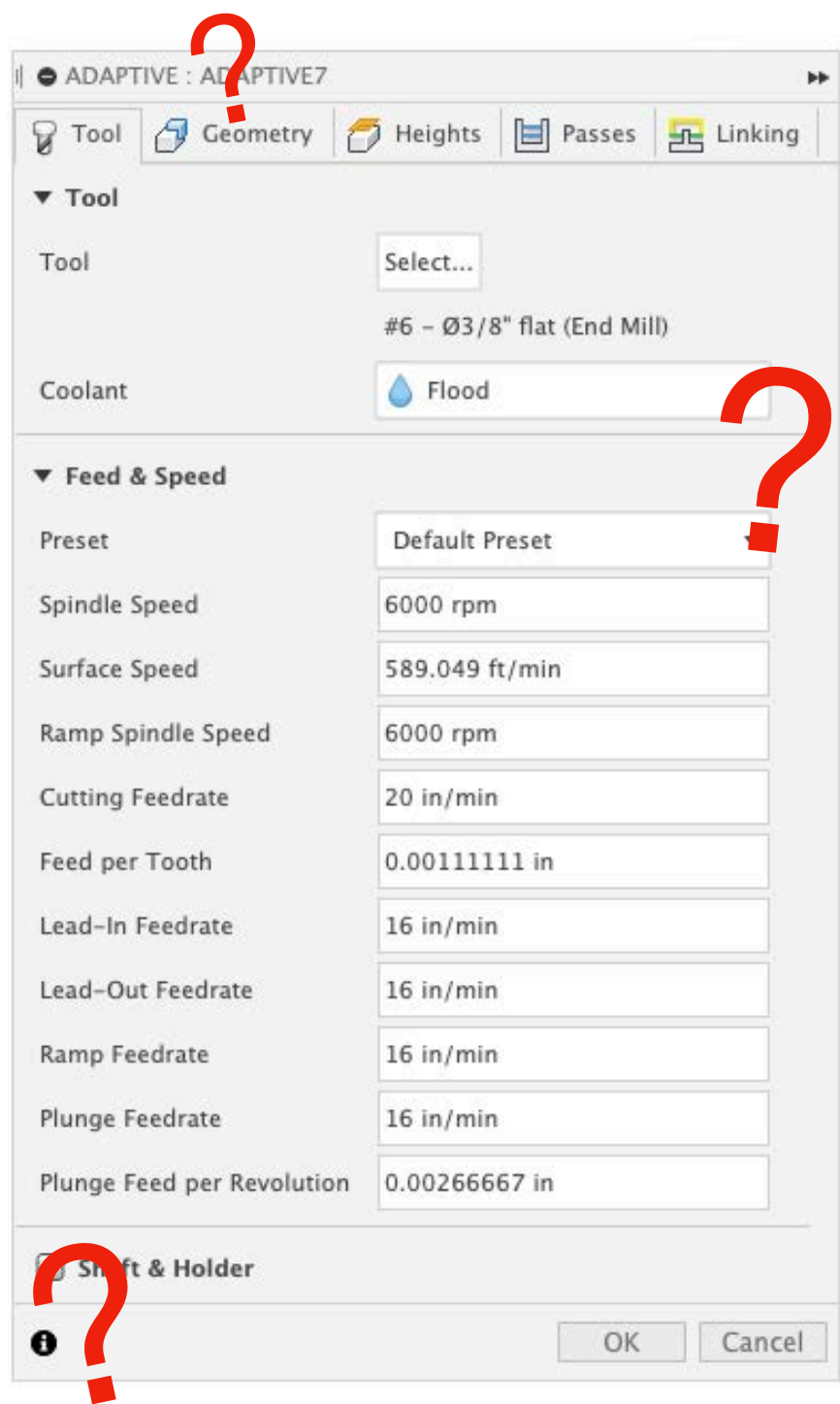


Cutting #3

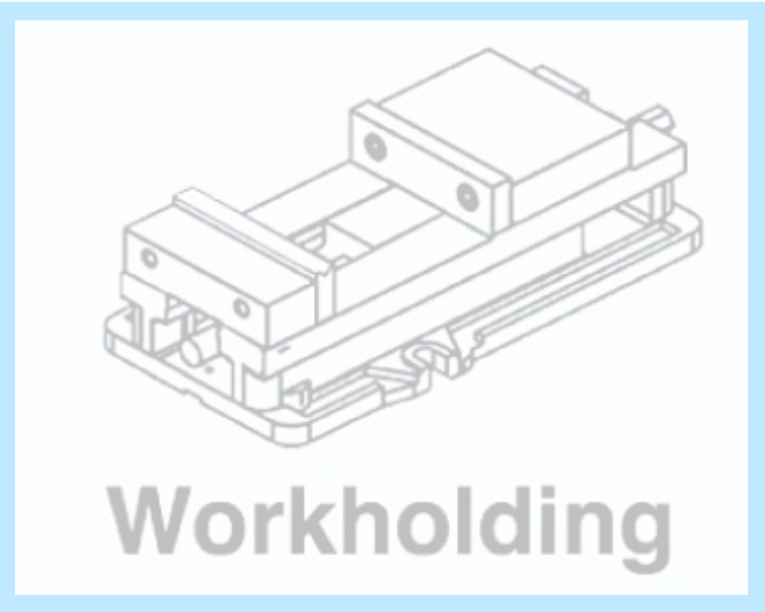
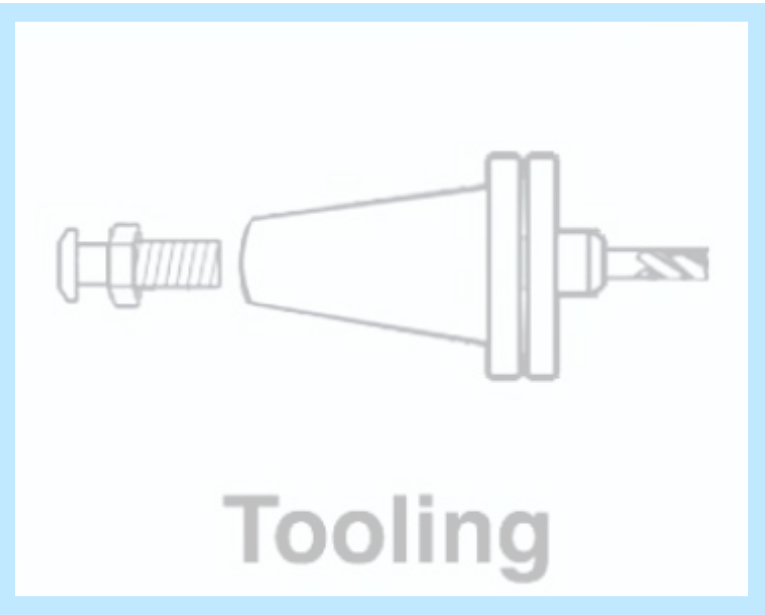
Machining in Practice

Feed and Speeds

where do you start?



Design for Manufacturing: Machining



Roughing of steel
CMC 02.1

P R

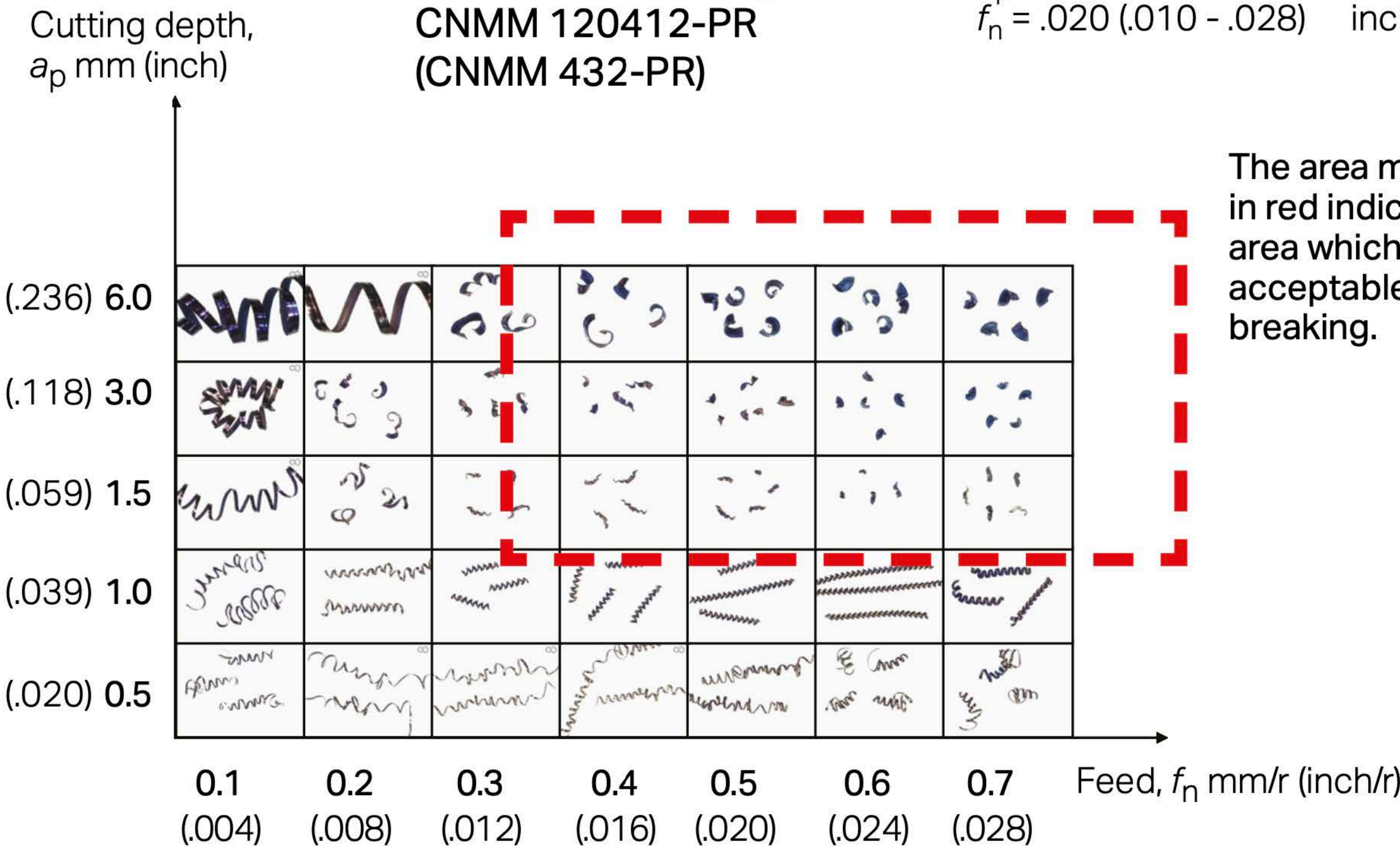


Chip breaking area:

