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Chapter 3: Subtractive Manufacturing

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[1] https://www.siempelkamp.com/products-and-technologies/machine-and-plant-engineering/composites/?L=1

Outline

Subtractive Manufacturing

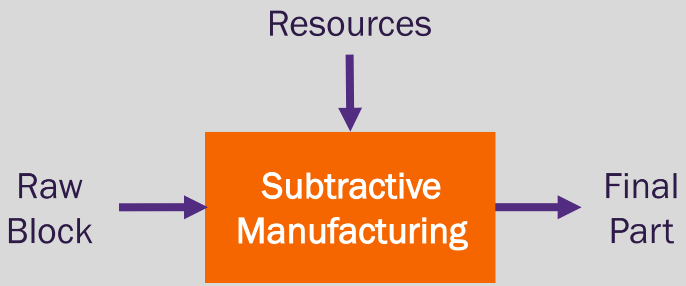
- Subtractive manufacturing represents processes where we transform the part from Form A to Form B by subtraction of material.
- The fundamental concept is that we reduce the volume of materials throughout the process.
- Milling, Drilling, Turning are examples of Subtractive Manufacturing.
- Other examples are Etching, Grinding …

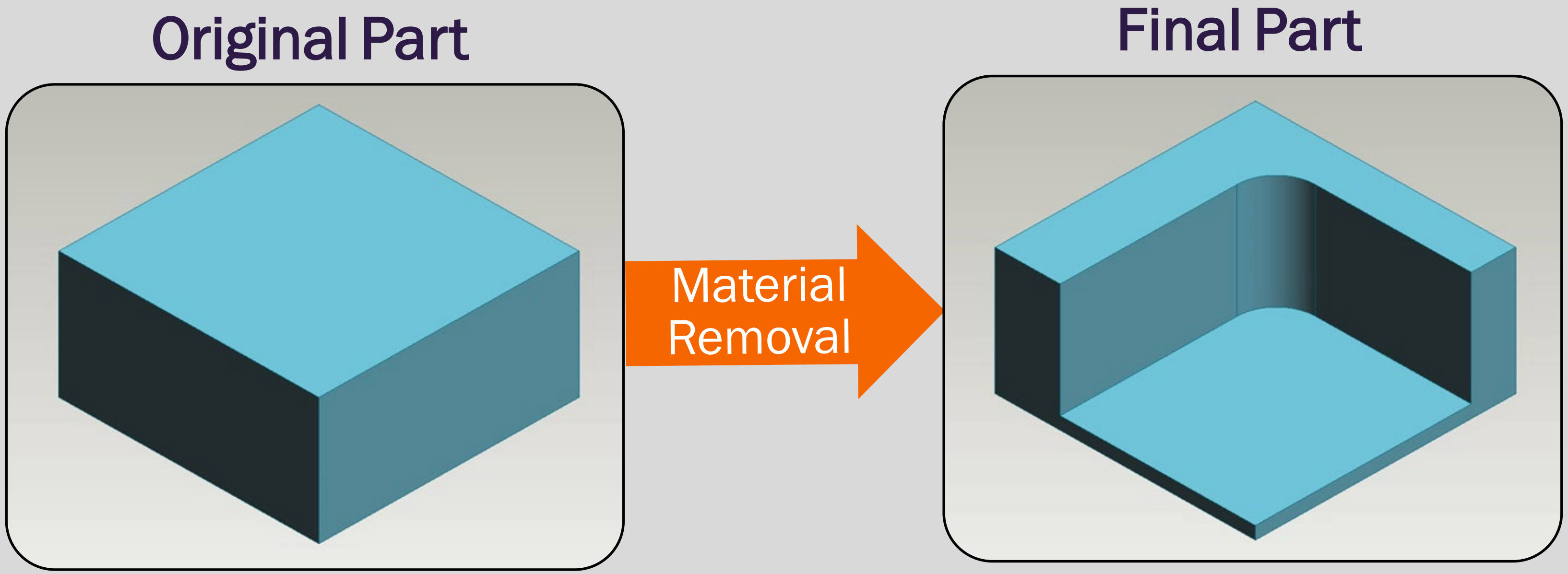
Chapter 3

Chapter 6

Subtractive Manufacturing

- Subtractive manufacturing uses machinery, tools and operators (classified as manufacturing resources) to transform a block of raw materials into a final part.
- This transformation process can be seen as an economical one: the usage of resources is creating value added to the original starting block.





From the Billet … to the Final Part

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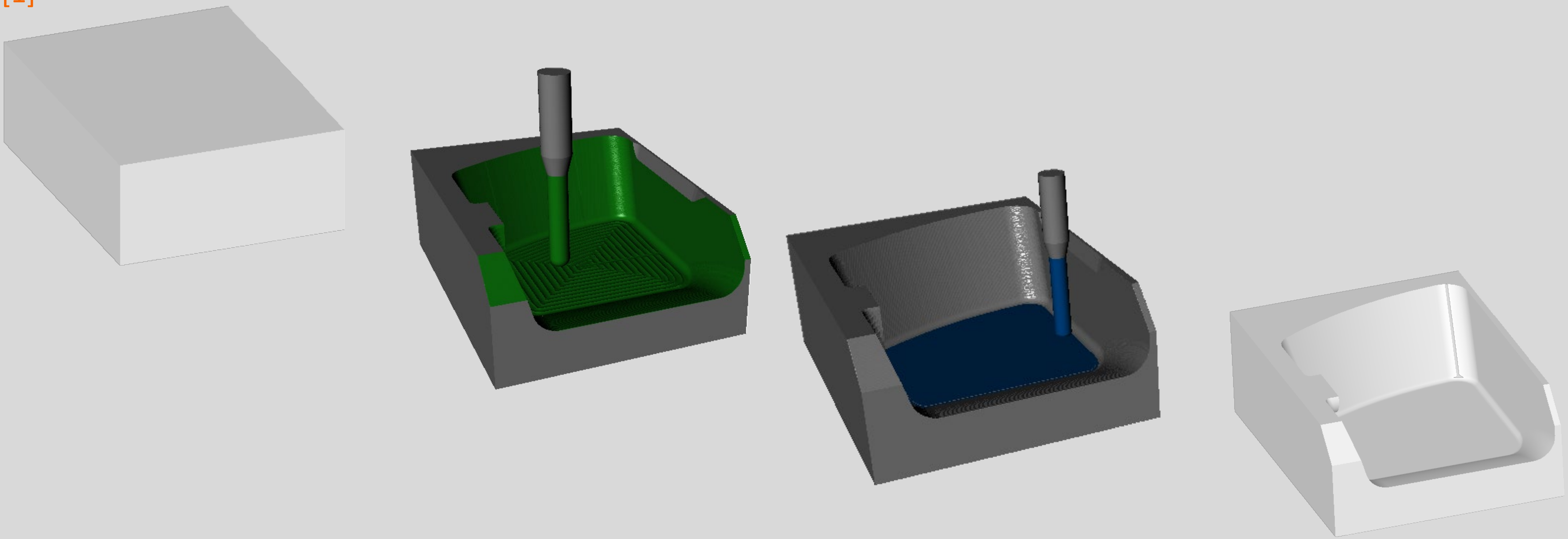


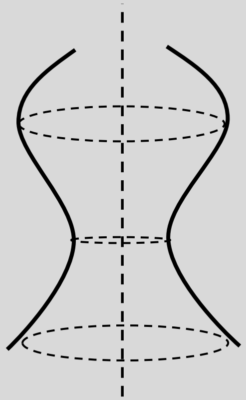
[1] R. Harik, “Spécifications de fonctions pour un système d’aide à la génération automatique de gamme d’usinage : Application aux pièces aéronautiques de structure, prototype logiciel dans le cadre du projet RNTL USIQUICK,” Jun. 2007, Accessed: Jan. 03, 2023. [Online]. Available: https://theses.hal.science/tel-00173161

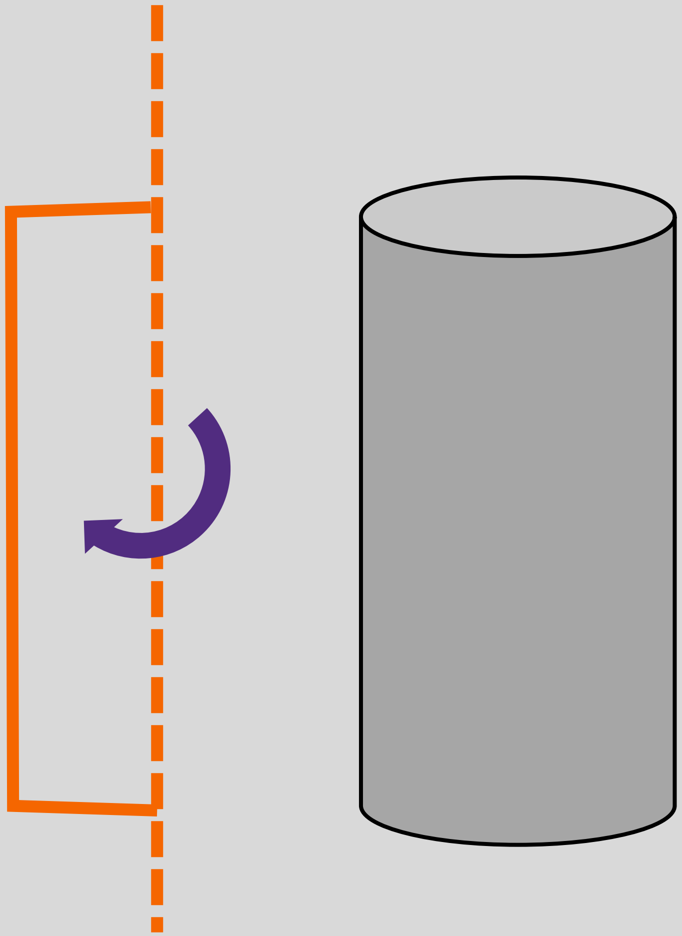
Shape Classification

Section I

I.A | Revolution Parts

- Shape is obtained by revolving a profile around an axis.
- Multiple parts are designed using the revolution feature to obtain revolution parts.
- Revolution parts are a primary indication that a Lathe Machine will be used to perform the turning operations.

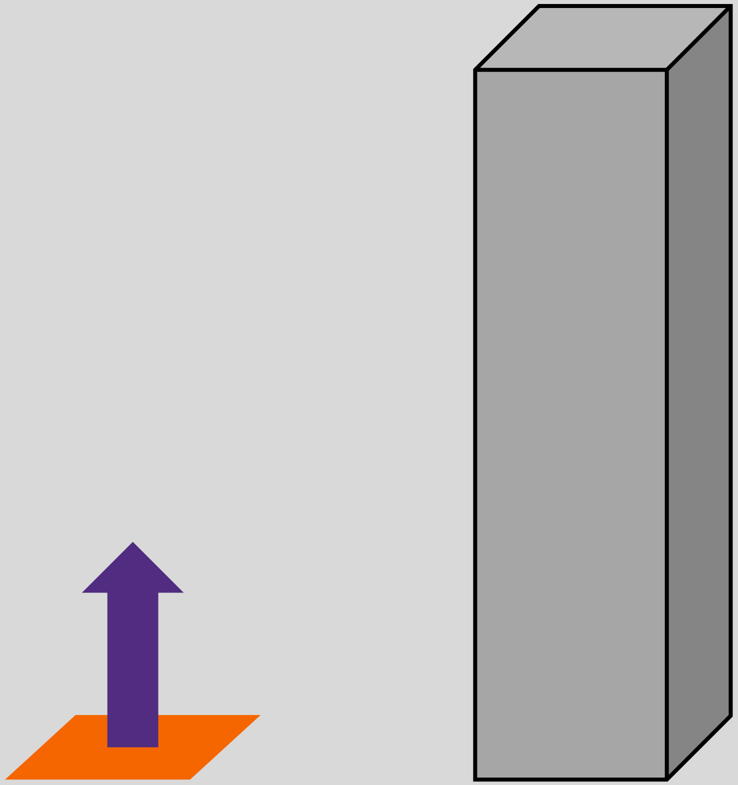




I.B | Prismatic Parts

- Shape is obtained by **extruding a profile** along an axis.
- Multiple parts are designed using the extrusion feature to obtain prismatic parts.
- Prismatic parts are a primary indication that a **Milling Machine** will be used to perform the machining operations.

Note: We can design a cylinder by extrusion as well, however that's not the logical manufacturing process.



I.C | Prismatic Vs. Revolution

Prismatic

Typically: Casting, then Milling

Revolution

Typically: Forging, then Turning (& Milling)

Knowledge Check

What primary type of manufacturing produces revolution parts?

A. Drilling
B. Broaching
C. Milling
D. Turning
E. Grinding

Knowledge Check

What primary type of manufacturing produces revolution parts?

A. Drilling
B. Broaching
C. Milling
D. **Turning**
E. Grinding

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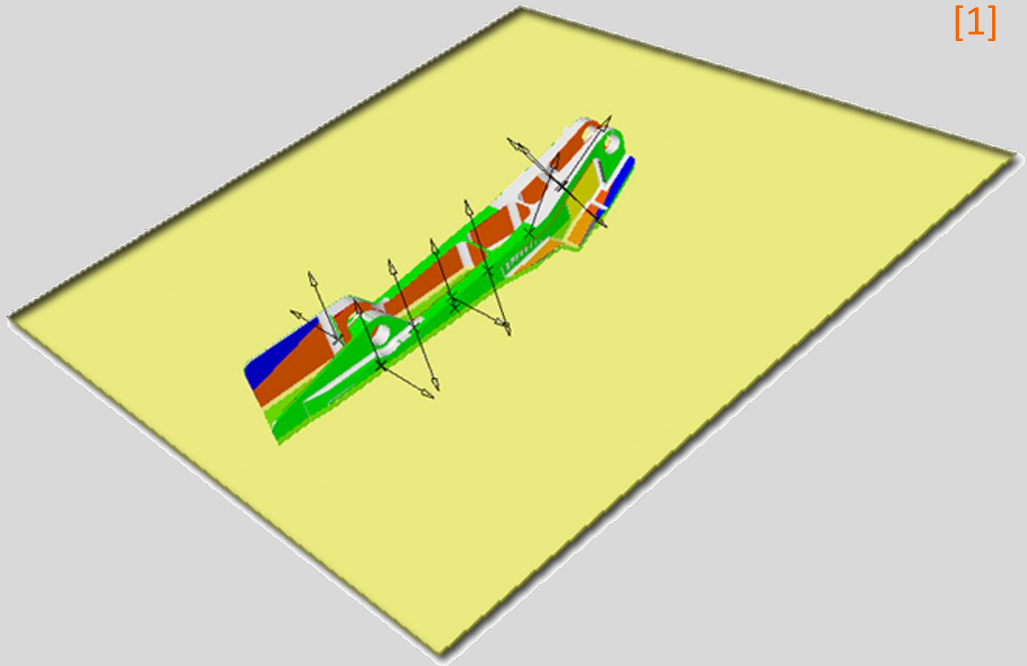
Process Planning

Section II

II | Introduction

- The process planner has a reconciliatory role: **matching the design** with the manufacturing resources.
- It requires **human analysis** of the mechanical part, which is often complex and time-consuming.
- Neglected machining difficulties or un-noticed ones, have detrimental consequences on meeting the allowable specified by the part designers.



