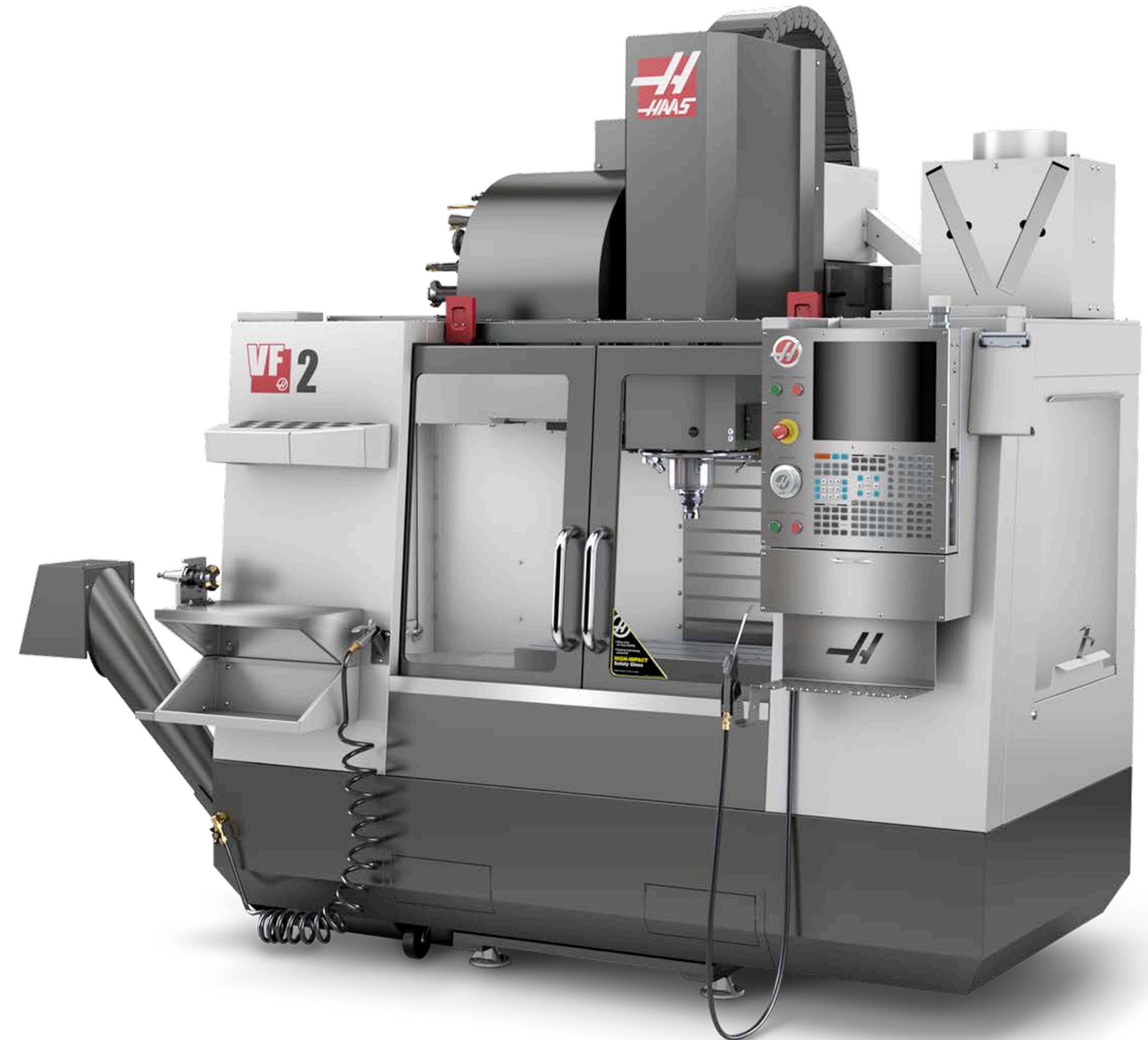


Cutting #3

Machining in Practice

1

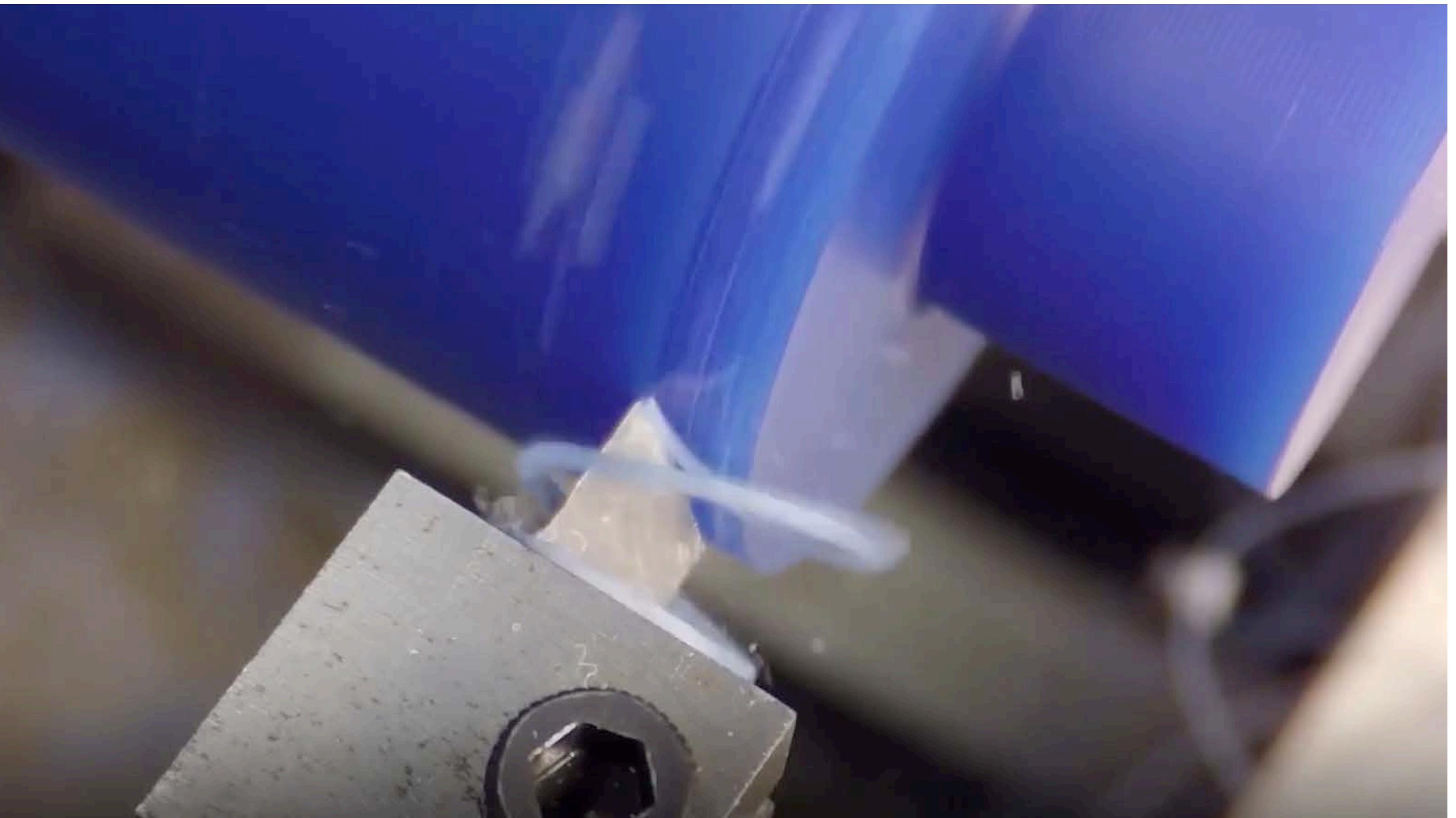
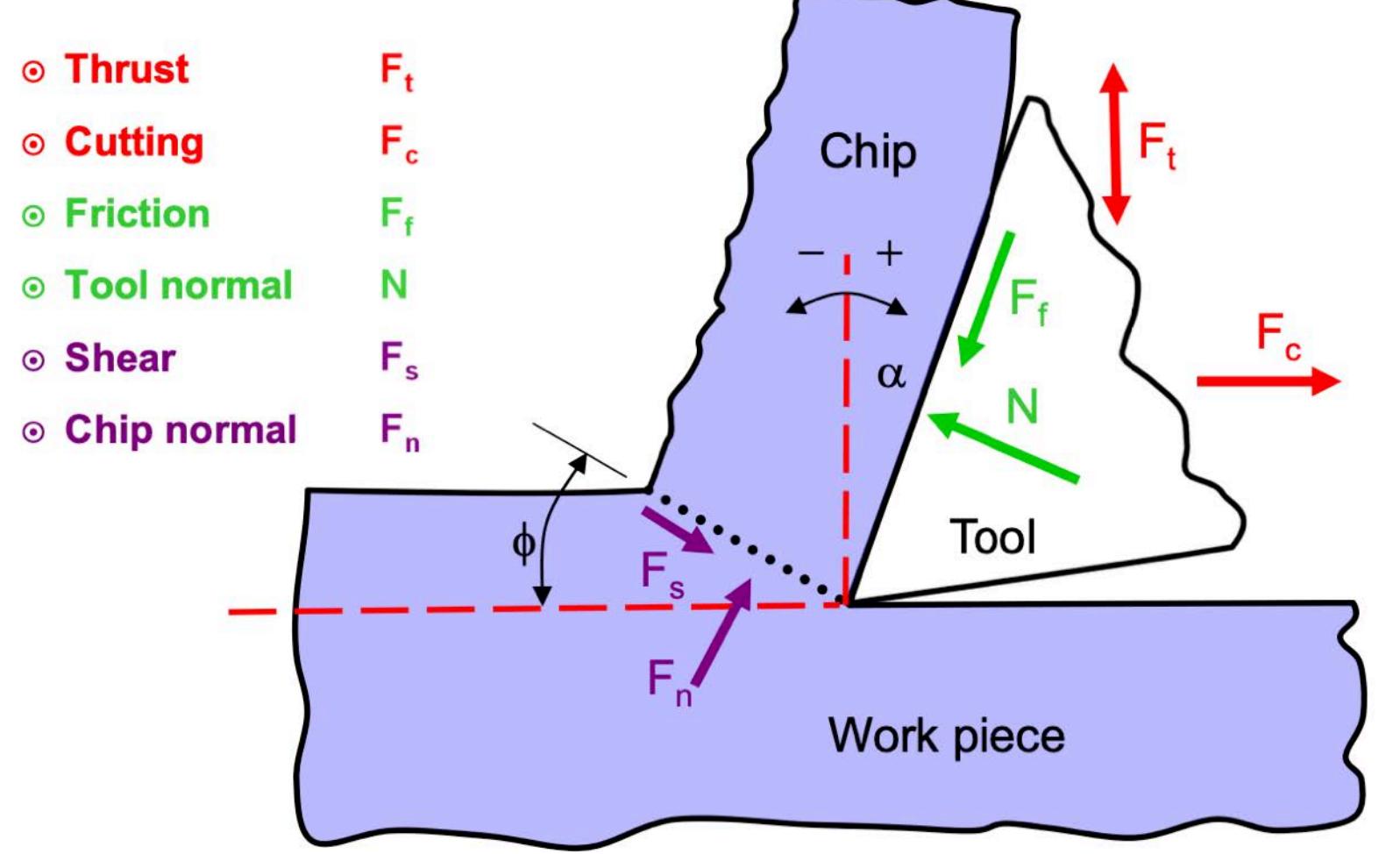


Cutting #3

Machining in Practice

2

Cutting Force Demo

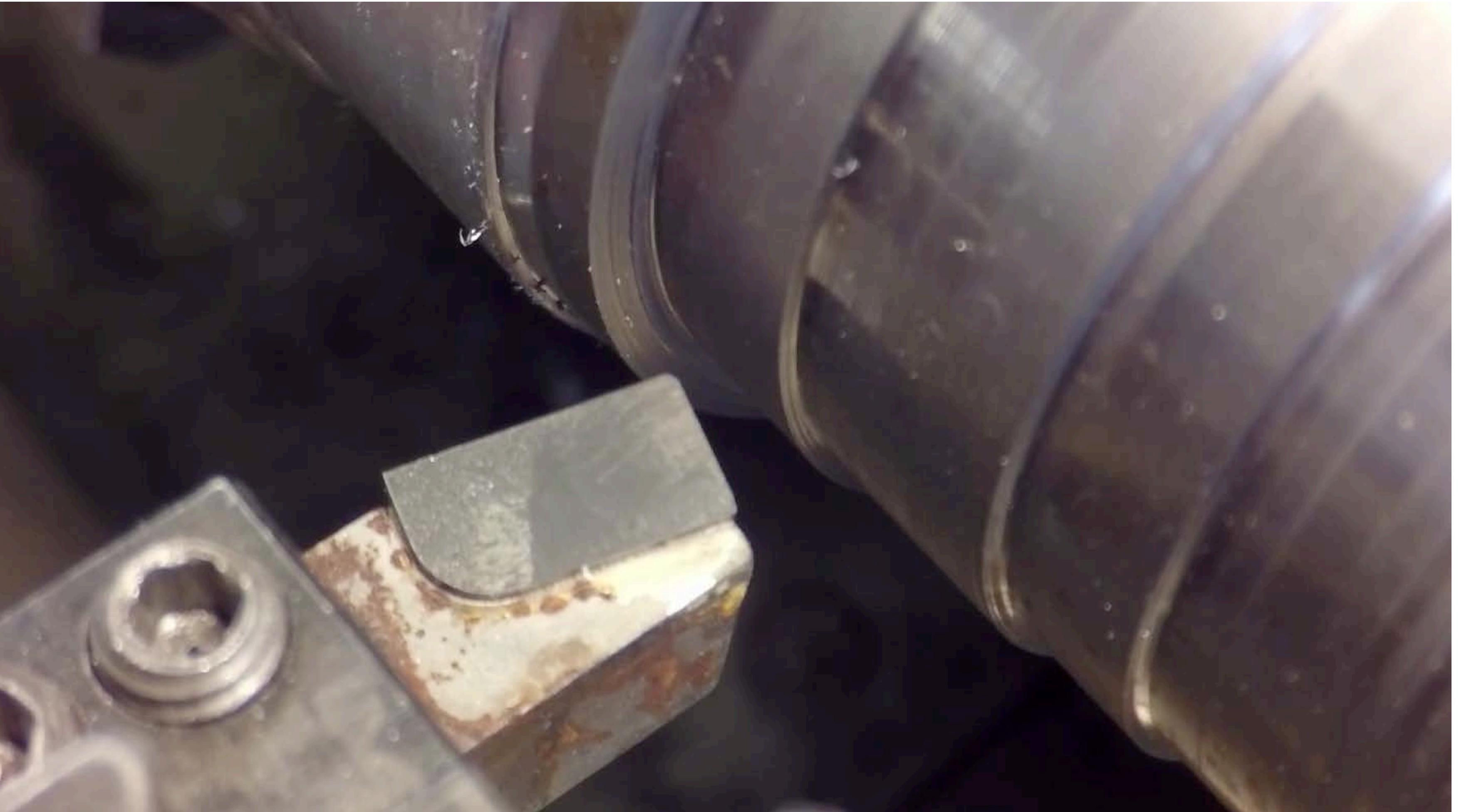


Cutting #3

Machining in Practice

3

Cutting Power Demo



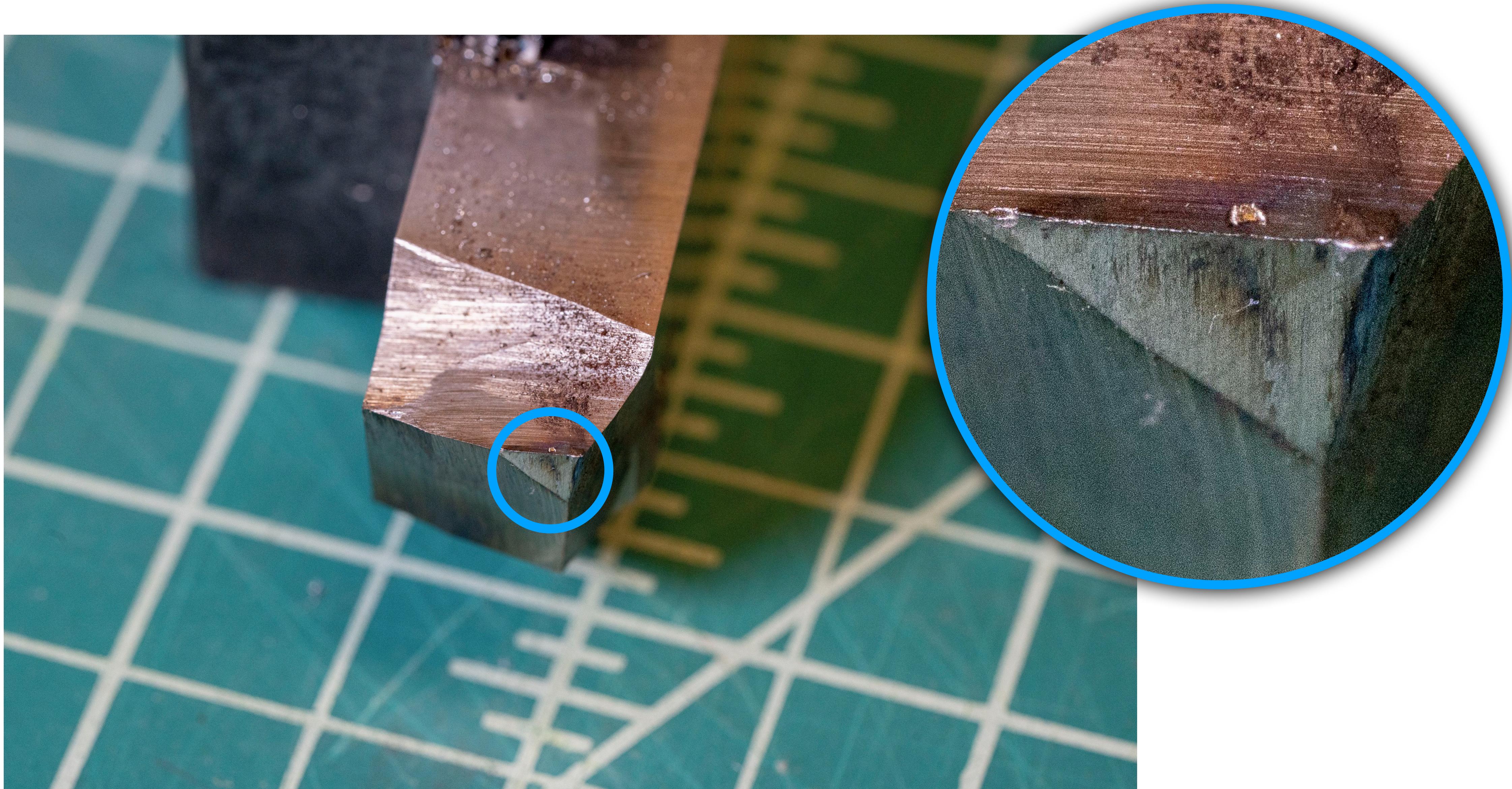
Cutting Power Demo

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			

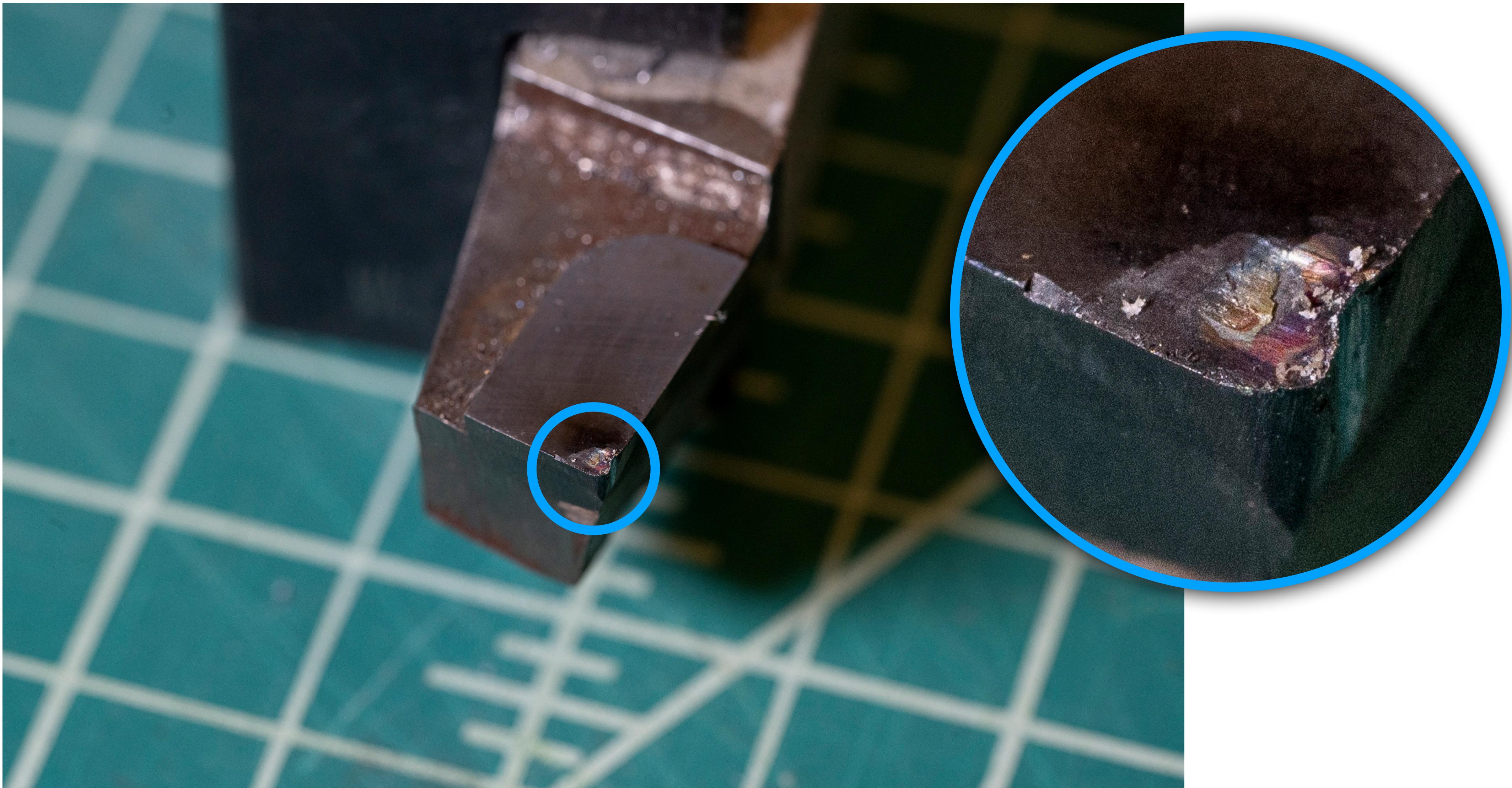
Cutting Power Demo

Rake angle (deg)	Tool	Spindle speed (RPM)	Diameter (in)	DOC (in)	Feed (in/in)	MRR (in ³ /min)	Power	Observations (chips, etc.)
7	HSS	90	3.87	0.050				<p>SHARP 1340F</p> <p>QUANTITY IN LMP SHOP: 6</p> <ul style="list-style-type: none"> • 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" <p>Motor Power: 3HP</p>
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



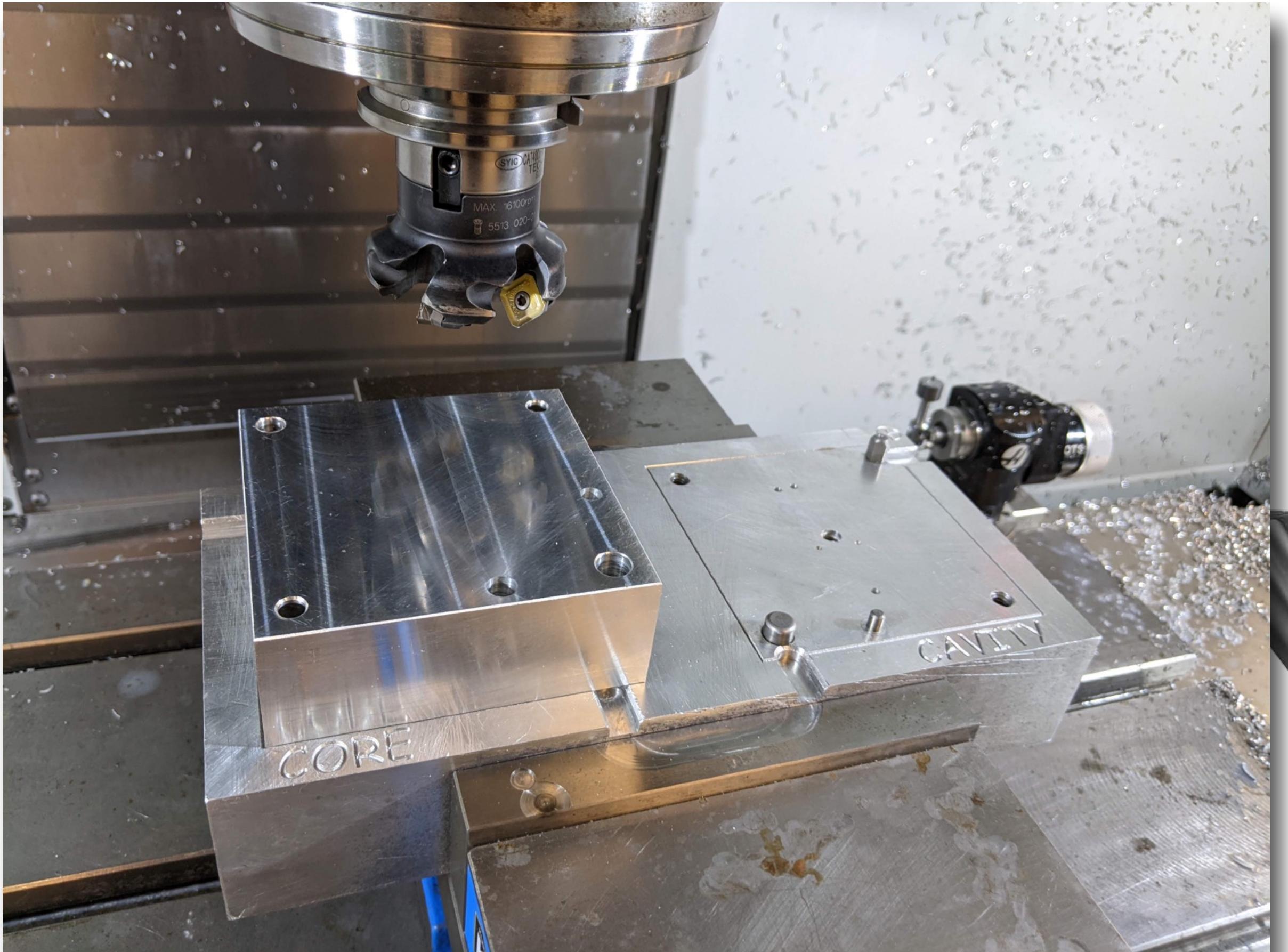
Cutting Power Demo: Results



Cutting #3

Machining in Practice

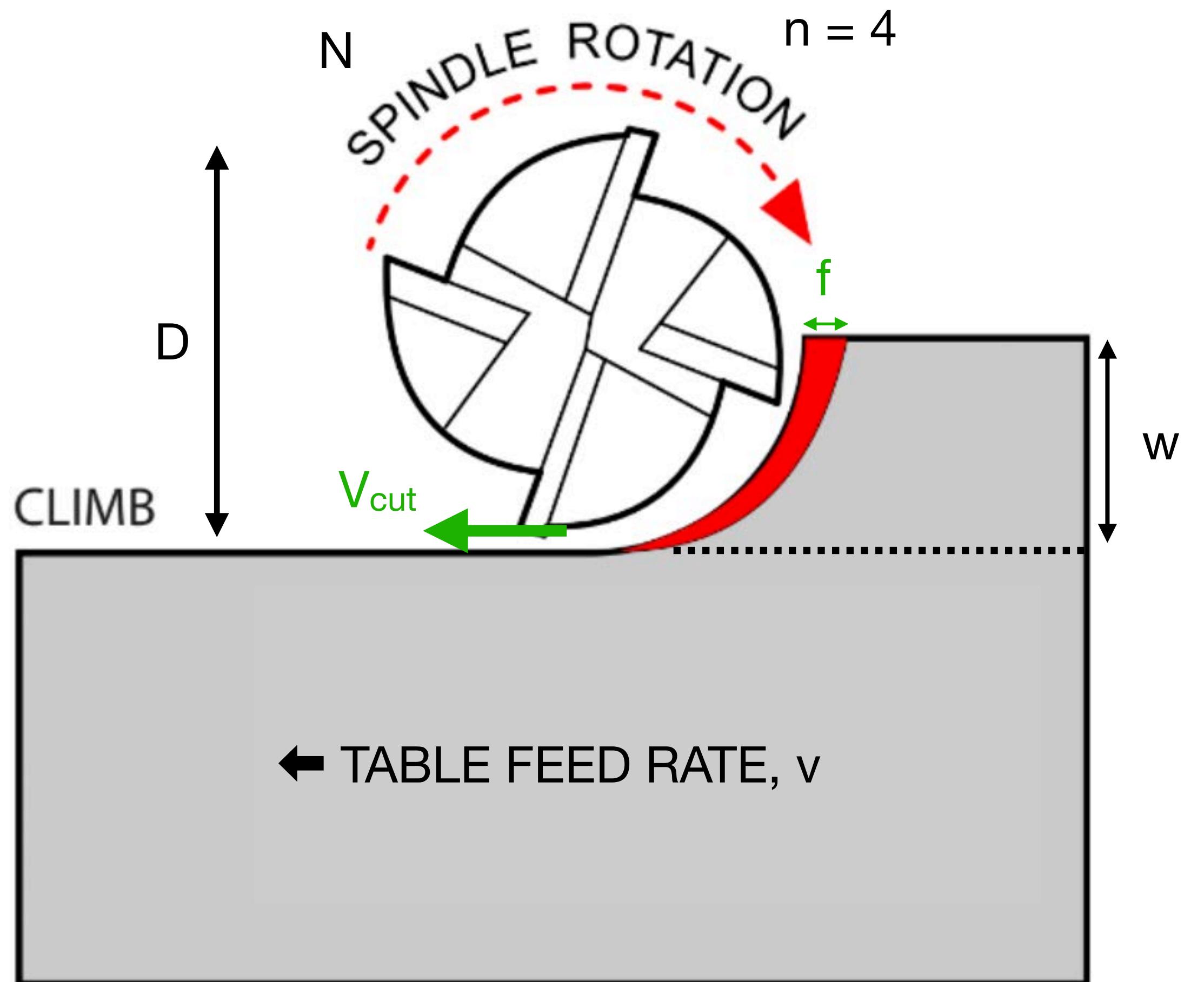
Machining in 2.008



Cutting #1

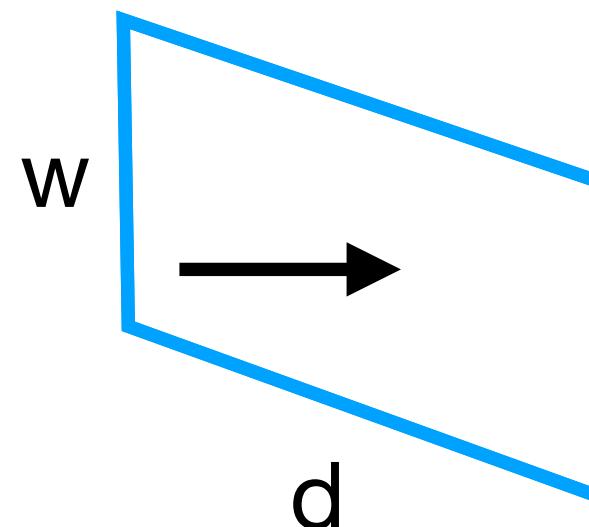
Machining in Practice

Material Removal Rate in Milling



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

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



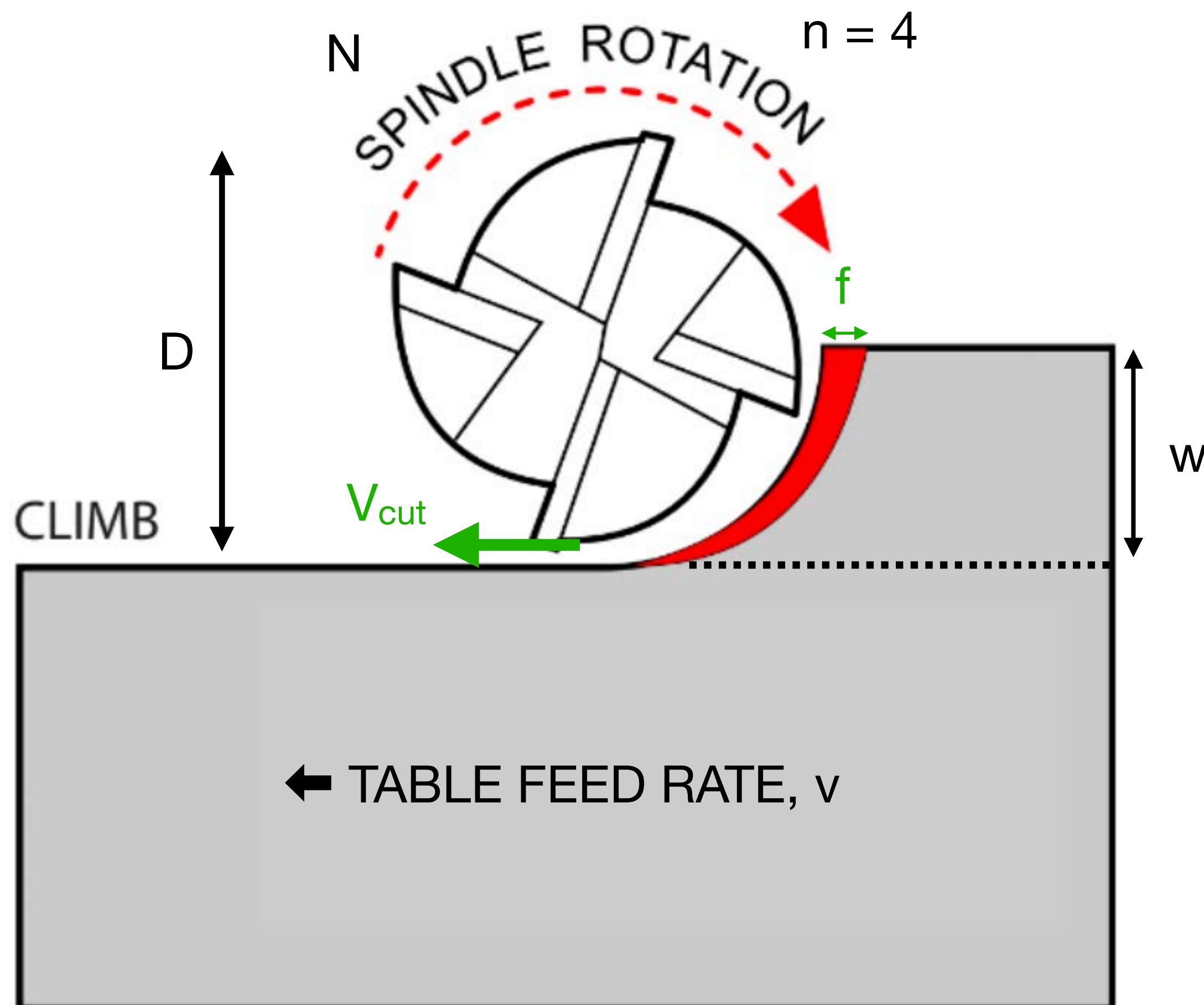
- f: feed per tooth [in/tooth]
- n: number of teeth [#]
- N: spindle speed [rpm]
- v: feed rate, velocity of tool (center) relative to workpiece [in/min]
- w: width of cut [in]
- d: depth of cut [in]
- D: cutter diameter [in]

Cutting #1

Machining in Practice

10

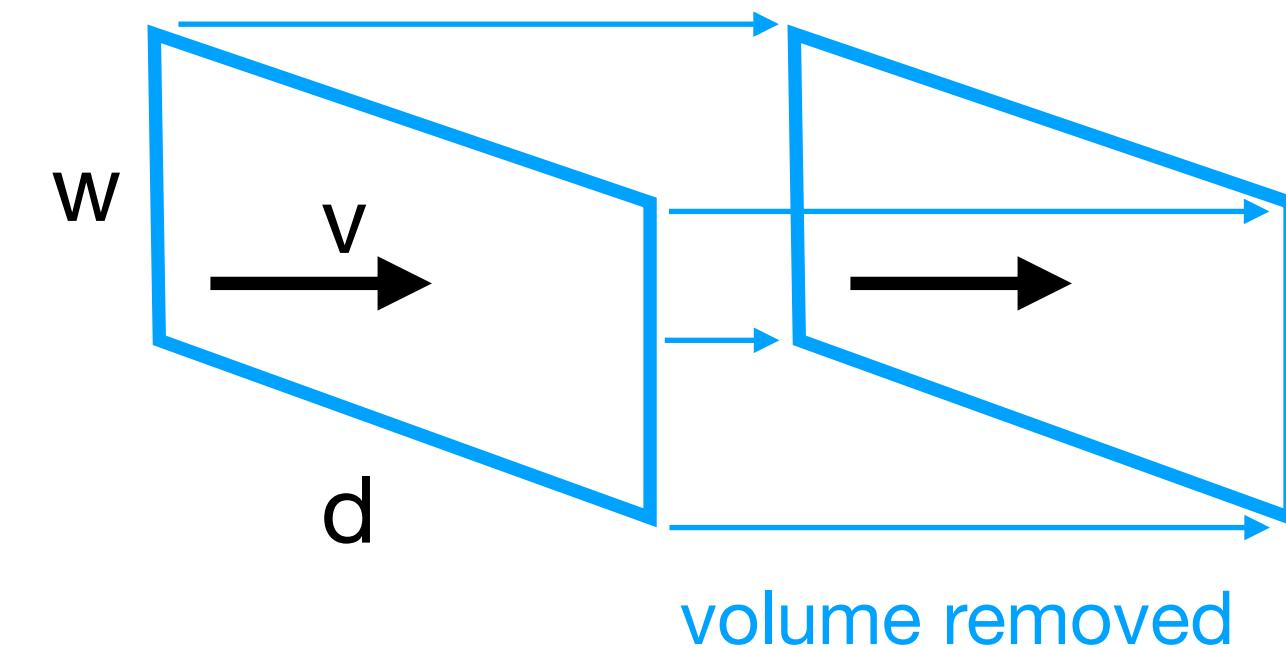
Material Removal Rate in Milling



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

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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]



$$MRR_{milling} = wdv$$

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

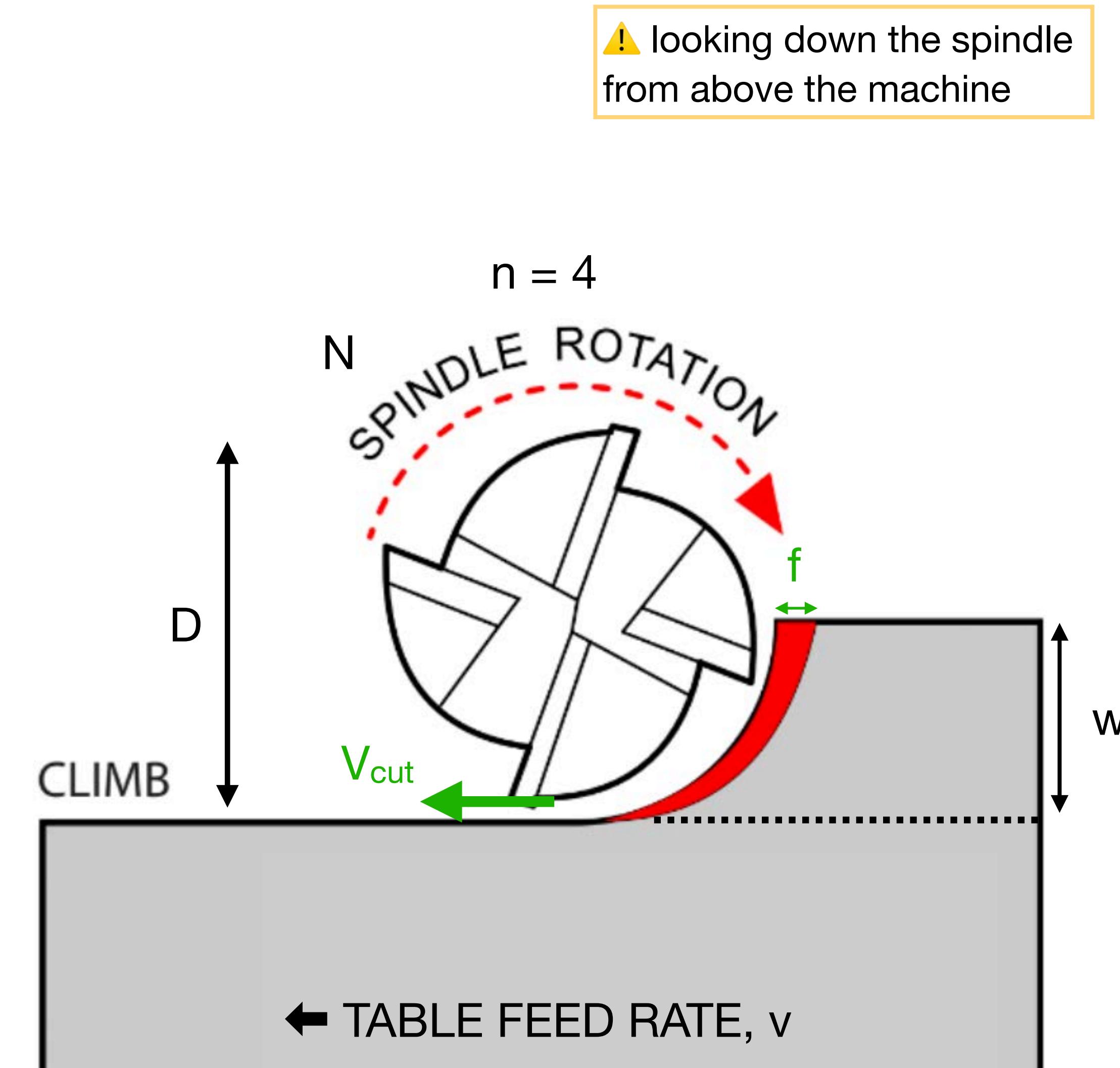
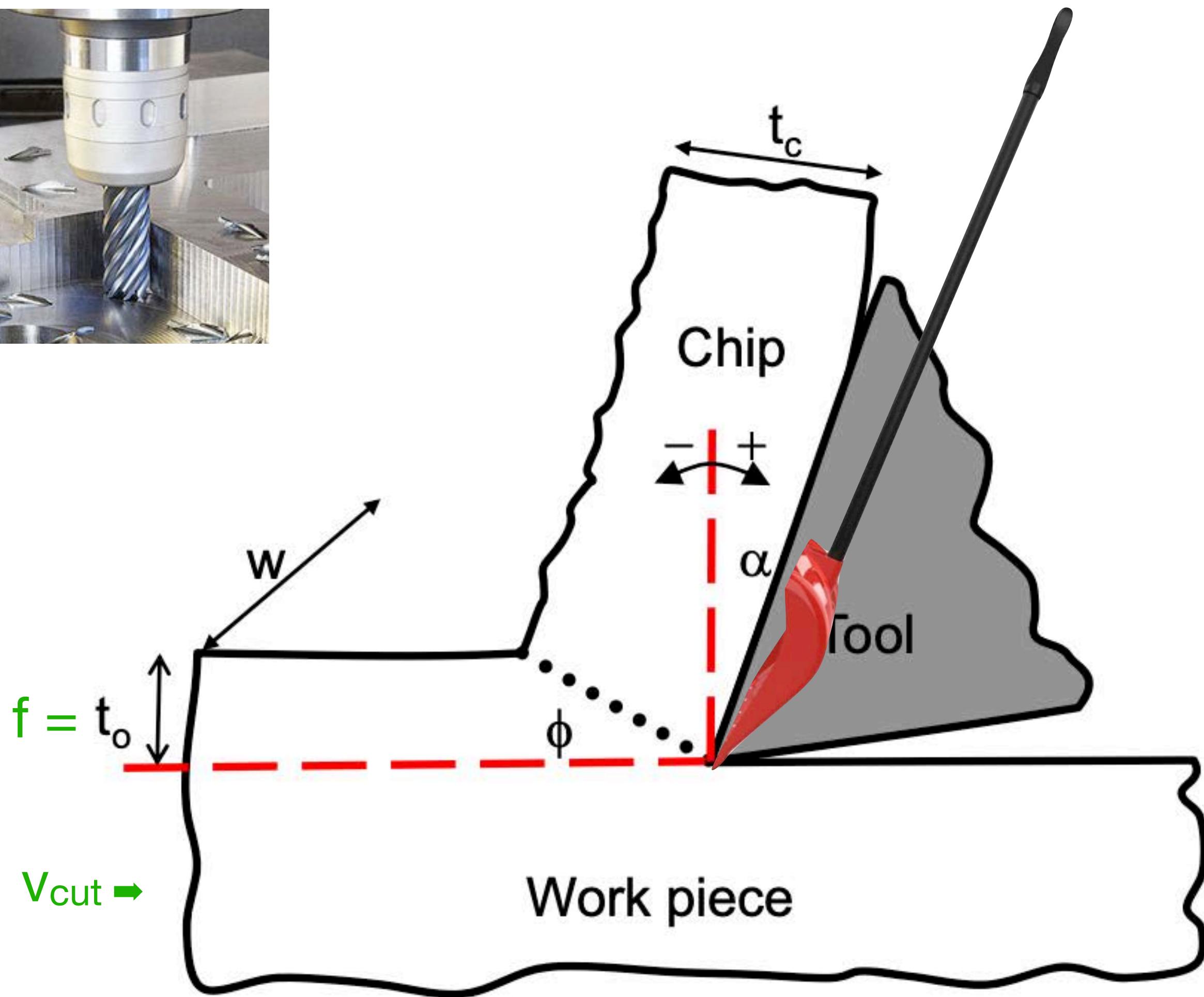
Power: total cutting power from
machine [W]
u: specific energy of the material
[W-s/mm³]
MRR: material removal rate [mm³/s]