$a_p = 5.0 \text{ (1.0 - 7.5)}$ mm
 $f_n = 0.5 \text{ (0.25 - 0.7)}$ mm/r

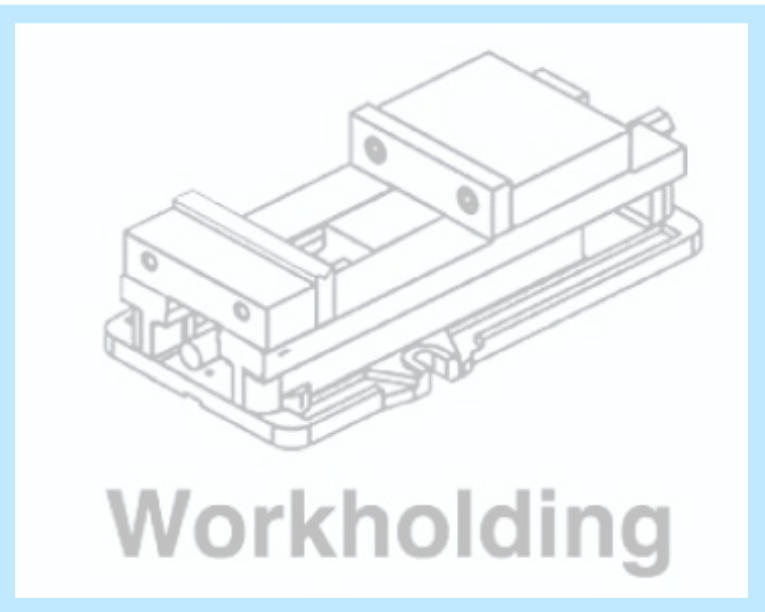
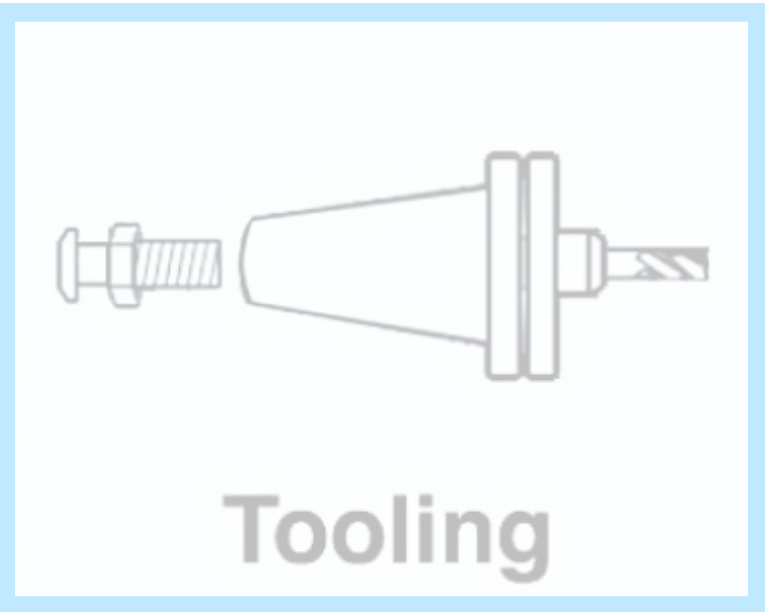
$a_p = .197 \text{ (.039 - .295)}$ inch
 $f_n = .020 \text{ (.010 - .028)}$ inch/r

CNMM 120412-PR
(CNMM 432-PR)

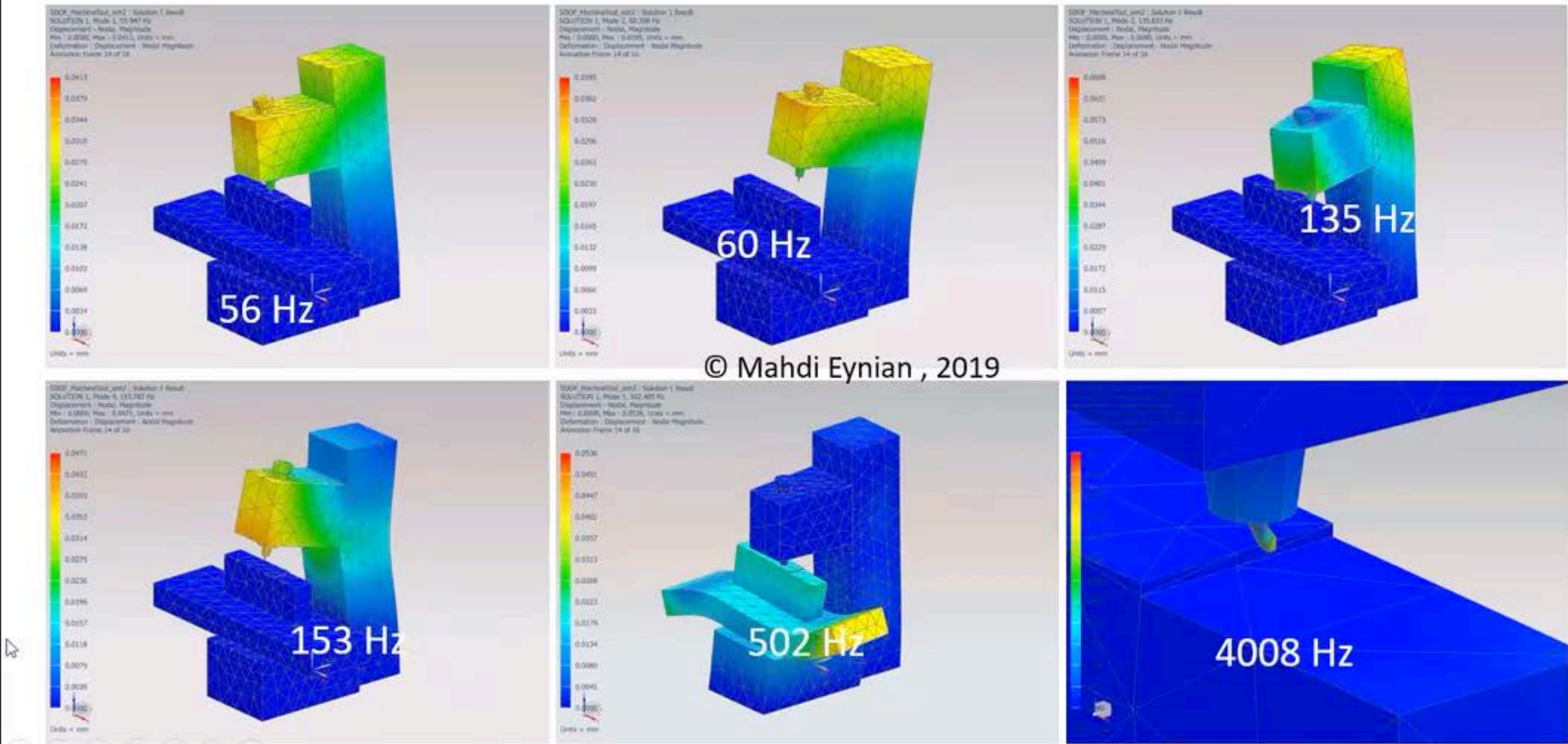


The area marked in red indicates the area which gives acceptable chip breaking.