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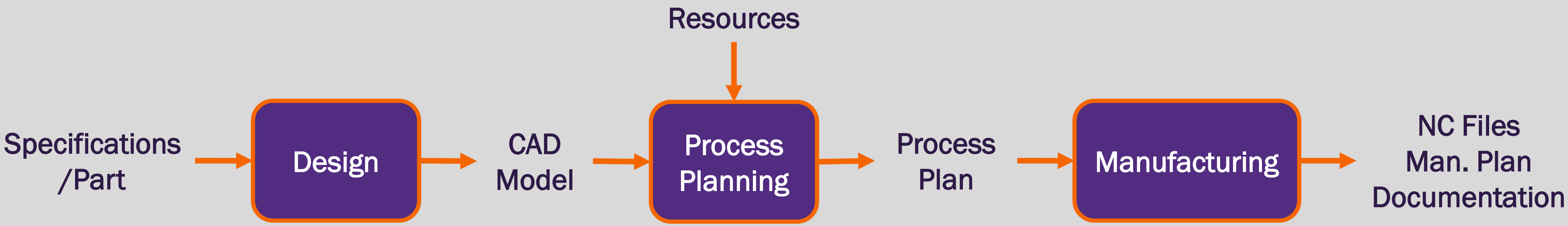
II | Process Planning

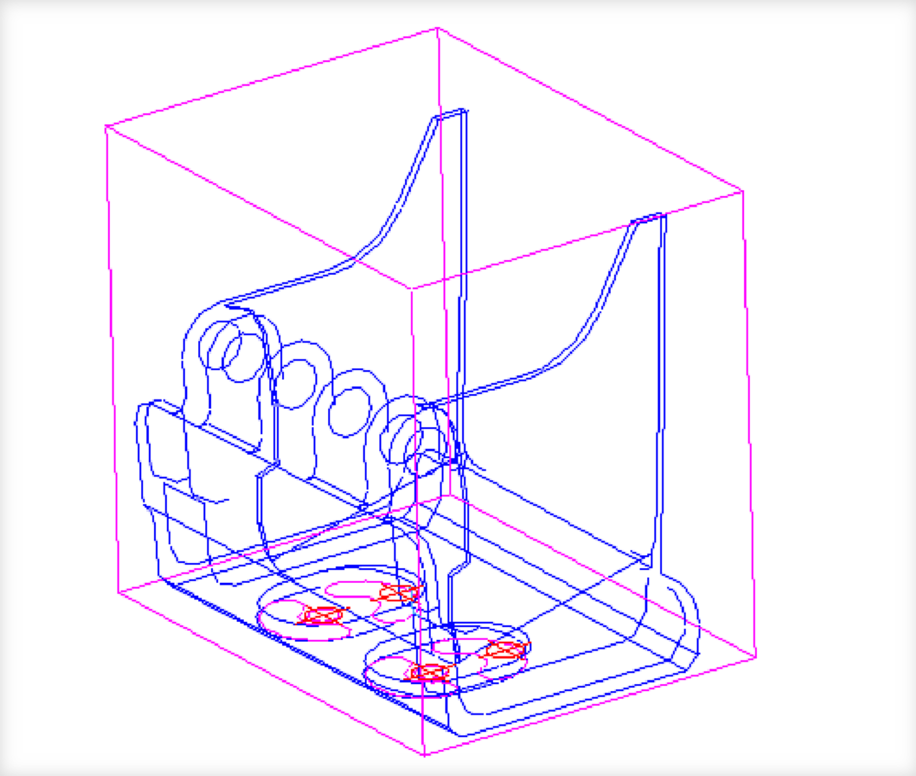
- Process Planning is at the heart of the numerical chain
- It links resources with the design to generate the process plan
- The process plan will include cutting conditions and strategy, enabling the manufacturing process
- An example, is Fixture Ears, where the process planner plans the link between the part and the fall off section



II.A | PP Function Sample 1: Billet Dimensions

- Firsthand estimation of the part size
- Enables selection of billet
- Provides first understanding of which machine to use

[1]



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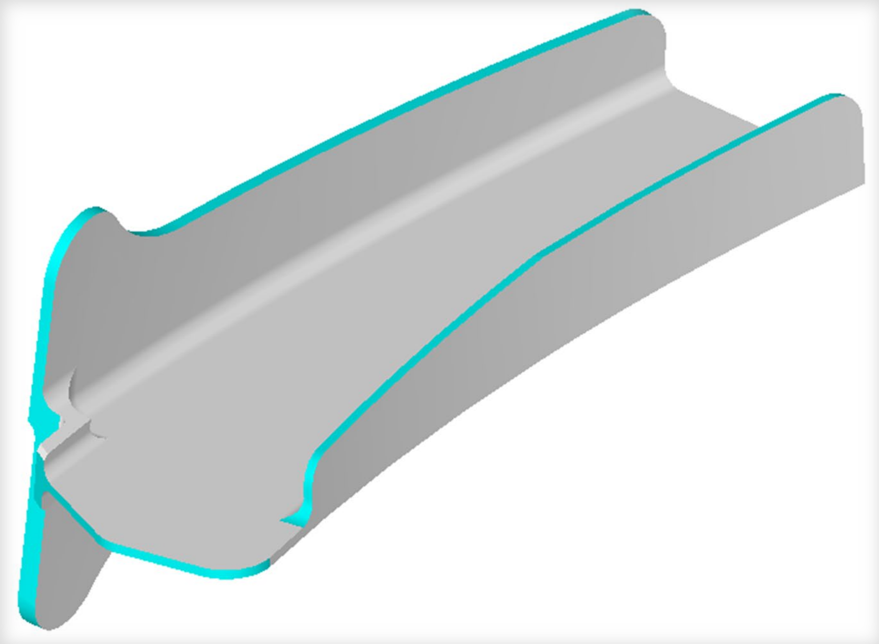
II.B | PP Function Sample 2: Thin Features

- Looks for particular features in a part
- Thin features require special manufacturing operations
- Pointing out these features help meeting design requirements

[1]



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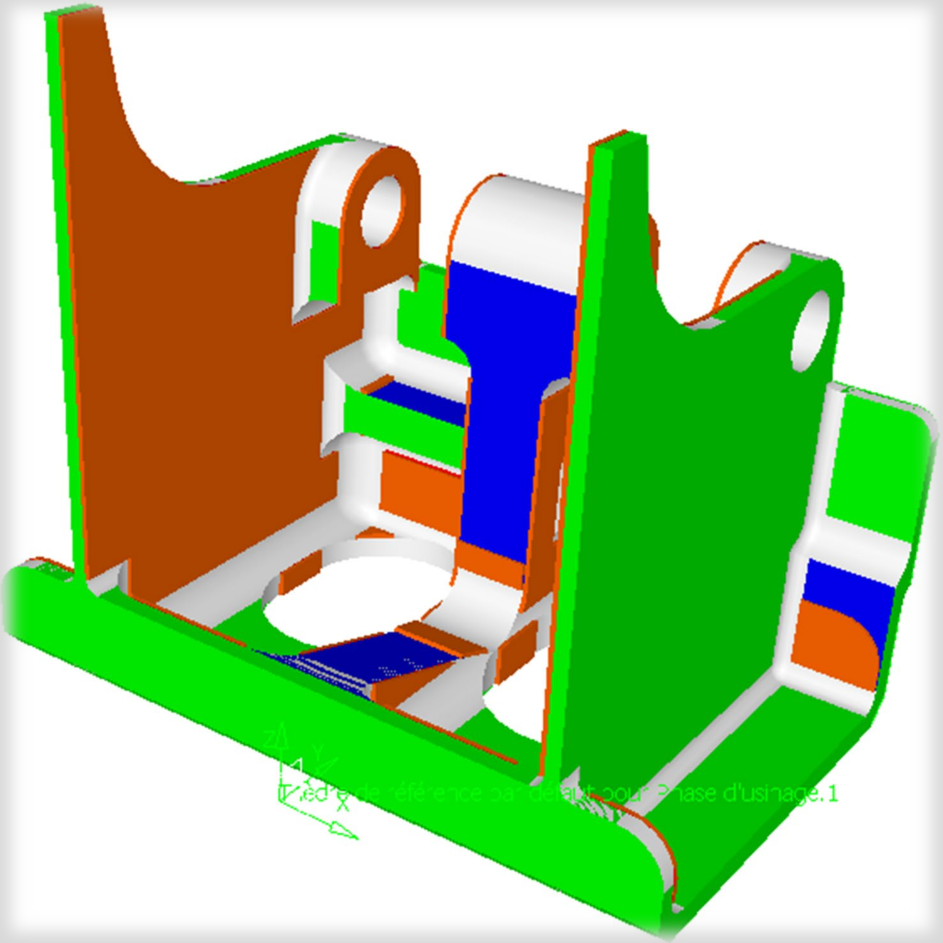
II.C | PP Function Sample 3: Manufacturing Modes

- Selection of optimal manufacturing mode
- Analysis of Flank vs End Milling
- Identification of potential conflict zones

[1]



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II.D | PP Function Sample 4: Accessibility Sphere

- Maps Machining directions on a sphere
- Helps selecting the fixture plans
- Supports verification of accessibility issues

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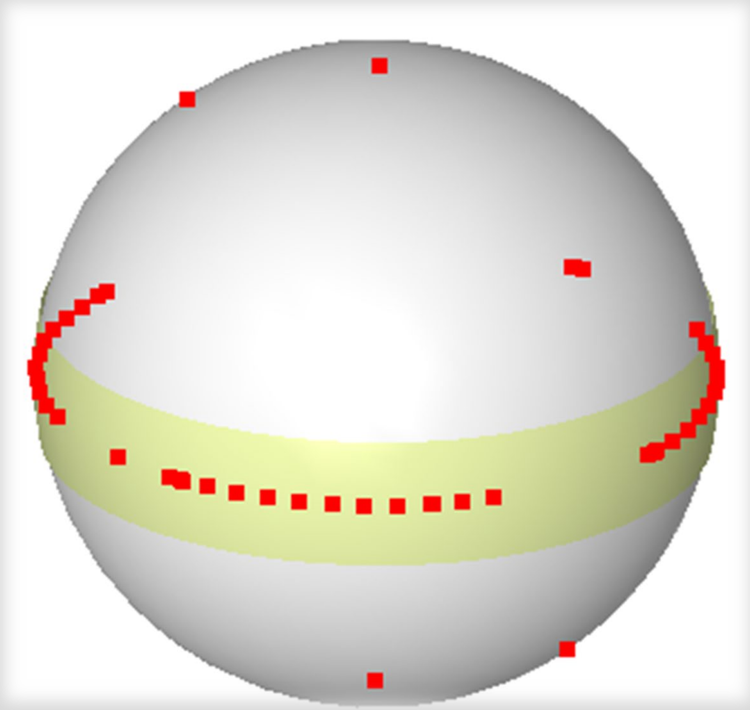

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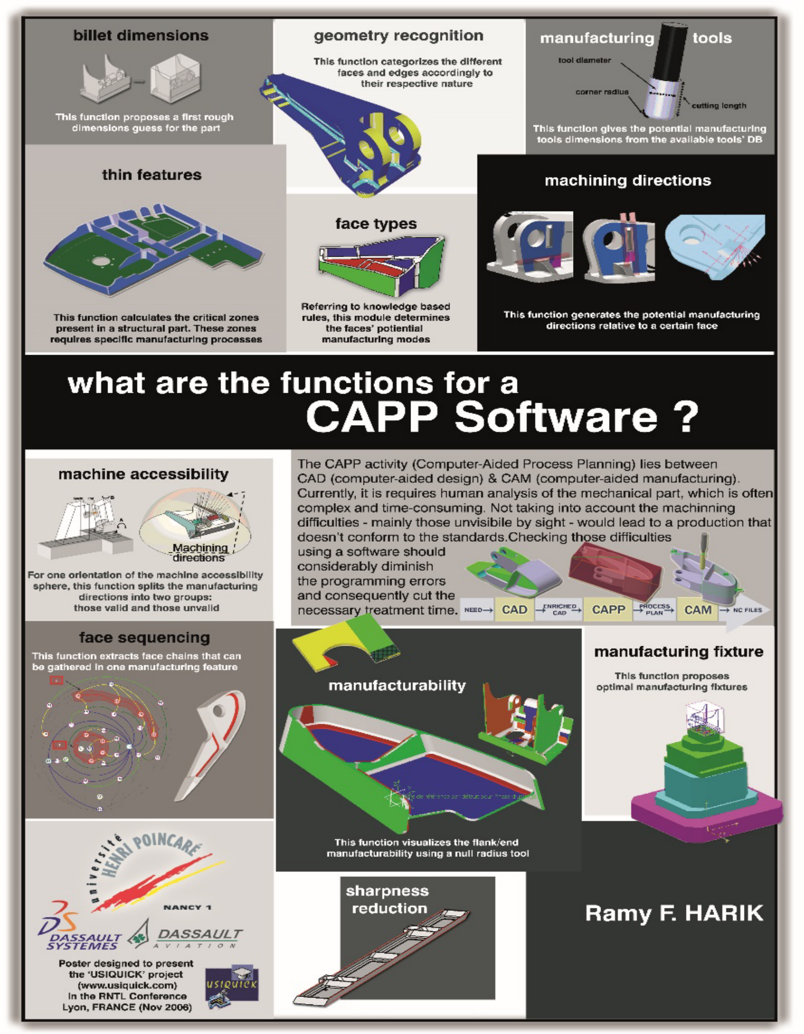
II.E | Process Planning Function

[1]



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Knowledge Check

What are the ‘Fixture Ears’ ?

A. Part of the Manufacturing Fixture attached to the machine.
B. Part of the part itself, a separation between the final part and the remaining bulk of materials.
C. A device that helps the machine hear what is going on.

Knowledge Check

What are the ‘Fixture Ears’ ?

A. Part of the Manufacturing Fixture attached to the machine.

B. Part of the part itself, a separation between the final part and the remaining bulk of materials.

C. A device that helps the machine hear what is going on.

Knowledge Check

Process Planning…

A. Connects NC codes to Documentation
B. Translates specification into a CAD model
C. Connects the CAD Model with the Design
D. Connects the Design with the Manufacturing Process

Knowledge Check

Process Planning…

A. Connects NC codes to Documentation
B. Translates specification into a CAD model
C. Connects the CAD Model with the Design
D. **Connects the Design with the Manufacturing Process**

Knowledge Check

Thin Features are…

A. Easy to manufacture

B. Require extra attention to manufacture

Knowledge Check

Thin Features are…

A. Easy to manufacture

B. **Require extra attention to manufacture**

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Milling

Section III

III | Complexity of Milling

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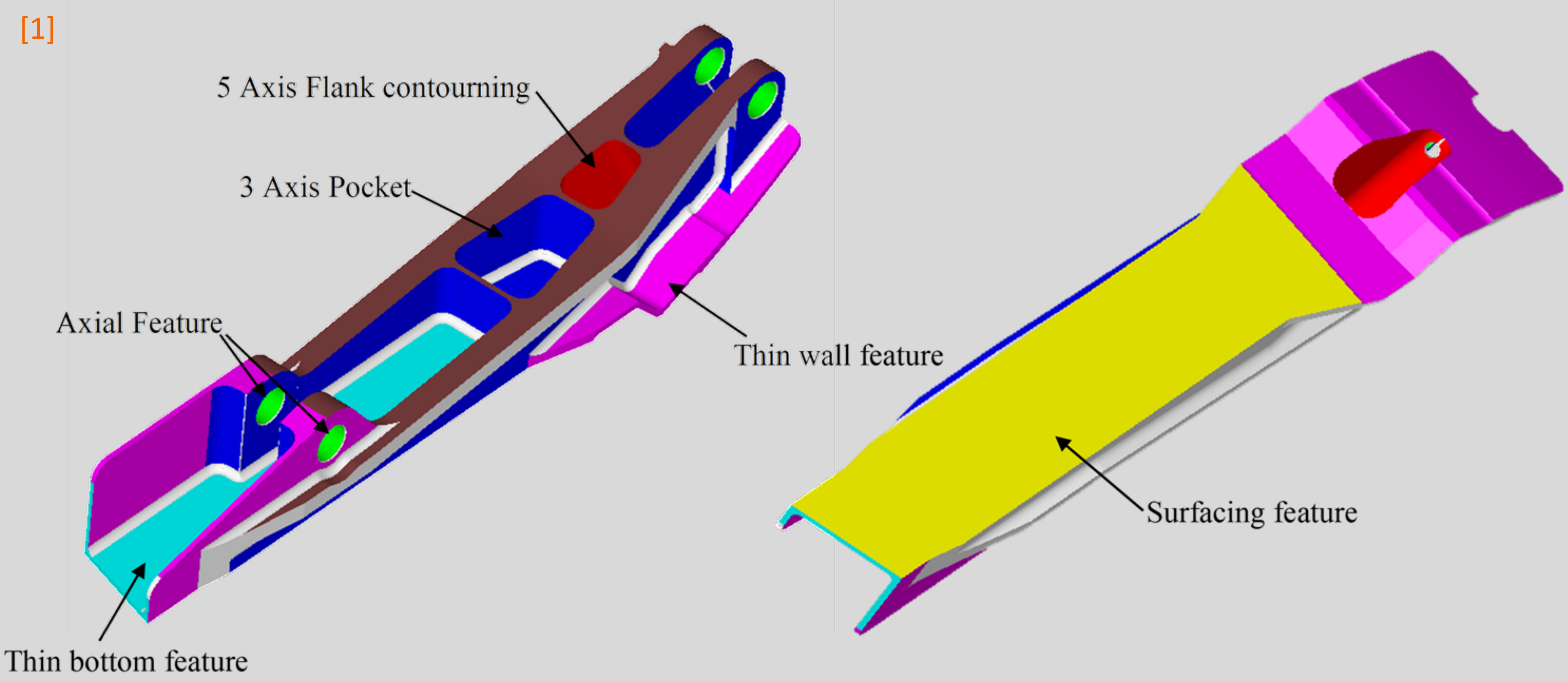

