MANUFACTURING PROCESSES

JuEun Lee
California State Polytechnic University, Humboldt

LibreTexts™

Manufacturing Processes

The LibreTexts libraries are Powered by NICE CXone Expert and was supported by the Department of Education Open Textbook Pilot Project, the California Education Learning Lab, the UC Davis Office of the Provost, the UC Davis Library, the California State University Affordable Learning Solutions Program, and Merlot. This material is based upon work supported by the National Science Foundation under Grant No. 1246120, 1525057, and 1413739.

This text was compiled on 03/15/2026

TABLE OF CONTENTS

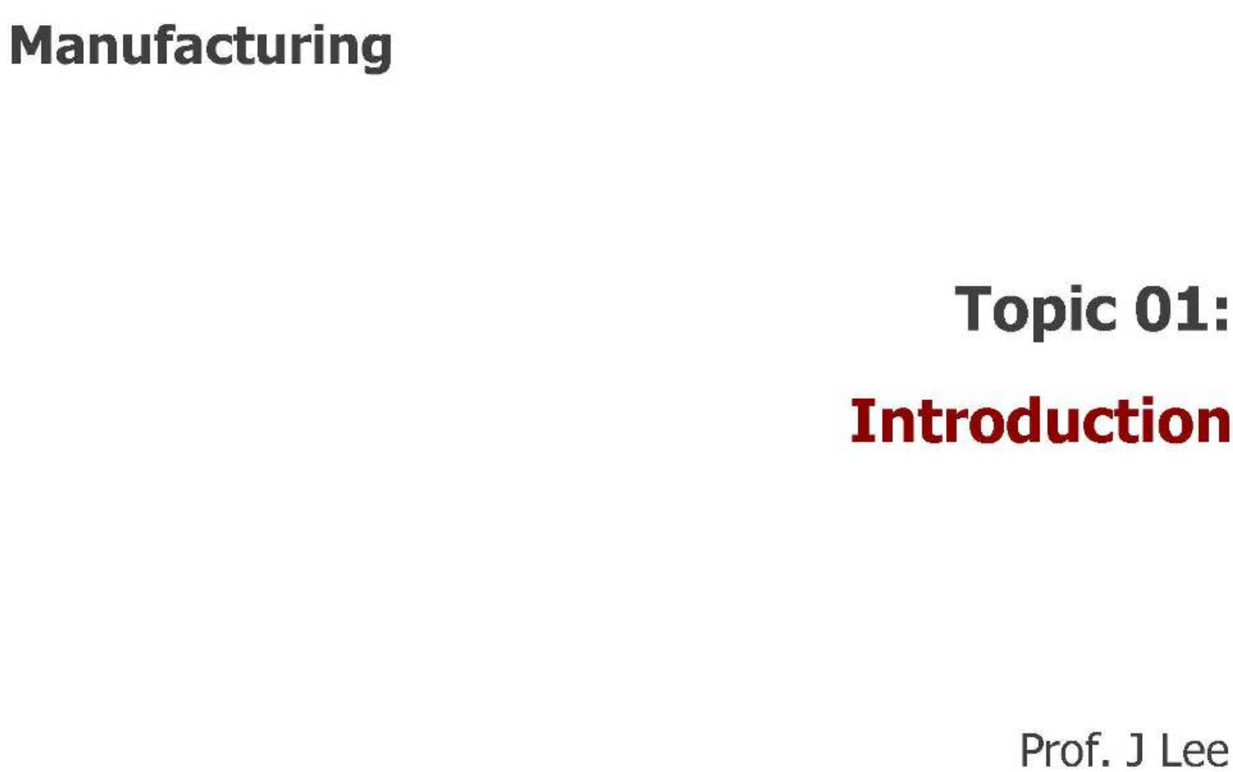
Licensing

A detailed breakdown of this resource's licensing can be found in ***Back Matter/Detailed Licensing****.*

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.

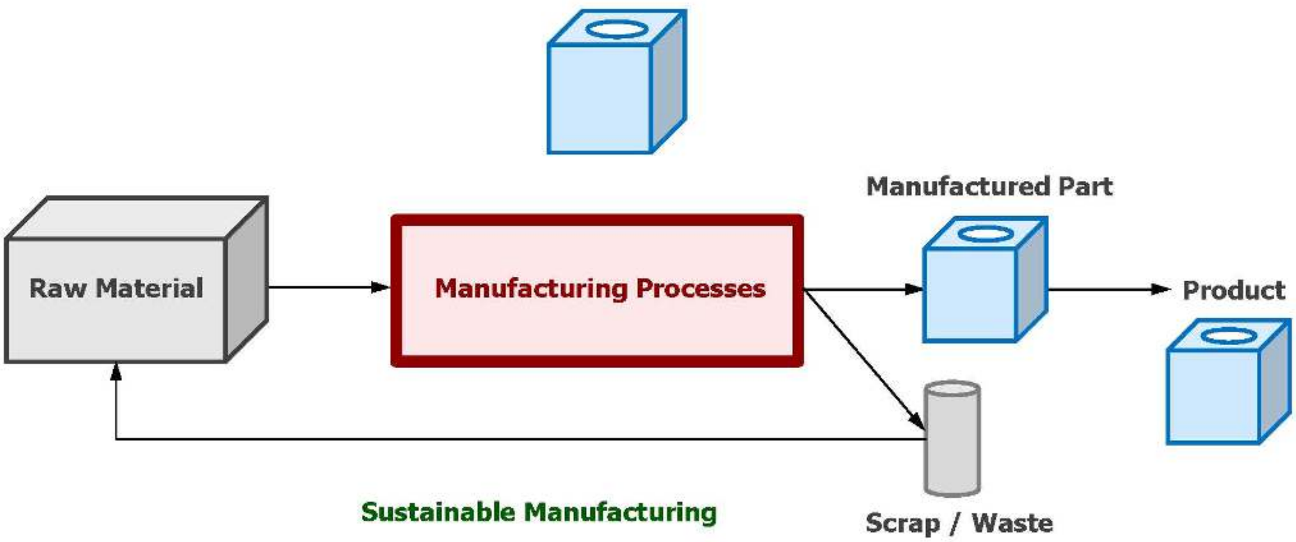


Manufacturing

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

: the process of transforming _______ **materials** into ___________ ____________

through coordinated application of human labor, machinery, tools, and automation



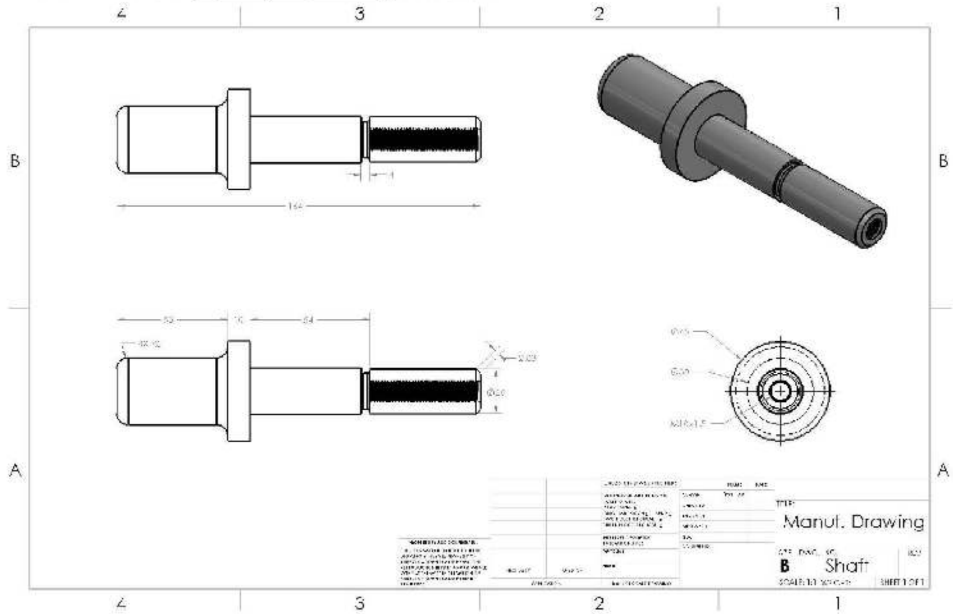
Core Requirements for Modern Manufacturing

- 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.

Manufacturing

Product Design to Manufacturing

: In manufacturing, a precise engineering ________ translates a product _________ into a standardized, actionable blueprint that guides all downstream ____________ processes.

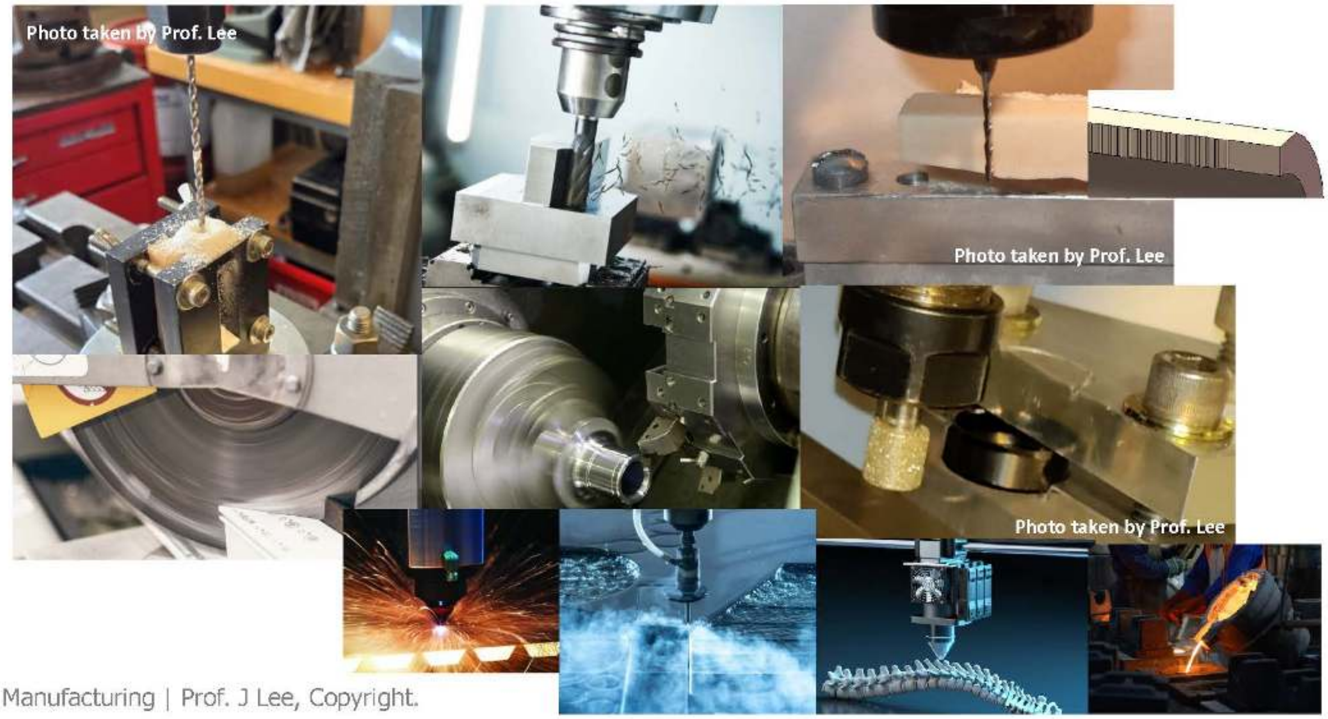


: Manufacturing cannot begin without a clear, standardized, and fully defined representation of the product, including all critical ____________, ____________, ____________, and _________ requirements.