Vibration and Chatter

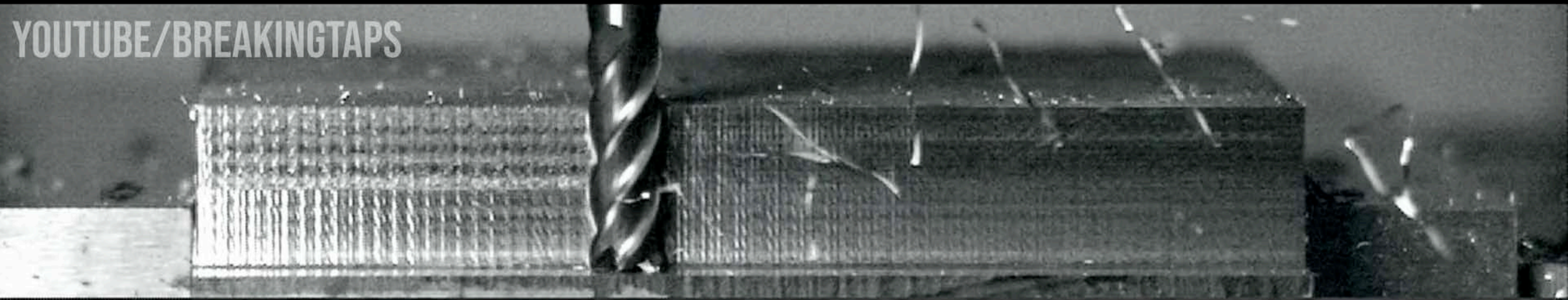


Vibration Modes in a Simplified Machine Tool Model



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

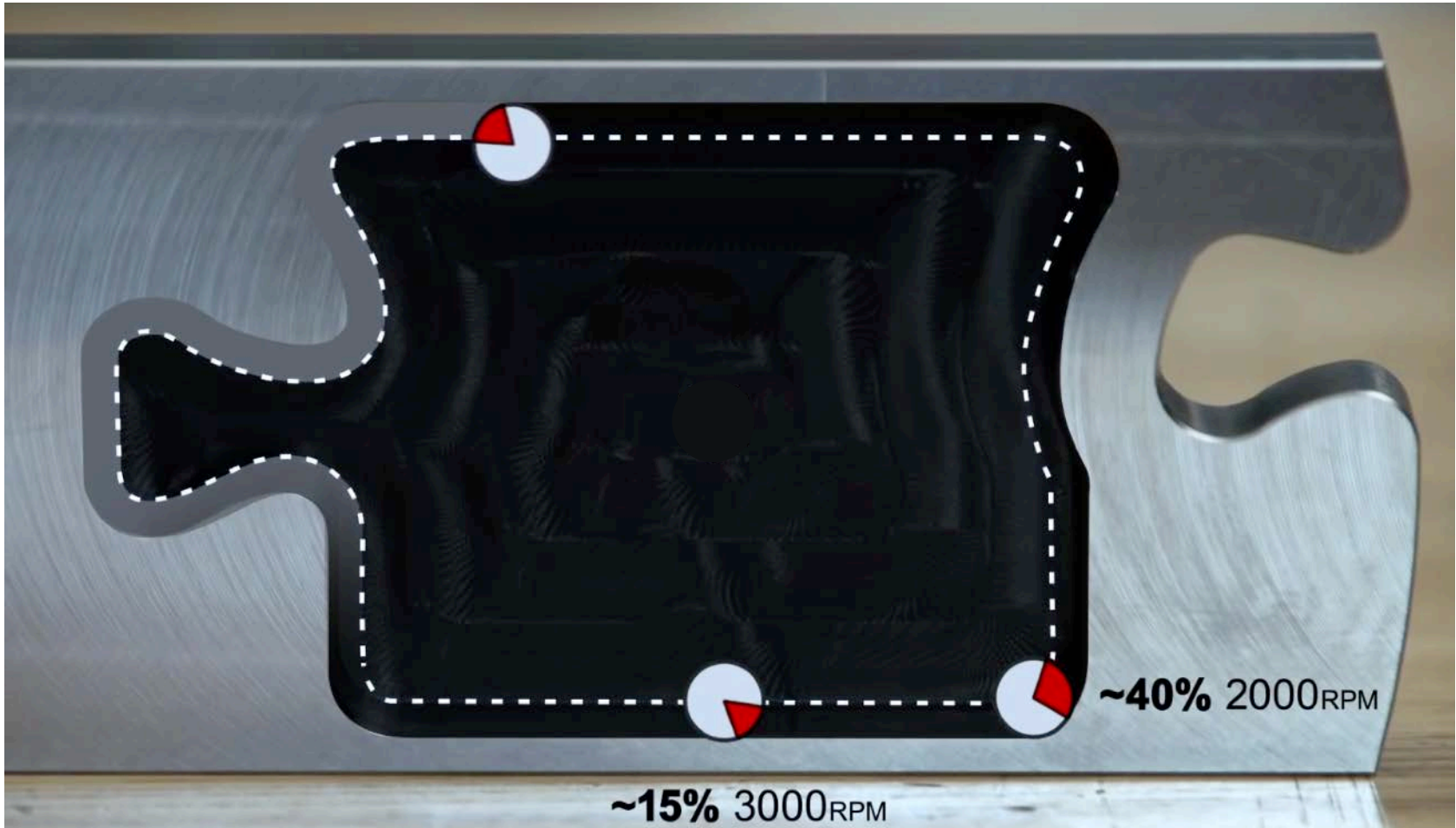
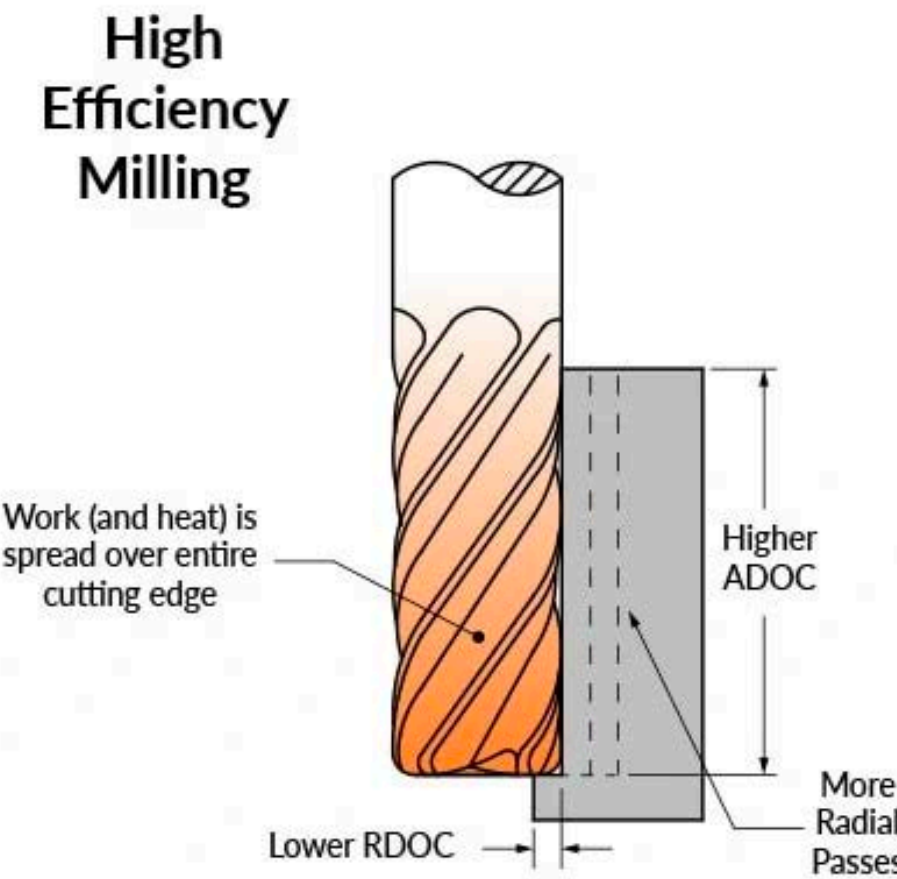
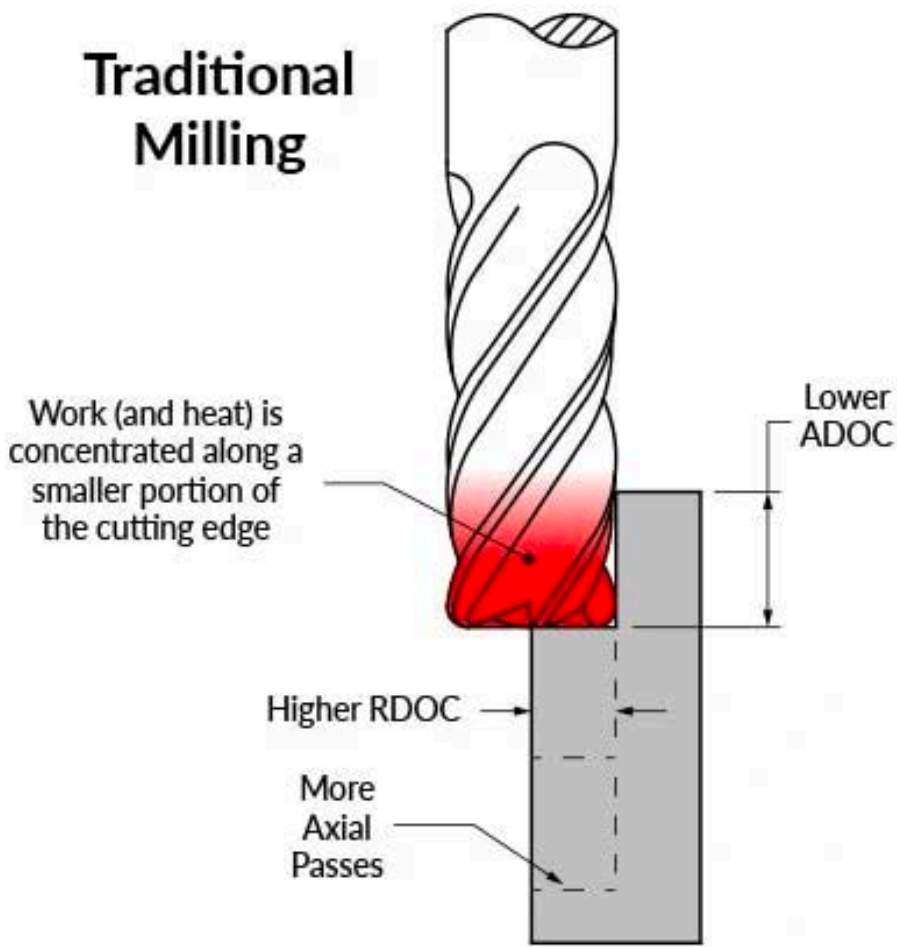
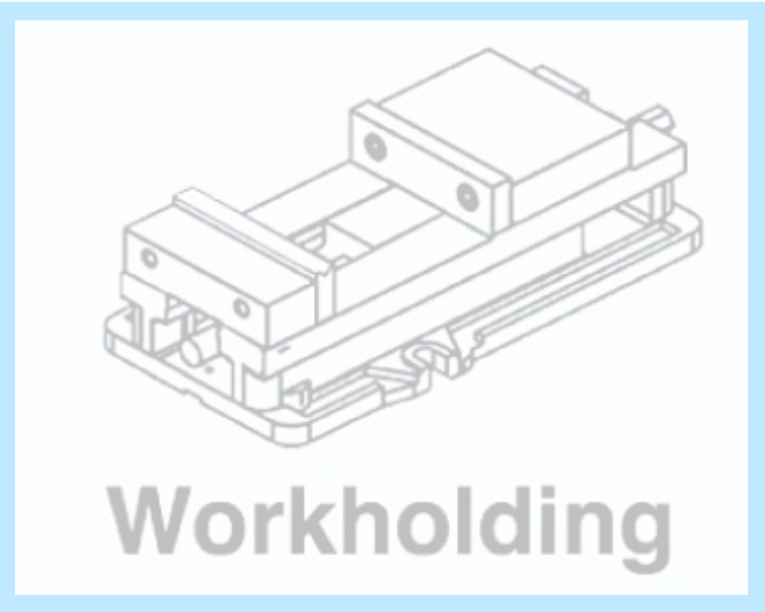
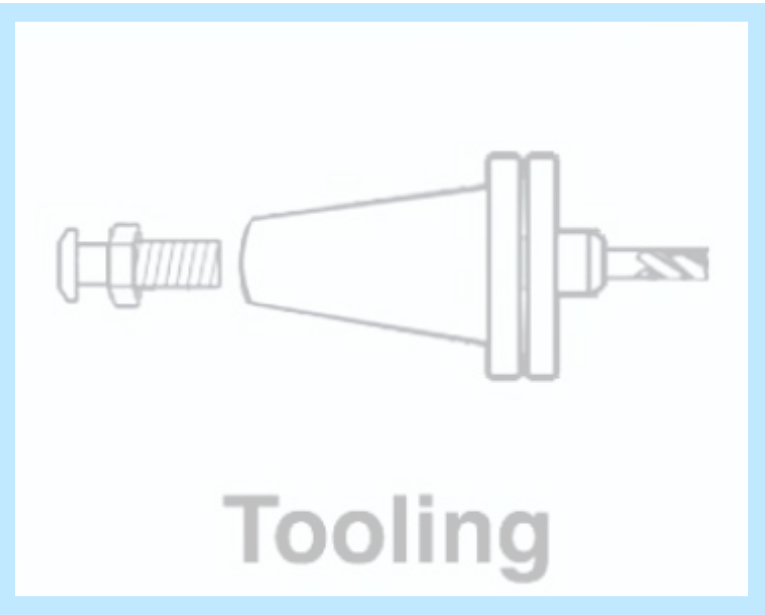
YOUTUBE/BREAKINGTAPS