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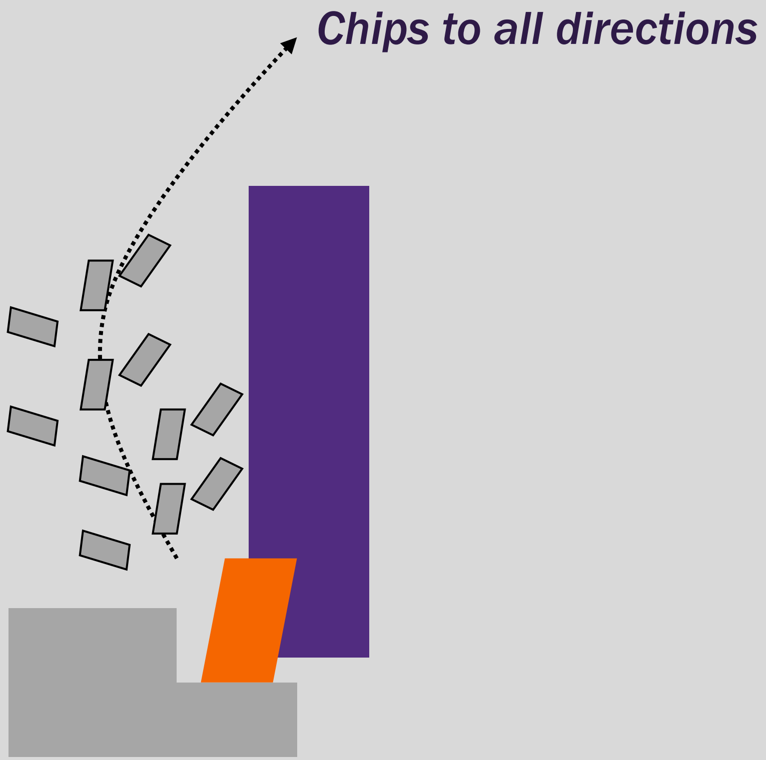
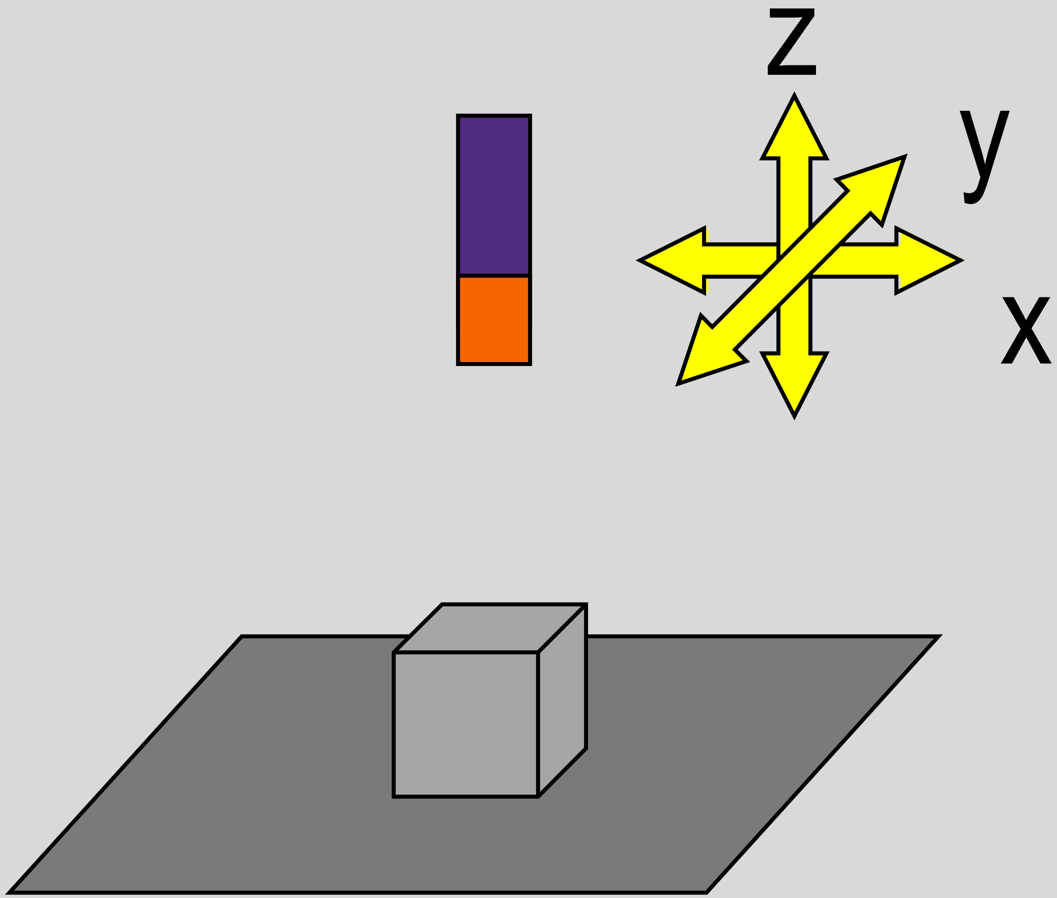
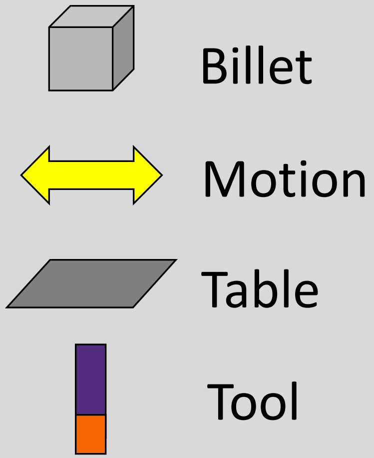
III | Milling Concept

- Tool attacks the material.
- Chips are formed and ejected.
- Rotation of tool, feed at which it advanced to attack the material, depth of the contact constitutes the cutting conditions.

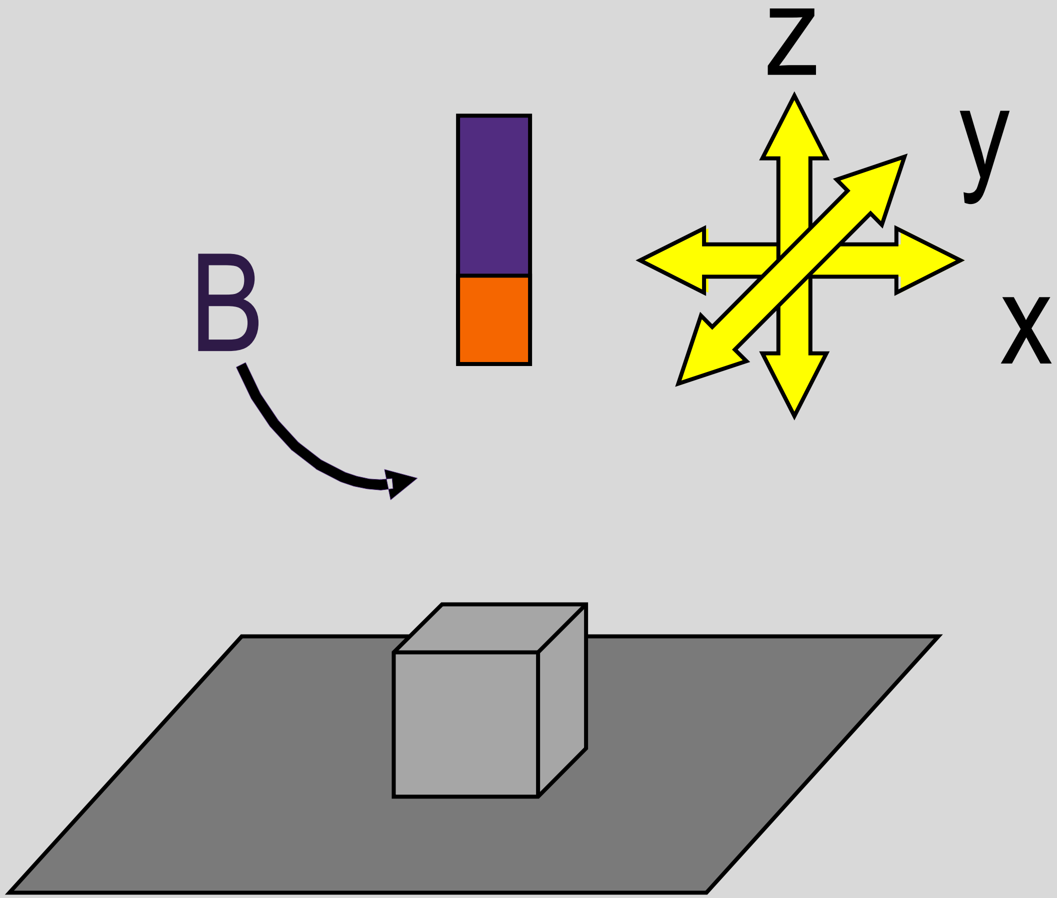


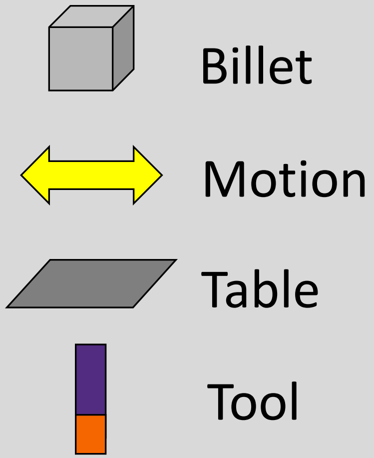
III.A.1 | 3 Axis CNC



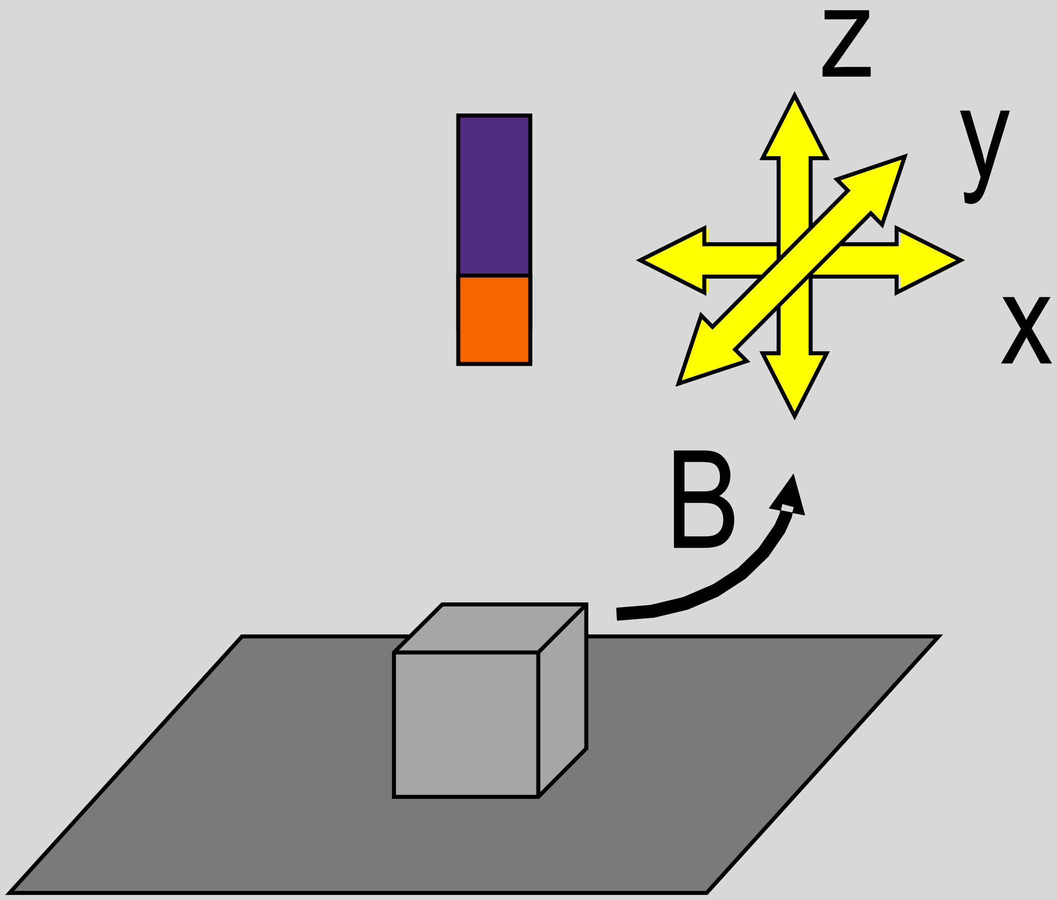


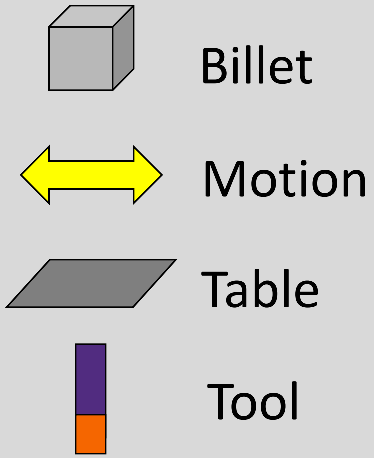
III.A.2 | 4 Axis CNC



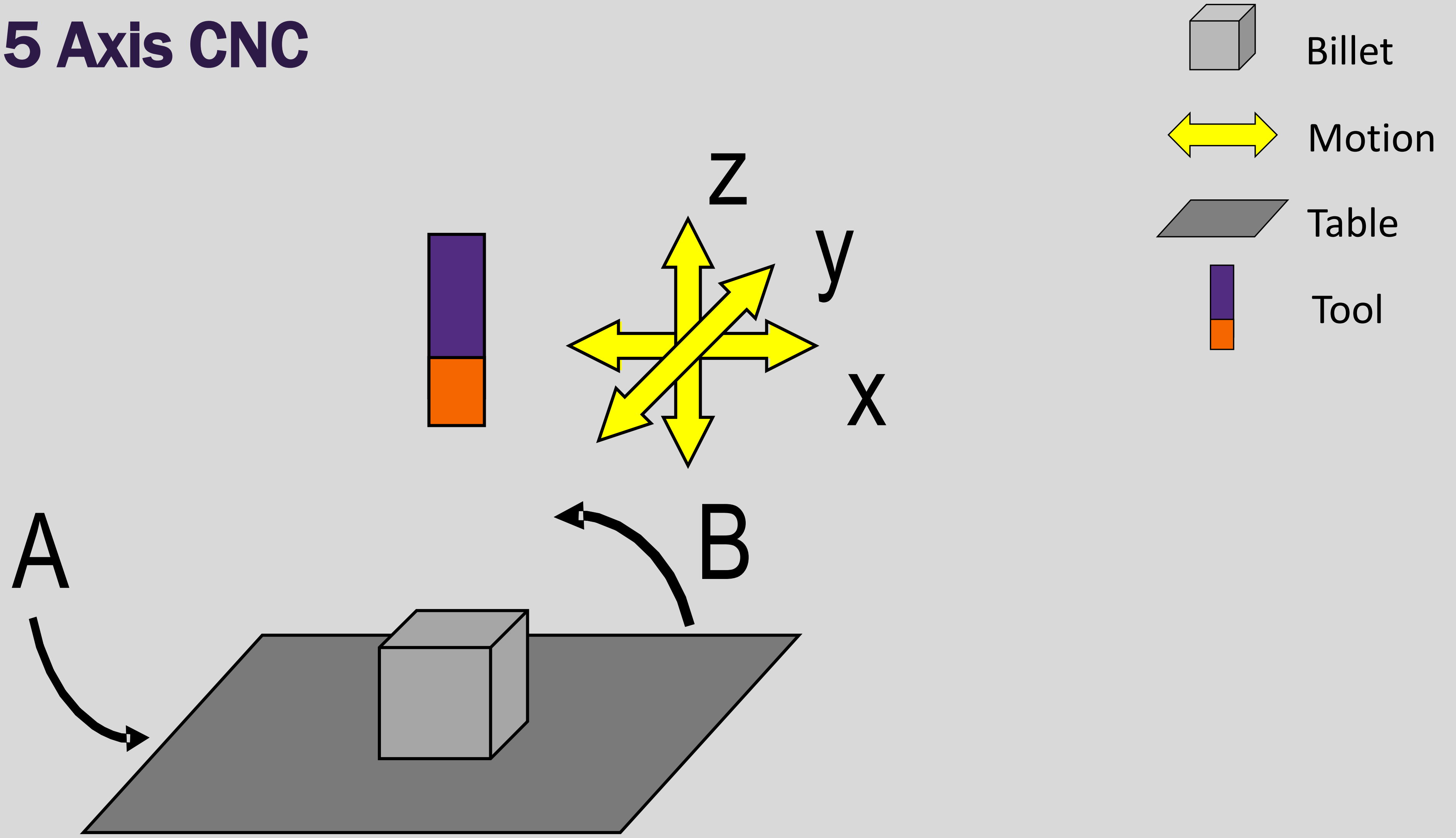


III.A.3 | 4 Axis CNC (Alternate Configuration)



