

MANUFACTURING PROCESSES



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Humboldt

Manufacturing Processes

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Topic 01: Introduction to Manufacturing Processes

Manufacturing processes are the foundation of modern engineering, enabling the transformation of raw materials into functional components and finished products. Whether producing high-precision surgical implants, lightweight aerospace structures, or everyday consumer goods, manufacturing integrates science, design, and execution to bridge the gap between concept and reality.

This chapter introduces the core manufacturing processes that underpin mechanical engineering practice. Students will gain a comprehensive understanding of how materials are shaped, joined, and finished to meet specific functional, economic, and aesthetic goals. Drawing on principles from materials science, mechanical behavior, and process control, this topic emphasizes how process selection influences part performance, cost, tolerances, and scalability.

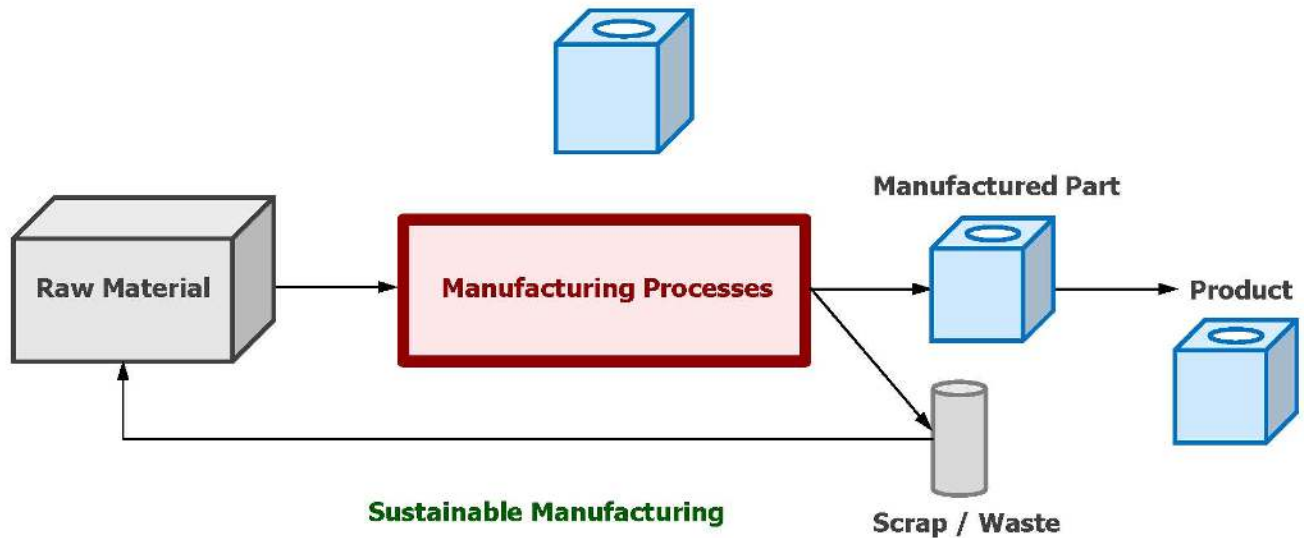
Manufacturing

Topic 01: Introduction

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“**manus (Hand)**” + **factus (I Do Make)**”

: the process of transforming _____ **materials** into _____
through coordinated application of human labor, machinery, tools, and automation



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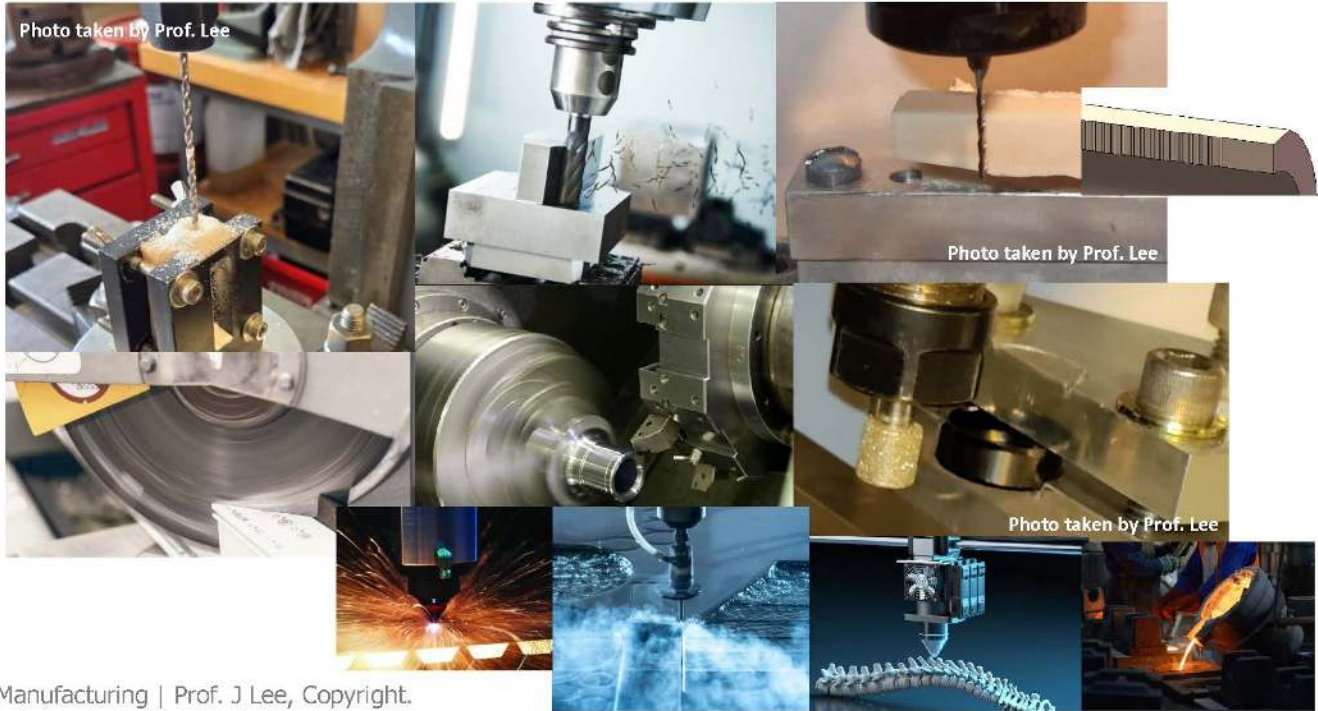
Core Requirements for Modern Manufacturing

- Products must fully meet the intended _____ requirements, specifications, and applicable _____ to ensure functionality and performance.
- Manufacturing processes should be carried out using the most _____-effective and environmentally _____ methods.
- _____ must be systematically integrated at _____ stage - from initial design through production and assembly - rather than relying solely on post-production inspection.
- Production methods must maintain sufficient _____ to _____ to evolving market demands, including variations in product types, production volumes, delivery schedules, and customer requirements.

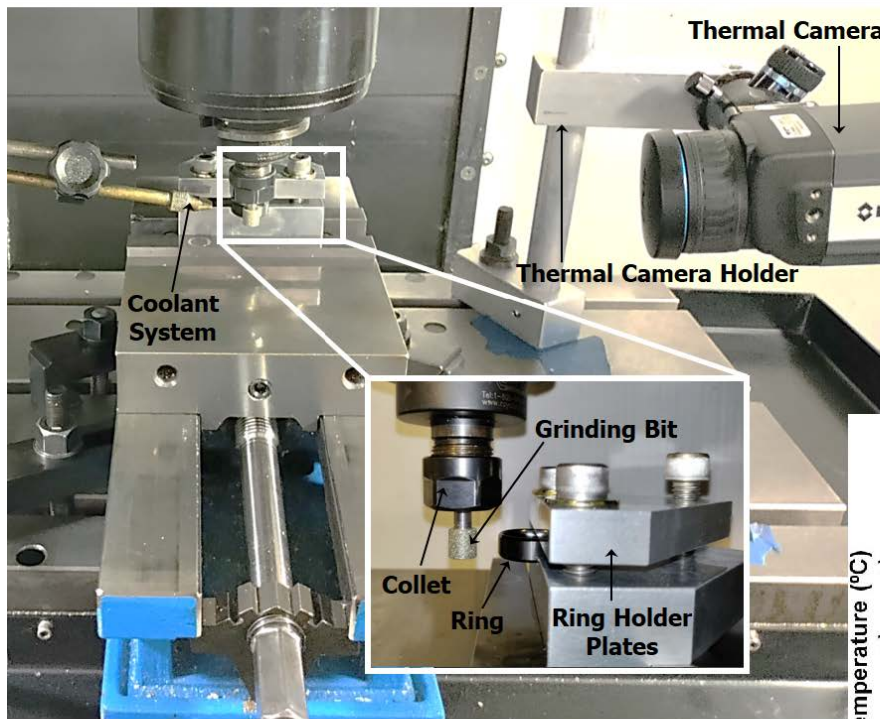
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Manufacturing Processes

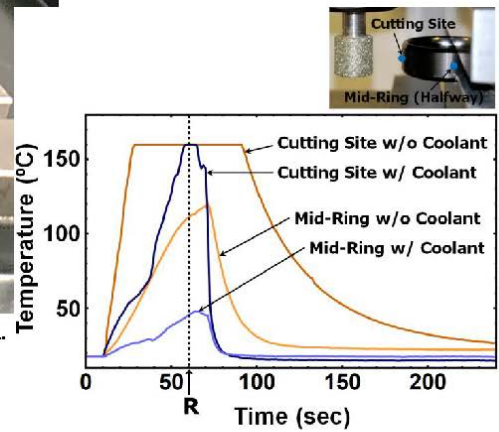
: to determine how it will be manufactured, selecting the most suitable _____, _____,
and _____ to transform the _____ into a physical _____.



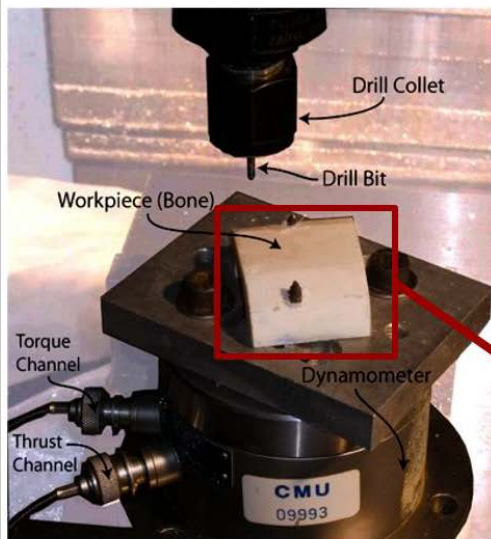
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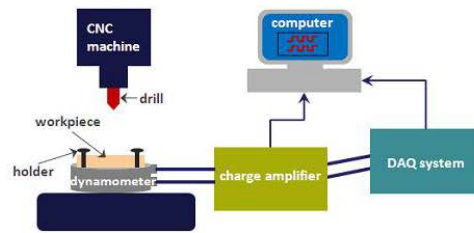
Lee *et al.* 2025, J. Bone and Joint Surgery. 50. 8-11.



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Lee *et al.* 2012. *J Biomechanics*. 45 (6). 1076-1083.

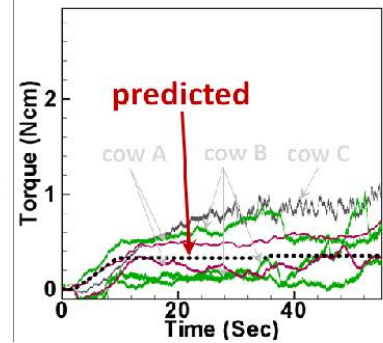
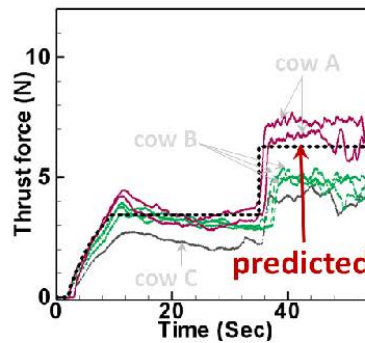


Schematic Image of the Setup

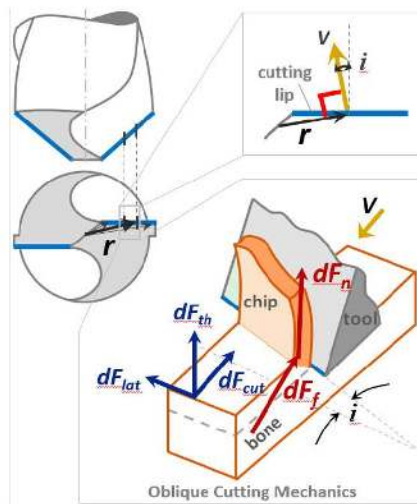


Thrust Force

Torque



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Elemental Forces along the Cutting Lips

$$dF_{cut}$$

$$dF_{th} = f(dF_n, dF_f)$$

$$dF_{lat}$$

Elemental Thrust Force and Torque

$$dF_{thrust} = f(dF_{th}, dF_{lat})$$

$$dT = f(r, F_{cut})$$

Total Drilling Forces

$$F_{thrust} = \sum \sum_{lips \ elements} dF_{thrust}$$

$$T = \sum \sum_{lips \ elements} dT$$

$$\overline{dF_{th}} = \overline{dF_f} \cos \gamma_n \cos \eta_c - \overline{dF_n} \sin \gamma_n$$

Thrust Force

$$\overline{dF_{ns}} = \overline{dF_f} (\sin \eta_c \sin \lambda + \sin \gamma_n \cos \eta_c \cos \lambda) + \overline{dF_n} \cos \gamma_n \cos \lambda$$

Cutting Force

$$\overline{dF_{lat}} = -\overline{dF_f} (\sin \eta_c \sin \lambda + \sin \gamma_n \cos \eta_c \sin \lambda) + \overline{dF_n} \cos \gamma_n \sin \lambda$$

Lateral Force

Elemental forces on the cutting lip

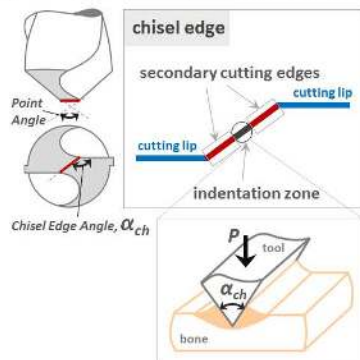
$$\overline{dF_z} = \overline{dF_{th}} \frac{\cos \beta_w \sin p}{\cos \lambda} - \overline{dF_{lat}} \frac{\cos p}{\cos \lambda}$$

Total forces on the cutting lip

$$\overline{F_z} = \sum \sum_{lips \ elements} \overline{dF_z}$$

$$\overline{dM_z} = \overline{r_{el}} \overline{dF_{cut}}$$

$$\overline{M_z} = \sum \sum_{lips \ elements} \overline{dM_z}$$



Indentation Zone

Not by Cutting, But by **Extrusion**

Radius of Indentation Zone

$$R_{ind} = f(\text{Feed}, \text{Point Angle})$$

Forces on the Indentation Zone

$$F_{thrust} = f(P, \alpha_{ch})$$

$$T = f(P, \alpha_{ch}, R_{ind})$$

Radius of the Indentation Zone

$$R_{ind} = \frac{f_r}{2 \tan(\frac{\pi}{2} - p)}$$

f_r | feed rate
 $2p$ | point angle

Indentation Forces

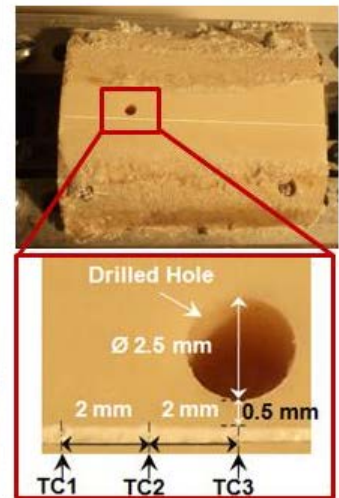
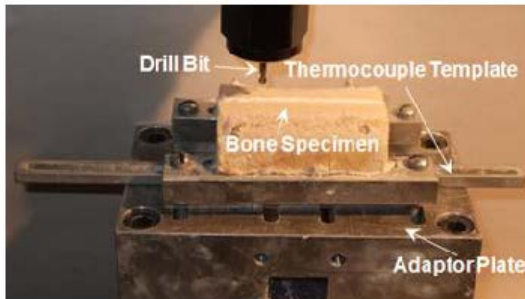
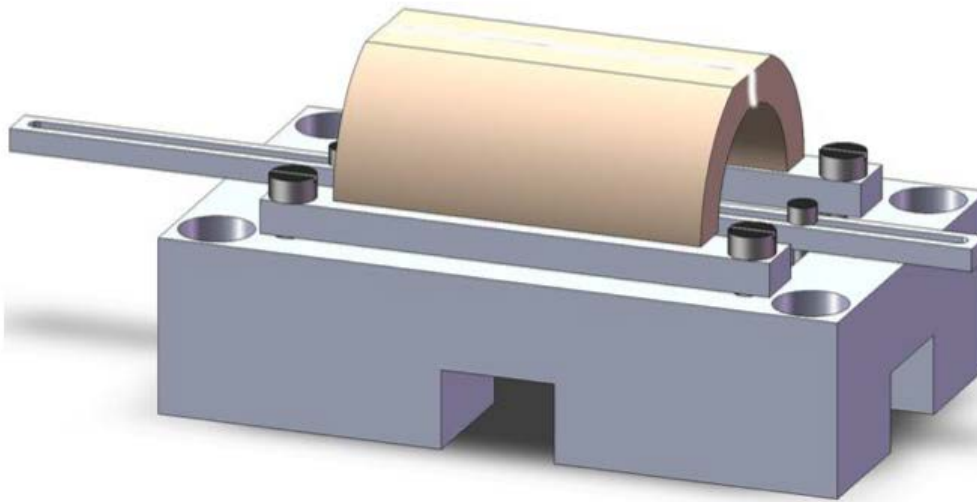
$$Th_{ind} = 2P \sin \phi_w$$

$$T_{ind} = P \cos \phi_w R_{ind}$$

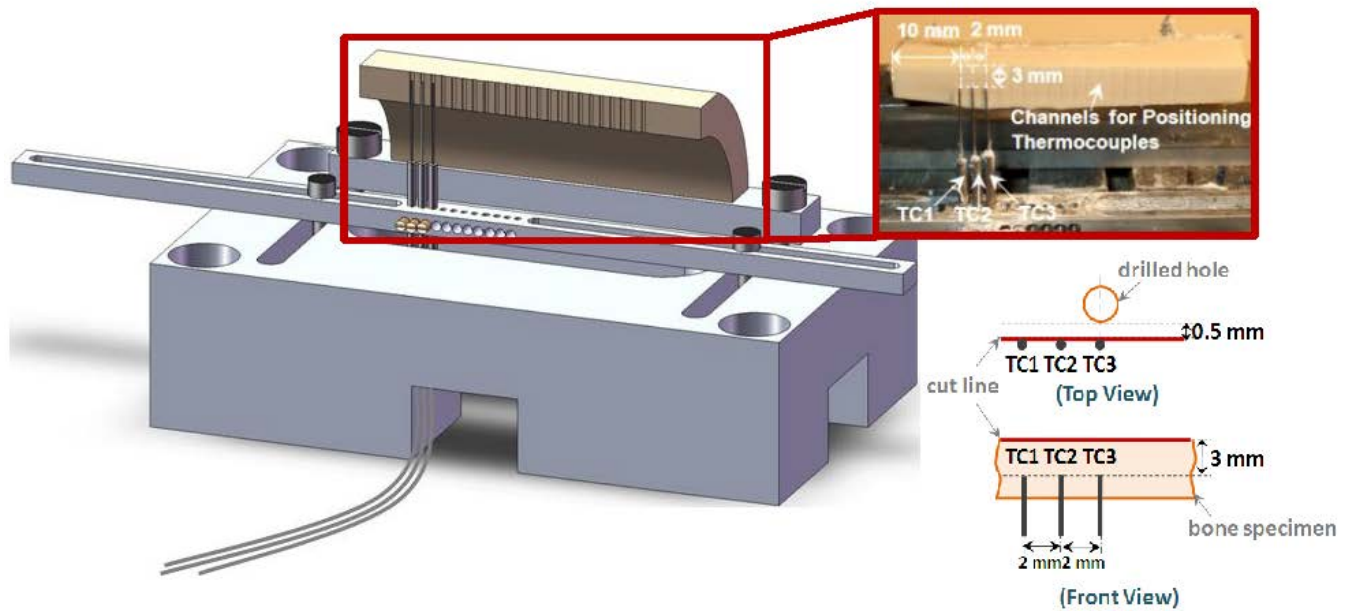
$2\phi_w$ | the wedge angle P | the normal force

Lee et al. 2012. J Biomechanics. 45 (6). 1076-1083.

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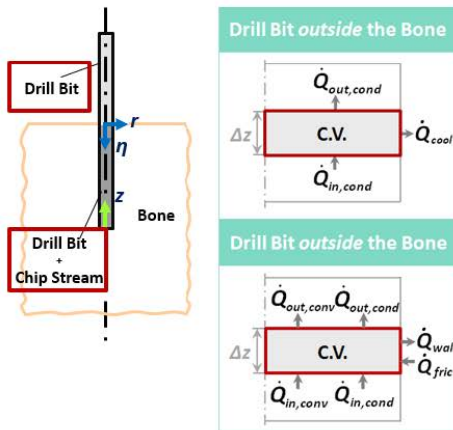


Lee *et al.* 2012. Med. Eng. Phys. 34(10), 1510-1520.



Lee et al. 2012. Med. Eng. Phys. 34(10), 1510-1520.

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Lee et al. 2011. Med. Eng. Phys. 33(10), 1234-1244.

$\Omega = 0$: when outside the bone
 $\Omega = 1$: when inside the bone

$$(\Omega \rho_c A_c C_{p,c} + \rho_d A_d C_{p,d}) \frac{\partial T}{\partial t} = (\Omega k_c A_c + k_d A_d) \frac{\partial^2 T}{\partial z^2} - \Omega \rho_c A_c C_{p,c} \frac{\partial T}{\partial z} + 2\Omega k_b \pi R \frac{\partial T}{\partial r} \Big|_{r=R^+} + 2(\Omega - 1) h \pi R (T - T_\infty)$$



B.C. at the drill tip ($z=0$)

$$\dot{Q}_T = -(k_d A_d + k_c A_c) \frac{\partial T}{\partial z} \Big|_{z=0} + k_b (A_d + A_c) \frac{\partial T}{\partial r} \Big|_{r=R}$$

Heat generated at drill tip

$$\dot{Q}_T = \dot{Q}_s + \dot{Q}_f$$

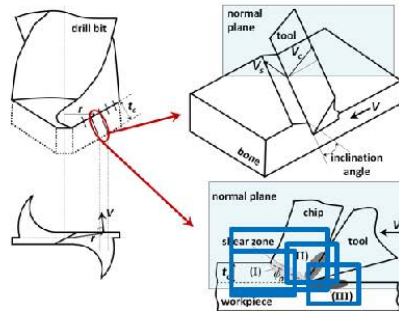
$$\dot{Q}_s = \zeta \dot{Q}_{sh}$$

$$\dot{Q}_{sh} = F_s V_s$$

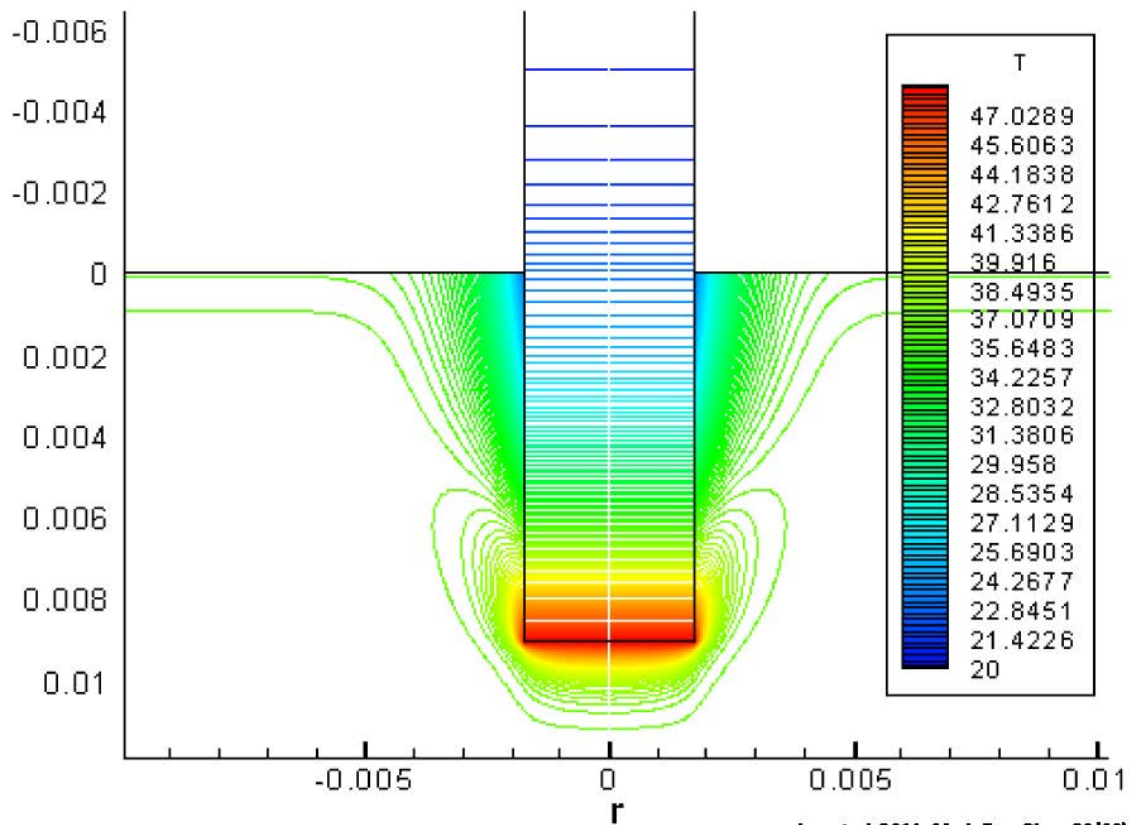
$$\zeta = \begin{cases} 0.5 - 0.35 \log(R_t \tan \phi_n) & \text{if } 0.04 < R_t \tan \phi_n \leq 10 \\ 0.3 - 0.15 \log(R_t \tan \phi_n) & \text{if } 10 < R_t \tan \phi_n \end{cases}$$

$$R_t = \frac{1}{k} (\rho C_p l_c V_c)$$

(Boothroyd, 1963)

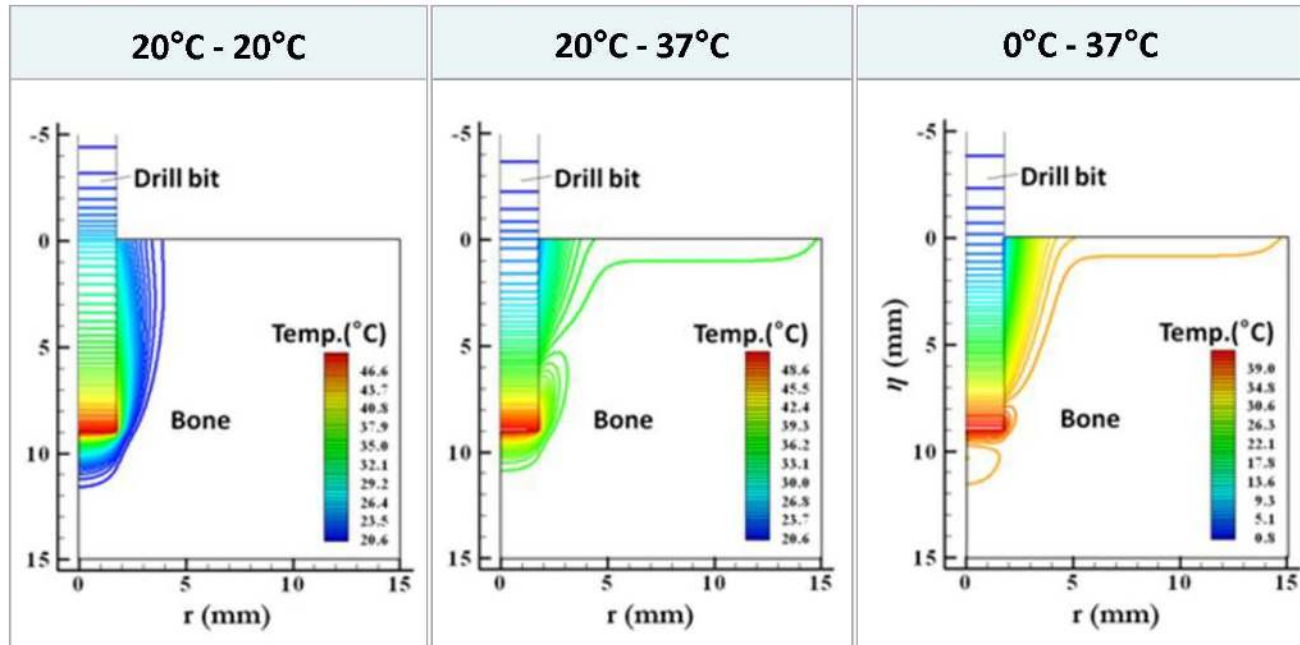


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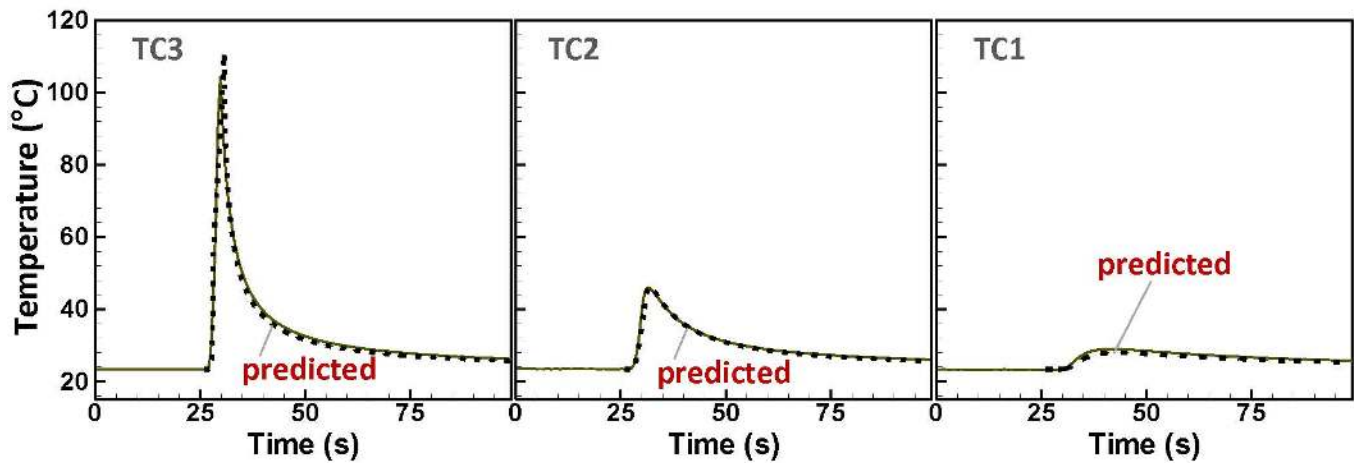
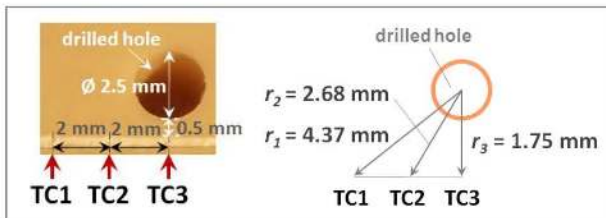
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Lee *et al.* 2011. Med. Eng. Phys. 33 (10), 1234-1244.