Cutting #1

Cutting Analysis: Mechanics, Forces, and Power

11

Milling

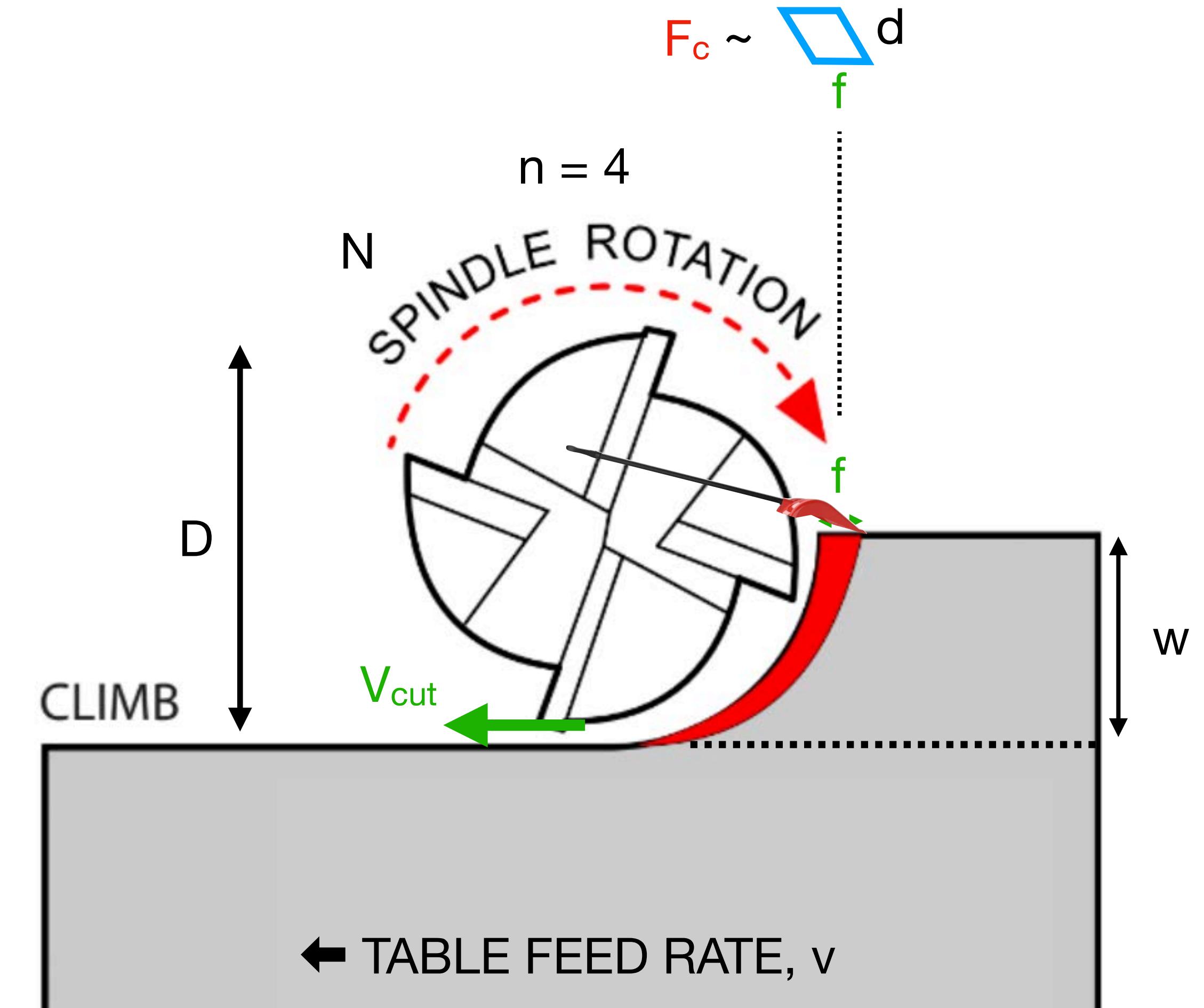
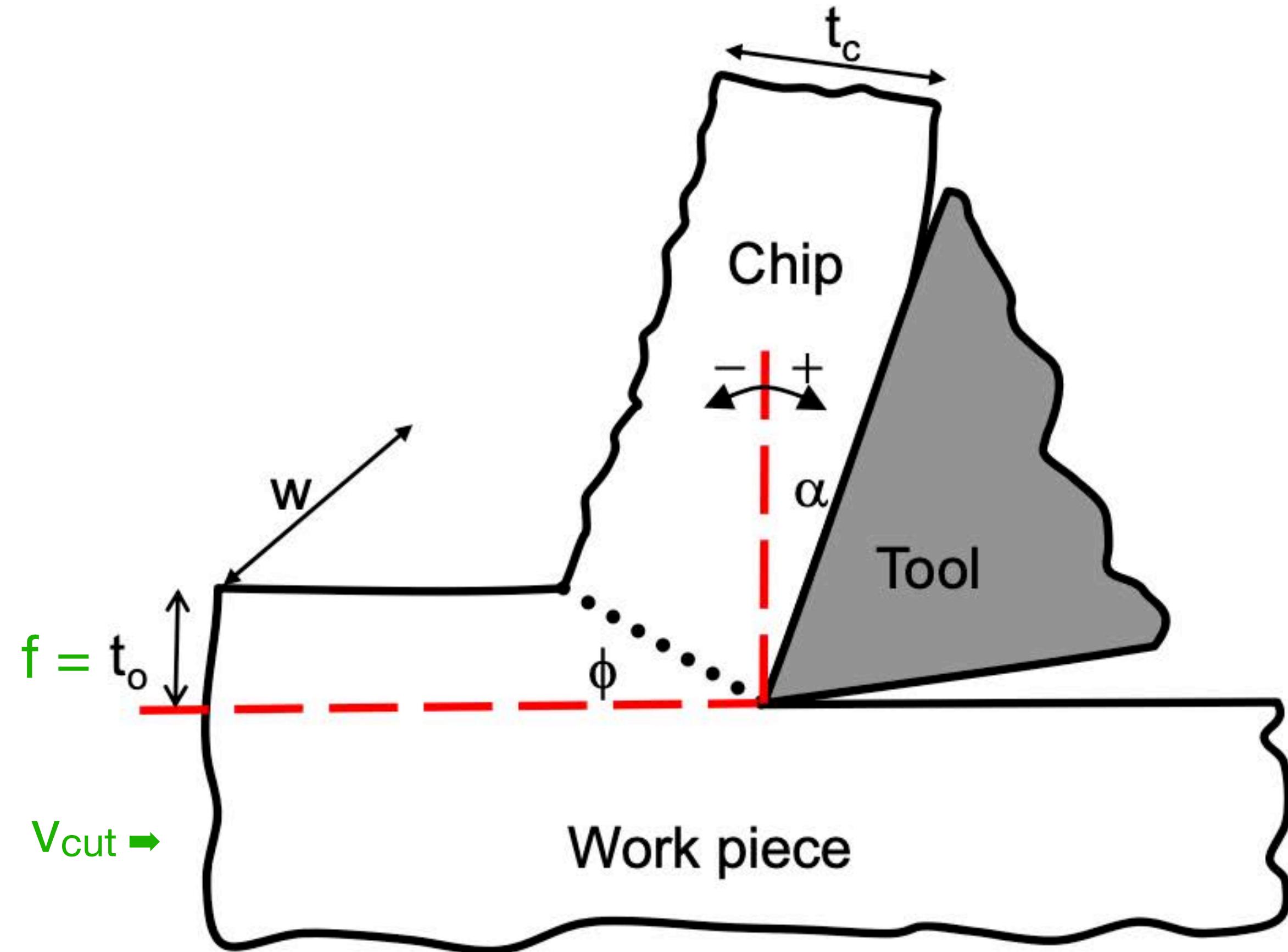


Cutting #1

Cutting Analysis: Mechanics, Forces, and Power

12

Milling



Cutting #1

Cutting Analysis: Mechanics, Forces, and Power

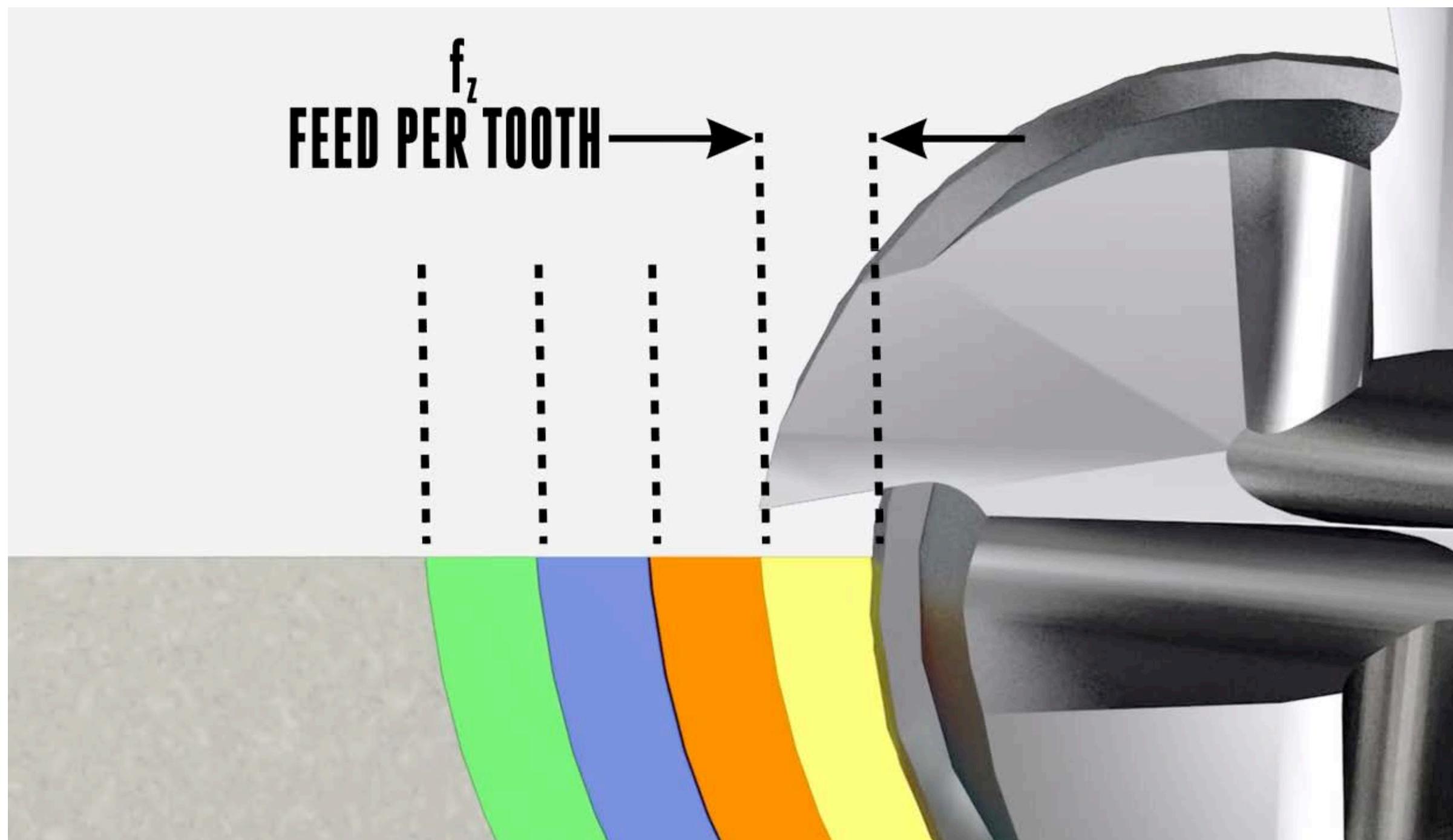
13

Cutting Forces in Milling

⚠ connection between spindle speed and feed makes this confusing

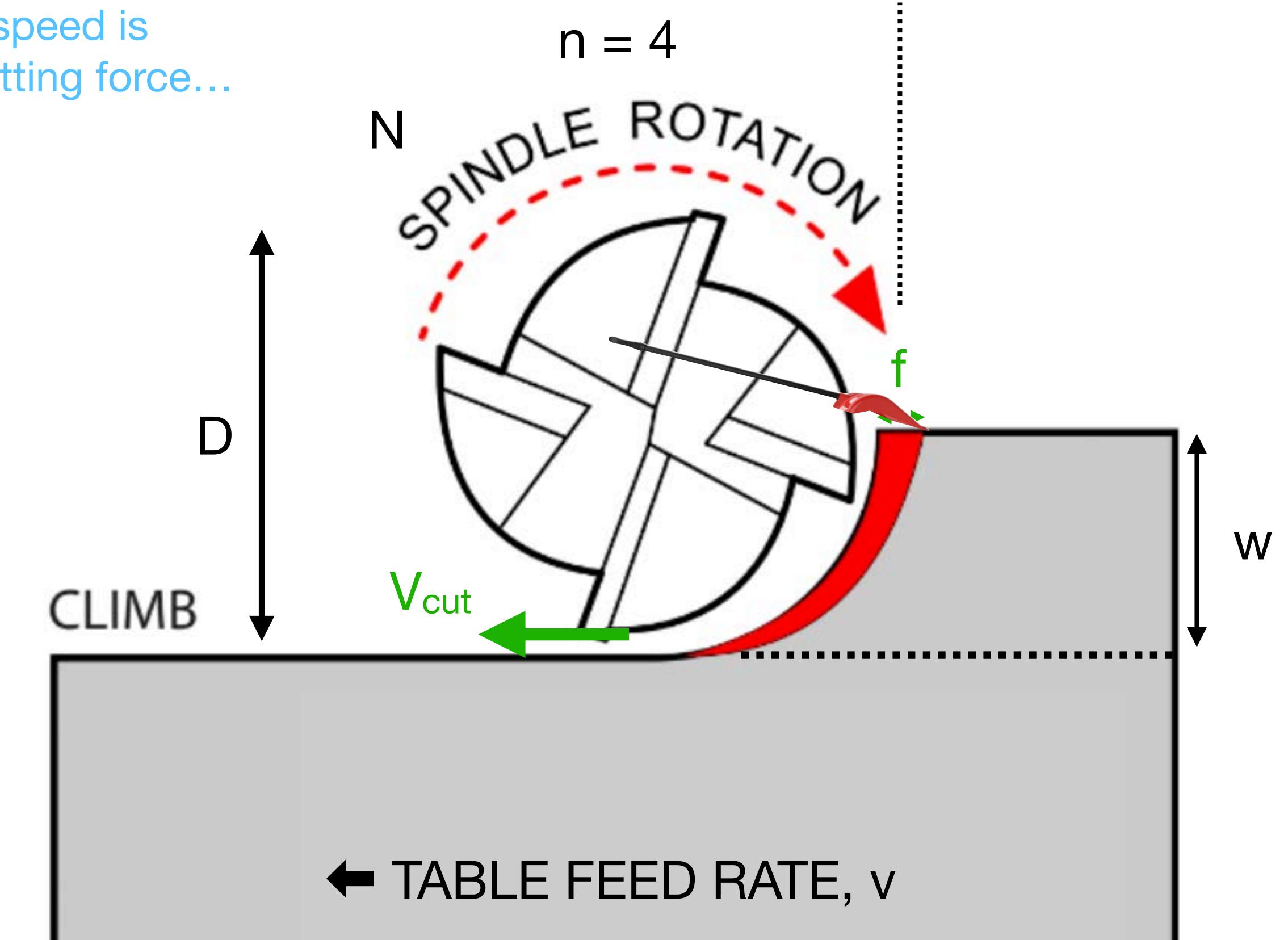
adjust N with v constant: f changes (v_{cut} also changes)

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]

$$F_c \sim \frac{d}{f}$$



Cutting #1

Forces and Power Demos

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)

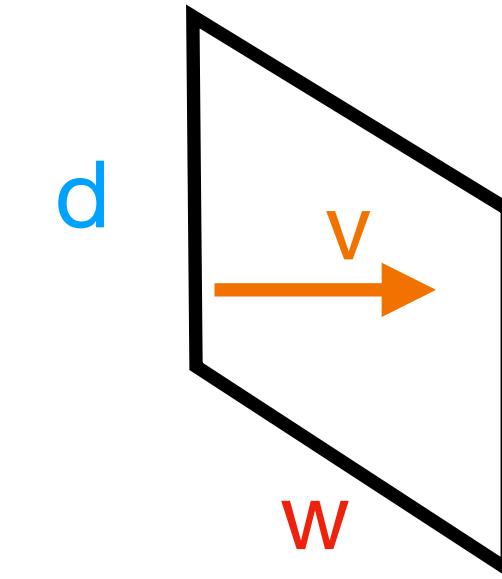
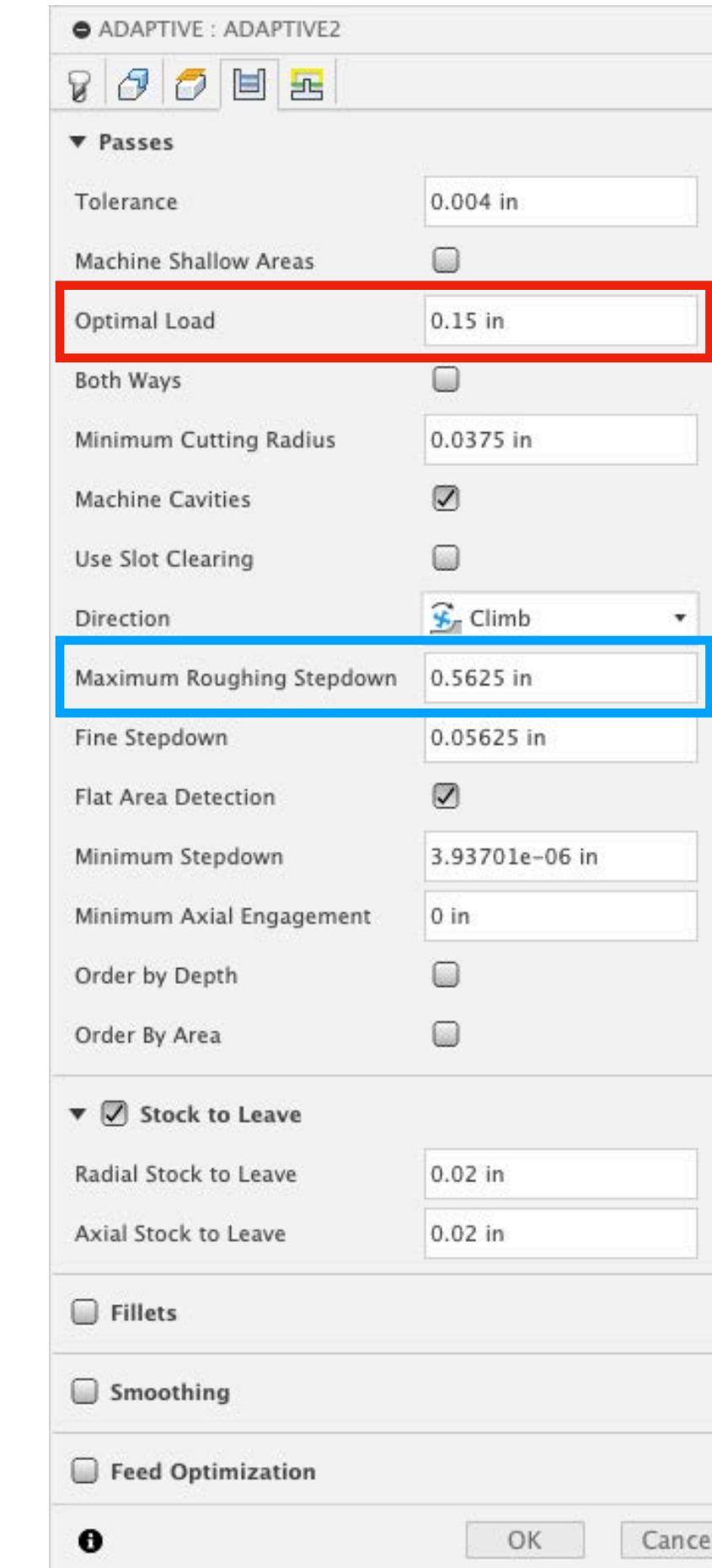
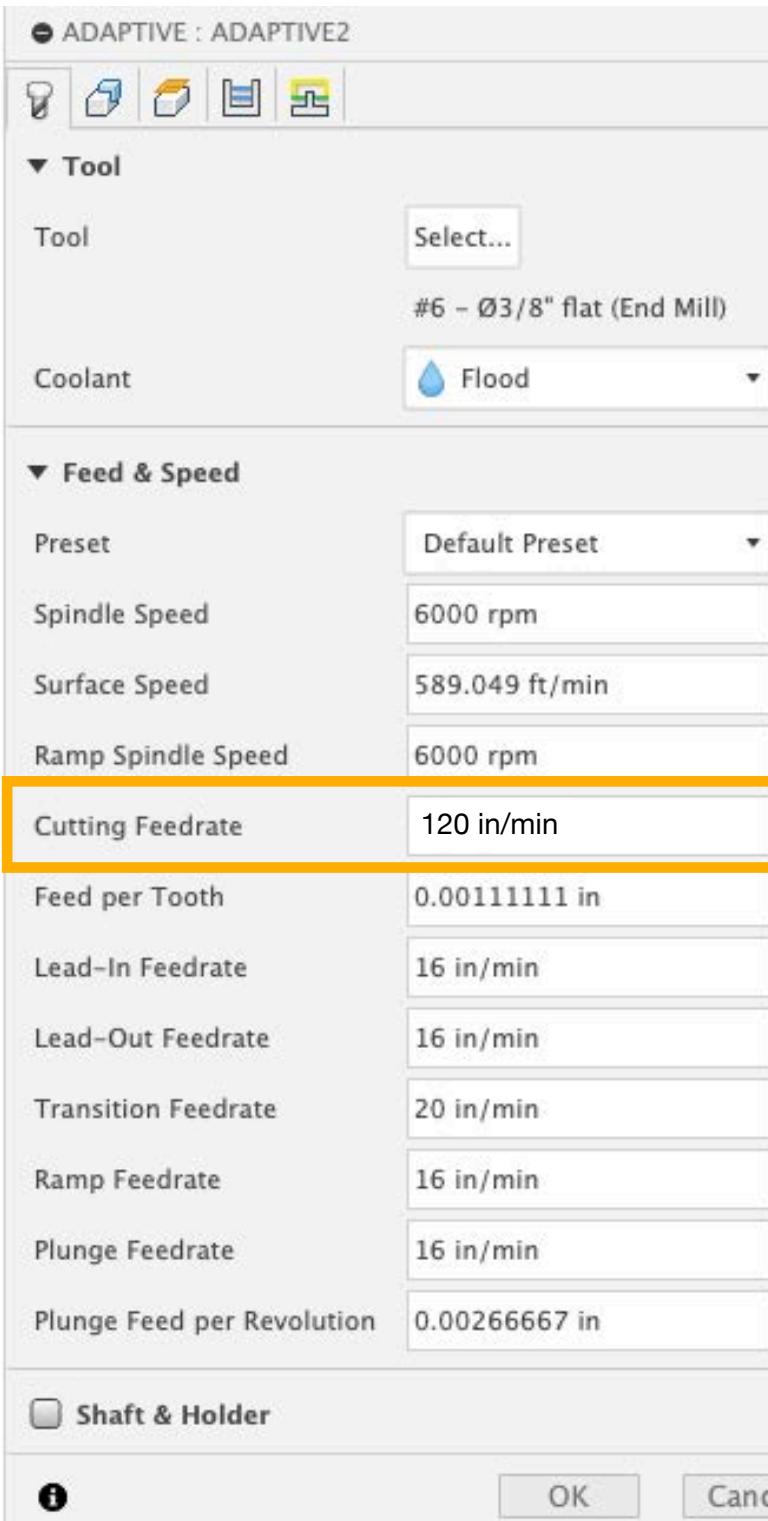
Material	Specific energy	
	W-s/mm ³	hp-min/in ³
Aluminum alloys	0.4–1	0.15–0.4
Cast irons	1.1–5.4	0.4–2
Copper alloys	1.4–3.2	0.5–1.2
High-temperature alloys	3.2–8	1.2–3
Magnesium alloys	0.3–0.6	0.1–0.2
Nickel alloys	4.8–6.7	1.8–2.5
Refractory alloys	3–9	1.1–3.5
Stainless steels	2–5	0.8–1.9
Steels	2–9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

Cutting #3

Forces and Power Demos

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Specific Energy: Milling



$$MRR_{milling} = wdv$$

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

$$(w)(d)(v) = (0.15)(0.5625)(120) \text{ in}^3/\text{min}$$

$$(w)(d)(v) = 10.1 \text{ in}^3/\text{min}$$

Material	Specific energy	
	W-s/mm ³	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)

Cutting #3

Machining in Practice

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HAAS video highlights



Cutting #3

Machining in Practice

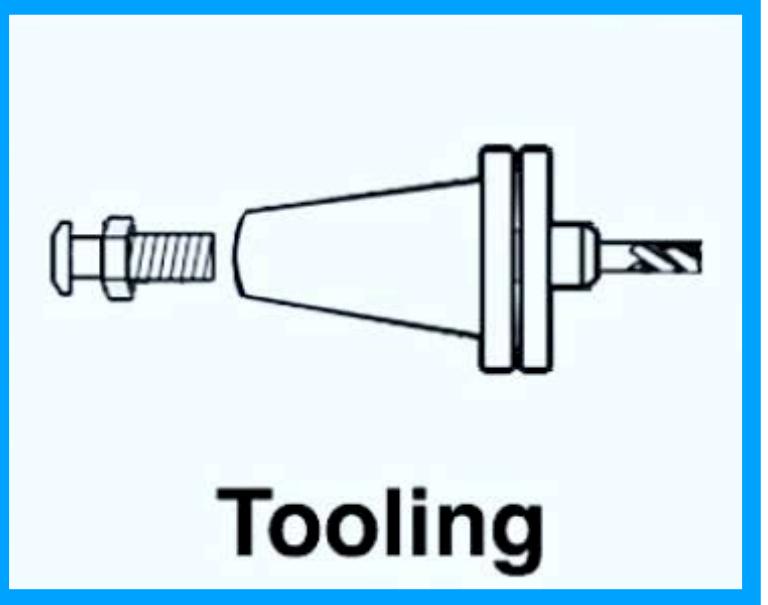
18

HAAS video highlights



Cutting #3

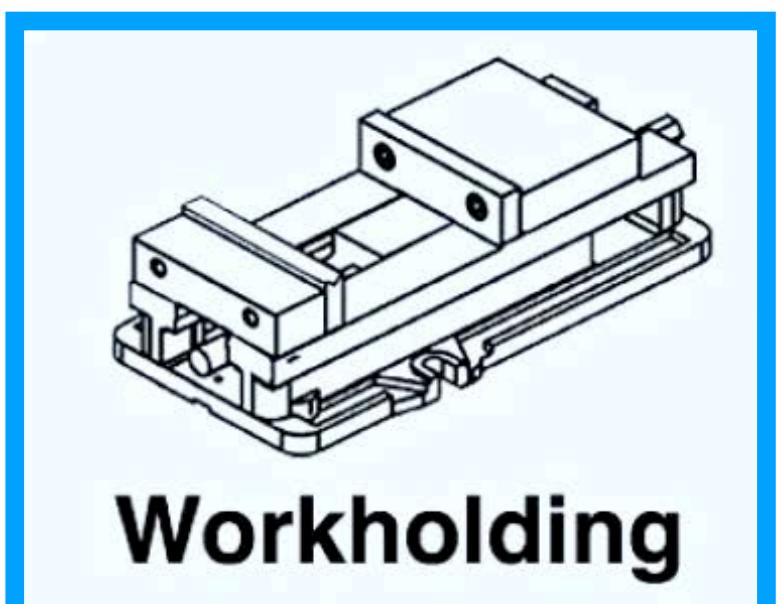
Machining in Practice



Tooling



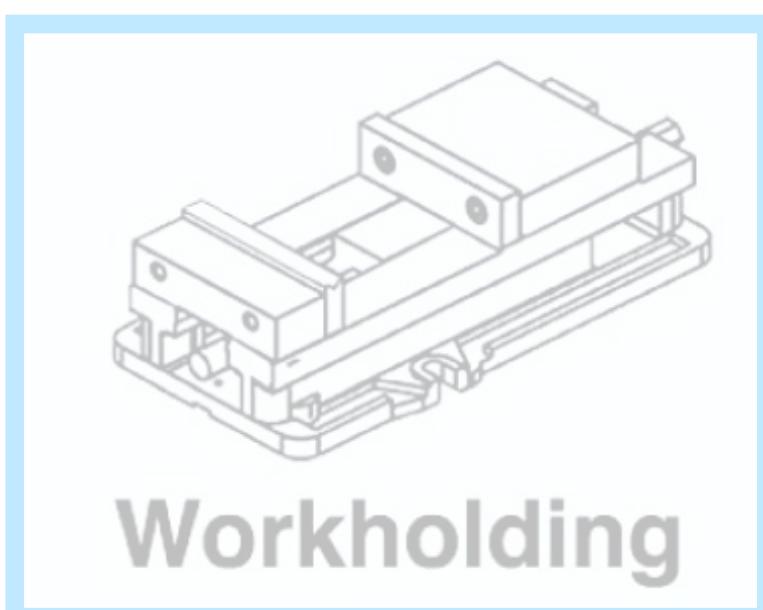
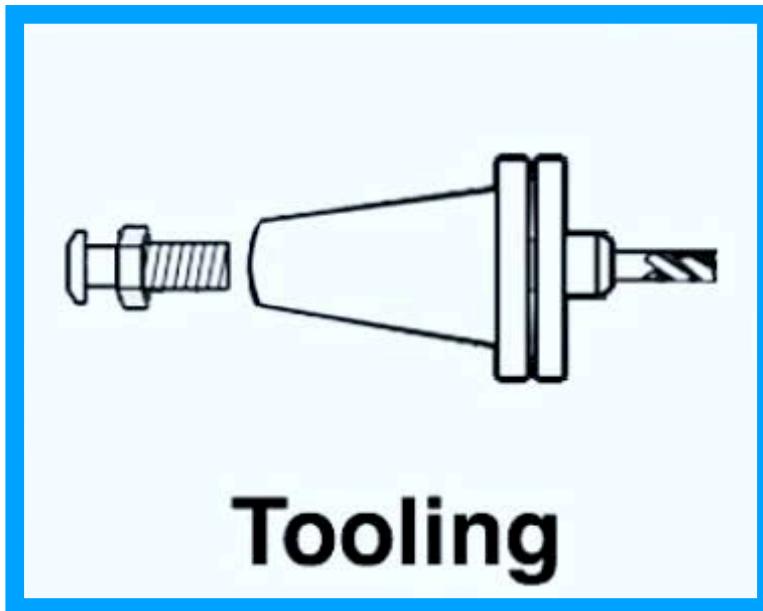
Program



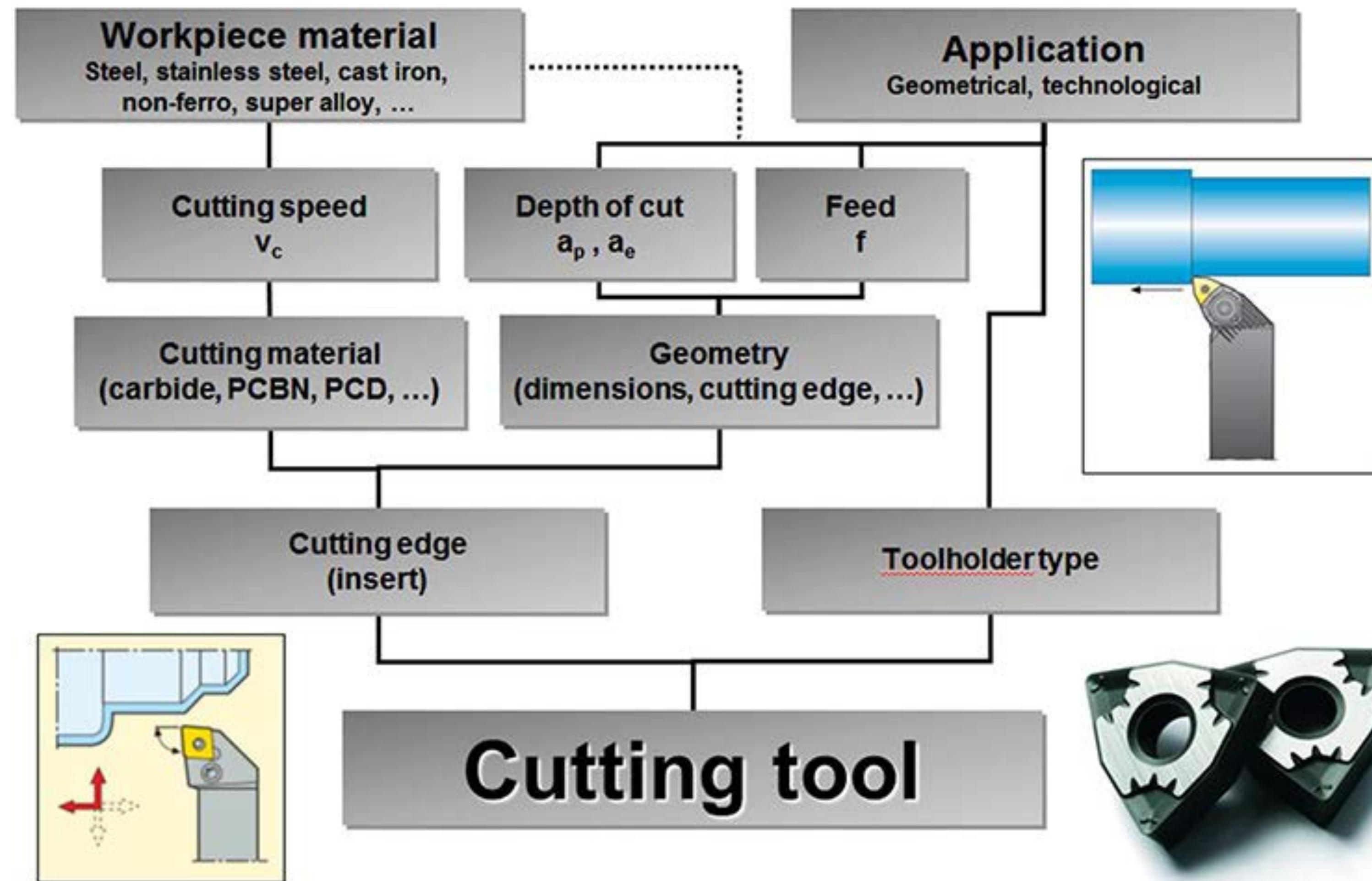
Workholding

Cutting #3

Machining in Practice



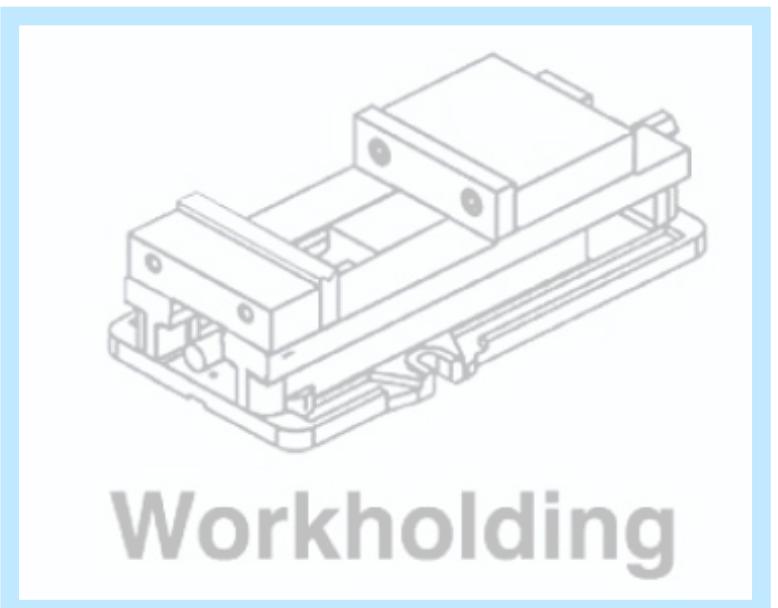
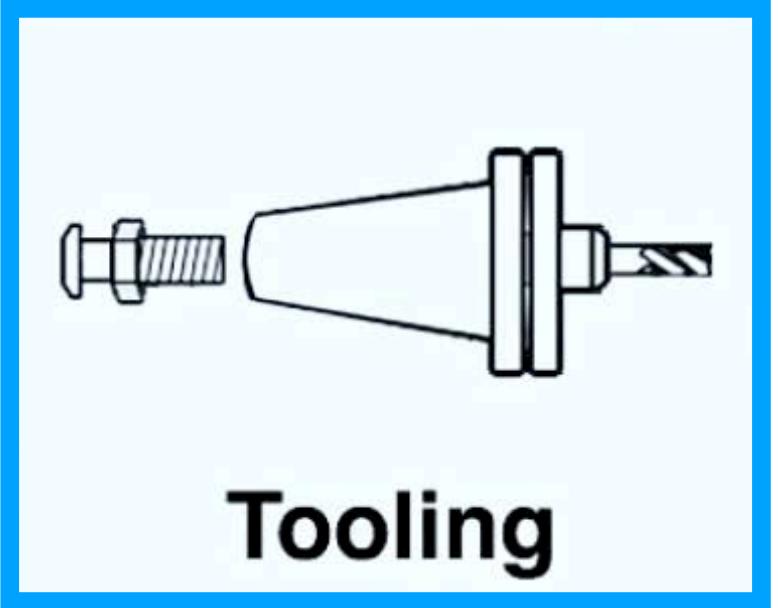
Tool Selection



Cutting #3

Machining in Practice

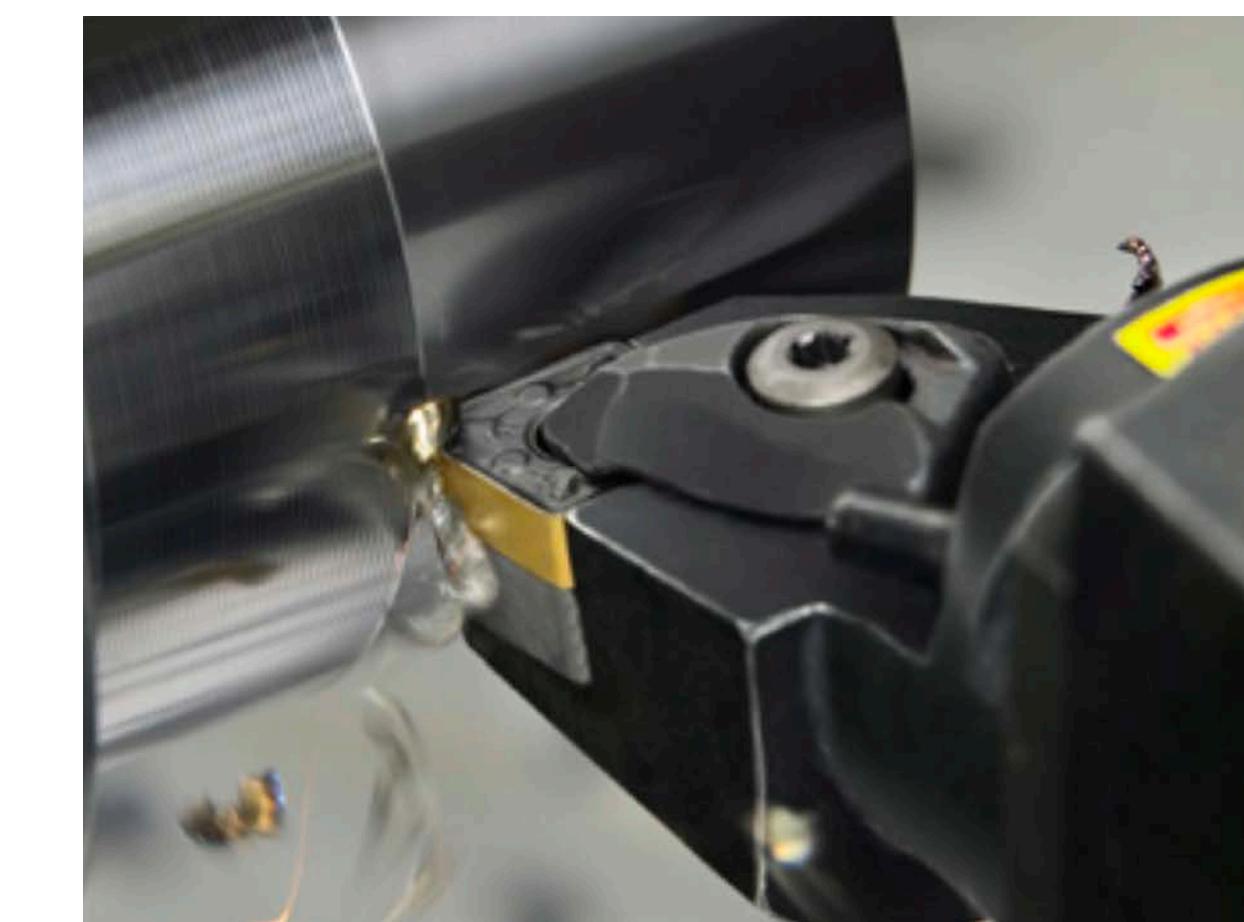
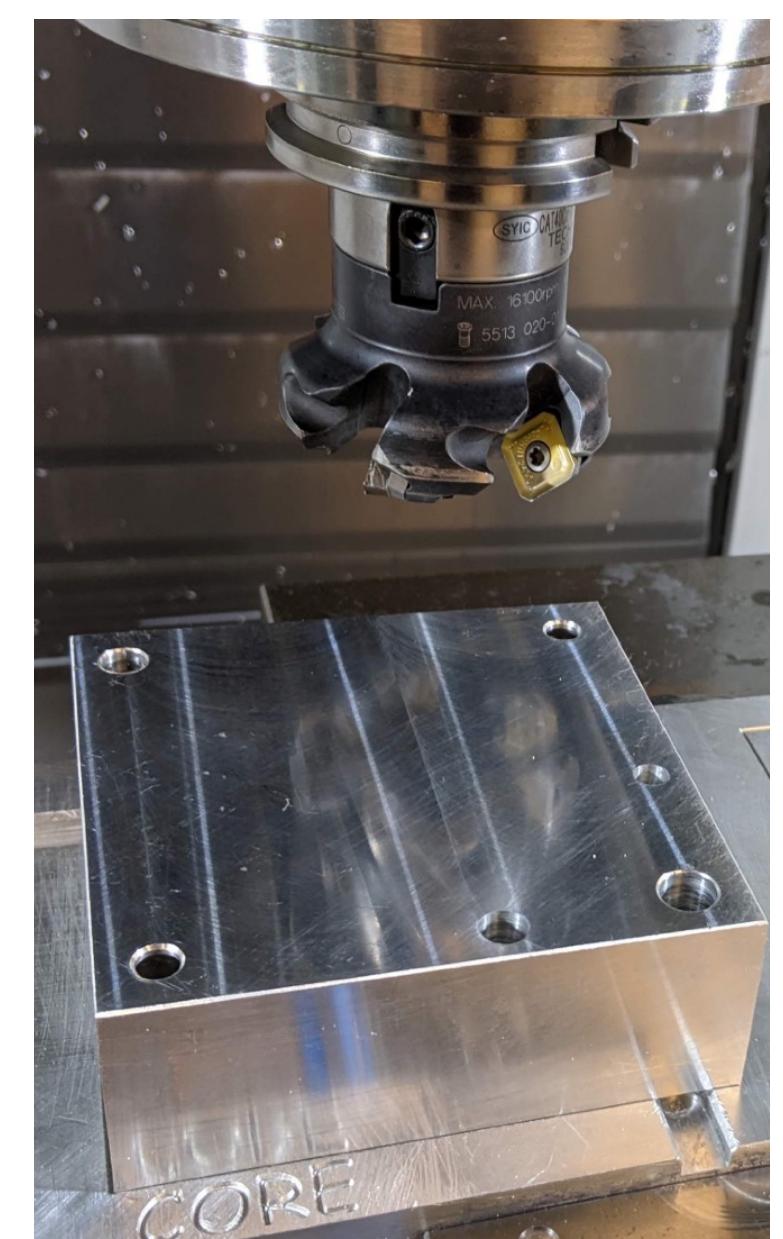
21



Tool Types

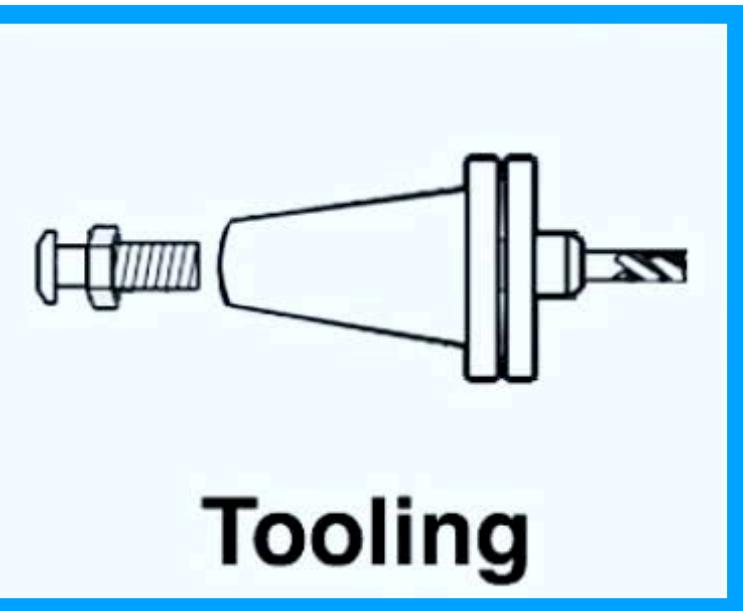


tool examples
can be passed
around!