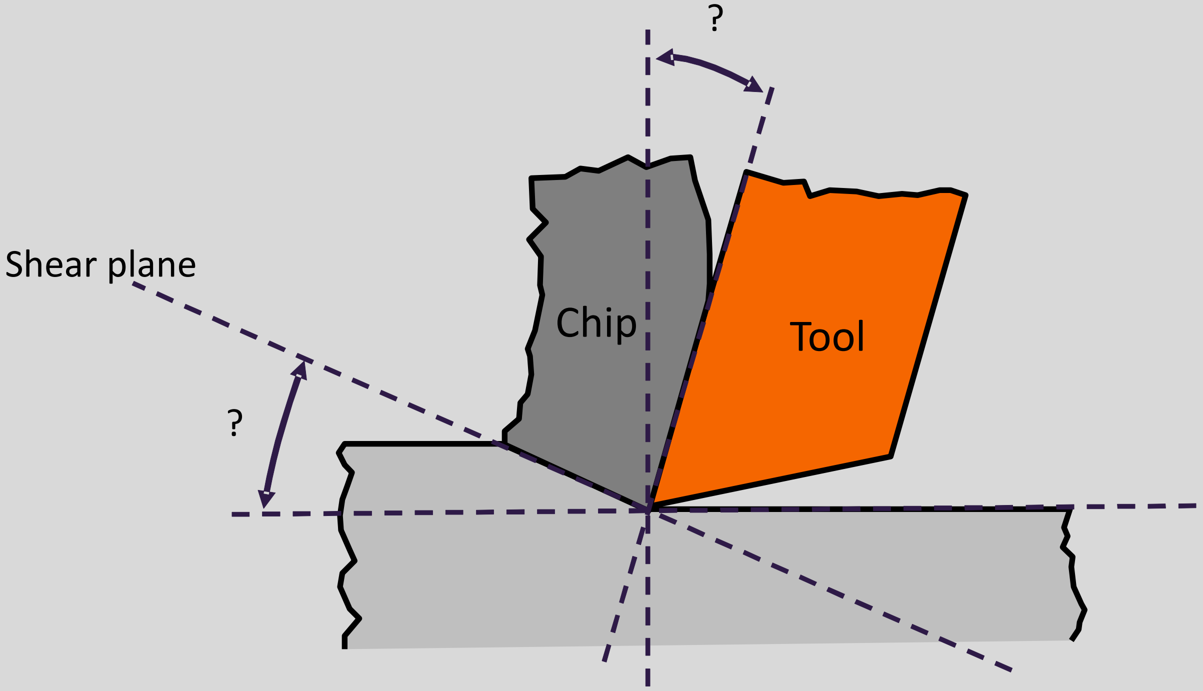


III.A.4 | 5 Axis CNC



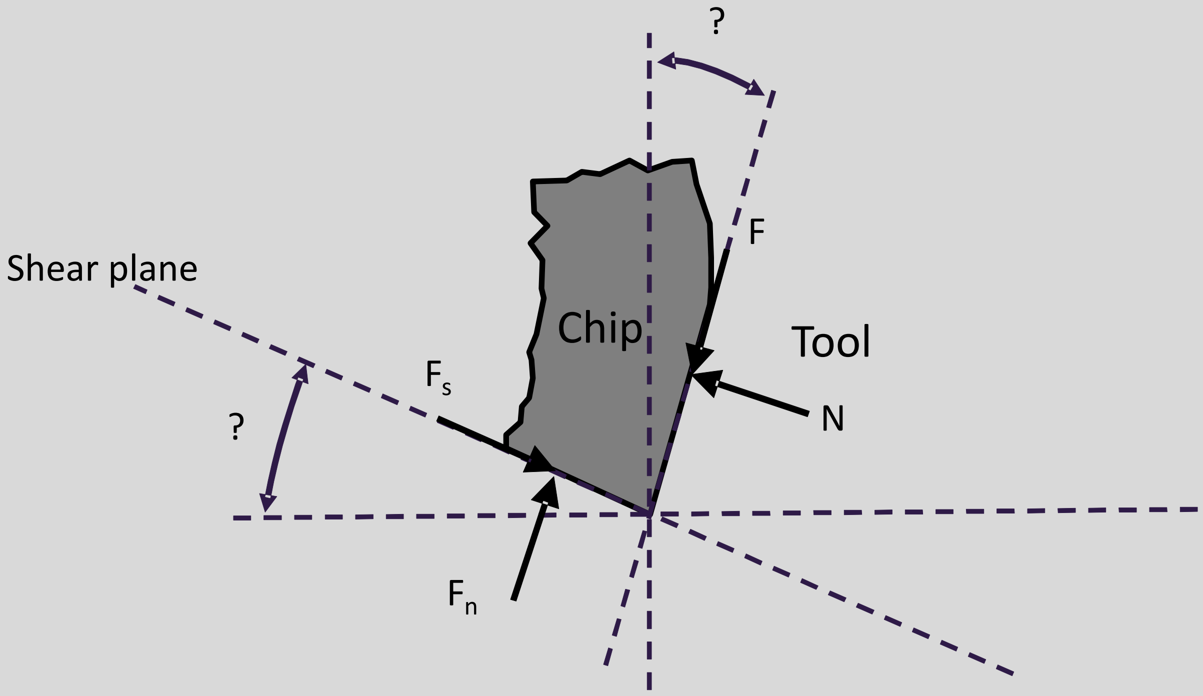
III.B.1 | Chip Formation

- The tool attacks the material with an angle α based on the tool geometry
- The material forms a chip and 'shears' at an angle φ
- The shear location, simplified as a plane, is actually a volumetric shear zone



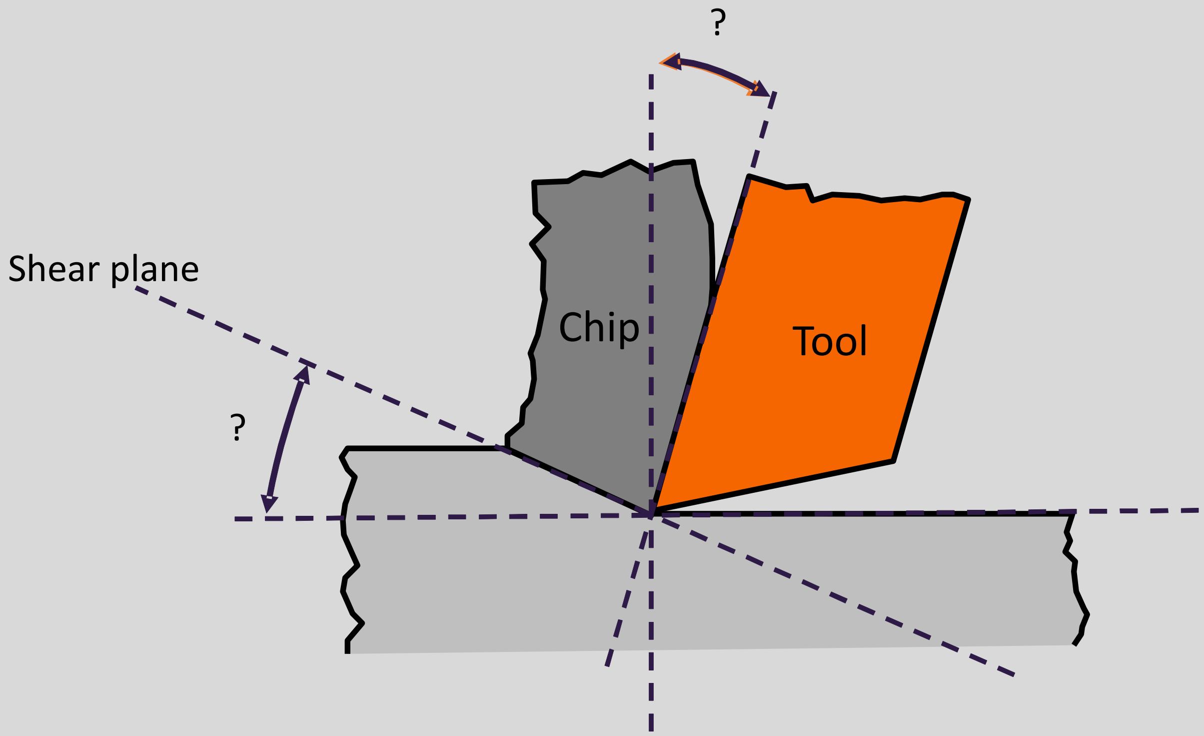
III.B.2 | Free Body Diagram

- Isolating the chip and constructing the Free Body Diagram, the chip is subject to 4 forces
  - F = Frictional Resistance
  - N = Normal to Friction
  - Fs = Resistance to shear
  - Fn = Normal to shear
- The resultant on the part/chip shear zone is of equal magnitude as the resultant on the tool/chip interface



III.C.1 | Forces in Cutting

- None of the previous forces are measurable
- We use a dynamometer to measure the horizontal and vertical components of this resultant force
- The horizontal is the Cutting Force $\boldsymbol{F_c}$
- The vertical is the Thrust Force $\boldsymbol{F_t}$



III.C.2 | Free Body Diagram Resolution

$$F = F_c \sin\alpha + F_t \cos\alpha$$
$$N = F_c \cos\alpha - F_t \sin\alpha$$
$$F_s = F_c \cos\varphi - F_t \sin\varphi$$
$$F_n = F_c \sin\varphi + F_t \cos\varphi$$

- Forces at the tool/chip interface (F, N) are principally affected by the tool angle **α**
- Forces at the shear zone (F_s, F_n) are principally affected by the shear angle **φ**

- $\boldsymbol{F_c}$, $\boldsymbol{F_t}$ and **α** are either measured or given, however we need to determine the value **φ** of to resolve the above equations.

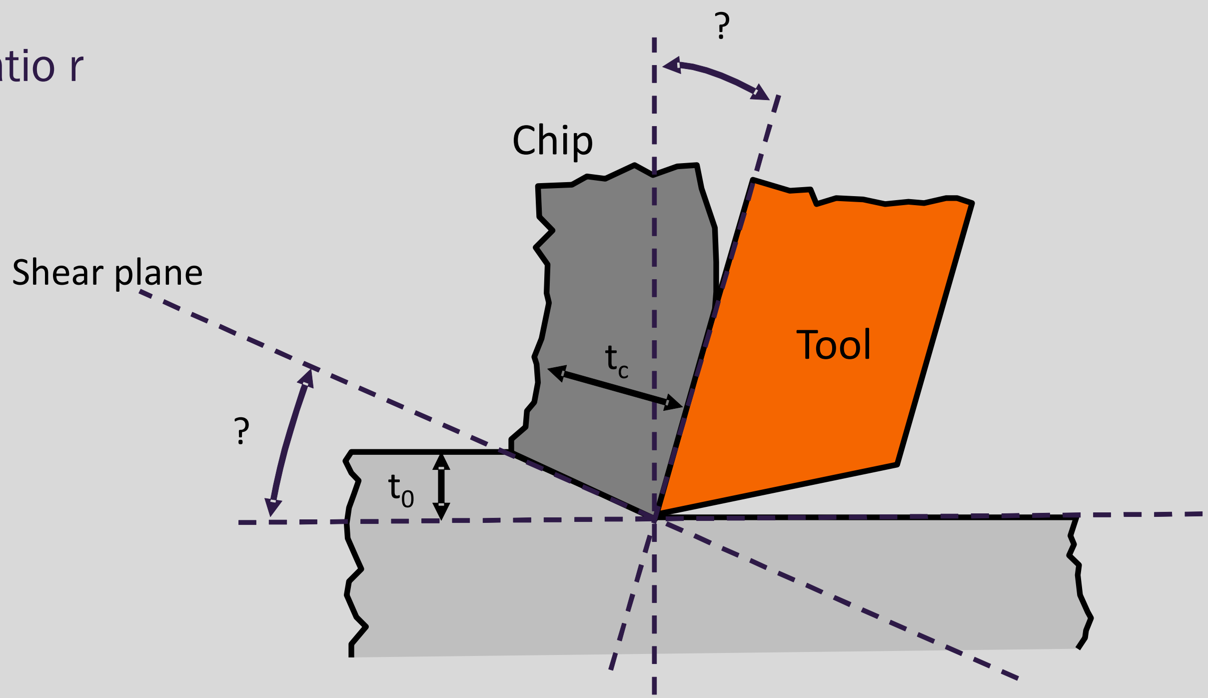
III.C.3 | Determining the Shear Angle φ

- The shear angle can be determined geometrically function of the uncut chip length t0, the chip length tc and the tool rake angle α

$$\tan \varphi = \frac{r \cos \alpha}{1 - r \sin \alpha}$$

- For simplification we define the chip reduction ratio r

$$r = \frac{t_0}{t_c}$$



III.C.3 | Determining the Shear Angle φ

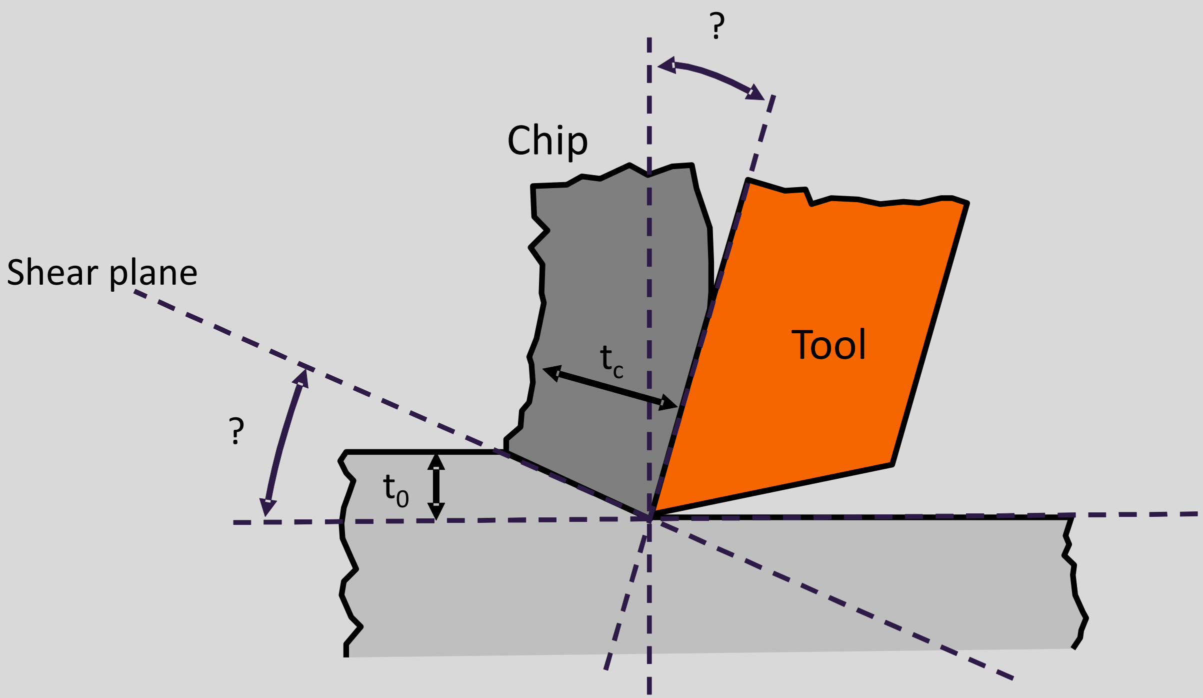
- The experiment to measure the shear angle based on the cutting length can take a lot of time
- Other less complicated methods are based on movement velocities recorded with high-speed motion systems

$$r = \frac{t_0}{t_c} = \frac{\sin \varphi}{\cos(\varphi - \alpha)} = \frac{V_c}{V}$$

V = Cutting Velocity

Vc = Chip Velocity

Vs = Shear Velocity



Knowledge Check

A milling operation generates a 0.5 in chip for a depth of cut equal to 0.25 in, what is the chip reduction ratio?