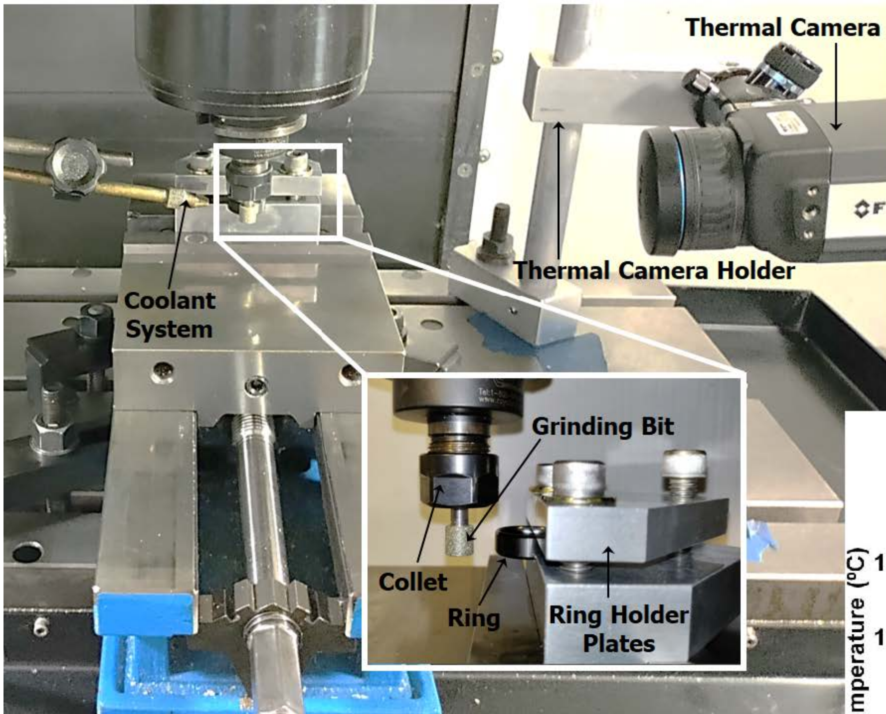
Manufacturing Processes

: to determine how it will be manufactured, selecting the most suitable ___________, ________,

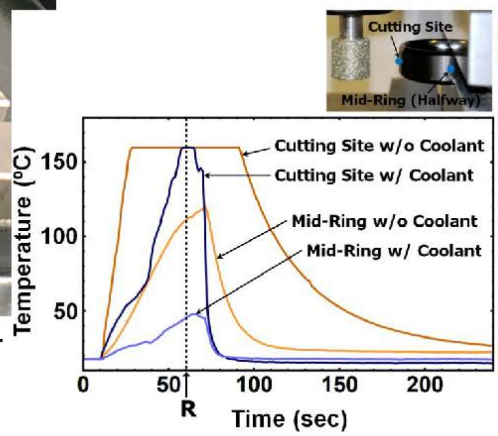
and ____________ to transform the ____________ into a physical _____________



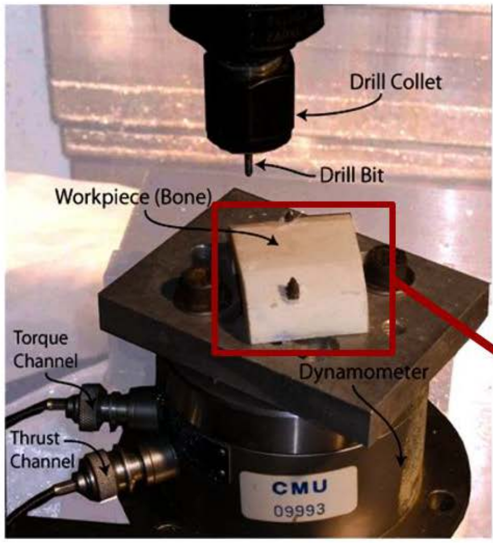
Manufacturing: Example



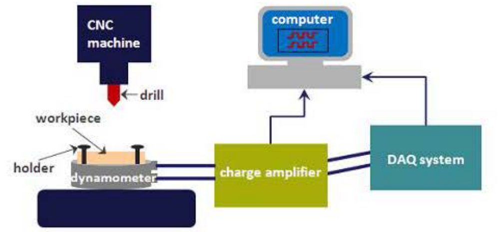
Lee *et al*. 2025, J. Bone and Joint Surgery. 50. 8-11.



Manufacturing: Example

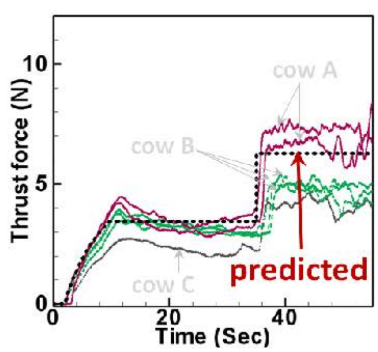


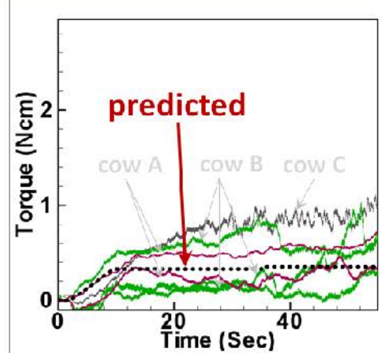
Lee *et al*. 2012. J Biomechanics. 45 (6). 1076-1083.