Cutting #3

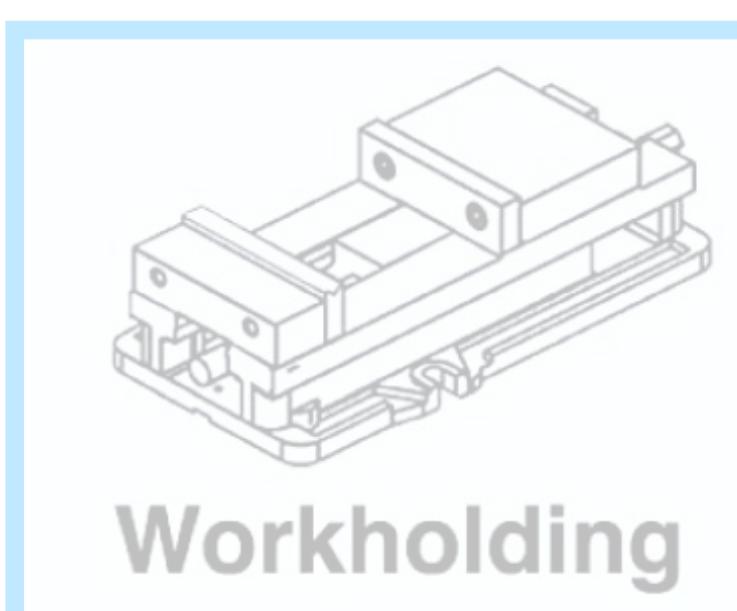
Machining in Practice



Tooling



Program



Workholding

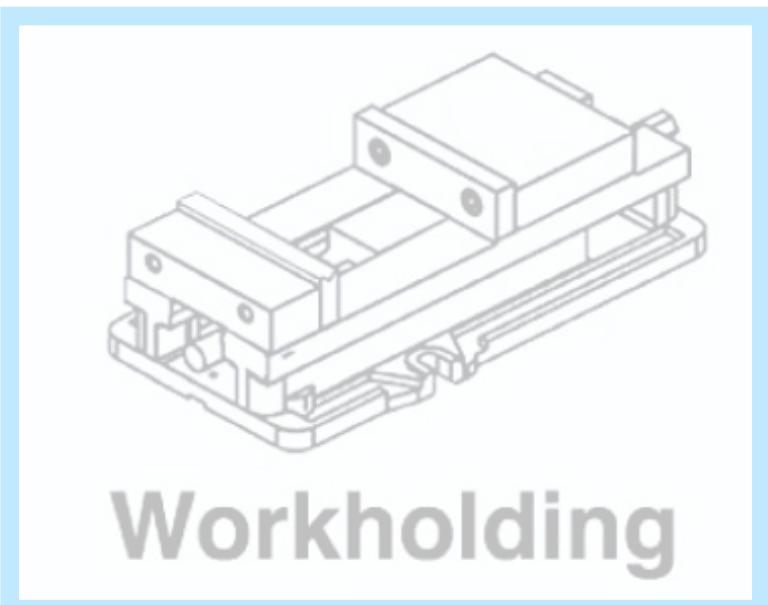
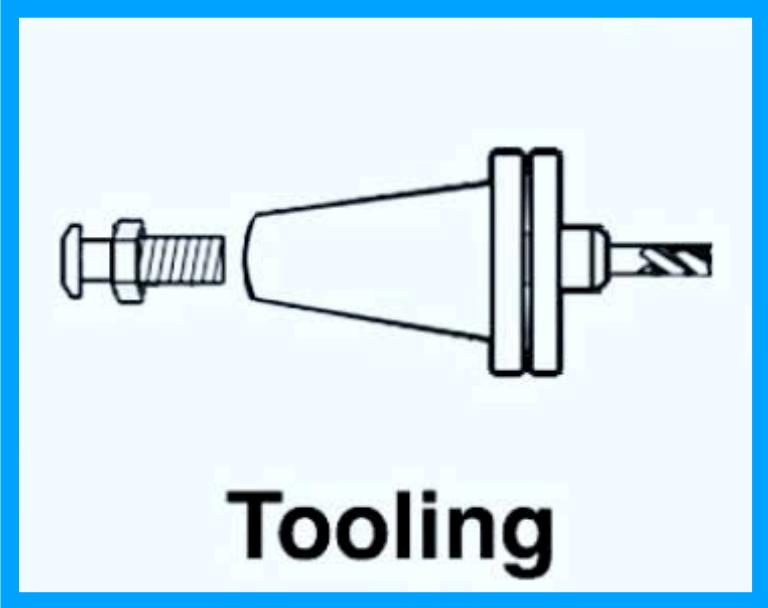
Tool Restrictions

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

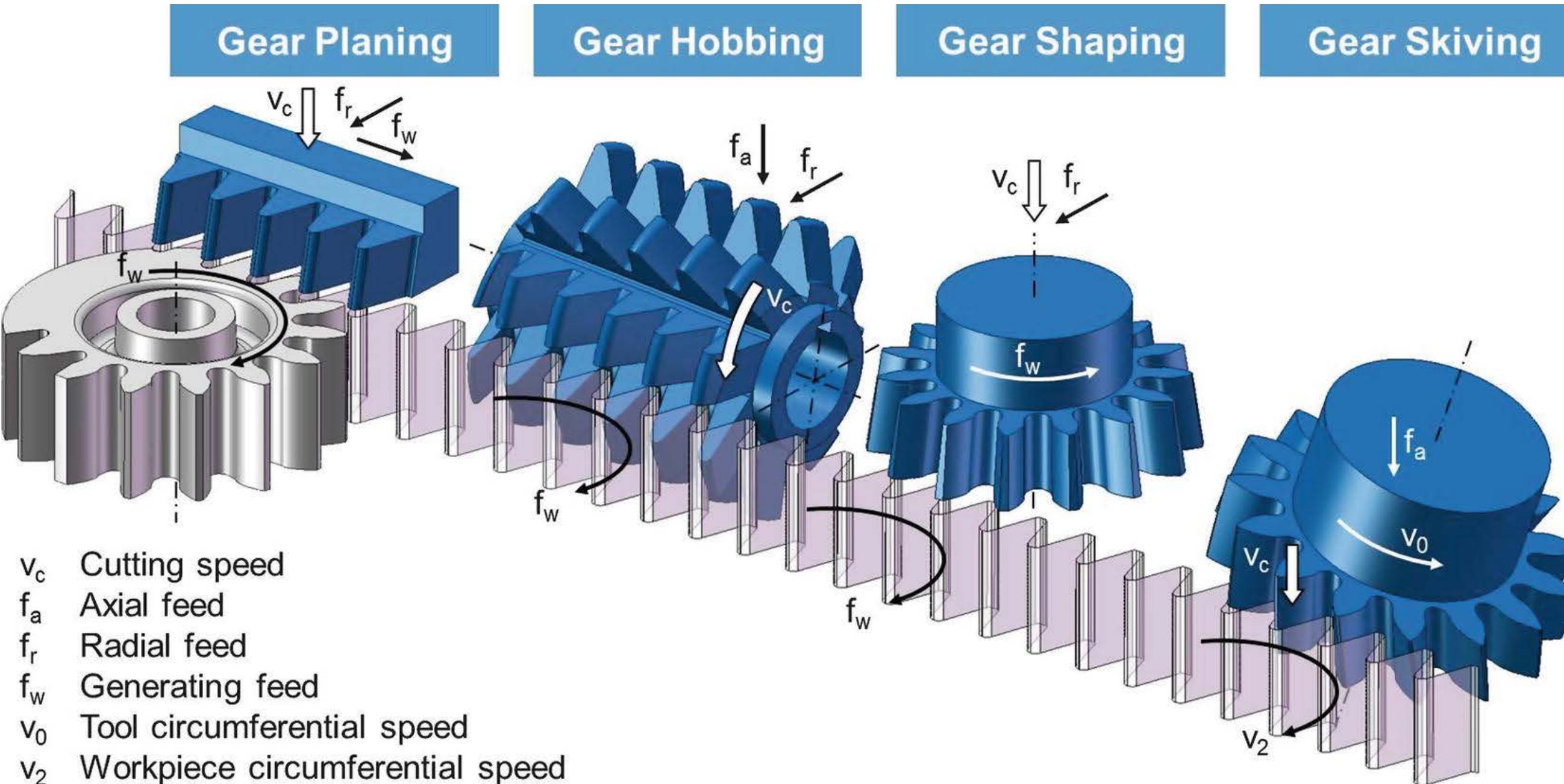
Cutting #3

Machining in Practice

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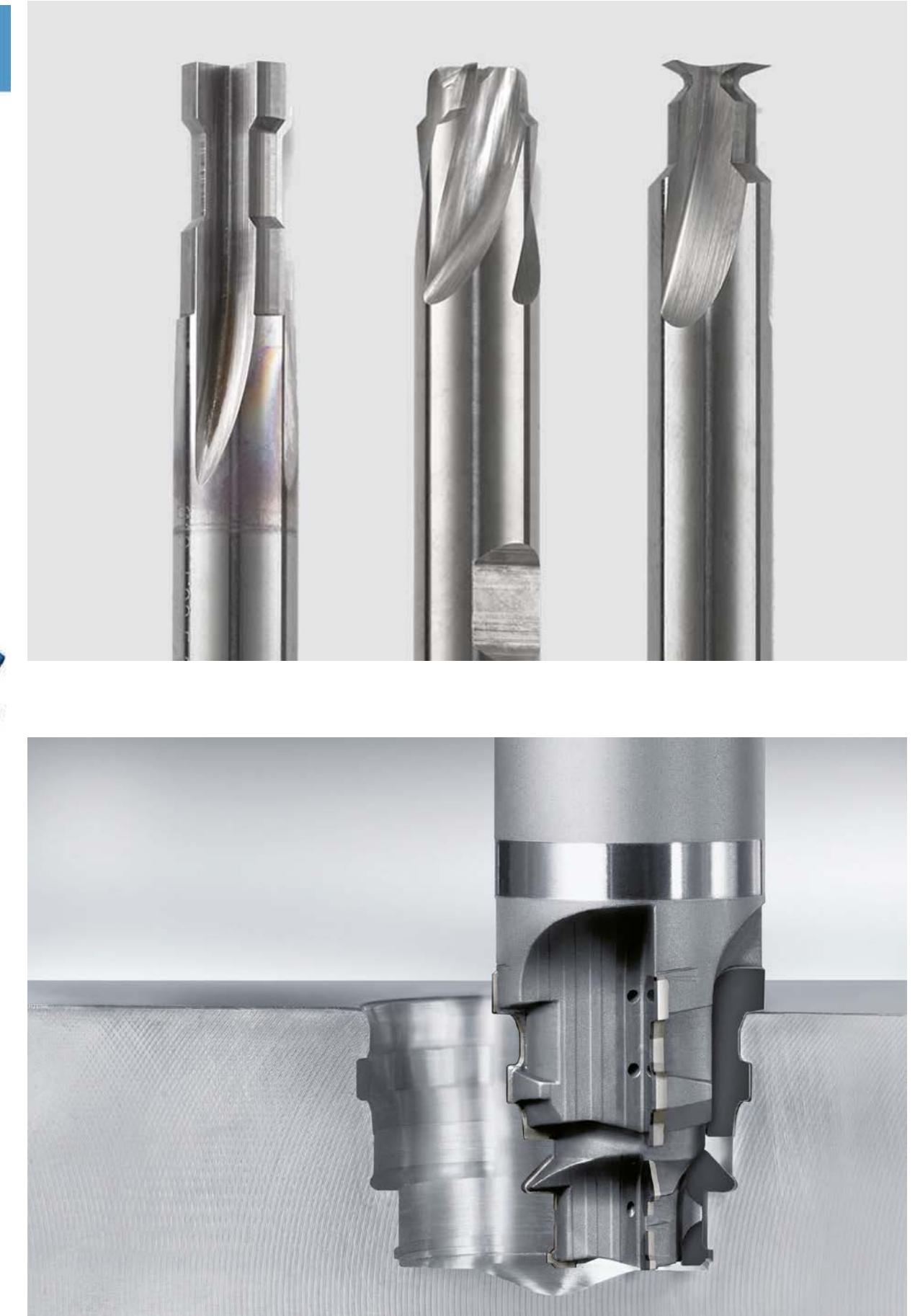


Dedicated Tools



form tools: match the job you want to do

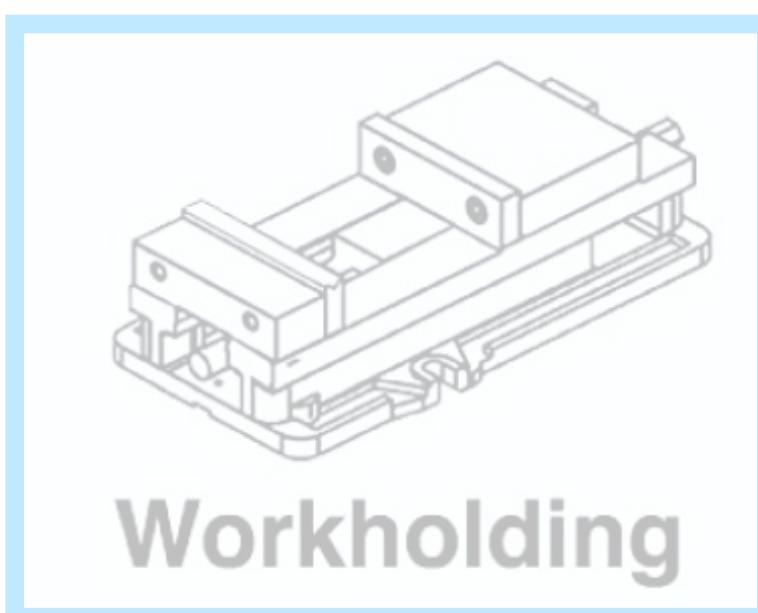
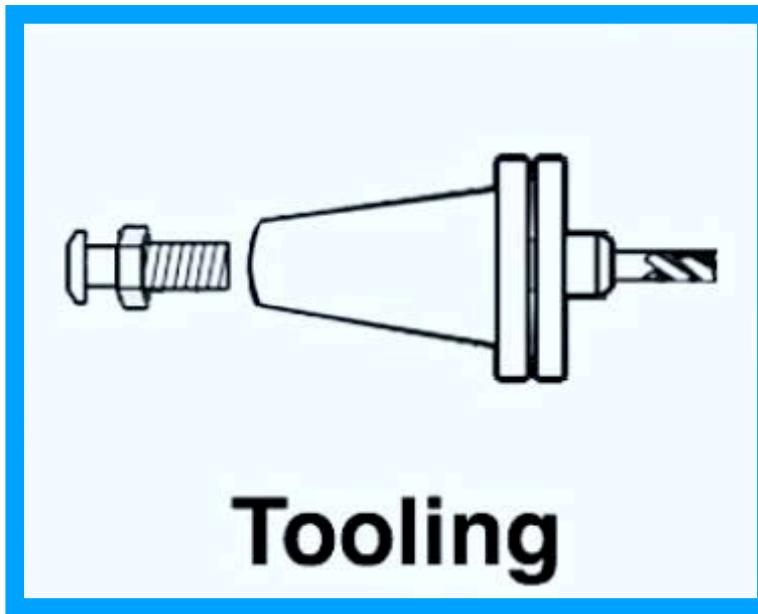
↓flexibility, but ↑rate



Cutting #3

Machining in Practice

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Tool Materials

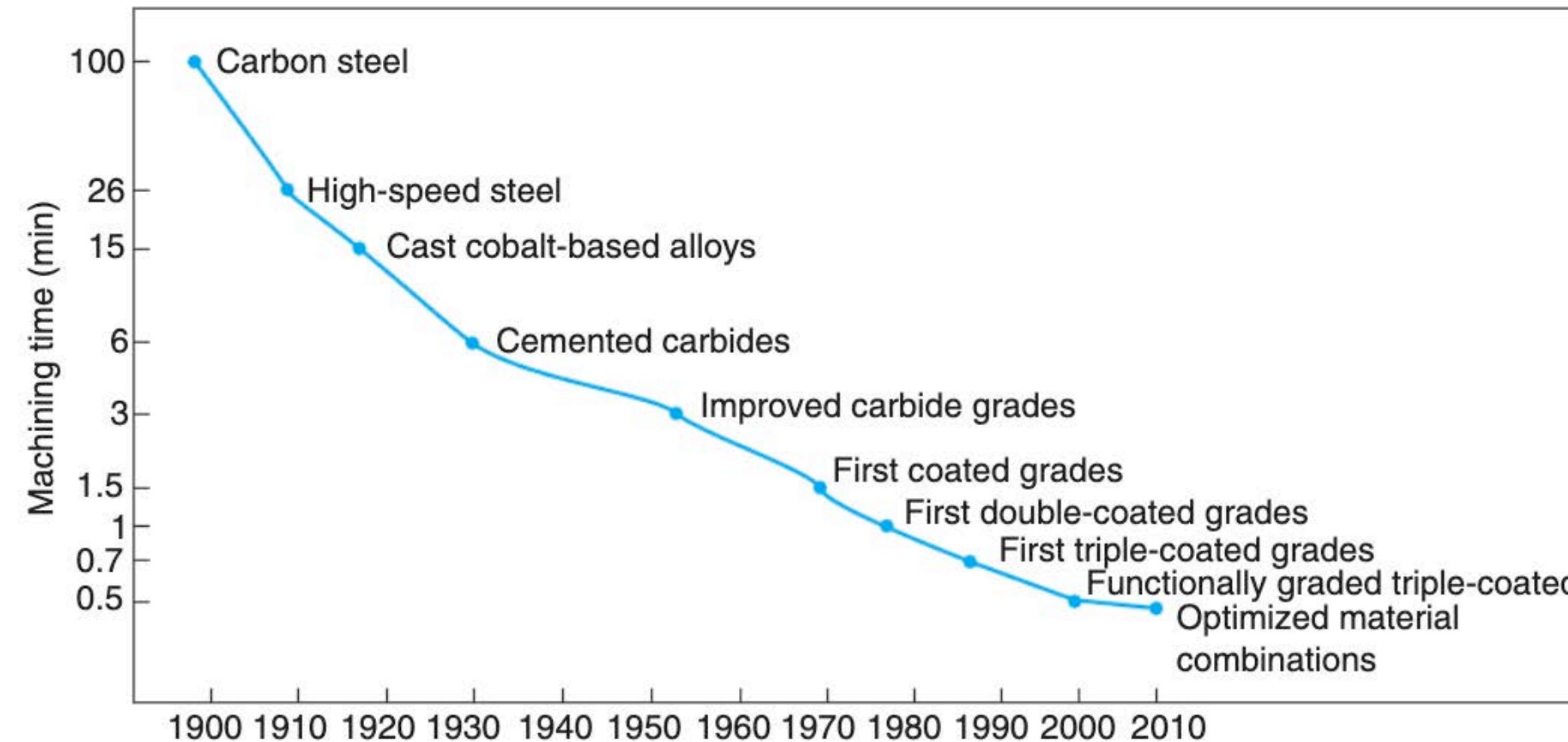


FIGURE 22.6 Relative time required to machine with various cutting-tool materials, indicating the year the tool materials were first introduced; note that machining time has been reduced by two orders of magnitude within a 100 years. *Source:* Courtesy of Sandvik.

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

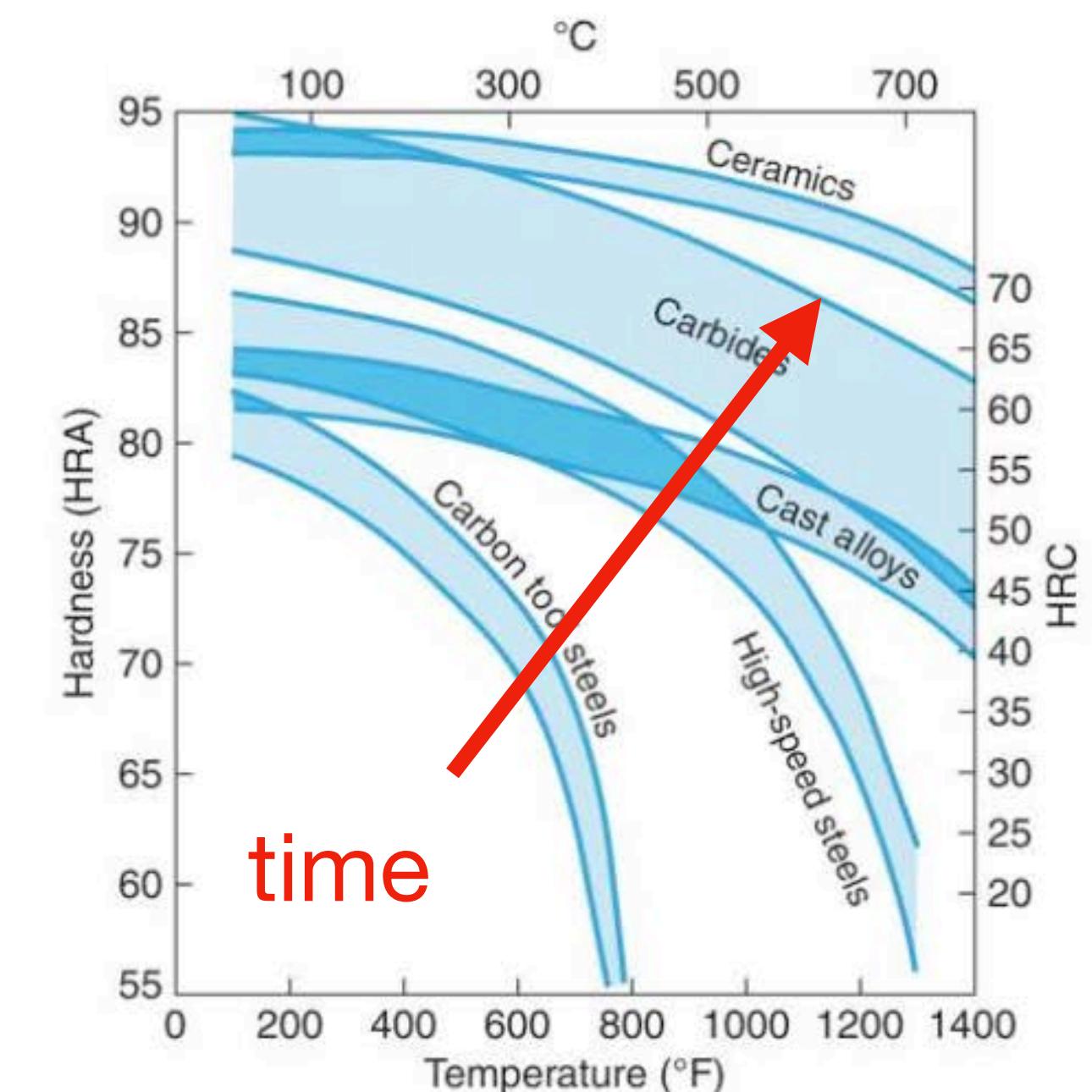
1868- 2% carbon, 2.5% manganese, and 7% tungsten “**Mushet**” steel, lose hardness at 200 degrees C

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,

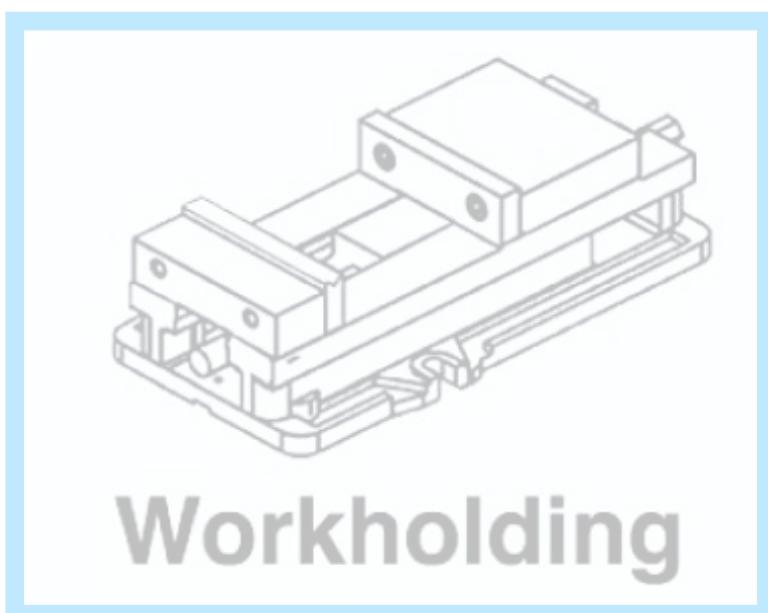
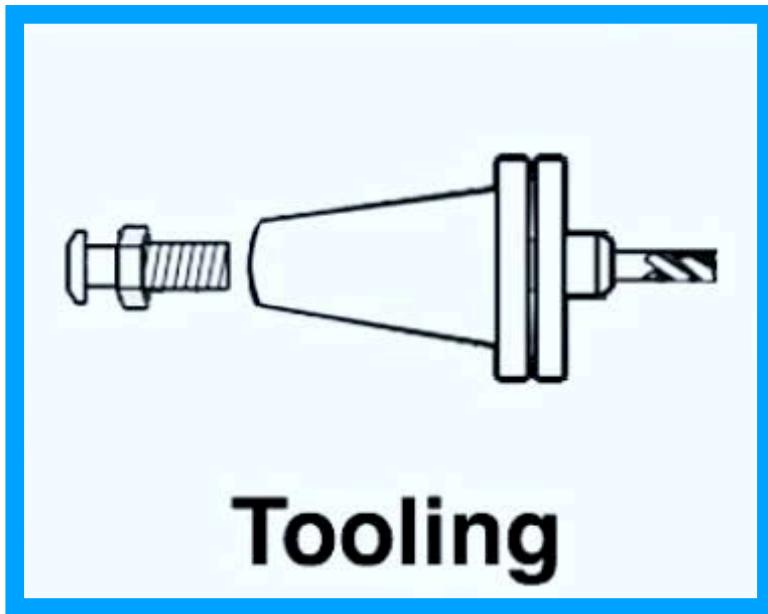
2011- 2 to 20% aluminum, 1 to 12% oxygen, 2 to 12% total of one or more rare earth elements, a balance of silicon and nitrogen. “**Ceramic**” end mill operate above 800 C, where Ni-based alloys soften.



Cutting #3

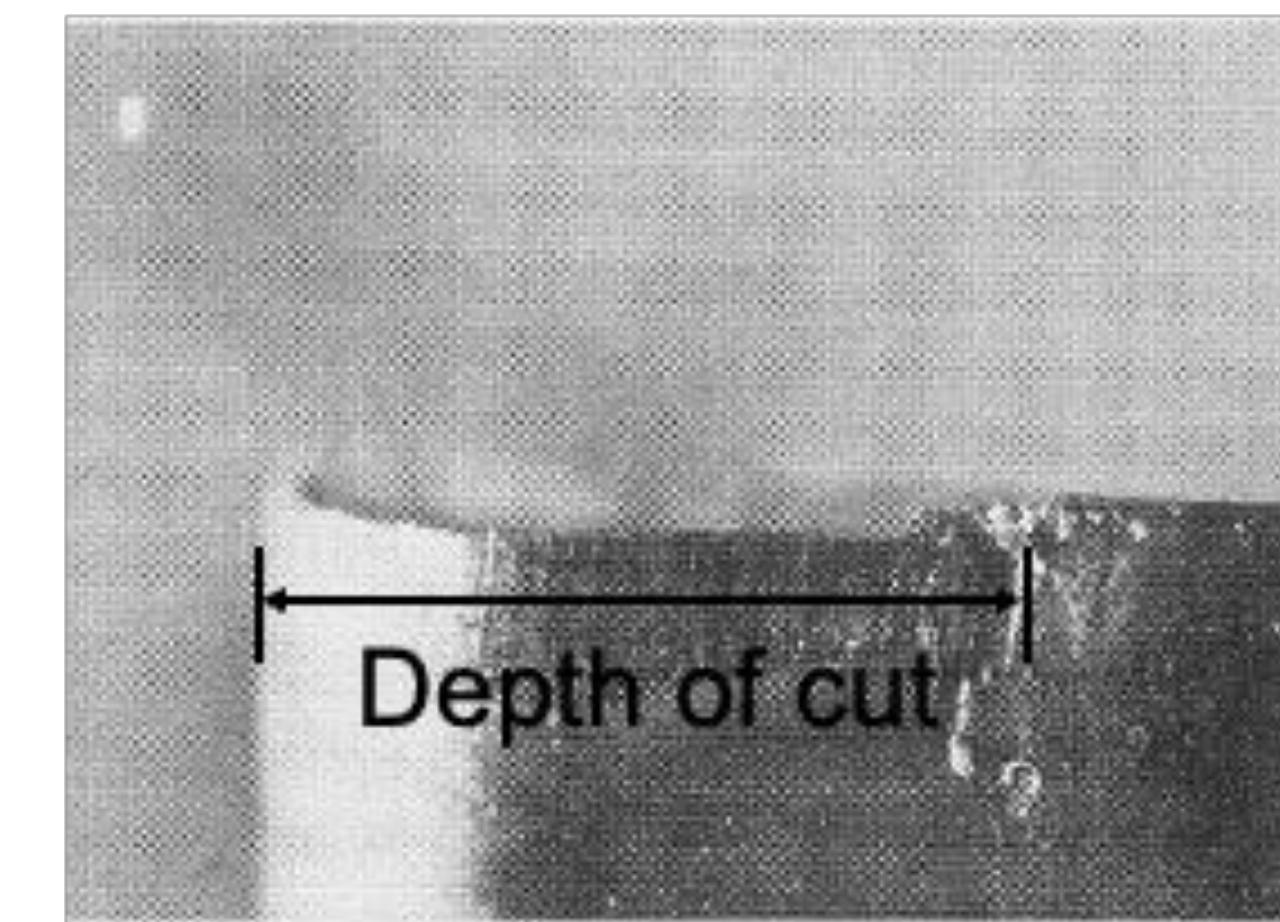
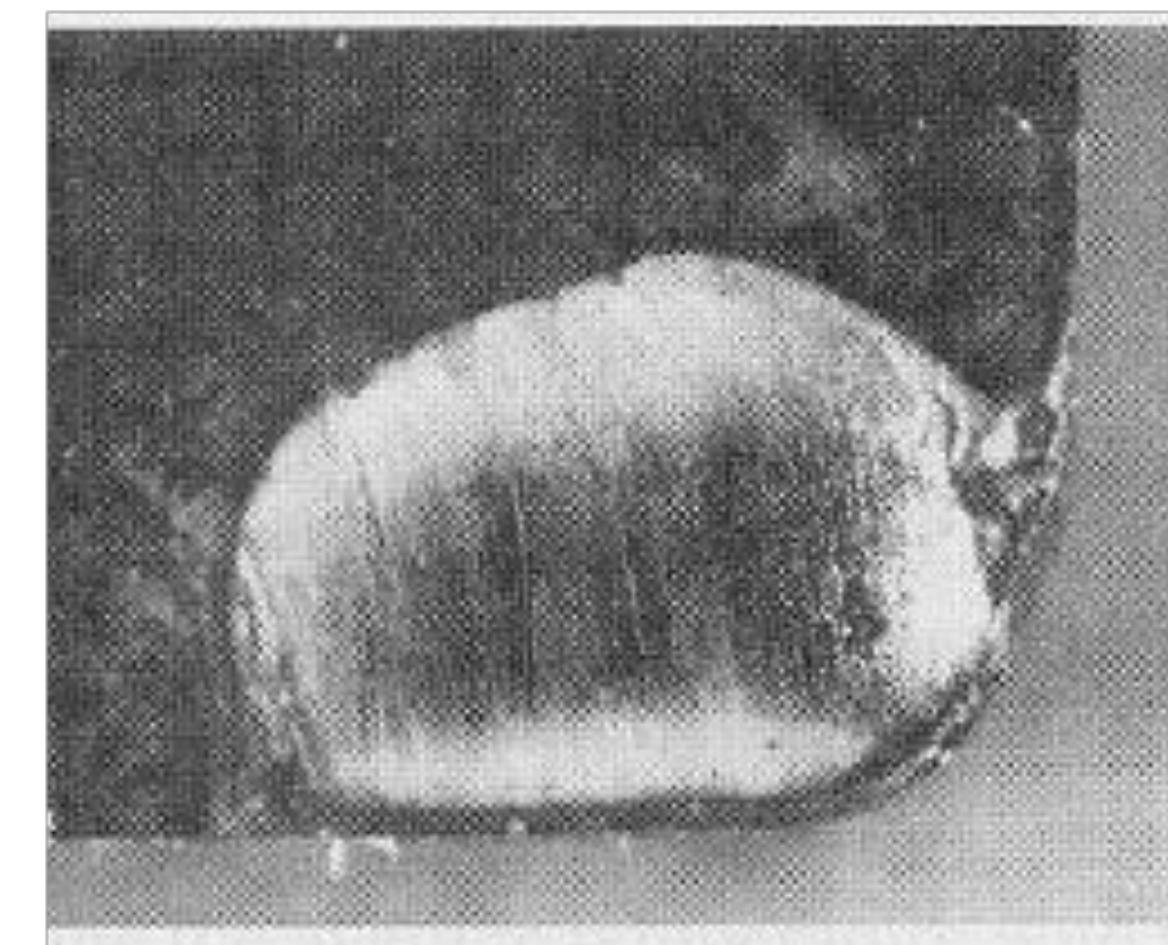
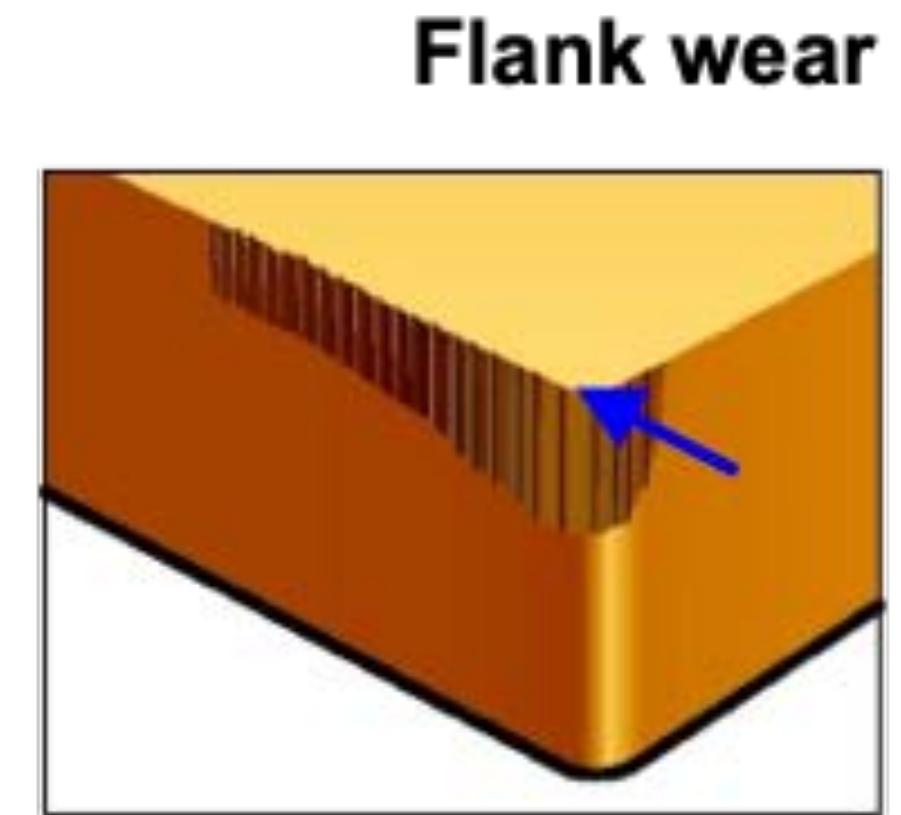
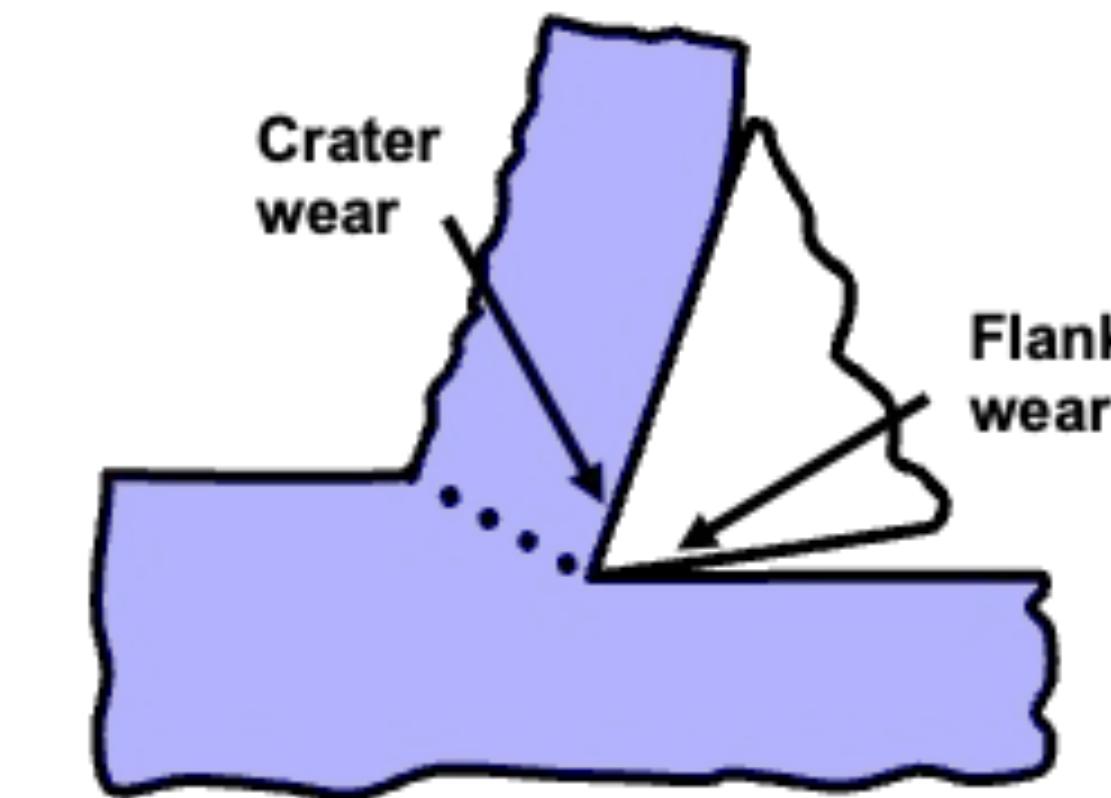
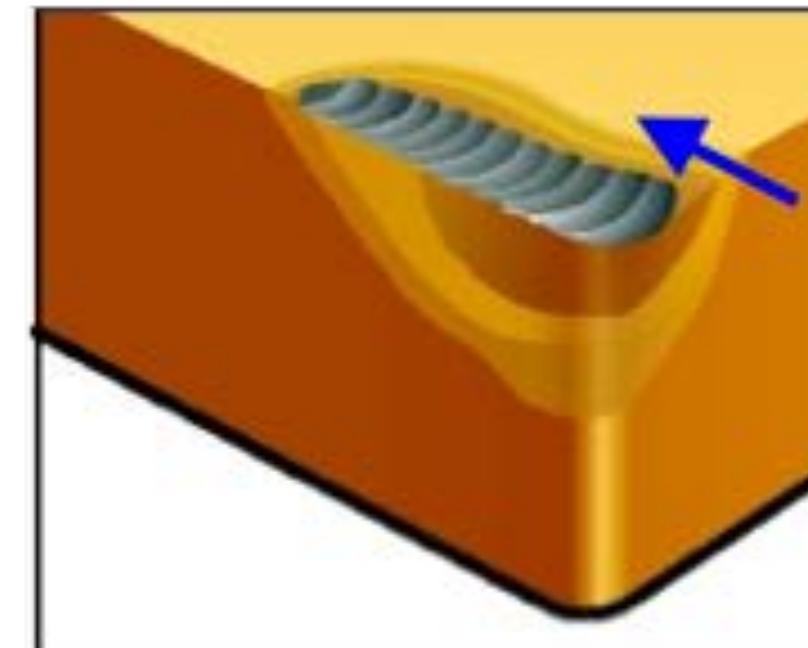
Machining in Practice

25



Tool Wear

Crater wear

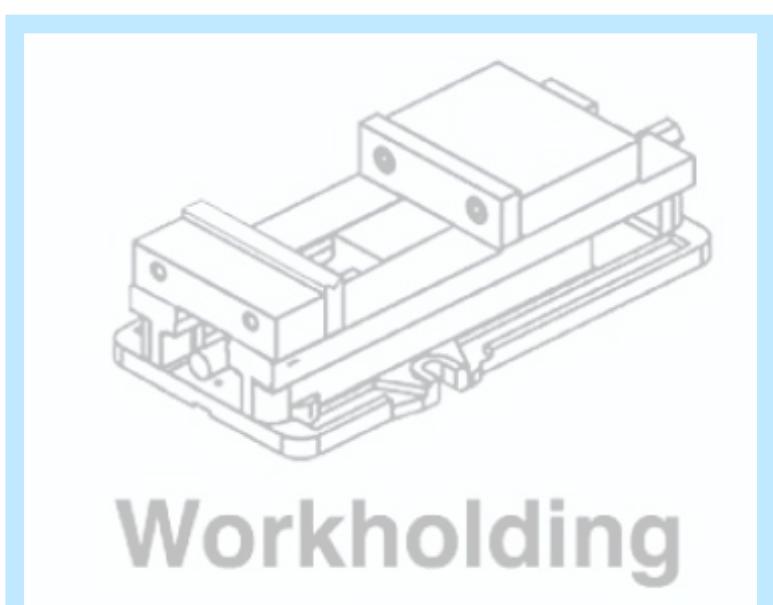
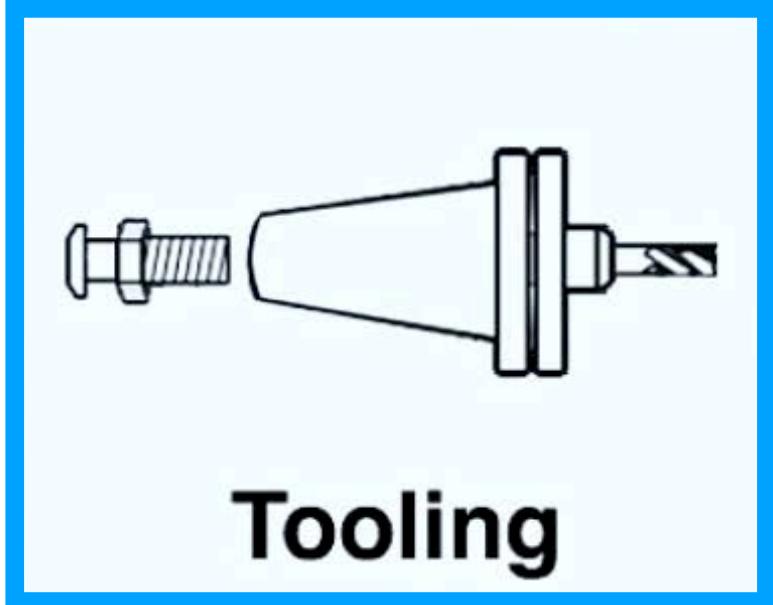


Images from Figure 23.2 Fundamentals of Modern Manufacturing (4th Edition) by Groover. (c) Wiley (2010).