A. 0.5
B. 0.25
C. 2
D. 1.5

Knowledge Check

A milling operation generates a 0.5 in chip for a depth of cut equal to 0.25 in, what is the chip reduction ratio?

A. 0.5
B. 0.25
C. 2
D. 1.5

$$r = \frac{t_0}{t_c} = \frac{0.25}{0.5} = 0.5$$

Knowledge Check

What is the shear angle of the previous process if the rake angle is 30˚?

A. 15
B. 30
C. 45
D. 60

Knowledge Check

What is the shear angle of the previous process if the rake angle is 30˚?

A. 15
B. 30
C. 45
D. 60

$$tan\,\varphi = \frac{r\cos\alpha}{1 - r\,sin\alpha}$$

$$tan\,\varphi = \frac{0.5\cos 30}{1 - 0.5\,sin30}$$

$$\varphi = 30$$

Include a movie of your selection.
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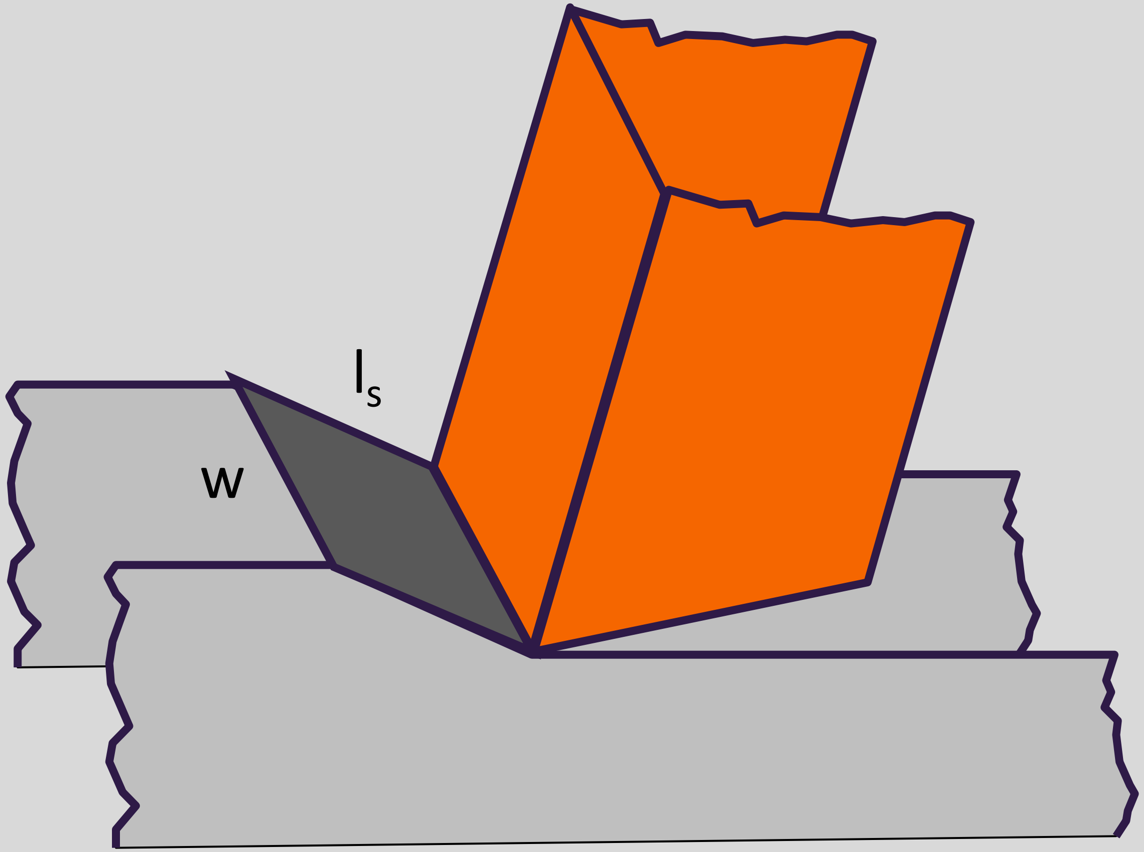
III.D | Computing the Shear Stress

- The Shear Stress is calculated by

$$S = \frac{F_S}{A_S}$$

- The Shear area can be determined with

$$A_s = \frac{t_0 w}{\sin \varphi}$$



III.D | Understanding the Friction Angle λ

- The coefficient of friction μ at the tool/chip interface and the resulting friction angle λ can be computed with:

$$\mu = \frac{F}{N} = \frac{F_c \sin\alpha + F_t \cos\alpha}{F_c \cos\alpha - F_t \sin\alpha} = \tan\lambda$$

- The friction angle is fundamental for the understanding of the ‘Energy minimization’ concept

III.D | Merchant's Concept

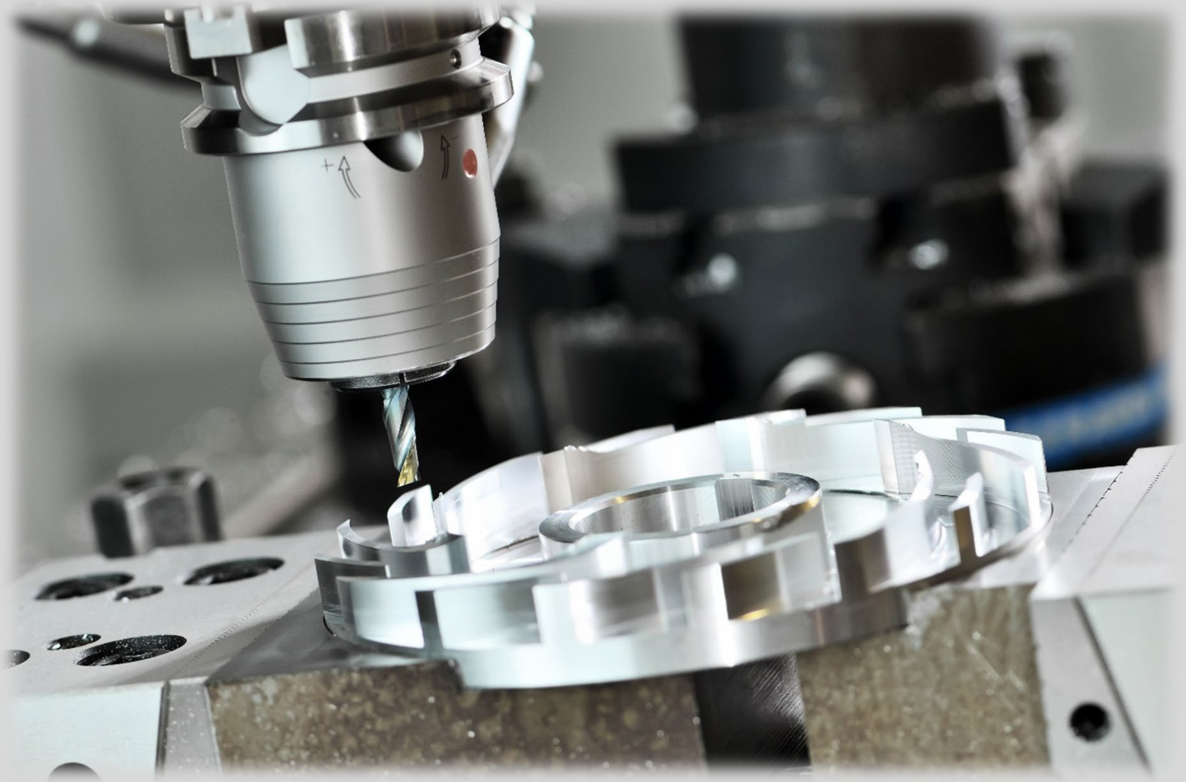
- Merchant Equation theoretical prediction of the **minimization of energy**

$$\varphi = 45 + \frac{\alpha}{2} - \frac{\lambda}{2}$$

- Zvorykin's law

$$\varphi = A_1 + A_2\,(\alpha - \lambda)$$

- **A1** and **A2** constants are experimentally obtained



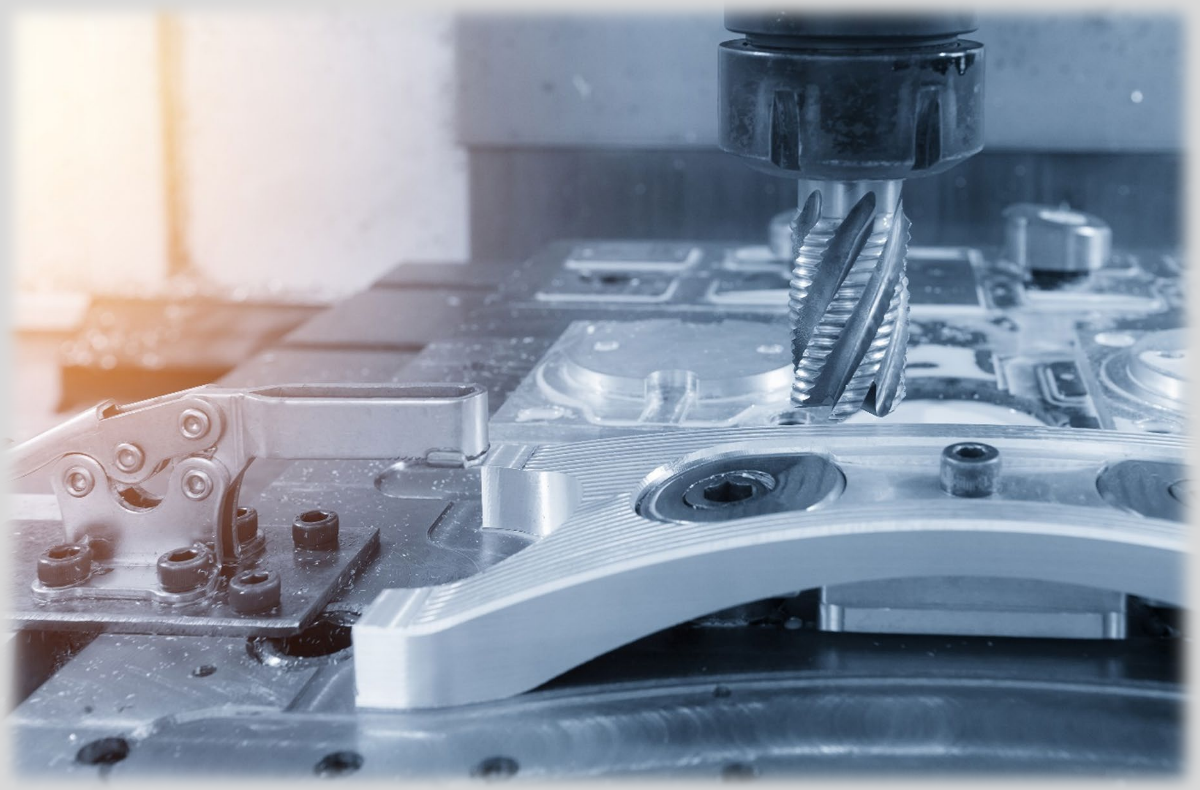
III.E | Power Requirements

- Total power used by the cutting operation $\boldsymbol{P_c}$ is computed as

$$P_c = F_c V$$

- To validate that a certain machine can perform a calculated function, we need to account for the machine efficiency η .

- The power is connected as well to the operation cutting conditions.



Knowledge Check

What is the value of the shear force if the cutting force is equal to 1500 N and the thrust force is equal to 1000 N ?

A. 1616 N
B. 799 N
C. 1647 N
D. 2000 N

Knowledge Check

What is the value of the shear force if the cutting force is equal to 1500 N and the thrust force is equal to 1000 N ?

A. 1616 N
B. 799 N
C. 1647 N
D. 2000 N

$$F_s = F_c \cos \varphi - F_t \sin \varphi$$

$$F_s = 1500 \cos 30 - 1000 \sin 30$$

Knowledge Check

And the shear stress if the width of cut is 10 mm ?

A. 68.90
B. 6.29
C. 2015.55
D. 159.80

Knowledge Check

And the shear stress if the width of cut is 10 mm ?

A. 68.90
B. 6.29
C. 2015.55
D. 159.80

$$A_s = \frac{t_0 w}{\sin \varphi} = \frac{0.25 \ * 25.4 \ * 10}{\sin 30}$$

$$A_s = 127 \ mm^2$$

$$S = \frac{F_S}{A_S} = \frac{799}{127} = 6.29 \ MPa$$

III.F | Cutting Conditions

- In machining, we identify the following cutting conditions
  - V = Cutting Velocity
  - f = Feed rate
  - d = Depth of cut

- The above parameters defines all the other cutting parameters.

III.F | How do we Select the Cutting Conditions?

- Materials have an optimal SFM (Surface Feet per Minute) based on the tool material.
- The dimension of the tool, combined with the optimal SFM determines N the spindle speed RPM.

$$N = SFM \cdot \left(\frac{12}{Pi}\right) \cdot \frac{1}{Tool\ diameter}$$

- It is a common industrial practice to approximate the above equation with

$$N = SFM \cdot (4) \cdot \frac{1}{Tool\ diameter}$$

Part Material	Carbide Tool	HSS Tool
Aluminum	600	300
Copper	200	100
Cast Iron	100	50
Tool Steel	100	50
Titanium	100	50
Wood	800	400

Standard SFM values (guideline) in *ft per minute*
Various from multiple sources (estimates)

III.F | How do we Select the Cutting Conditions?

- The feed f is calculated also based on recommended values that are material depended.

$$f = IPT * nt * N$$

- IPT is provided by experimental tables, a couple of examples is given on the right.
- nt is the number of teeth the tool have.
- RPM is the spindle speed computed in the previous slide.
- f is in in/minute

Part Material	1/8”	3/4”
Aluminum	0.001	0.006
Copper	0.004	0.008
Cast Iron	0.002	0.006
Tool Steel	0.001	0.004
Titanium	0.002	0.004
Wood	0.003	0.025

Estimates for 0.05-0.25” depth of cut
Various from multiple sources (estimates)

Knowledge Check

What are the speed (in rpm) and feed (in ipm) for a facing operation on aluminum with a 1/8 diameter HSS tool, having 4 teeth?

A. 9167 RPM and 37 IPM
B. 300 RPM and 45 IPM
C. 8254 RPM and 545 IPM
D. 5478 RPM and 98 IPM

Knowledge Check

What are the speed (in rpm) and feed (in ipm) for a facing operation on aluminum with a 1/8 diameter HSS tool, having 4 teeth?