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Lee *et al.* 2017. Proceedings of the ASME 2016 IMECE, Vol 3, V003T04A058.

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Tool Selection



Image ref. Jackspaint.co.za

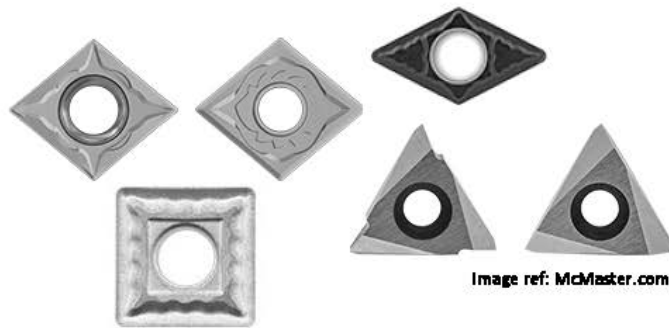


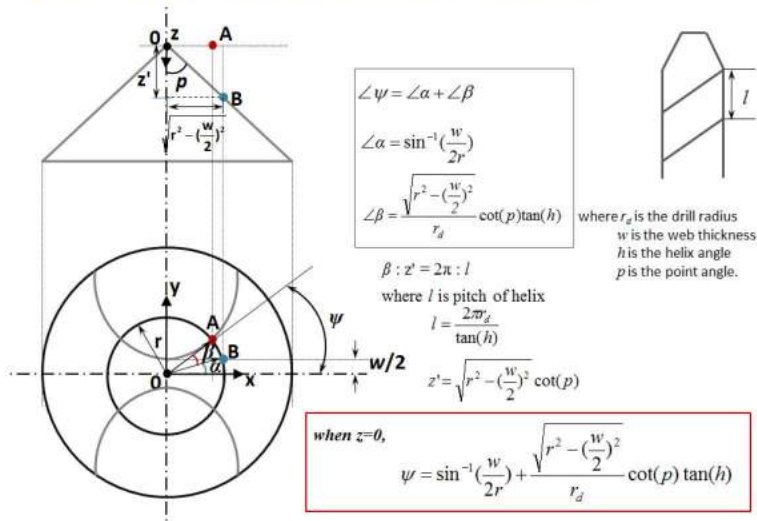
Image ref: McMaster.com



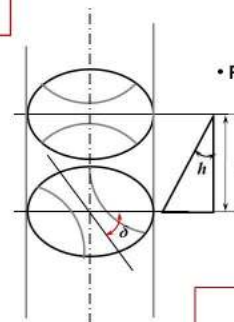
Image ref. hamedepot.com

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Tool Design: Mathematical Modeling



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- Flute rotation with different z elevations

$$\tan(h) = \frac{r_d \delta}{z}$$

$$\therefore \delta = \frac{z}{r_d} \tan(h)$$

$$\psi = \sin^{-1}\left(\frac{w}{2r}\right) + \frac{\sqrt{r^2 - \left(\frac{w}{2}\right)^2}}{r_d} \cot(p) \tan(h) + \frac{z}{r_d} \tan(h)$$

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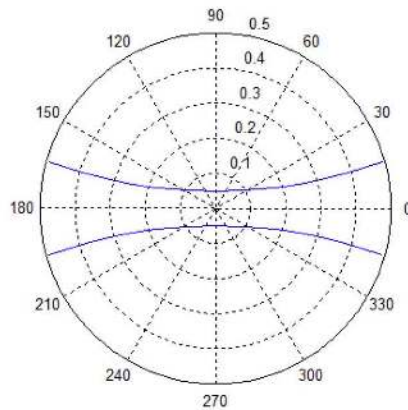
Tool Design: Simulations

when $z=0$,

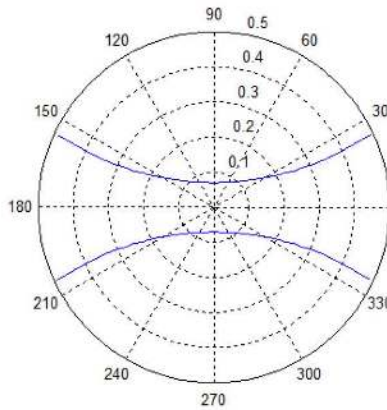
$$\psi = \sin^{-1}\left(\frac{w}{2r}\right) + \frac{\sqrt{r^2 - \left(\frac{w}{2}\right)^2}}{r_d} \cot(p) \tan(h)$$



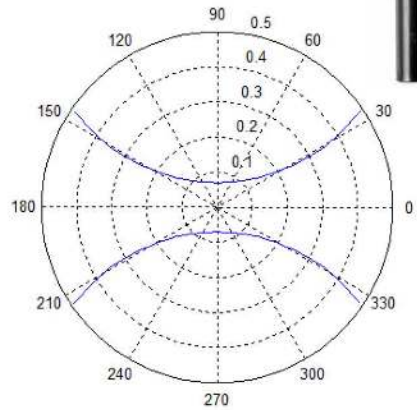
$h = 30^\circ, 2p = 118^\circ$



$h = 45^\circ, 2p = 118^\circ$



$h = 45^\circ, 2p = 95^\circ$



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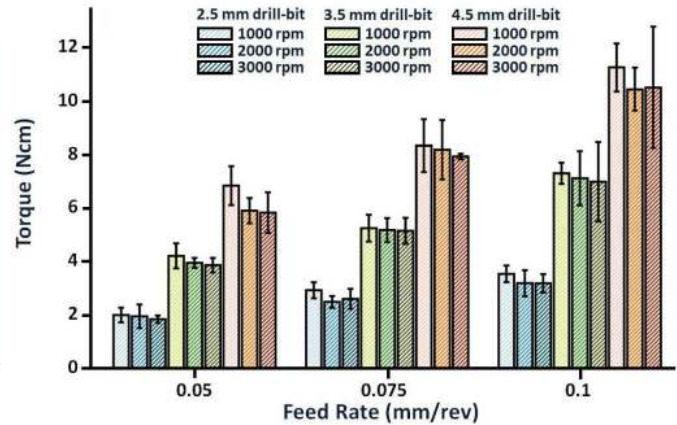
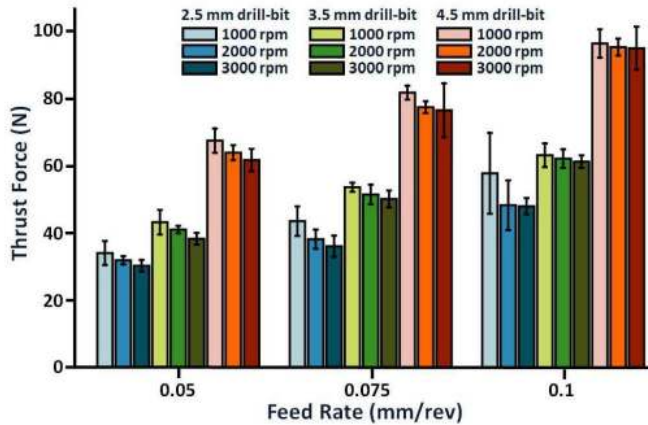
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Machining Operation Conditions

Topic 01 – 17



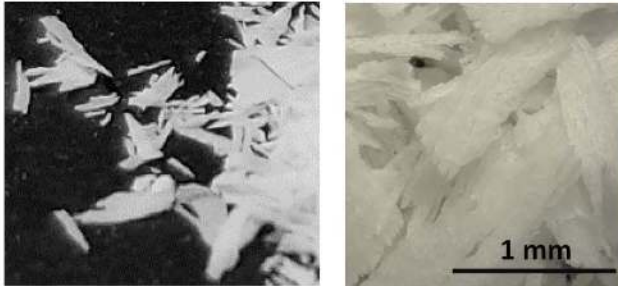
- Drilling Depth: 7 and 36 mm
- Drill-Bit Diameter: 2.5, 3.5, and 4.5 mm
- Spindle Speed: 1000, 2000, and 3000 rpm
- Feed Rate: 0.05, 0.075, and 0.1 mm/rev



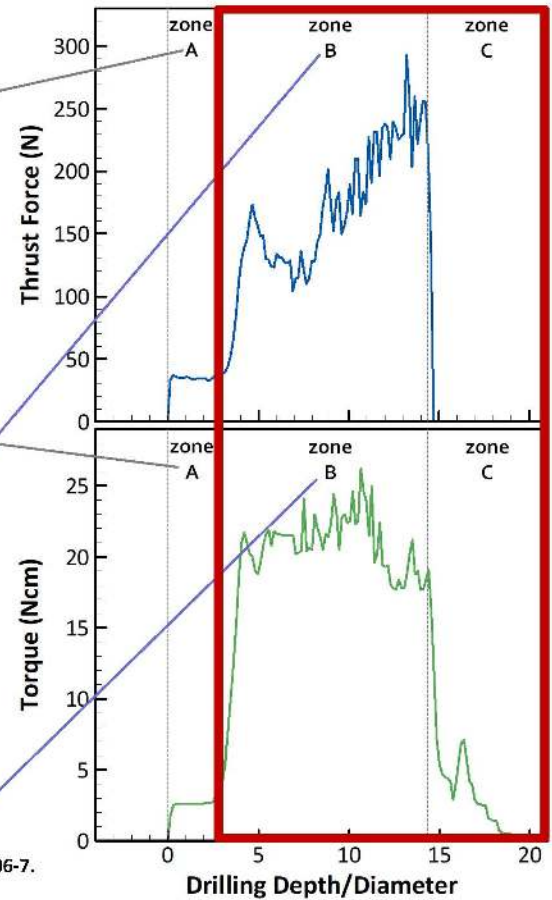
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Lee *et al.* 2025. ASME J of Eng and Sci in Med Diagnostics & Therapy.

At 7 mm Drilling Depth: *Fragmented Chip Type*



At 20 mm Drilling Depth: *Powdery Chip Type*



Lee *et al.* 2020. ASME J of Eng and Sci in Med Diagnostics & Therapy, 3(3), 031006-1-031006-7.

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Topic 02: Engineering Drawing Review - Dimensioning

Topic 02 reviews the essential principles and best practices of engineering drawing and dimensioning, reinforcing foundational concepts introduced in the Engineering Graphics course. This chapter emphasizes the role of accurate dimensioning in supporting part fabrication, assembly, and mechanical functionality. It highlights key conventions that uphold design intent, ensure interchangeability, and facilitate proper fit within mechanical systems. While referencing ASME Y14.5 standards and practices observed at leading institutions, the focus remains on reinforcing existing knowledge and terminology to strengthen students' ability to communicate technical information precisely and effectively.

Manufacturing

Topic 02: Engineering Drawing Review : Dimensioning

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Create and interpret an engineering drawing following dimensioning rules

- Review "Drawing Standards" by ASME;
- Review multiview drawing
 - : define multiview drawing and understand its purpose
 - : understand orthographic projection method
 - : understand arrangement of orthographic views
 - : sketch multiview drawings with third angle projection (3D to 2D)
- Review to explain Dimensioning;
- Review the Principles of the Dimensioning
 - Types of Dimension
 - Unit Expression
- Review for the following cases
 - : Linear Dimension
 - : Angular Dimension
 - : Simple Hole Dimension
 - : Equally Spaced Hole Dimension
 - : Radius Dimension
 - : Arc Dimension
 - : Slot Dimension
 - : Fastener Hole Dimension
 - : ANSI Hole Depth Symbol
 - : ANSI Counterbore Symbol
 - : ANSI Countersink Symbol
- Review the dimensioning rules and apply to the practical problems

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Standards

- ASME Y14.5-2018 (R2024): Dimensioning and Tolerancing
- ASME Y14.1-2020: Drawing Sheet Size and Format.
- ASME Y14.5.1-2019: Mathematical Definition of Dimensioning and Tolerancing Principles
- ASME Y14.100-2017 (updated from 2004) Engineering Drawing Practices
- ASME Y14.4M-1989 (R2004): Pictorial Drawing
- ASME Y14.3-2012: Multi and Sectional View Drawings
- ASME Y14.1M-2012: Metric Drawing Sheet Size and Format
- ASME Y14.2-2008 (R2019): Line Conventions and Lettering
- ASME Y14.13M-1981 (R1995): Mechanical Spring Representation

Note

: Very Important **to follow the standards**

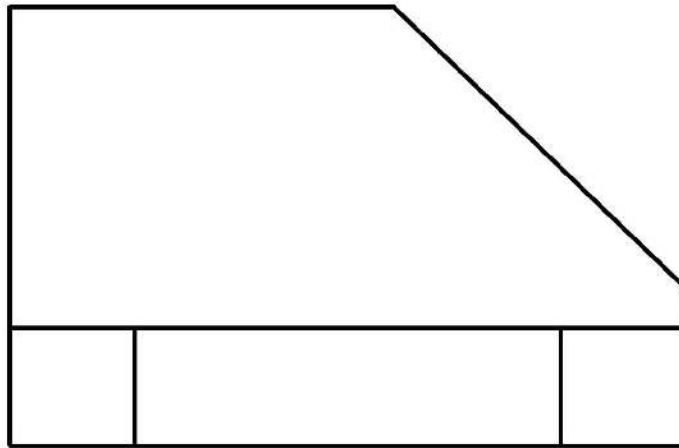
to ensure your drawings are interpreted correctly by others.

: Always **consult the standard** when it doubt!

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Why are multiple views required in an engineering drawing?

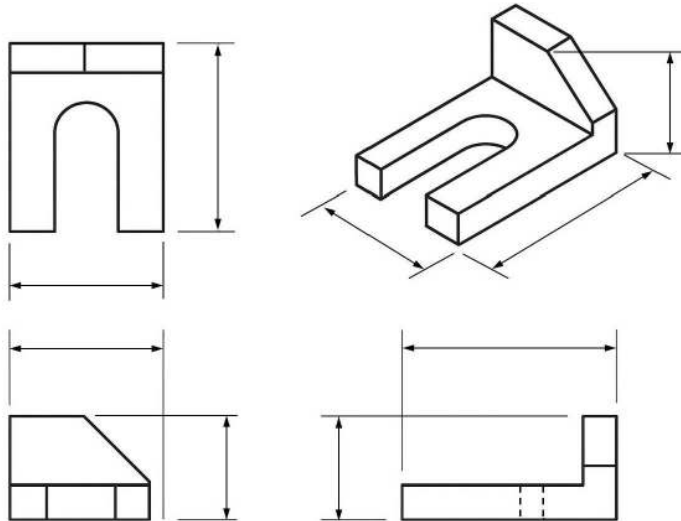
- What information does this single view provide about the object?



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What

- : Presents a series of ___-dimensional views that collectively represent an object with precision.
- : Clearly conveys all three principal dimensions - _____, _____, and _____ - using _____ projections for optimal interpretability in manufacturing and engineering contexts.



HEIGHT : Top-to-Bottom

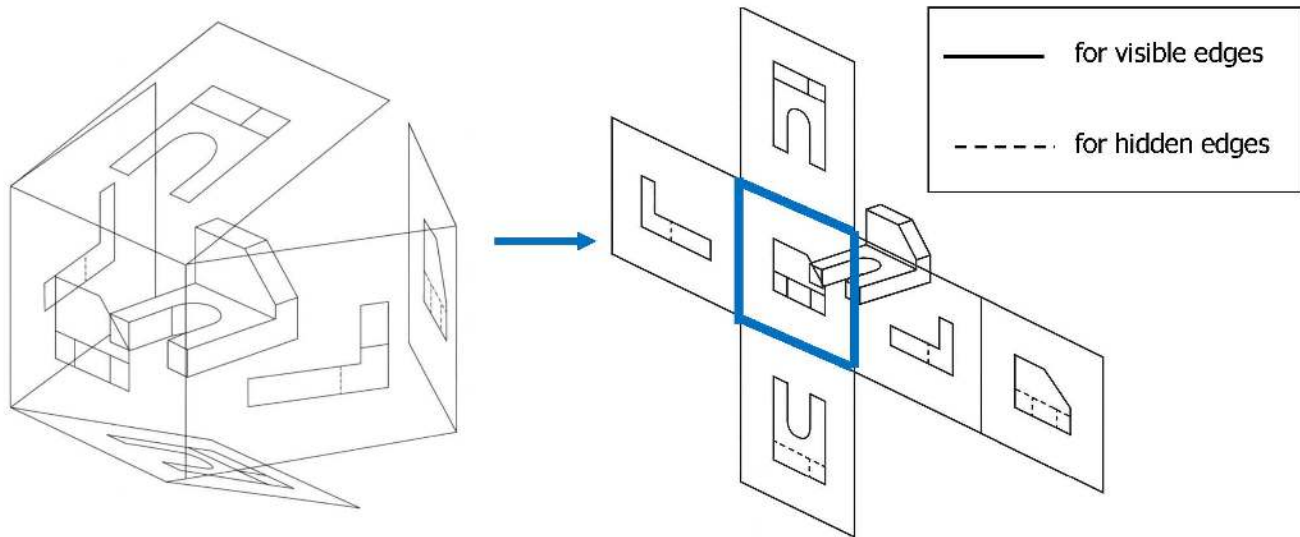
WIDTH : Side-to-Side

DEPTH : Front-to-Back

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Front View Guidelines

- : Front view establishes other views.
- : Front view provides the _____ shape description or _____ characteristic contours.
- : Front view has the _____ features.



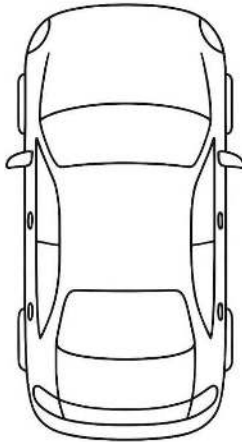
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Practice Problem

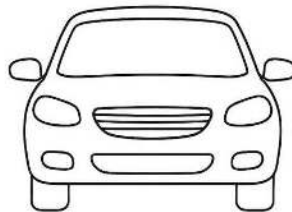
Topic 02 – 6

In engineering drawings, which image correctly represents the front view of an automobile?

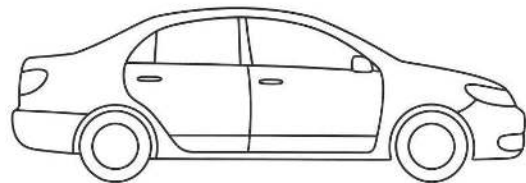
(a)



(b)



(c)

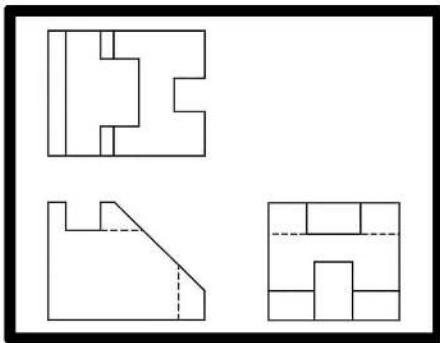
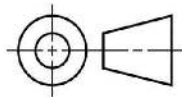


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Standards

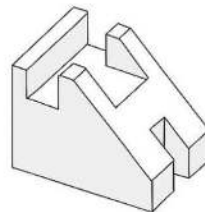
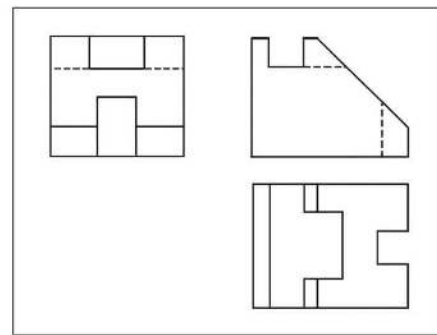
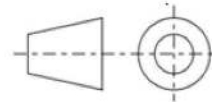
Third Angle Projection by ANSI
(see ASME Y14-3-2003)

Used in United States and Canada



First Angle Projection by ISO
(see ISO 128-30)

Used in Asia and Europe

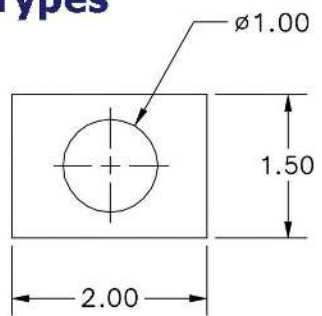


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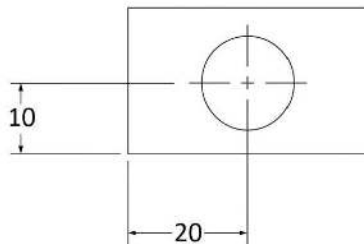
• What

- : A dimension is a measurement of a feature of an object, expressed using appropriate _____.
- : Dimensions are used to define the form, size, orientation, and location of features on a part.
- : The process of dimensioning involves specifying part information through the use of **numerical values, symbols, and notes**.
- : Unless otherwise stated, all dimensions must be measured at _____ °C, the standard reference temperature.

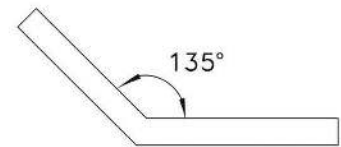
• Types



_____ Dimension



_____ Dimension



_____ Dimension

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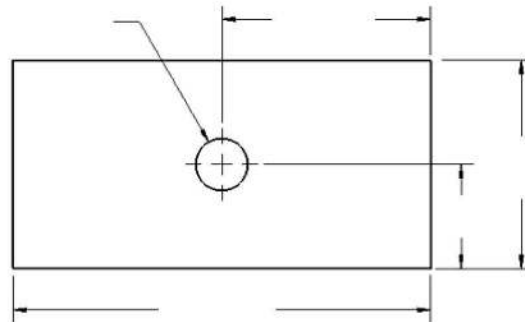
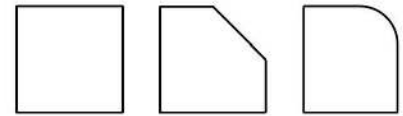
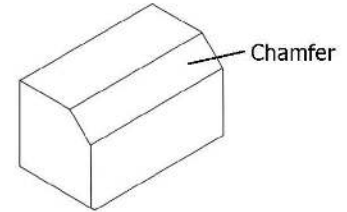
- **Size Dimension**

: specifies the size of an individual feature, such as an _____, _____, _____, and similar attributes.

- **Location Dimension**

: specifies the horizontal, vertical, or central position of features such as holes, slots, chamfers, or other geometric elements.

: defines the spatial relationship between two or more geometric features relative to each other.



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• Identify the Units

: All dimensions are in _____ or _____ unless otherwise specified.

• Difference between Milimeters and Inches

Milimeters

: Use a _____ zero.

: _____ decimal point and trailing zeros for whole numbers.

: Do _____ use _____ or spaces.

Inches

: Do _____ use leading zero.

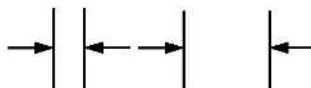
: Do _____ use commas or spaces.

Milimeters

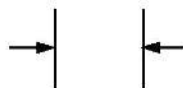
Use zero in front of decimal.



Omit trailing zeros and decimal.

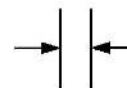


Do NOT use commas or spaces.



Inches

Do NOT use zero in front of decimal.



Use the same number of decimal places as the tolerance.



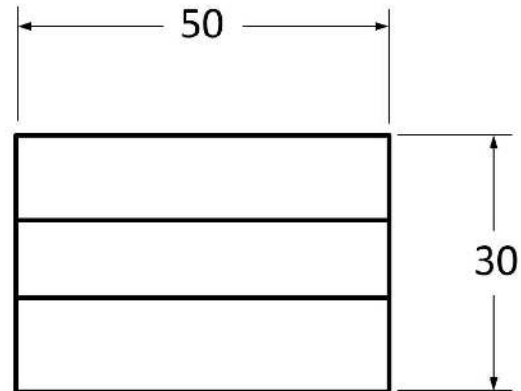
Do NOT use commas or spaces.



• **Line Thickness Types**

_____ for Object

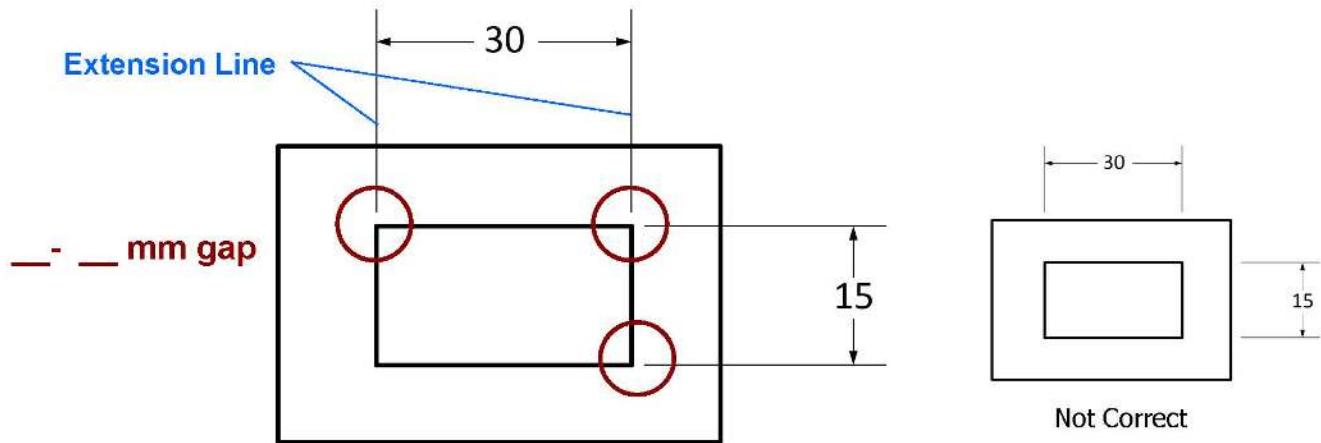
_____ for Dimension



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• Extension Line

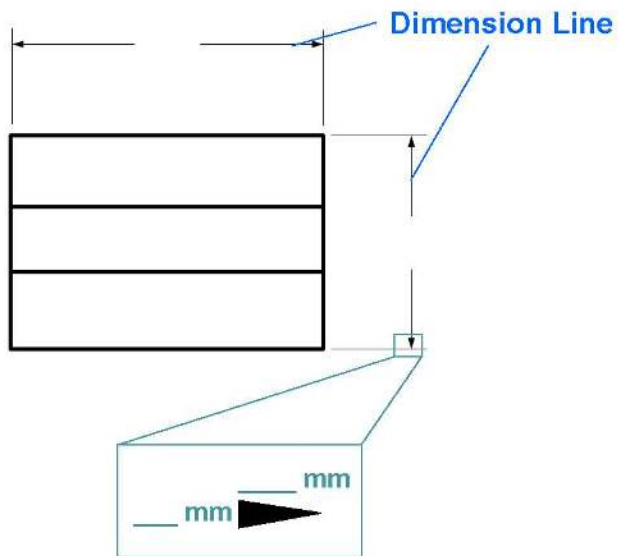
- : a thin line extending from an _____ for dimensioning
- : must _____ touch the feature from which it extends.
- : includes an approximately _____ mm visible gap between the object and the start of the line.
- : must not leave it hanging in space. Always originate from the feature being dimensioned.