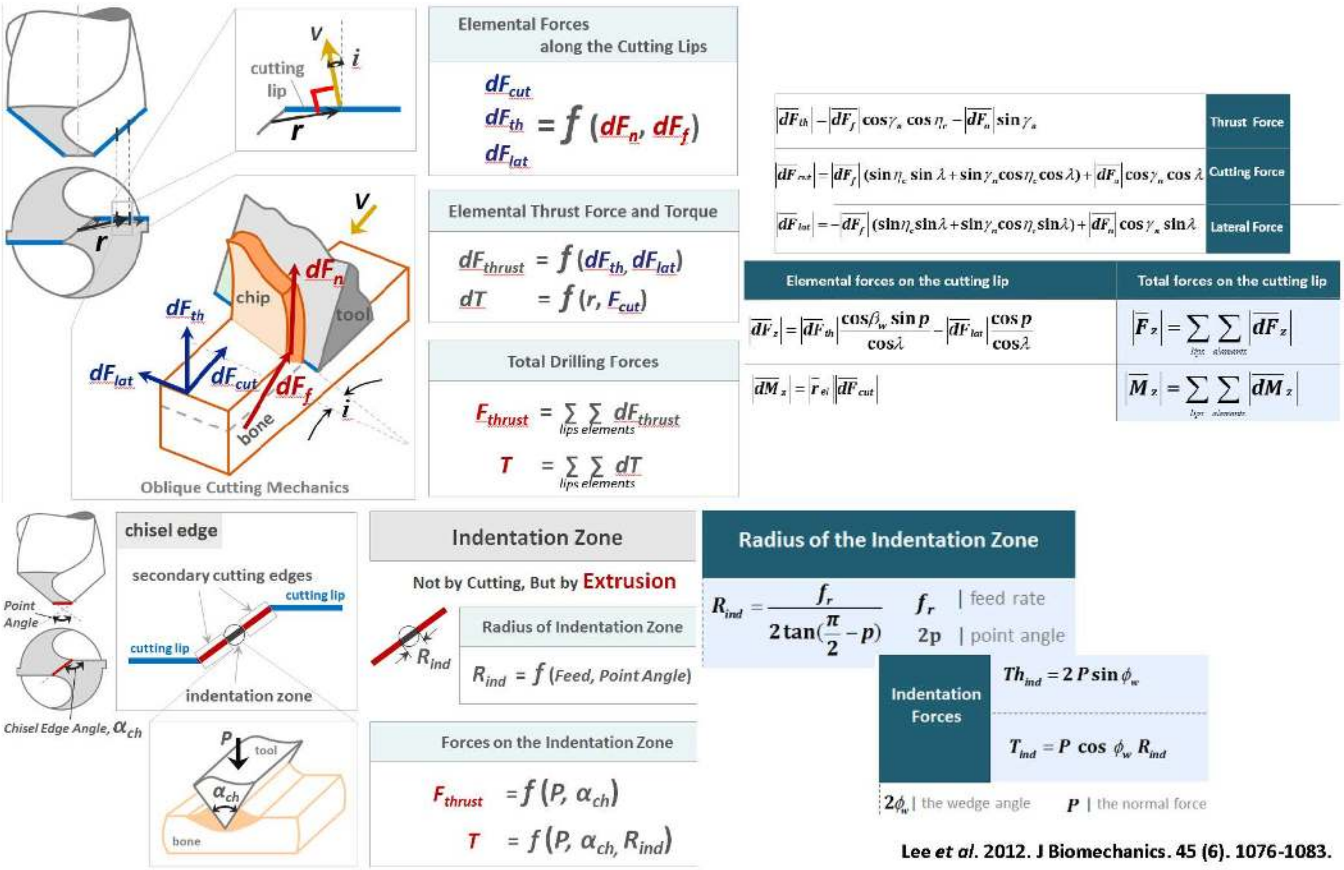
Schematic Image of the Setup

Thrust Force	Torque



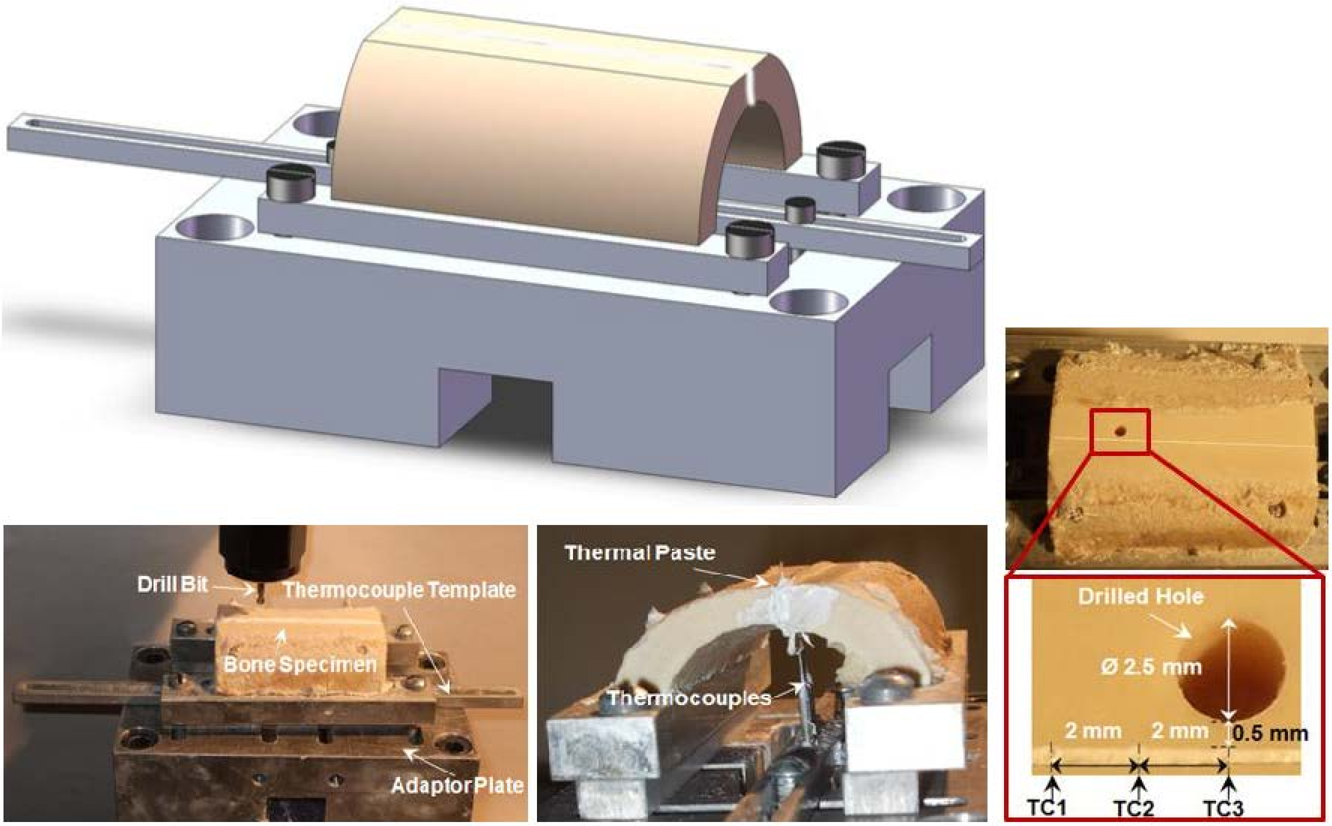


Manufacturing: Example



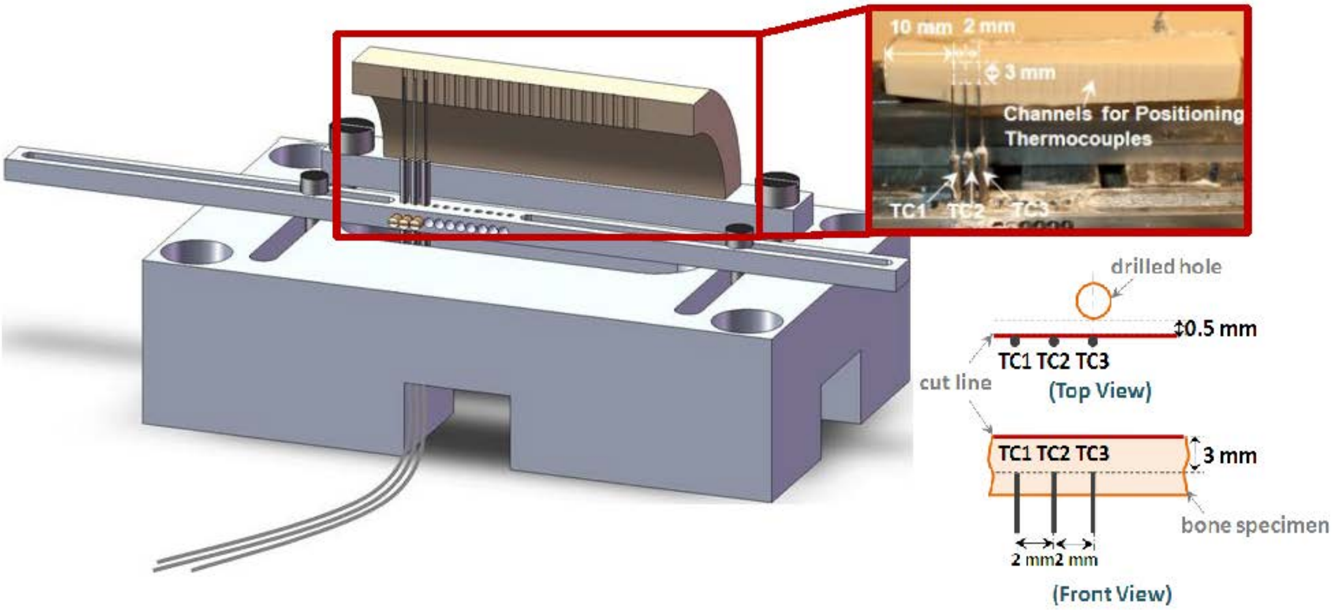
Manufacturing | Prof. J Lee, Copyright.

Manufacturing: Example



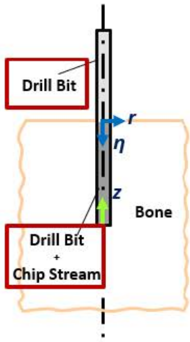
Lee *et al.* 2012. Med. Eng. Phys. 34(10), 1510-1520.

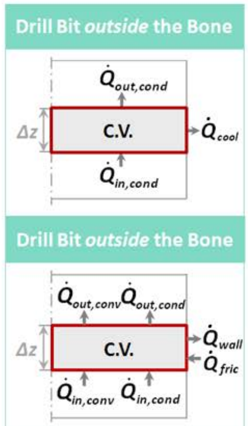
Manufacturing: Example



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

Manufacturing: Example

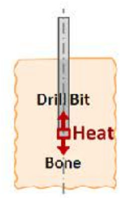




Lee *et al*. 2011. Med. Eng. Phys. 33(10), 1234-1244.

Ω = 0: when outside the bone
Ω = 1: when inside the bone

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



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

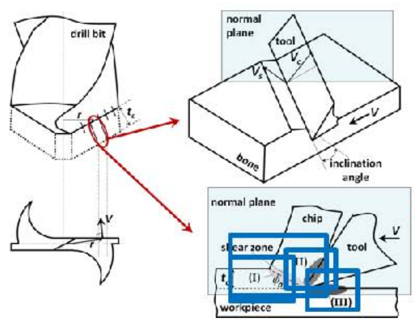
$$\dot{Q}_T = -(k_d A_d + k_c A_c)\frac{\partial T}{\partial z}\bigg|_{z=0} + k_b(A_d + A_c)\frac{\partial T}{\partial \eta}\bigg|_{\eta=\eta_d}$$

Heat generated at drill tip

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

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

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

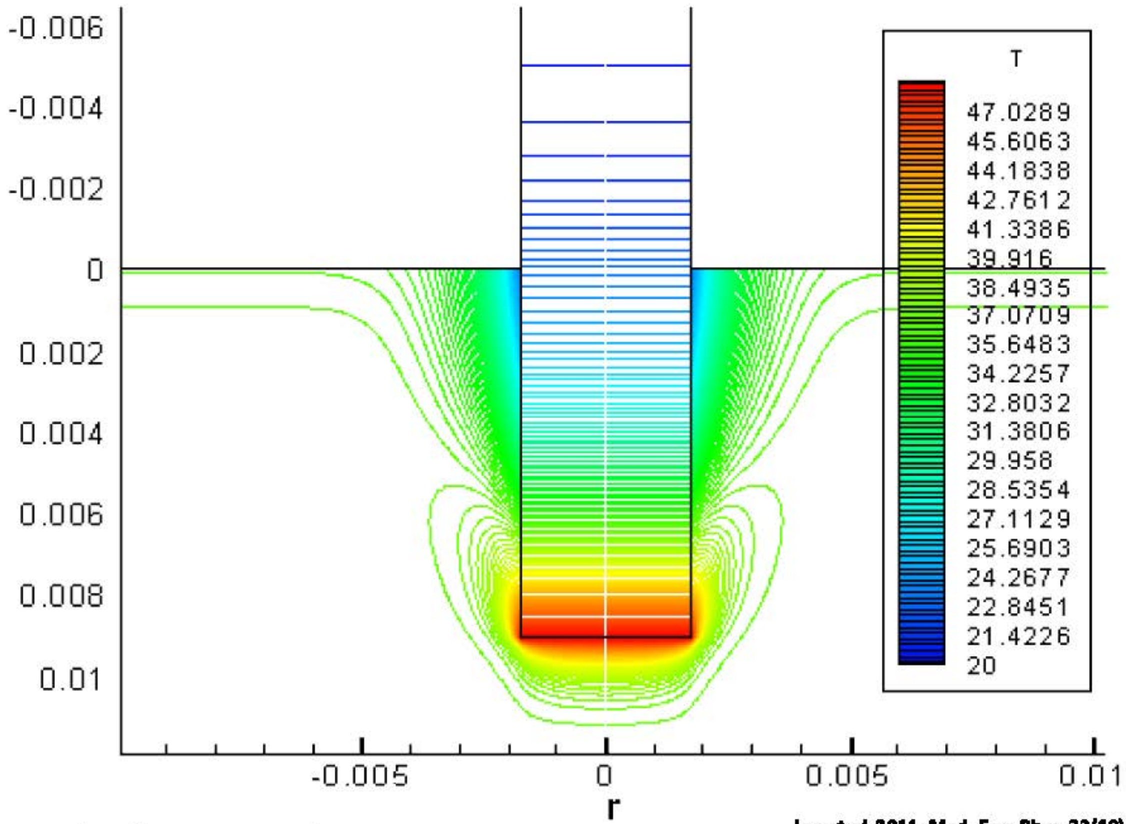


$$\zeta = \begin{cases} 0.5 - 0.35\log(R_t\tan\phi_n) & \text{if } 0.04 < R_t\tan\phi_n \le 10 \\ 0.3 - 0.15\log(R_t\tan\phi_n) & \text{if } 10 < R_t\tan\phi_n \end{cases}$$