A. 9167 RPM and 37 IPM
B. 300 RPM and 45 IPM
C. 8254 RPM and 545 IPM
D. 5478 RPM and 98 IPM

$$N = SFM \,.\left(\frac{12}{Pi}\right).\frac{1}{Tool\ diameter}$$

$$N = 300\,.\left(\frac{12}{Pi}\right).\frac{1}{0.125} = 9167$$

$$f = IPT\ * nt\ * N$$

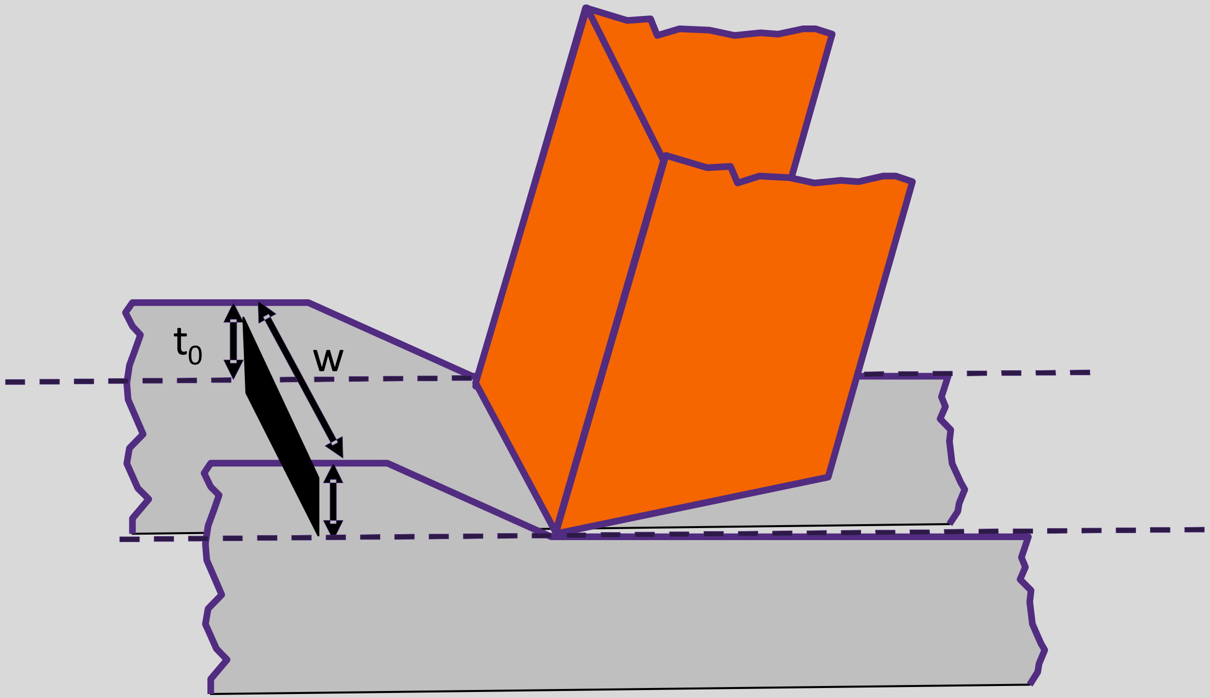
$$f = 0.001\ * 4\ * 9167 = 37$$

III.G | Material Removal Rate

- The cutting conditions (v, f, d) determines the rate of material removal R_{MR}
- The material removal rate can be computed as the uncut area multiplied by the tool movement
- The depth of cut d is the same as t_0
- The uncut area in milling is w.t_0

$$R_{MR} = f.(w.t_0)$$

- RMR is in in^3/minute



III.G | Specific Power

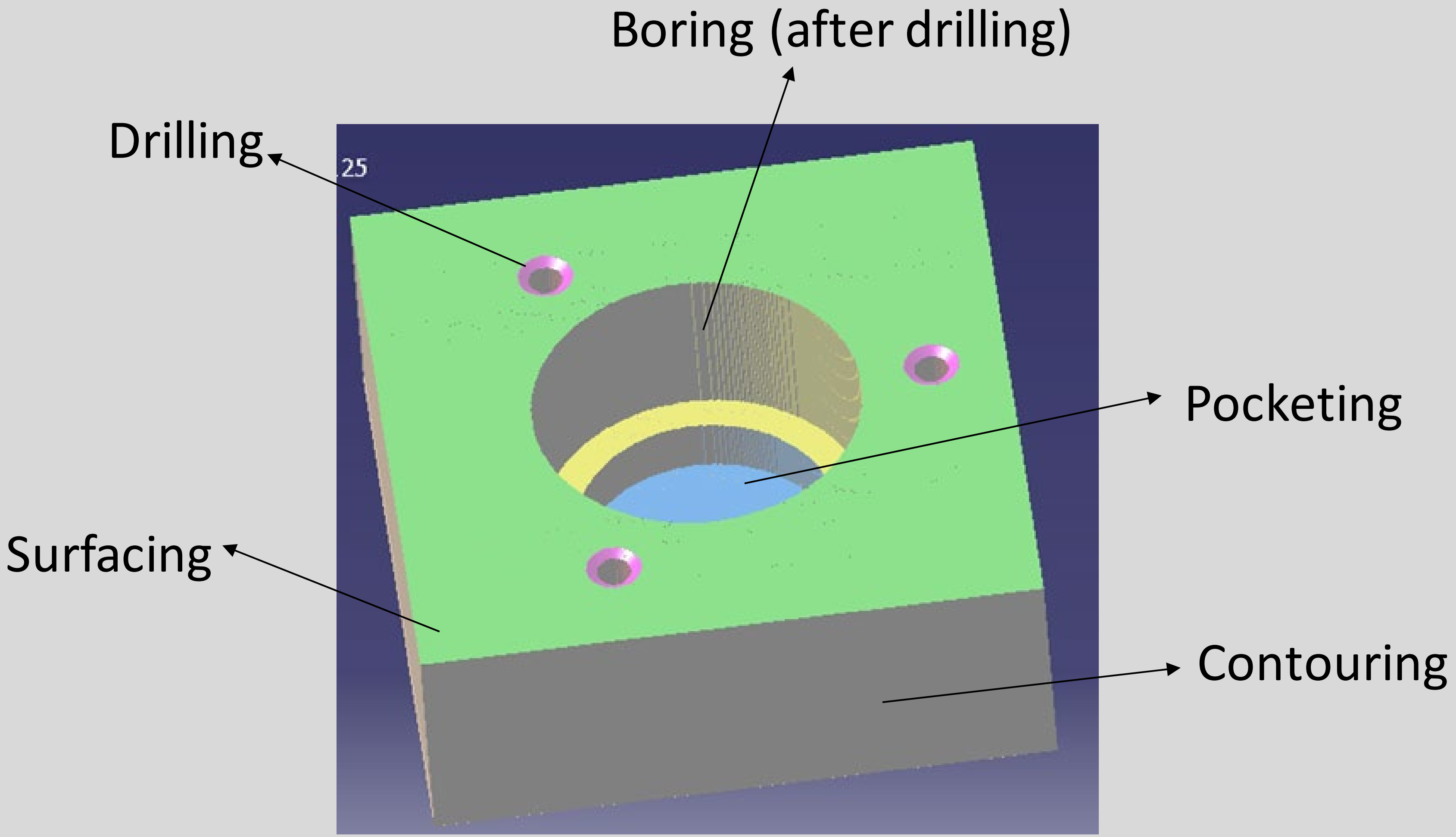
- The total energy is typically normalized by dividing the cutting power and the rate of material removal
- This energy value is computed by

$$u = \frac{P_c}{R_{MR}}$$

- The specific energy is composed of shear, friction, kinetic and surface energy
- Specific energies are readily accessible for most engineering materials and can be used from tables
- Sometimes a correction is needed for the experiment generated table

Specific energy of Aluminum is 0.25 hp/ (in^3/min)
0.7 N-m/mm³

III.H | Categorization of Milling Processes



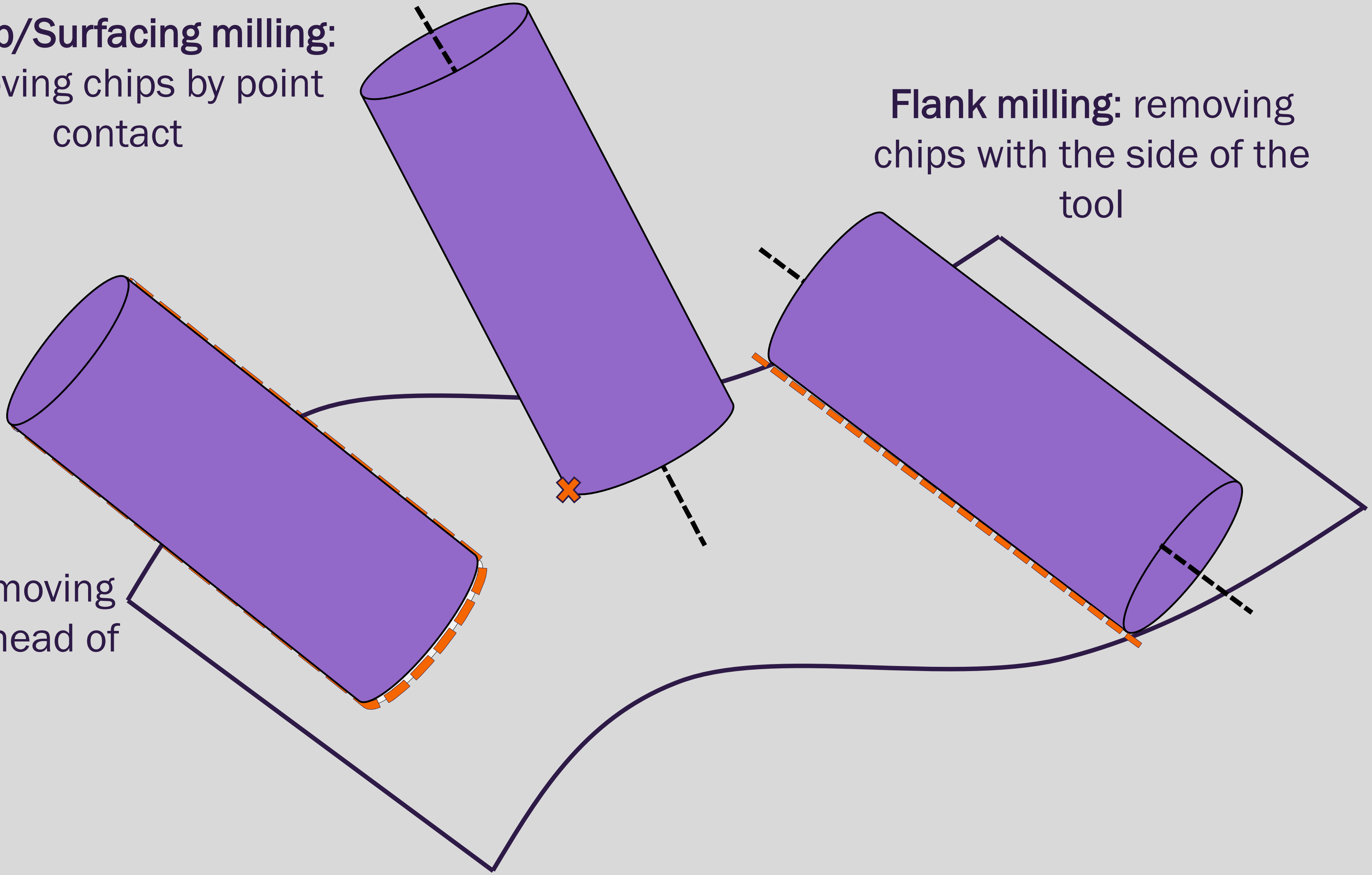
III.H | Categorization of Milling Processes

- Boring process to enlarge existing holes and achieve tight tolerance and/or surface finish

III.H | Categorization of Milling Processes

Sweep/Surfacing milling: removing chips by point contact

Flank milling: removing chips with the side of the tool



End milling: removing chips with the head of the tool

Knowledge Check

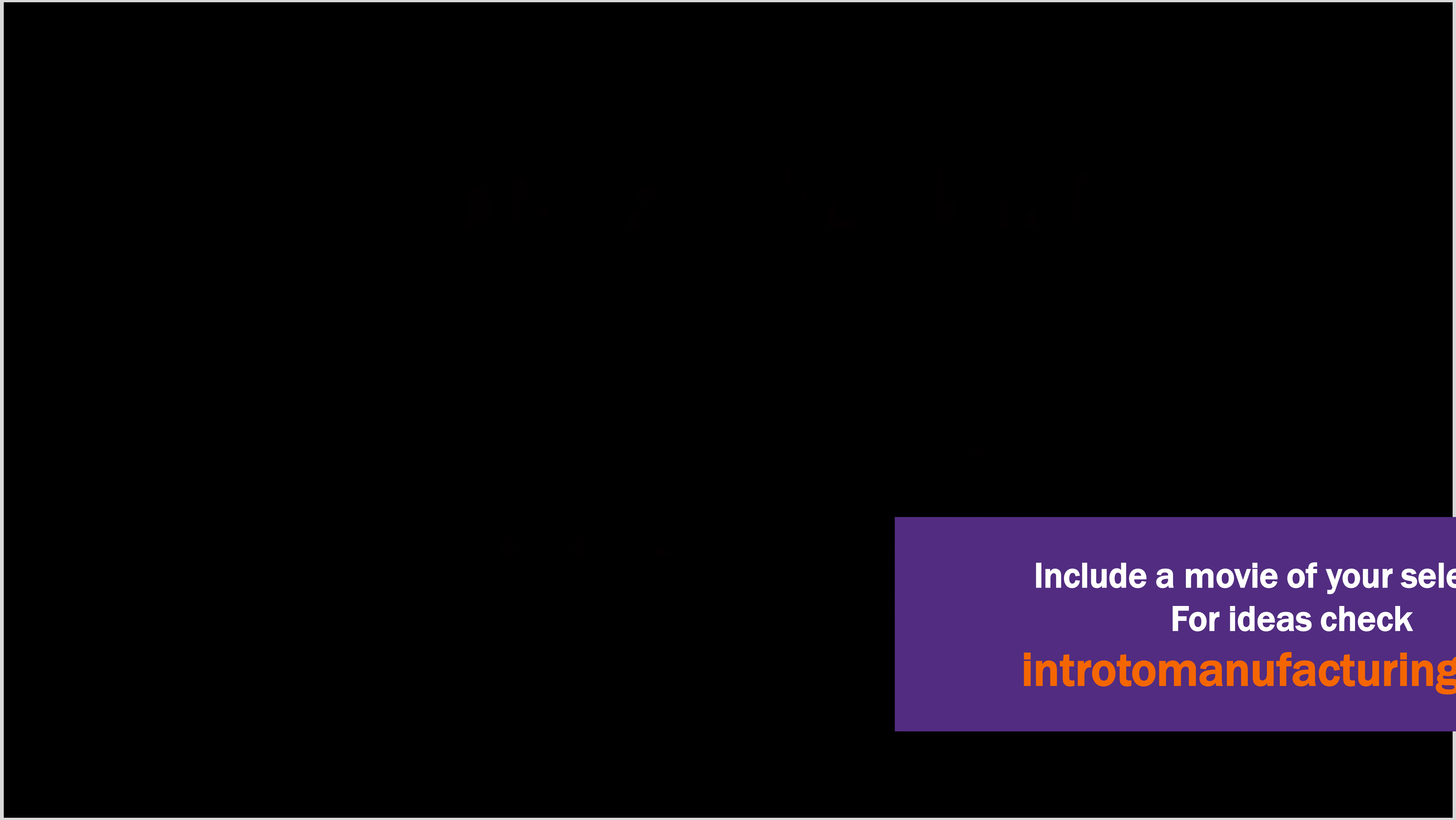
What is Flank milling?

A. Removing parts with the end of the tool
B. Removing parts with the side of the tool
C. Removing parts with the tip of the tool

Knowledge Check

What is Flank milling?