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• Dimension Line

- : a thin line with an arrowhead ($\approx$ ____ mm long and ____ mm wide) at each end
- : drawn parallel to the feature or object being dimensioned.
- : is **broken** for the placement of the dimension value.



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Order of Preference

1. Arrows In / Dimension In



2. Arrows Out / Dimension In



3. Arrows In / Dimension Out

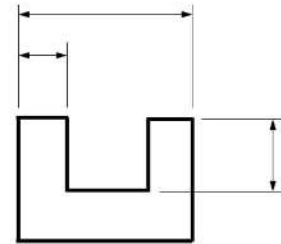


4. Arrows Out / Dimension Out



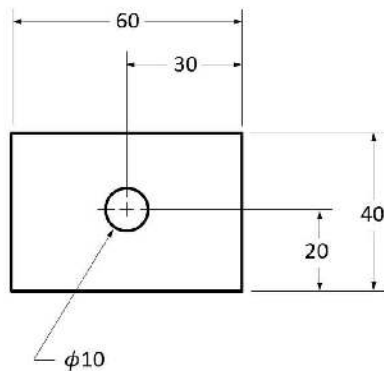
• Dimension Line

: must be **aligned and grouped** for uniform appearance if possible.



: Place **the first-dimension line** at least _____ mm from the object, and **the second** at least _____ mm from the first. Space **all further dimensions** equally, using the same _____ mm gap.

: Numerals must remain **the same size throughout the drawing**, regardless of available space.

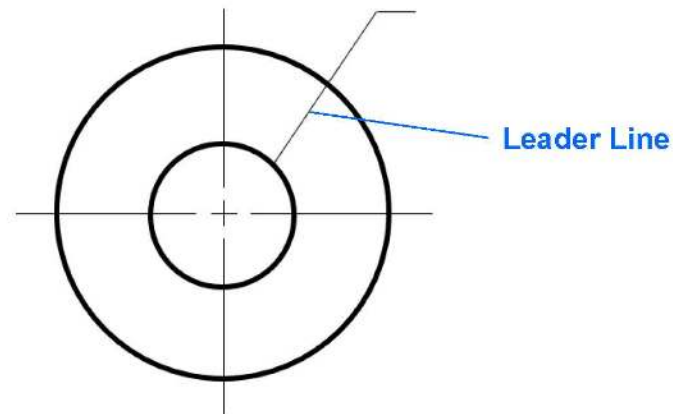


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- **Leader Line**

: a straight thin line that extends at an angle from a note or dimension.

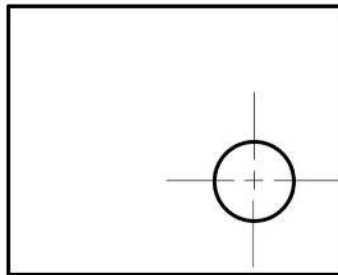
: terminates with an arrowhead that _____ the referenced feature.



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• Centerline

- : a thin line with alternating long and short dashes.
- : used to show axes of _____, bolt circles, motion paths, and pitch circles.
- : extends approximately _____ mm beyond features unless continuing as extension lines.
- : _____ gap between centerlines and extension lines.
- : _____ continued across views.
- : Circular features should have two intersecting centerlines.



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- All _____.
- Select a _____ view that best describes part.
- _____ "Hidden Lines" always, unless absolutely necessary.
- Do _____ dimensions, use reference dims if necessary to duplicate.
- Place dimensions _____ views if possible.
- _____ dimensions allowed on body of part.
- Place all dimensions for _____ feature in _____ view if possible.
- Dimension lines should _____ cross extension lines.
- Extension lines _____ cross extension lines.
- Apply center marks in views only when the circular feature is dimensioned in that view or required for clarity.
- Use centerlines and center marks only when the feature is dimensioned or referenced in the view. Omit them if they are not functionally required.
- When multiples of the same feature exists in a view, dimension only one of the features and label the dimension
as "NumberX" Dimension meaning that the feature exists in that view "Number" times.
i.e., "4X .250": there exists _____ like dimensions from the dimensioned feature in the view.

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- Dimension to _____ lines and avoid dimensioning _____ lines.
- Dimension the _____ rather than the _____.
- Dimension should be selected to suit the function of the model or feature.
- Dimensions should be placed in the _____ descriptive view of the feature being dimensioned.
- Each feature should be dimensioned or identified with a note.
- Place detail dimensions in _____.
- Omit _____ detail dimension in a _____.

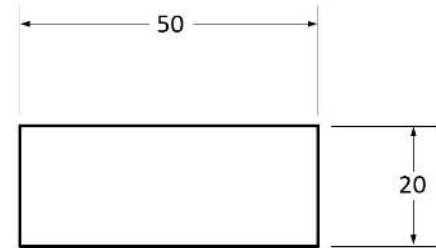
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- **Accuracy:** correct values must be given.
- **Clearness:** dimensions must be placed in appropriate positions.
- **Completeness:** nothing must be left out, and nothing must be duplicated.
: “ ____ **More**, and ____ **Less**.”
- **Readability:** the appropriate line quality must be used for legibility.

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Linear Dimension

: is measured along horizontal or vertical lines relative to the drawing plane.



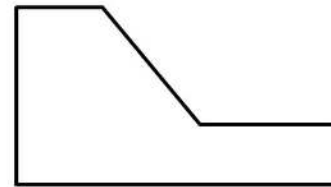
Angular Dimension

: to dimension an angle, use a circular dimension line centered at the _____ (intersection point) of the angle.

: Arrowheads should be placed at the ends of the arc, clearly indicating the measured angle.

: used to ensure clarity in defining inclined or slanted features in a drawing.

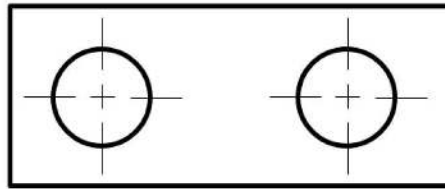
: must be specified with a numerical value followed by the degree symbol (°).



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Simple Hole Dimension

- : must be dimensioned by its _____ with the symbol _____. If the hole is _____ through, the _____ must also be specified.
- : If a hole goes completely through the feature & it is not clearly shown on the drawing, indicate " _____ " or "THRU _____" in all upper case follows the dimension.



NOTE

- : The repetitive features or dimensions can be specified by using the symbol " _____ " along with the _____ of times the feature.
- : There is _____ space between the number of times the feature and the " X " symbol; but there _____ a space between the symbol " X " and dimension.

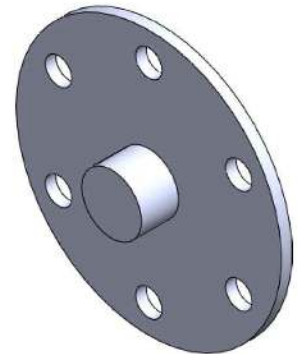
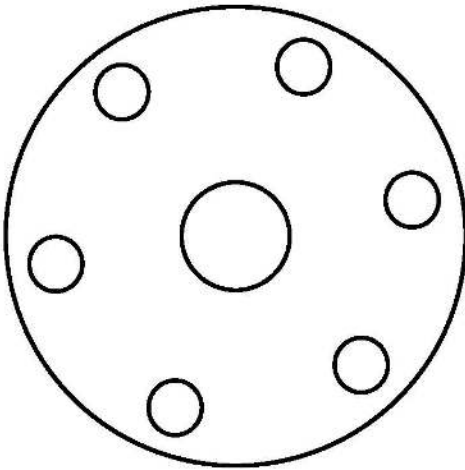
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Equally Spaced Hole Dimension

: The exact location of the _____ hole is specified with a location dimension.

: To indicate the remaining holes, the location dimension is followed by:

1) ____ of the holes, 2) ____ of each hole, 3) the notation "EQUALLY SPACED" or "_____"



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Cylinder Dimension

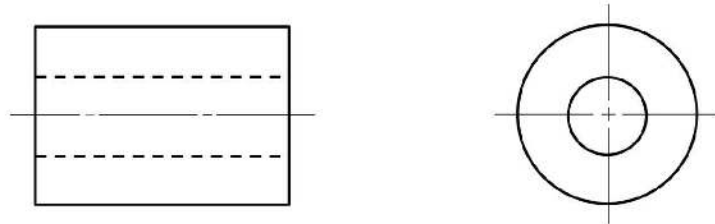
For an External Cylinder (Shaft or Pin)

- : In the _____ view, both the _____ and the _____ of the external cylinder should be shown.
- : The length is shown as a linear dimension, and the diameter is indicated with the symbol () placed.
- : A circular view is _____ required to dimension the diameter of an external cylinder.

For an Internal Cylinder (Hole)

- : Use a view that shows the hole as a circle.
- : The hole diameter with the symbol _____ and _____ if not through, must be specified with a _____ line.

Note: The diameter symbol () must be placed _____ the numerical value to indicate that the dimension refers to a cylindrical or circular feature.



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Arc Dimension

: Using a leader line, the _____ of an arc is dimensioned, preceded by an "_____".



Slot Dimension

: dimensioned using a combination of _____ and _____ measurements.

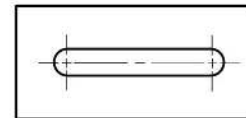
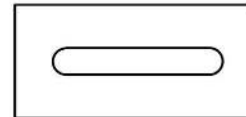
: can be dimensioned by

1) Overall dimension method: Specify the total _____ of the slot and the _____ (distance between the rounded ends).

2) Center-to-center method: Define the slot width by giving the distance between the centers of the rounded end arcs, along with their radius.

: **Fully rounded ends** may display arc outlines _____ specifying their radii.

: **Partially rounded or specified-radius ends** must include a clear indication of the radii.



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Hole Depth Dimension

: Features such as blind holes and counterbores must include a _____ dimension, indicated using the symbol _____, to fully describe their geometry.

Fastener Hole Dimension

: are specified using a leader line that points to the feature, typically indicating the hole diameter, depth, and any additional features such as countersinks or counterbores. Use appropriate ANSI symbols to ensure clarity and standardization.

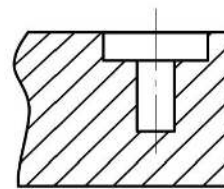
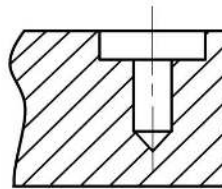
Counterbore Dimension

: Used to indicate a counterbored hole, typically required to recess a machine screw head or bolt head.

: The counterbore symbol () must be used when indicating a counterbored hole.

: Use a _____ line pointing to the hole in the _____ or section view.

: The _____ hole information including _____ and _____ must be specified first, followed by the counterbore dimensions including _____ and _____.

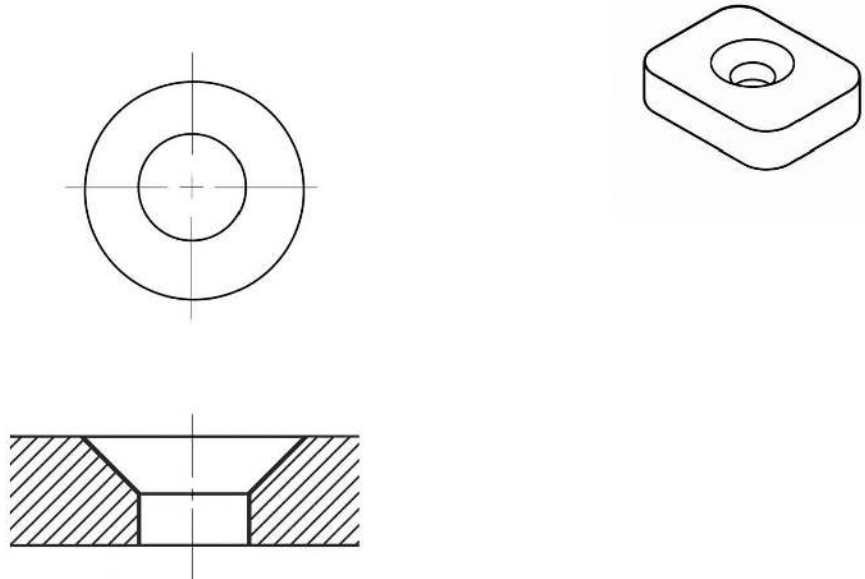


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Fastener Hole Dimension

Countersink Dimension

- : Used to indicate a countersunk hole, typically required to recess the flat head of a machine screw or bolt.
- : The countersink symbol () must be used when specifying a countersunk hole.
- : Use a leader line pointing to the hole in the top or section view for clarity.
- : The drilled hole information must be specified first, followed by the countersink _____ and included _____.

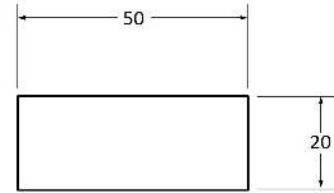


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Linear Dimensioning

: is measured along horizontal or vertical lines relative to the drawing plane.

: read _____ to _____ and _____ to _____.

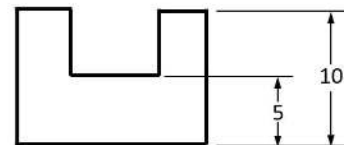


Staggered Dimensioning

: multiple parallel dimensions in a stepped or staggered format to avoid crowding and improve clarity.

: always place the _____ dimensions closest to the object.

: progressively place _____ dimensions outward from the object.

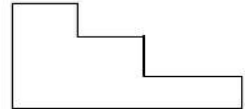


Chain Dimensioning

: dimensioning from one feature to the next in sequence.

: Each dimension depends on the previous one, which may cause errors to accumulate.

: may lead to tolerance buildup (stacking), where small variations add up across features.

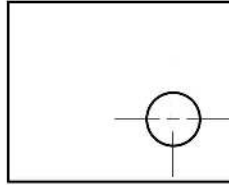


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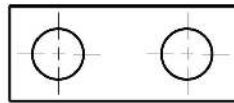
Practice Problems

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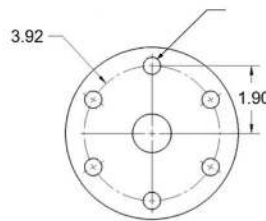
1. On the top view, dimension the center of the hole as located 0.6 inches from the right edge and 0.56 inches from the bottom edge of the part.



2. On the front view, add dimensions for the holes, specifying a diameter of 0.25 inches and indicating that the holes are through.



3. The drawing shows the front view of the part. Complete the drawing by adding the appropriate features. The part contains multiple holes that are equally spaced and extend all the way through the part. Each hole has a diameter of 0.5 inches.

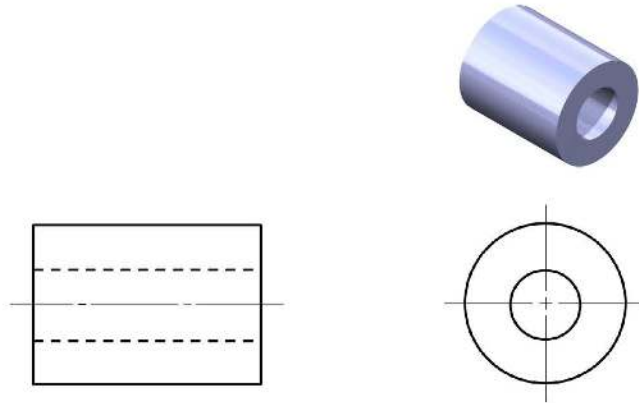


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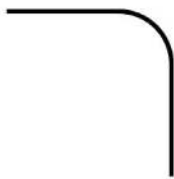
Practice Problems

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4. The cylinder has the total length of 2 inches and outer diameter of 1.5 inches. The hole diameter is 0.63 inches. Add the required dimensions directly to the given drawing to fully define the cylindrical feature.



5. Dimension the arc feature with a radius of 0.38 mm.



6. Add dimensions on the right view for the arcs that have the same radius of 0.25 inches.

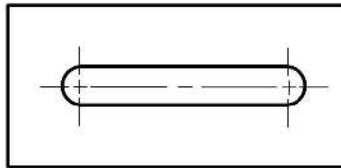
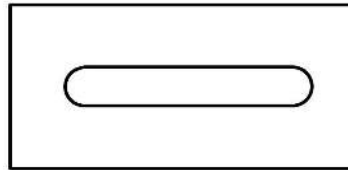


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Practice Problems

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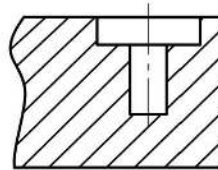
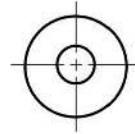
7. The slot has a total length of 40 mm and a width of 10 mm, with fully rounded ends. Complete the dimensioning on the top views.



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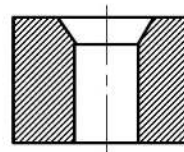
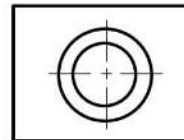
8. Include dimensions for the counterbore hole using ANSI standards with the following specifications:

- Drilled Hole: 0.5 inches in diameter with a depth of 1 inch
- Counterbore: 1 inch in diameter with a depth of 0.5 inches



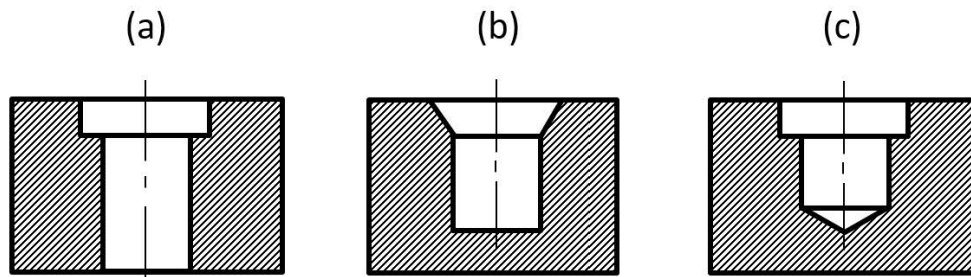
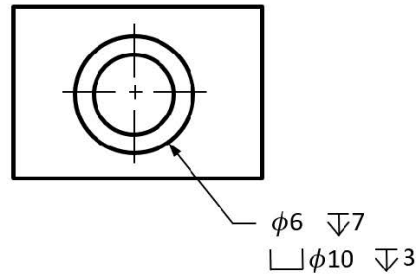
9. Include a dimension for a countersink hole according to ANSI standards with the following specifications:

- Drilled Hole: 9 mm in diameter with a drilling depth of through.
- Countersink: 13 mm in diameter at an 80° angle



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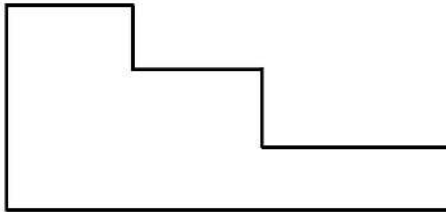
10. The figure shows the top view of a part with hole information specified according to ANSI standards.
- (1) Interpret the top view and select the correct front view.
 - (2) On the selected front view, apply linear dimensions to indicate all hole diameters and depths specified in the top view.



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11. The drawing below shows the front view of an object. Add all required linear dimensions directly onto the drawing using chain dimensioning. Use the following information to specify sizes:

- Total horizontal length: 50 mm
- Internal horizontal segment lengths from the left: 15 mm, 15 mm, and 20 mm
- Total vertical height: 25 mm
- Vertical segment heights from the bottom: 5 mm, 5 mm, and 15 mm



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Manufacturing

Topic 03: Dimensioning & Tolerancing

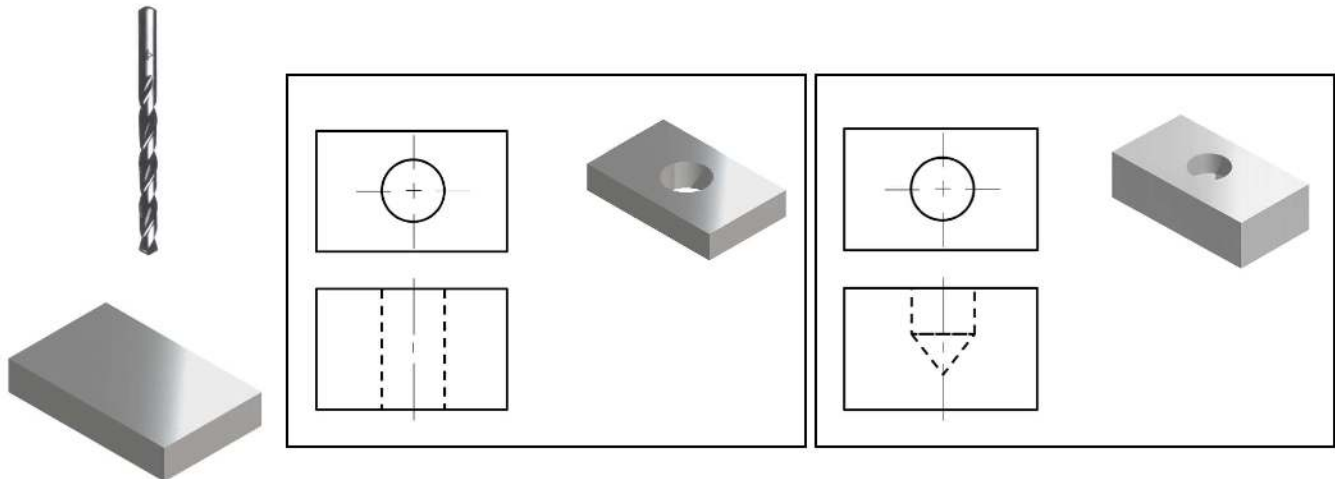
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- Understand the specific machining operations and their ASME dimensioning standards for
 - Drilling
 - Boring
 - Reaming
- Understand the key terms used in dimensioning practices, including:
 - Feature
 - Basic Size
 - Nominal Size
 - Size Dimension
 - Actual Size – Actual Local / Mating Size
 - Limits of Size
 - MMC
 - Allowance
 - Clearance
- Explore the concepts of tolerance and the different types of tolerances used in engineering drawings.
- Distinguish between specified and unspecified tolerances and their applications.
- Analyze tolerance stacking and its impact on design and assembly.

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Drilling

- : a tool used to machine new _____ or _____ existing holes in material.
- : _____ and _____ dimension must be provided.
- : can go through the material with a note in drawing, "_____".
- : when the views of the hole clearly show that the hole goes through the part, THRU can be omitted.

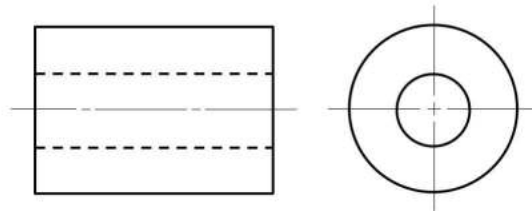
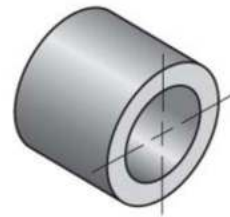
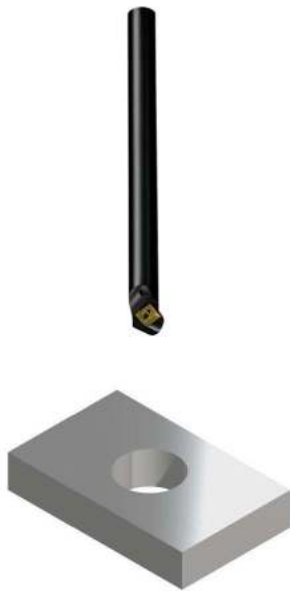


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Boring

: to _____ an existing hole.

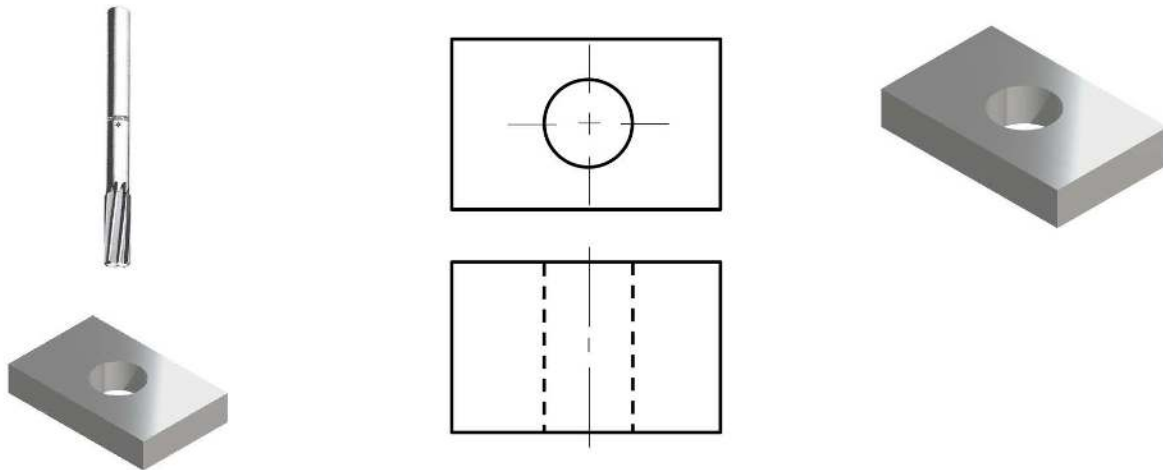
: to make a drilled hole in a part “_____ with or _____ to” other part’s feature.



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Reaming

- : used to _____ or _____ a hole that has been drilled or bored.
- : does _____ create a hole as with a drill.
- : removes only a _____ amount of material to clear up and _____ the hole size.
- : to provide a _____ surface finish and a closer tolerance than is available with the _____ hole.
- : _____ or REAMED in the dimensioning must be provided.



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- Feature

: _____ portion of a _____ or object.

- _____ Dimension

: _____ size, location, orientation, or profile of a feature or point specified by the designer, from which permissible variations (tolerances) are applied.

: provides a _____ for the application of _____.

: nominal specifications are defined by _____ dimensions.

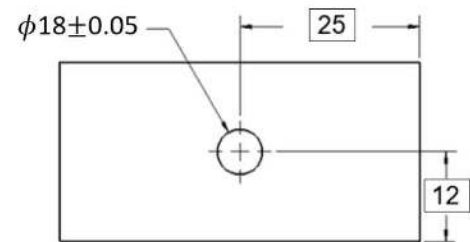
: a formally defined, _____ - _____ value used only to define exact geometry.

- _____ Size

: a size used for _____ identification.

: remains _____ the _____.

: for a feature that would be the _____ outcome without any error.



- Size Dimension

: exact measurement given for a feature, including any tolerances.

: defines the acceptable range within which the _____ size of the part must fall.

- _____ Size

: _____ size of a feature or part _____ manufacturing.

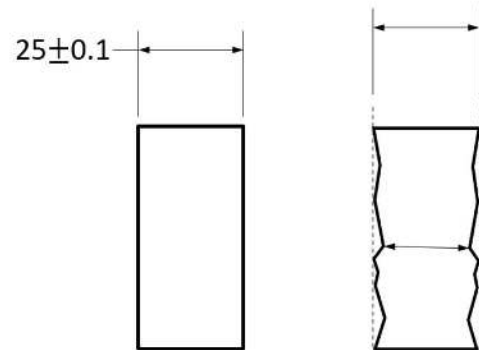
: The size of the feature must _____ violate the size tolerance.

- Actual _____ Size

: any cross-sectional measurement at any two adjacent points.

- Actual _____ Size

: distance between two parallel planes within
which _____ the actual surface features are contained.



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- _____ of Size

: the _____st and _____est possible boundaries to which a feature can be made as related to the tolerance of the dimension.

: the larger value for each part is the _____ limit, and the smaller value is the _____ limit.