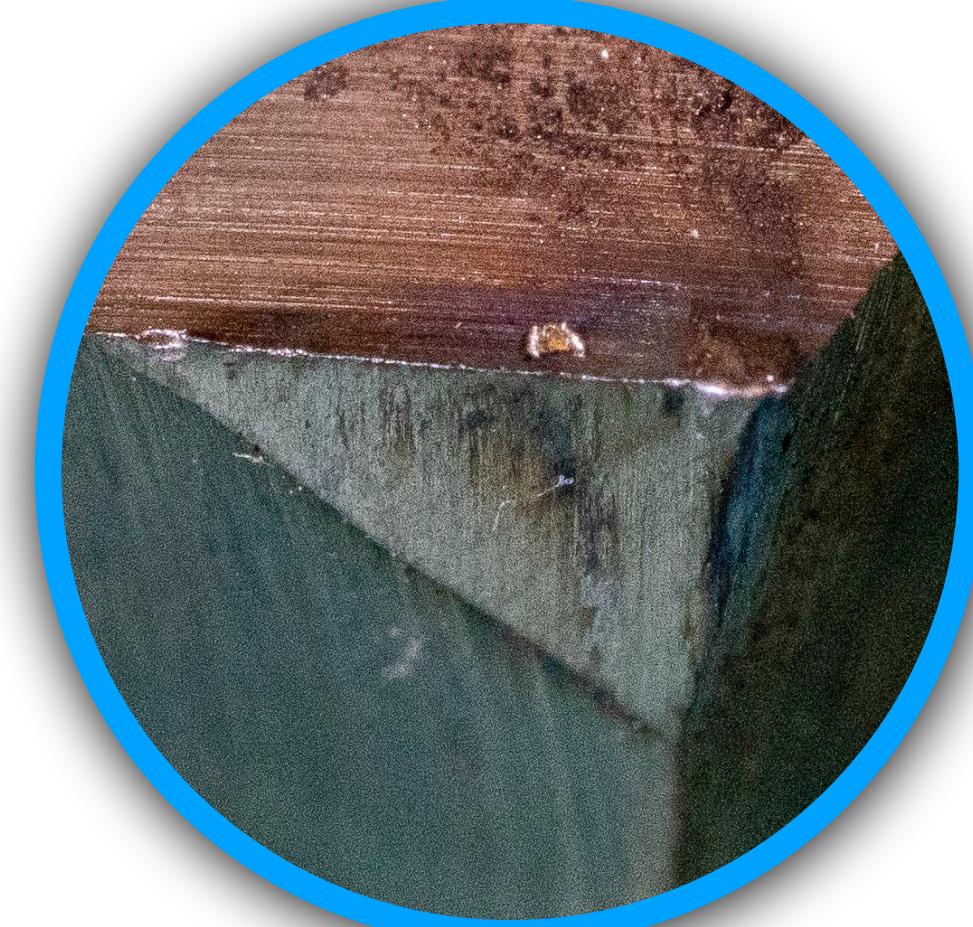
Wear schematics from: http://www.sandvik.coromant.com/en-us/knowledge/milling/troubleshooting/tool_wear

Cutting #3

Machining in Practice



Tool Wear

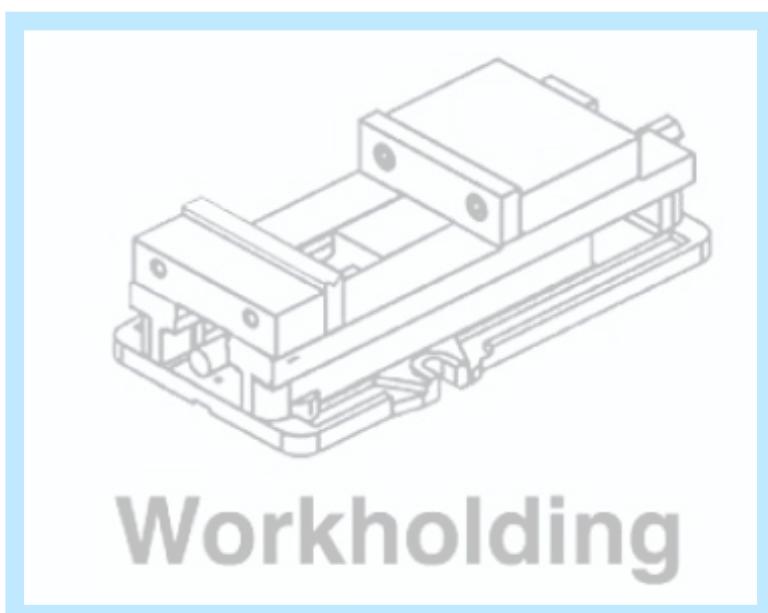
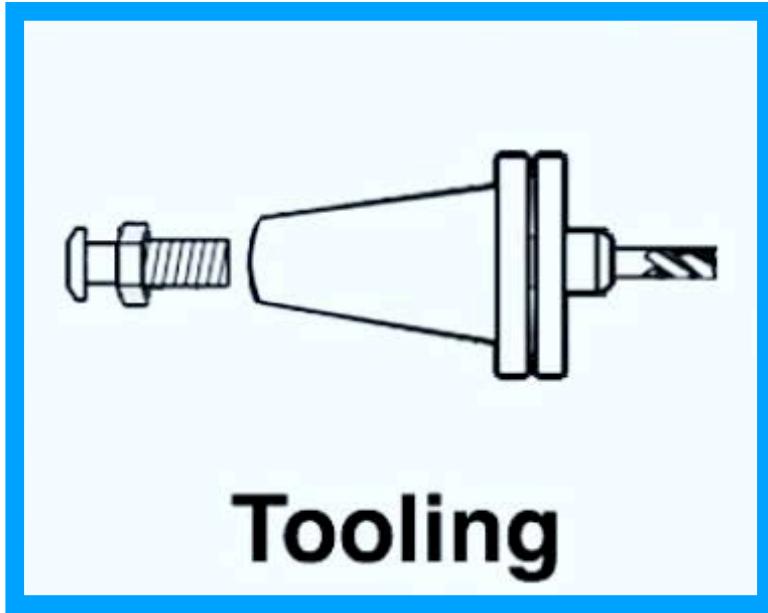


Tool Damage Form	Cause	Countermeasure
Flank Wear	<ul style="list-style-type: none">• Tool grade is too soft.• Cutting speed is too high.• Flank angle is too small.• Feed rate is extremely low.	<ul style="list-style-type: none">• Tool grade with high wear resistance.• Lower cutting speed.• Increase flank 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.• Lack of shank or holder rigidity.	<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.• Lack of shank or holder rigidity.	<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.

Cutting #3

Machining in Practice

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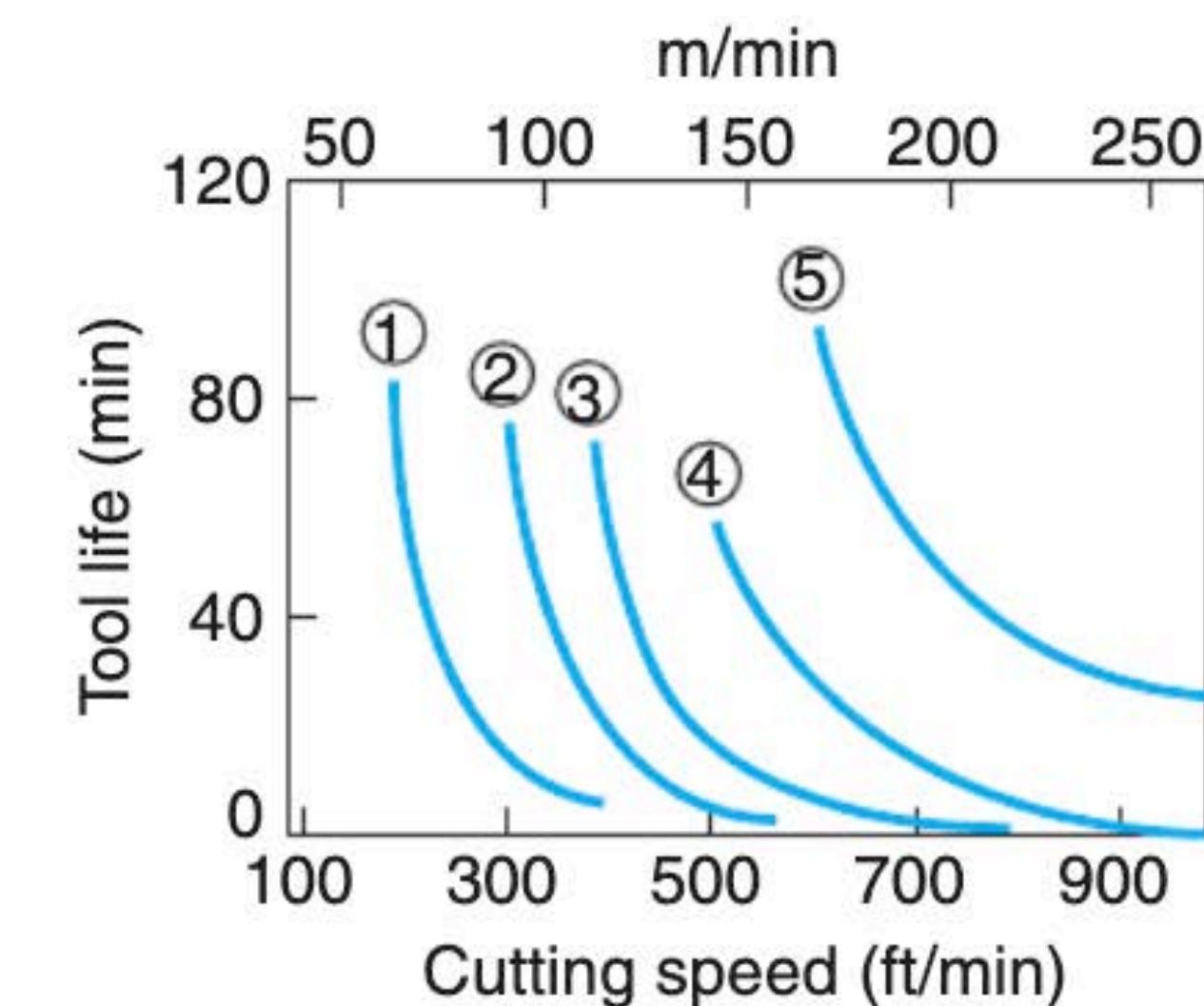


Taylor's Tool Life Equation

cutting velocity significantly affects rate of tool wear

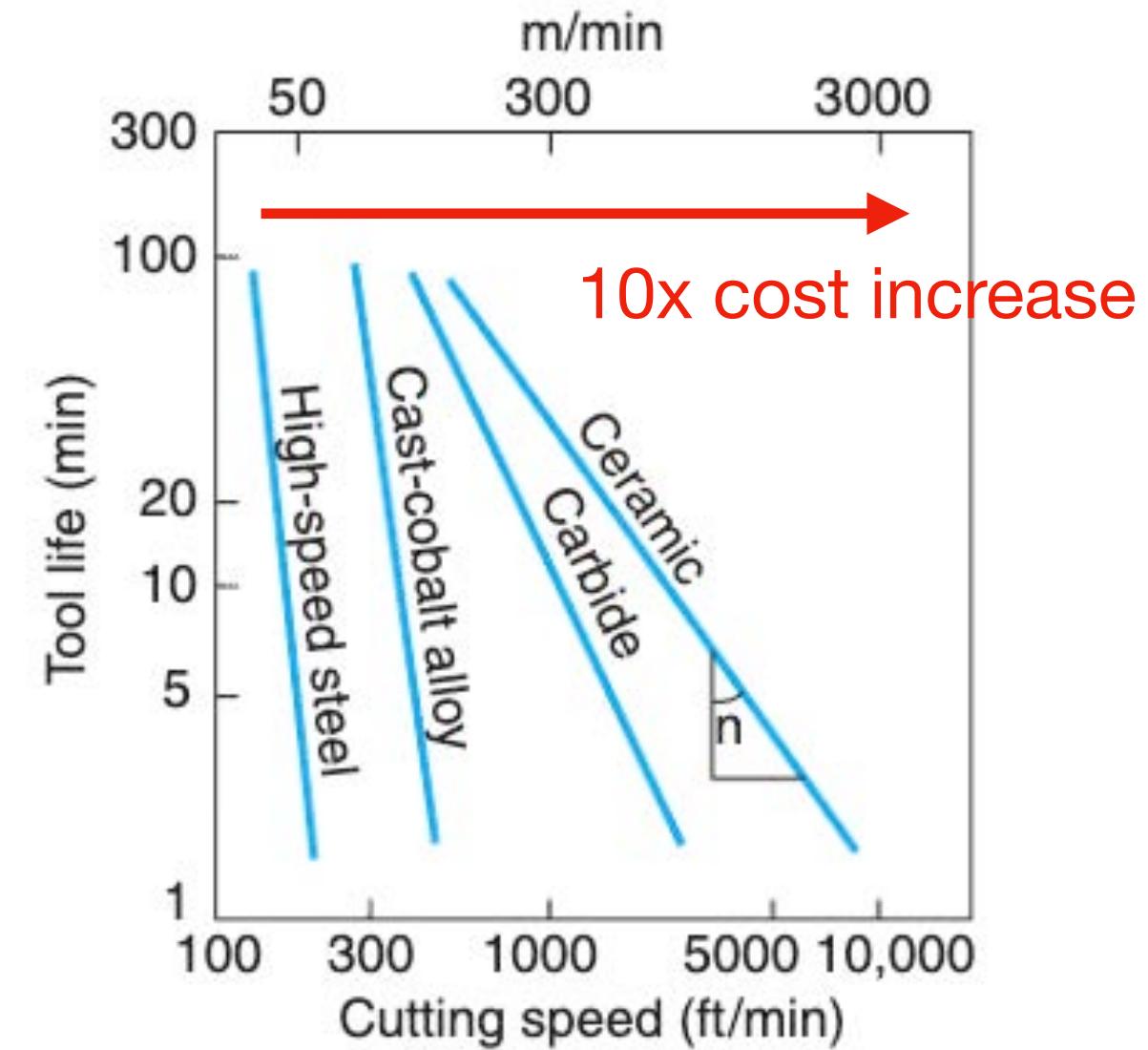
$$v_{cut} \cdot t^n = C$$

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	—

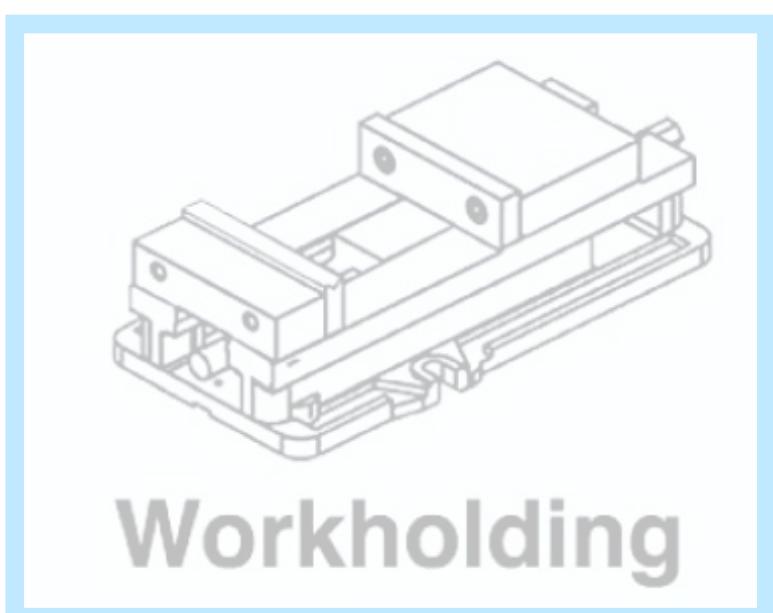
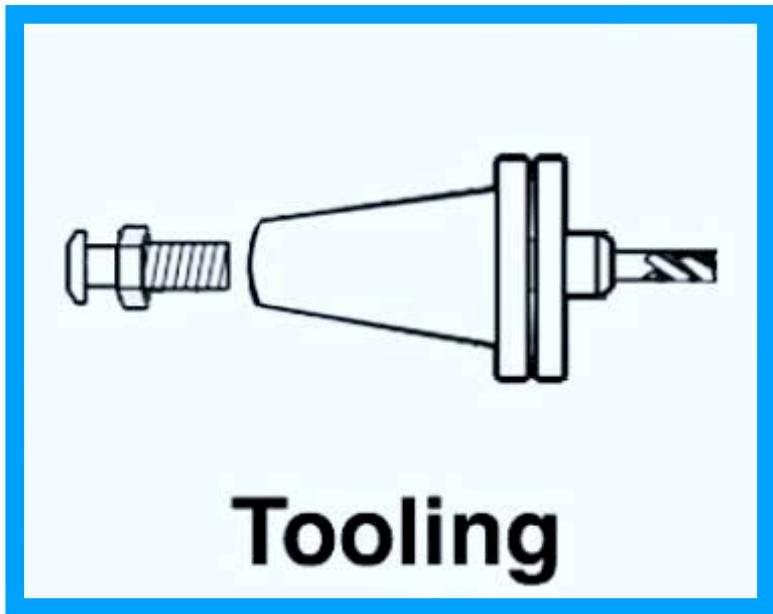
softer workpiece



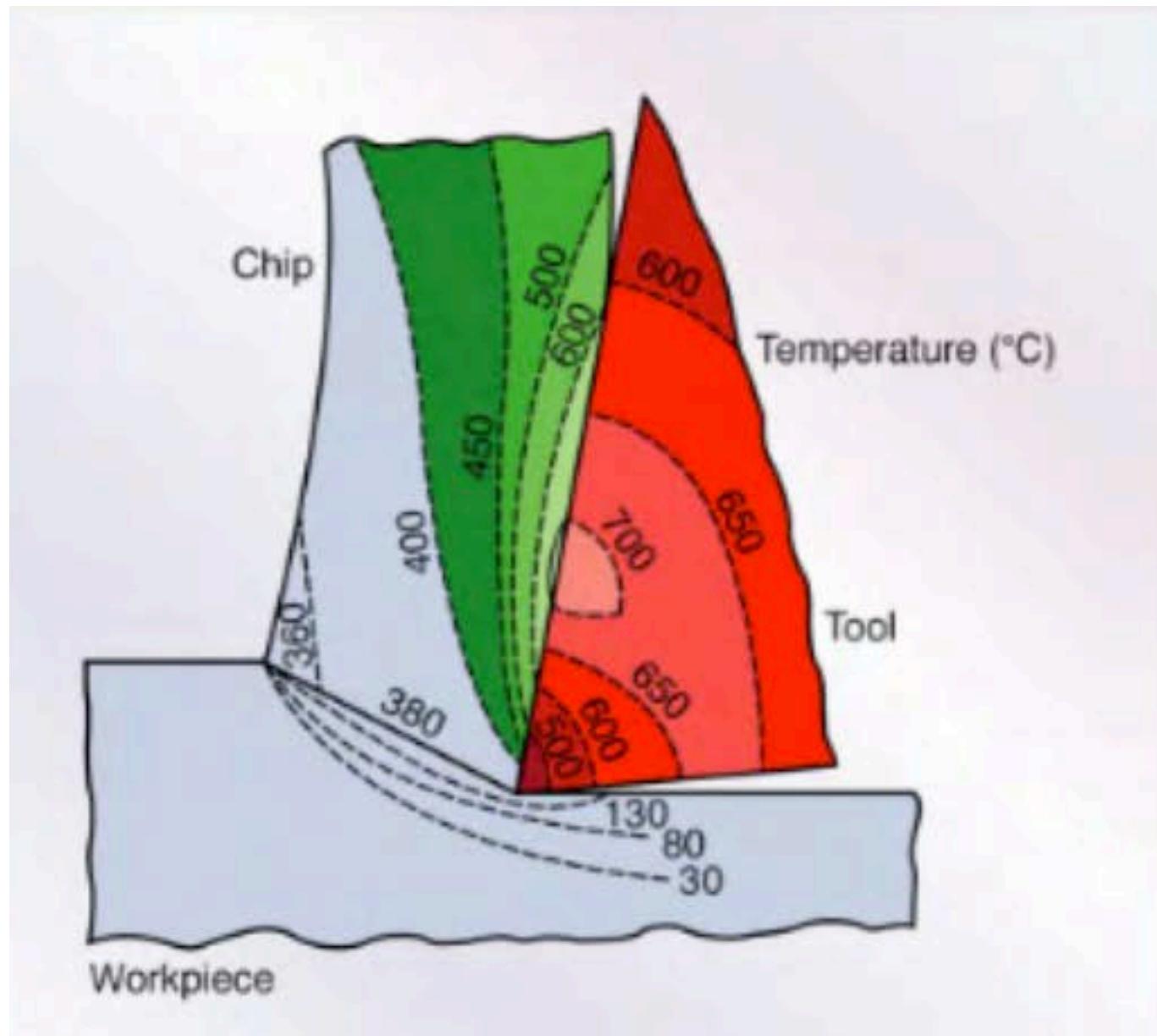
C: empirical constant
(cutting speed at $t = 1$ min)
n: empirical constant
t: tool life (time to failure)
 v_{cut} : cutting velocity

Cutting #3

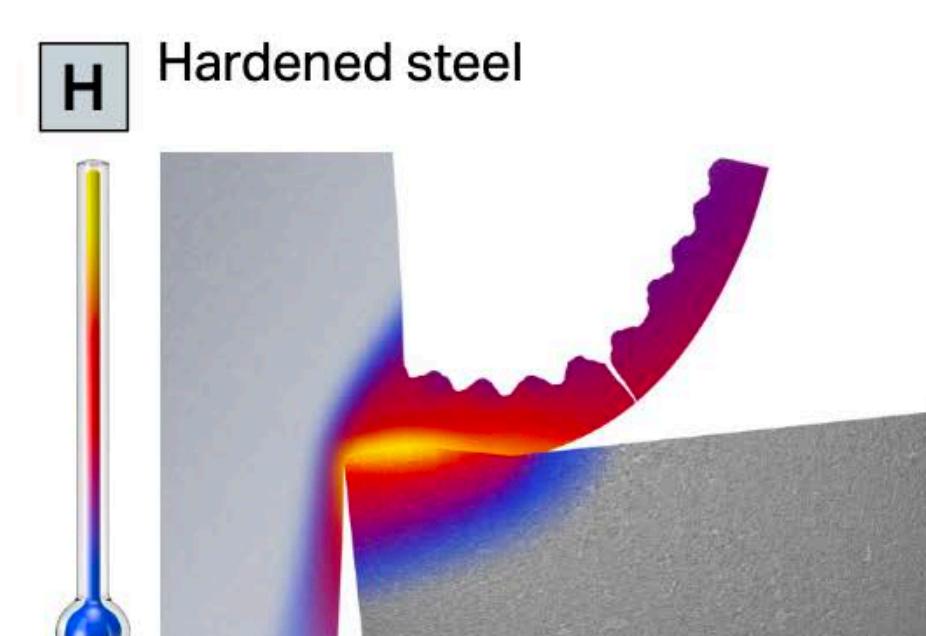
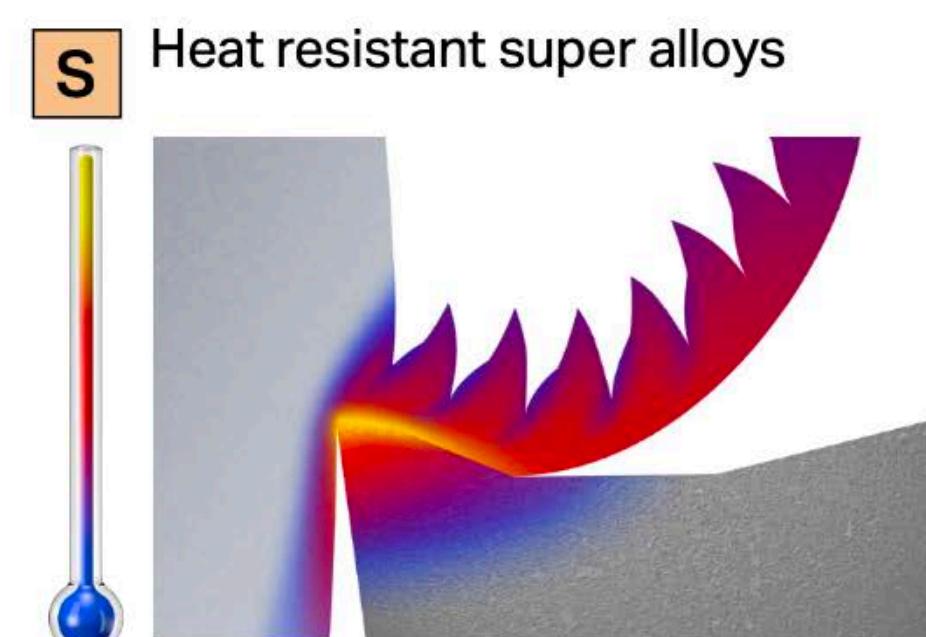
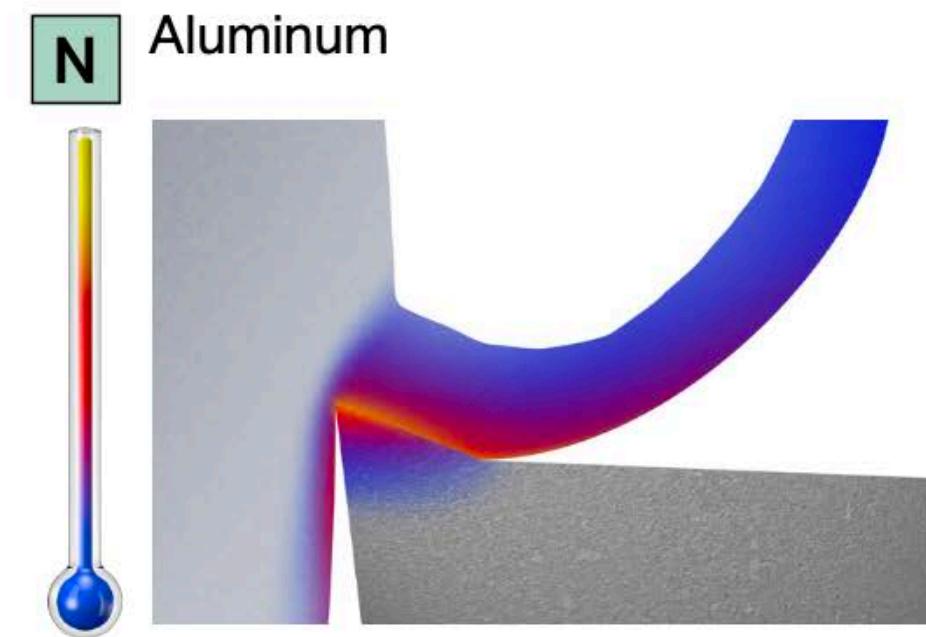
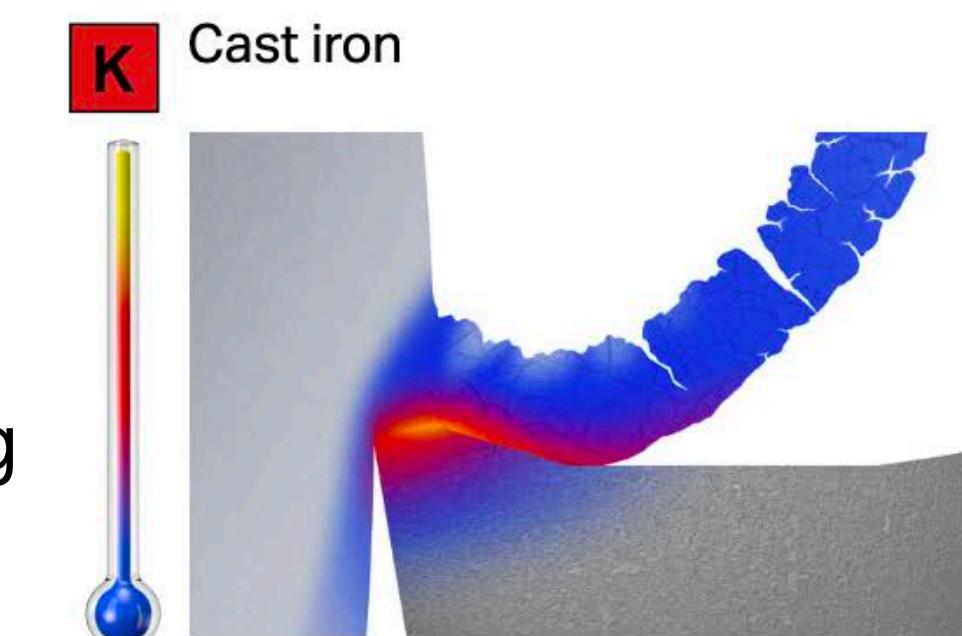
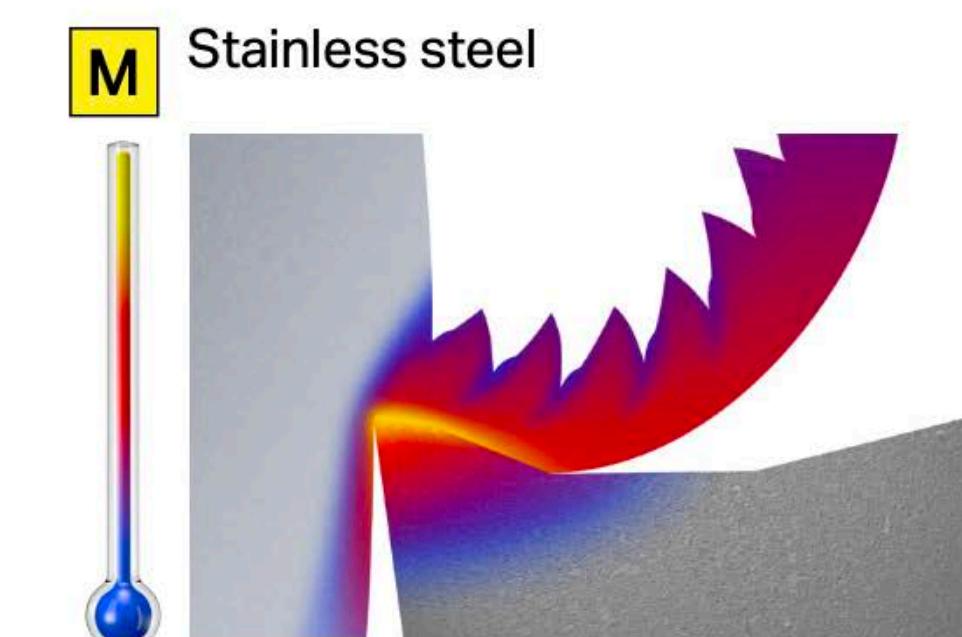
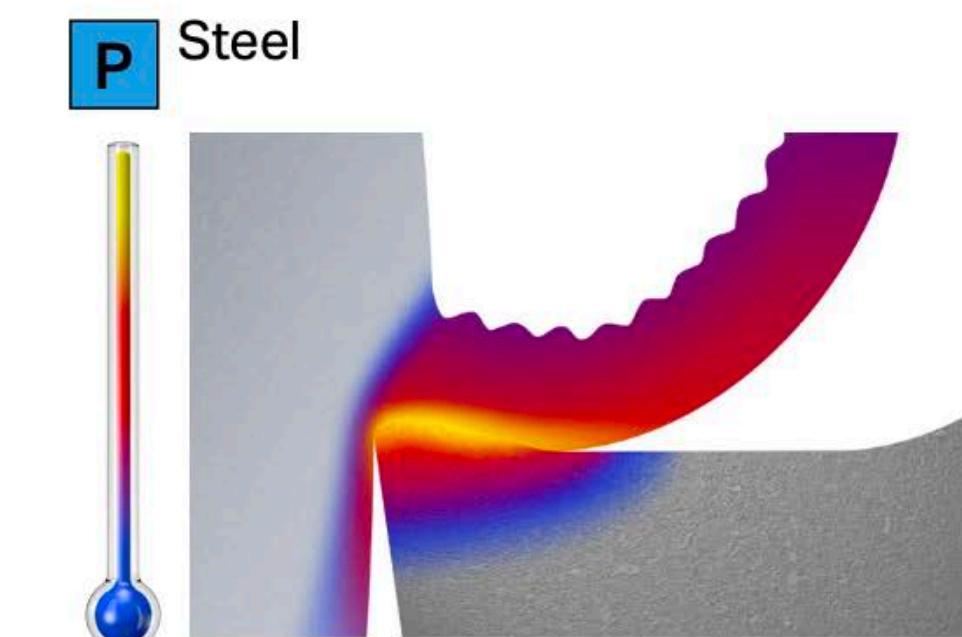
Machining in Practice



Tool Materials

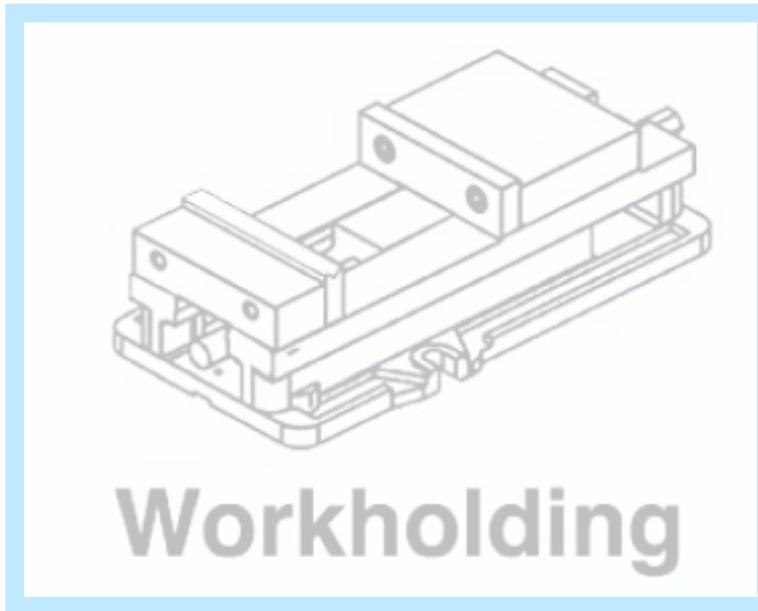
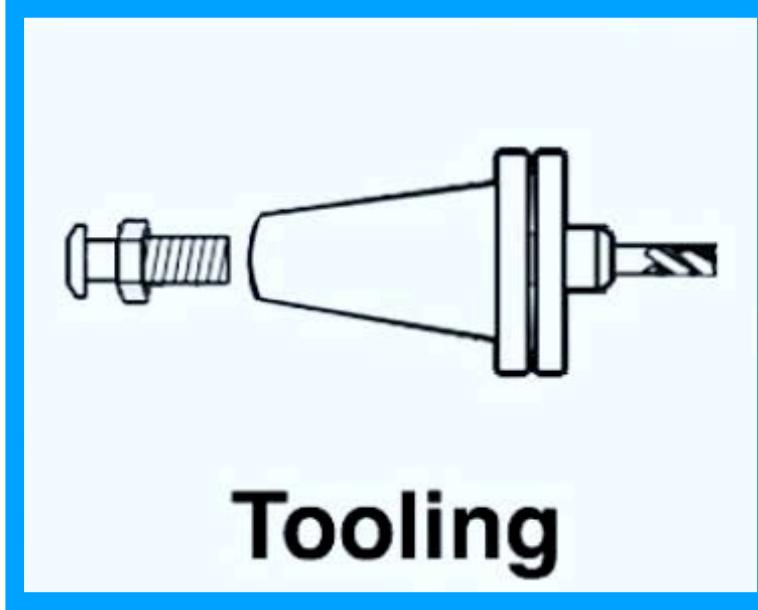


temperature: sensitive to cutting speed
heat is generated rapidly and cannot dissipate
- work done in shearing
- friction: tool + chip and tool + workpiece rubbing
get info from tool manufacturers



Cutting #3

Machining in Practice



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

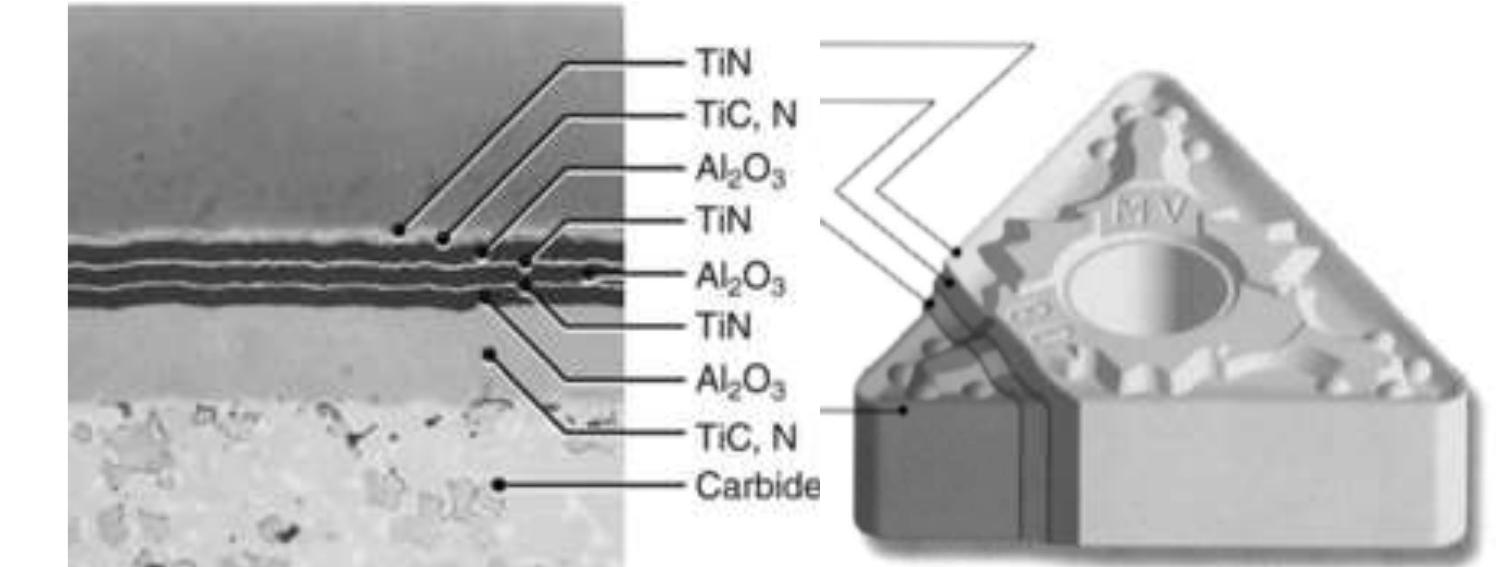
TiN: low friction

TiCN: wear resistance

Al₂O₃: high thermal stability

Carbide: hardness and fracture toughness

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



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

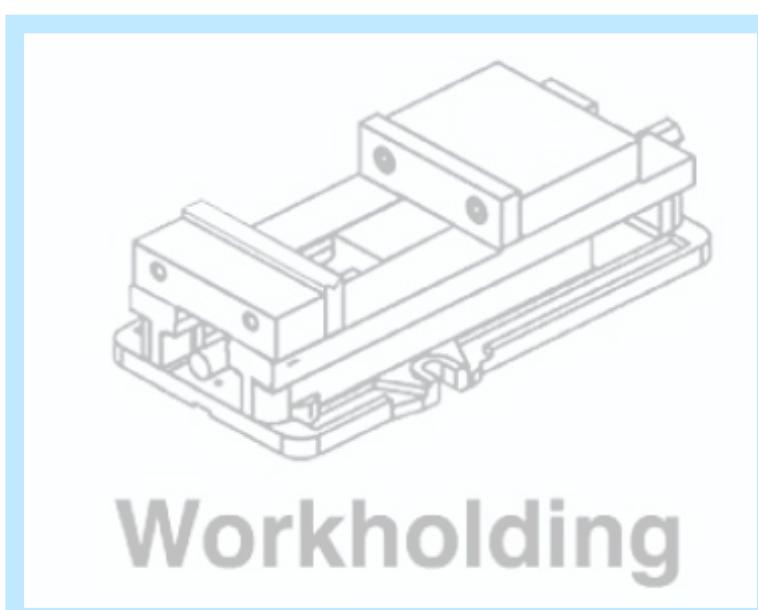
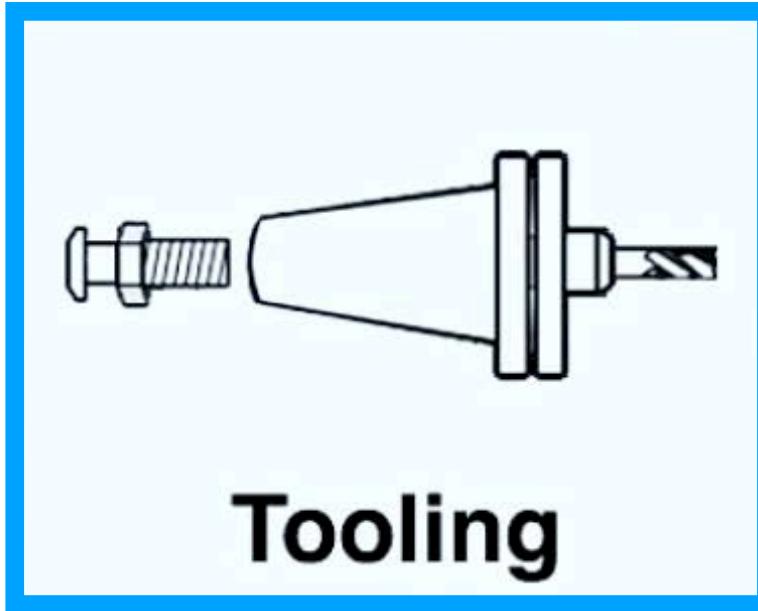