A. Removing parts with the end of the tool
B. **Removing parts with the side of the tool**
C. Removing parts with the tip of the tool



Include a movie of your selection.
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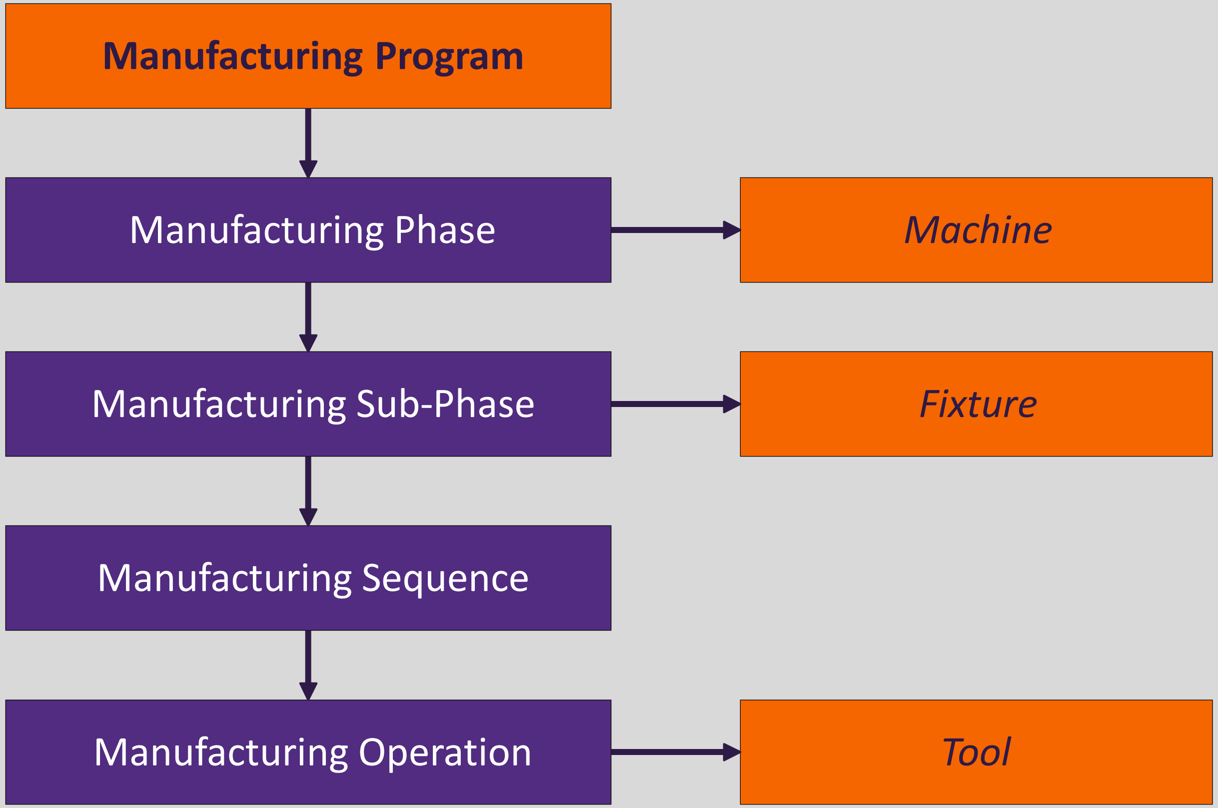
Drilling

Section IV

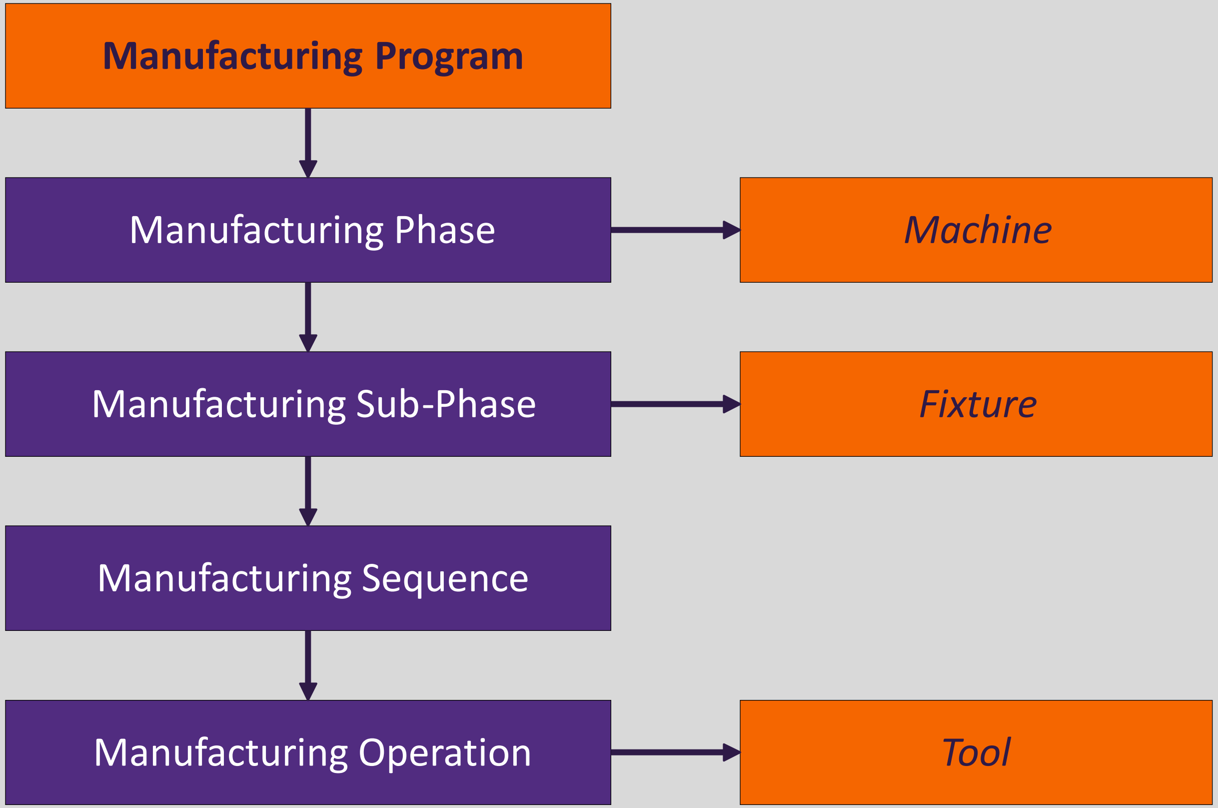
IV | Manufacturing Program

- Parts are typically manufactured using multiple Machines, Fixtures and Tools
- It is more economical usually, if the part holds multiple holes, to finish milling/turning on mills/lathe and then move the part to a drilling machine
- A new Manufacturing Phase is initiated for every new Machine used in the Manufacturing Program



IV | Manufacturing Program

- The most typical change is the usage of multiple cutting tools
- A new Manufacturing Operation is initiated for every new Manufacturing Tool used
- If the same tool is used to perform two different operations, i.e. an end mill used for pocketing and contouring, this identifies a new Manufacturing Sequence
- Finally, Manufacturing Sub-Phases are linked to the definition of new Manufacturing Fixtures
- We discuss referencing related to fixtures in the chapter on CAM



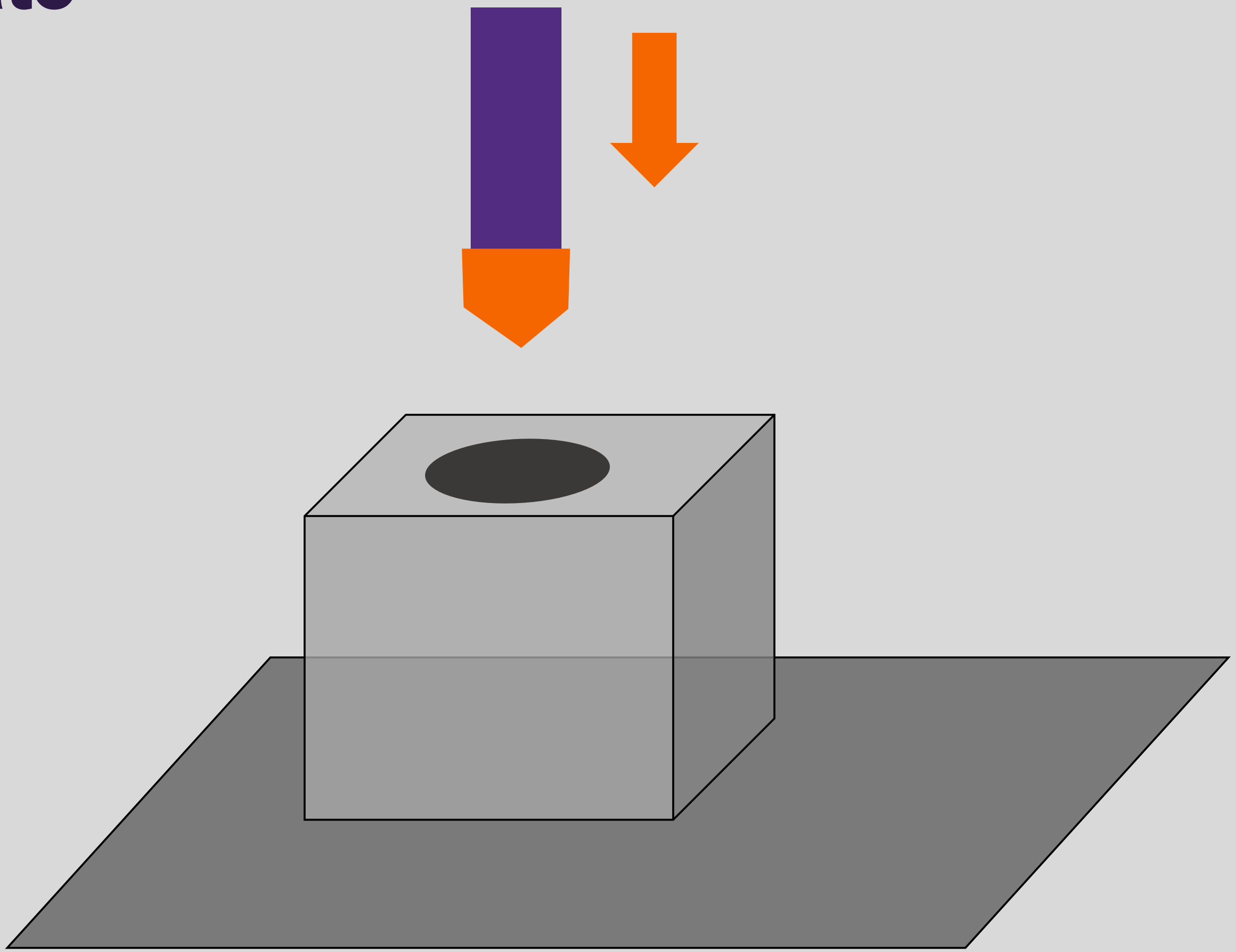
IV.A | Material Removal Rate

- The material removal rate can be computed as the uncut area multiplied by the tool movement
- The uncut area is a simple circular area dependent on the tool diameter

$$A = \frac{\pi D^2}{4}$$

- Feed can be computer similarly to milling, without taking into account the number of teeth

$$R_{MR} = f.\frac{\pi D^2}{4}$$



IV.A | Special Drilling Operations: Reaming

- Following drilling, multiple operations are possible on a drill press
- An example is the Reaming process used to slightly enlarge a drilled hole

IV.B | Special Drilling Operations: Tapping

- Following drilling, multiple operations are possible on a drill press

- An example is the Tapping process used to create internal threads in a hole

IV.C | Drill Press

- Drilling, which is a particular milling motion where the tool only moves along its axis, to create axial features, is done on a Drill Press

- The operator uses the handle to drive down the tool into the part

Knowledge Check

What is Reaming?

A. Creating a hole
B. Creating internal threads in a previously drilled hole
C. Slightly Enlarging a hole

Knowledge Check

What is Reaming?

A. Creating a hole
B. Creating internal threads in a previously drilled hole
C. Slightly Enlarging a hole

Knowledge Check

A drilling tool of diameter 0.5 in plunges into the part at a feed of 5 in/min, what is the rate of material removal?

A. 0.32 in3/min
B. 0.92 in3/min
C. 0.98 in3/min
D. 1.14 in3/min

Knowledge Check

A drilling tool of diameter 0.5 in plunges into the part at a feed of 5 in/min, what is the rate of material removal?

A. 0.32 in3/min
B. 0.92 in3/min
C. 0.98 in3/min
D. 1.14 in3/min

$$R_{MR} = f.\frac{\pi D^2}{4}$$

$$R_{MR} = 5.\frac{\pi 0.5^2}{4}$$

Include a movie of your selection.
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Turning