- Maximum Material Condition (_____)

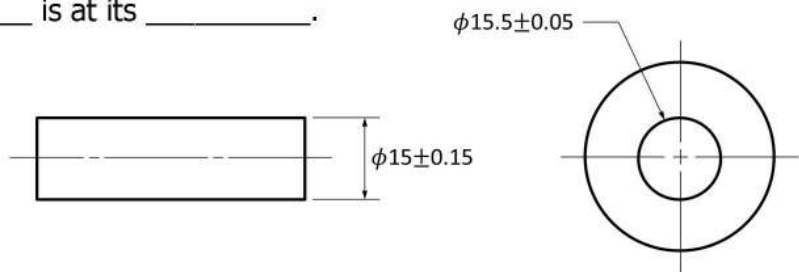
: condition of a feature or part where the _____ amount of _____ within its dimensional tolerance.

: _____ material

: _____st limit for an _____ternal; the smallest limit for an _____ternal feature.

: a _____'s MMC is when its _____ is at its _____,

while a _____'s MMC is when its _____ is at its _____.



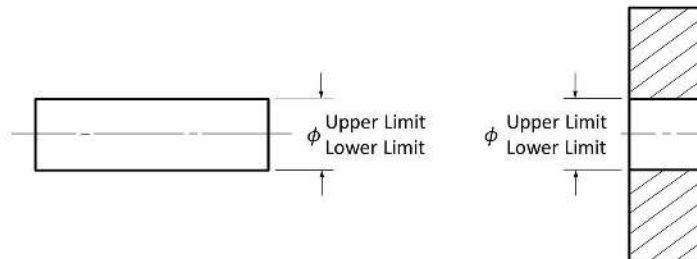
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-

: Intentional desired difference between the dimensions of two _____ so there is guaranteed space or controlled interference.

: _____ possible fit between two mating parts.

Allowance =	Feature	Feature
-------------	---------	---------



-

: The actual distance between surfaces of mating parts when assembled.

: _____ clearance is often used to indicate the smallest possible gap between parts.

: Always _____ in a clearance fit.

: to allow the mating parts to move freely relative to each other, enabling easy assembly and disassembly

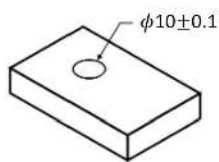
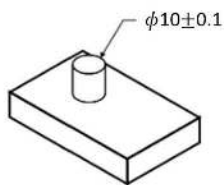
_____ need for force.

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1. In a drawing, the size dimension is given as $.750 \pm .005$.

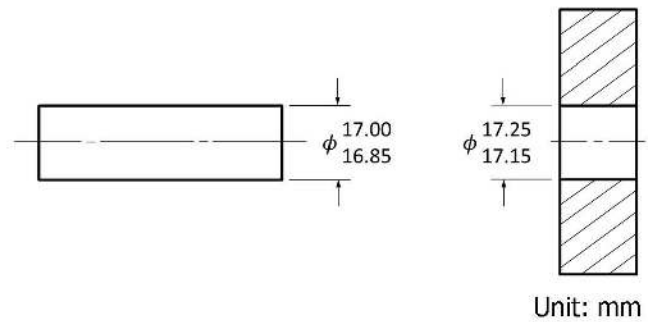
- (1) Identify the basic size.
- (2) Determine the limits of size.

2. For the size dimensions of the pin and the hole, determine the Maximum Material Condition (MMC) of both the pin and the hole.



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3. Determine the allowance and minimum clearance between the mating parts based on the given dimensions.



Recall:

Allowance = $\text{Hole's Minimum Dimension} - \text{Shaft's Maximum Dimension}$

What

- : _____ amount _____ to _____ for a specific dimension.
- : an undesirable but permissible deviation from a desired dimension.
- : difference between the _____ and _____
- : _____ dimensions on a drawing have a tolerance except reference, max, min, or stock size dimensions.

Why Needed

- For _____
: to provide the manufacture an _____ limits for deviation during production.
- For _____
: to help ensure parts fit together and function in an assembly.
- For _____
: to ensure the required _____ for the part or specific feature.

Note:

- Specifying unnecessarily tight tolerances for every dimension can lead to increased costs.
- Identify which dimensions require precision and allow for greater flexibility on others.

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____lateral Tolerance

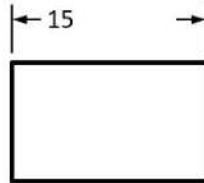
: most common tolerancing method.

: varies in _____ directions from the basic size.

(1) _____ Bilateral Tolerance: often preferred by manufactures.



(2) _____equal Bilateral Tolerance:

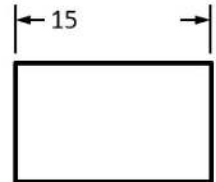
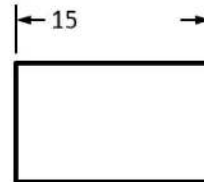


____lateral Tolerance

: has a variation in only _____ direction from the size dimension.

: the variation is permitted increase ____ decrease in only _____ direction from the size dimension.

: typically used to define tolerances in _____ fit parts.



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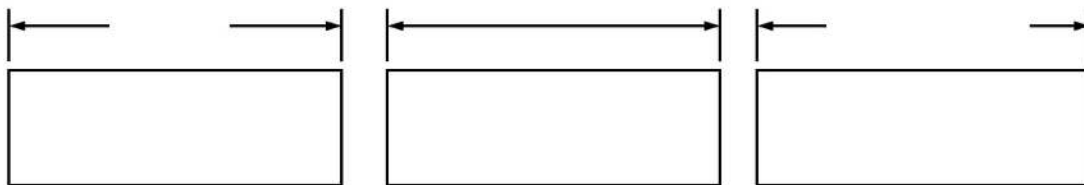
_____ Dimensioning

: calculate the tolerance from the _____ and _____ limits.

: Max. and Min. sizes are specified a part of the dimension.

: typically used to define tolerances in _____ fit parts.

: _____ size is unknown.



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Specified Tolerance

: applied _____ to the dimension.



Unspecified Tolerance

: dimensions _____ a specified tolerance.

: specified in the dimensioning and tolerancing _____ or a



UNLESS OTHERWISE SIZE DIMENSIONS ARE IN
INCHES (IN) TOLERANCE: 1 PLACE $\pm .1$
2 PLACE $\pm .01$ 3 PLACE $\pm .005$

or

3 PLACE DECIMALS ARE $\pm .005$

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Placing Dimensions on Drawings: Metric vs Inch Standards

Metric Dimensions	Inch Dimensions
• The basic size does not need to trailing zeros to match the decimal places of the tolerance. • When using unilateral tolerance, a single 0 is used without a + or – sign for the 0 part of the value.	• A basic size is expressed to the same number of decimal places as its tolerance. Zeros are added to the right of the decimal point if needed. • Unilateral tolerance use the + and – symbols, and the 0 value has the same number of decimal places as the value that is greater or less than 0.

Both Metric and Inch

- Plus and minus values of a tolerance have the same number of decimal places. Zeros are added to fill in where needed.
- Limit tolerance values (in limits of size) have the same number of decimal points.
 - In a single line:
 - As a stacked dimension:

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- **Tolerance Stacking/**

: the tolerance of each dimension can be _____ on the next.

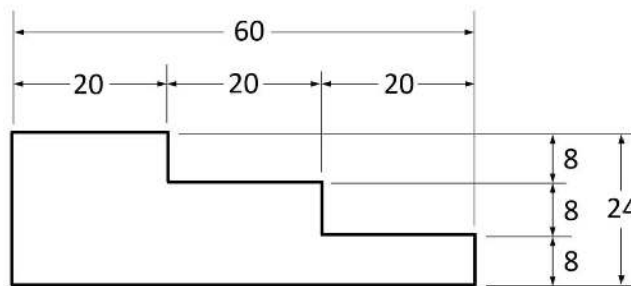
- **Effect of Dimension Types on Tolerance Stacking**

- **Chain Dimensioning**

: dimensioning from one feature to the next.

: each dimension is _____ on the _____ dimension(s).

: provides _____ tolerance accumulation.



Note: If the overall length is critical, _____ one intermediate or the overall dimension.

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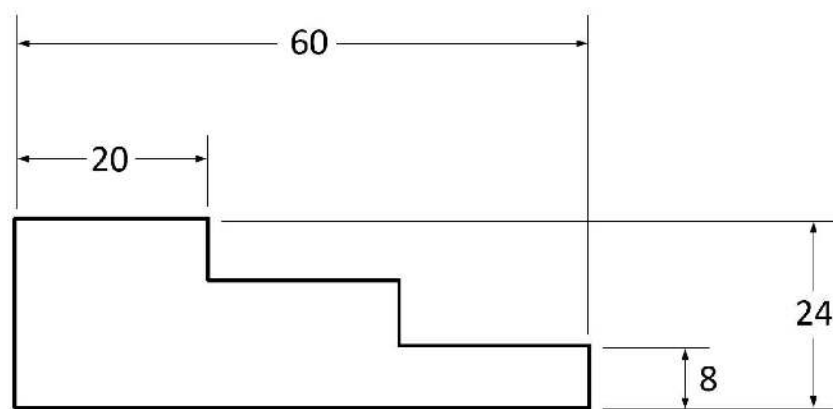
• Effect of Dimension Types on Tolerance Stacking: How To Resolve

- Baseline Dimensioning

: Each feature dimension originates from a reference point, edge, or center plane.

: used when the size or location of features must be controlled from a reference point or edge and less tolerance accumulation is desired.

: Each dimension is ____dependent, reducing the possibility of tolerance ____.



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4. Express the correct dimensioning as it should appear on a technical drawing.

(1) The basic size is 1.5 inches, and the tolerance is unilateral, increasing by 0.002 inches from zero.

(2) The basic size is 38.5 mm, with a unilateral tolerance that allows an increase of 0.05 mm from zero.

(3) The basic size is 0.625 inches, with a unilateral tolerance that permits a decrease of 0.004 inches from zero.

(4) The basic size is 24 mm, with an equal bilateral tolerance that permits ± 0.1 mm.

(5) The basic size is 24 mm, with an unequal bilateral tolerance of -0.2 mm and $+0.08$ mm.

(6) Express the limit dimensioning using a stacked format, given that the lower limit is 1.245 inches and the upper limit is 1.25 inches.



(7) Express the limit dimensioning in a single line, given that the lower limit is 38.5 mm and the upper limit is 38.55 mm.



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5. Correct each incorrect dimensioning expression as it would appear in a drawing.

(1) $24.00 \begin{smallmatrix} +0.45 \\ -0.2 \end{smallmatrix}$

(4) $.75 \begin{smallmatrix} +.005 \\ -.0 \end{smallmatrix}$

(2) $\begin{smallmatrix} 24.45 \\ 24.2 \end{smallmatrix}$

(5) $\begin{smallmatrix} .5 \\ .498 \end{smallmatrix}$

(3) $24 \begin{smallmatrix} +0.0 \\ -0.2 \end{smallmatrix}$

(6) $.5 \pm .002$

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Manufacturing

Topic 04: Fundamentals of Machining & Chip Morphology

Prof. J Lee

1. Cutting Operation

- Define the cutting operation.
- Identify the parameters which affect to the cutting operation.

2. Rake Angle

- Define the rake angle of the tool
- Identify the effect of the rake angle to the machining operation.

3. Chip Morphology

- Understand factors affect to chip formation.
- Understand types of chip.
- Understand the effect of the chip breaker

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Cutting Operation



etc.

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Cutting Operation

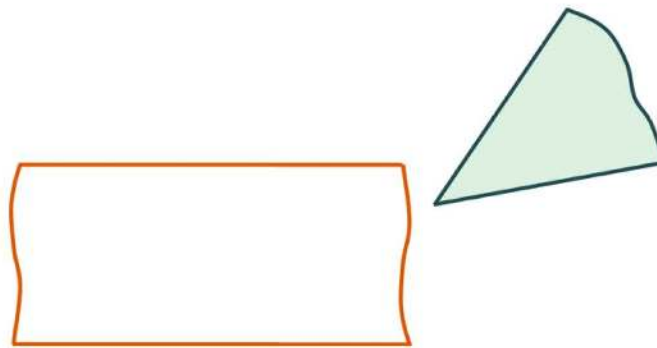
: Machining _____ to _____ material from the _____

: Key components in cutting operation

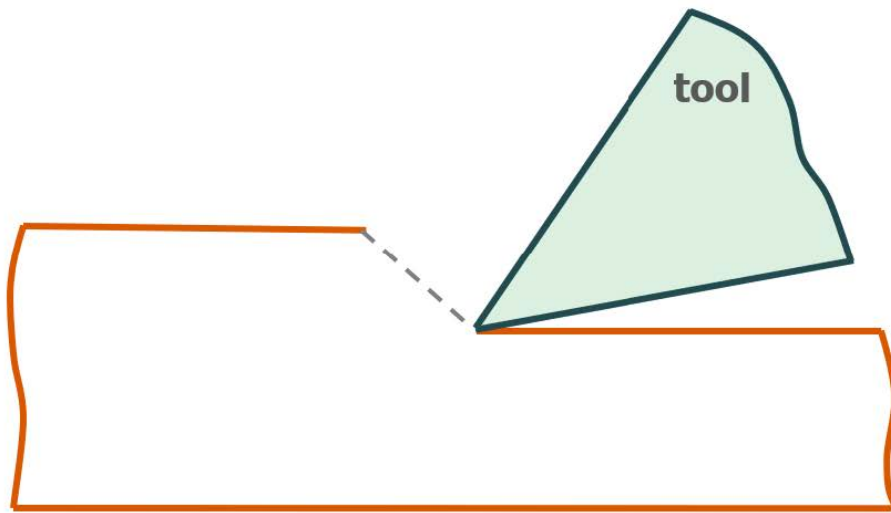
(1) _____ (): a piece of _____ to _____

(2) _____ : to _____ the _____

(3) _____ () : for _____



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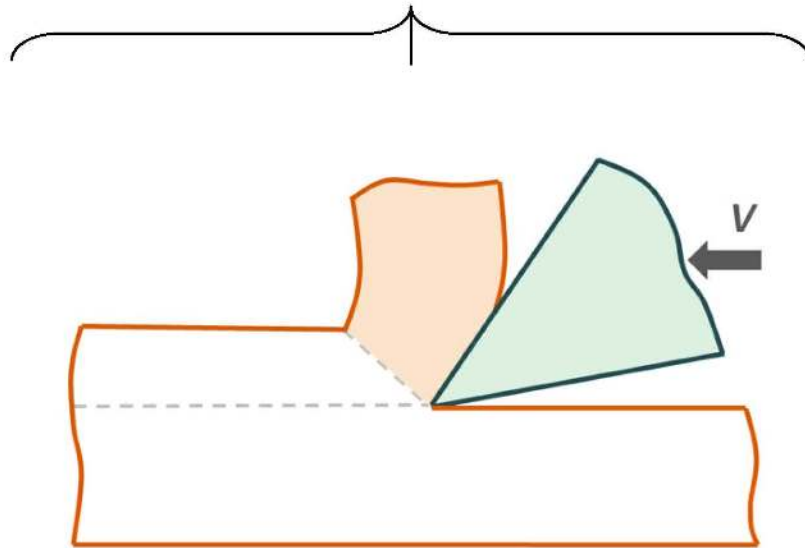
Rake Angle

Topic 04 – 5

_____ ()

: an angle between the tool _____ face and _____ the _____.

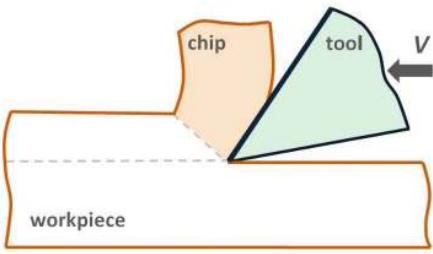
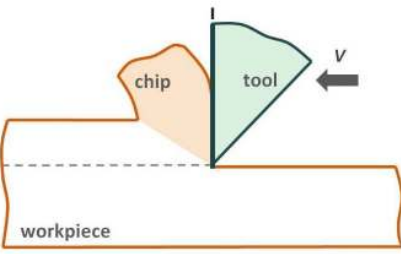
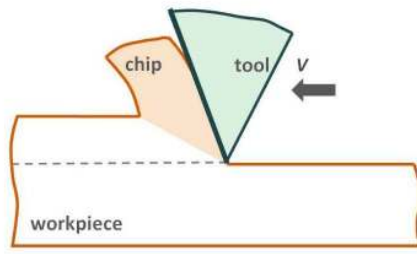
: affects (1) tool _____, (2) _____ morphology (formation), (3) overall machining processes.



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Rake Angle

Topic 04 – 6

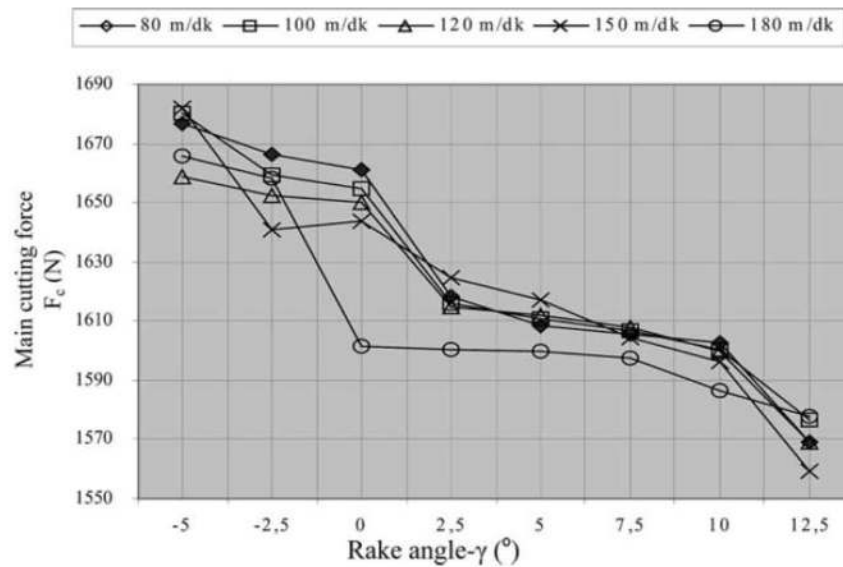
_____ Rake Angle ()	_____ Rake Angle ()	_____ Rake Angle ()
 workpiece chip tool V If tool rake face is - Steeper: _____ ; _____ - Lower slope: _____ ; _____ + : _____ cutting force and temperature : _____ cutting operation - : premature tool _____	 workpiece chip tool V + : simple to _____ and _____ of the cutting tool	 workpiece chip tool V + : creates _____ chip : increase tool _____ - : _____ cutting force and temp.

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Practice Problem

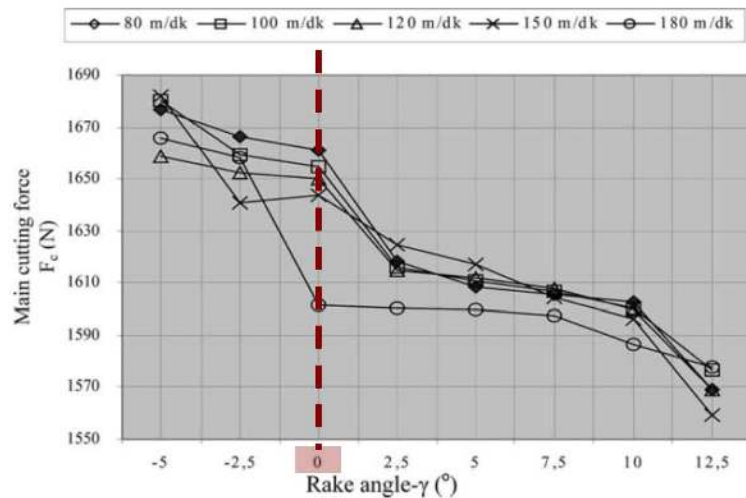
Topic 04 – 7

Discuss the effect of rake angle (γ) on the main cutting force (F_c) based on the experimental results provided in the graph. Provide reasoning for the observed behavior and any implications for tool design or machining strategy.



Gunay *et al.*, 2004, International J of Machine Tools & Manufacture, 44, 953-959

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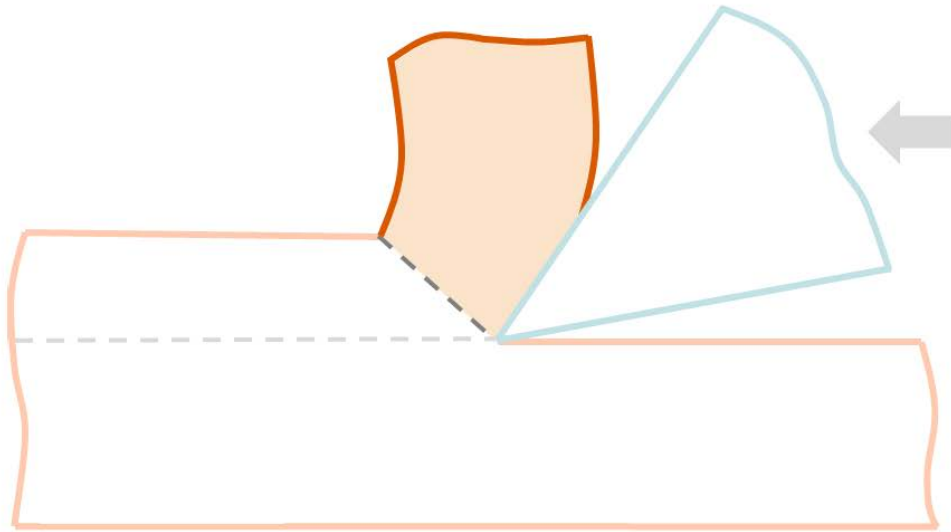
Gunay *et al.*, 2004, International J of Machine Tools & Manufacture, 44, 953-959

Key Findings Summary

- Cutting _____ with tool _____ in different cutting _____
- Cutting Force _____ w/ _____ in _____
- Biggest decrease in cutting force was observed when _____ $\leq$ _____ $\leq$ _____
- Cutting force for all speeds is high for _____
- Cutting speed has _____ relations to the cutting force.

Chip morphology

: directly indicates the _____ of the cutting process.



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• **Chip formation** depends on:

(1) _____

: e.g., _____ or _____

(2) Cutting _____

: e.g., _____ of cutting _____, _____

(3) Cutting _____: e.g., _____



Cutting Operation

• **Chip formation** indicates:

(1) Characteristics of the _____

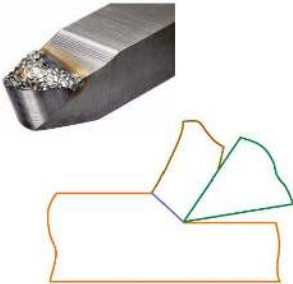
(2) Amount of _____ required to remove the workpiece material

(3) Nature of interaction at the _____ - _____

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Chip Morphology

Topic 04 – 11

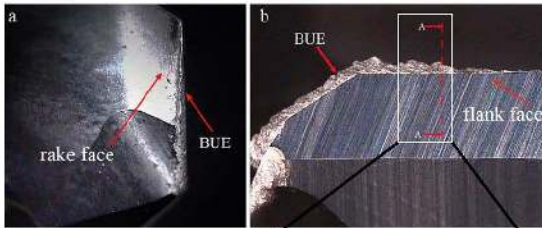
Types of Chips	W.P. Material	Cutting Conditions	Tool Geometry	Pros/Cons
				+ : Good for
				+ : Good for – : Not good for
				– : Not good for : Not good for : Change tool

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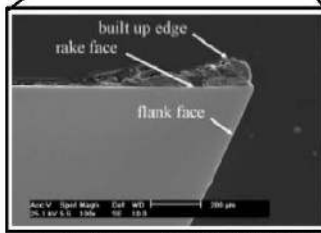


- **BUE formation** can occur due to

→ _____, moderate temperature, and sufficient _____
 between the _____ and _____ face.
 → Deformed chips tend to _____ or _____ to the tool.
 → Create a _____ built-up edge ().



Cross-sectioned A-A of the cutting edge



Farid *et al.*, 2011, International J of Advanced Manf Tech, 57, 555-564

- **BUE:** is _____ than the workpiece material
 : causes a _____ edge.
 : causes the formation of an _____ regular cutting edge and _____ even chip formation.

• How to reduce the tendency for BUE formation

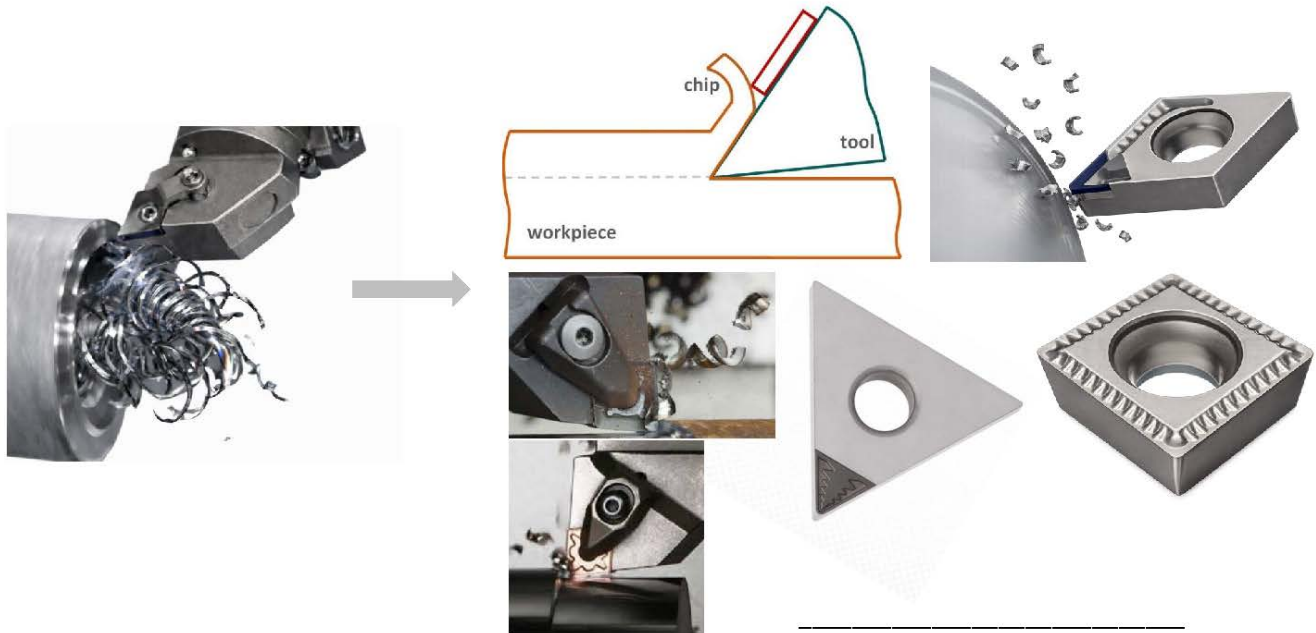
- _____
- _____
- _____
- Use a _____ tool.
- Use an effective cutting _____.
- Use a cutting tool which has _____ affinity
 for the workpiece material.

Chip Morphology: Chip Breaker

Topic 04 – 13

Why : continuous and long chips tend to become _____, severely _____ with the tool, and present a _____.

How to Solve : _____ the chip intermittently → cutting tool can have _____ features.



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Practice Problems

Topic 04 – 14

1. Discuss the importance of studying chip morphology in machining operations. Explain how analyzing the type, shape, and behavior of chips can provide insights into tool performance, cutting conditions, and material properties.

2. Why might continuous chips not always be desirable in machining? Discuss potential challenges posed by continuous chips during cutting processes, including safety, surface finish, and tool wear implications.

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3. Compare positive and negative rake angles and explain the significance of rake angle in machining. Describe how rake angle affects cutting force, chip flow, and tool life, and contrast the functional effects of positive versus negative rake geometries.

4. Define Built-Up Edge (BUE) and explain its formation. Discuss why BUE occurs during machining and outline strategies to minimize its formation through tool material, cutting parameters, or lubrication.