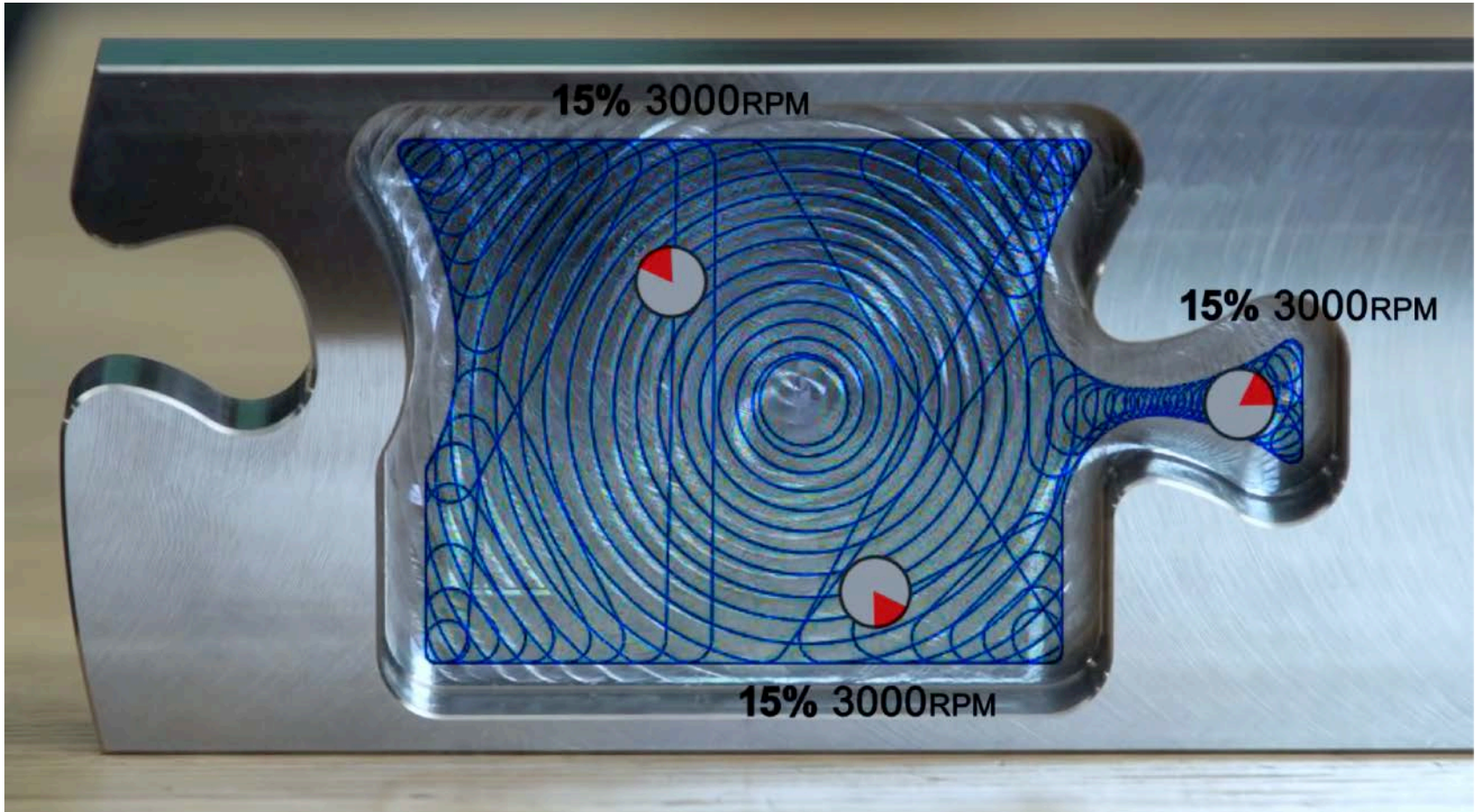
Cutting #3

Machining in Practice

Adaptive Toolpaths



simple program and machine



needs fast computers and machines

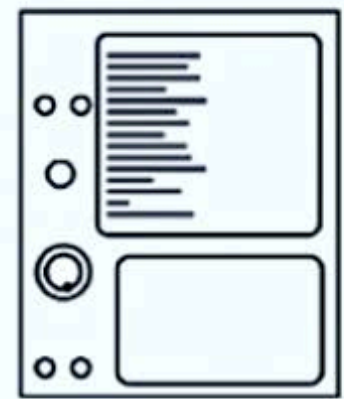
Cutting #3

Machining in Practice

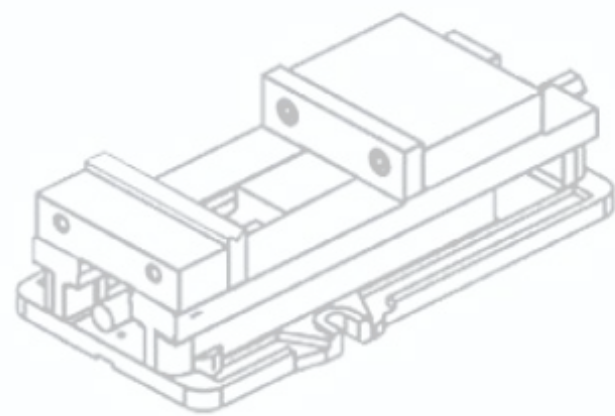
41



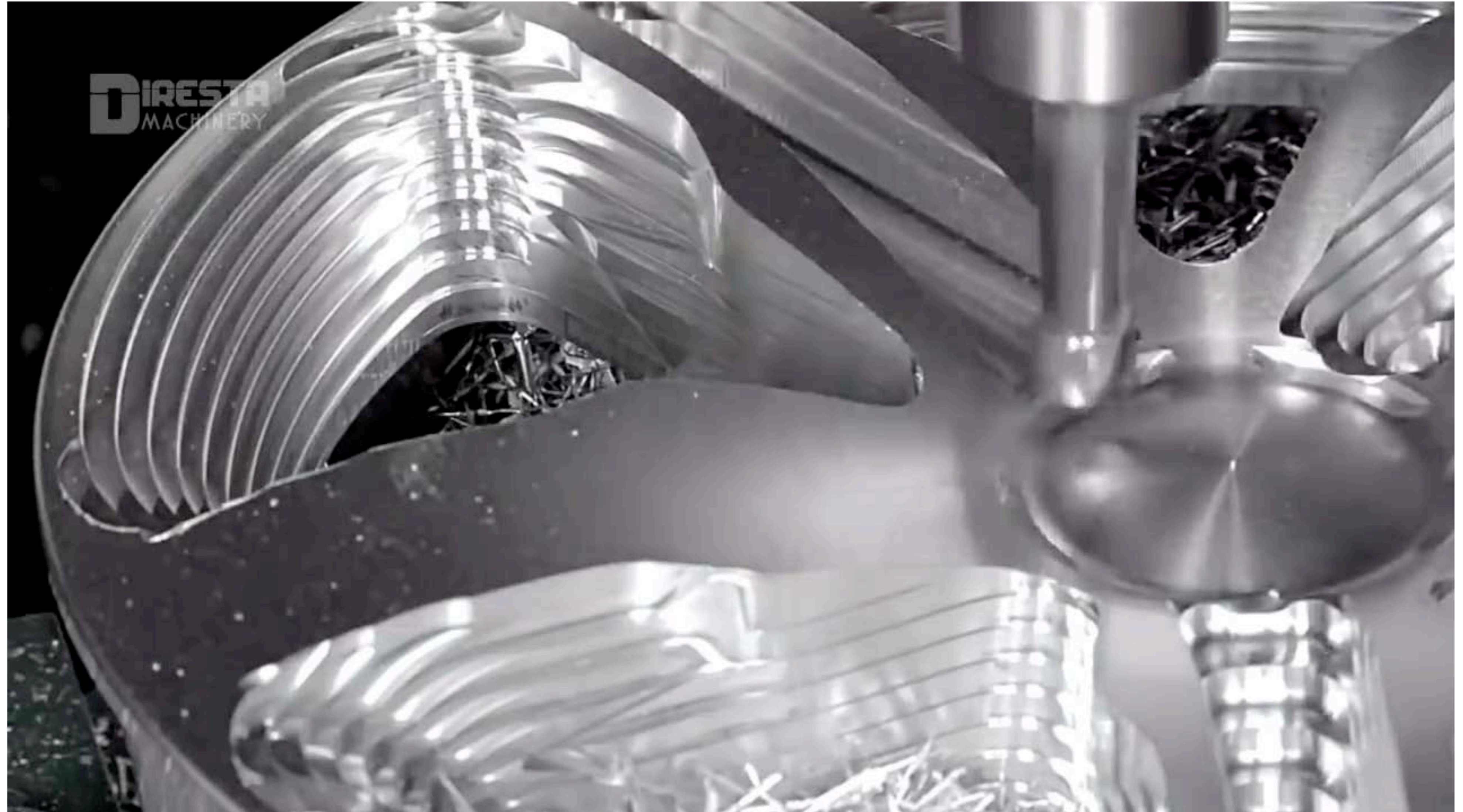
Tooling



Program



Workholding



Cutting #3

Machining in Practice

42

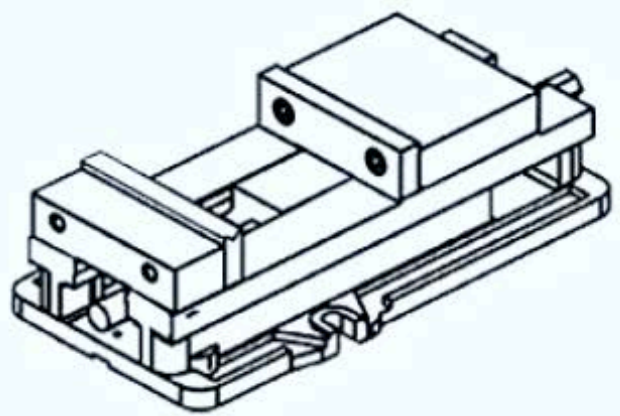
Stiffness Returns!