Section V

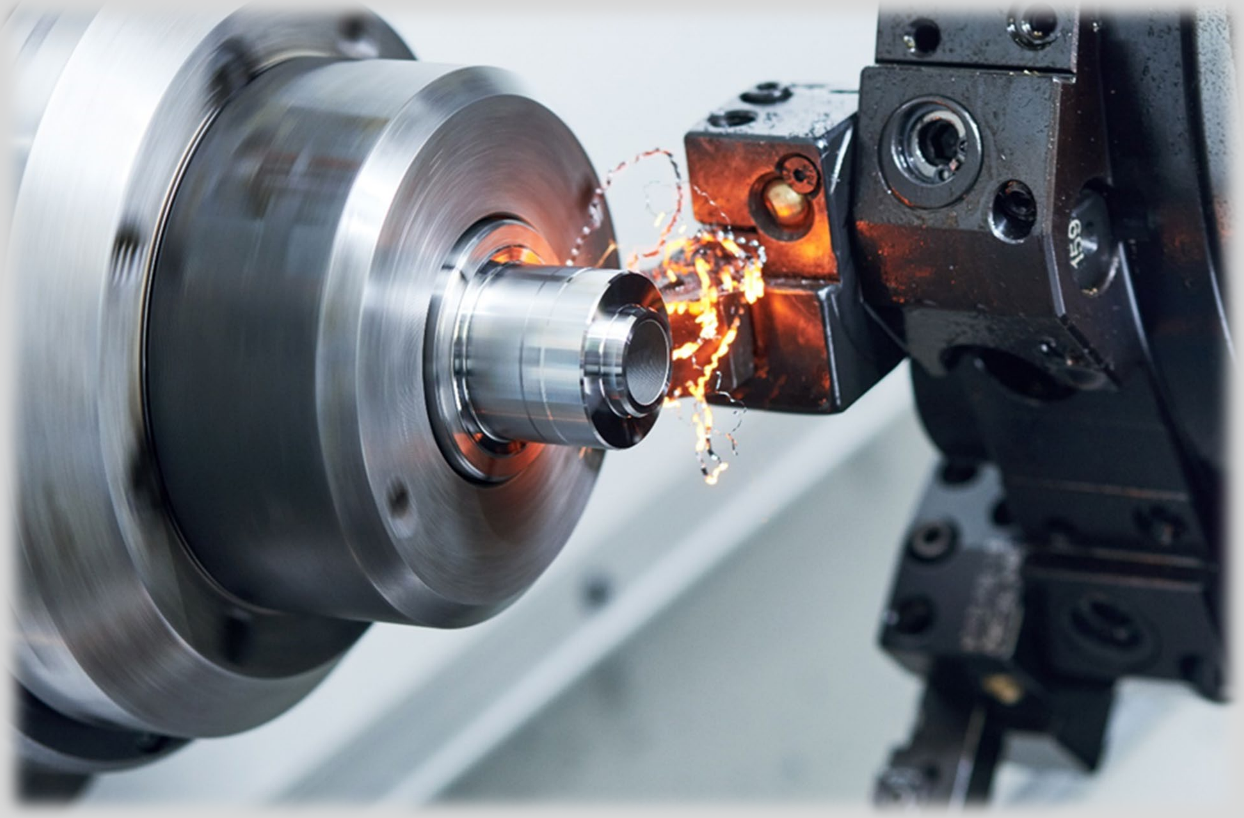
V | Lathe Machine

- Lathe machining produces Revolution Parts

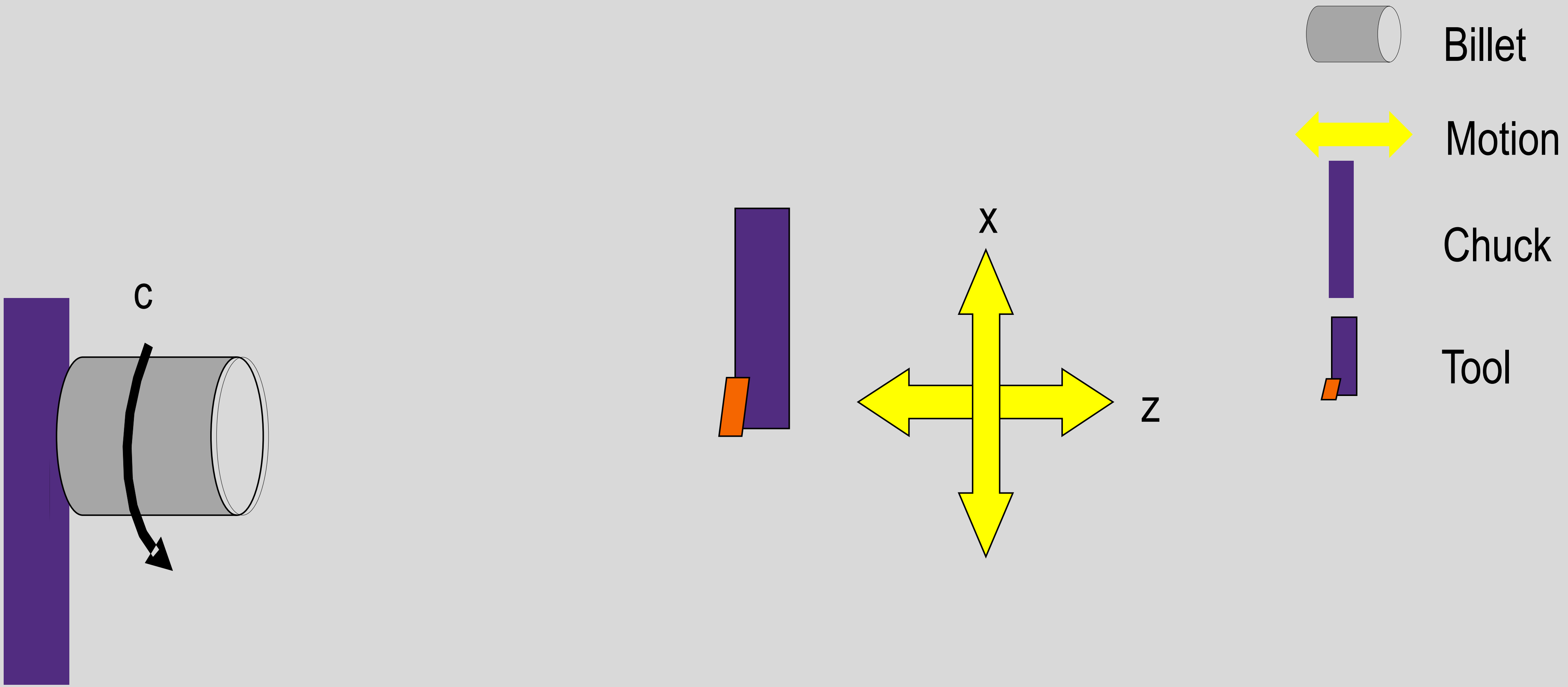
- Cutting tools in turning are single cutting points

- The motion of the turret, which holds the tools, is linear

- The work part itself is mounted on a spindle and rotates at high velocity



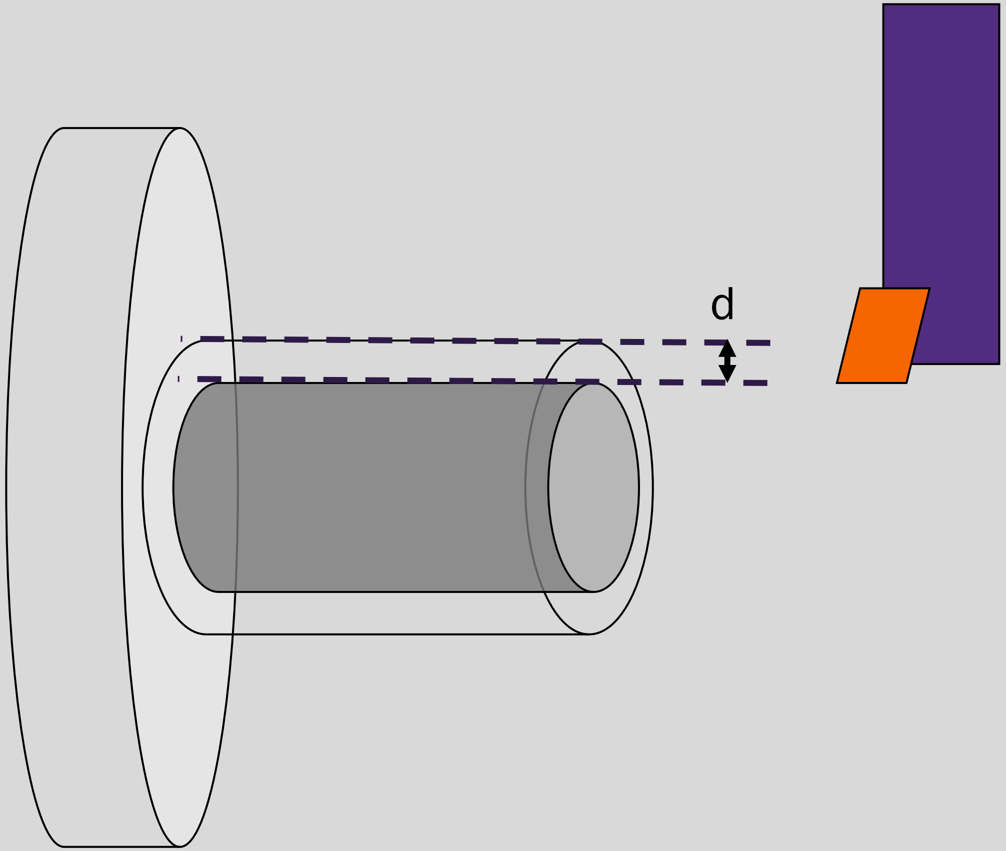
V | Lathe Configuration



V.A | Material Removal Rate

- The material removal rate can be computed as the uncut area multiplied by the tool movement
- The uncut area is computed on the next slide
- The depth of cut d, due to revolution, is generated on the full rotation of the part
- The relationship between the starting diameter D_o, the final diameter D_F and the depth of cut d is given by

$$d = \frac{D_o - D_F}{2}$$



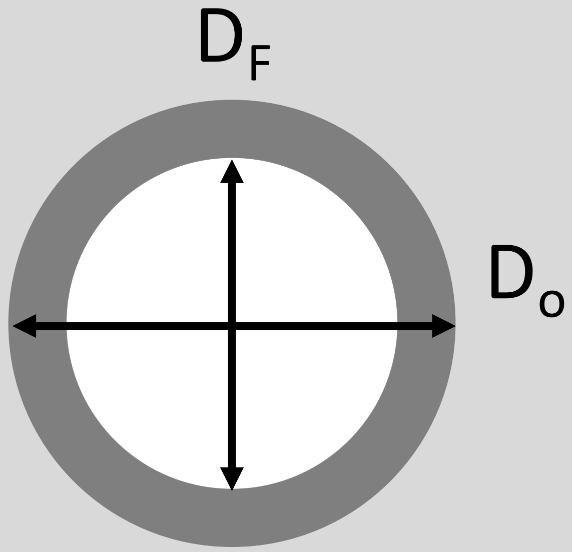
V.A | Material Removal Rate

- The uncut area is the gray area

$$A = \frac{\pi D_O^2}{4} - \frac{\pi D_F^2}{4}$$

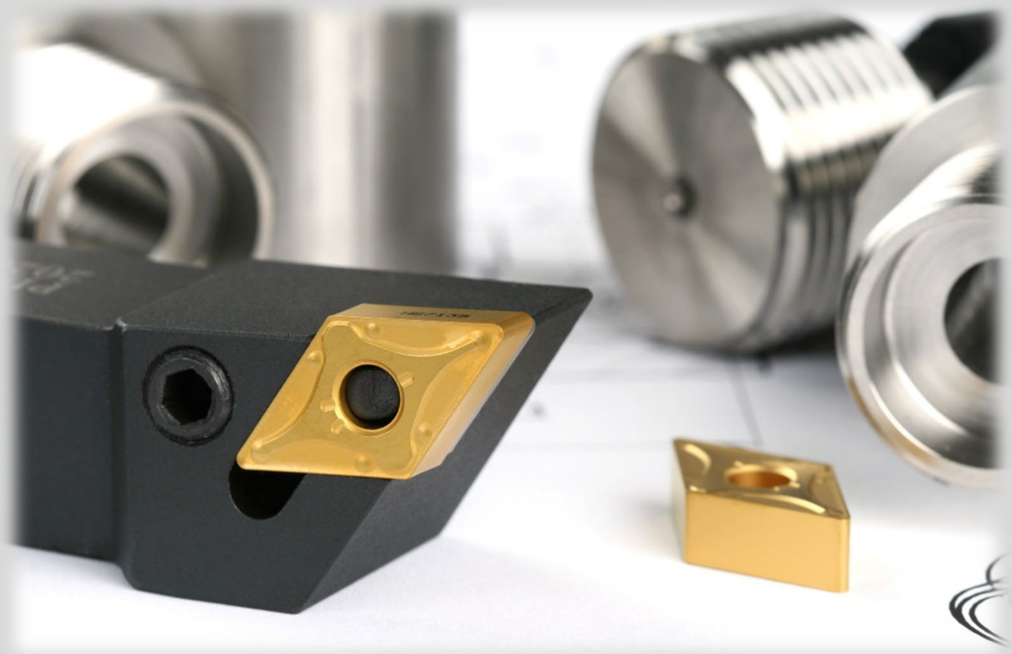
- Feed can be computer similarly to milling, where the number of teeth is 1, since turning tool are single cutting points

$$R_{MR} = f.\left(\frac{\pi D_O^2}{4} - \frac{\pi D_F^2}{4}\right)$$



V.B | Single vs Multi Cutting Points

Single Cutting Tool



Multi Cutting Tool

V.B | Single vs Multi Cutting Points

- Tools in Turning are single cutting point tools

- The tip of the tool holds the insert that performs the chip removal operation

- Narrow insert angles are most suitable for Finishing Operations

Knowledge Check

A turning operation on a 40 mm diameter blank has a depth of cut of 3 mm, what is the resulting final diameter?

A. 40
B. 37
C. 34
D. 31
E. 28

Knowledge Check

A turning operation on a 40 mm diameter blank has a depth of cut of 3 mm, what is the resulting final diameter?

A. 40
B. 37
C. 34
D. 31
E. 28

$$d = \frac{D_o - D_F}{2}$$

$$3 = \frac{40 - D_F}{2}$$

$$D_F = 34$$

Knowledge Check

If the previous problem is conducted with a feed of 20 mm/min on aluminum, what would be the power needed (in watts) to perform the operation?

A. 81 watts
B. 123 watts
C. 318 watts
D. 512 watts

Knowledge Check

If the previous problem is conducted with a feed of 20 mm/min on aluminum, what would be the power needed (in watts) to perform the operation?

A. 81 watts
B. 123 watts
C. 318 watts
D. 512 watts

u=0.7 N-m/mm^3

$$R_{MR} = 20.\left(\frac{\pi 40^2}{4} - \frac{\pi 34^2}{4}\right)$$

$$P_c = u * R_{MR}$$

$$P_c = 0.7 * R_{MR}$$

Knowledge Check

The lathe available in the workshop has a power of 1 hp with an 86% efficiency. Can we use it to conduct the previously computed turning operation?

A. Yes

B. No

Knowledge Check

The lathe available in the workshop has a power of 1 hp with an 86% efficiency. Can we use it to conduct the previously computed turning operation?

A. Yes

B. No

81 W is 0.1 hp, with the 86% efficiency, we will need 0.12hp, which is smaller than 1hp

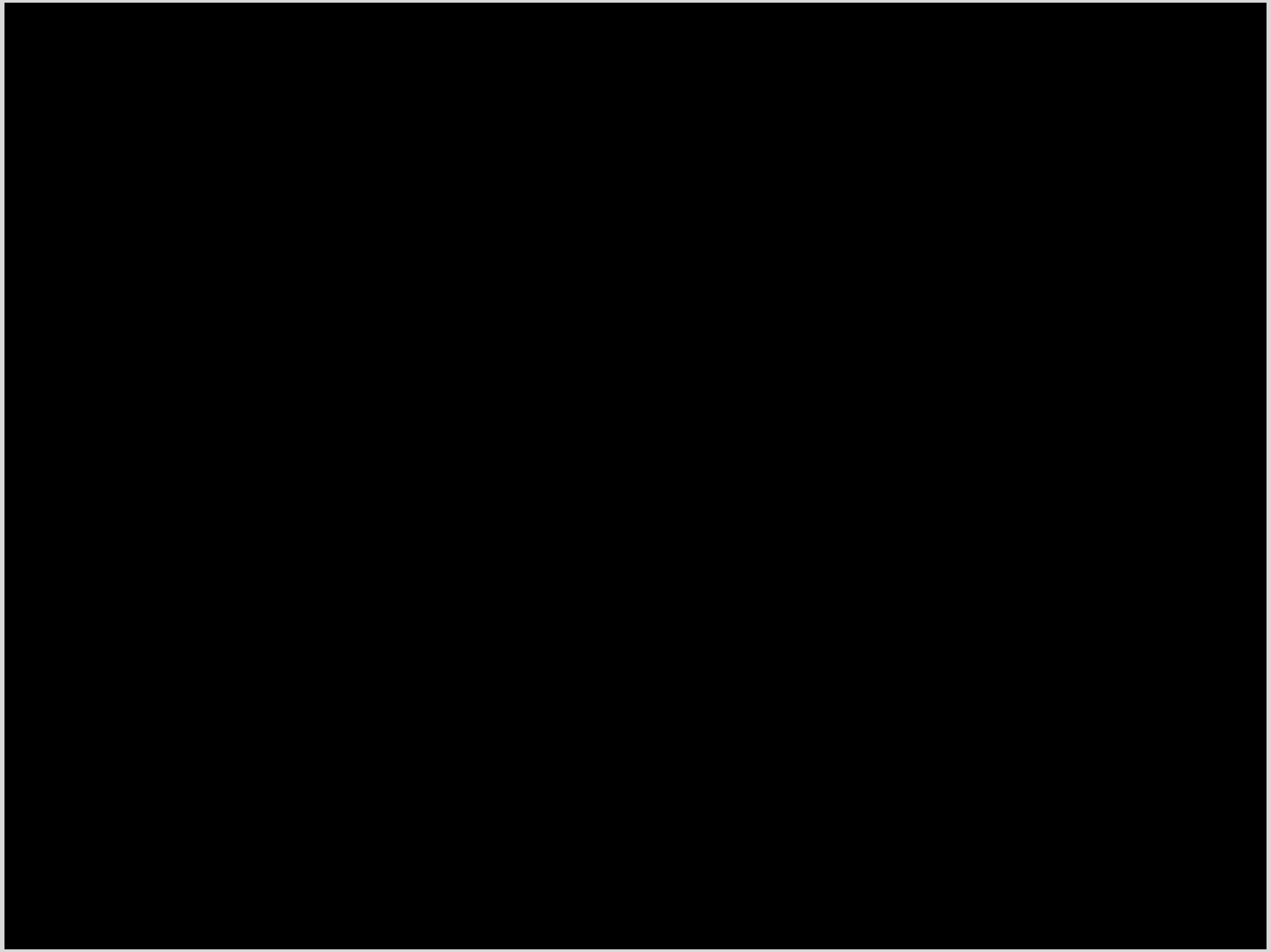
V.C | Roughing vs Finishing Operations

- In roughing operations, the target is to remove the maximum number of materials at a fast rate
- Attention is needed not to break the tool with the selected cutting conditions
- Typically, the depth of cut and the feed are increased, while the cutting velocity is decreased

- In finishing operations, the target is to obtain the desired surface quality
- Attention is needed not to decrease the surface quality or to generate marking
- Typically, the cutting velocity is increased, and we decrease the depth of the cut and the feed

V.C | Lathe Chuck

- The part in turning is subject to high rotation
- The fixture that holds the part is called Chuck
- The most widespread configuration is the three-chuck jaw



THANK YOU

- This set of slides is retrieved from the textbook: Intro to Advanced Manufacturing, Harik/Wuest, ISBN 978-0-7680-9327-8 978-0-7680-9327-8
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