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

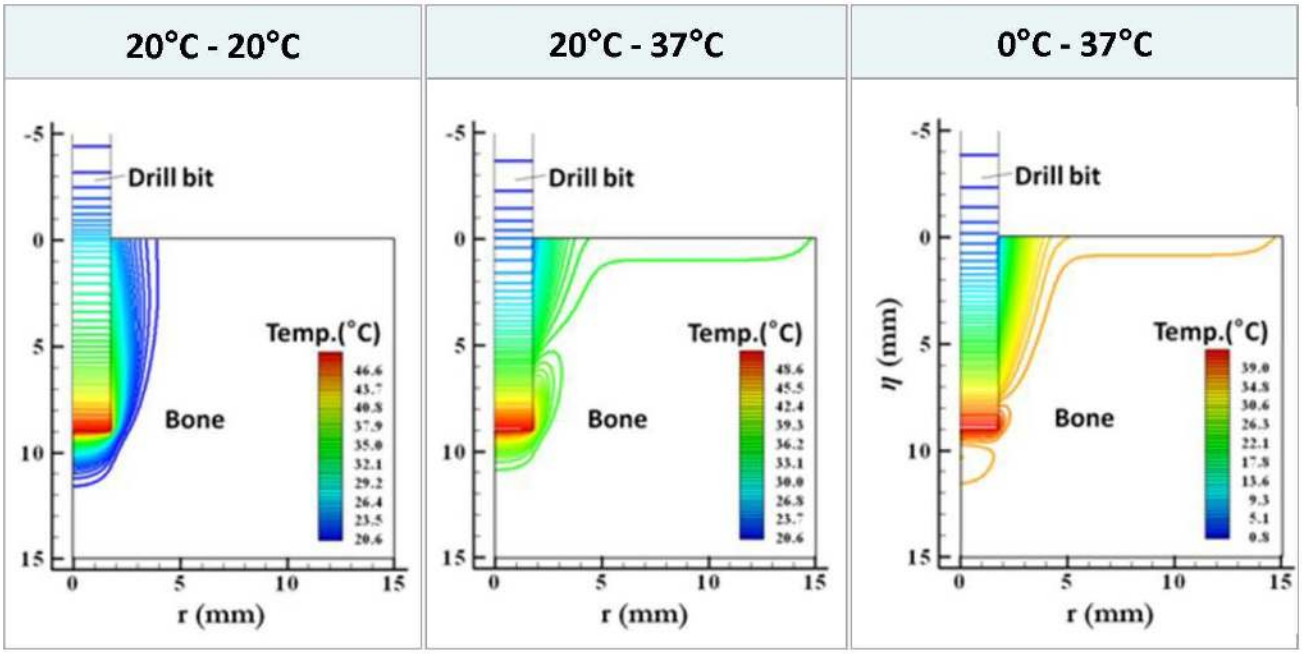
(Boothroyd, 1963)

Manufacturing: Example



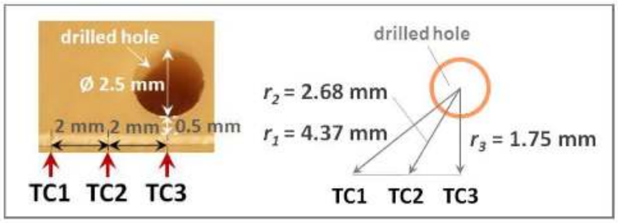
Lee *et al.* 2011. Med. Eng. Phys. 33(10), 1234-1244.

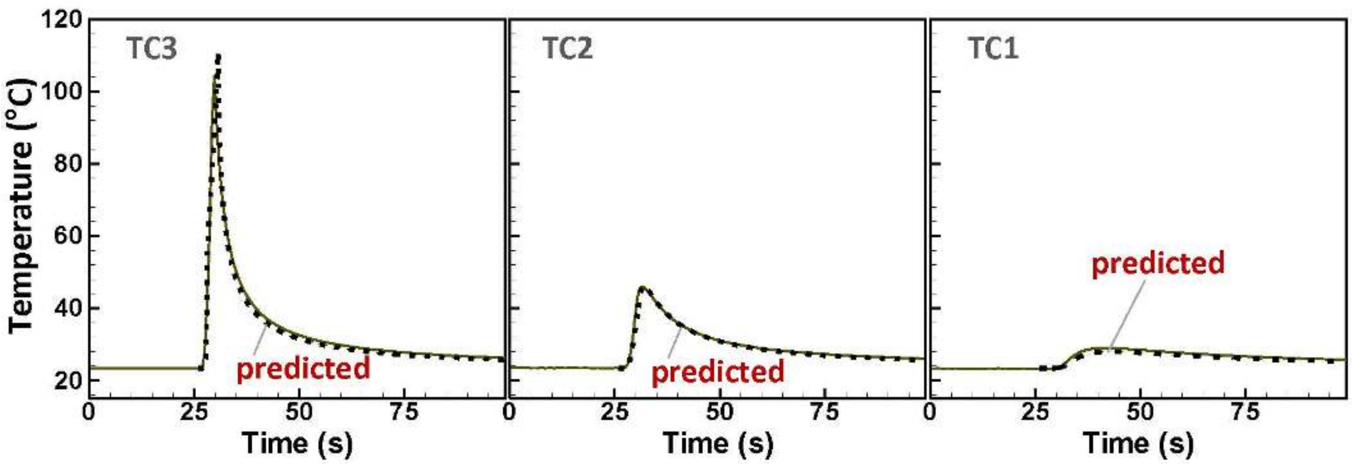
Manufacturing: Example



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

Manufacturing: Example





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

Tool Selection

Image ref. Jackspaint.co.za

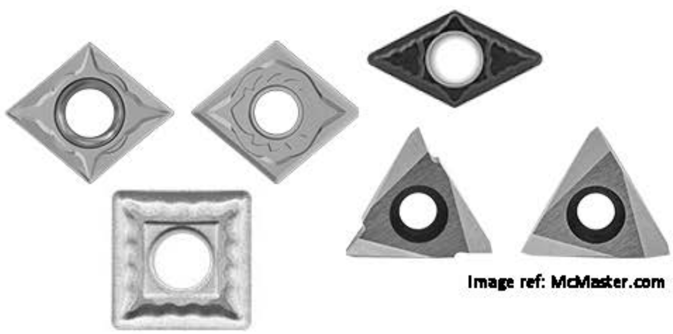
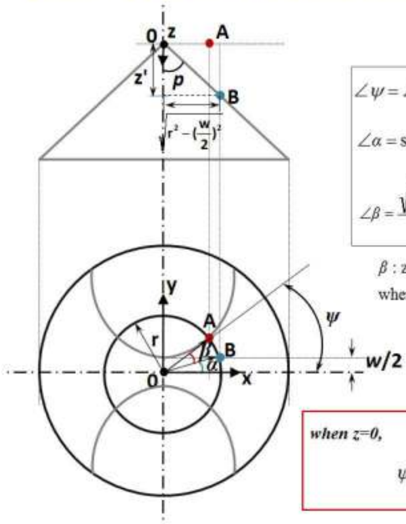


Image ref: McMaster.com

Image ref. homedepot.com

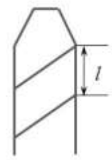
Tool Design: Mathematical Modeling



$$\angle\psi = \angle\alpha + \angle\beta$$

$$\angle\alpha = \sin^{-1}(\frac{w}{2r})$$

$$\angle\beta = \frac{\sqrt{r^2-(\frac{w}{2})^2}}{r_d}\cot(p)\tan(h)$$



where r_d is the drill radius
w is the web thickness
h is the helix angle
p is the point angle.

$$\beta : z' = 2\pi : l$$

where l is pitch of helix

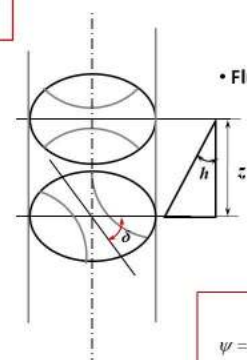
$$l = \frac{2\pi r_d}{\tan(h)}$$

$$z' = \sqrt{r^2-(\frac{w}{2})^2}\cot(p)$$

when z=0,

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

Prof. J Lee, Copyright.



- Flute rotation with different z elevations

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

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

rotation angle

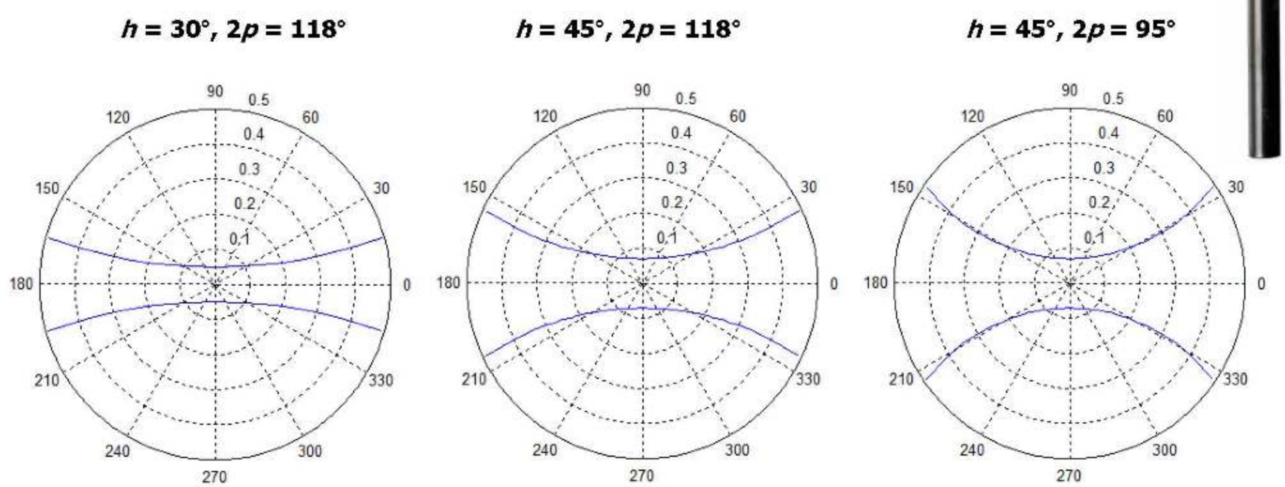
$$\psi = \sin^{-1}(\frac{w}{2r}) + \frac{\sqrt{r^2-(\frac{w}{2})^2}}{r_d}\cot(p)\tan(h) + \frac{z}{r_d}\tan(h)$$

Prof. J Lee, Copyright.