Tooling



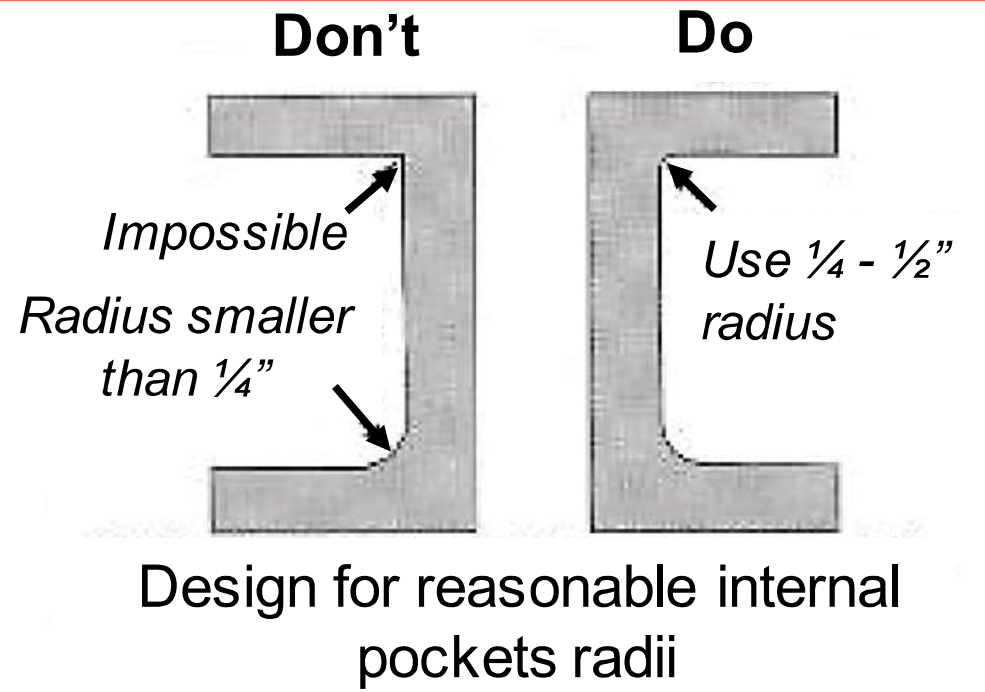
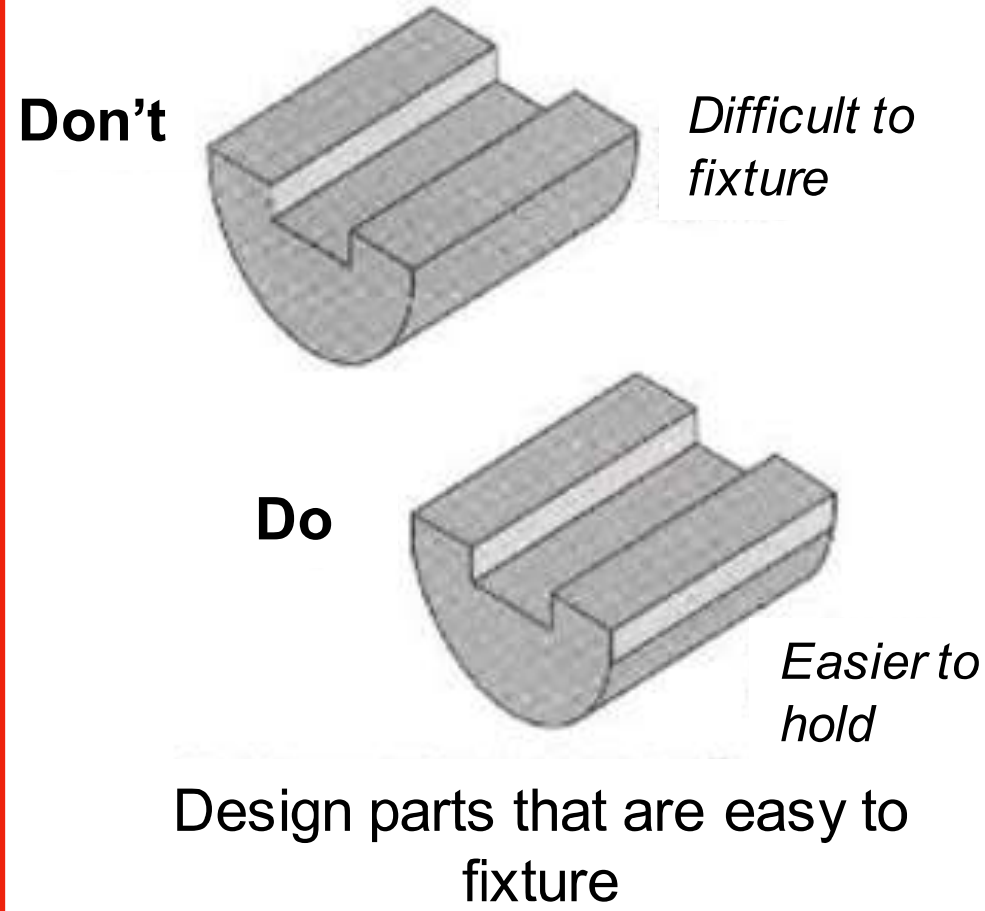
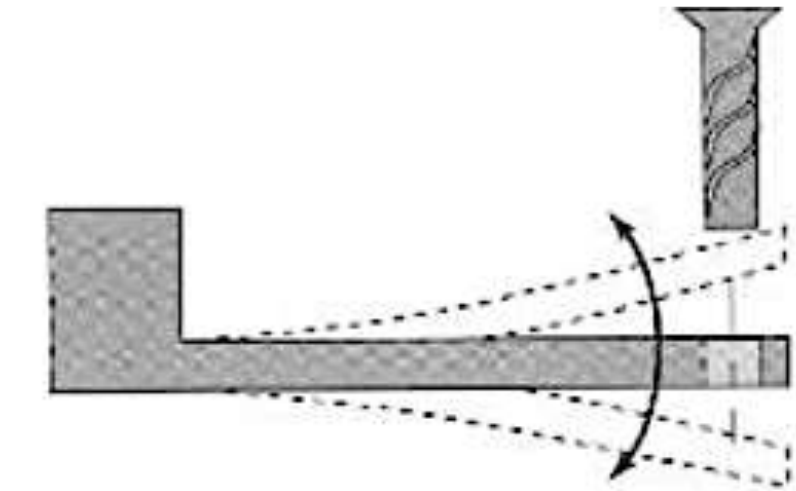
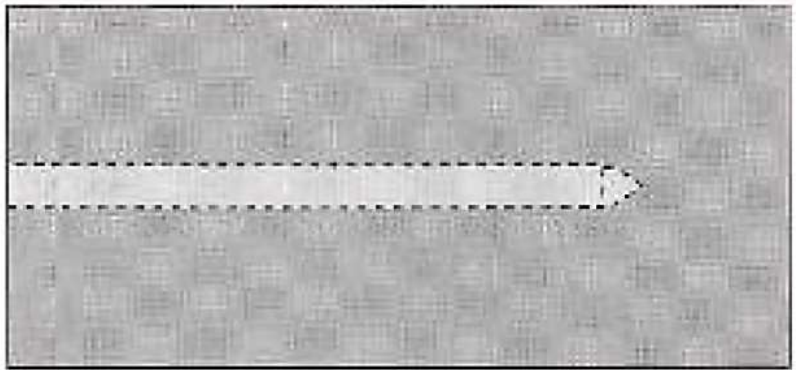
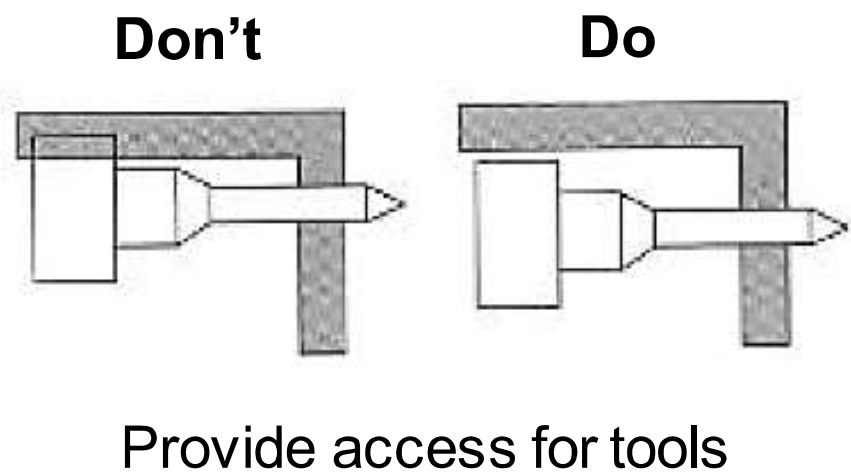
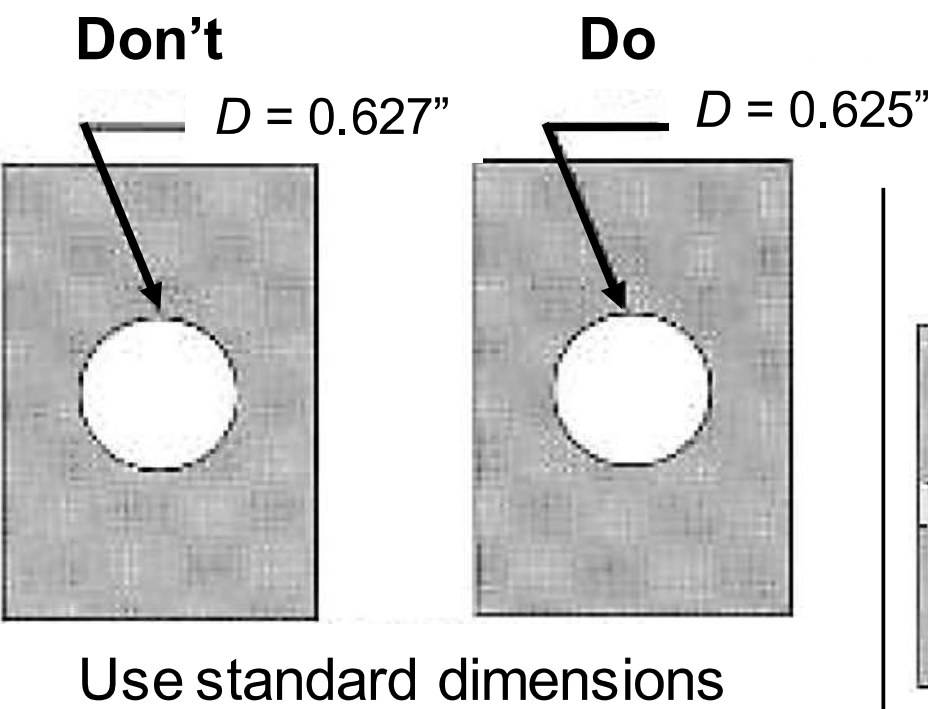
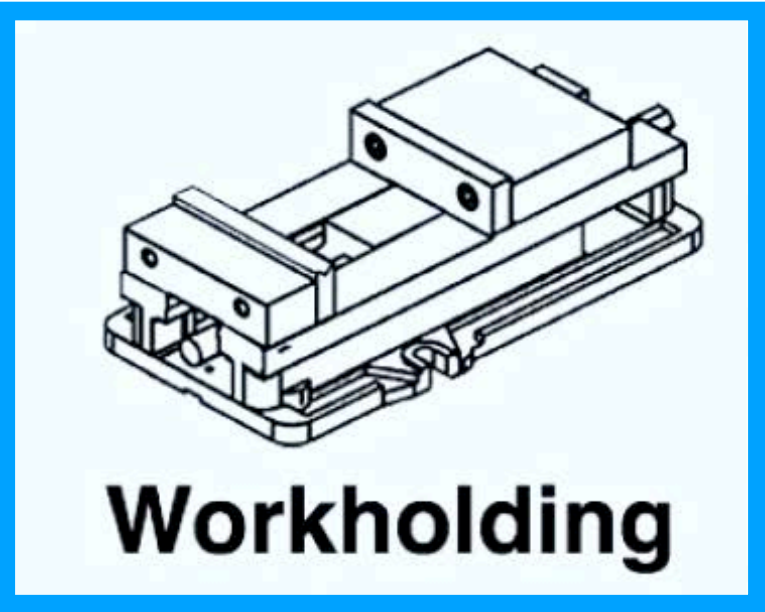
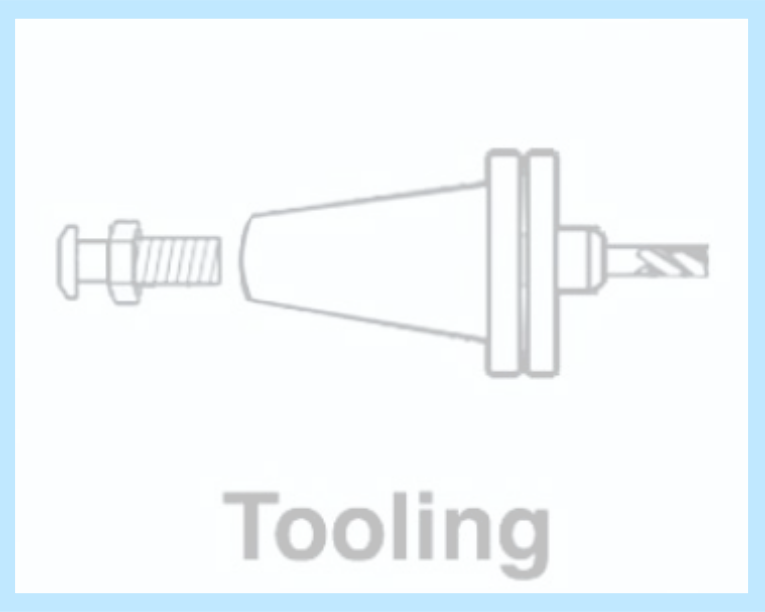
Program