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Practical Applications: Chip Morphology Variation in Machining Processes

Ref. J.E. Lee *et al.* 2026. Influence of Drilling Parameters on Force Dynamics and Transitional Drilling Depth in Deep-Hole Bone Drilling. *ASME J of Medical Diagnostics*. 9(1), 011204. <https://doi.org/10.1115/1.4069000>

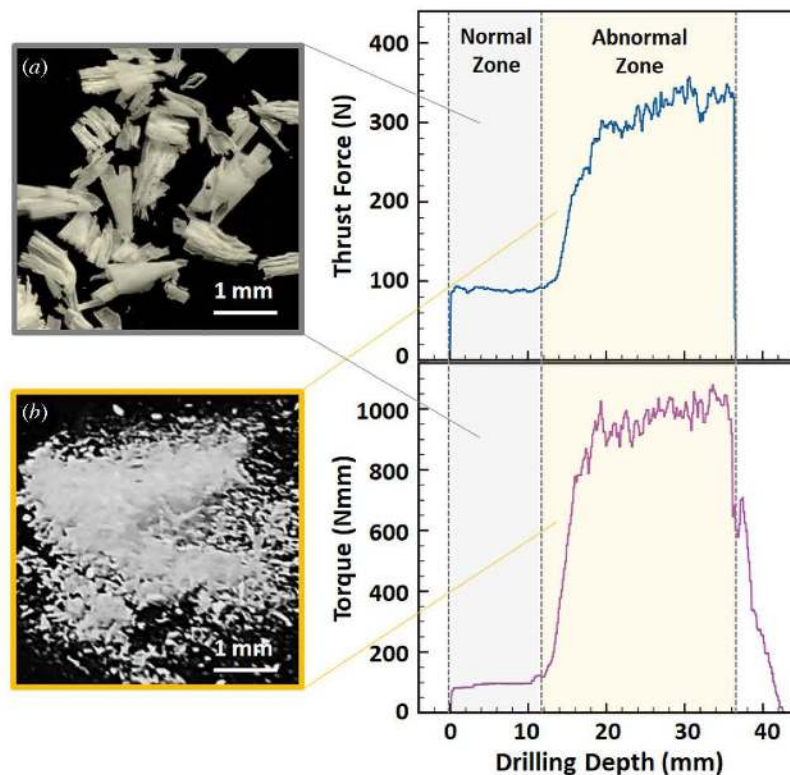


Fig. 1 Typical thrust force and torque profiles during deep-hole bone drilling, showing characteristic chip morphology variations with depth: (a) fragmented chips collected at 7 mm in the normal zone and (b) powdery chips collected at 20 mm in the abnormal zone

increased these values by 24.4% and 32.2%. Spindle speed, by comparison, exhibited minimal influence, as the lowest speed (1000 rpm) led to modest increases of 7.3% and 3.2% in thrust force and torque, while the highest speed (3000 rpm) resulted in slight reductions of 6.8% and 9.6%, respectively.

These findings highlight the dominant influence of drill-bit diameter and feed rate on thrust force and torque variations during bone drilling, with spindle speed playing a comparatively minor role within the normal zone. The significant increases in thrust force and torque associated with larger drill-bit diameters and higher feed rates emphasize their critical impact on force dynamics, underscoring the necessity of precise parameter optimization to prevent mechanical overload and reduce the risk of tool damage.

Table 3 presents the statistical analysis evaluating the effects and contributions of the parameters on drilling forces. The ANOVA results indicated that drill-bit diameter, spindle speed, and feed rate each had a statistically significant impact on thrust force and torque within the normal zone ($p < 0.001$). A statistically significant interaction between drill-bit diameter and feed rate was also observed ($p < 0.001$), highlighting their combined influence on force generation during bone drilling. However, interactions involving spindle speed—whether with drill-bit diameter, feed rate, or both—were not statistically significant ($p > 0.05$), indicating a weaker interactive effect compared to the other parameter contribution.

Following the ANOVA, post-hoc testing was conducted to identify which specific parameter levels contributed to the observed significant differences. This method enables pairwise comparisons across all factor levels. Post-hoc testing revealed significant differences in thrust force across all levels of drill-bit diameter

(2.5 mm, 3.5 mm, and 4.5 mm), spindle speed (1000 rpm, 2000 rpm, and 3000 rpm), and feed rate (0.05 mm/rev, 0.075 mm/rev, and 0.1 mm/rev) within the normal zone. Similar patterns were observed for torque, with statistically significant differences across all levels of drill-bit diameter and feed rate. However, no significant differences in torque were observed between 1000 rpm and 2000 rpm, whereas torque differences between 1000 rpm and 3000 rpm, and between 2000 rpm and 3000 rpm, were statistically significant. The minimal variation in torque between 1000 rpm and 2000 rpm suggests that, at lower spindle speeds, torque is primarily influenced by material removal and cutting engagement rather than by rotational speed, which becomes a more dominant factor at higher spindle speeds [36].

Partial eta-squared (η^2) analysis further quantified the relative contributions of the parameters by evaluating the proportion of variance in force outcomes explained by each parameter, offering insight into their practical significance and the relative magnitude of their effects. Drill-bit diameter exhibited the strongest effect, with η^2 values of 0.97 for thrust force and 0.96 for torque. Feed rate followed closely, with η^2 values of 0.91 and 0.89, respectively. In contrast, spindle speed showed a comparatively lower impact ($\eta^2 = 0.29$ for thrust force and 0.15 for torque). The interaction between drill-bit diameter and feed rate also had a notable influence, with $\eta^2 = 0.33$ for thrust force and 0.58 for torque, highlighting the importance of coordinated parameter control in force modulation. In contrast, interactions involving spindle speed exhibited small effect sizes ($\eta^2 < 0.14$) for both thrust force and torque within the normal zone, further reinforcing its comparatively minor role relative to drill-bit diameter and feed rate in modulating drilling forces.

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Manufacturing

Topic 05: Cutting Mechanics

Prof. J Lee

Orthogonal Cutting and Oblique Cutting

- Define the orthogonal and oblique cutting.
- Understand their characteristics.

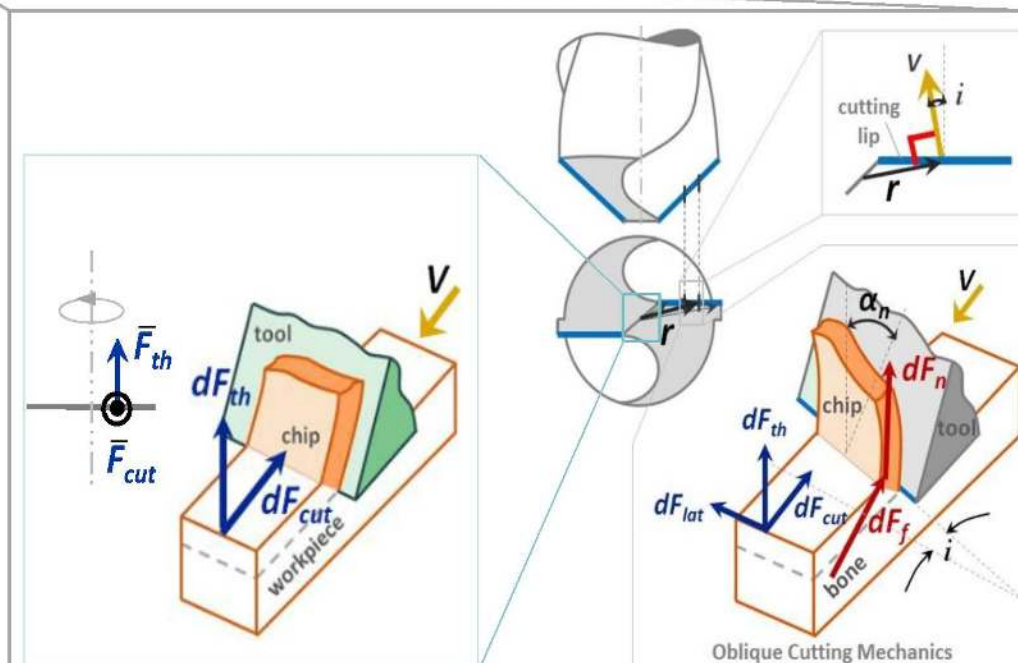
Oblique Cutting

- Define the inclination angle and understand its impact on cutting.
- Define the chip flow angle and its effect on material removal.

Rake Angle

- Identify the rake angle in both orthogonal and oblique cutting.
- Understand the normal plane and its significance.
- Identify the normal rake angle.
- Understand the effective rake angle in oblique cutting.

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Lee *et al.* 2012. Journal of Biomechanics, 45(6), 1076-1083.

Why

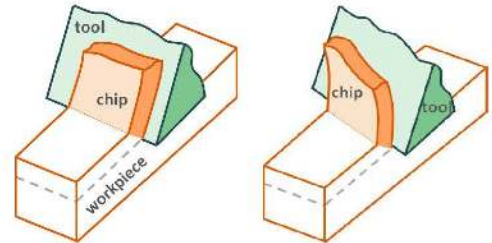
- To understand the _____.
- To analyze how the _____ are applied to the _____ and _____ during the process.

- Understand the _____ characteristics of the cutting process.

: Identify an _____ to apply for the cutting process

e.g., _____ or _____ cutting mechanics

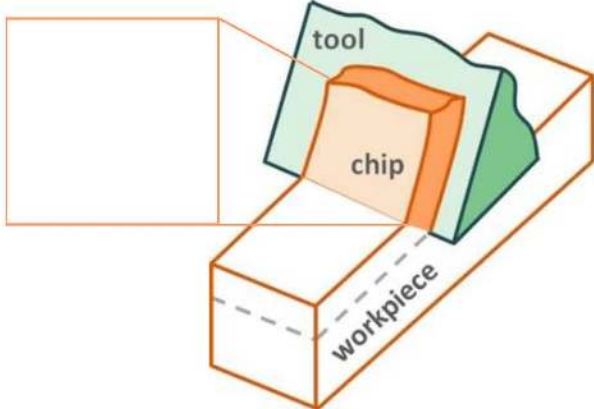
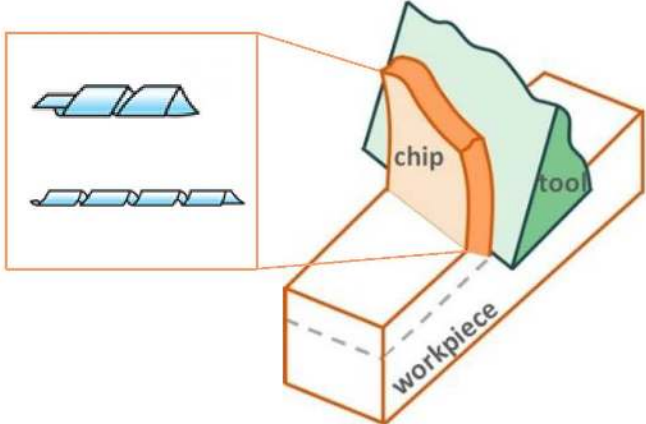
- Identify the _____ under the given cutting conditions and tool geometries.
- Use the geometric relations to analyze _____ acting during the process.



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Orthogonal vs Oblique Cutting

Topic 05 – 5

_____ Cutting	_____ Cutting
 • Cutting _____ Cutting _____. • _____ flows _____ the _____. • Chip _____ in tight, and becomes _____. • Only _____ force components acting on the _____. • Enough to describe with the _____ angle.	 • Cutting _____ Cutting _____. • Chip flows _____ the rake face w/ an _____ angle. • Chip flows _____ ways in a _____. • _____ force components of the forces acting on the _____. • Defined by _____, _____, _____ angles.

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To Define _____ Cutting Mechanics,

- _____ angle ()
 - _____ angle ()
 - _____ ()
 - _____ ()
 - _____
 - _____ angle ()
 - _____ angle ()
- } must be defined.

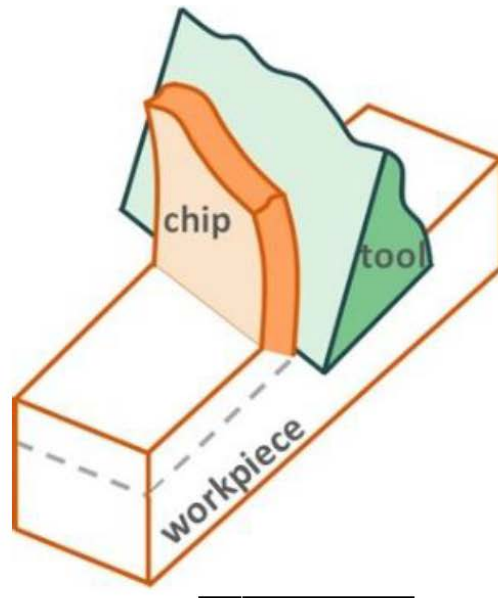
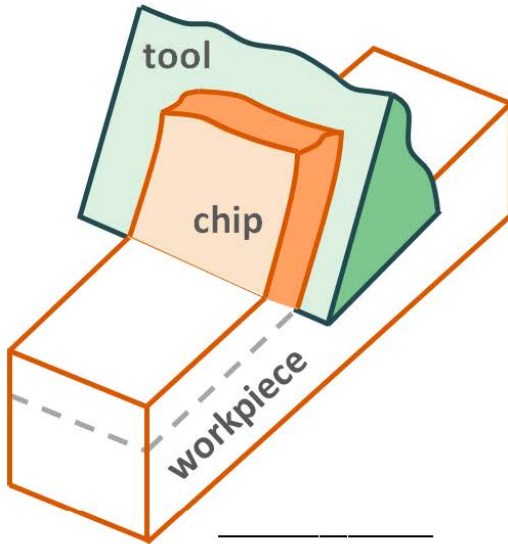
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_____ Angle ()

: Angle between the cutting _____ and the line _____ the line of action (LOA) of cutting _____

: _____ characteristic in _____ cutting

: Known from the cutting _____.



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_____ Angle ()

: Angle between the _____ (), which is in the direction _____ to the _____, and the _____ ()

: Chip has a _____ with _____.

: More _____ cutting mechanism for material removal

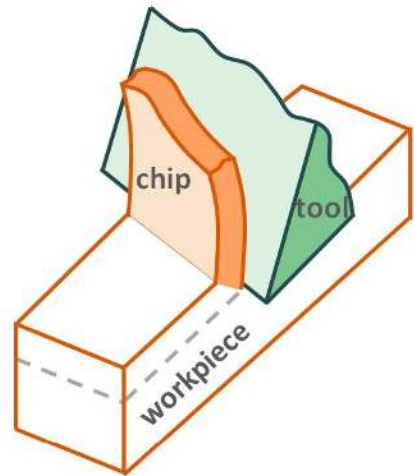
: Better _____ and _____.

How to find:

According to the _____,

_____ Angle () _____ Angle ()

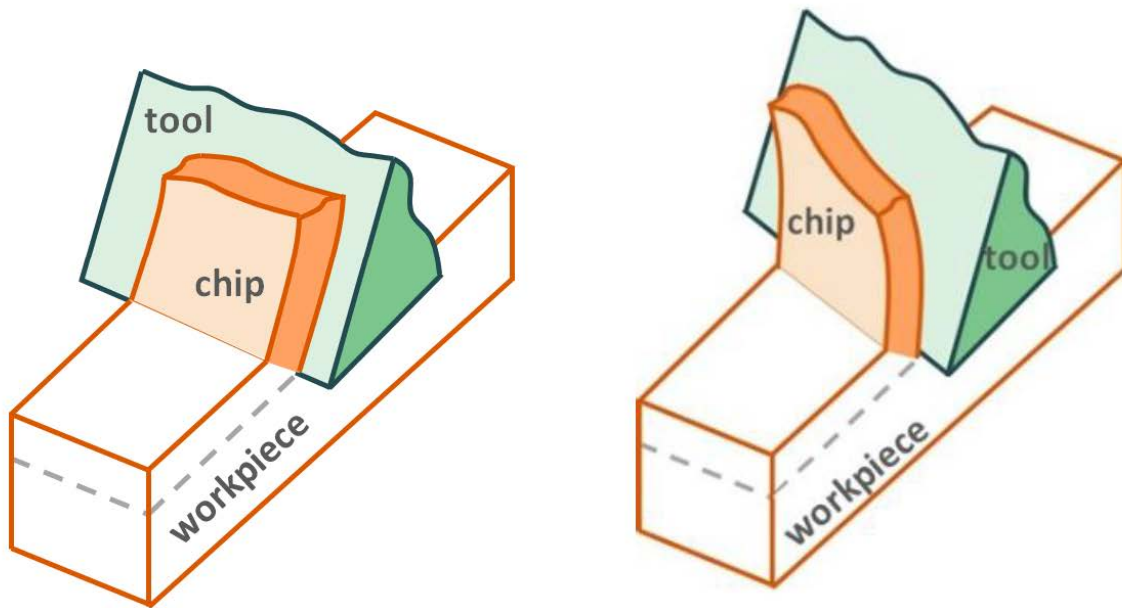
→ Hence, _____ is _____ from the cutting _____.



Rake Angle

Topic 05 – 9

_____ Rake Angle () _____ Rake Angle ()



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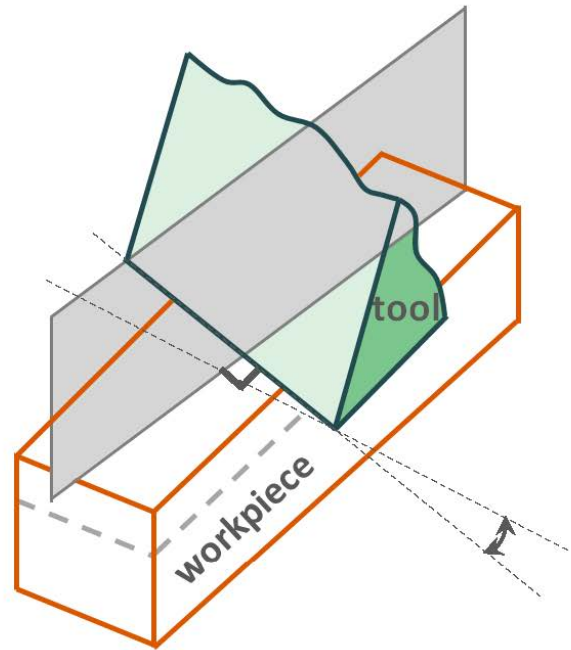
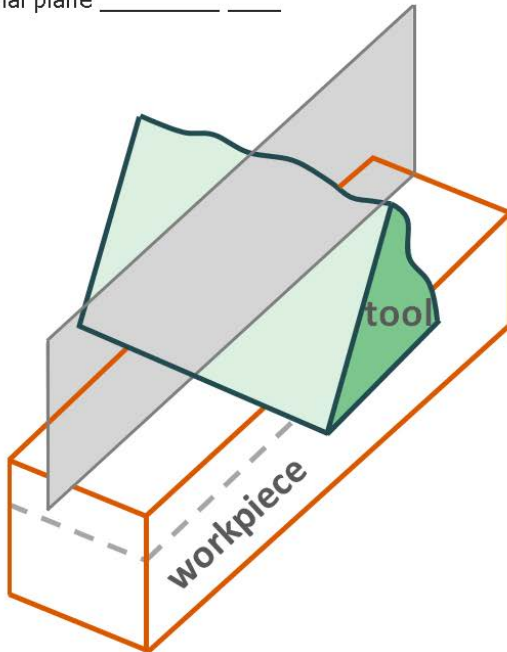
_____ : Plane _____ the Cutting _____ () & _____ the Machined Surface ()

In orthogonal cutting:

- the normal plane _____
- the normal plane _____

In oblique cutting:

- the normal plane does _____ due to _____



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Normal Rake Angle

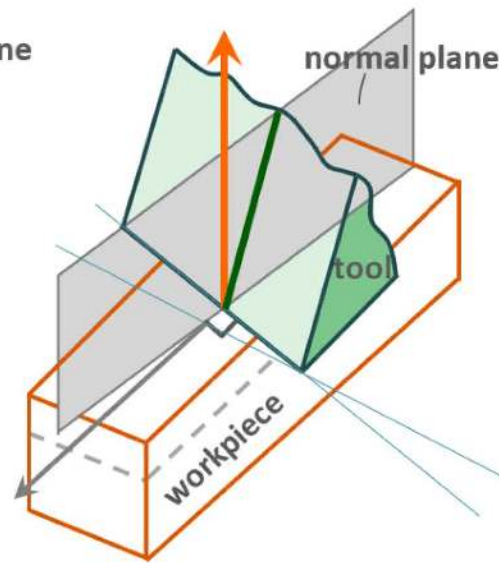
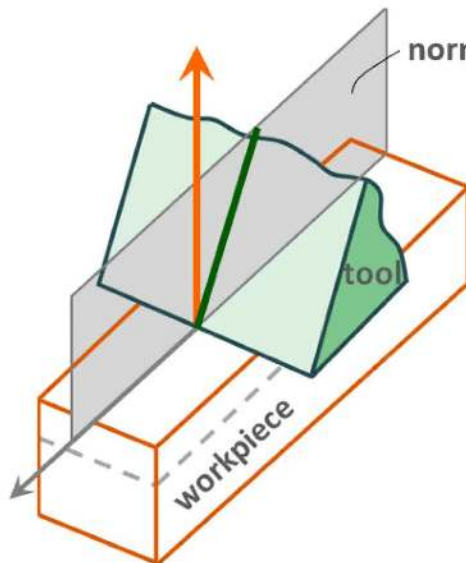
Topic 05 – 11

_____ **Rake Angle** () : w.r.t _____

: Angle between _____ and _____

: on the _____.

: Known from the _____.



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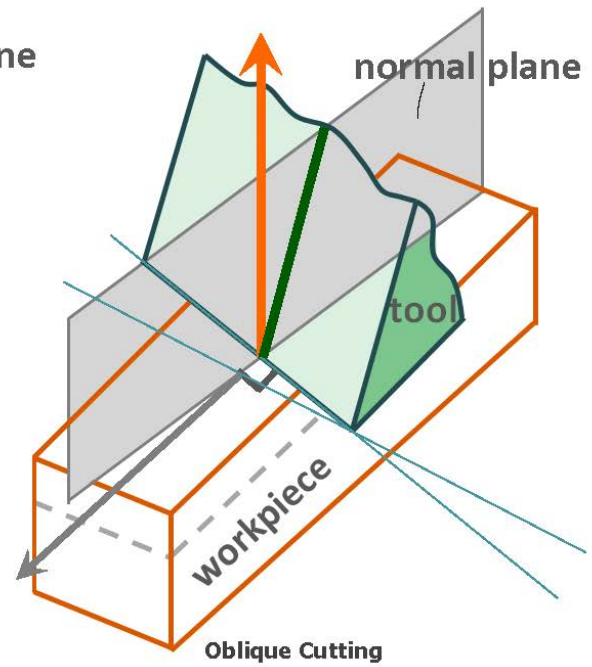
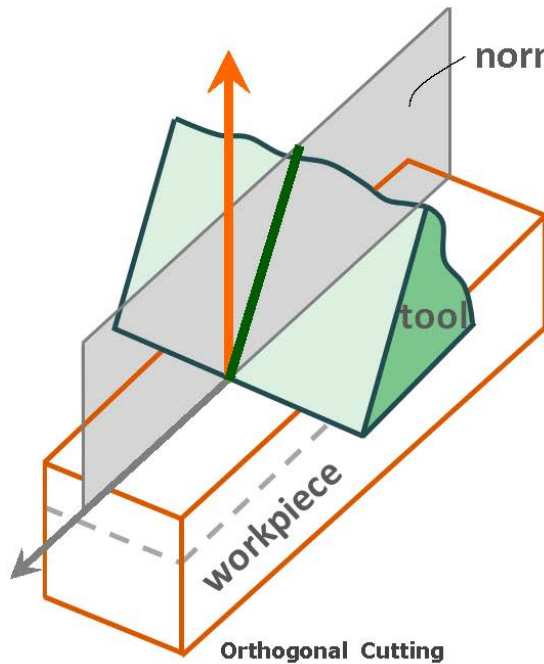
Normal Rake Angle

Topic 05 – 12

cutting edge
workpiece

w.r.t the **Tool**

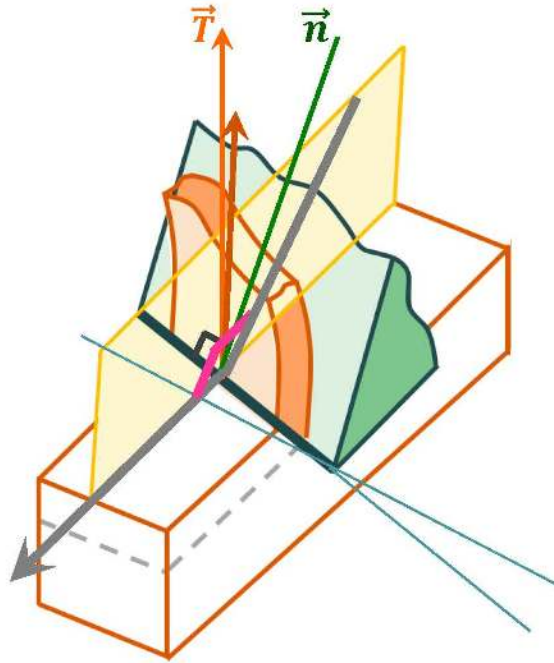
an angle between and



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_____ **Rake Angle** (): w.r.t _____ =

: Angle between _____ and _____ in the plane containing _____ and _____



$$\alpha_e =$$

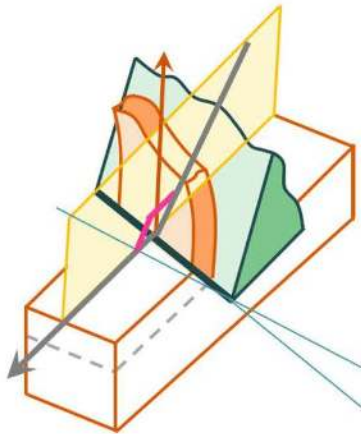
=

According to *Stabler's Rule*,

=

Hence, **the Effective Rake** can be found using:

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Effects of the Effective Rake Angle

- As ____ increases, ____ increases.
- If ____, the chip becomes ____ and ____.
→ Consequently, the cutting ____.

- If $i =$ ____ : ____ →



$$\alpha_e = f(\quad , \quad , \quad)$$

By _____

$$= f(\quad)$$

$$\alpha_e = \sin^{-1} (\sin^2 i + \cos^2 i \sin \alpha_n)$$



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• Cutting Mechanics

- _____ cutting • cutting _____

- _____ cutting {
 - cutting edge $\perp$ cutting velocity due to _____!
 - should be presented in _____.

- Inclination Angle (): _____ from the cutting _____
 - Chip Flow Angle (): by Stabler's Rule,
 - Normal Plane
 - Normal Rake Angle (): _____ from the _____
 - Effective Rake Angle (): $\alpha_e = \sin^{-1} (\sin^2 \quad + \cos^2 \sin \quad)$
- Cutting _____**
Analysis

Relations

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Practical Applications: Cutting Mechanics and Geometric Relationships in Drilling

Ref. J.E. Lee *et al.* 2012. Modeling and Experimentation of Bone Drilling Forces. J of Biomechanics. 45 (6), 1076-1083, <https://doi.org/10.1016/j.jbiomech.2011.12.012>.

drill breakthrough. Twist drill bits with larger (fast) helix angles were seen to not only lower the drilling forces, but also enable more effective chip removal (Farnworth and Burton, 1974; Sneath, 1964). However, large helix angles were also seen to cause frequent drill breakthroughs (Farnworth and Burton, 1974). Other geometric parameters such as web thickness (Farnworth and Burton, 1974; Saha et al., 1982), rake angle (Jacobs et al., 1976) and flute geometry (Saha et al., 1982) have also been analyzed.

Only a few studies in the literature have attempted to derive models of bone drilling process to capture the effect of drilling conditions and drill-bit geometry. Simplified models of cutting mechanics were applied to model the thrust forces and torques during bone drilling (Jacobs et al., 1974, 1976; Wiggins and Malkin, 1976). It was concluded that whereas both the chisel edge and the cutting lips contribute significantly drilling forces, the thrust forces are dominated by forces from the chisel edge. More recently, an enhanced model of the drilling forces during bone drilling was derived (Tsai et al., 2007), where the cutting lips were divided into small elements. However, the model was not validated against experiments.

Although the aforementioned studies resulted in various (and sometimes conflicting) conclusions, they have not provided a functional relationship that represent the effects of drilling conditions and drill-bit geometry on drilling forces. The literature, however, provides two critical insights about the bone drilling process: First, while the bone-drilling progresses by creating micro-scale fractures, the overall characteristics of the process closely resemble that of shearing of material seen in metal and polymer machining. And second, the mechanical characteristics of bone during drilling depend strongly upon the amount of strain, strain rate (cutting speed), and temperatures (Crowninshield and Pope, 1974; Jacobs et al., 1976; Pope and Outwater, 1974). Therefore, the mechanics of bone drilling directly depends upon drilling conditions and drill-bit geometry.

Considering the similarity of mechanics of bone drilling to that of drilling metals and polymers, the diverse literature in machining becomes relevant. The fundamental understanding of material removal mechanics (Merchant, 1944, 1945) was applied to model the drilling process (Mauch and Launderbaugh, 1990; Stephenson and Agapiou, 1992). Mauch and Launderbaugh (1990) developed an analytical model, where the cutting lips were divided into small oblique-cutting elements. Chandrasekharan et al. (1998), and later Gupta et al. (2003) significantly enhanced drilling models by applying the mechanistic modeling technique. In mechanistic modeling, the cutting geometry is analytically determined, whereas the material parameters and friction are obtained from a small number of calibration tests that are valid for a broad range of cutting conditions and drill-bit geometries. A myriad of experiments has proven that the mechanistic modeling is effective in predicting drilling forces under varying drill-bit geometry and drilling conditions.