Tool Design: Simulations

when z=0,

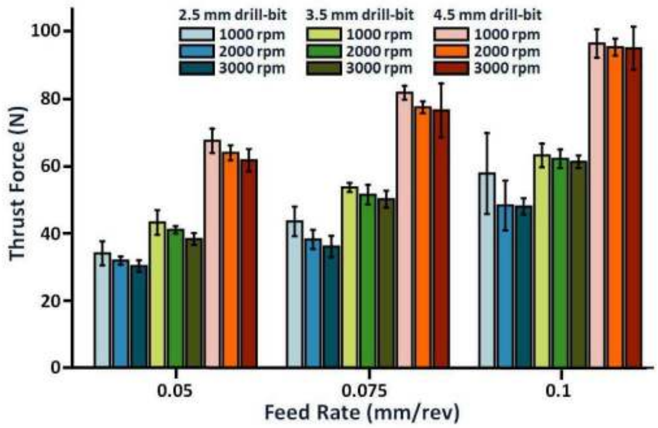
$$\psi = \sin^{-1}\left(\frac{w}{2r}\right) + \frac{\sqrt{r^2 - \left(\frac{w}{2}\right)^2}}{r_d}\cot(p)\tan(h)$$

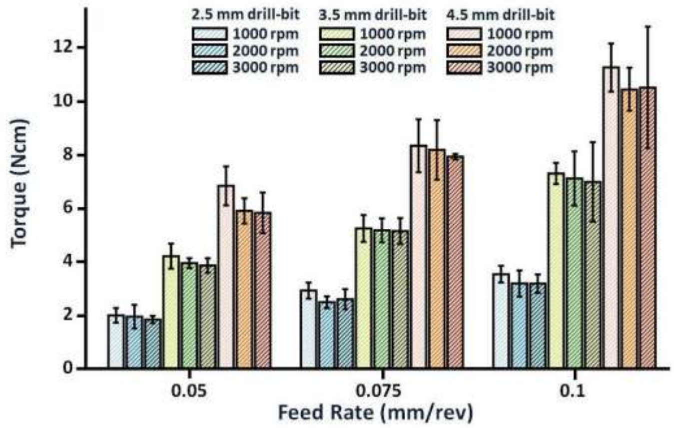


Prof. J Lee, Copyright.

Machining Operation Conditions

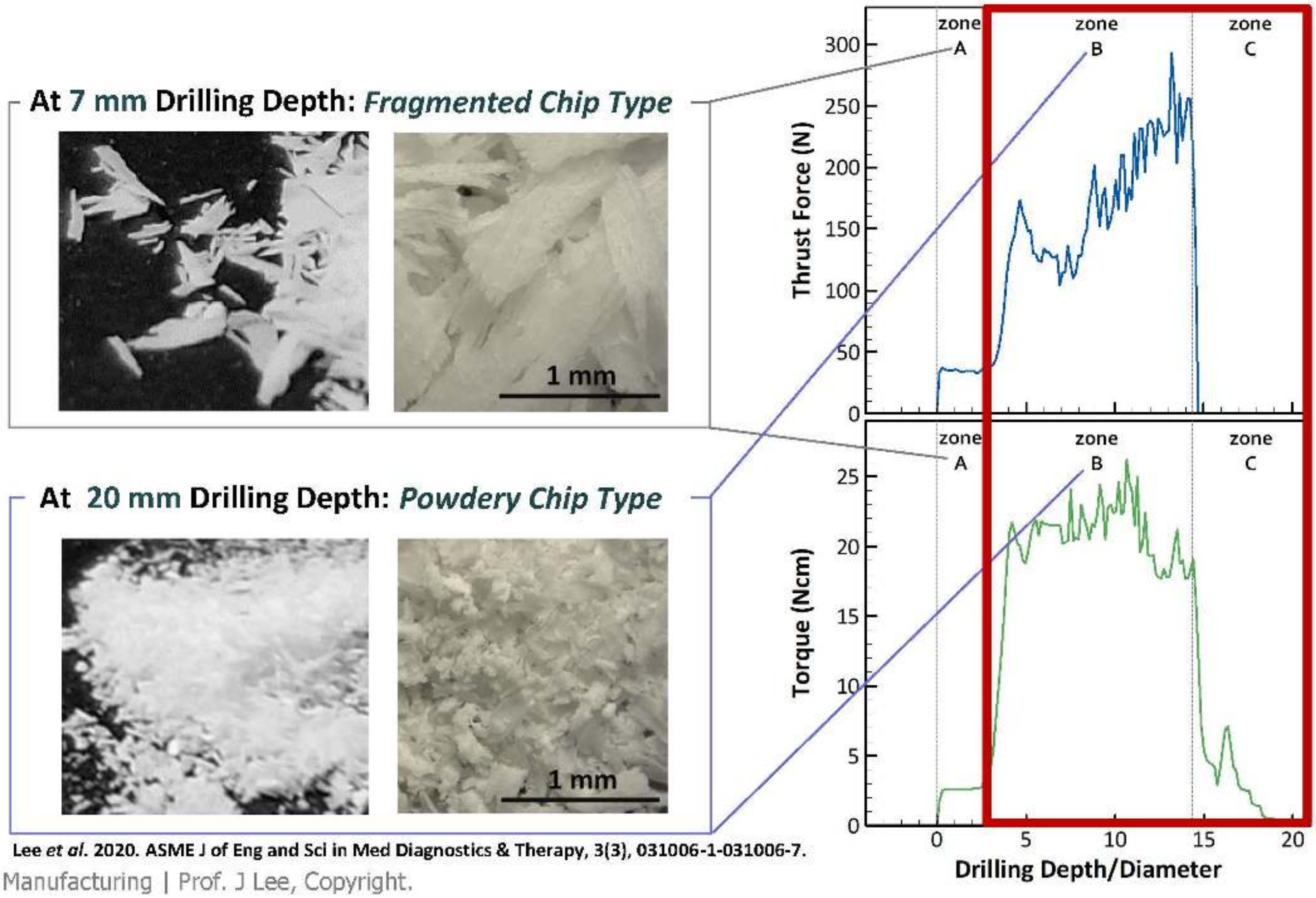
- Drilling Depth: 7 and 36 mm
- Drill-Bit Diameter: 2.5, 3.5, and 4.5 mm
- Spindle Speed: 1000, 2000, and 3000 rpm
- Feed Rate: 0.05, 0.075, and 0.1 mm/rev





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

Chip Morphology and Chip Removal Technique

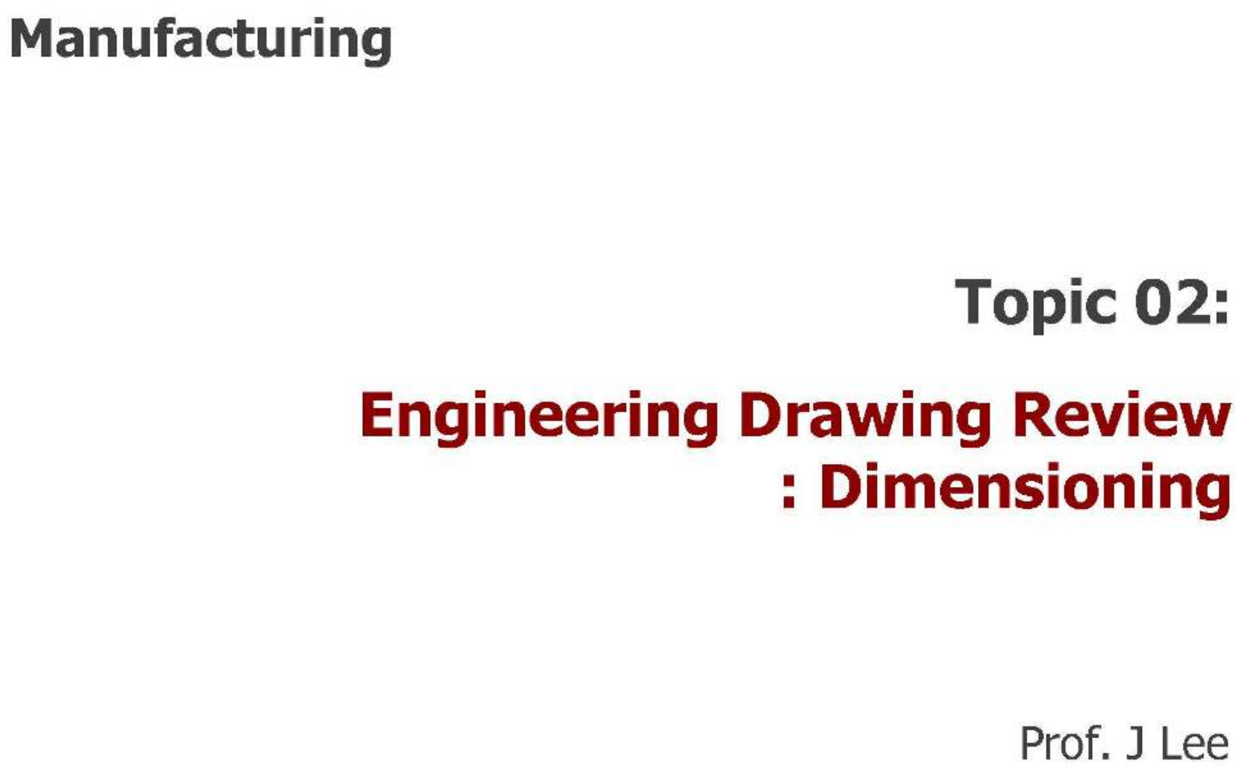


Lee *et al*. 2020. ASME J of Eng and Sci in Med Diagnostics & Therapy, 3(3), 031006-1-031006-7.


Topic 01 – 19
Manufacturing!
Photo taken by Prof. J Lee ©
Manufacturing | Prof. J Lee, Copyright.

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.



Objectives

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

ASME Drawing Standards

_______ Standards

- ASMEY14.5-2018 (R2024): Dimensioning and Tolerancing
- ASMEY14.1-2020: 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

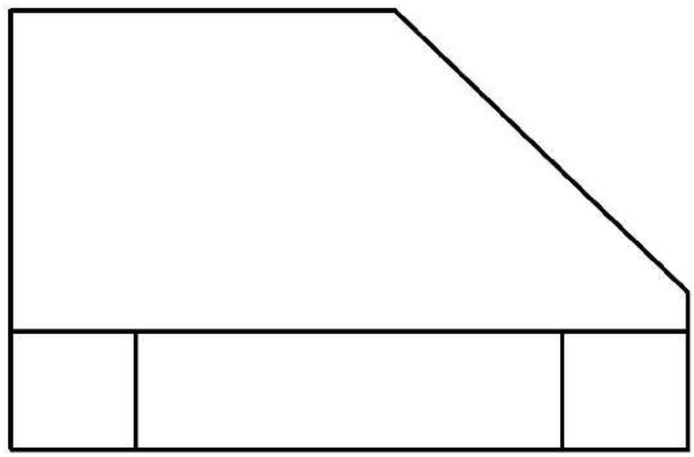
Note

: Very Important **to follow the standards** to ensure your drawings are interpreted correctly by others.

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

Why are multiple views required in an engineering drawing?