Workholding



Strategies

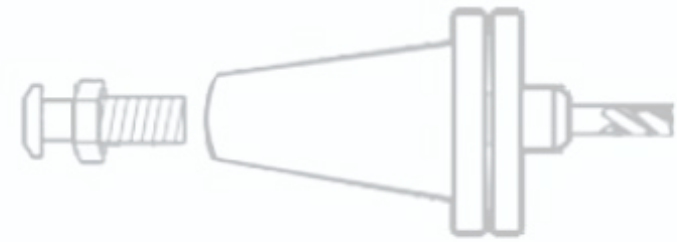


Cutting #3

Machining in Practice

44

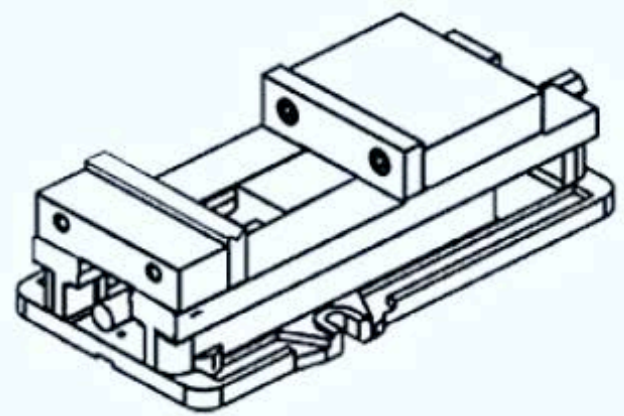
Strategies



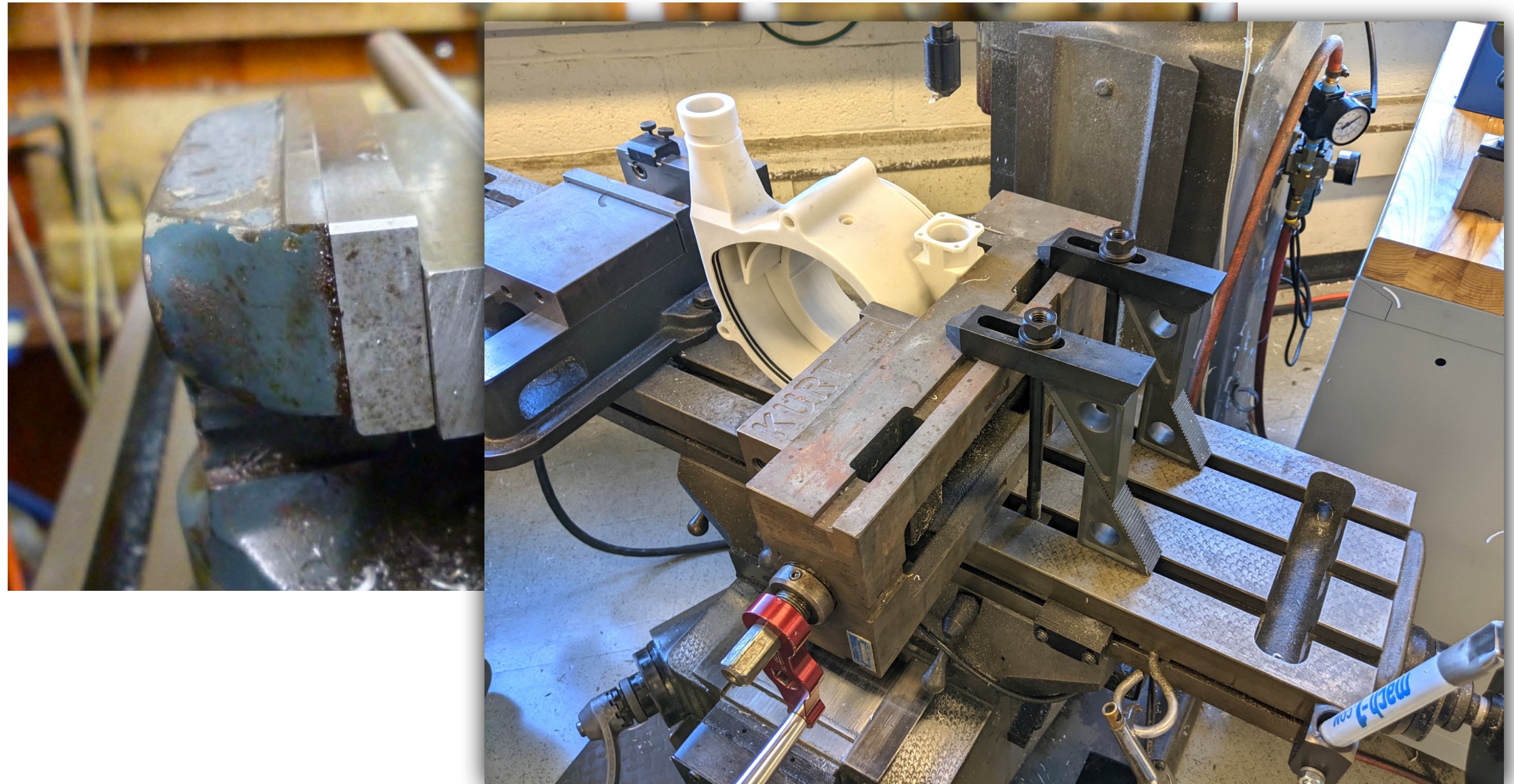
Tooling



Program



Workholding

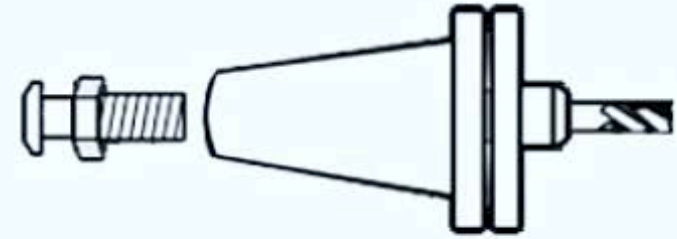


Cutting #3

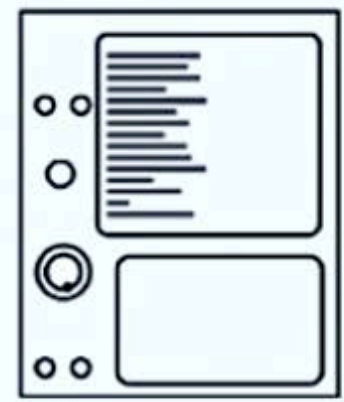
Machining in Practice

45

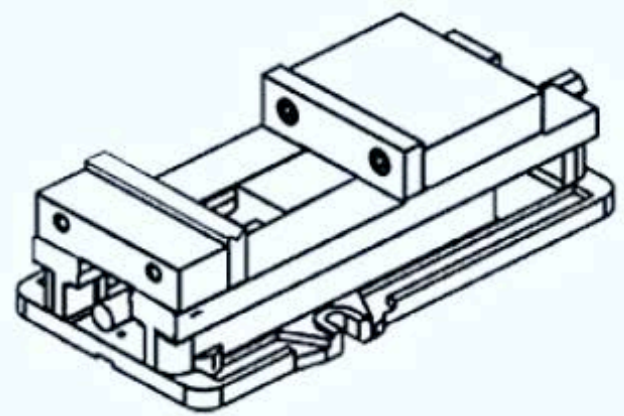
Surface Finish