In this work, we present a mechanistic model for the bone drilling process to enable prediction of bone drilling forces as a function of drill-bit geometry and drilling conditions. First, the model, including the analytical description of drill-bit geometry and drilling thrust and torque, is derived. Next, a set of calibration experiments was conducted to determine the variation of material parameters with the drill-bit geometry and cutting conditions, and to identify the calibration coefficients. The model is then evaluated against validation experiments on cortical portions of bovine tibia.

2. Model derivation

Fig. 1 describes the twist drill-bit geometry. As the tool is rotated about and fed along the tool axis, the material is removed primarily by the two cutting lips, oriented at a point angle of $2p$. The twisting (or fluting) provides a means for evacuating the chips away from the cutting zone. The chisel edge provides stability to the drill motions, and is a large contributor to the thrust forces. The forces arising from the margins of the drill bit are generally negligible (Stephenson and Agapiou, 1992).

2.1. Forces from the cutting lips

Due to the rotary motion of the drill bit, the cutting speed varies along the cutting lips with the radial position. The chisel edge causes the orientation of the cutting velocity to vary with the radial position (see Fig. 2(a)). Furthermore, the tool angles,

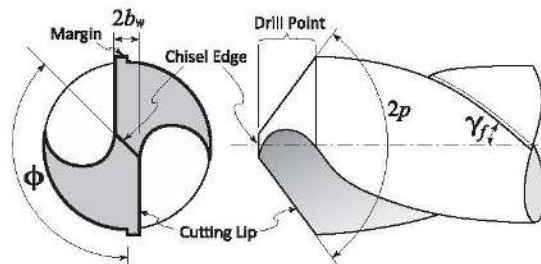


Fig. 1. Geometry of a twist drill-bit.

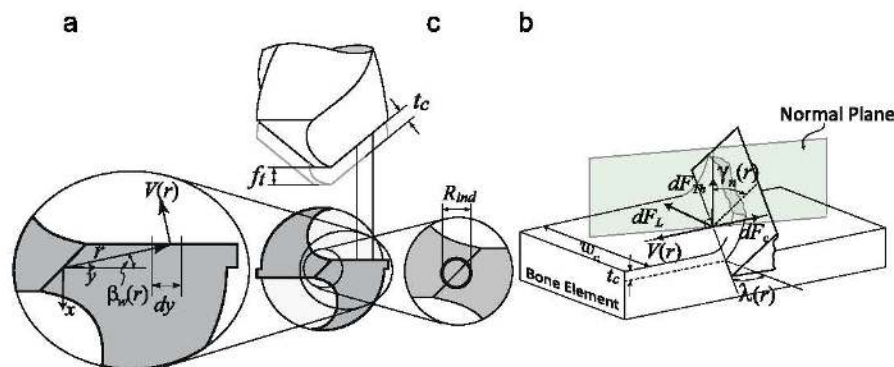


Fig. 2. Cutting geometry during drilling: (a) kinematic parameters for a cutting-lip element, (b) oblique cutting geometry and cutting forces, and (c) the indentation radius on the chisel edge.

such as the normal rake angle, vary considerably along the cutting lips due to the drill-bit geometry.

Since the drill-bit geometry and cutting velocity vary along the cutting lips, each cutting lip will be divided into a (large) number of cutting elements (Fig. 2(a)). In our mechanistic model, the forces acting on each element are composed of normal and friction forces

$$dF_n = u_n a \quad \text{and} \quad dF_f = u_f a, \quad (1)$$

respectively, where a is the chip area, u_n is the specific normal energy, and u_f is the specific friction energy. The specific energies represent the amount of energy required for removal of unit amount of material, and are empirical functions of material parameters and cutting conditions.

The oblique cutting geometry experienced at each cutting element along the cutting lips is illustrated in Fig. 2(b). For the material being removed, the (uncut) chip area is defined as the planar area perpendicular to the cutting velocity as

$$a(r) = t_c w_c(r) = (f_t \sin(p)) \left(\frac{dy}{\sin(p)} \cos(\lambda(r)) \right) = f_t dy \cos(\lambda(r)), \quad (2)$$

where r is the radial distance, $f_t = f_r/2$ is the feed-per-flute, f_r is the feed-per-revolution, w_c is the width of cut, dy is the width of the cutting edge along the y direction, and

$$\lambda(r) = \sin^{-1} \left(\frac{b_w}{r} \sin(p) \right), \quad (3)$$

where $\lambda(r)$ is the inclination angle, b_w is the half of the web thickness and p is the half of the point angle.

Considering the cutting geometry, the cutting velocity, normal rake angle and inclination angle can be written as a function of the cutting conditions and drill-bit geometry. For each element, the cutting velocity is given as $V(r) = 2\pi n_s/60$, where n_s is the spindle speed in rpm. The normal rake angle, which is measured within a plane normal to the cutting edge between the rake face and the plane normal to the cutting velocity, can be expressed as (Oxford, 1955)

$$\gamma_n(r) = \tan^{-1} \left(\frac{\sqrt{r^2 - b_w^2} \tan(\gamma_f)}{r \sin(p) - b_w \cos(p) \tan(\gamma_f)} \right) - \tan^{-1} \left(\frac{b_w \cos(p)}{\sqrt{r^2 - b_w^2}} \right), \quad (4)$$

where γ_f is the helix angle of the drill bit. The inclination angle $\lambda(r)$ is the angle between the cutting edge and a plane normal to the cutting velocity. For each cutting element at radius r , Eqs. (2)–(4) can now be evaluated.

The elemental oblique machining force components, including the cutting force dF_c , the thrust force dF_{th} and the lateral force dF_L , can now be related to elemental normal and friction forces as

$$\begin{Bmatrix} dF_c \\ dF_{th} \\ dF_L \end{Bmatrix} = \begin{bmatrix} \cos(\gamma_n) \cos(\lambda) & (\sin(\eta_c) \sin(\lambda) + \sin(\gamma_n) \cos(\eta_c) \cos(\lambda)) \\ -\sin(\gamma_n) & \cos(\gamma_n) \cos(\eta_c) \\ \cos(\gamma_n) \sin(\lambda) & (-\sin(\eta_c) \sin(\lambda) + \sin(\gamma_n) \cos(\eta_c) \sin(\lambda)) \end{bmatrix} \times \begin{Bmatrix} dF_n \\ dF_f \end{Bmatrix}, \quad (5)$$

where η_c is the chip flow angle, which is set to be equal to the inclination angle (Stabler, 1951). Each angular parameter in Eq. (5) is a function of radial position of the element under consideration. Setting $r = r_k$, the contribution of the k th cutting element of the cutting lips to the global thrust force and torque can then be written as

$$\begin{aligned} dF_T &= dF_{th}(r_k) \frac{\cos(\beta_w(r_k)) \sin(p)}{\cos(\lambda(r_k))} - dF_L(r_k) \frac{\cos(p)}{\cos(\lambda(r_k))} \\ \text{and} \\ dM_Z &= r_k dF_T(r_k), \end{aligned} \quad (6)$$

respectively, where $\beta_w(r_k) = \sin^{-1}(w/r_k)$ is the web-offset angle (see Fig. 2(a)). The total contribution F_{tip} and M_{Ztip} of the cutting lips can then be calculated by summing up contributions from each element.

2.2. Forces from the chisel edge

In the vicinity of the drill-bit axis, the cutting velocity is too small for the material to be removed by cutting (Jacobs et al., 1974; Wiggins and Malkin, 1976). The inner portion of the chisel edge experiences an indentation process, and the outer portion (secondary cutting zone) experiences orthogonal cutting with a highly negative rake angle (Galloway, 1957). Modeling the forces from the chisel edge is important since a large portion of the drilling thrust force arises from the chisel edge (Stephenson and Agapiou, 1992).

The forces from the indentation zone can be derived by considering an extrusion process within the indentation radius (Mauch and Launderbaugh, 1990)

$$R_{ind} = \frac{f_r}{2 \tan(\pi/2 - p)}, \quad (7)$$

where the tool acts as a rigid wedge (Oxford, 1955). From the slip-line field theory, the thrust force and torque from the indentation zone can be calculated as (Kachanov, 1971; Oxford, 1955)

$$F_{ind} = \frac{22\sigma_y(1 + \epsilon)f_r R_{ind} \sin(\alpha_n)}{\cos(\alpha_n) - \sin(\alpha_n - \epsilon)} \quad \text{and} \quad M_{ind} = \frac{2\sigma_y(1 + \epsilon)f_r R_{ind}^2 \cos(\alpha_n)}{\cos(\alpha_n) - \sin(\alpha_n - \epsilon)}, \quad (8)$$

where σ_y is the yield stress of the bone and ϵ is the solution for the slip lines, which can be obtained from

$$-2\alpha_n = \epsilon + \cos^{-1}(\tan(\pi/4 - \epsilon/2)), \quad (9)$$

where the normal rake angle α_n is

$$\alpha_n = -\tan^{-1}(\tan(p) \cos(\pi - \phi)) \quad (10)$$

and ϕ is the chisel angle (see Fig. 1).

The force contributions from the secondary cutting edge are calculated in the same manner as those from the cutting lips. Since the tangential velocity is small in this region, the feed velocity cannot be neglected. The cutting geometry for each element resembles that of orthogonal cutting process with a rake angle

$$\gamma_{ch} = \alpha_n + \phi_f \quad \text{where} \quad \phi_f = -\tan^{-1} \left(\frac{f_t}{\pi r} \right) \quad (11)$$

is the angle between the resultant (including feed velocity) and the tangential velocity vectors.

3. Experimental methods

Experiments were performed on bovine cortical bones (the mid-diaphysis section of tibia, $\sigma_y = 160 \text{ N/mm}^2$, Reilly and Burstein, 1975) to calibrate the specific energies and to validate the model. The bones were obtained from a local slaughterhouse short time after the slaughter of the animals. To study the repeatability, multiple bones from different cows were acquired. The bones were then maintained in saline solution and kept in a frozen state at -10°C according to the guidelines in Sedlin and Hirsch (1966). Prior to the conducting experiments, the specimens were completely thawed at room temperature for 24 h, and fully immersed in saline solution until needed.

To conduct the experiments (see Fig. 3), each bone specimen was attached to a drilling dynamometer (KIAG SWISS 9271A), which measures thrust force and torque during drilling as a function of time. A CNC machine (Fadal CNC88HS, see Fig. 3)

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Manufacturing

Topic 06: Plastic Deformation in Cutting

Prof. J Lee

Plastic Deformation in Cutting

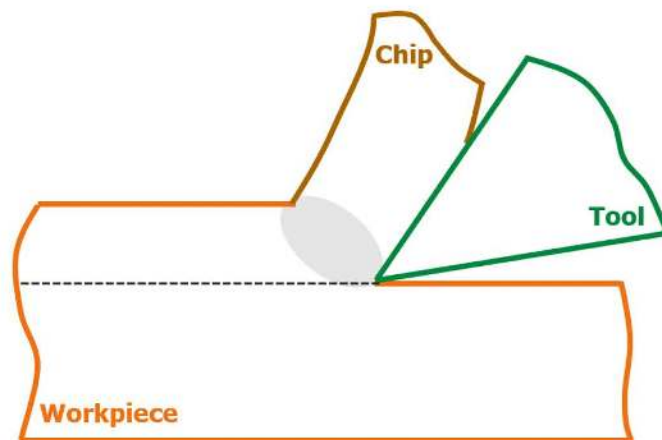
- Understand the assumptions for an idealized orthogonal cutting.
- Determine the cutting ratio.
- Determine the shear plane.
- Determine the shear angle.

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Plastic Deformation in Cutting

Topic 06 – 2

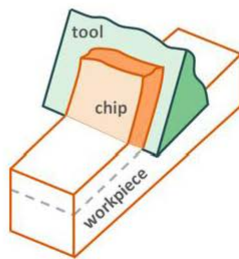
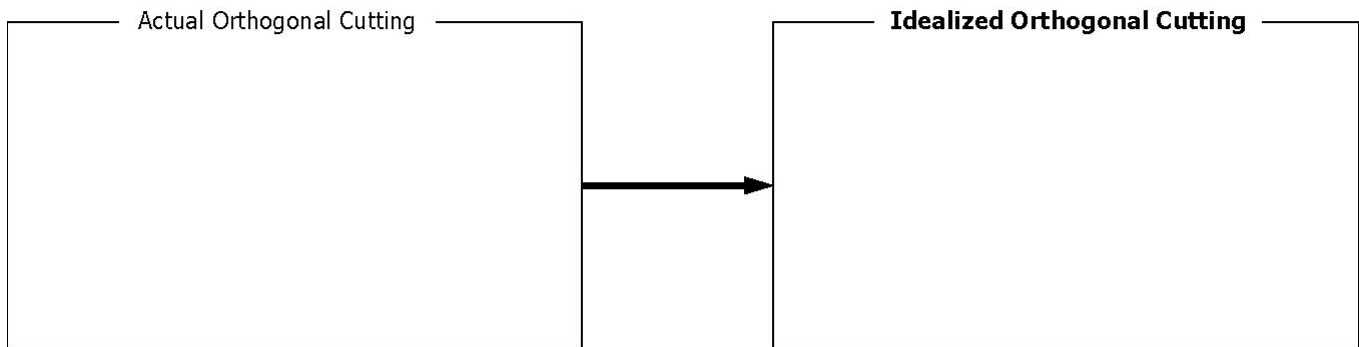
- _____: a process of extensive _____ to _____ a _____ which is removed afterward
- Chip formation in metal cutting is accompanied by substantial _____ in the _____.
- _____ takes place within a _____, which is also called a _____ zone.



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Assumptions

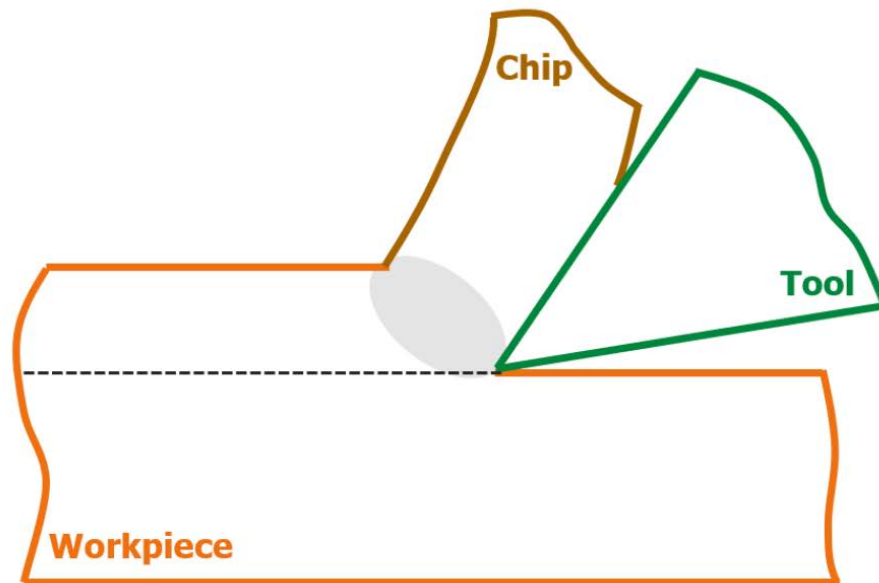
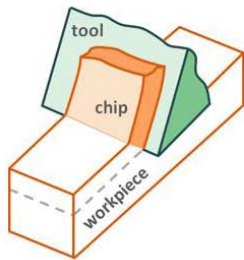
Topic 06 – 3



Assumptions:

- Tool is perfectly _____: very _____
- Tool only contacts _____ on its _____.
- Cutting edge is _____.
- Cutting edge is _____ to the cutting direction (_____).
- _____ does _____ flow to either side.
- _____ chip _____.
- Cutting velocity (_____) is _____.
- _____

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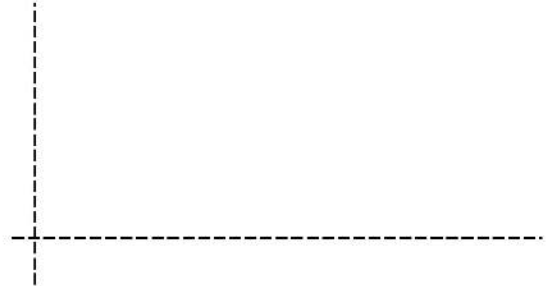
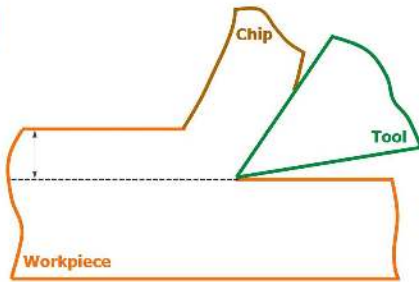
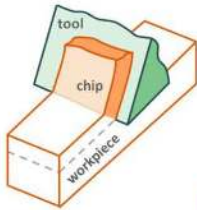


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Cutting Ratio

Topic 06 – 5

Cutting Ratio () or Chip-Thickness Ratio: the ratio of



Cutting Ratio, r = _____ = _____ = _____

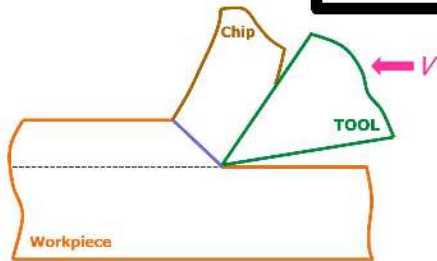
_____ thickness () :

_____ thickness () :

- Chip thickness () can be determined from (1) _____ (2) _____ (3) _____.
- Cutting ratio is related to the two angles _____ and _____.
- Cutting ratio is important and useful parameter to evaluate cutting _____.
- Cutting ratio can be used to calculate _____ : i) _____ is set; ii) _____ can be measured w/ micrometer;
iii) _____ is known from _____.

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_____ () :



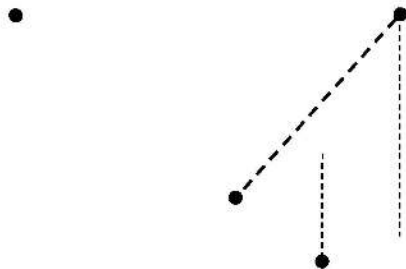
= _____

= _____

= _____

= _____

Shear Strain () =



• Characteristics of the Shear Strain

- Large shear strains associated with (1) _____
and with (2) _____ or _____.
- In actual machining cutting operations, _____ in general.
- Deformation in cutting generally takes place within a very _____ zone,
and therefore the dimension OC is very _____.

Recall:

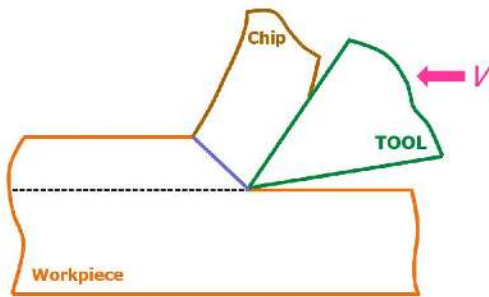
cot = _____

tan = _____

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Shear Angle Model

Topic 06 – 7



• Ernst-Merchant Model

(based on "Maximum Shear Stress Principle")

Assumptions:

- (1) The shear angle adjusts itself to minimize the cutting force
- (2) The shear plane is a plane of maximum shear stress.

Shear Angle (ϕ) = _____ = _____

where β : _____ at the tool-chip interface

μ : _____ of _____ at the tool-chip interface



Note: In metal cutting, $\phi < \beta$ and $\phi < \mu$

• Lee-Shaffer Model

(based on "Plasticity-Slip-Line Theory")

Shear Angle (ϕ) = _____ = _____

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Shear Angle

Topic 06 – 8

- **Shear Angle (ϕ):** One of the major significance in the cutting mechanics.

Why: The shear angle influences (1) Cutting _____ and _____;
 (2) _____;
 (3) _____ rise.

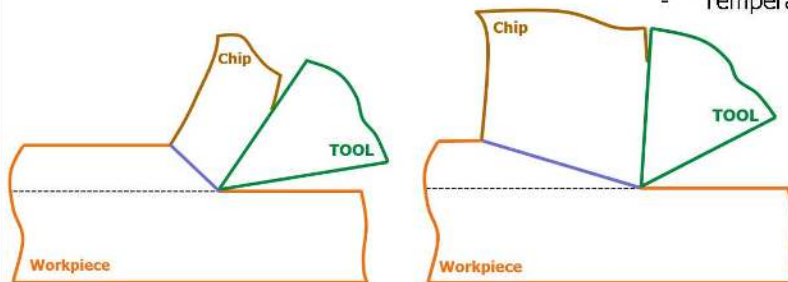
Message from Shear Angle Model

$$\phi = 45^\circ + \frac{\alpha - \beta}{2} \quad \text{or} \quad \phi = 45^\circ + \alpha - \beta$$

means:

If α or β

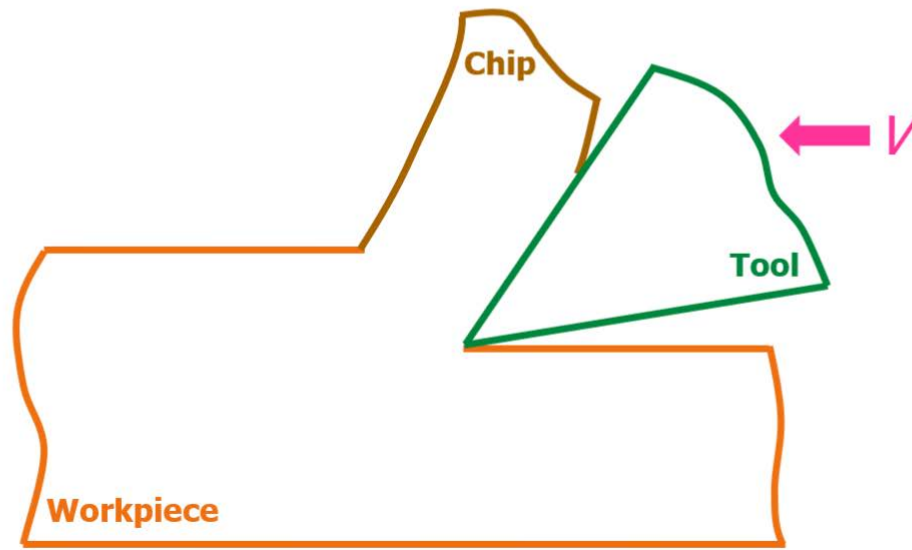
- ϕ _____ $\rightarrow$ chip becomes _____.
- _____ chips $\rightarrow$ _____ $\rightarrow$ more _____ dissipation
- Temperature rise _____ since the work done during cutting is converted into _____.



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1. The image shows an ideal orthogonal cutting diagram in 2D. Identify and label the following parameters:

- a) Rake angle
- b) Clearance angle
- c) Primary zone
- d) Uncut chip thickness
- e) Chip thickness
- f) Shear Plane
- g) Shear angle

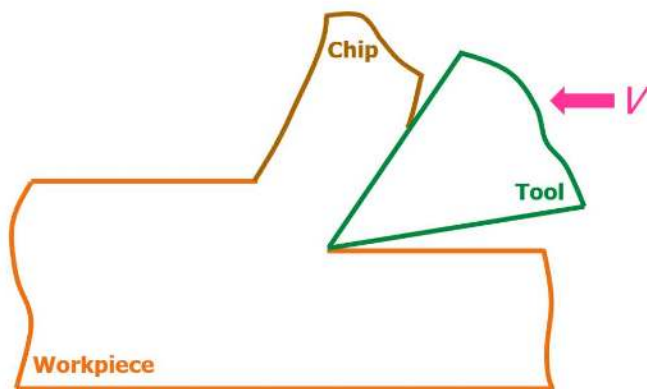


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2. The uncut chip thickness (t_o) and chip thickness (t_c) can be expressed as $t_o = l \sin \phi$ and $t_c = l \cos (\phi - \alpha)$, respectively. To derive these equations, indicate the corresponding parameters in the figure (a) and (b), respectively. In the figure (b), clearly mark the angle $(\phi - \alpha)$.

V_c : chip flow vector
 V_s : shear plane vector
 t_o : uncut chip thickness
 t_c : chip thickness
 l : the length of the shear plane
 ϕ : the shear angle
 α : the rake angle

(a)



(b)



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Practice Problems

Topic 06 – 11

3. In orthogonal cutting, the rake angle is 15° and the coefficient of friction is 0.2. Using Ernst-Merchant Model, determine the percentage increase in chip thickness when the friction coefficient is doubled.

Given:

Find: % increase of _____ when

Solution:

$$\% \text{ increase} = \frac{\text{ } - \text{ }}{\text{ }} \times 100 = \frac{\text{ } - \text{ }}{\text{ }} \times 100$$

i) Original $\mu = 0.2$:

$$r = \frac{t_o}{t_c} = \frac{\cos(\phi_1 - \alpha)}{\sin(\phi_1)} \rightarrow \therefore t_{c1} = \frac{t_o \cos(\phi_1 - \alpha)}{\sin(\phi_1)} = \frac{t_o \cos(46.8450^\circ - 15^\circ)}{\sin(46.8450^\circ)} =$$

$$, \text{ where } \phi_1 = \alpha + \frac{15^\circ - \tan^{-1}(\mu)}{2} = 46.8450$$

ii) When doubled $\mu = 0.4$:

$$r = \frac{t_o}{t_c} = \frac{\cos(\phi_2 - \alpha)}{\sin(\phi_2)} \rightarrow \therefore t_{c2} = \frac{t_o \cos(\phi_2 - \alpha)}{\sin(\phi_2)} = \frac{t_o \cos(41.5993^\circ - 15^\circ)}{\sin(41.5993^\circ)} =$$

$$, \text{ where } \phi_2 = \alpha + \frac{15^\circ - \tan^{-1}(\mu)}{2} = 41.5993$$

$$\text{iii) \% increase} = \frac{t_{c2} - t_{c1}}{t_{c1}} \times 100 = \frac{(1.3468 - 1.1645) t_o}{1.1645 t_o} \times 100 = 15.6587$$

Answer:

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Manufacturing

Topic 07: Forces in Cutting

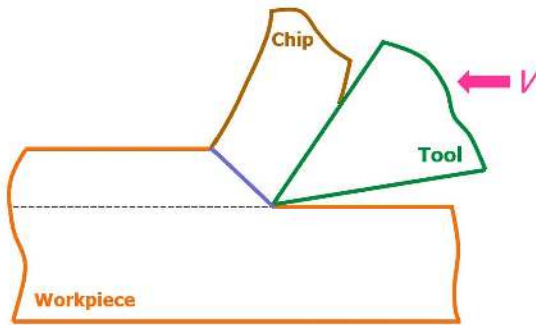
Prof. J Lee

Analyze and Predict Forces in Cutting

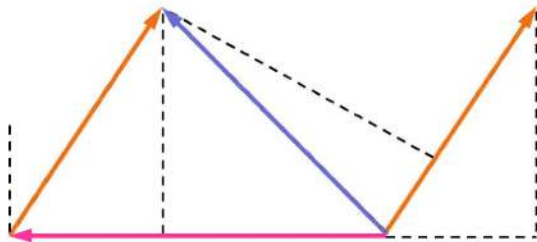
- Analyze the velocity relations within the cutting zone.
- Understand the various forces applied in the cutting zone and how they affect the machining process.
- Identify the geometric relationships of the cutting forces.
- Draw and interpret the Merchant's force circle diagram.
- Determine the resultant cutting force in cutting.

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- Express the chip and shear velocities in terms of the known parameters, $\frac{V_c}{V}$, $\frac{V_s}{V}$, $\frac{V_f}{V}$



Velocity Diagram



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- According to the Mass Continuity,



Recall the cutting ratio: $r_c = \frac{V_c}{V} = \frac{t_o}{f} = \frac{V_f}{V}$

Hence, the **Chip Velocity** can be expressed as:



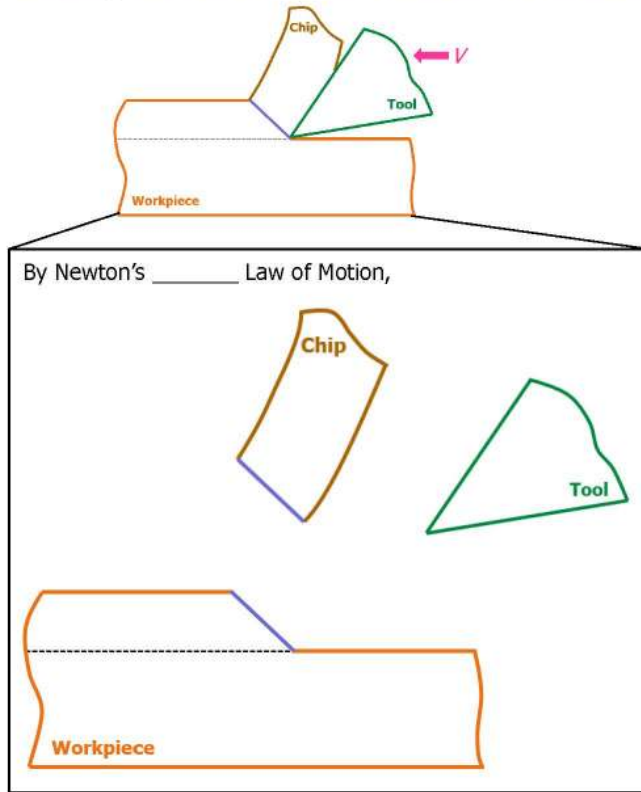
In the velocity diagram, $t_o = \frac{V_c}{V_s}$

$$\therefore \frac{V_c}{V} = \frac{V_s}{V} \left(\frac{\cos \alpha}{\sin \phi} \right)$$

Hence, the **Shear Velocity** can be expressed as:



• Identify the forces in the interfaces in cutting



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I. "Workpiece – Tool" Interface

- _____ : _____ Force (Primary Force)
- : acts in the cutting _____ direction.
- : supplies the _____ required for cutting.
- _____ : _____ force
- : acts _____ to the cutting direction.
- : acts into the _____.