Examples:

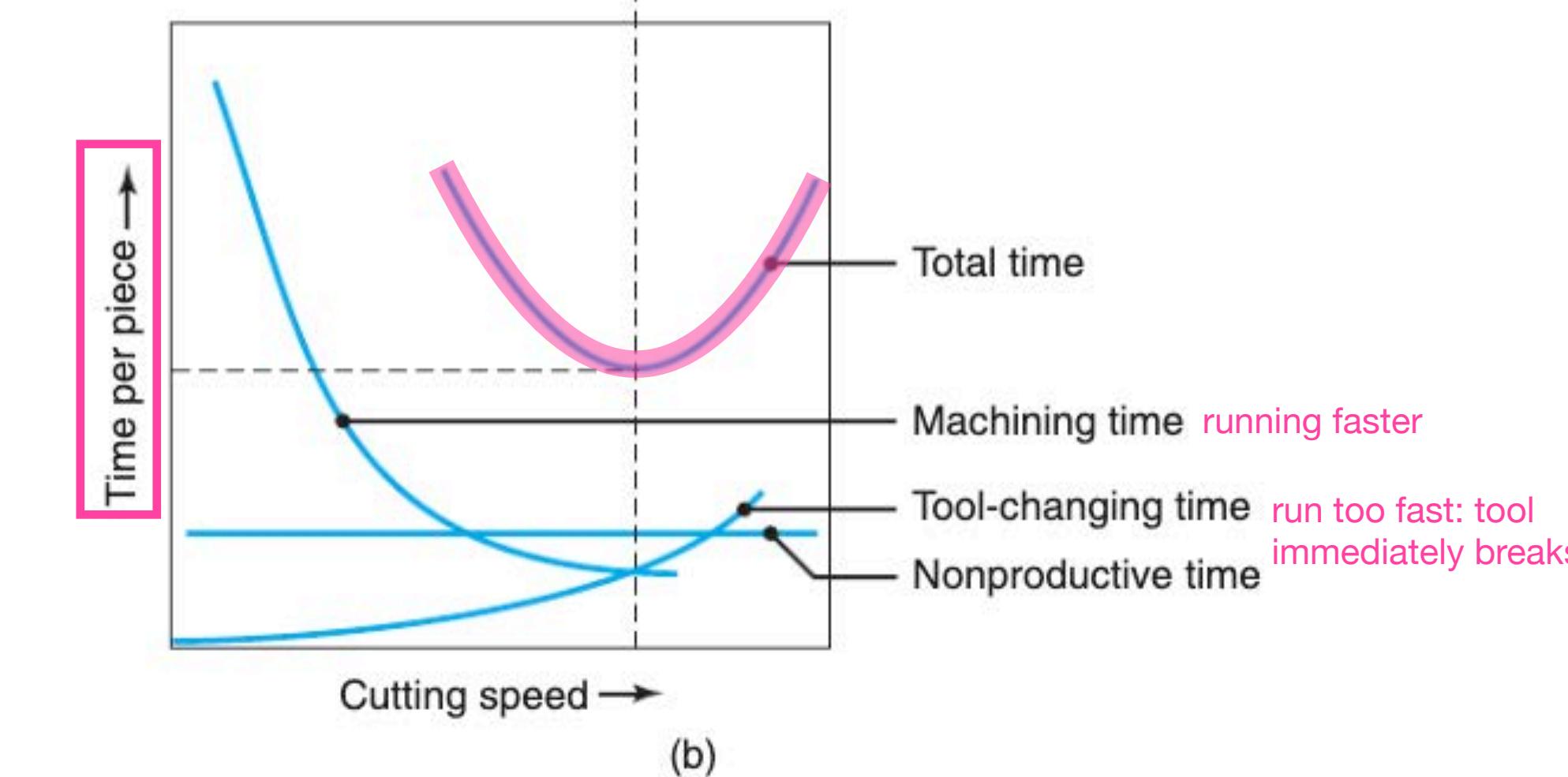
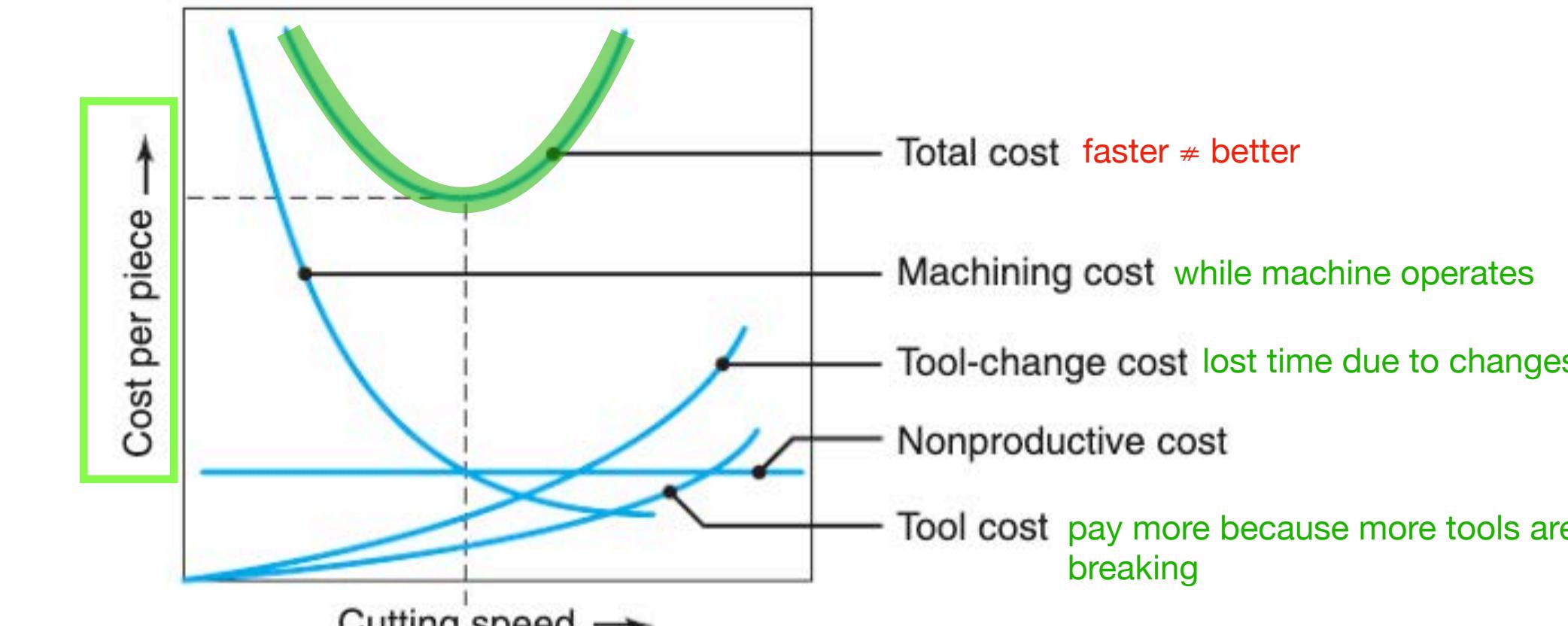
- **TiN** (a basic yellowish coating that has fallen out of wide use)
- **TiCN** (a popular bluish-grey coating)
- **TiAlN and AlTiN** (an extremely popular dark purple coating)
- **TiAlCrN, AlTiCrN and AlCrTiN** (**PVD** coating)
- **PCD:** polycrystalline diamond

Cutting #3

Machining in Practice



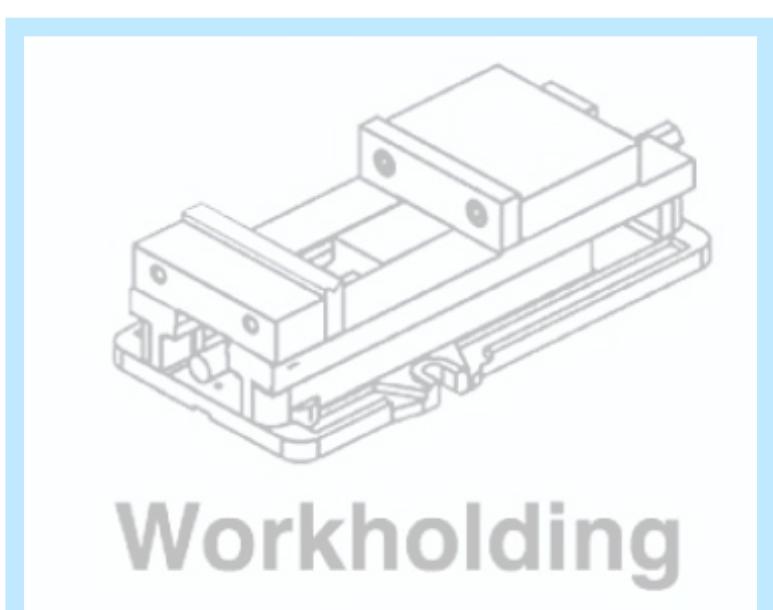
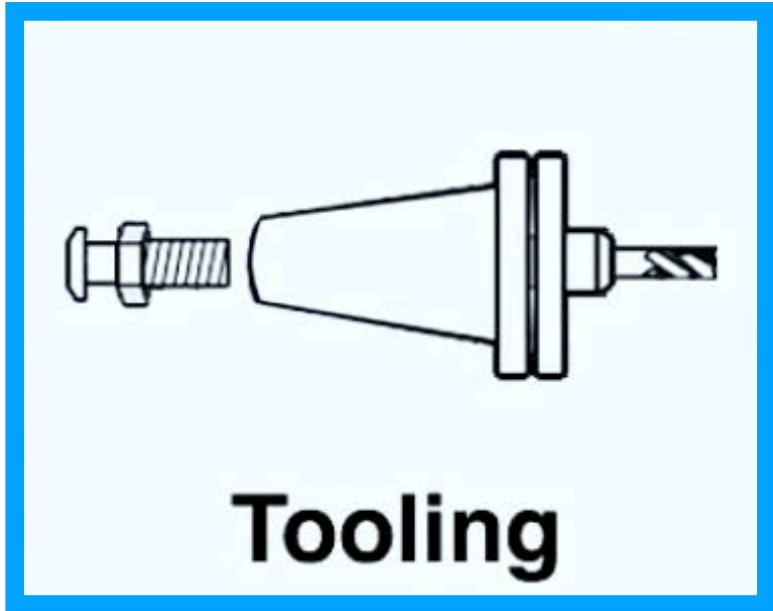
Machining Cost



Cutting #3

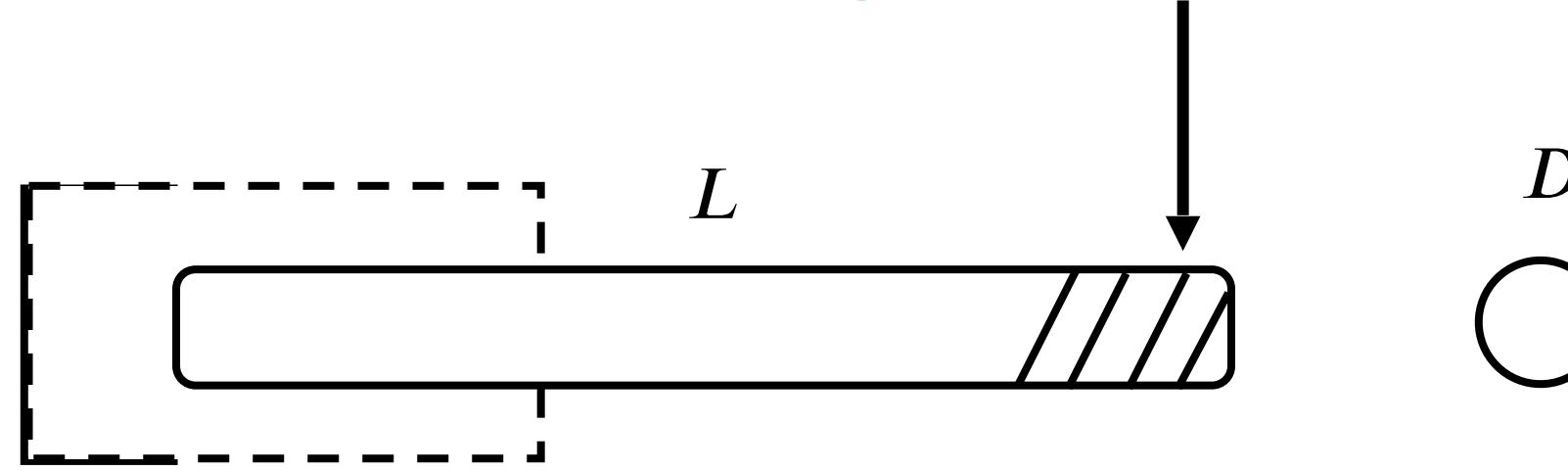
Machining in Practice

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Tool Stiffness

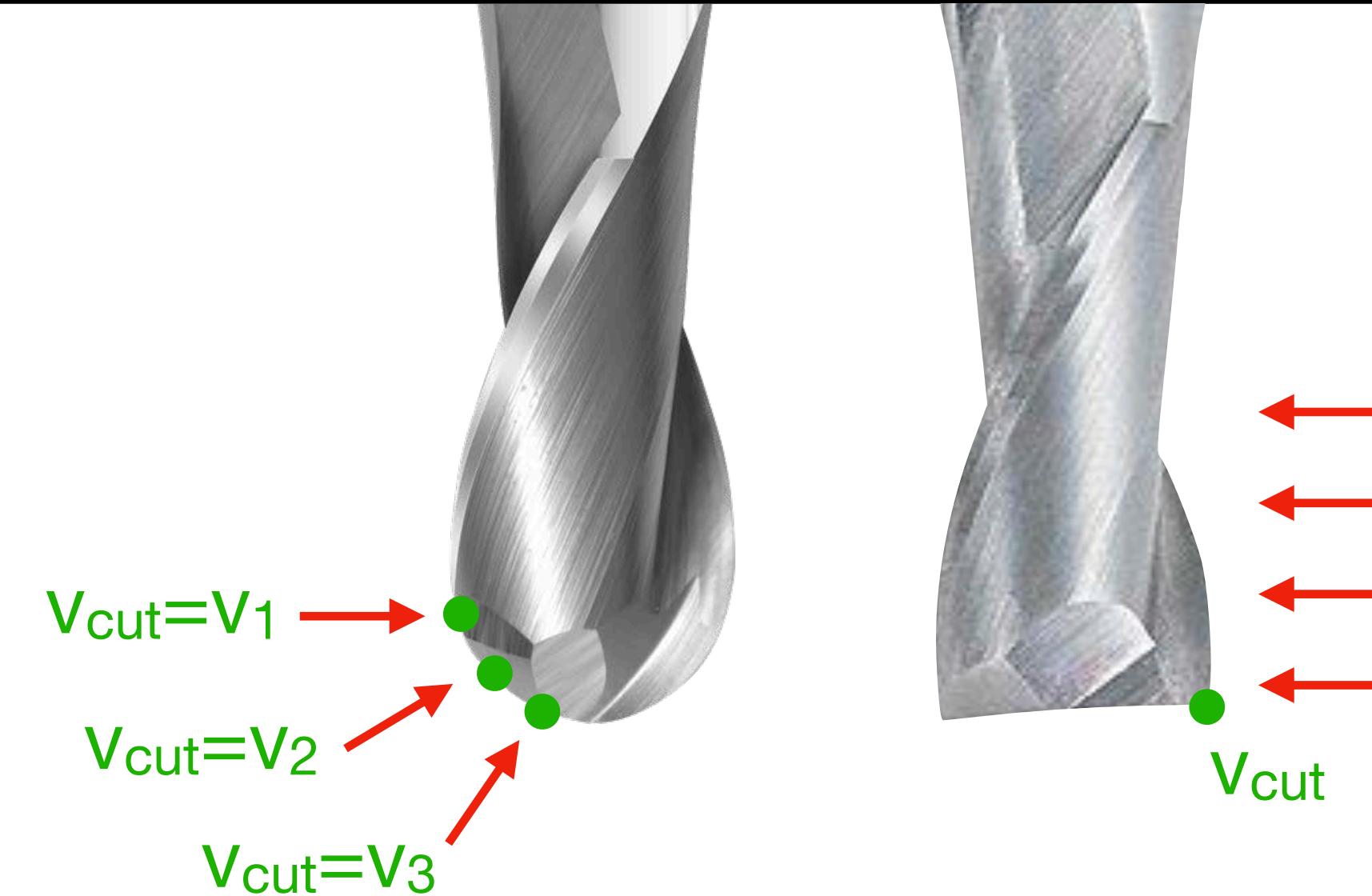
beam bending!



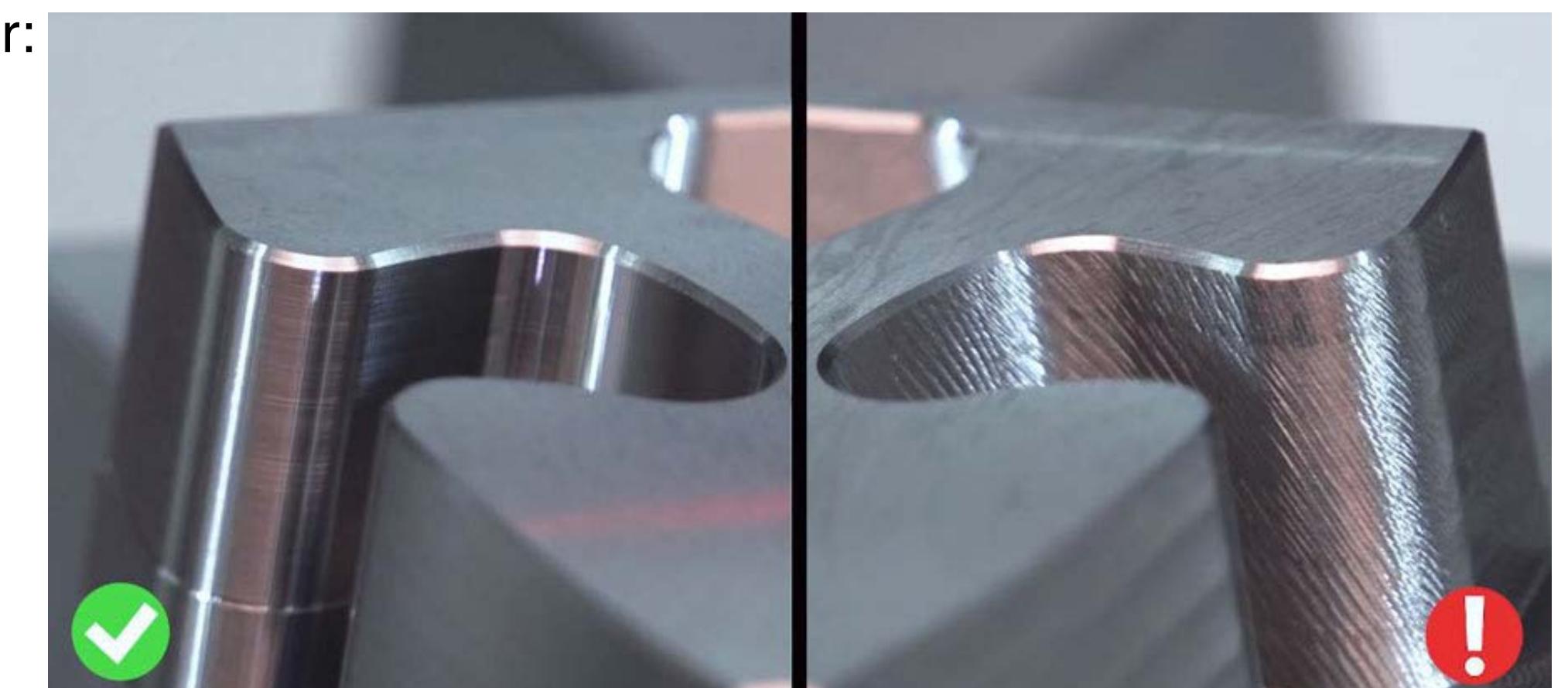
$$\delta = \frac{FL^3}{3EI} \quad F = \frac{3\delta EI}{L^3}$$

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

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



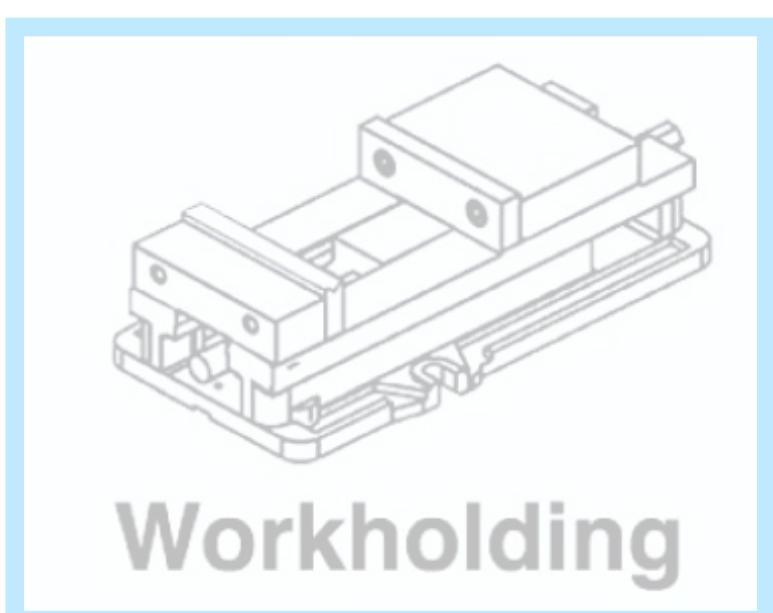
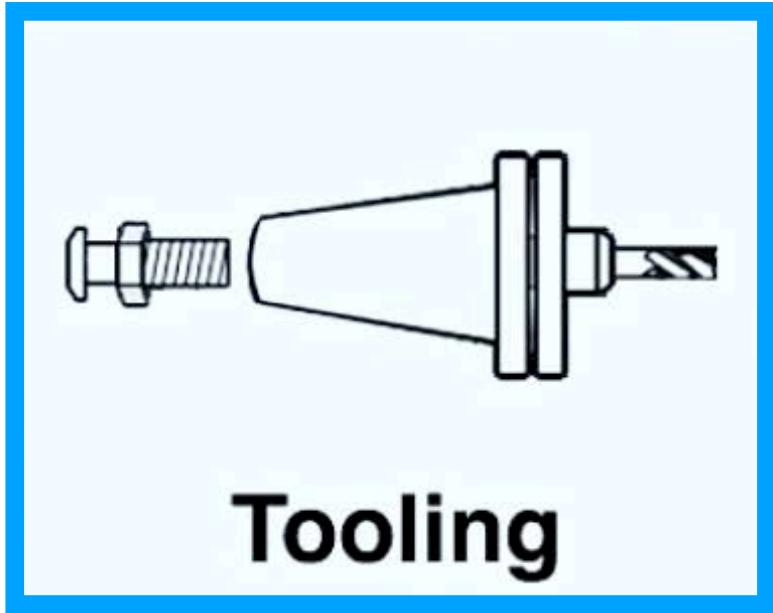
chatter:



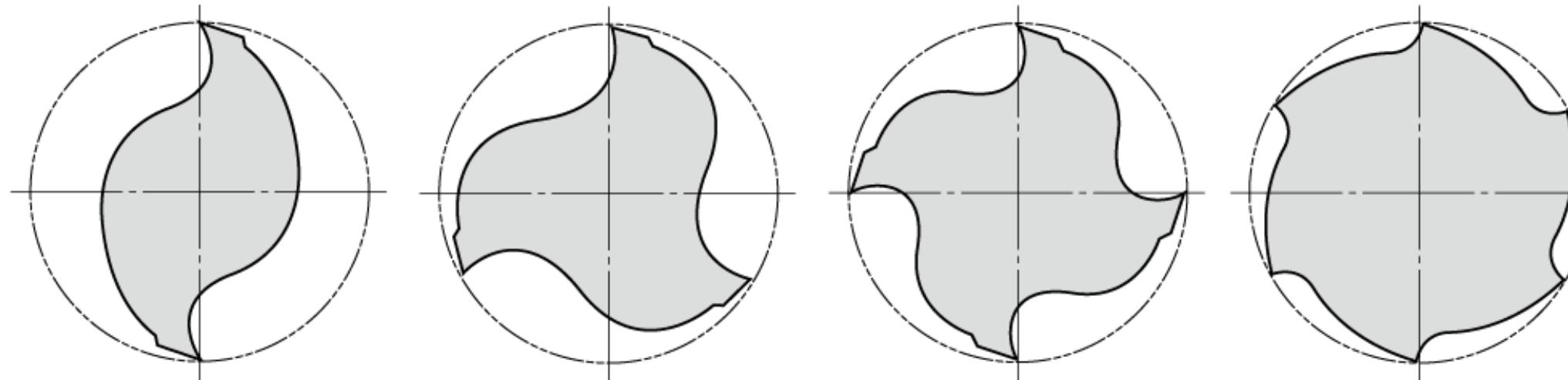
Cutting #3

Machining in Practice

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Tool Stiffness

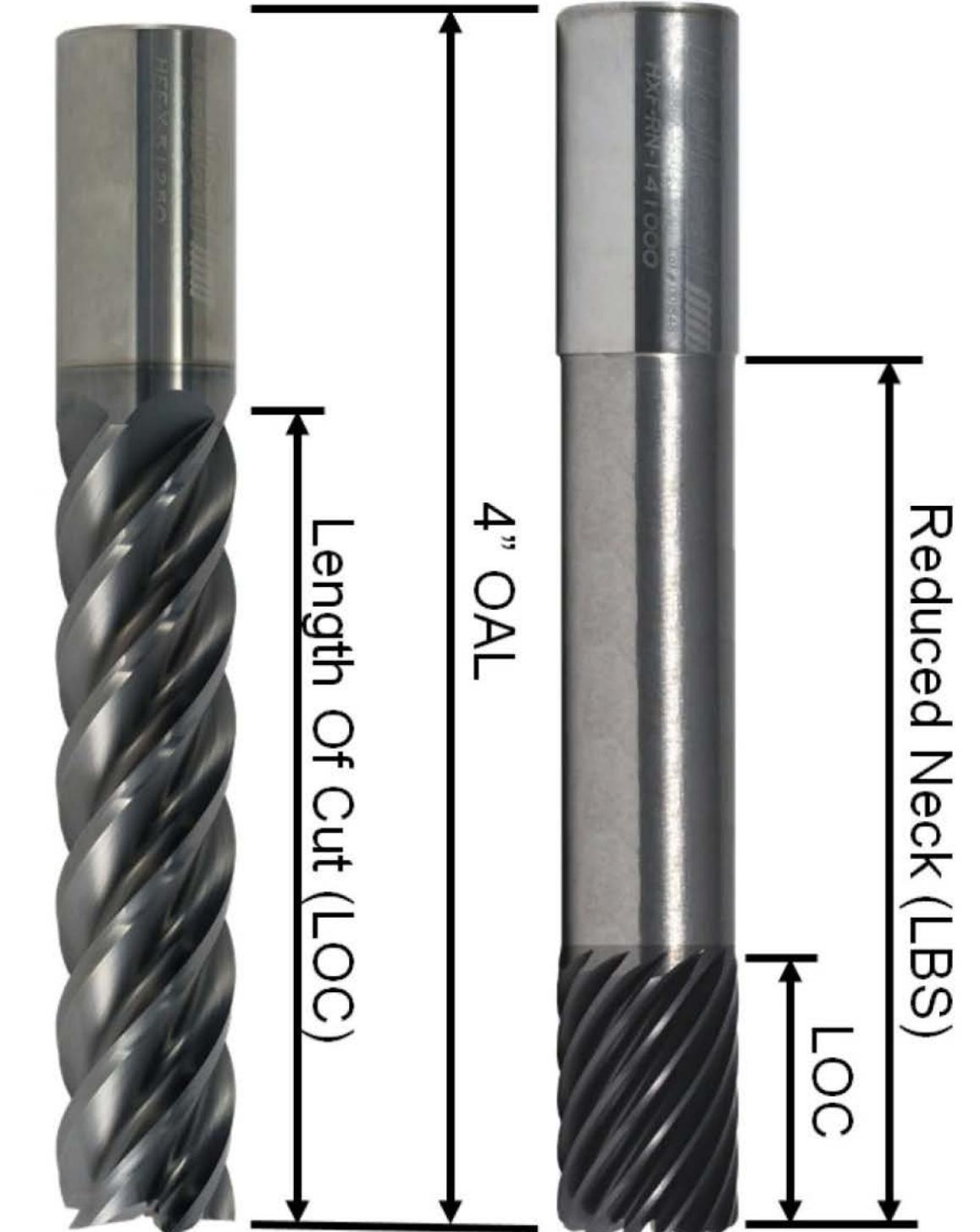


More chip space

Two Flute Centercutting Three Flute Centercutting Four Flute Centercutting Six Flute Centercutting Eight Flute Centercutting



Harder materials

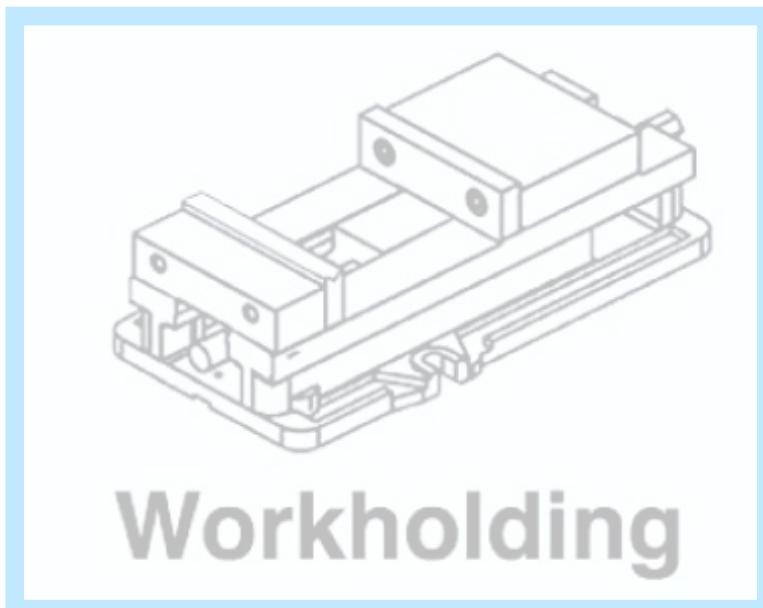
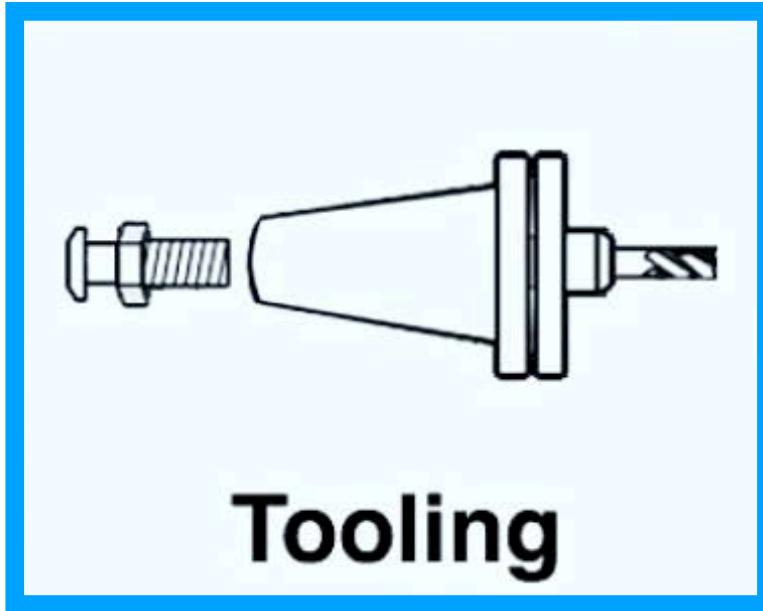


▲ **Stronger Choice**

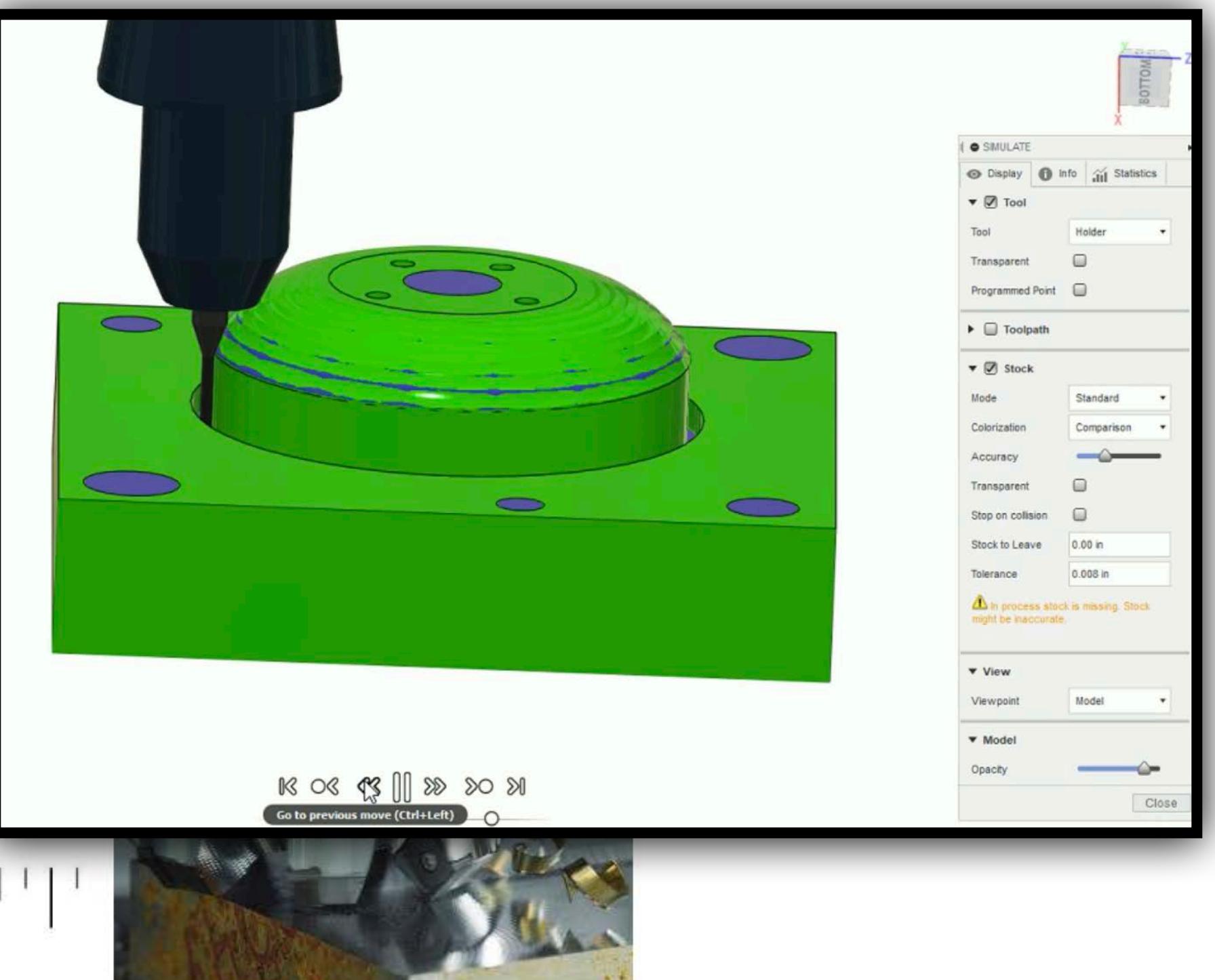
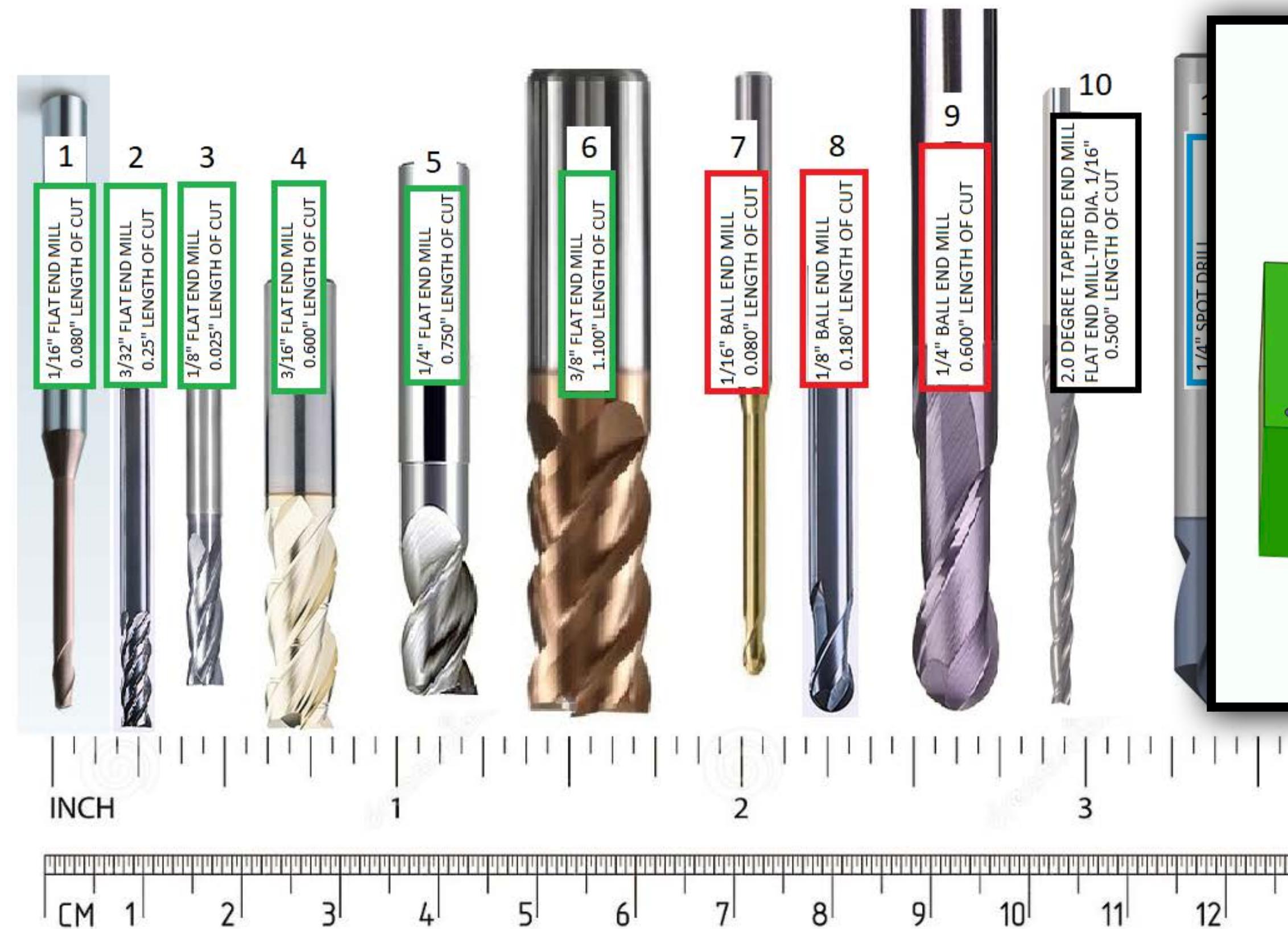
Cutting #3

Machining in Practice

33



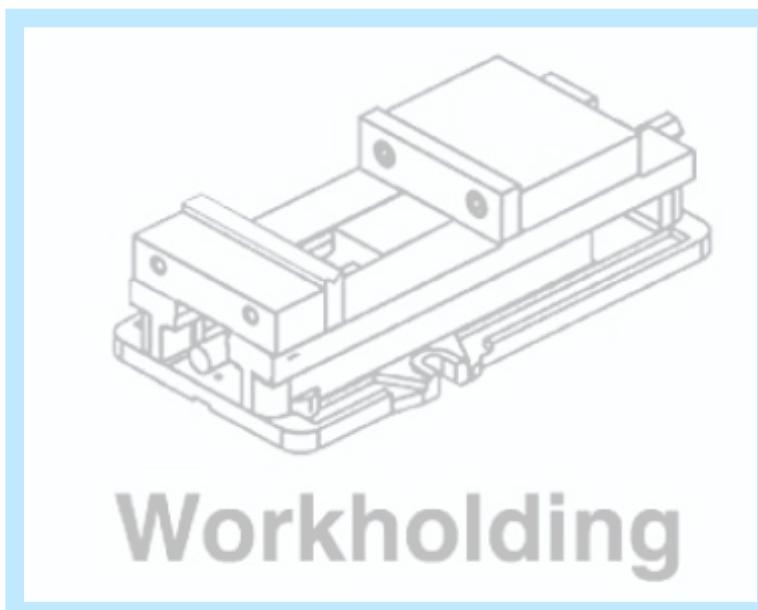
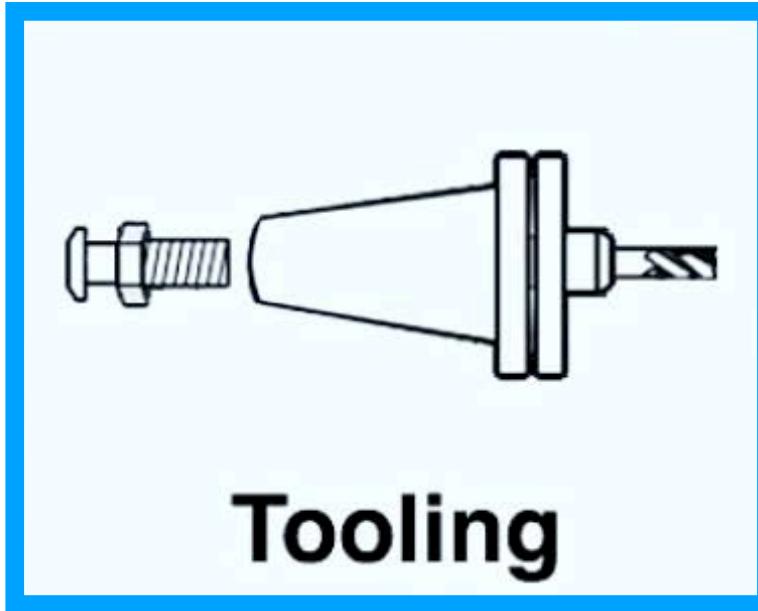
Design for Manufacturing: Machining