Tooling



Program



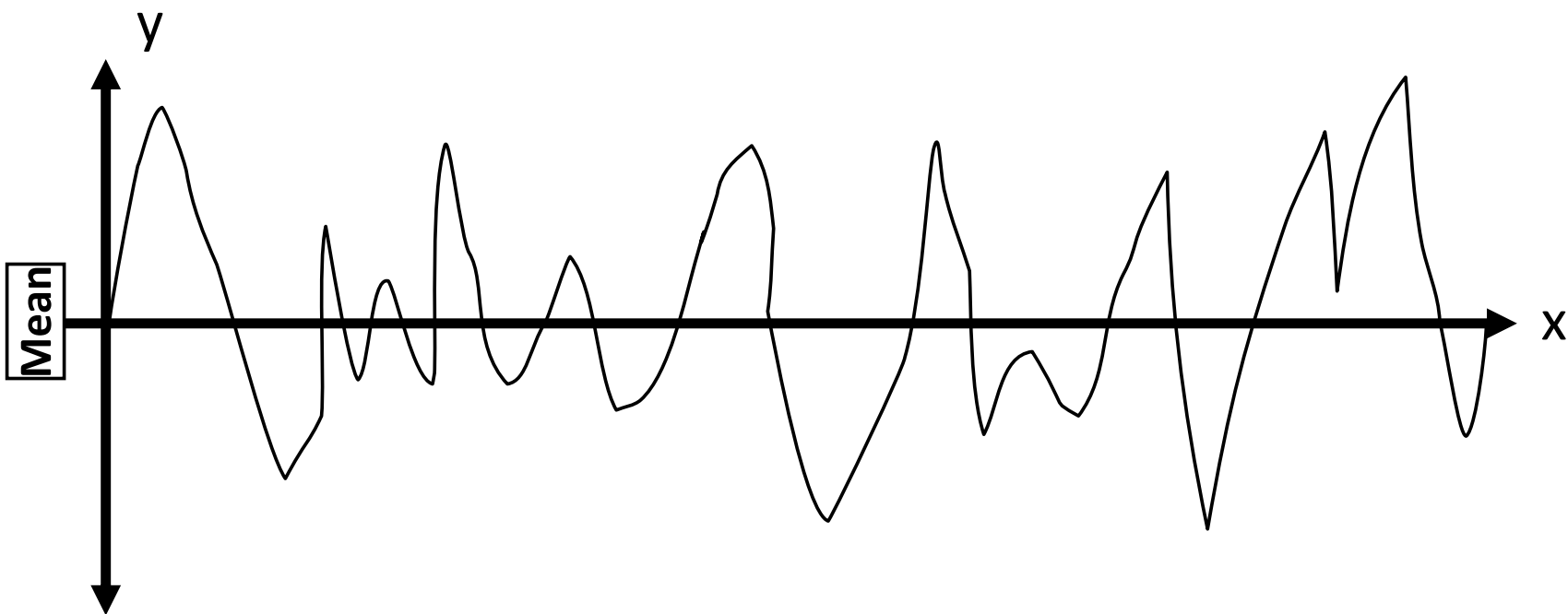
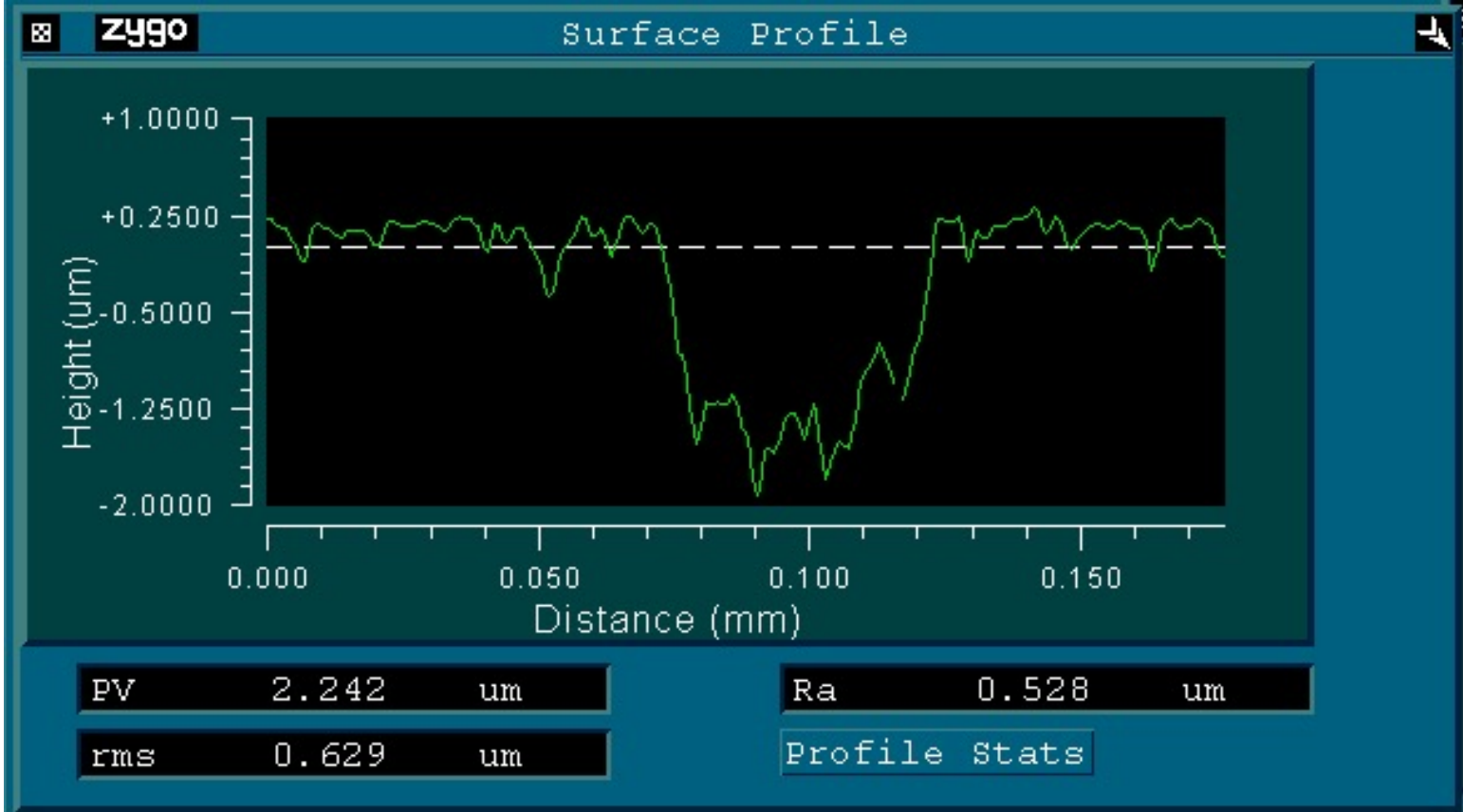
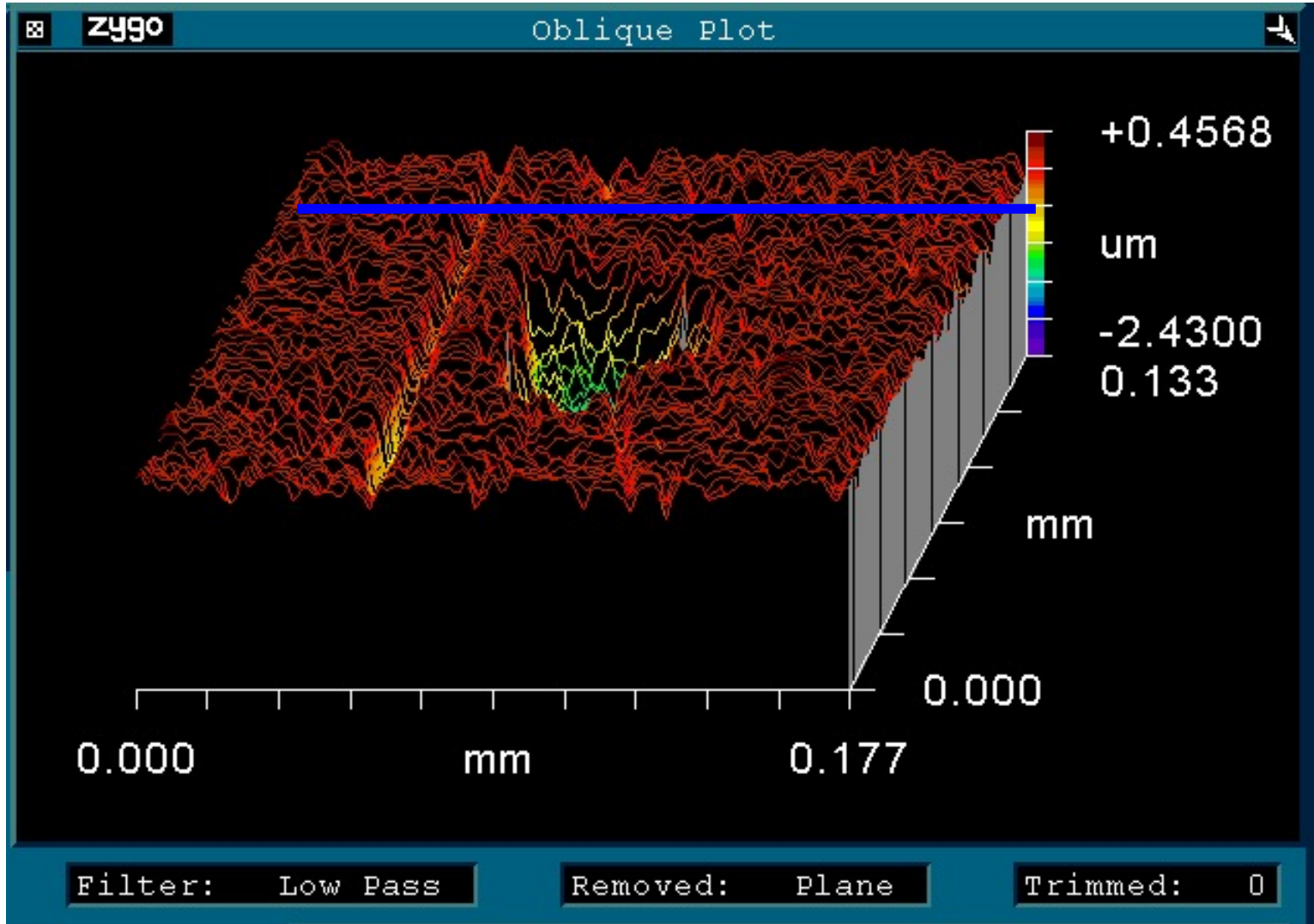
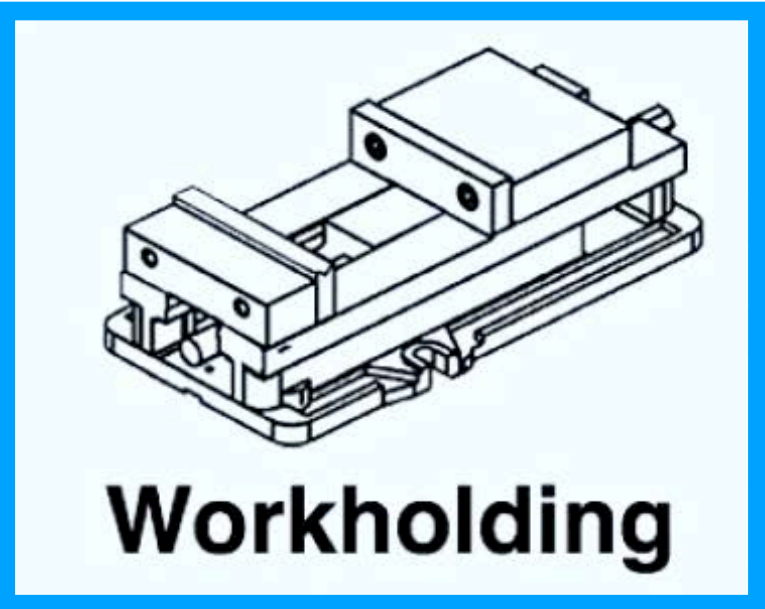
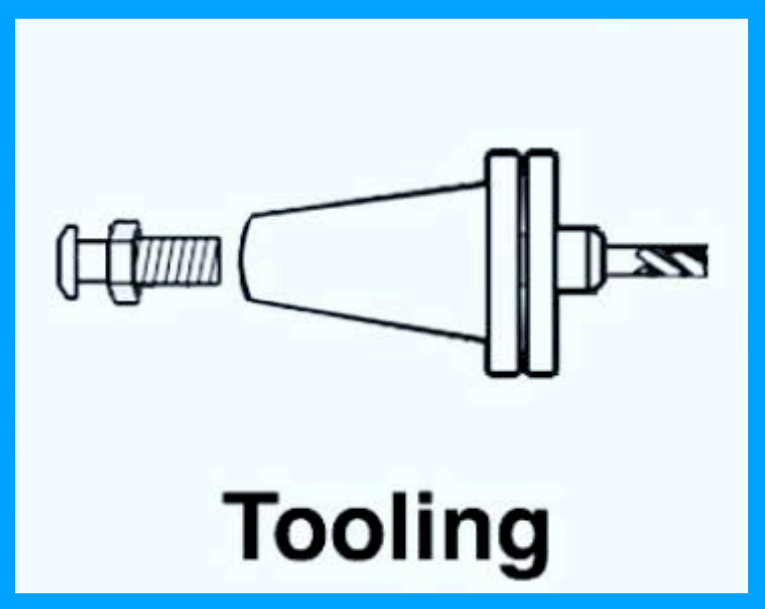
Workholding



Cutting #3

Machining in Practice

Surface Finish



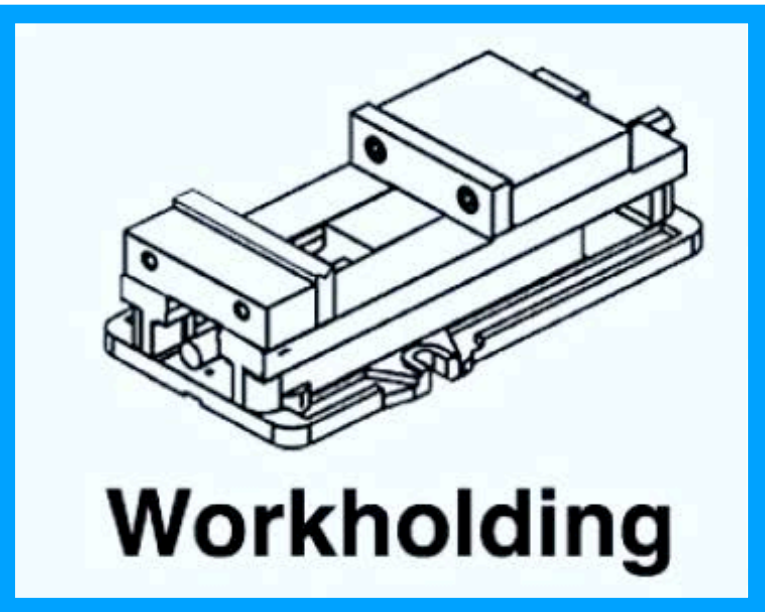
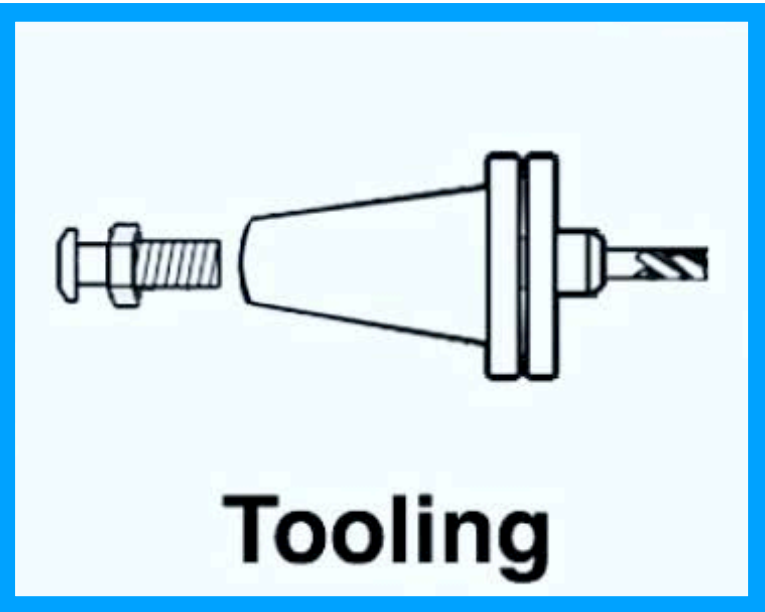
$$R_a = \frac{1}{L} \int_0^L |y| dx$$