II. "Tool – Chip" Interface

- _____ : _____ force
- : acts along the _____ face on the tool.
- _____ : _____ force
- : acts _____ to the rake face.
- : acts _____ the tool.

III. "Shear Plane – Workpiece" Interface

- _____ : _____ force
- : acts along the _____.
- : causes _____ of the material.
- _____ : _____ force
- : acts _____ to the shear plane.

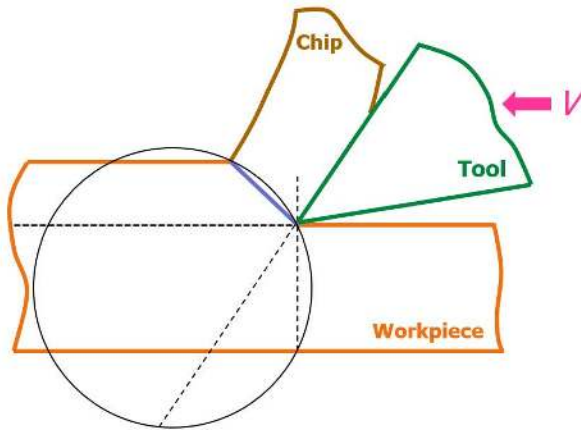


Merchant's Force Circle Diagram

Topic 07 – 4

- **Merchant's Force Circle Diagram** () : _____ circle to determine forces acting in the cutting zone.

Note: Draw the force directions assuming all forces acting on the _____.



- Determine _____ using the force vectors

I. "Workpiece – Tool" Interface

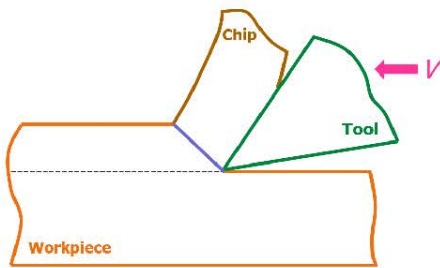
II. "Tool – Chip" Interface

III. "Shear Plane – Workpiece" Interface

- | | |
|----------------|-------------------------------|
| ① Rake Angle: | ② Friction Angle: |
| ③ | angle between _____ and _____ |
| ④ | |
| ⑤ Shear Angle: | |
| ⑥ | |

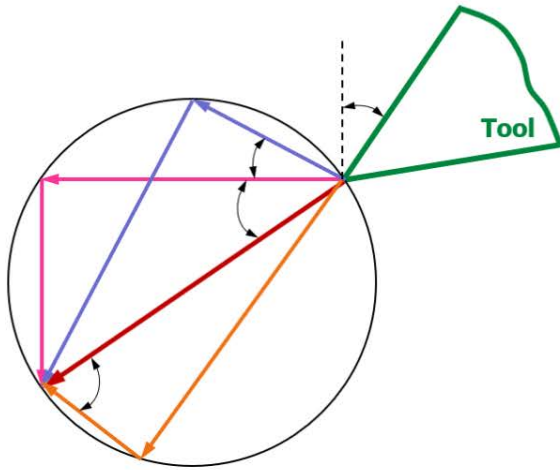
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- **Resultant Force ()**



Recall:

$$\tan \theta = \underline{\hspace{2cm}}$$



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- Determine the magnitude of the forces using $\vec{F}_R$

I. Cutting Forces at “Workpiece – Tool” Interface

--

II. Friction Forces at “Tool – Chip” Interface

--

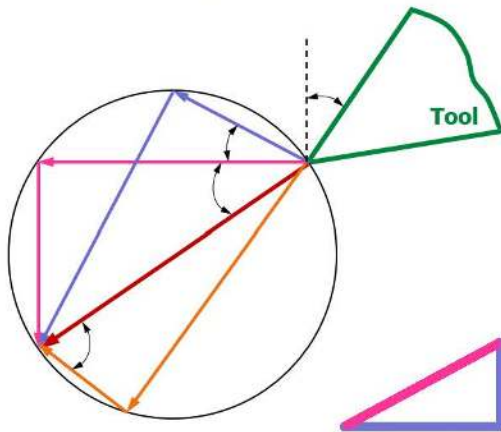
III. Shear Forces at "Shear Plane – Workpiece" Interface

--

- **Determine the magnitude of $\vec{F}_R$ using the forces**

--

• Identify the geometric relations in cutting forces



Determine the magnitude of forces using F_c and F_t

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

$$F_{sn} = F_c \sin \phi + F_t \cos \phi$$

$$F_f = F_c \sin \alpha + F_t \cos \alpha$$

$$F_n = F_c \cos \alpha - F_t \sin \alpha$$

$$= \text{—————} \rightarrow F_s = \text{—————} \quad (\text{Eq 1) and}$$

$$= \text{—————} \rightarrow \text{—————} = \text{—————} \quad (\text{Eq 2})$$

Substituting Eq 2 into Eq 1,

$$F_s =$$

$$=$$

$$, \text{ where } \tan \phi = \text{—————}$$

$$\therefore F_s =$$

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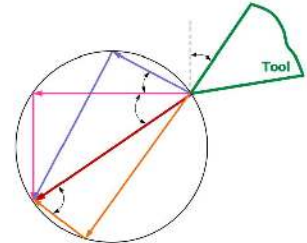
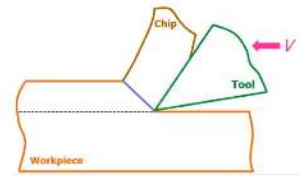
• Messages in Cutting Forces

1. Shear Forces at "Shear Plane – Workpiece" Interface:

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

$$F_{sn} = F_c \sin \phi + F_t \cos \phi$$

- Area of the shear plane can be calculated by: (1) _____; (2) _____
- Hence, _____ and _____ stresses in the shear plane can be determined.



2. Friction Forces at "Tool – Chip" Interface:

- Coefficient of Friction = _____ = $\frac{(F_c \sin \alpha + F_t \cos \alpha)}{(F_c \cos \alpha - F_t \sin \alpha)}$ = _____

Recall:

$$\tan \alpha = \frac{F_t}{F_c}$$

- In the shear zone, the local shear stresses and the pressure on the cutting tool are _____.
- Consequently, the tool _____ is subjected to very _____ stresses
- → lead to (1) _____; (2) _____ of the tool; and (3) _____ of the tool.

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3. Cutting Forces at “Workpiece – Tool” Interface:

- Thrust Force _____ can be determined by:



- Thrust Force is important. **Why?**

: If _____ is too _____ in the upward direction, the tool will be _____ the workpiece surface.

→ _____ actual tool engagement → _____ dimensional accuracy.

: Hence, the work _____ devices and machine-tool structure must be sufficiently _____

to support that force with minimal deflection.

- Magnitude of _____ is always _____ because _____ is defined in the cutting _____ and determines the cutting _____ required.

- Sign of _____ can be either _____ or _____ depending on the mag. of _____ and _____:

e.g. if $\beta > \alpha$: _____ acts _____ ()

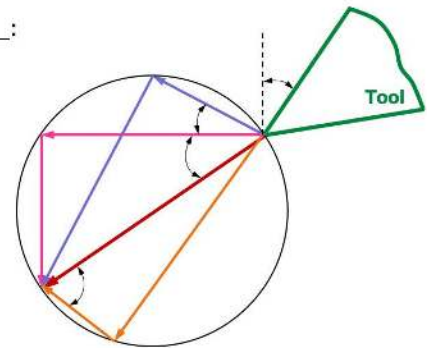
if $\beta < \alpha$: _____ acts _____ ()

- Hence, an upward thrust force will be under the conditions of:

i) _____

ii) _____: _____ at the tool-chip interface

iii) or _____



Note: _____ can have significant implications for the design of machine tools and work holders,

as well as for the overall stability of the cutting process.

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Practice Problems

Topic 07 – 9

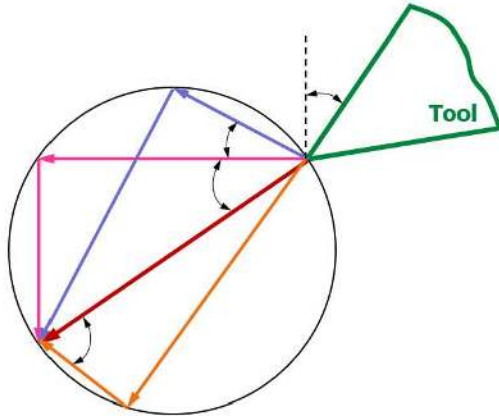
-
1. An upward thrust force generated during a cutting operation is generally considered undesirable. Explain how an upward thrust force can negatively affect each of the following aspects of machining:
 - (1) Workpiece Holding
 - (2) Machining Stability
 - (3) Tool Wear and Tool Stability

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Practice Problems

Topic 07 – 10

2. The normal force F_n on the tool rake face in orthogonal cutting can be expressed as $F_n = F_c \cos \alpha - F_t \sin \alpha$, where F_c is the cutting force, F_t is the thrust force, and α is the rake angle of the tool. Using Merchant's force circle diagram, derive the expression for the normal force F_n .



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Extra Sheet for Mass Continuity

Mass Continuity

In Fluid Dynamics, mass continuity is the principle that ensures the conservation of mass in a flow system. It states that for any control volume (a defined region in space), the mass entering must equal the mass exiting, assuming no accumulation or loss of mass within the system.

Mass continuity ensures that mass is conserved in a flow system, following the law of conservation of mass.

For incompressible fluids (i.e., water, oil), the continuity equation is expressed as:

$$v_1 A_1 = v_2 A_2$$

where

v_1 and v_2 : the flow velocities at points 1 and 2

A_1 and A_2 : the cross-sectional areas at points 1 and 2

This equation shows that the flow rate (volume per unit time) remains constant along a streamline in an incompressible fluid. As the area decreases, velocity must increase to maintain mass conservation, and vice versa.

For compressible fluids (i.e., air, natural gas), the equation becomes more complex, accounting for variations in density, and is expressed as:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho v) = 0$$

where

ρ : the density of the fluid

v : the flow velocity

$\nabla \cdot (\rho v)$: the mass flow rate per unit volume

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Manufacturing

Topic 08: Thermal Energy in Machining

Prof. J Lee

1. Thermal Energy in Machining

- Understand the mechanisms of heat generation during machining operations.
- Identify the primary sources of heat generated in machining

2. Temperature Measurement in Machining

- Explore techniques for measuring temperatures in real-time during machining processes.

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• Heat Generation in Machining

- In metal cutting, most of the mechanical energy used for plastic deformation and friction is converted into heat.
- This heat is generated mainly in the primary shear zone, at the tool-chip interface, and at the tool-workpiece interface.
- As a result, the temperature increases in the chip, cutting tool, and workpiece surface near the cutting zone.

Why is temperature rise important in machining?

(1) Cutting tool:

- Excessive temperature reduces the hot hardness, strength, and wear resistance of the cutting tool.
- Tools may soften, wear rapidly, or undergo plastic deformation. This may alter the cutting edge geometry and reduce tool life.

(2) Dimensional accuracy and tolerances:

- Increased heat causes thermal expansion and distortion in the workpiece, tool, and machine structure.
- This can cause dimensional errors and poor tolerance control.

(3) Thermal damage:

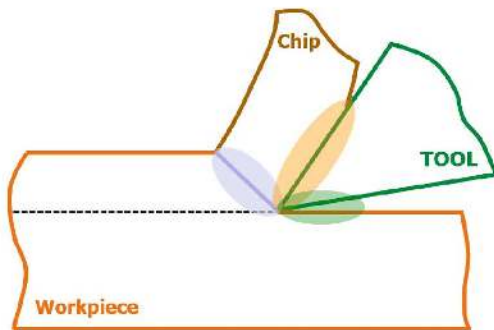
- Excessive temperature rise can induce thermal damage in the machined surface, adversely affecting surface integrity and material properties.

Note:

Almost all, **about 90% or more, of the mechanical energy** consumed in machining **is converted into heat**. Heat elevates the temperature of the chip, cutting tool, and workpiece.

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• Main Sources of Heat in Machining



(1) Primary Zone (Shear Zone)

: the work done in **shearing** in the primary (shear) zone.

(2) Secondary Zone

: energy dissipated as **friction** at the tool-chip interface.

(3) Zone for Workpiece-Tool Interface

: heat generated as **the tool rub** against the machined surface.

: friction between the flank face of the tool and
the newly created workpiece surface.

: negligible if a cutting tool is sharp enough.

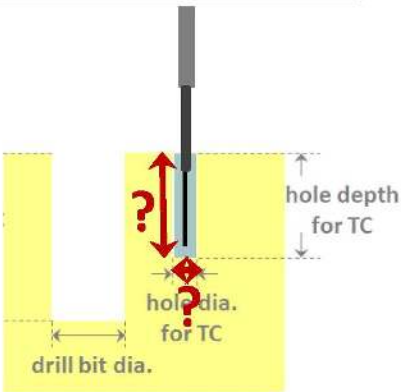
How to determine the Rate of Heat Generation

$$q = q_s + q_f = F_s V_s + F_f V_c \quad \text{Unit: [W]}$$

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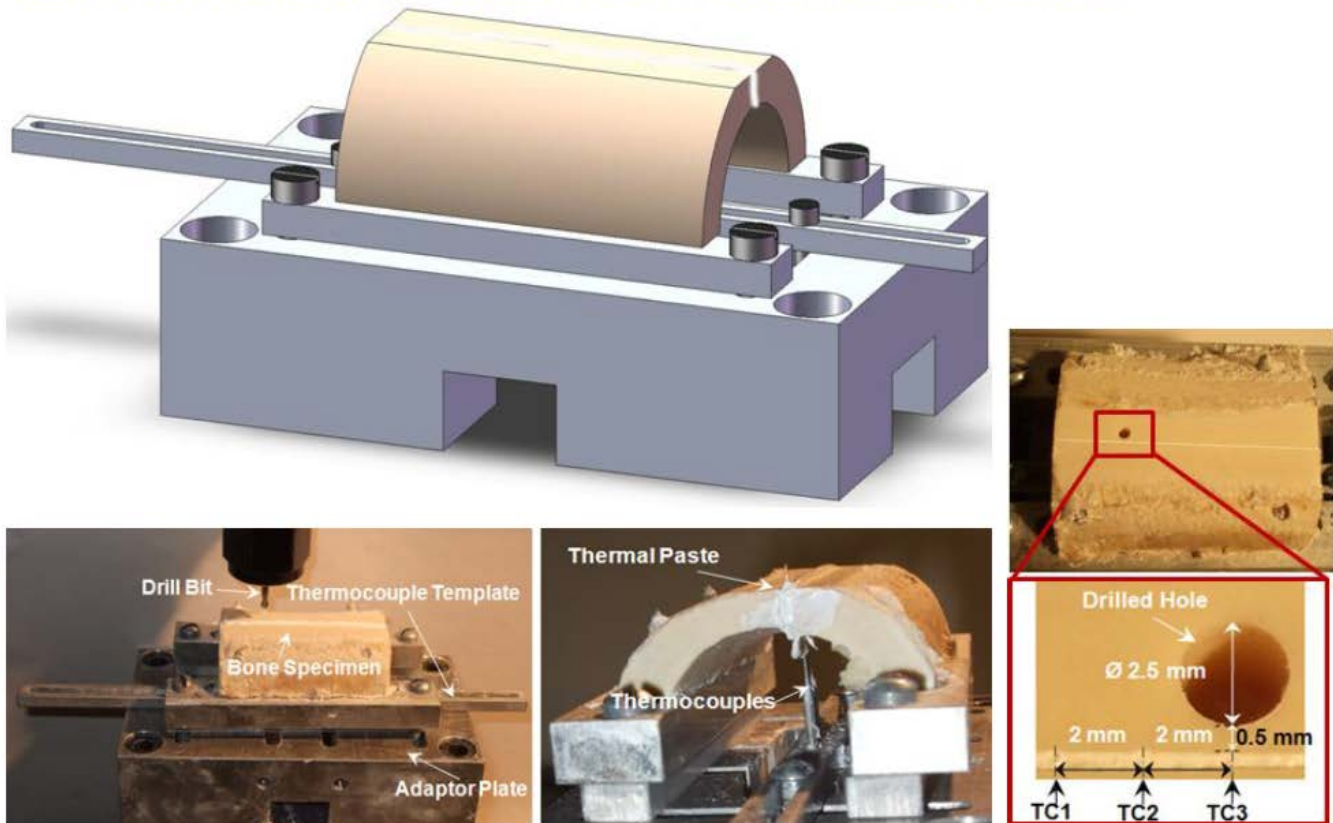
• Experimental Setup

: During machining, temperature can be measured using thermocouples or a thermal camera.

Thermocouple (TC)	Thermal Camera
 Ref. Lee et al. 2012. Med. Eng. Phys., 34(1), 1510-1520. + : can measure the temperature at the location where we want to know. – : uncertainty can result from the TC location and/or from thermal resistance effects.	 + : convenient and straightforward measurement. – : only allows the surface temperature measurement.

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• How to Resolve the Uncertainty Issues from TC Measurement Technique?



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Manufacturing

Topic 11: Drilling Operations

Prof. J Lee

- Define the drilling process and its role in manufacturing.
- Describe practical outcomes and applications of drilling.
- Analyze drill-bit geometry and performance impacts.
- Differentiate types of drilling operations.
- Identify common issues in drilling operations and mitigations strategies.
- Analyze drilling forces.

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• What

- a material _____ process to create circular _____ or _____ existing holes
- a material is cut by a _____ cutting tool, “ _____ ”
- used to produce _____: _____ in shape and _____ in diameter

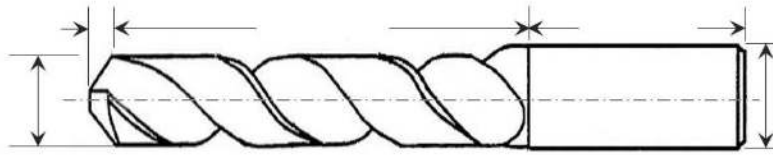
Applications in Drilling Process



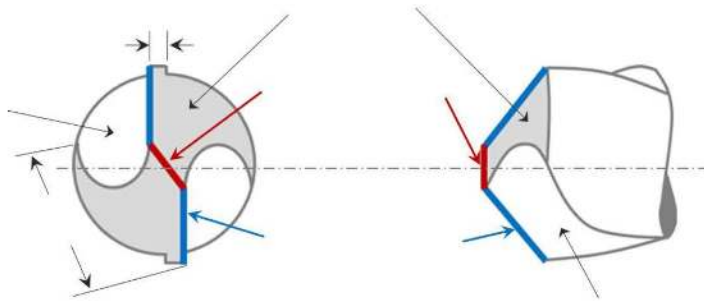
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• Tool : _____

Geometry of a _____ drill bit



_____ of a drill bit



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• Features of Twist Drill Bit

_____ : to _____ the drill bit from the _____

_____ : to _____ during drilling

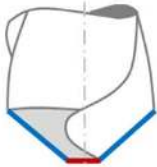
_____ : to _____ chips

_____ : the chips produced are guided _____ through the _____

_____ : to permit cutting _____ to reach the _____ of the drill bit

_____ : can be defined using the _____

_____ : to _____ the material



_____ : to mainly _____ the material

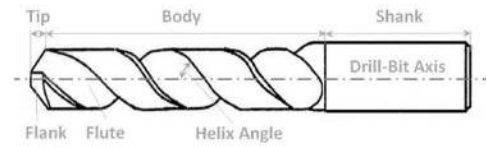
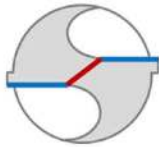
_____ : formed by the intersection of the _____ and _____

_____ : _____ defines the inclination of the cutting lips

_____ : to _____ into the workpiece

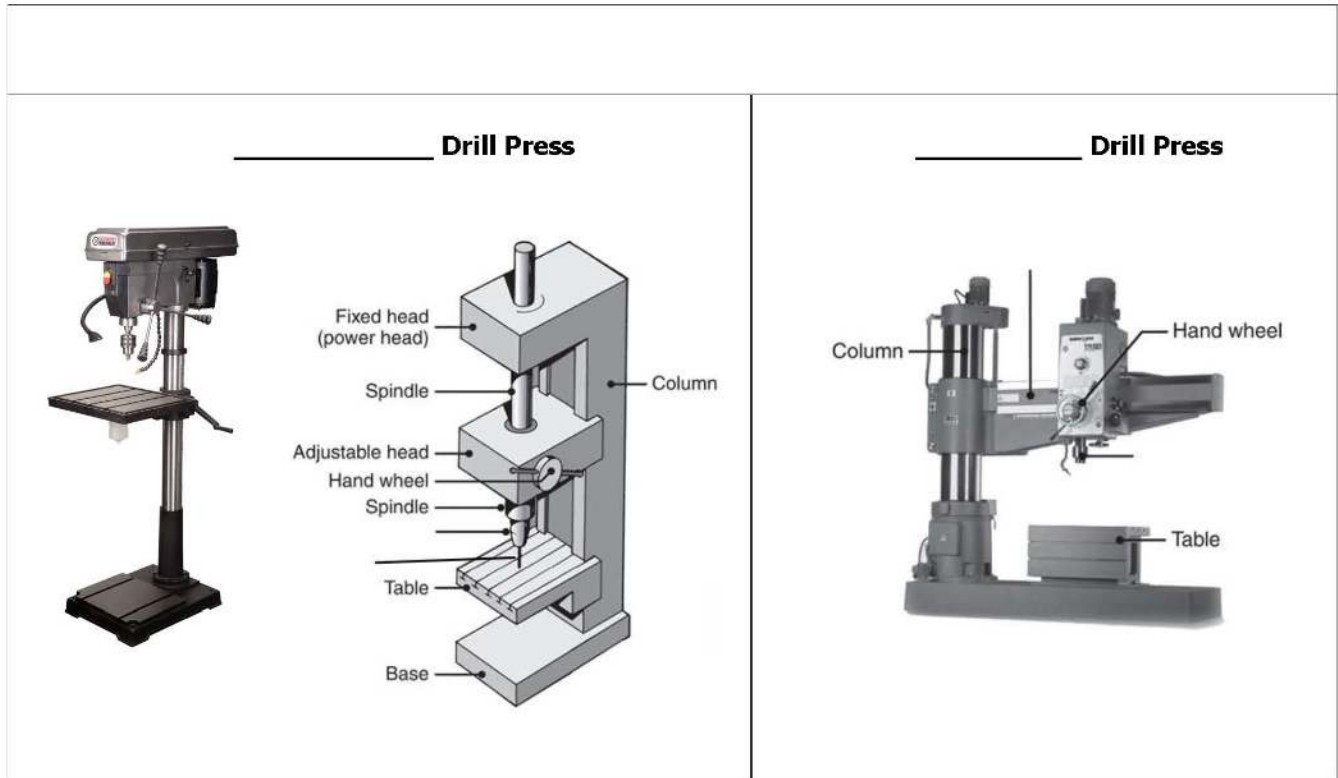
_____ : formed by the intersection of the _____

_____ : _____ defines the chisel edge.



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• Machine



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• Types of Drilling Operations

_____ Drilling 	: to drill a hole that will act as a _____ for drilling the _____ hole : hole is only drilled _____ way into the workpiece because it is only used to _____ the beginning of the next drilling process : designed to be extremely _____ so that it can precisely _____ a hole for a twist drill
_____ Drilling 	: to drill a hole that will act as a _____ of rotation for possible following operations
_____ Drilling	: defined when a hole _____ is greater than about _____ times the _____ of the hole : efficient _____ and _____ methods are required

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General Possible Problems in Drilling Operations

Topic 11 – 7

Problem	Possible Reasons
• Drill-bit	• Dull drill bit • Chip clogging • High feed rate
• Excessive	• Ineffective cutting fluid • High cutting speed
• hole	• Misaligned drill-bit • Bent drill-bit • Cutting lips may not be equal. • Web may not be centered.
• Poor	• Dull drill bit • Ineffective cutting fluid • Improper alignment

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Problem	How to Resolve
• Drill-bit	- Use a  to guide the drill bit. - Start with a small hole with a  - or Start with a 

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• Operation Sequence for Accurate Hole Creation



1. _____ (_____ Drilling or _____ Drilling)
: establishes a precise starting location to prevent drill wandering.



2. _____
: creates the initial hole close to the final diameter.



3. _____
: enlarges and improves the concentricity and alignment of the drilled hole.



4. _____
: finishes the hole to the final diameter with high accuracy and surface quality.
: For _____ metals, a reamer typically removes about _____ mm on the diameter of a drilled hole.
: For _____ metals, the material removed is approximately _____ mm.

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• Material-Removal Rate ()

: _____ of material _____ per unit _____

: For a drill-bit with diameter _____,



where

f : []

: _____ distance the drill bit advances into the workpiece per _____ of the drill bit.

: influences surface finish, tool wear, and cutting forces.

N : []

: _____ speed of the drill bit.

: determines the cutting speed at the drill's outer edge and directly affects heat generation, tool life, and surface finish.

V : []

: _____ speed of the drill bit's outer edge relative to the workpiece surface.

: represents the speed at which the cutting edge moves through the workpiece.

• Thrust Force

: _____ force applied by the drill on the workpiece _____ the axis of the tool in drilling.

: Acts in the directions of _____ and advance the drill into the workpiece.

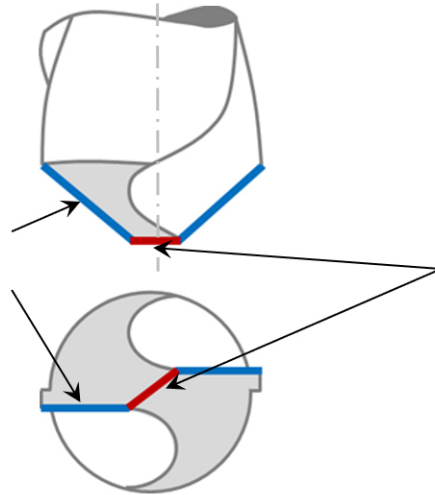
• Torque

: _____ force required to turn the drill against the resistance of the material during cutting.

: Acts about the drill axis and is responsible for _____ ing the material to form the chip.

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• Force Modeling



Source: J.E. Lee *et al.*, 2012. Modeling and Experimentation of Bone Drilling Forces. J of Biomechanics, 45(6), 1076-1083.