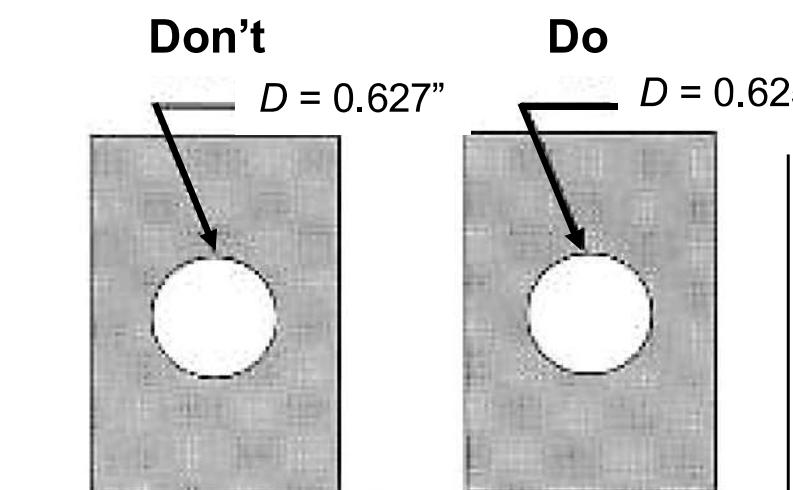
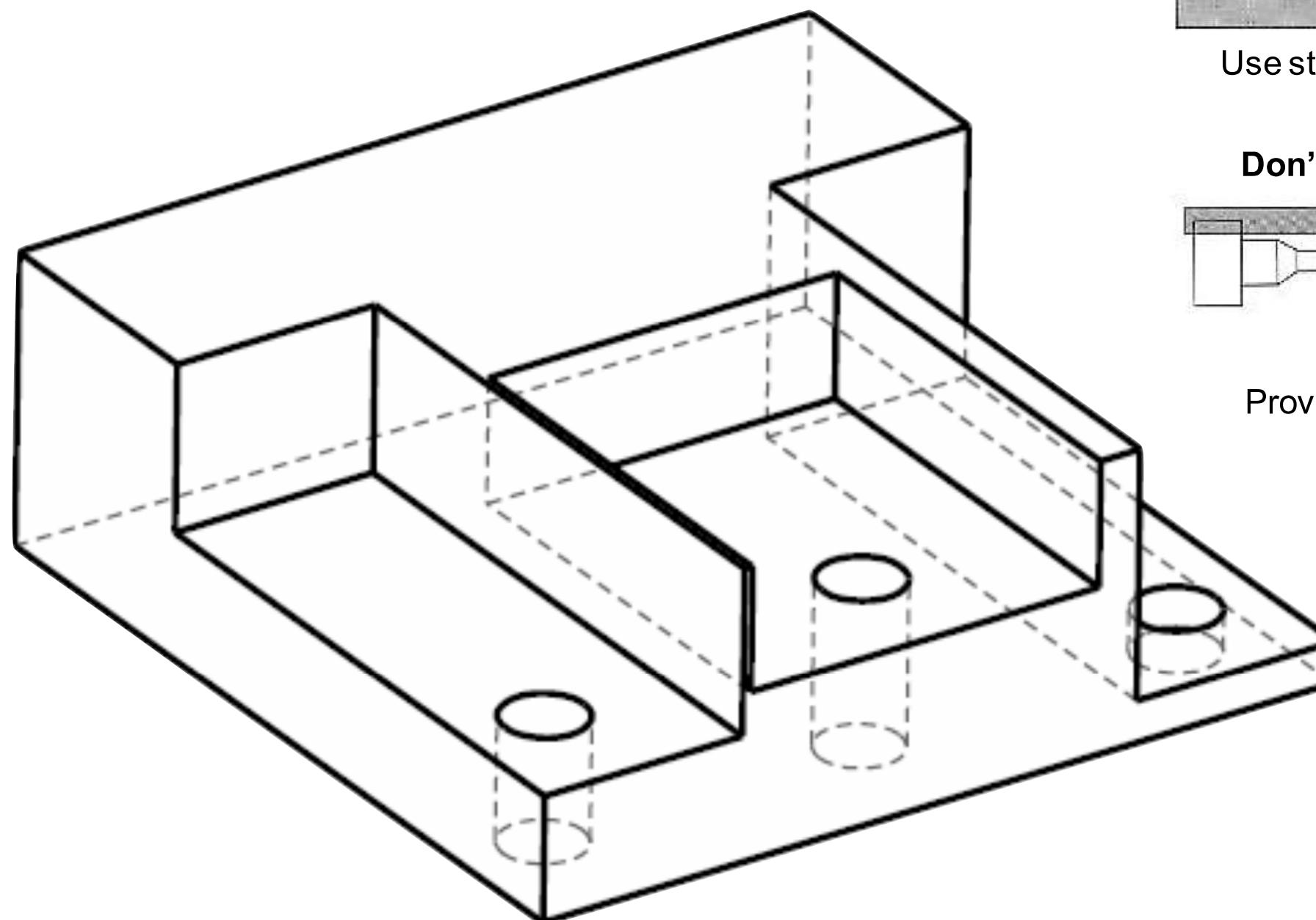
Cutting #3

Machining in Practice

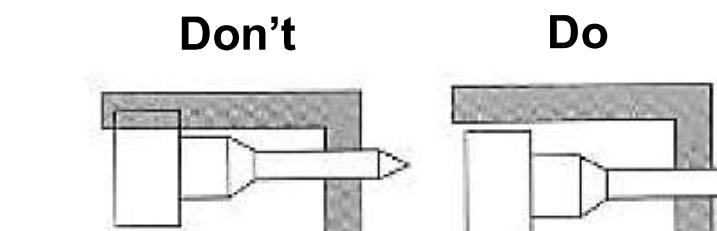
34



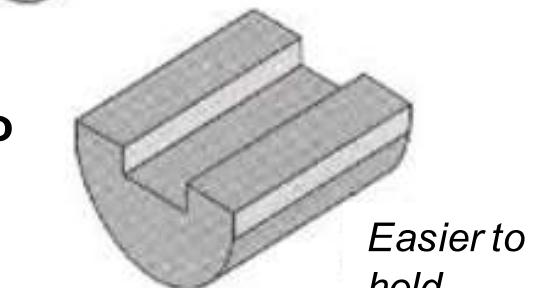
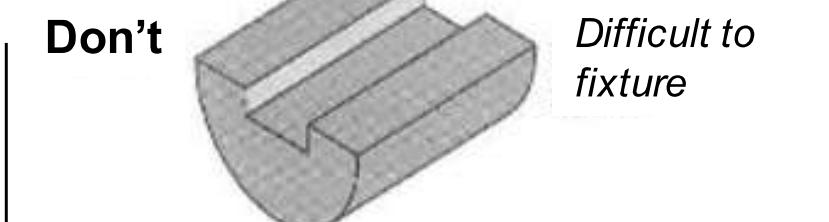
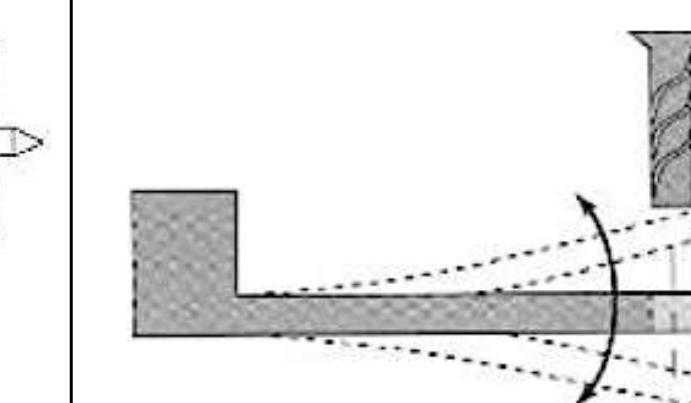
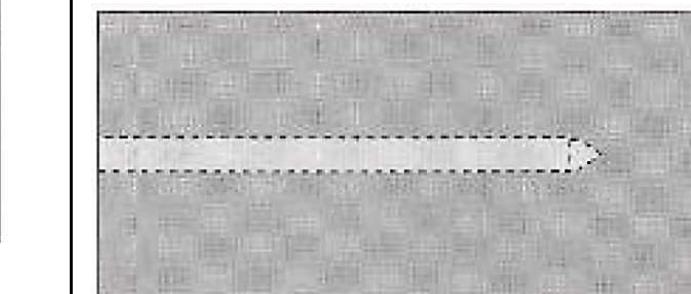
Design for Manufacturing: Machining



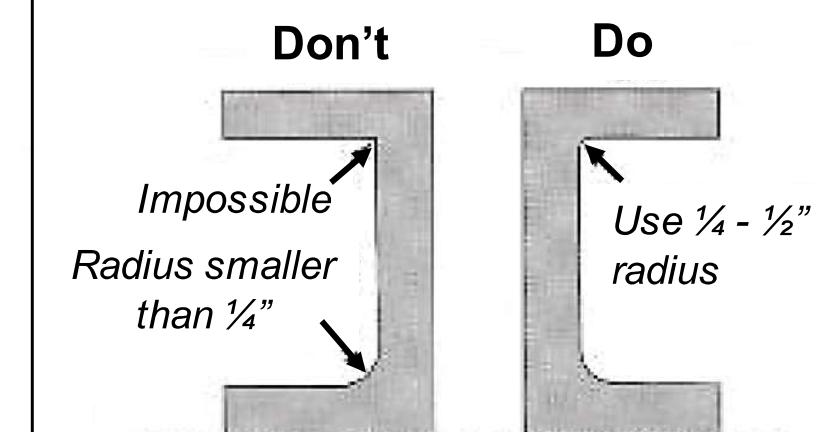
Use standard dimensions



Provide access for tools



Design parts that are easy to fixture



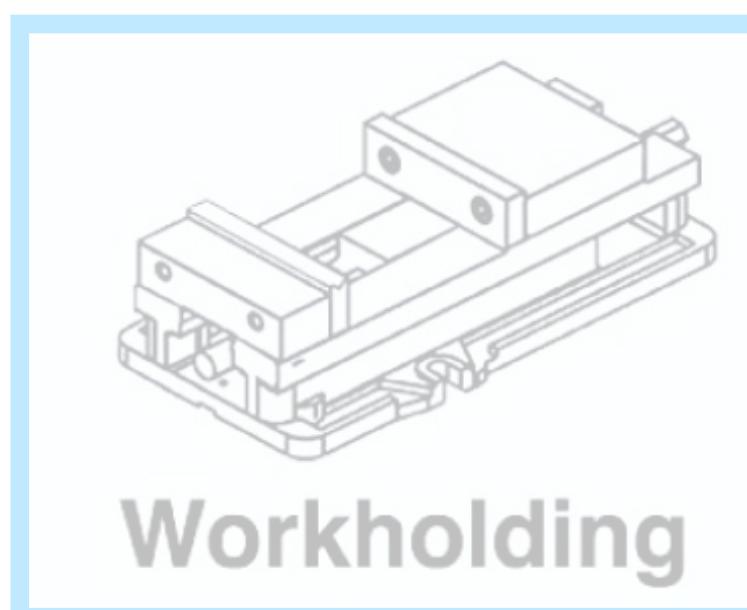
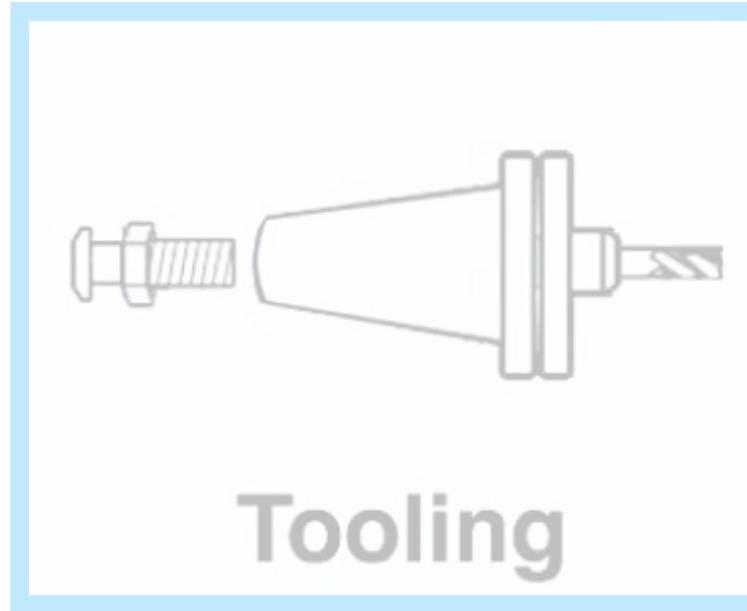
Design for reasonable internal pockets radii

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

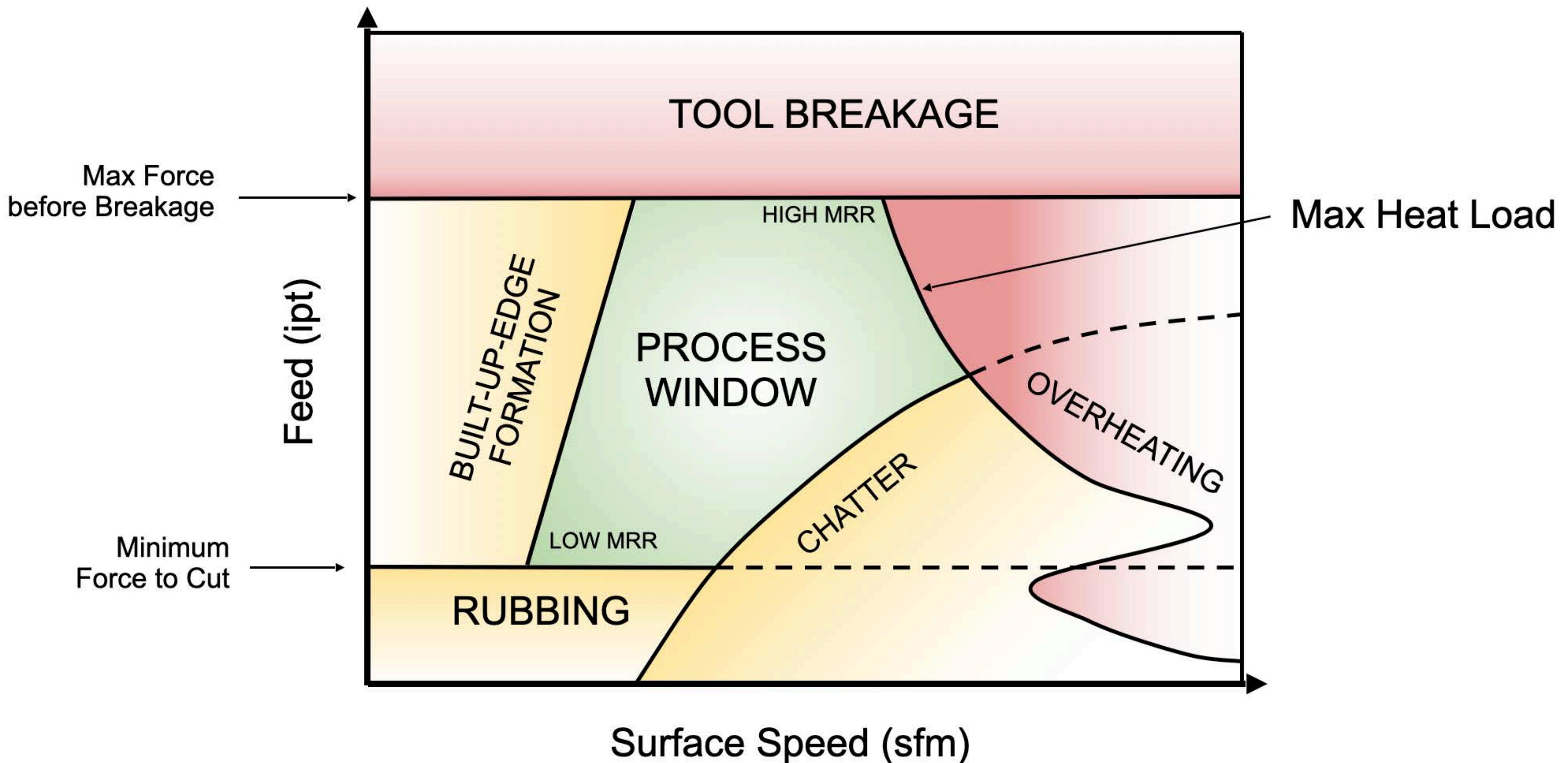
Cutting #3

Machining in Practice

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Design for Manufacturing: Machining

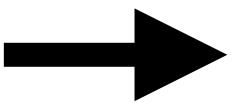
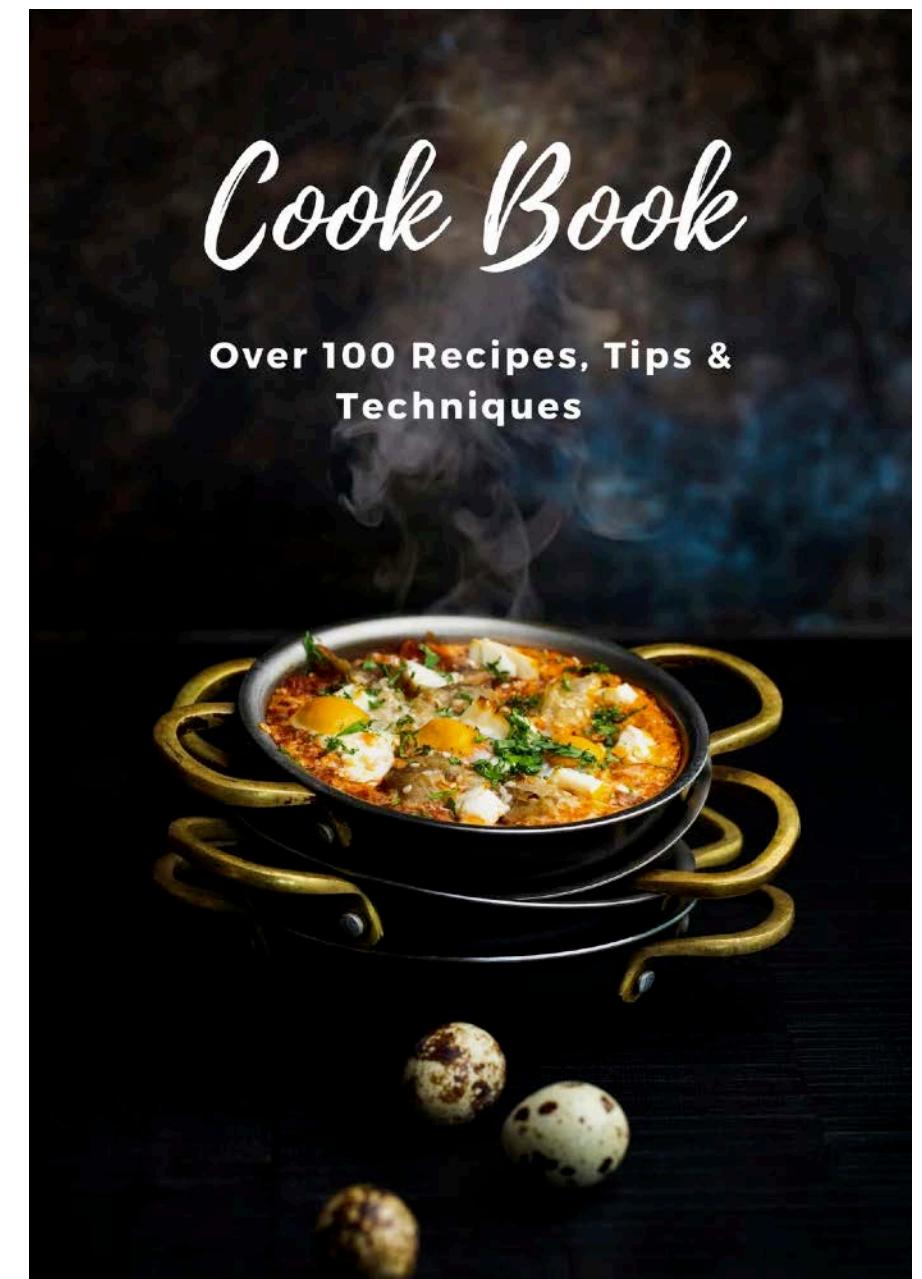
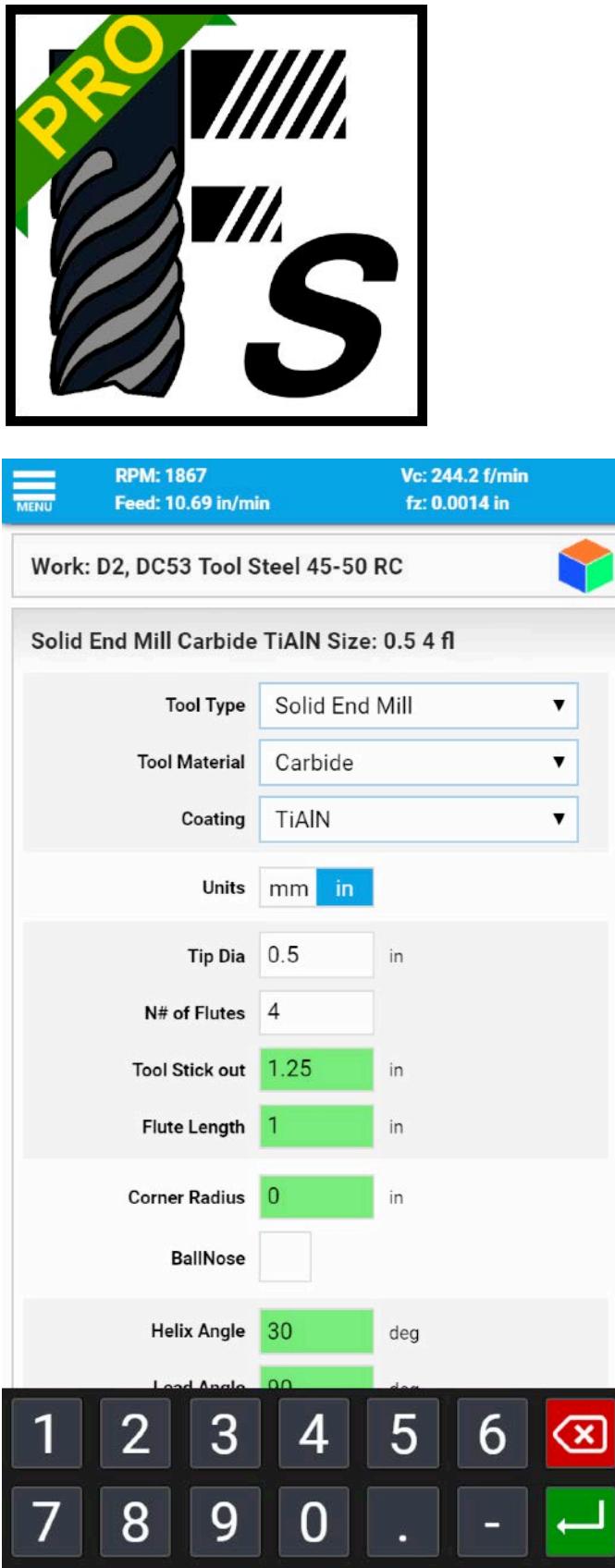
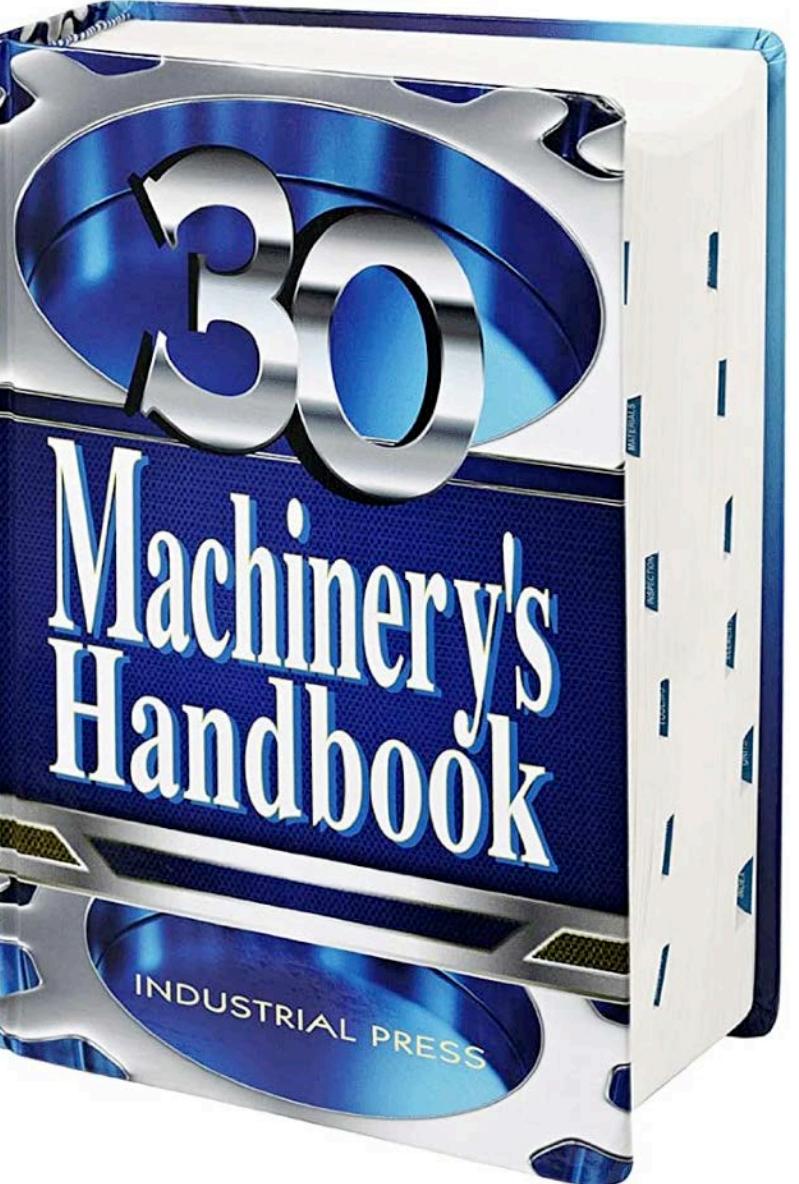
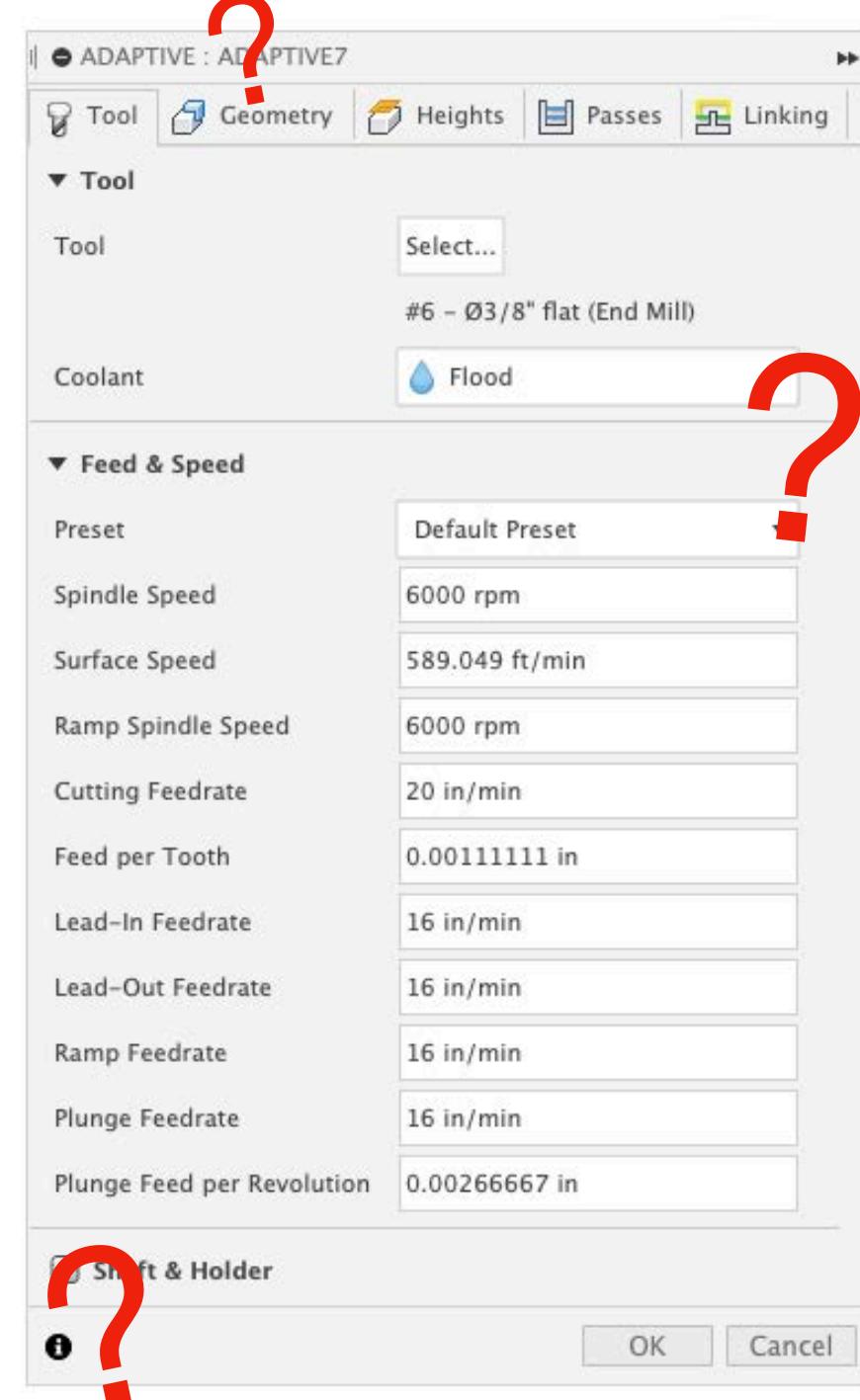


Cutting #3

Machining in Practice

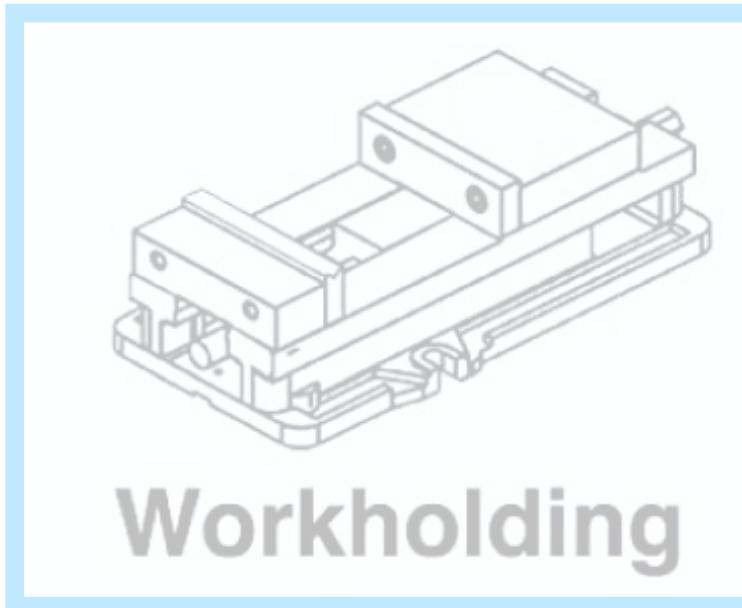
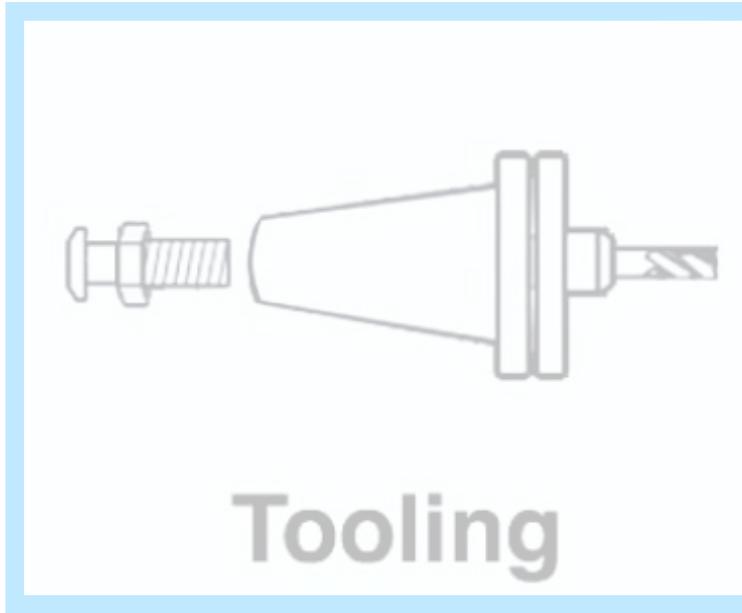
Feed and Speeds

where do you start?



Cutting #3

Machining in Practice



Design for Manufacturing: Machining

Roughing of steel
CMC 02.1

P R



Cutting depth,
 a_p mm (inch)

CNMM 120412-PR
(CNMM 432-PR)

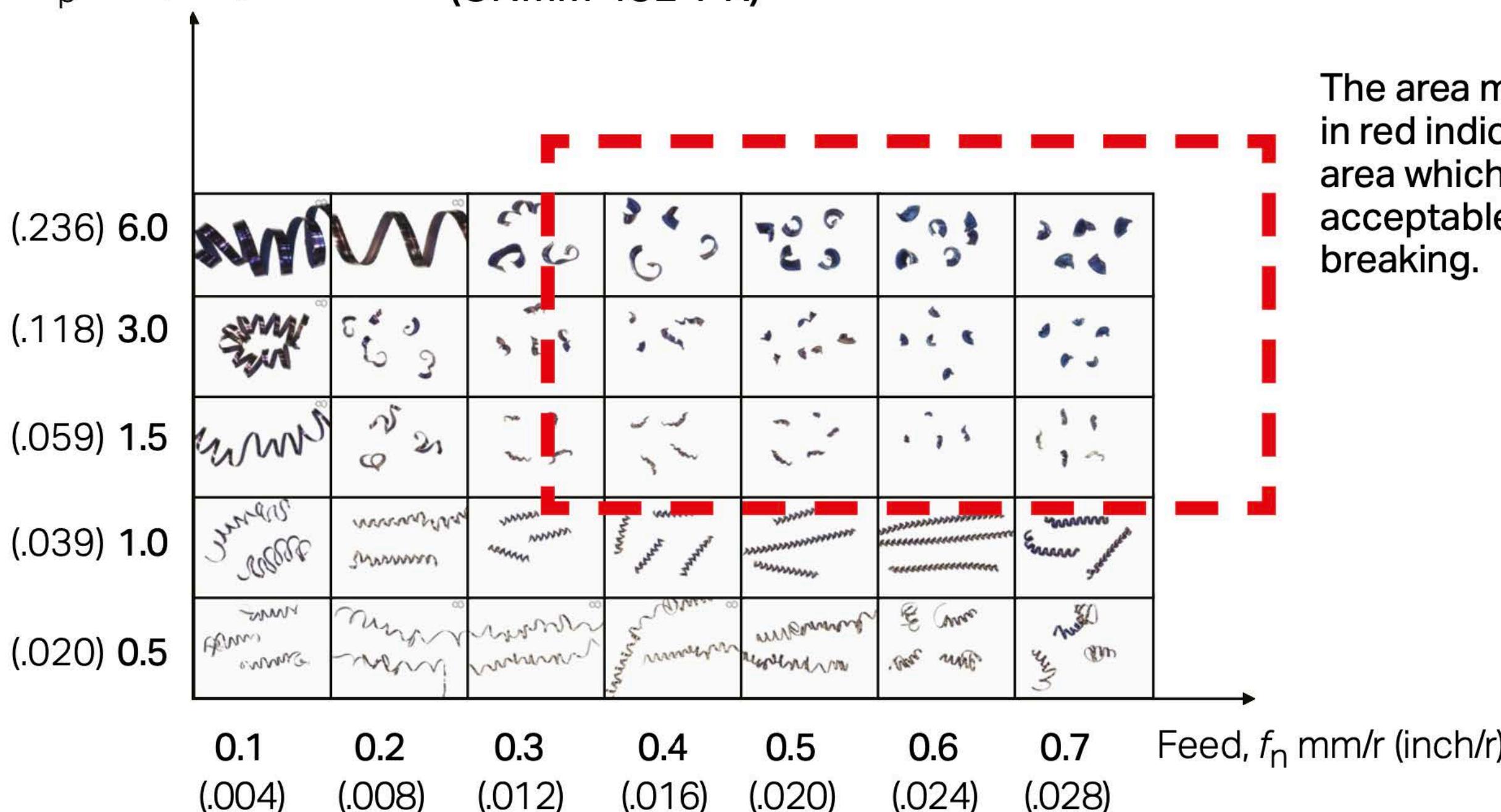
Chip breaking area:

$$a_p = 5.0 \text{ (1.0 - 7.5)} \text{ mm}$$

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

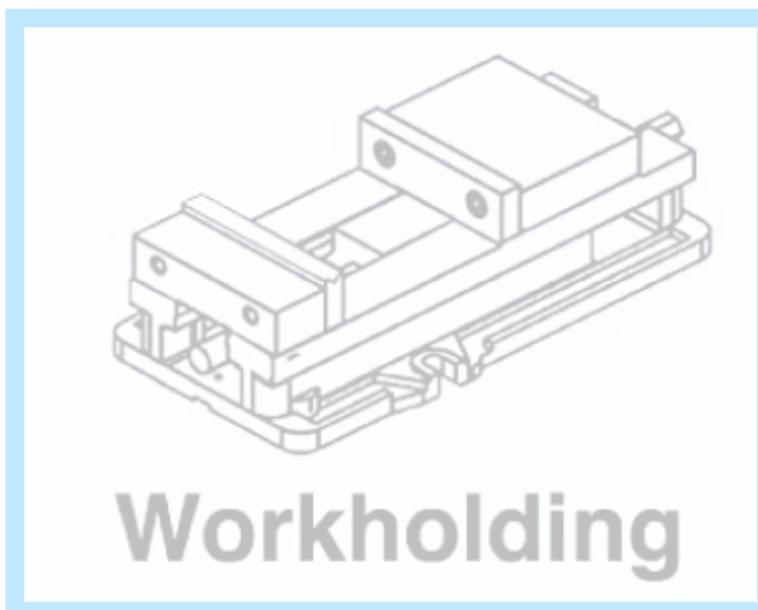
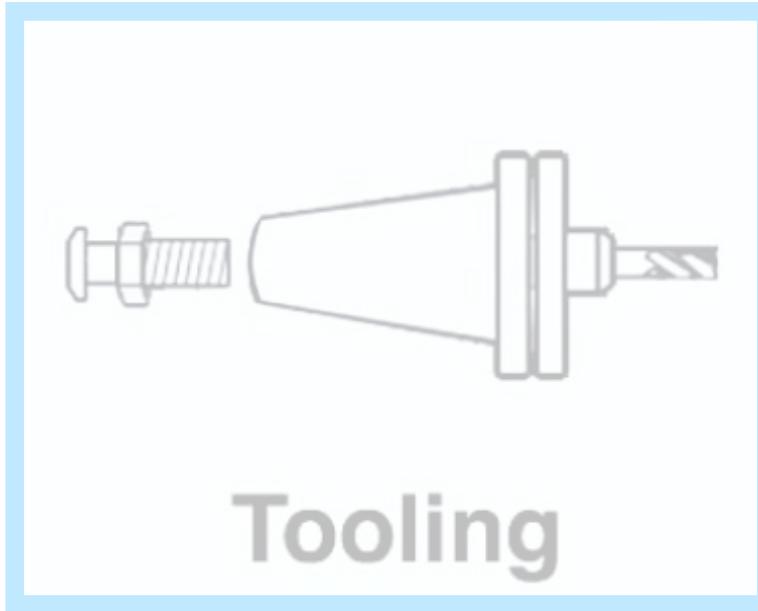
$$a_p = .197 \text{ (.039 - .295)} \text{ inch}$$