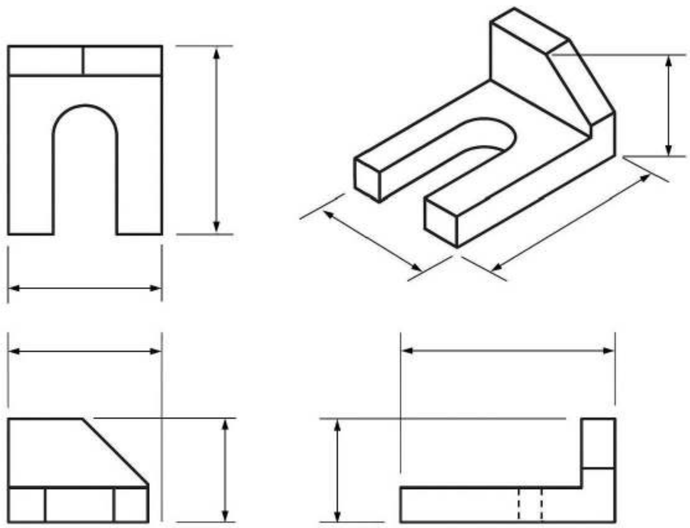
- **What information does this single view provide about the object?**



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

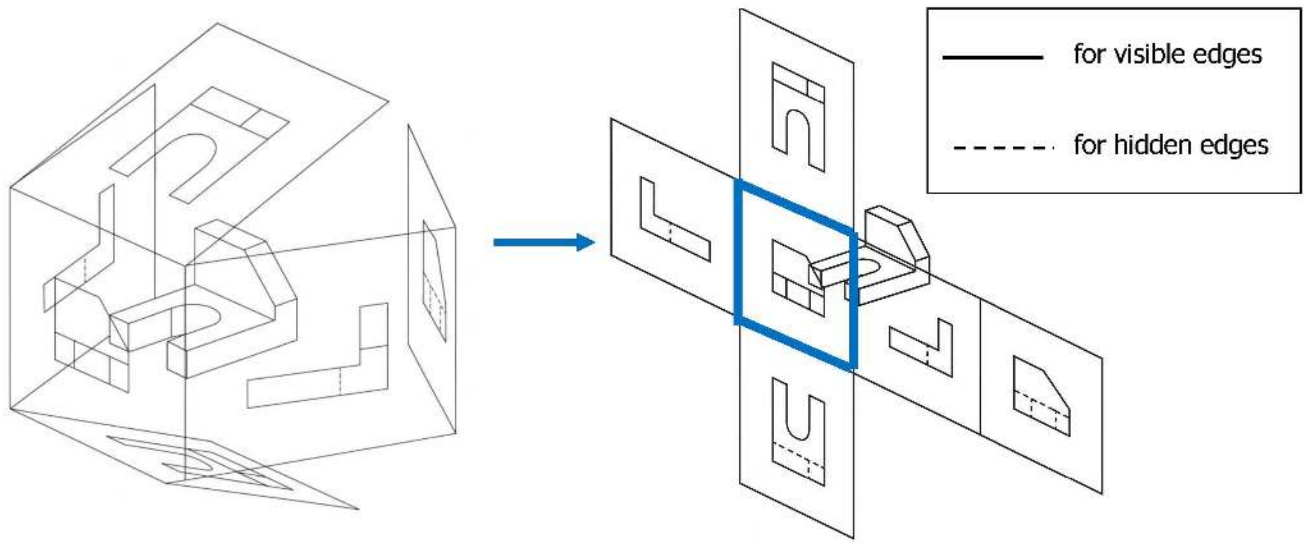
DEPTH : Front-to-Back

Front View Guidelines

: Front view establishes other views.

: Front view provides the _________ shape description or _________ characteristic contours.

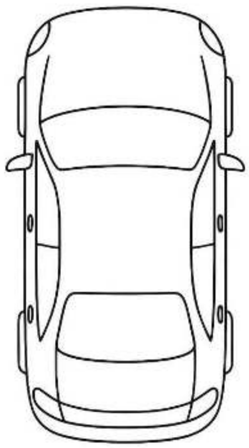
: Front view has the ______________________features.



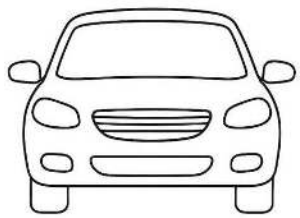
Practice Problem

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

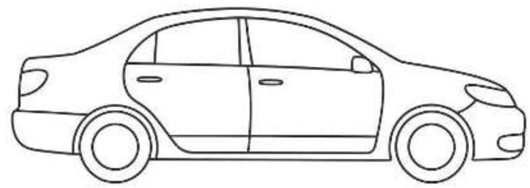
(a)



(b)



(c)



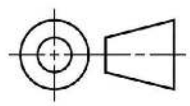
Arrangement of Orthographic Views

Standards

______Angle Projection by ANSI

(see ASME Y14-3-2003)

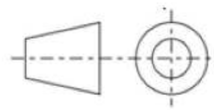
Used in United States and Canada

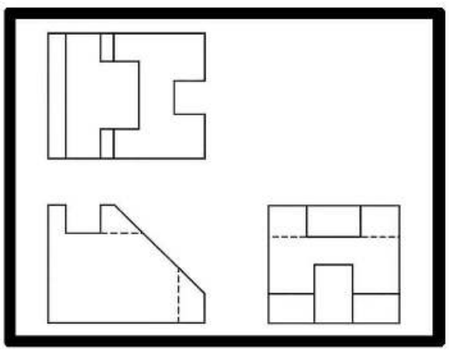


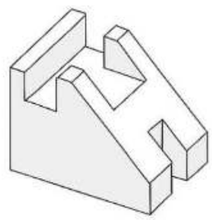
First Angle Projection by ISO

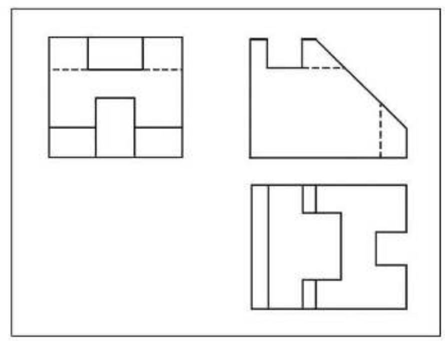
(see ISO 128-30)

Used in Asia and Europe









- **What**

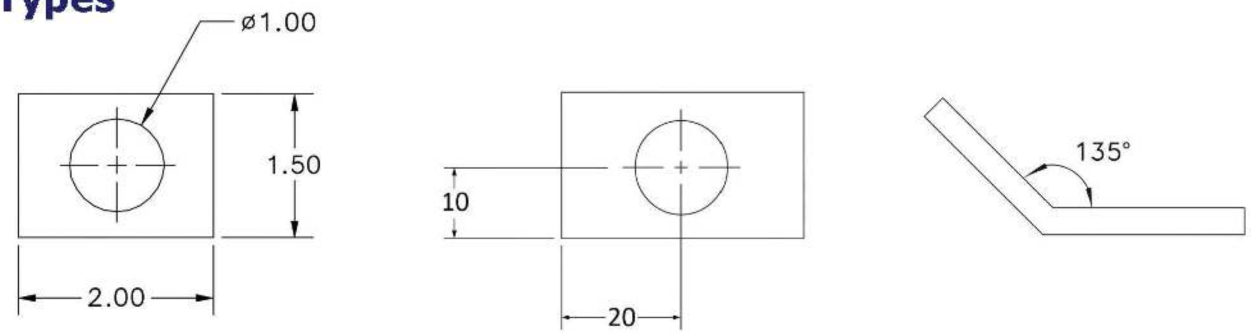
: A dimension is a measurement of a feature of an object, expressed using appropriate _______.

: 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

Dimensioning: Types of Dimension

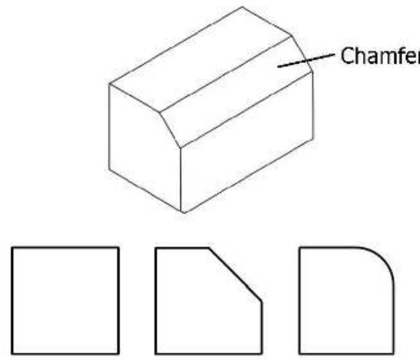
- **Size Dimension**

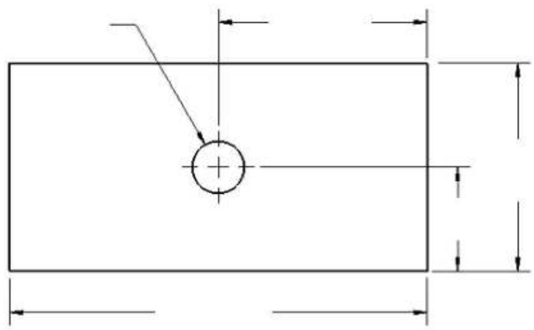
: specifies the size of an individual feature, such as an ________, _______, ___________, and similar attributes.

- **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.





Dimensioning

- **Identify the Units**

  : All dimensions are in _______ or ________ unless otherwise specified.

- **Difference between Milimeters and Inches**

Milimeters

: Use a _________ zero.

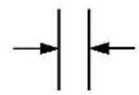
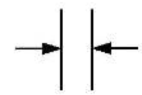
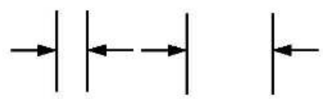
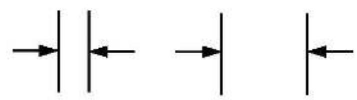
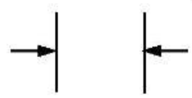
: ______ decimal point and trailing zeros for whole numbers.

: Do _______ use ____ or spaces.

Inches

: Do _____ use leading zero.

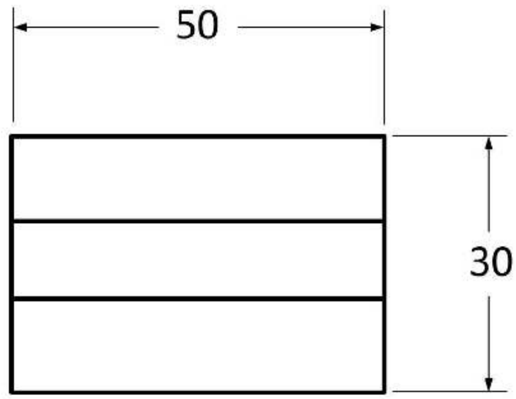
: Do _______ use commas or spaces.

Milimeters	Inches
Use zero in front of decimal. 	Do NOT use zero in front of decimal. 
Omit trailing zeros and decimal. 	Use the same number of decimal places as the tolerance. 
Do NOT use commas or spaces. 	Do NOT use commas or spaces. 