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

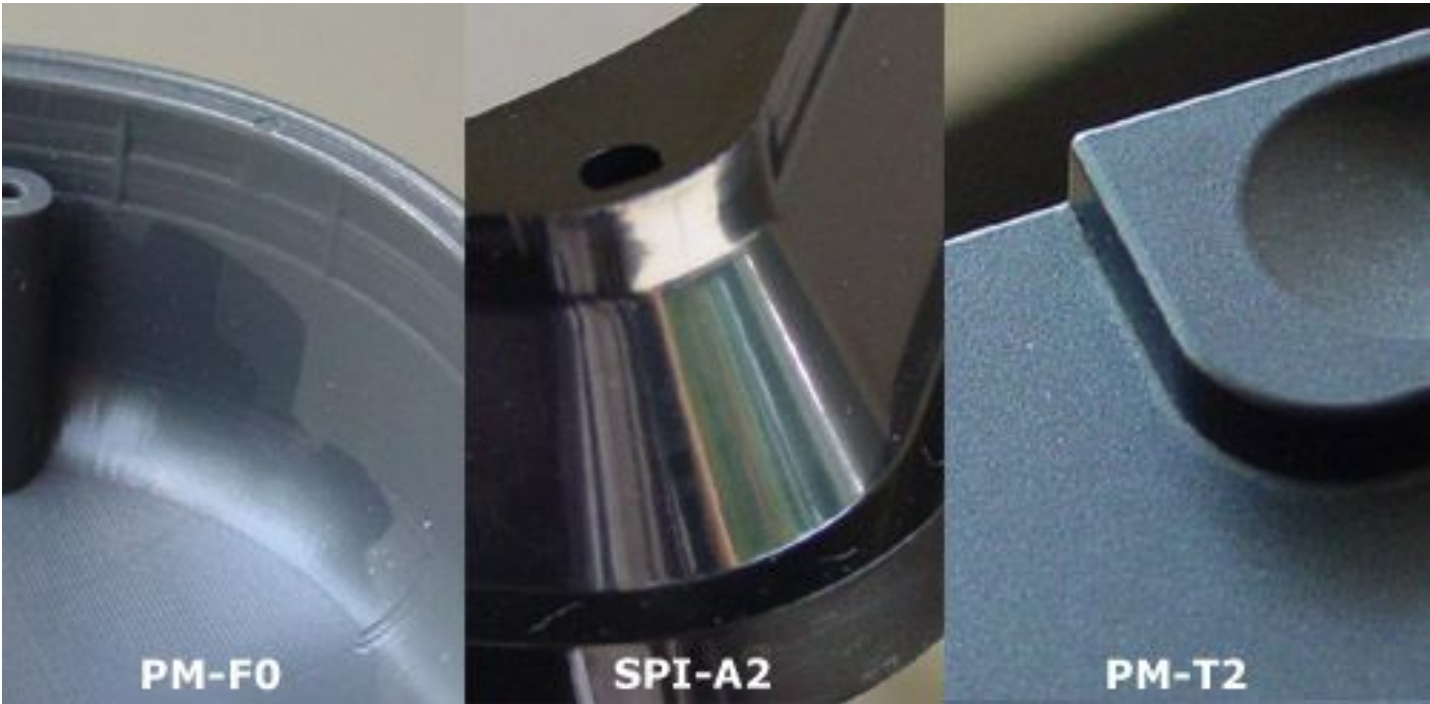
R_a: average roughness
f: feed
R: tool nose radius

Surface Finish

specify what you need, considering time and cost!



Common surface roughness (R _a in micro-inches)													
Process	2000	1000	500	250	125	63	32	16	8	4	2	1	½
Sawing													
Drilling													
Milling													
Turning													
Grinding													
Polishing													



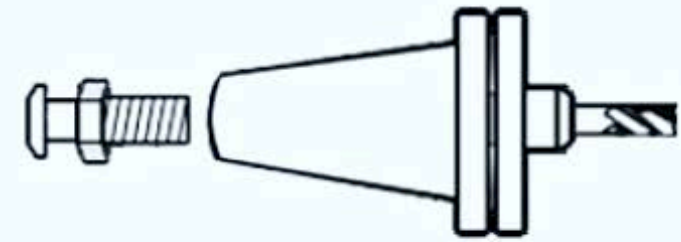
	▽	▽▽		▽▽▽		
	N10	N9	N8	N7	N6	N5
HORIZONTAL MILLING						
VERTICAL MILLING						
TURNING						
μm R _a	12.5	6.3	3.2	1.6	0.8	0.4
μ' AA	500	250	125	63	32	16

Cutting #3

Machining in Practice

48

Manufacturing Attributes (vs Injection Molding)



Tooling

Rate

low-medium

Quality

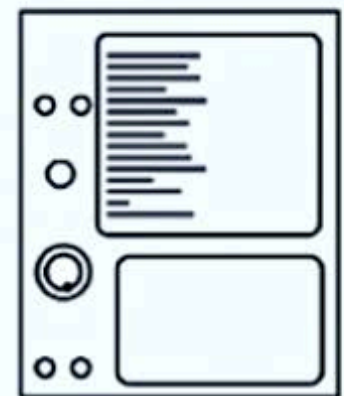
good!

Flexibility

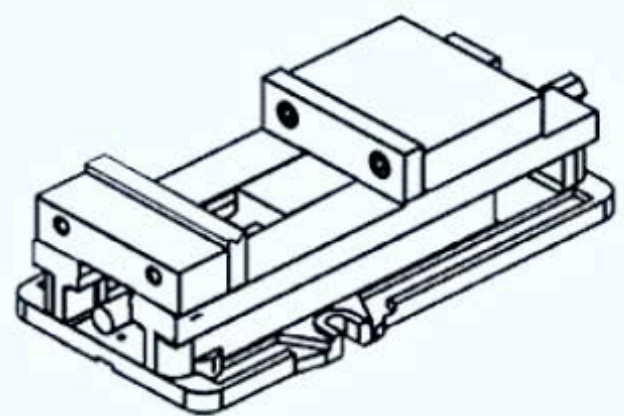
high

Cost

wide range:
depends on design,
material, volume



Program



Workholding

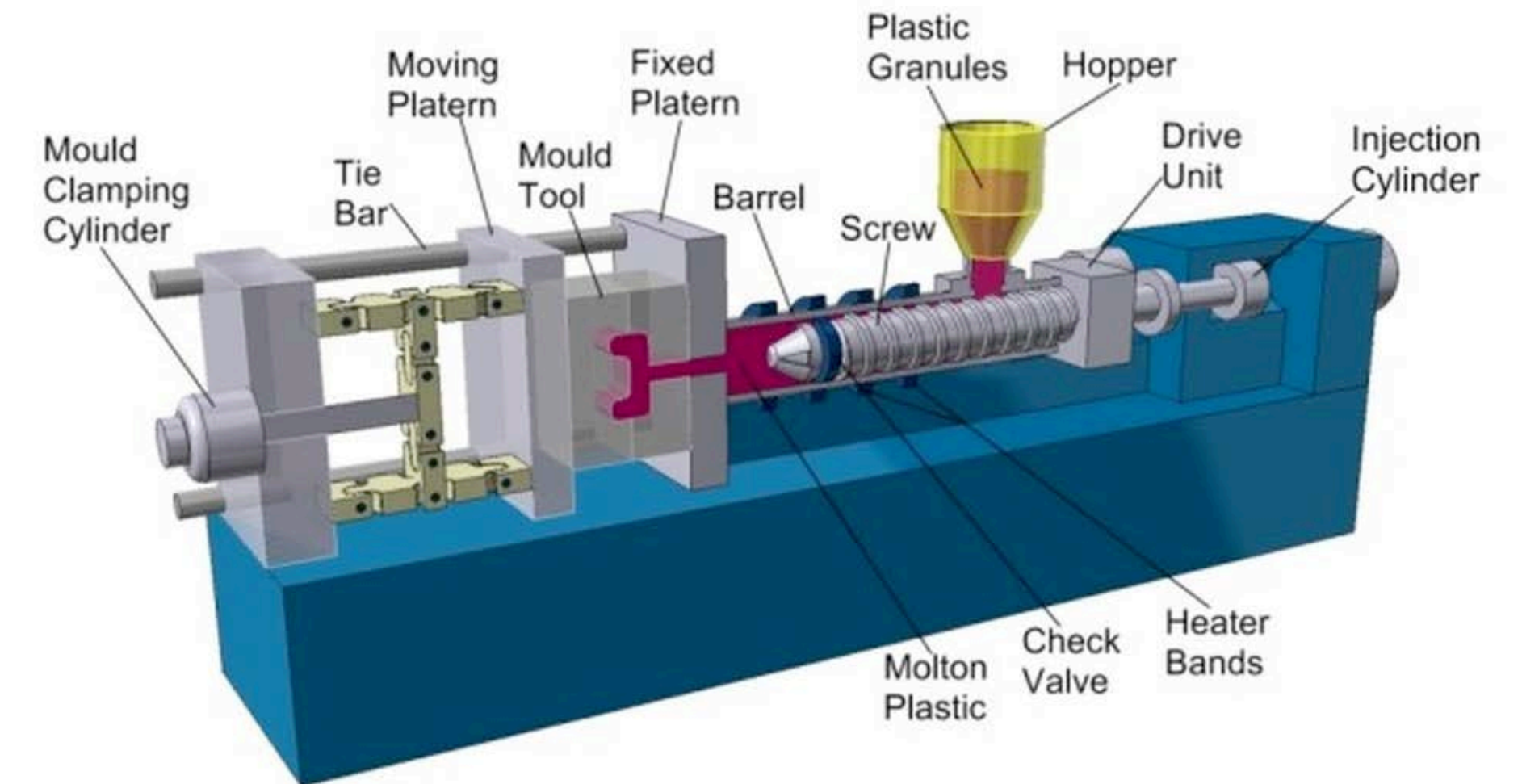


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