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

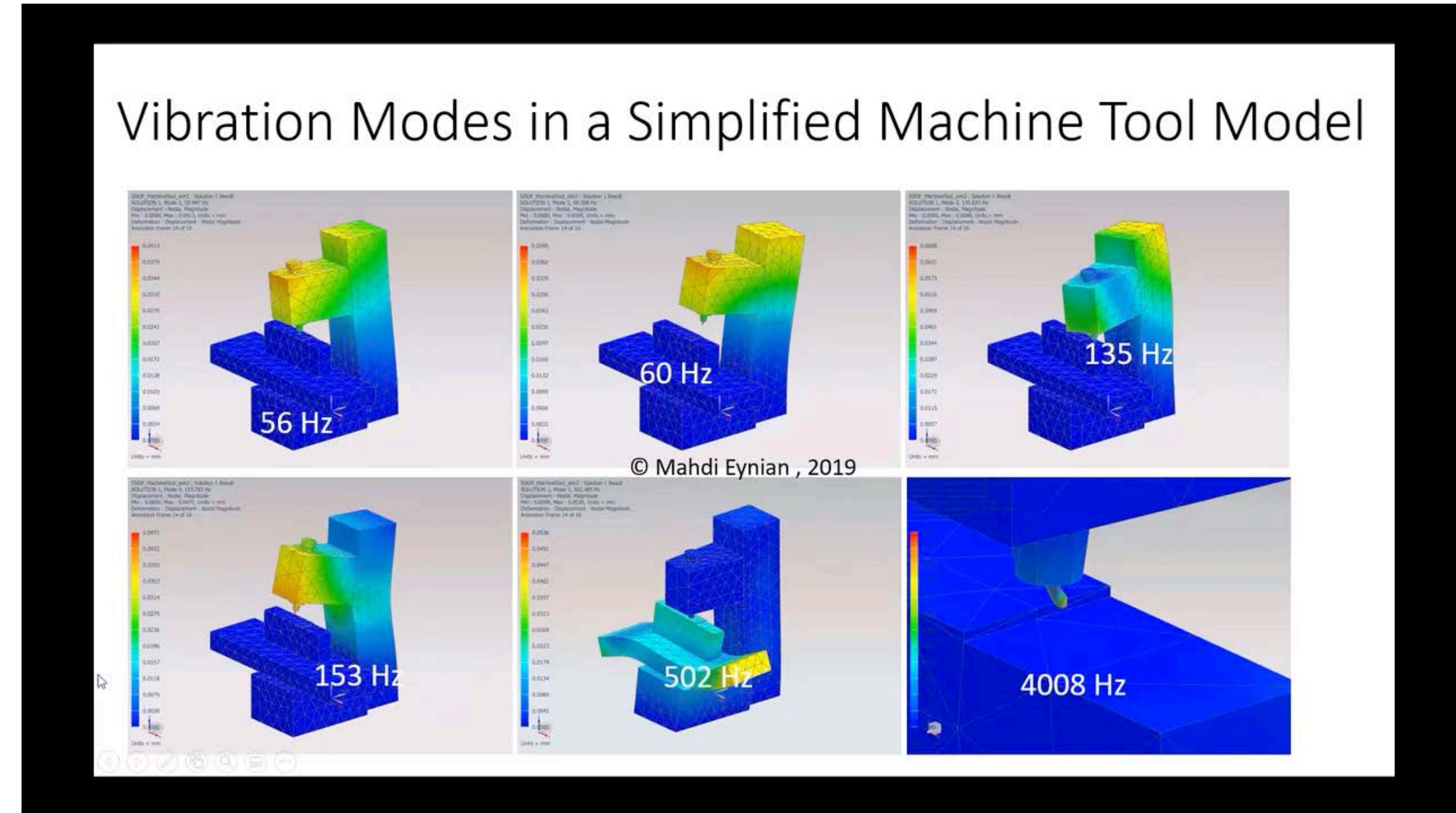


Cutting #3

Machining in Practice

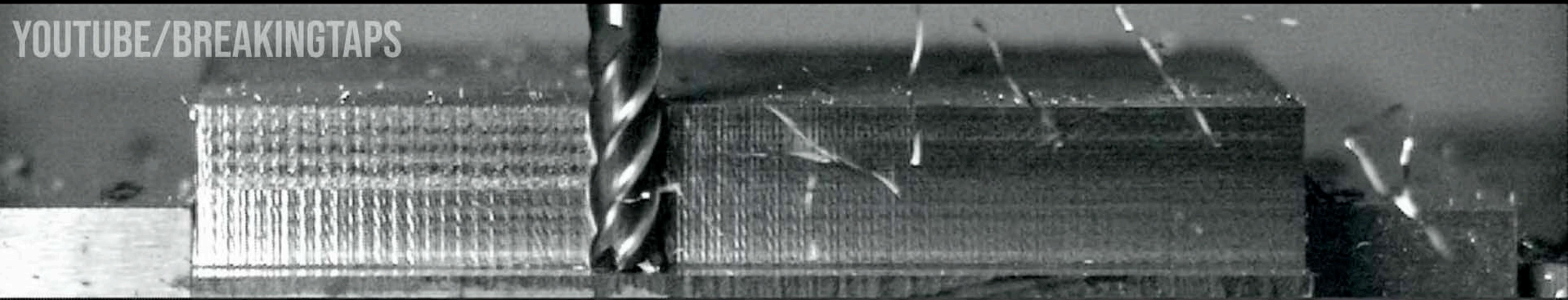


Vibration and Chatter



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

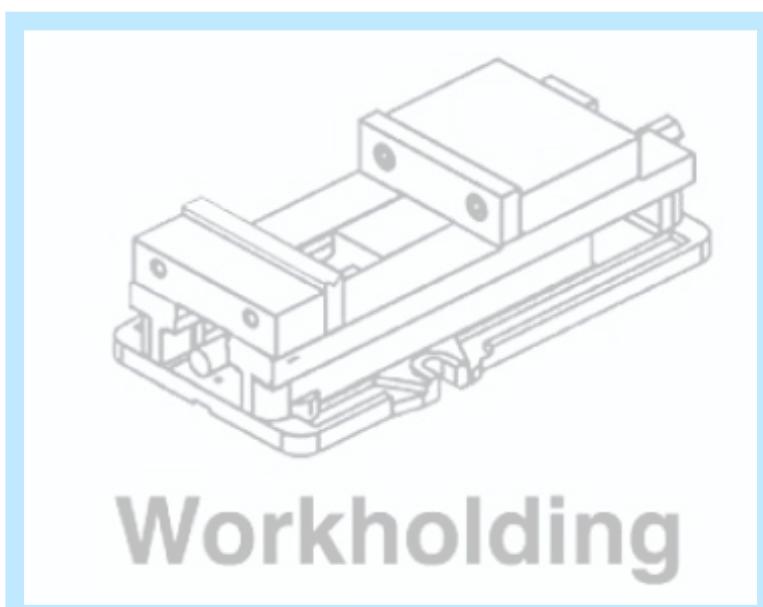
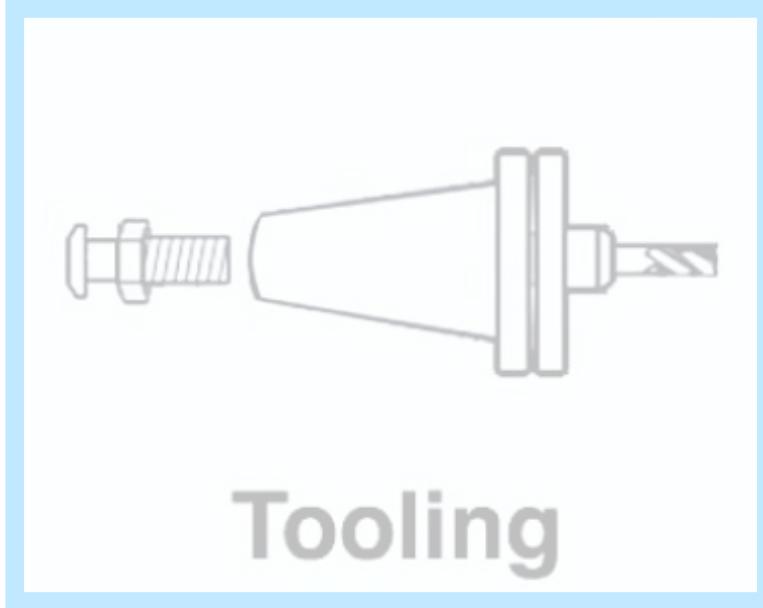
YOUTUBE/BREAKINGTAPS



Cutting #3

Machining in Practice

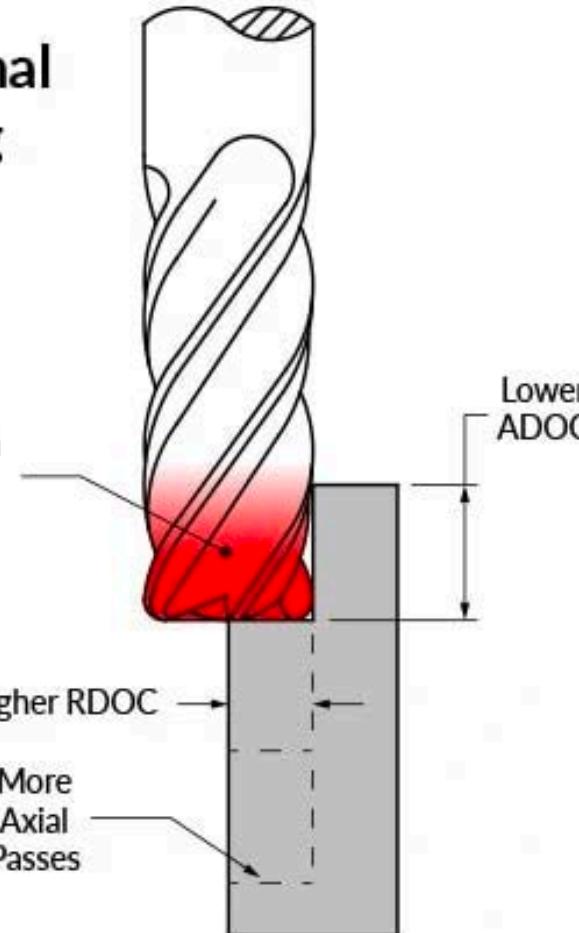
40



Adaptive Toolpaths

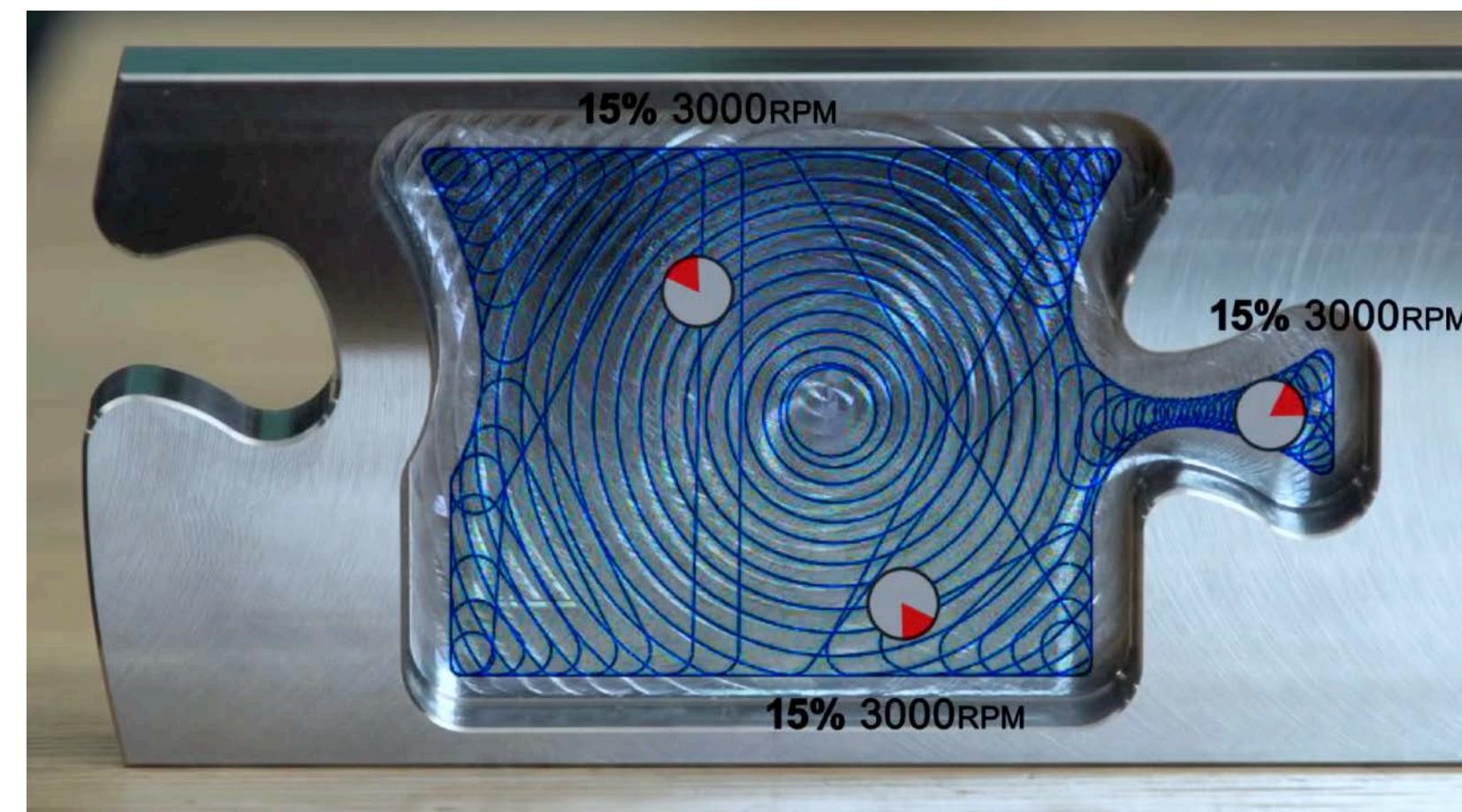
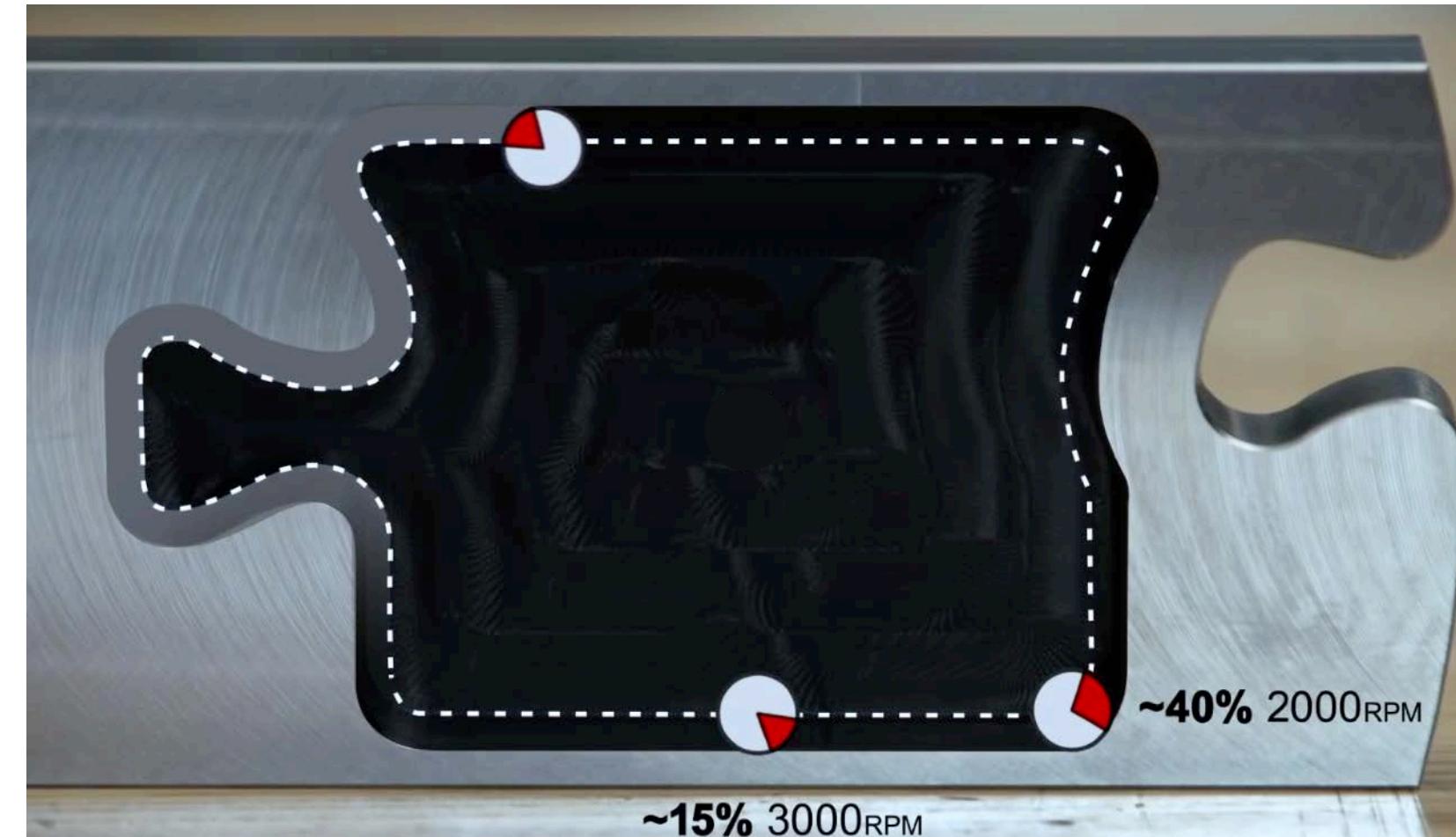
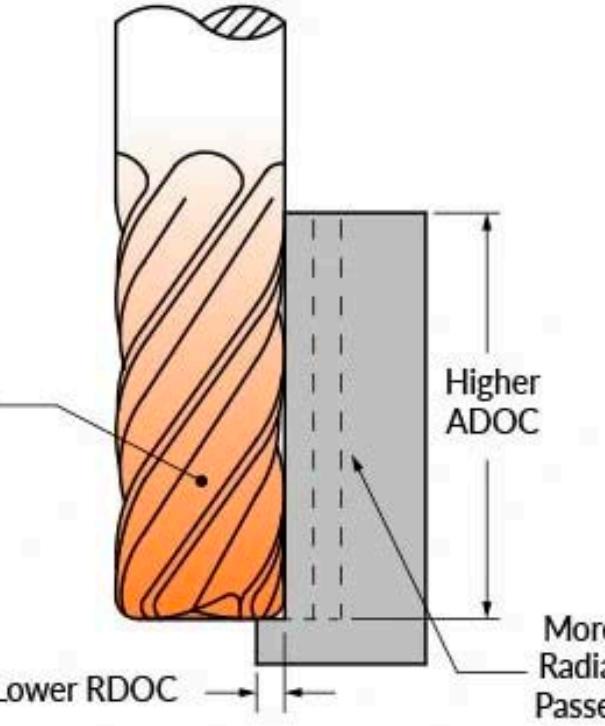
Traditional Milling

Work (and heat) is concentrated along a smaller portion of the cutting edge



High Efficiency Milling

Work (and heat) is spread over entire cutting edge

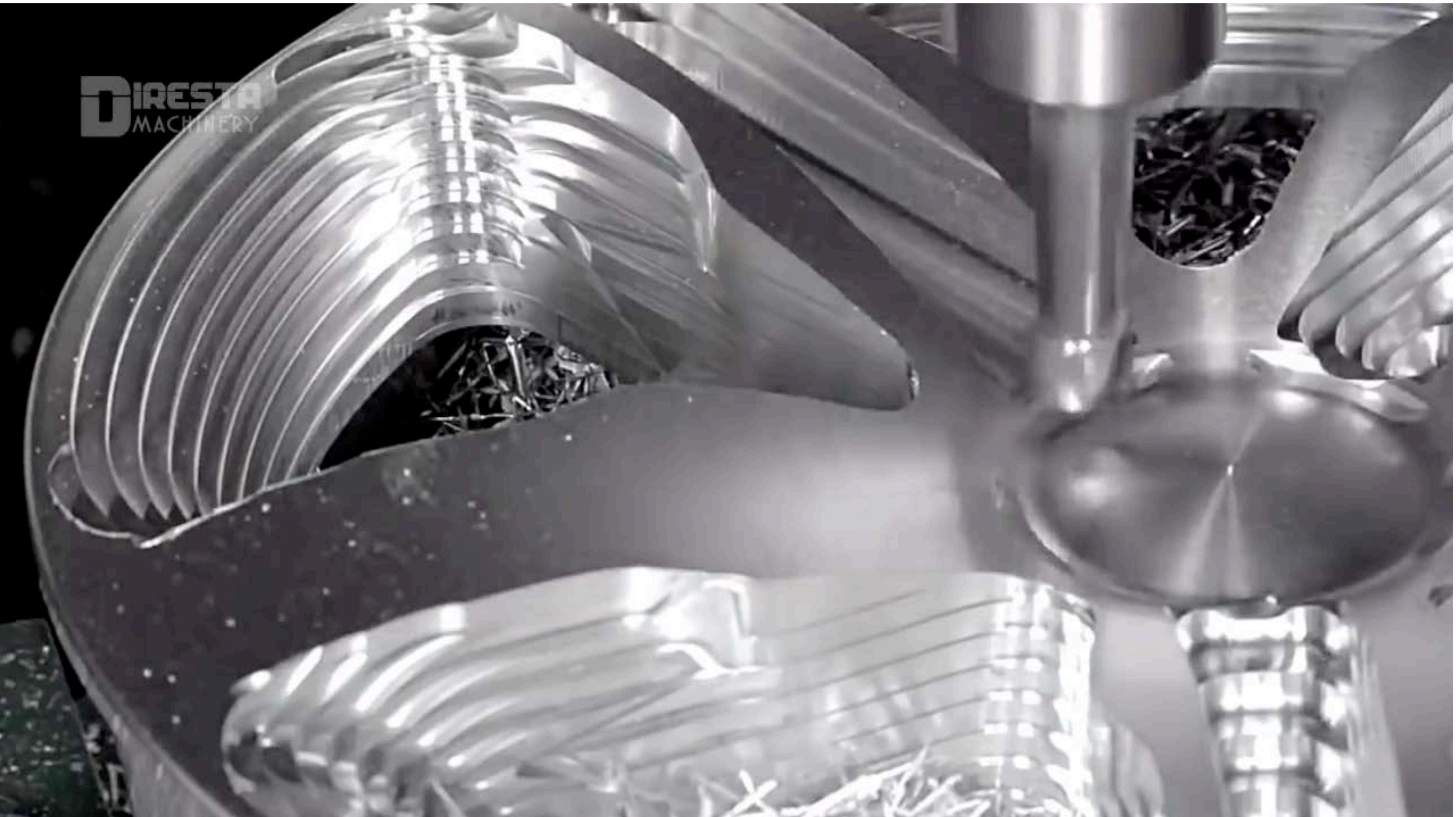
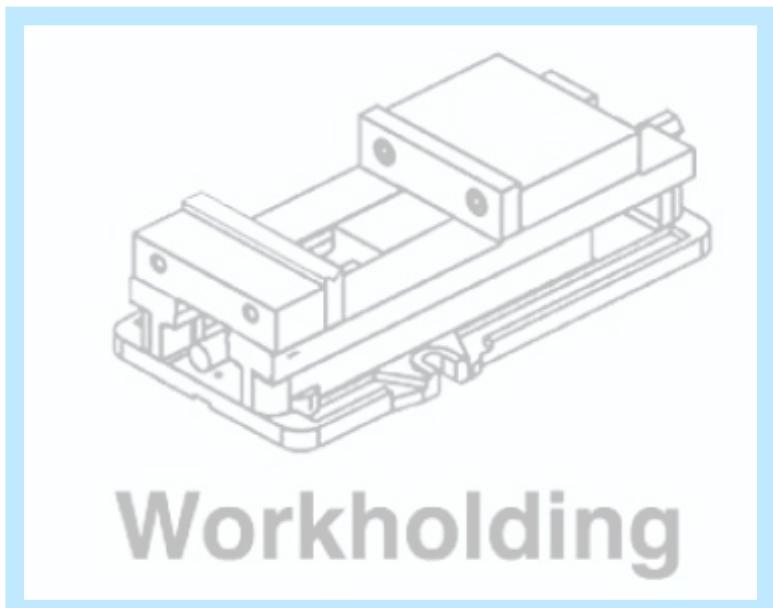
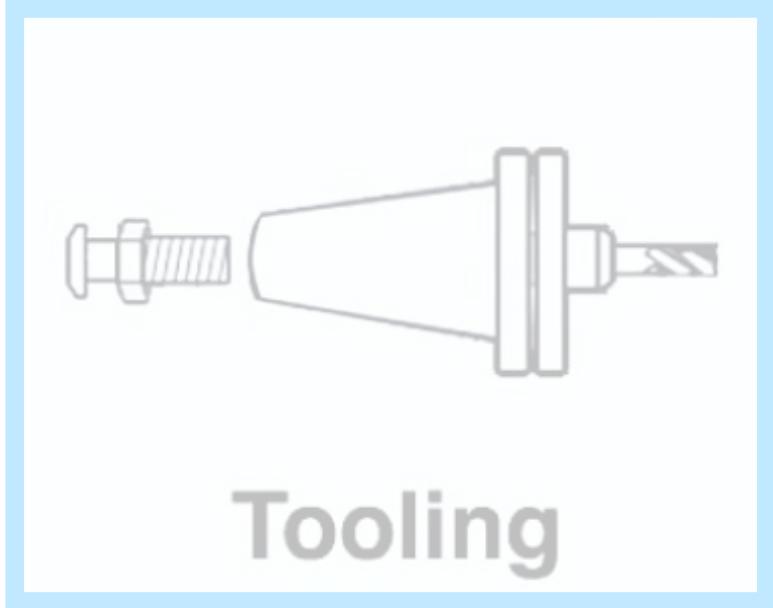


simple program and machine

needs fast computers and machines

Cutting #3

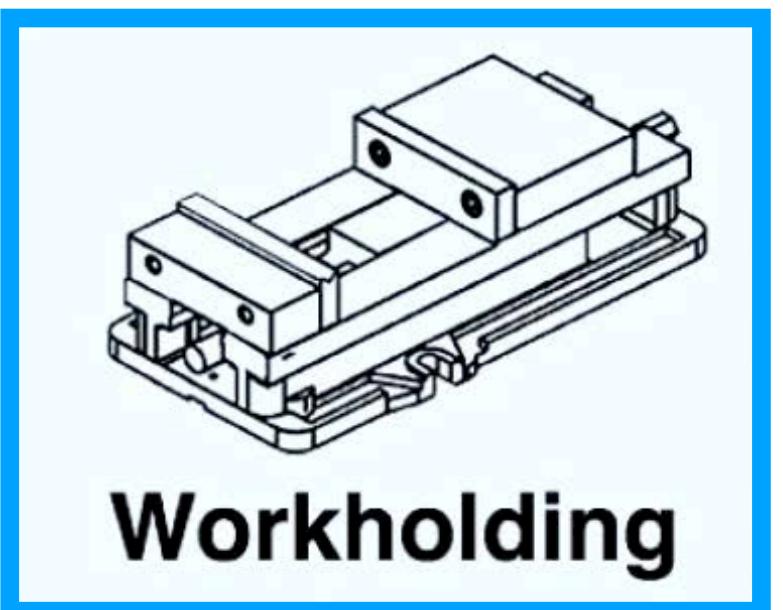
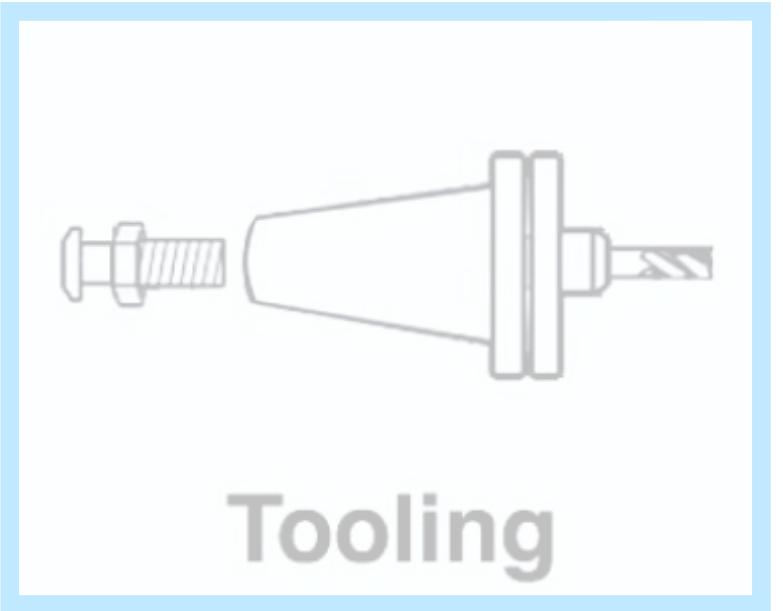
Machining in Practice



Cutting #3

Machining in Practice

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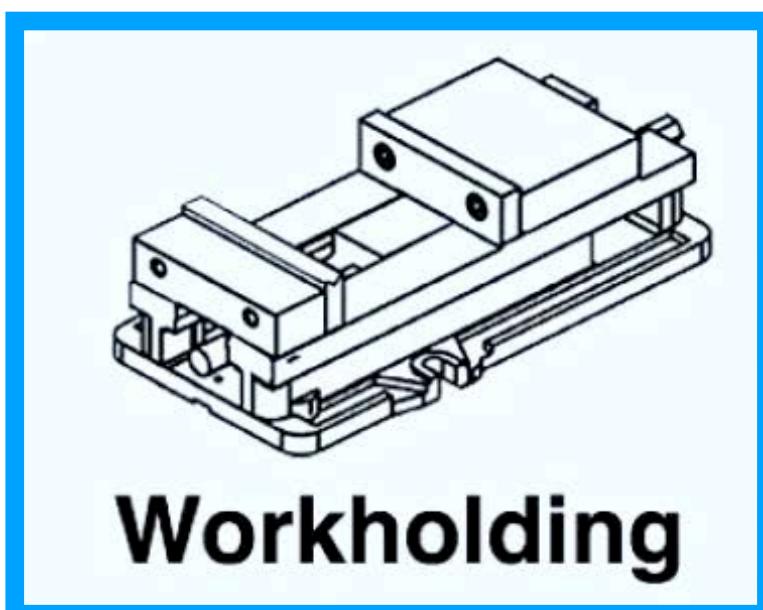
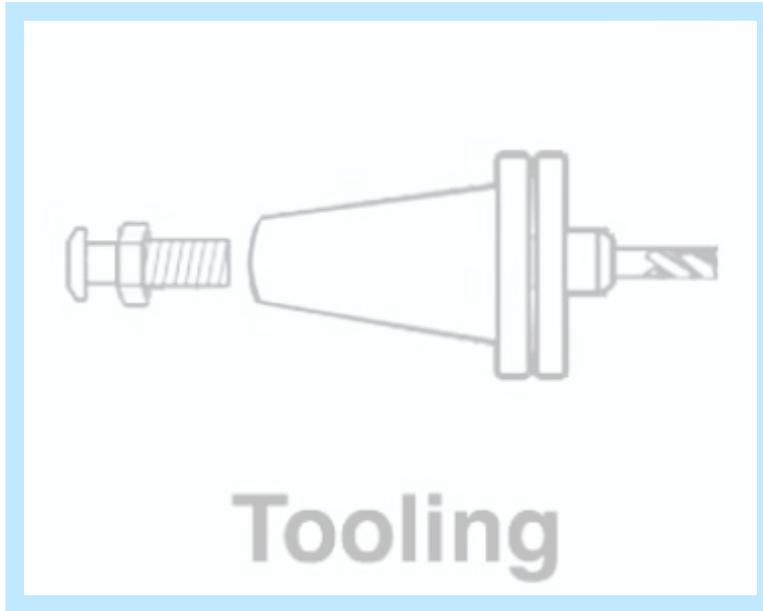
Stiffness Returns!



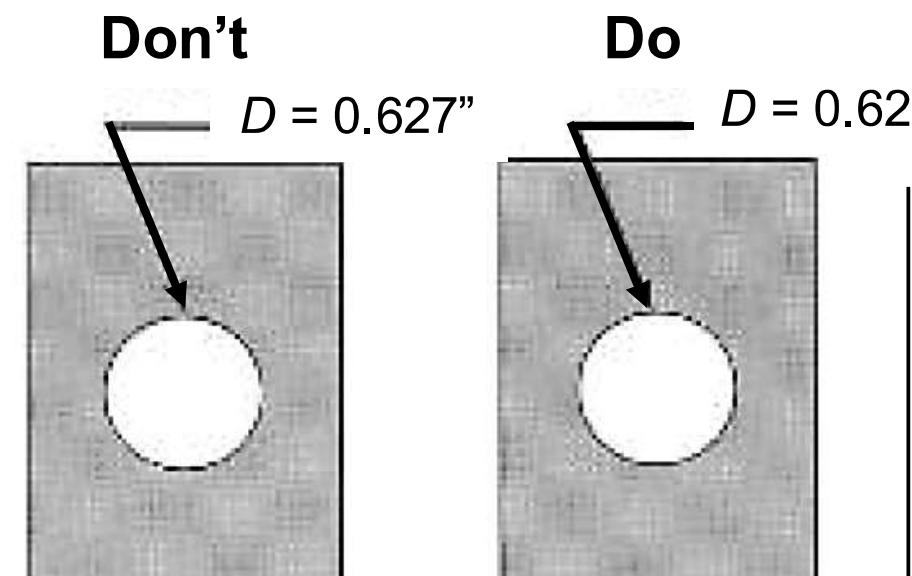
Cutting #3

Machining in Practice

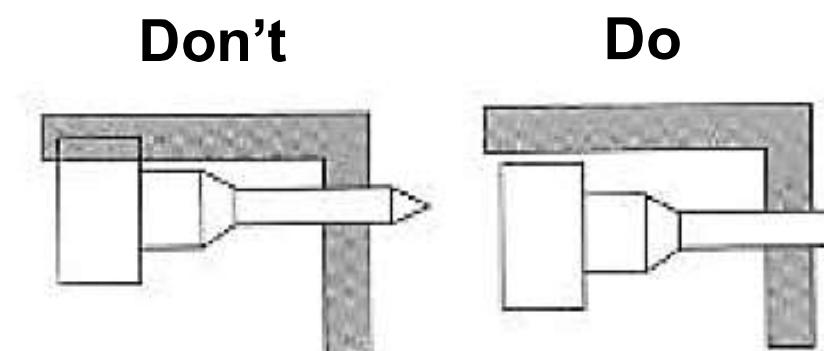
43



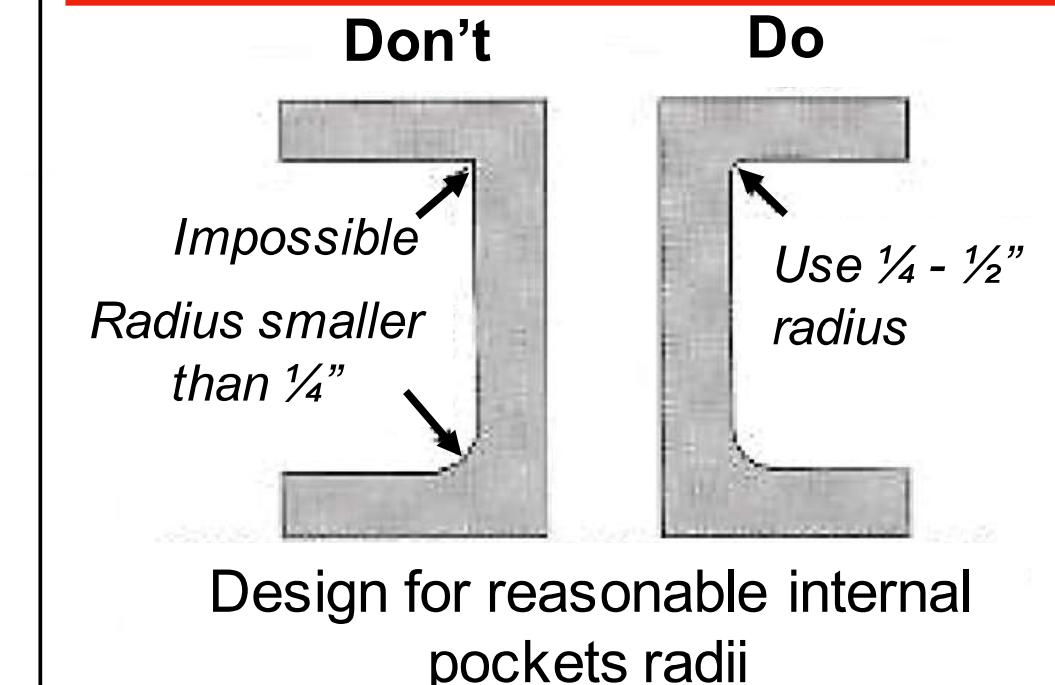
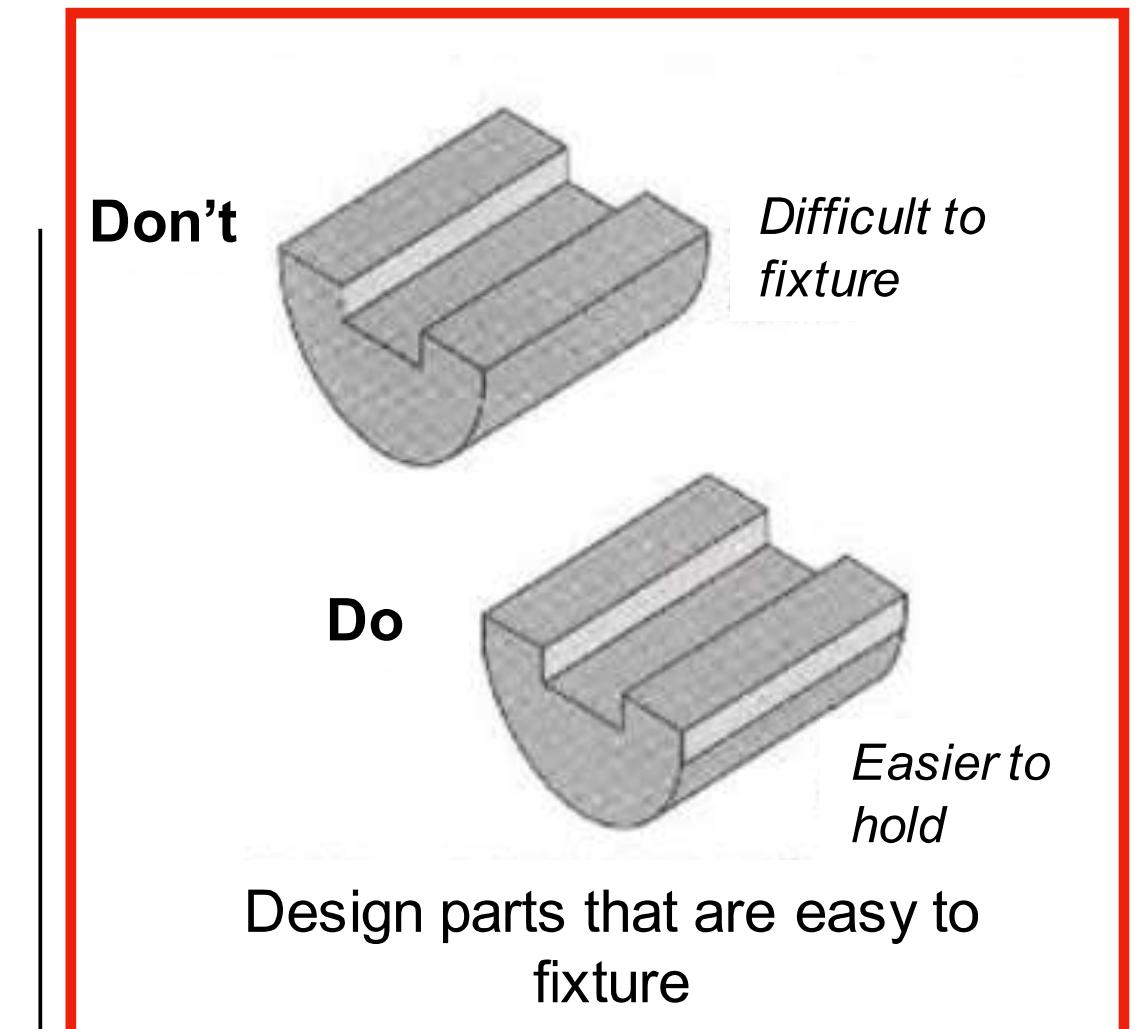
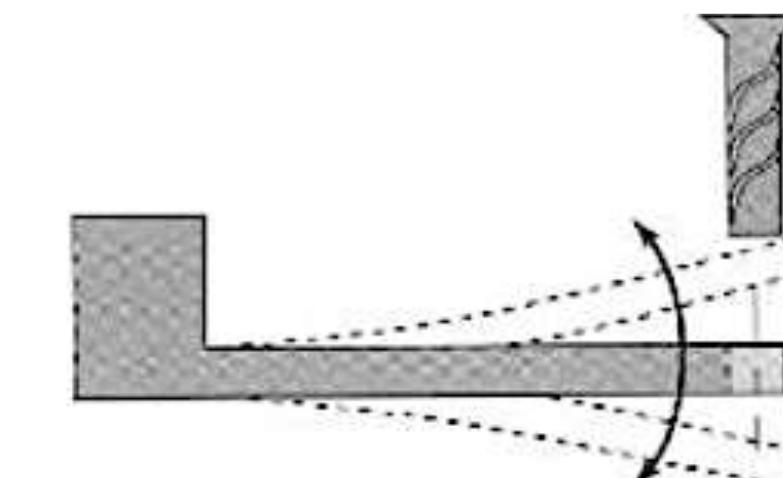
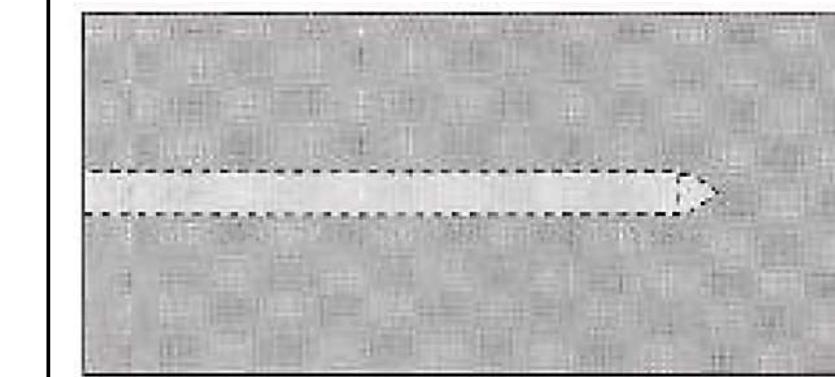
Strategies



Use standard dimensions



Provide access for tools

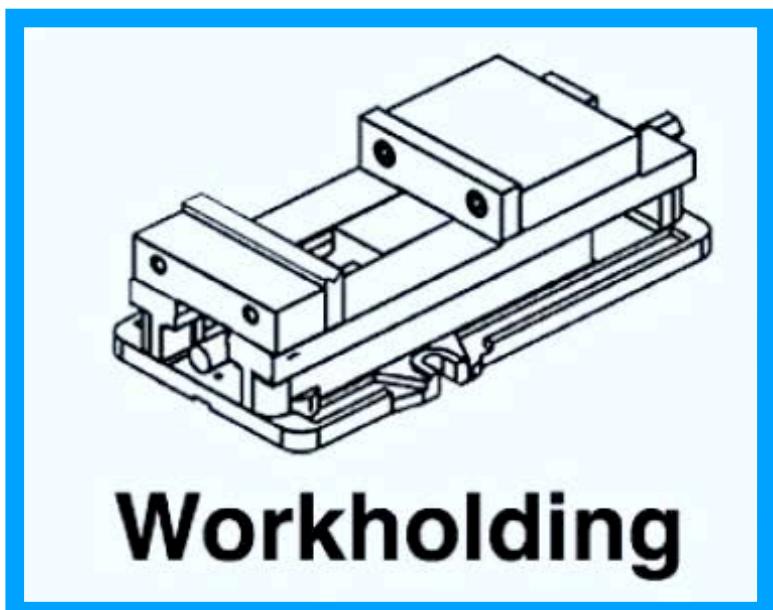
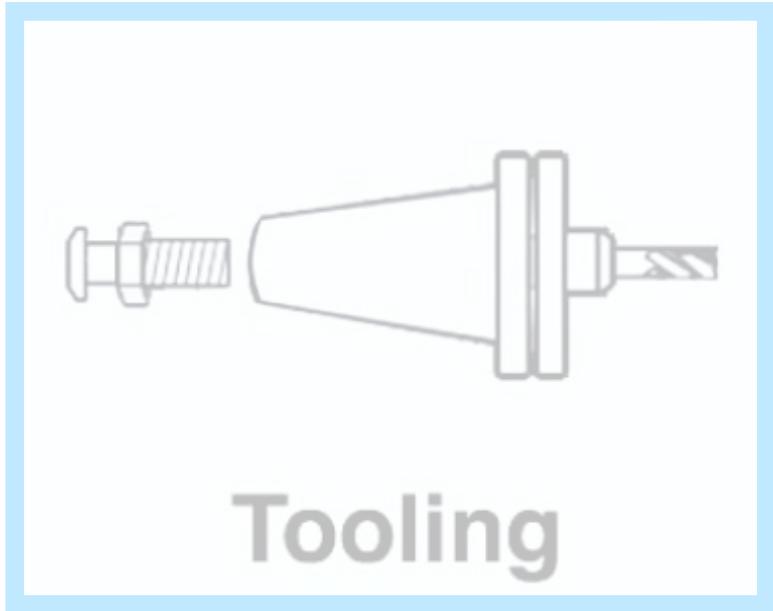


From Otto and Wood, *Product Design: Techniques in Reverse Engineering and New Product Development*