- **Line Thickness Types**

  ________ for Object

  ________ for Dimension



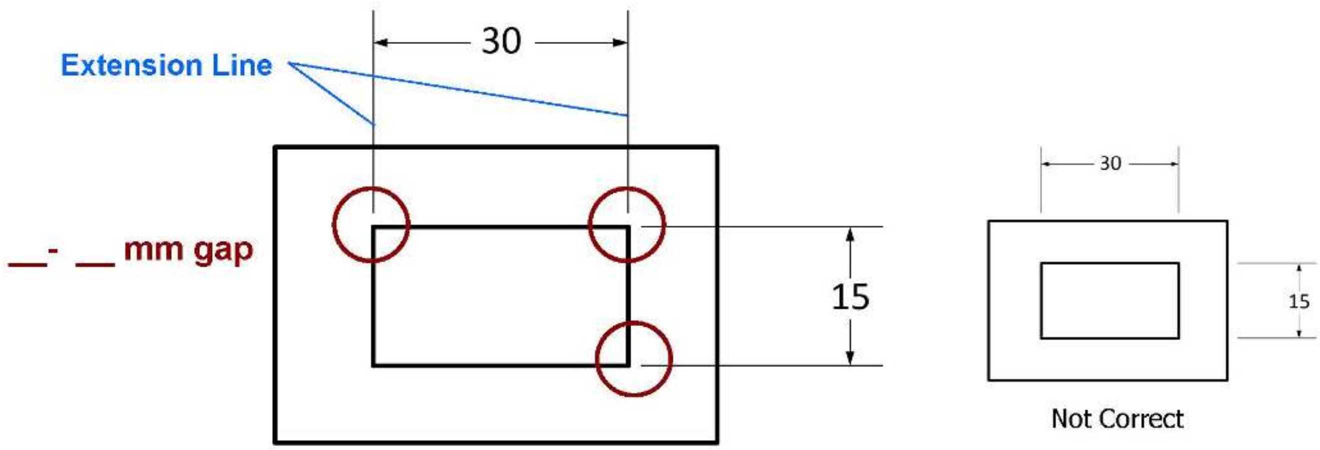
- **Extension Line**

: 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.



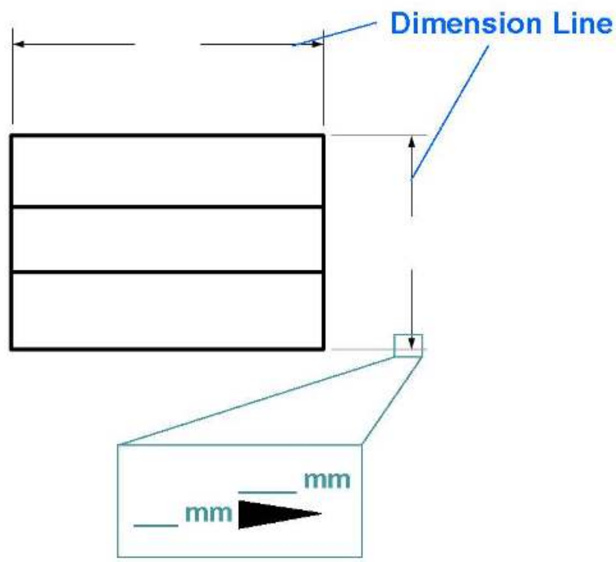
Drawing Standards: Line Types

- **Dimension Line**

: a thin line with an arrowhead (≈ ____ 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.

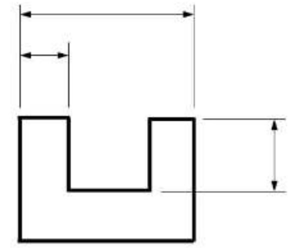


Order of Preference

1. Arrows In / Dimension In
2. Arrows Out / Dimension In
3. Arrows In / Dimension Out
4. Arrows Out / Dimension Out

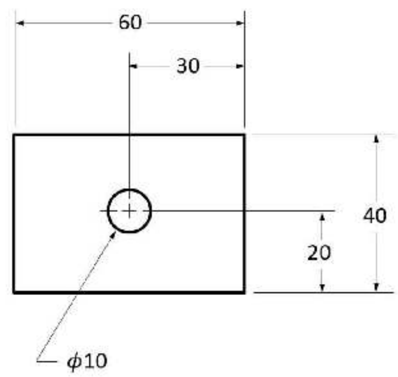
- **Dimension Line**

: 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.

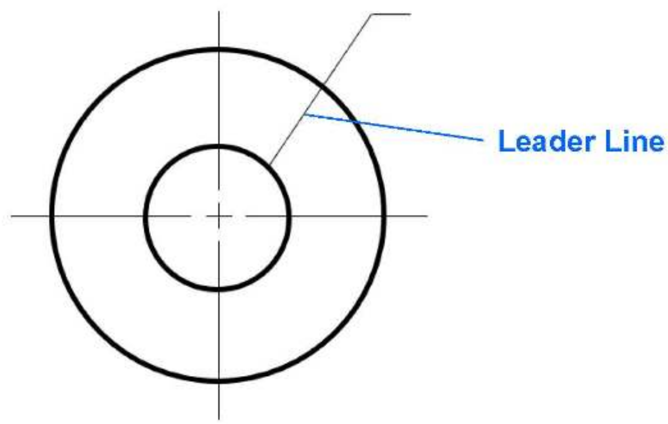
: Numerals must remain **the same size throughout the drawing**, regardless of available space.



- **Leader Line**

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

: terminates with an arrowhead that ____________ the referenced feature.



- **Centerline**

: a thin line with alternating long and short dashes.

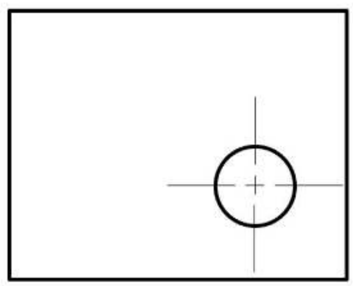
: used to show axes of _____________, bolt circles, motion paths, and pitch circles.

: 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.



Dimensioning Rules

- 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.

Dimensioning Rules

- 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 _________.

Dimensioning Rules

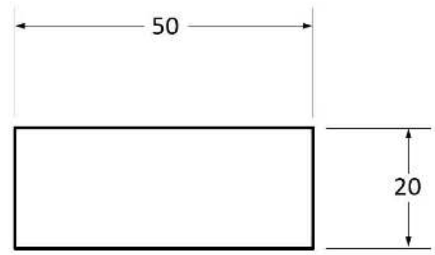
- **Accuracy:** correct values must be given.
- **Clearness:** dimensions must be placed in appropriate positions.
- **Completeness:** nothing must be left out, and nothing must be duplicated.

  : "**_____ More, and _____ Less.**"
- **Readability:** the appropriate line quality must be used for legibility.

Dimension Types

Linear Dimension

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



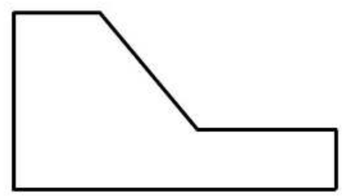
Angular Dimension

: 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.

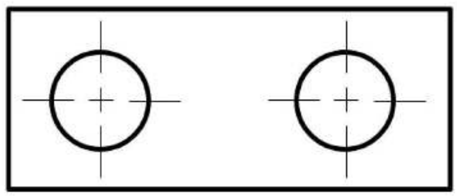
: must be specified with a numerical value followed by the degree symbol (   ).



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.

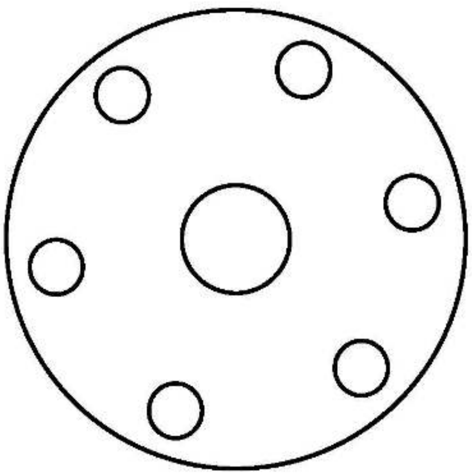
: There is _____ space between the number of times the feature and the " X " symbol; but there ____ a space between the symbol " X " and dimension.

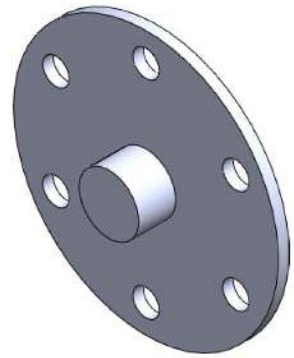
Equally Spaced Hole Dimension

: 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 "____________"





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.

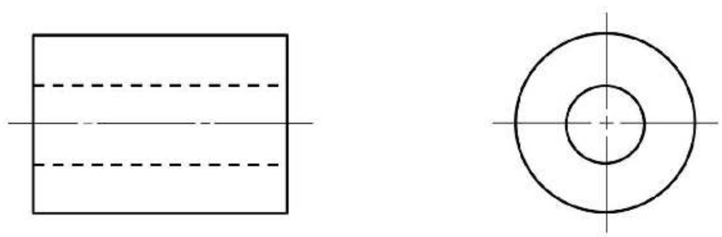
: A circular view is _____ required to dimension the diameter of an external cylinder.

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.

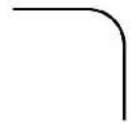
Note: The diameter symbol (   ) must be placed _________ the numerical value to indicate that the dimension refers to a cylindrical or circular feature.



Dimension Types

Arc Dimension

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



Slot Dimension

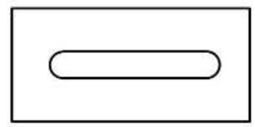
: dimensioned using a combination of __________ and _________ measurements.

: can be dimensioned by

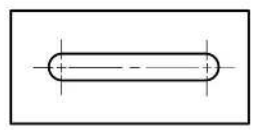
1) Overall dimension method: Specify the total __________ of the slot and the ________ (distance between the rounded ends).

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.



Dimension Types

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.

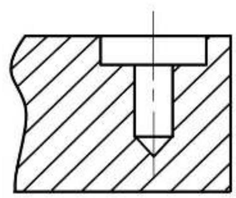
Counterbore Dimension

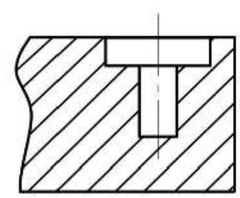
: Used to indicate a counterbored hole, typically required to recess a machine screw head or bolt head.

: 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 _________.





Fastener Hole Dimension

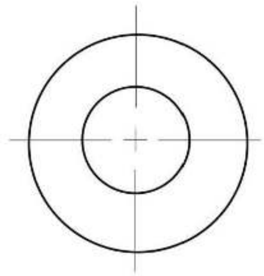
Countersink Dimension

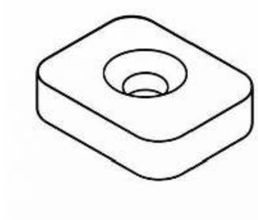
: Used to indicate a countersunk hole, typically required to recess the flat head of a machine screw or bolt.