Total Forces on a Drill Bit

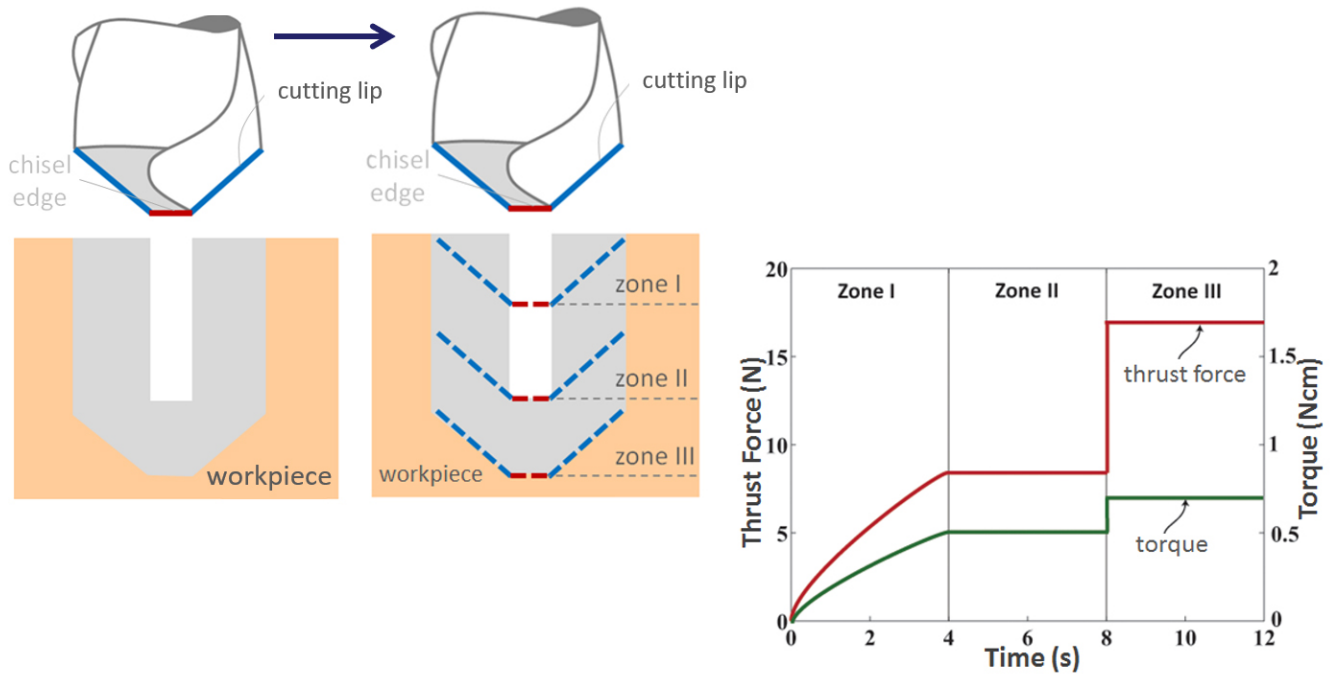
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Forces from

Forces from

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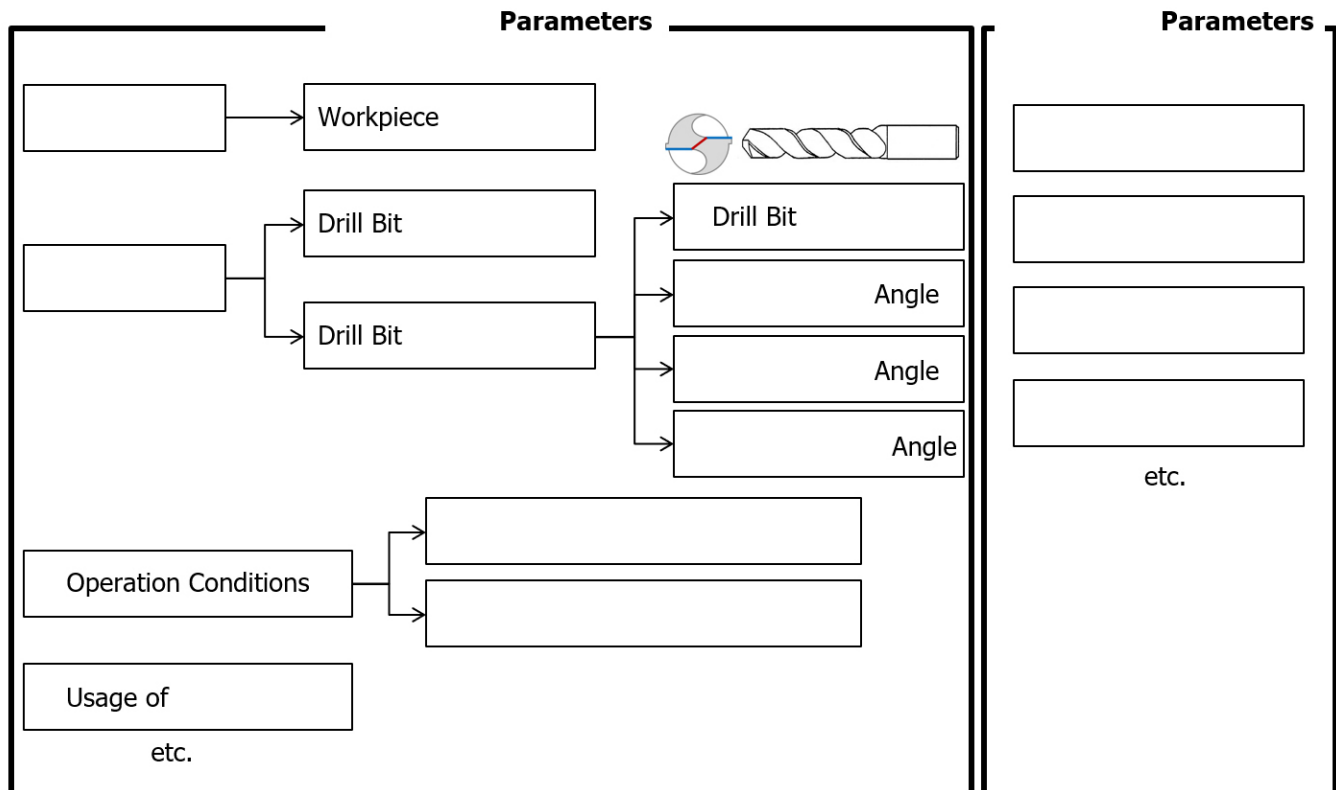
• Design of Experiments



Source: J.E. Lee *et al.*, 2012. Modeling and Experimentation of Bone Drilling Forces. *J of Biomechanics*, 45(6), 1076-1083.

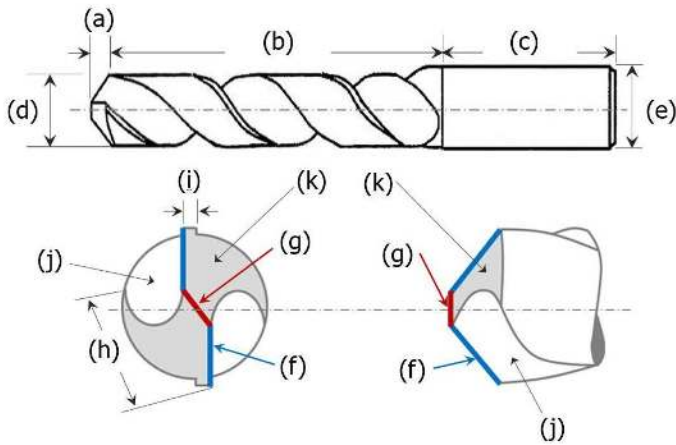
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• Design of Experiments



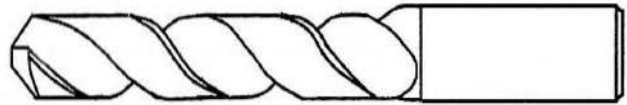
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1. The figures show a twist drill bit in different views. Label the drill bit geometry features corresponding to (a) through (k).



2. Indicate the following geometric features on the given figure.

- (1) Helix angle
- (2) Point angle



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3. Explain the primary function of each of the following drill bit features.

- (1) Tip
- (2) Body
- (3) Shank
- (4) Cutting lip
- (5) Chisel edge

4. In drilling operations, hole accuracy is improved using a sequence of processes. Explain how accuracy in location, size, and shape is achieved.

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Manufacturing

Topic 12: Milling Operations

Prof. J Lee

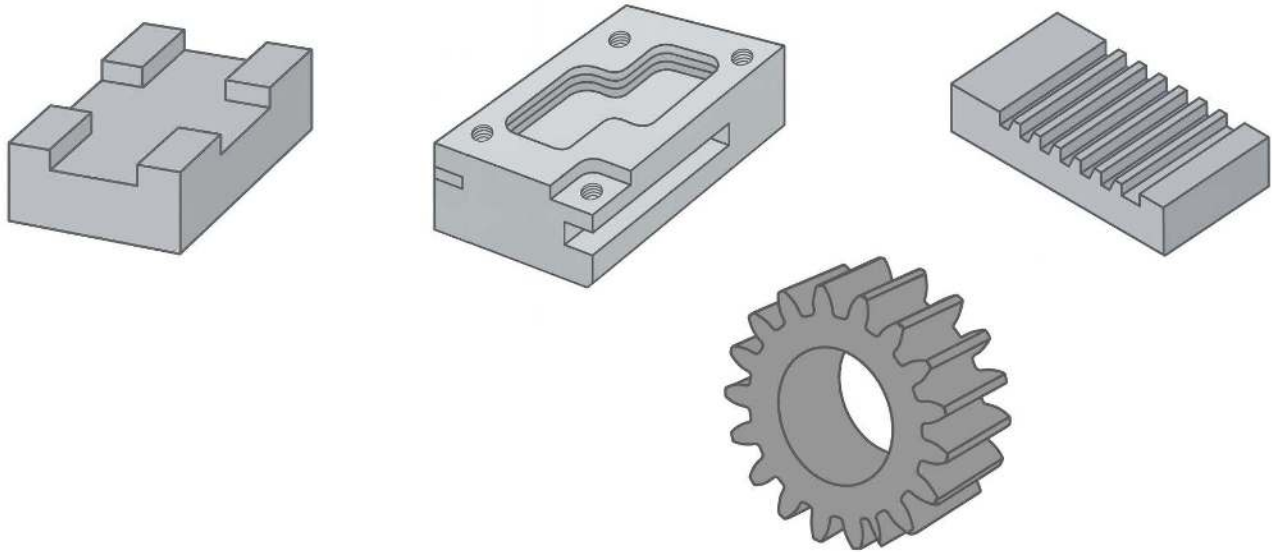
- Explain milling and its significance in material removal processes.
- Identify key outcomes and practical applications of milling operations.
- Analyze milling tools and cutter types, including their specific uses.
- Explain milling operations and their characteristics categorized by cutter types & feed direction.

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• What

- a material _____ process using a _____ cutter having cutting _____.
- used to machine _____ surfaces; _____; _____, etc.

• Applications

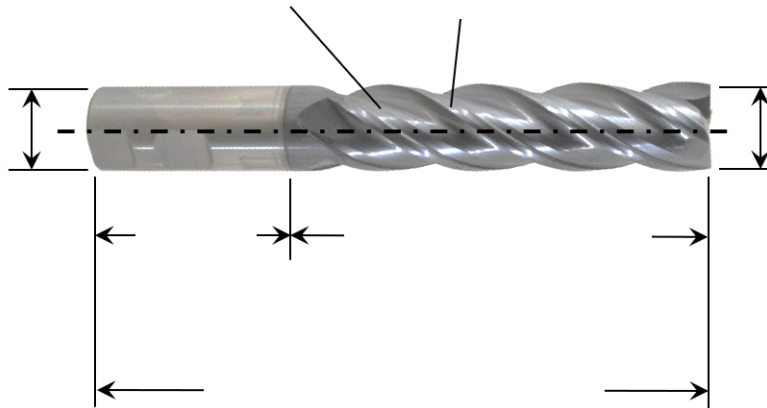


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• Tool

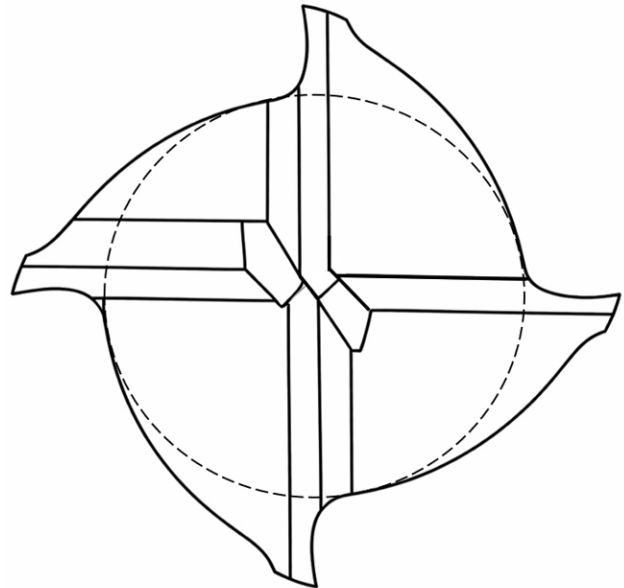
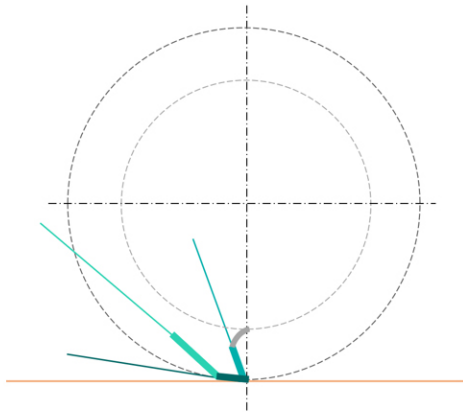
- _____
- can be typically specified by _____, _____ angle , _____ of _____, material, coating, etc

• Milling Cutter Geometry:



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• Milling Cutter Geometry: Tip



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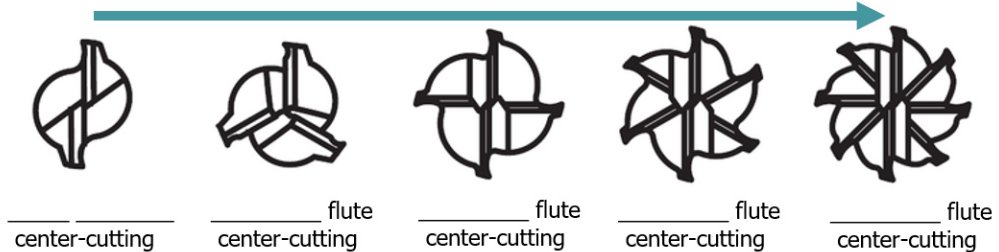
• Tool - Milling Cutter



" provides _____ : for _____ material"

_____ of _____ : Pros _____

Cons _____



" provides _____ : for _____ material"

_____ of tooth: Pros _____ chip ejection

Cons _____ tool rigidity

: The _____ will _____ engage and machine the workpiece.

∴ Milling is also called "_____ cutting."

: A _____ - flute end mill is generally preferred for _____ operations because _____ flute space _____ chip evacuation.

: _____ or _____ flutes improve surface finish and tool rigidity, so they are preferred for _____ operations.

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Milling Tool

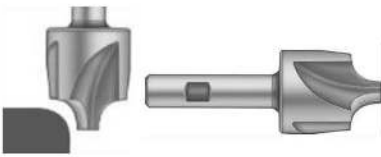
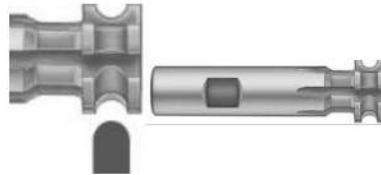
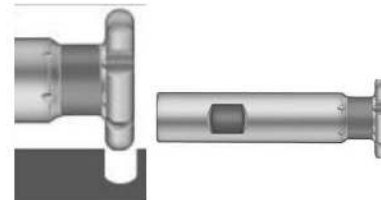
Topic 12 – 6

• Types of Milling Cutters

	roughing end mill	: leave rough finish, but cuts much _____ : recommended to use _____ cutting
	finishing end mill	: leave a _____ finish
	_____ end mill	: for a perfect _____ _____ at the bottom of the channel
	rounded edge OR bull nose end mill	: for rounded edges on the tip : for _____ milling
	_____ end mill	: for rounded details
	tapered end mill	: used for _____

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• Types of Milling Cutters

	corner rounding end mill	: to round off _____ corners on the edge
	_____ radius end mill	: for rounded, _____ward - curved edges
	_____ radius end mill	: for hollow, _____ward - curved edges

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• Types of Milling Cutters

	_____	: for _____ cutting of large and _____ surfaces
	side and face cutter	: has cutting edges on the _____ and _____ of the teeth : for cutting shoulders; _____
	slitting cutter	: for cutting a narrow slit into material : _____ used for removing lots of material
	_____ cutter	: for T-slots
	_____ cutter	: machine for slots; for a sliding fit
	_____ cutter	: for V - shaped slot, e.g. _____

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• Types of Milling Cutters

	_____	: for _____ cutting of large and _____ surfaces
	side and face cutter	: has cutting edges on the _____ and _____ of the teeth : for cutting shoulders; _____
	slitting cutter	: for cutting a narrow slit into material : _____ used for removing lots of material
	_____ cutter	: for T-slots
	_____ cutter	: machine for slots; for a sliding fit
	_____ cutter	: for V - shaped slot, e.g. _____

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• Machine

Milling Machine	Milling Machine
	

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• Types of Milling Operations

• w.r.t the Milling Cutter _____

- _____ Milling (_____ Milling)

- _____ Milling

• w.r.t the relation of the _____ Rotation to the _____ Direction

: _____ Cutting ____ at the _____ Point relative to the _____ Direction

- _____ Milling (_____ Milling)

- _____ Milling (_____ Milling)

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Milling Operations

Topic 12 – 12

• w.r.t the Milling _____

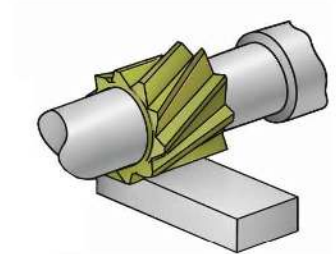
- _____ Milling (_____ Milling)

: the _____ of cutter rotation is _____ to the _____ surface

: the cutter _____ has a number of _____ along its circumference

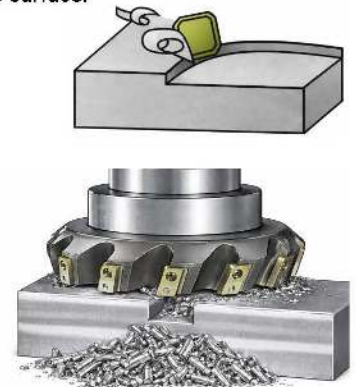
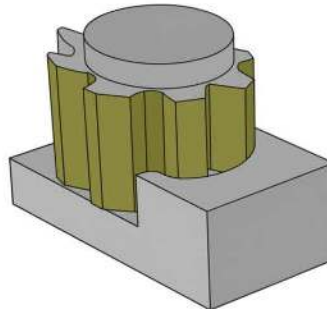
: each _____ acts like a _____ - _____ cutting tool

: when the cutter is _____ than the _____ of the cut, the operation is called " _____ milling "



- _____ Milling

: the cutter is mounted on a spindle having an _____ of cutter rotation _____ to the workpiece surface.

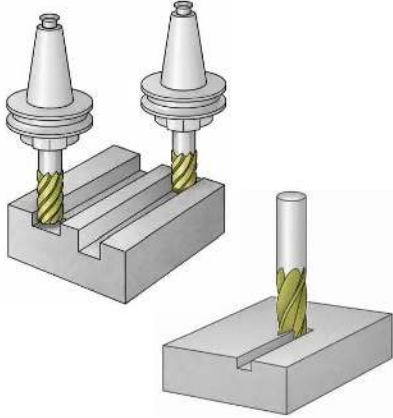
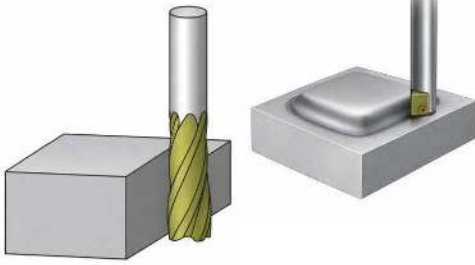
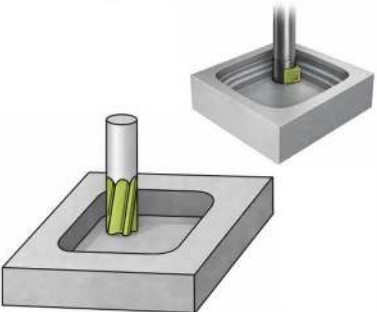


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• End Milling

When Used?

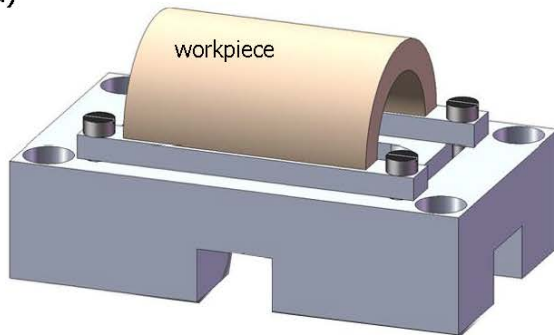
- : to perform both _____ and _____ milling operations simultaneously.
- : to produce _____, _____ or _____ surfaces
- : commonly used to perform slot milling, profile milling, and pocket milling operations.

_____ Milling	_____ Milling	_____ Milling
	To machine the _____ contour of a part 	To cut within a closed boundary to produce a _____ 

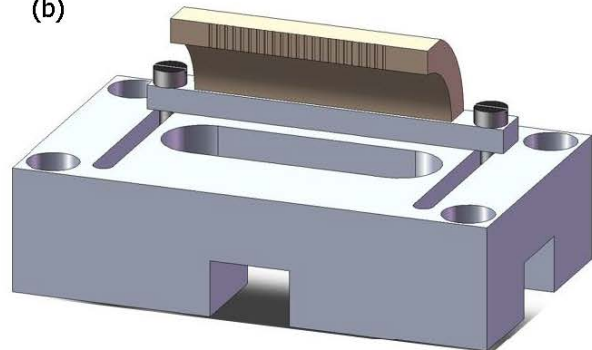
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1. Explain the milling procedures required to produce the finished machined component shown in (b) from the setup in (a), describing the types of milling operations, cutting tools, and machining sequence used to achieve the final geometry.

(a)



(b)



J.E. Lee *et al.* 2012, *Med. Eng. Phys.*, 34 (10), 1510-1520.

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Milling Operations

Topic 12 – 15

• w.r.t the relation of the _____ Rotation to the _____ Direction

: _____ Cutting ____ at the _____ Point relative to the _____ Direction

- _____ Milling (_____ Milling)

: The _____ rotates _____ the _____ direction.

: **Chip thickness** starts from _____ and _____

→ more _____ to diffuse _____ the _____ → workpiece _____.

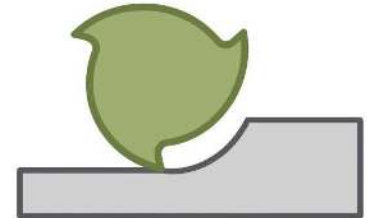
→ Tool _____ at the beginning of the cut causing _____ **tool wear** and ____ **tool life**.

: Chips are carried _____ by the tooth and fall in front of cutter.

→ _____ surface finish and _____ chips.

: _____ **forces** created tend to _____ the workpiece

→ _____ expansive work _____ are required.



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Milling Operations

Topic 12 – 16

• w.r.t the relation of the _____ Cutting ____ at the _____ Point to the _____ Direction

- _____ Milling (_____ Milling)

: The _____ rotates ____ the _____ direction.

: **Chip thickness** starts from _____ and ____.

→ _____ tool rubbing. → _____ tool life.

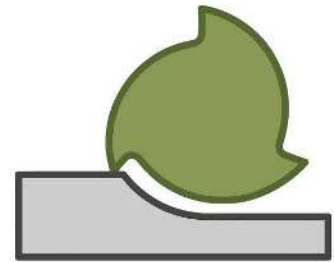
: Chips are removed _____ the cutter.

→ _____ the chance of chip recutting.

→ **Heat** is more likely to transfer to the _____ than to the _____.

: _____ **forces** created _____ to _____ the _____

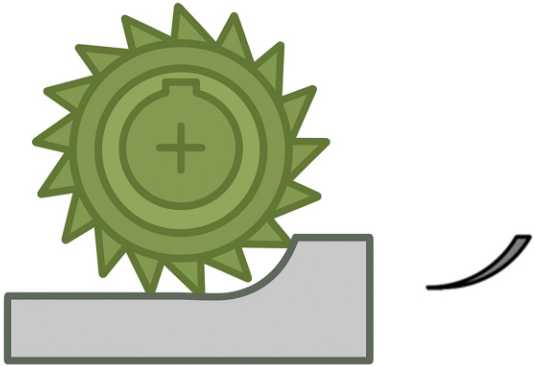
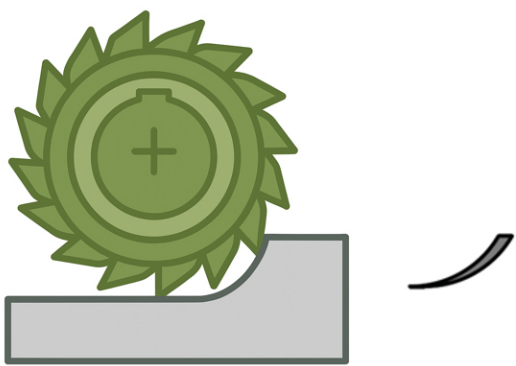
→ _____ complex work **holdings** are required.



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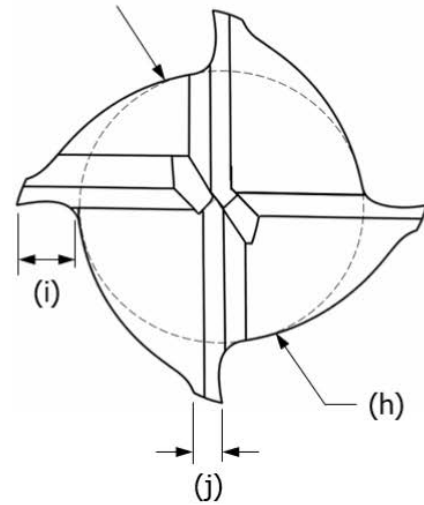
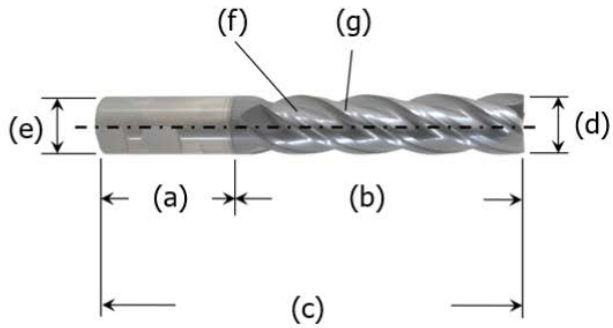
• Summary

w.r.t the relation of the _____ rotation to the _____ direction

Conventional Milling (_____ Milling)	Climb Milling (_____ Milling)
 - Chip thickness starts at (zero / maximum) and changes to (zero / maximum). - Chips are carried _____ by the tooth and fall in front of the cutter. - It can create (better / worse) surface finish and _____ recutting chips. - (Upward / Downward) forces are generated that tend to (lift / press) the workpiece.	 - Chip thickness starts at (zero / maximum) and changes to (zero / maximum). - Chips are removed _____ the cutter. - It can create (better / worse) surface finish and _____ recutting chips. - (Upward / Downward) forces are generated that tend to (lift / press) the workpiece.

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2. The figures show an end mill in different views. Label the geometry features corresponding to (a) through (j).



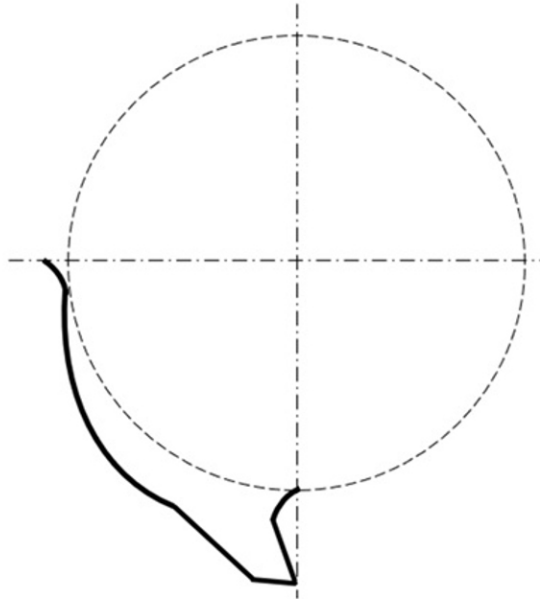
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Practice Problems

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3. The figure shows one tooth of a four-flute milling cutter in cross-sectional tip view. Label the following geometric features on the figure:

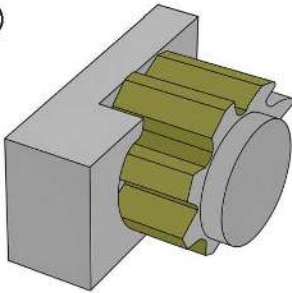
- (1) Cutting edge
- (2) Rake face
- (3) Flank face
- (4) Rake angle
- (5) Primary clearance angle
- (6) Secondary clearance angle



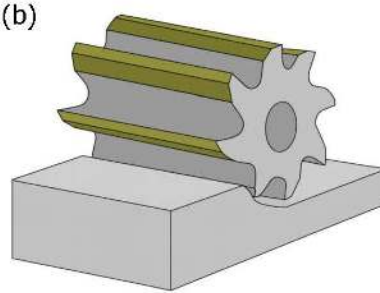
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4. Identify the type of milling operation illustrated in the figure with respect to the milling cutter types.

(a)

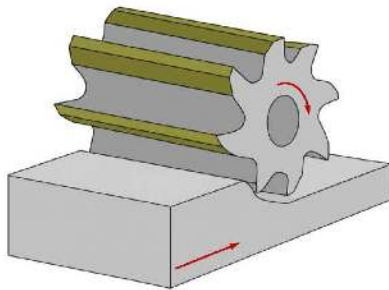


(b)



5. (1) Identify the type of milling operation illustrated in the figure with respect to the milling cutter rotation to the feed direction.

(2) Explain the disadvantages of this milling operation.



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