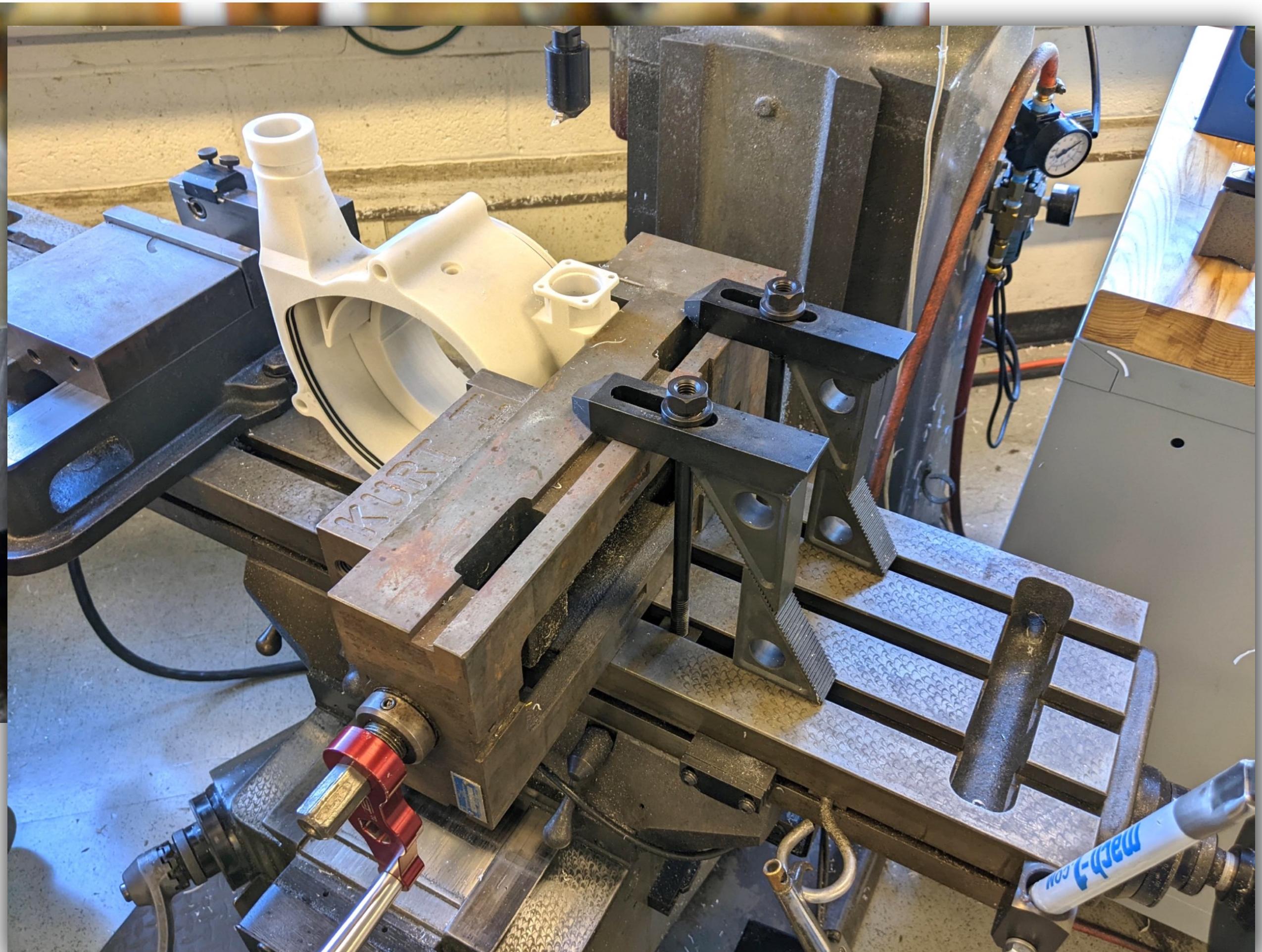
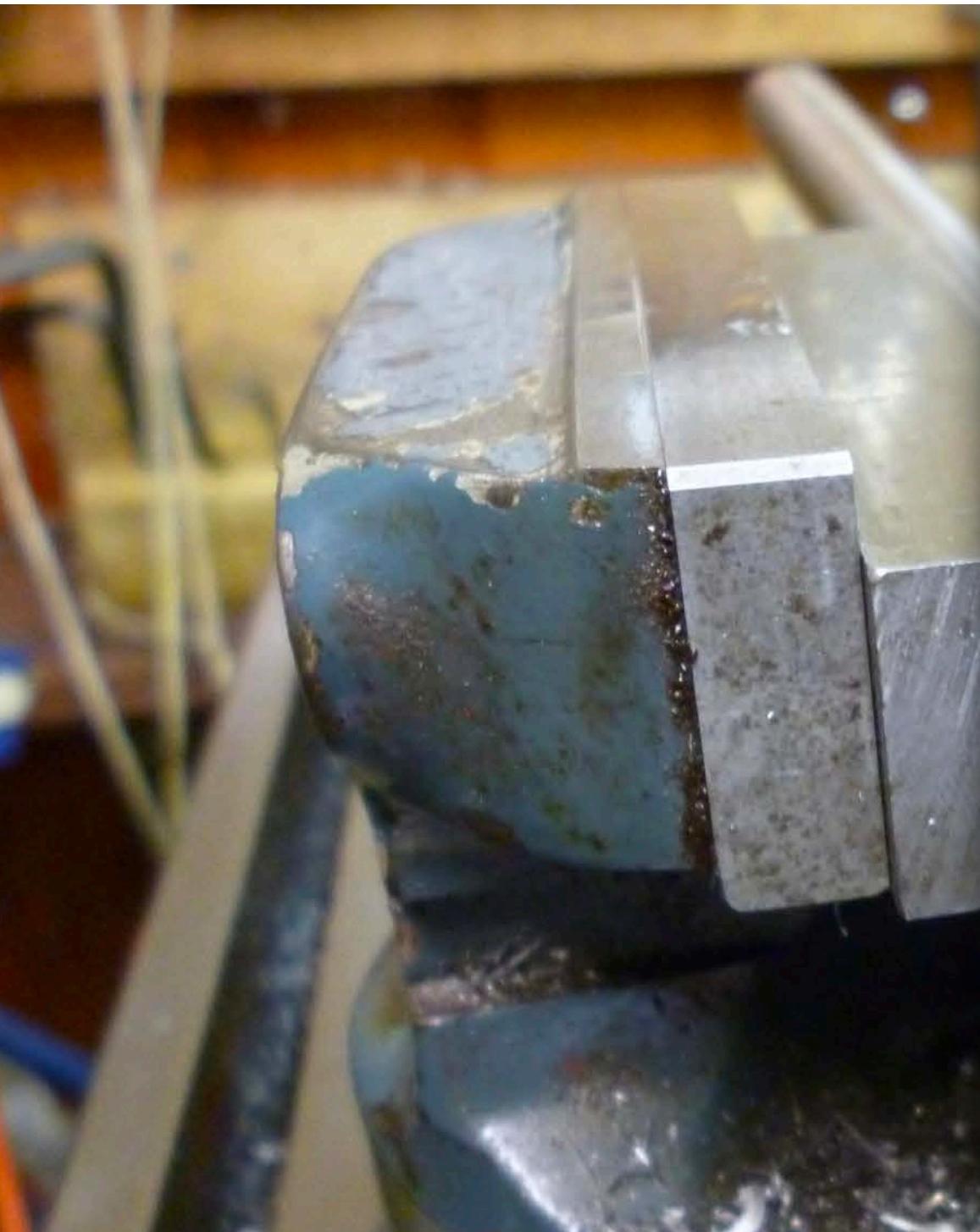
Cutting #3

Machining in Practice

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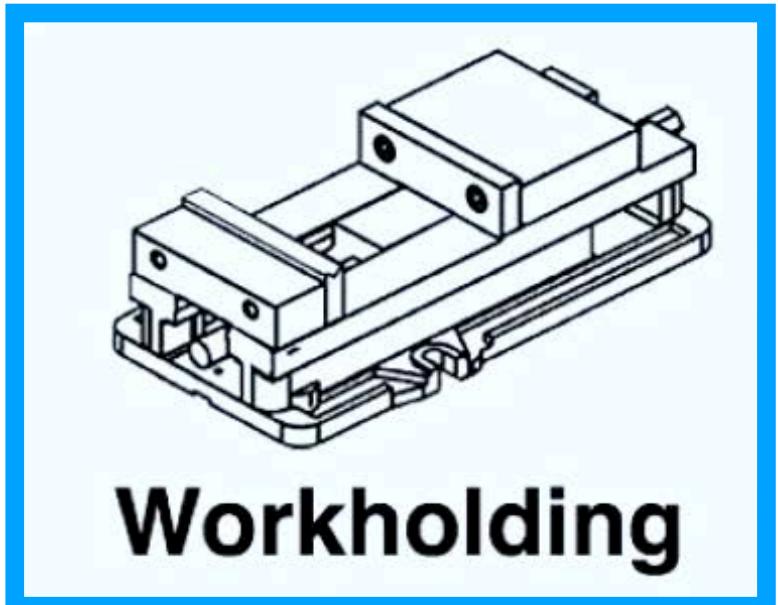
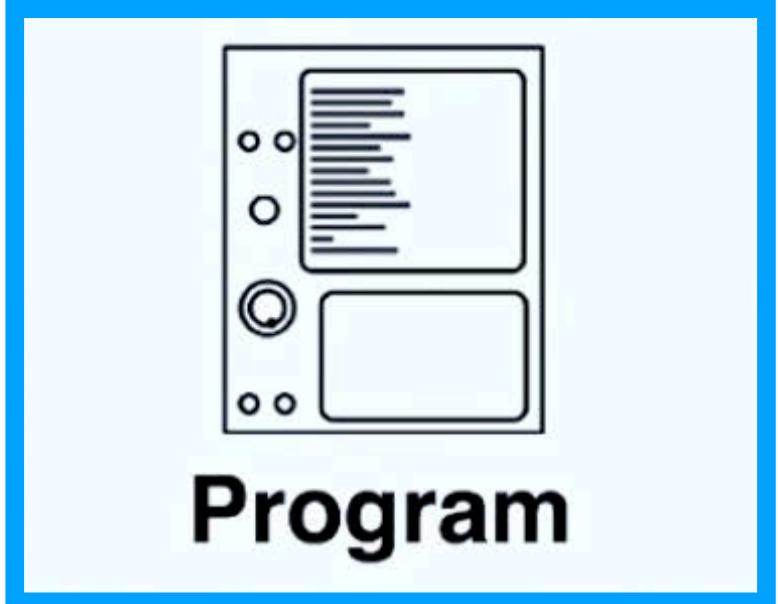
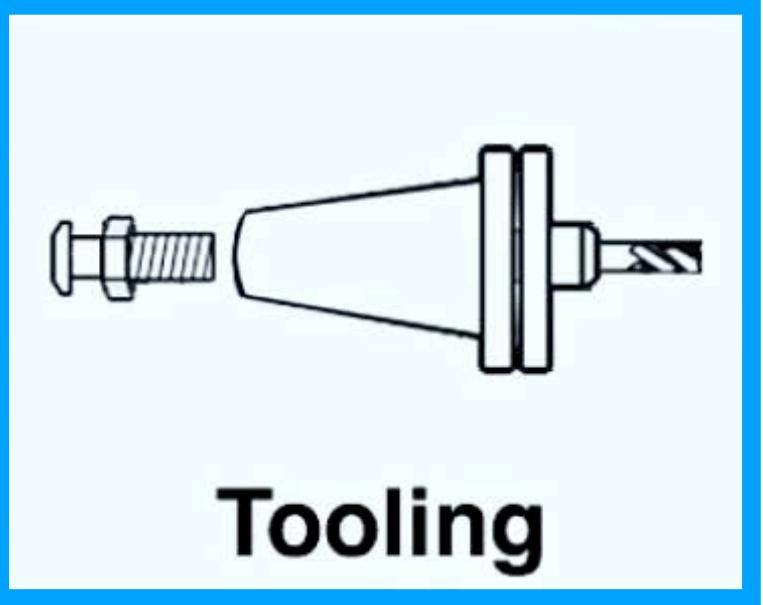


Strategies



Cutting #3

Machining in Practice



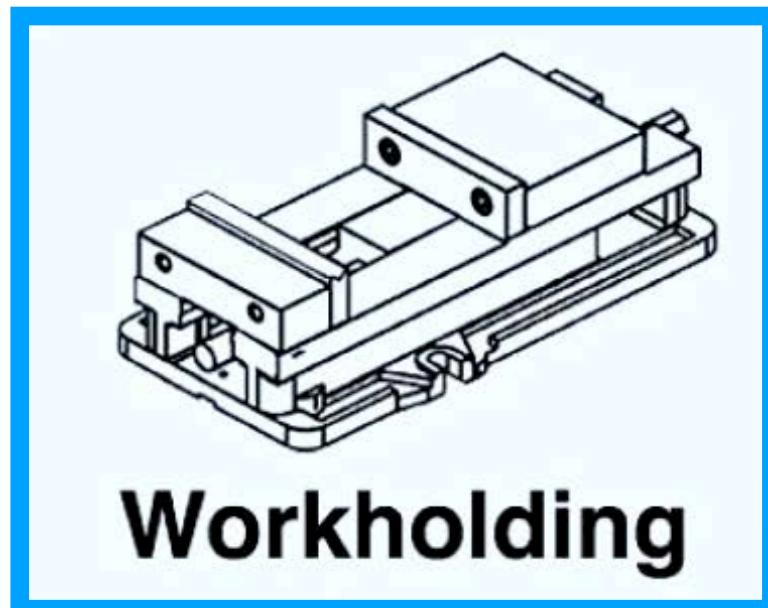
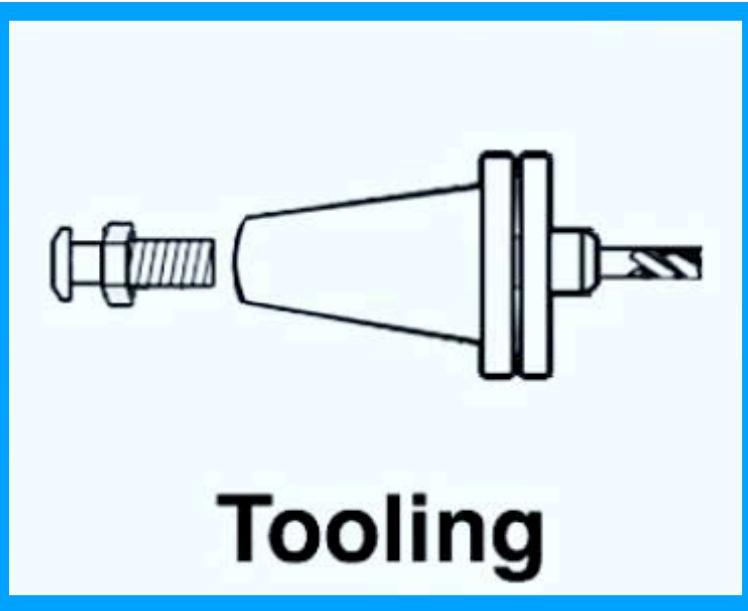
Surface Finish



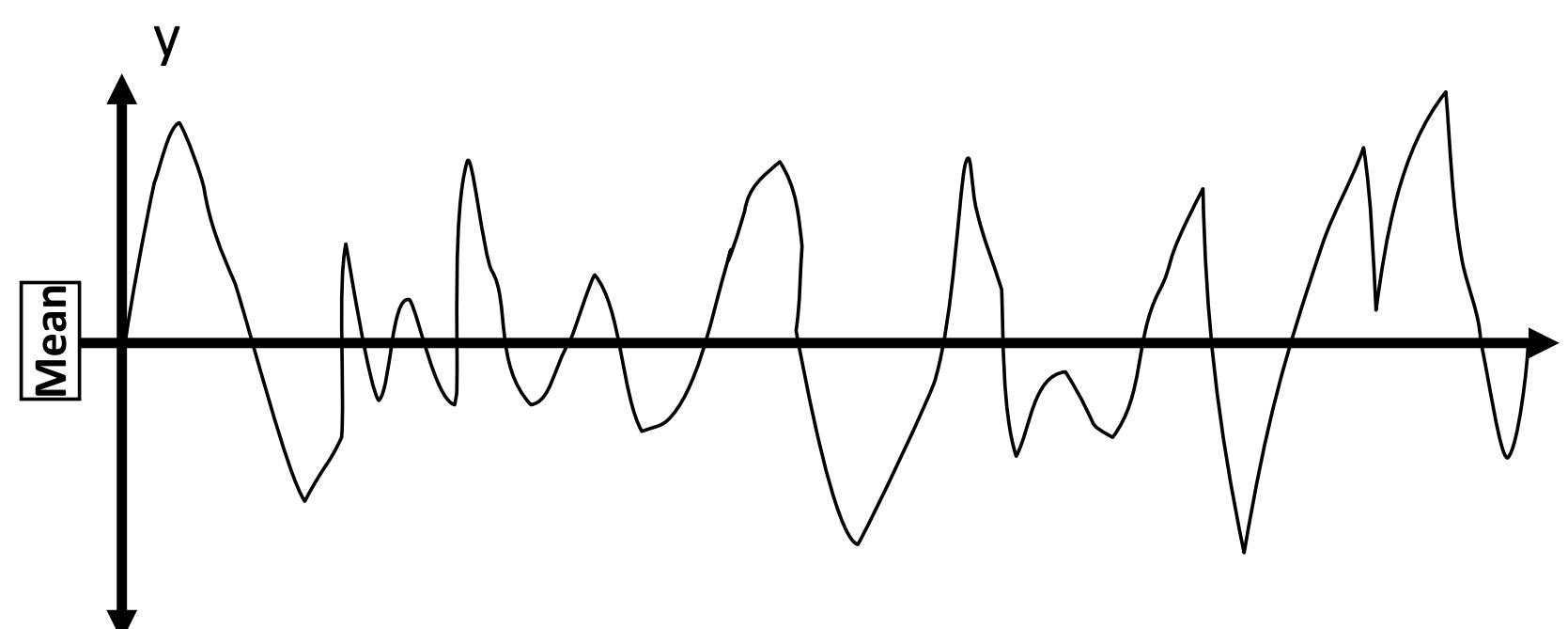
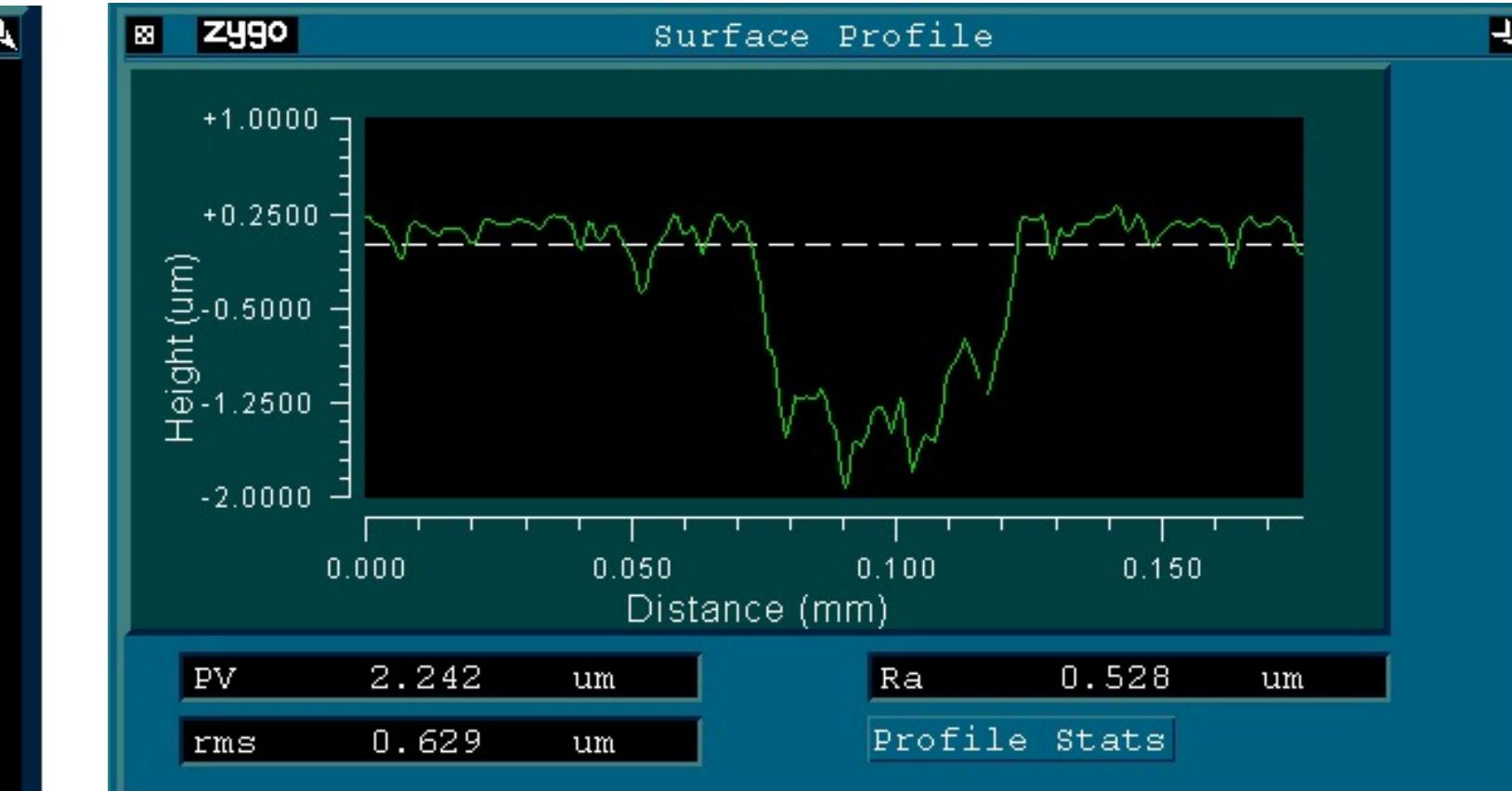
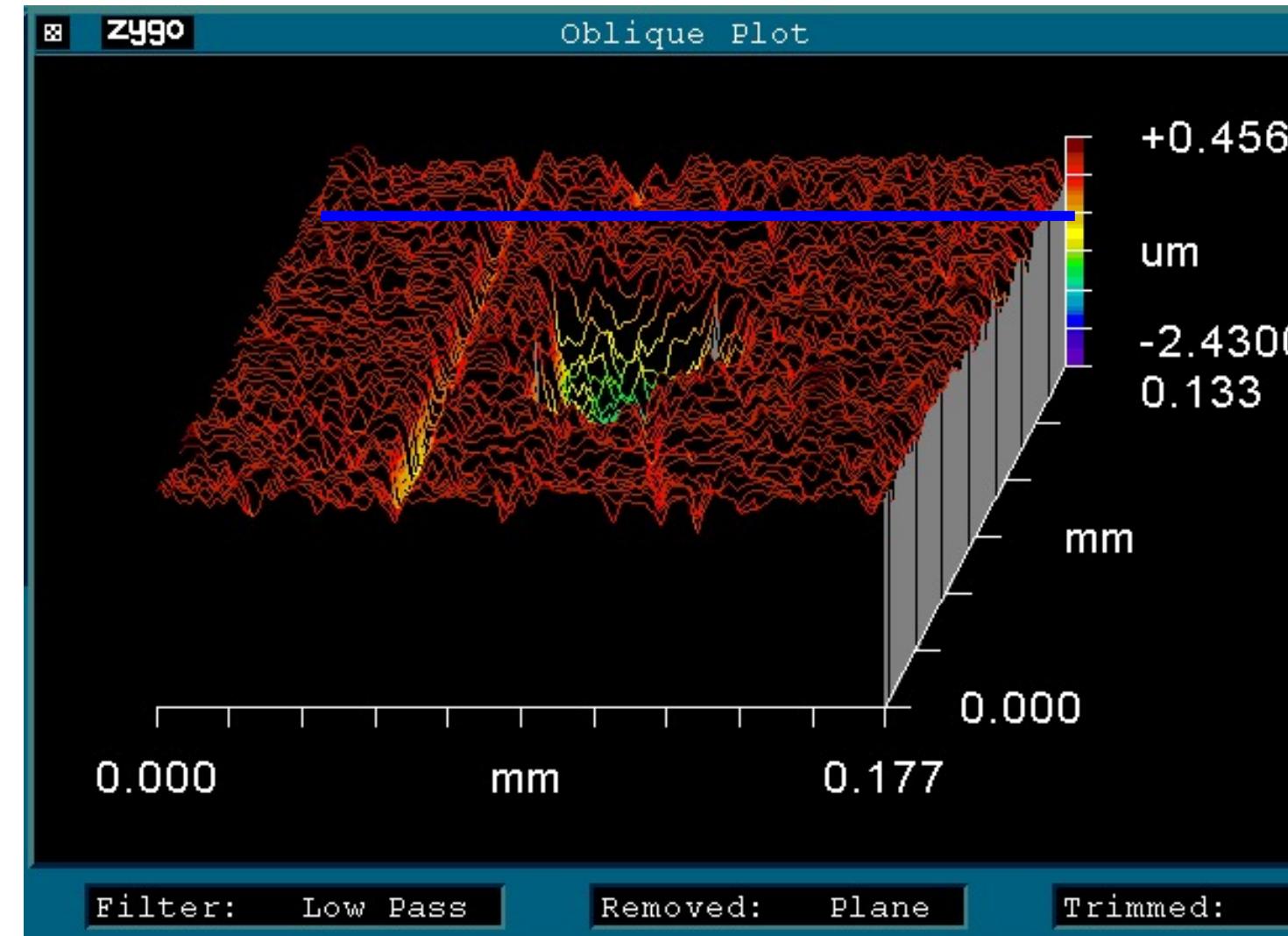
Cutting #3

Machining in Practice

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Surface Finish



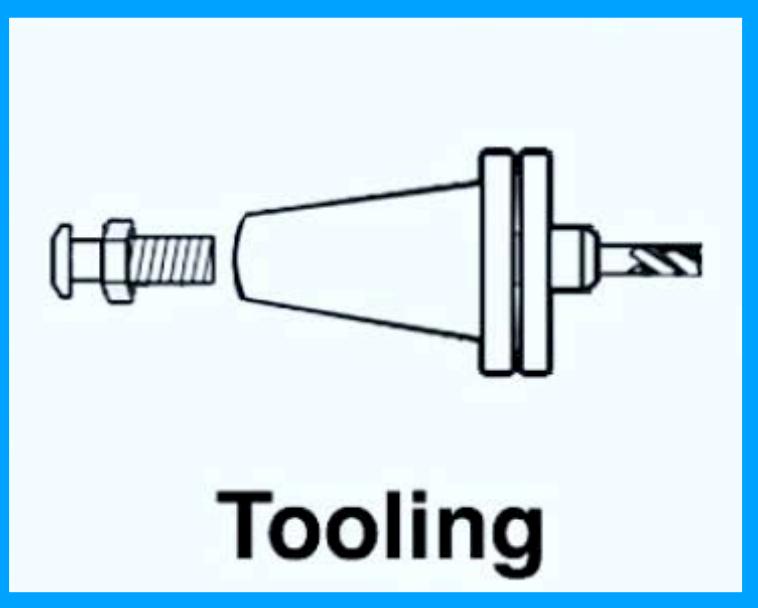
$$R_a = \frac{1}{L} \int_0^L |y| dx$$

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

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

Cutting #3

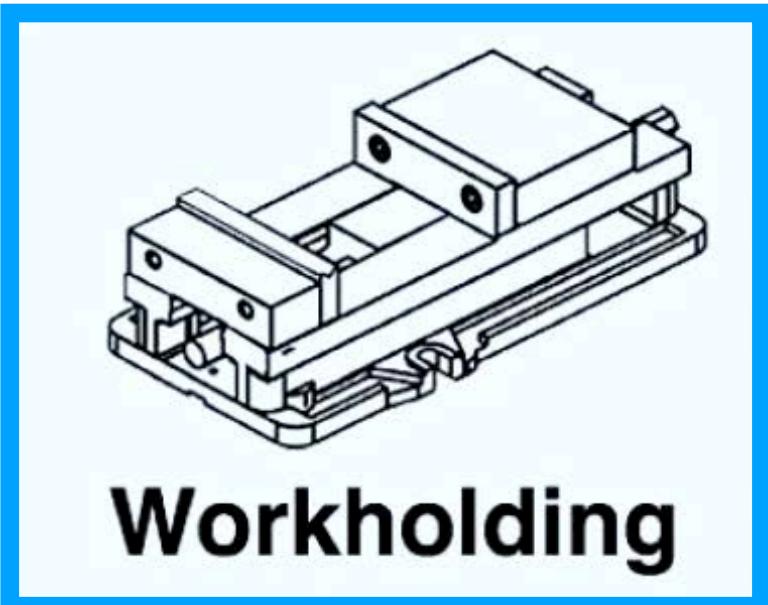
Machining in Practice



Tooling



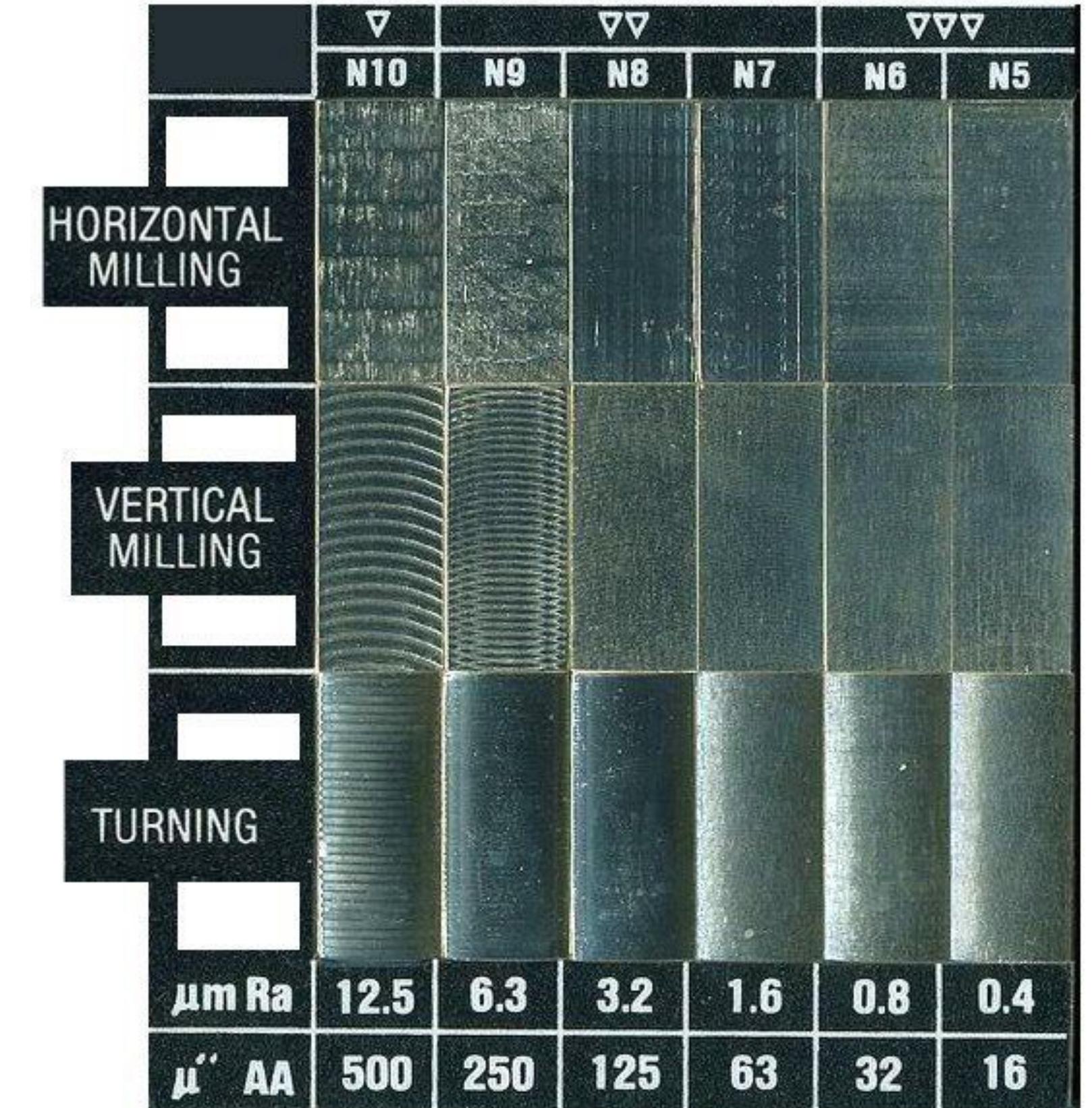
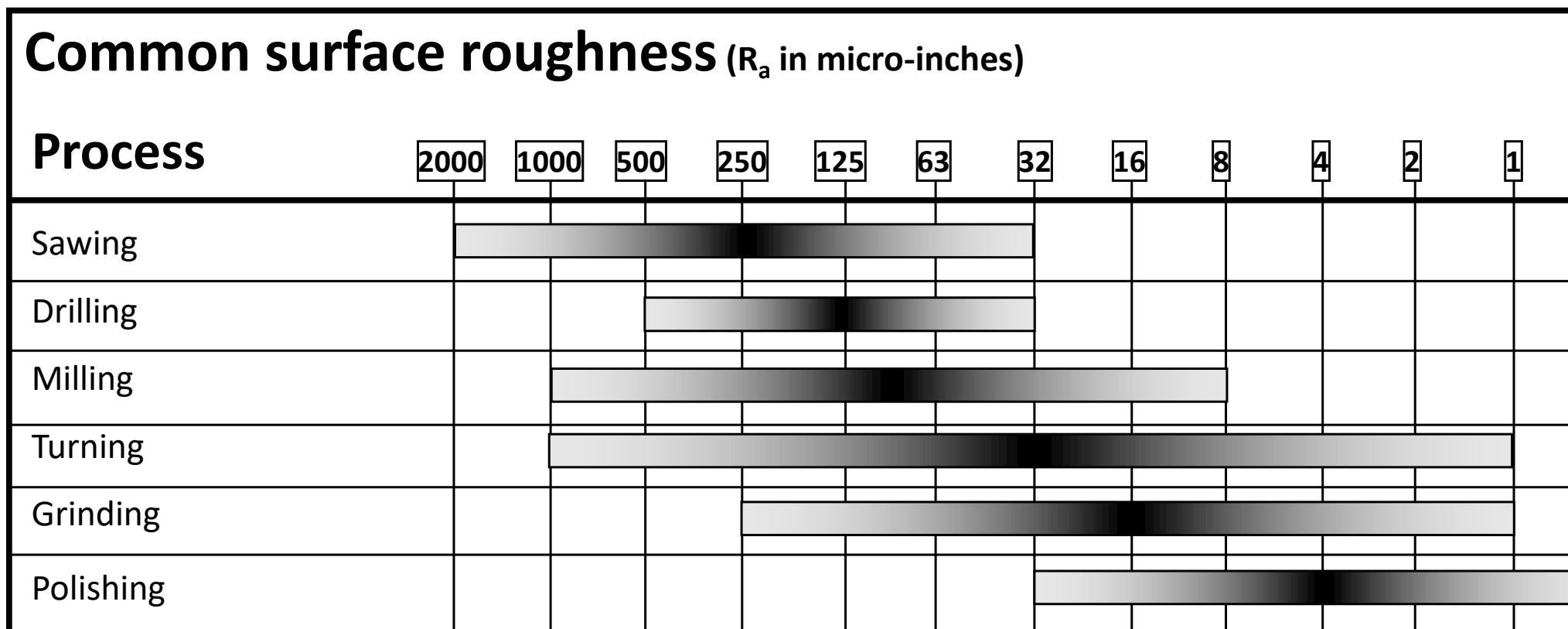
Program



Workholding

Surface Finish

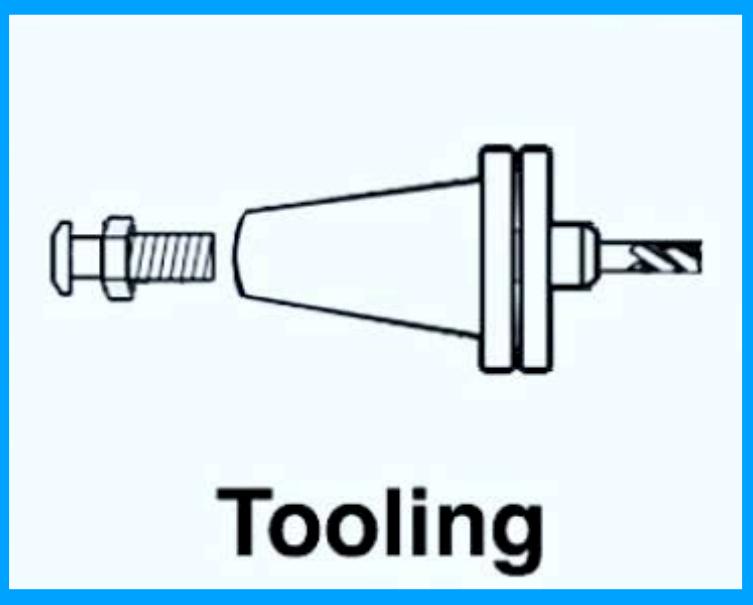
specify what you need, considering **time and cost!**



Cutting #3

Machining in Practice

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Manufacturing Attributes (vs Injection Molding)

Rate

low-medium

Quality

good!

Flexibility

high

Cost

wide range:
depends on design,
material, volume

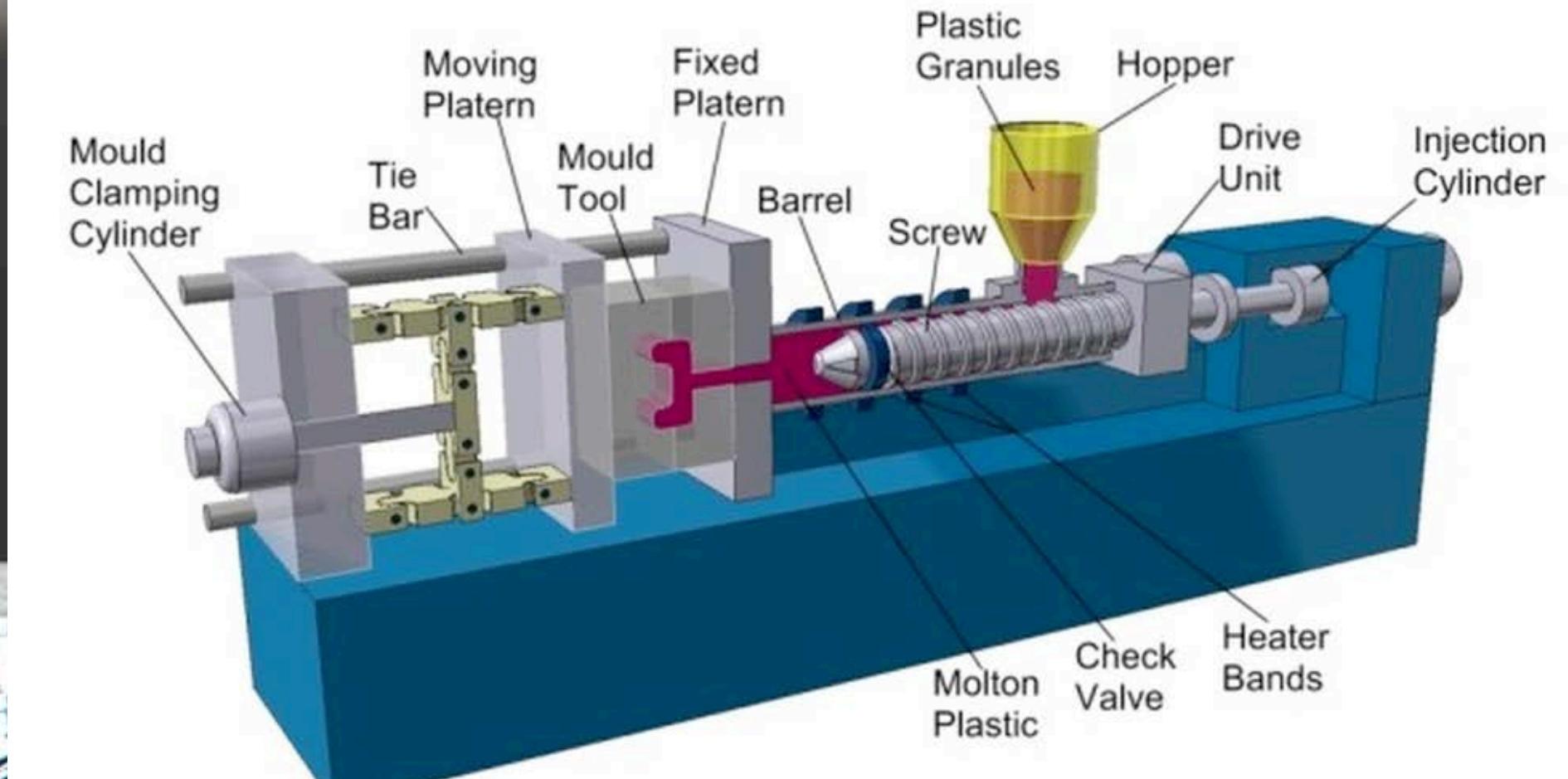
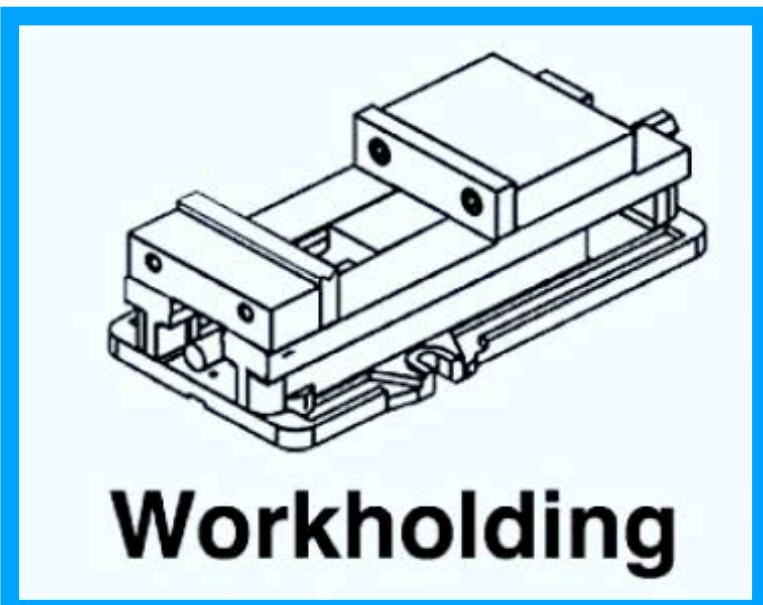
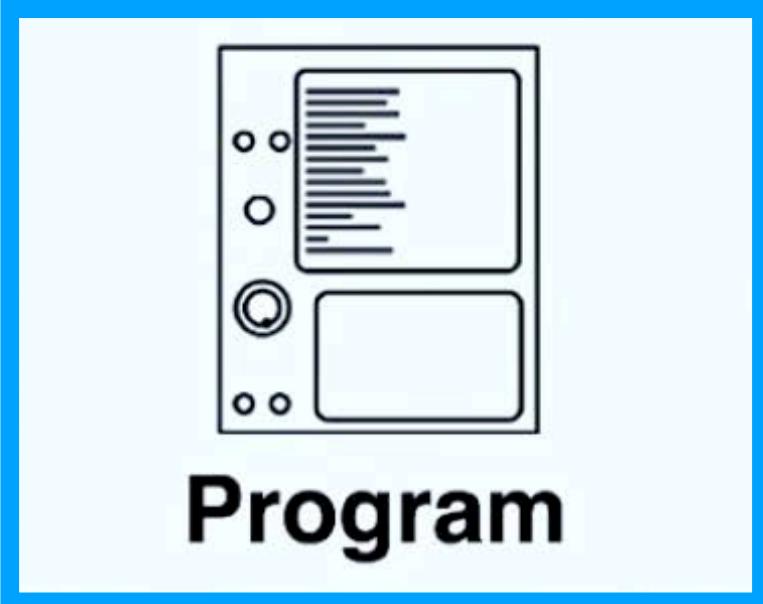


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