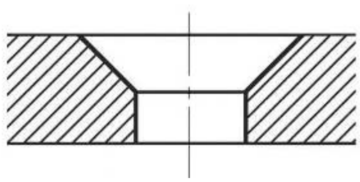
: The countersink symbol (   ) must be used when specifying a countersunk hole.

: 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 _________.



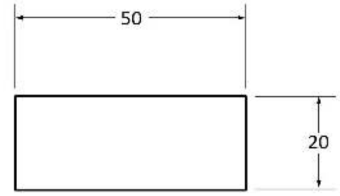




Linear Dimensioning

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

: read ________ to _________ and __________ to _______.

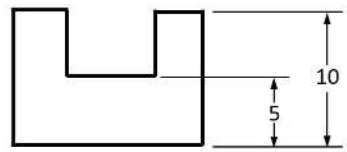


Staggered Dimensioning

: 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.

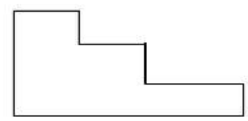


Chain Dimensioning

: dimensioning from one feature to the next in sequence.

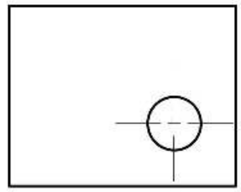
: Each dimension depends on the previous one, which may cause errors to accumulate.

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

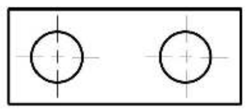


Practice Problems

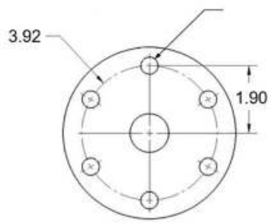
1. On the top view, dimension the center of the hole as located 0.6 inches from the right edge and 0.56 inches from the bottom edge of the part.



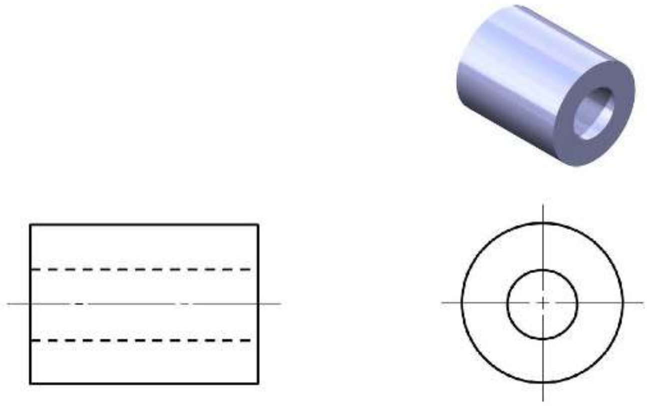
2. On the front view, add dimensions for the holes, specifying a diameter of 0.25 inches and indicating that the holes are through.



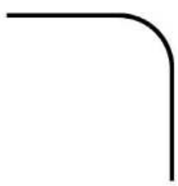
3. The drawing shows the front view of the part. Complete the drawing by adding the appropriate features. The part contains multiple holes that are equally spaced and extend all the way through the part. Each hole has a diameter of 0.5 inches.



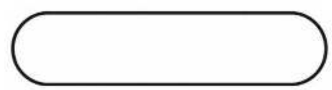
4. The cylinder has the total length of 2 inches and outer diameter of 1.5 inches. The hole diameter is 0.63 inches. Add the required dimensions directly to the given drawing to fully define the cylindrical feature.



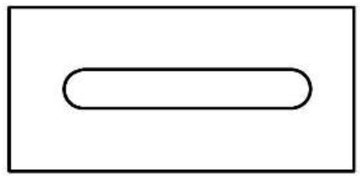
5. Dimension the arc feature with a radius of 0.38 mm.

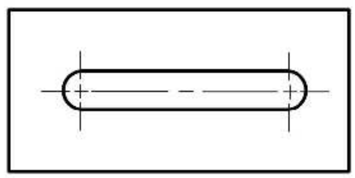


6. Add dimensions on the right view for the arcs that have the same radius of 0.25 inches.



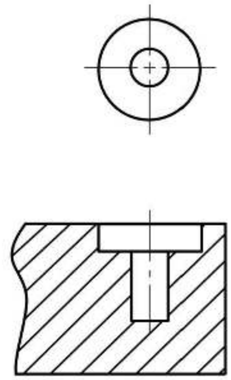
7. The slot has a total length of 40 mm and a width of 10 mm, with fully rounded ends. Complete the dimensioning on the top views.



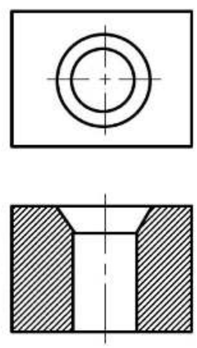


Practice Problems

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

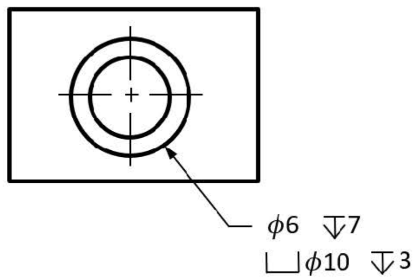


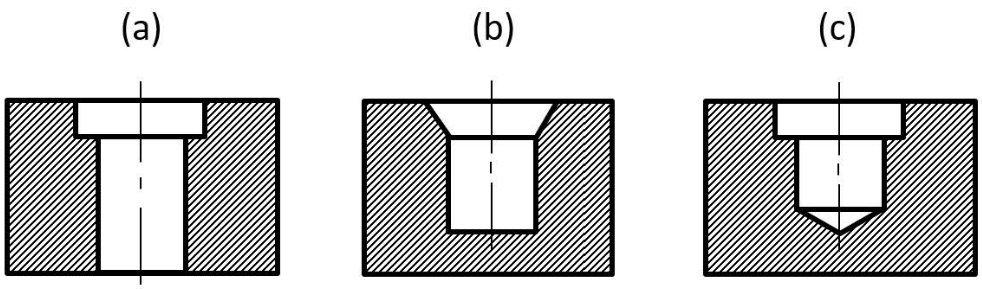
9. Include a dimension for a countersink hole according to ANSI standards with the following specifications:
   - Drilled Hole: 9 mm in diameter with a drilling depth of through.
   - Countersink: 13 mm in diameter at an 80° angle



Practice Problems

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.

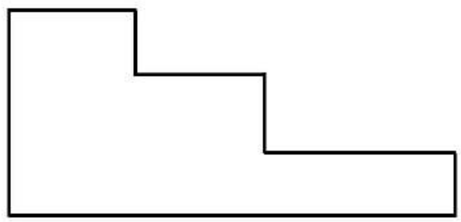




Practice Problems

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



Manufacturing

Topic 03:

Dimensioning & Tolerancing

Prof. J Lee

Objectives

- 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.

Dimensioning

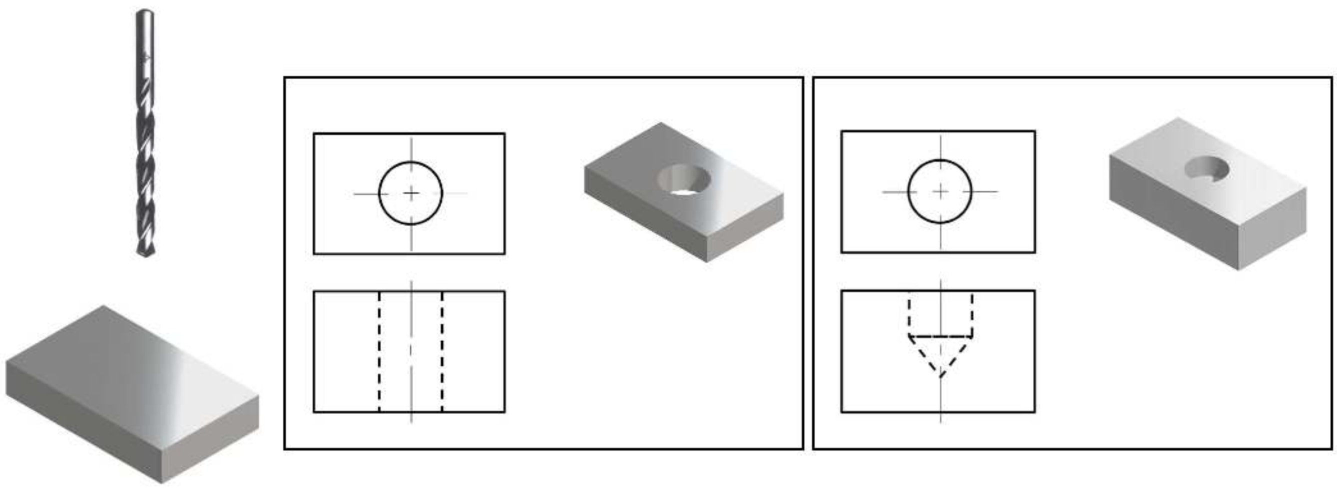
Drilling

: 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.

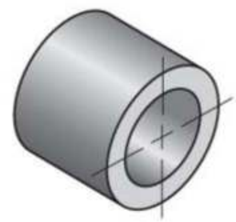


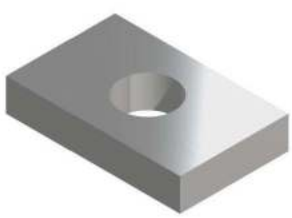
Dimensioning

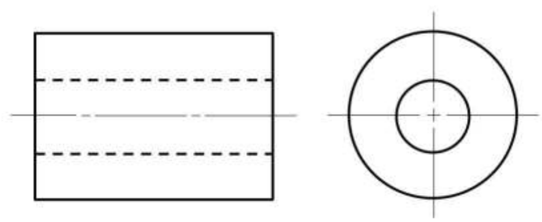
Boring

: to ___________ an existing hole.

: to make a drilled hole in a part "______________ with or ____ to" other part's feature.







Reaming

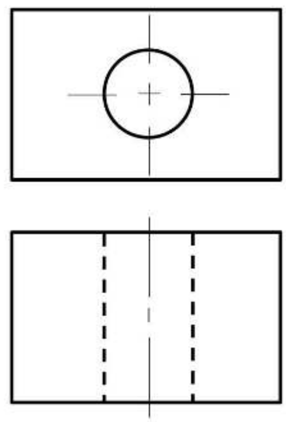
: used to __________ or __________ a hole that has been drilled or bored.

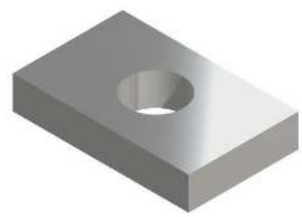
: does _____ create a hole as with a drill.

: 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.





Important Terms in Dimensioning Practices

- Feature

: ____________ portion of a ________ or object.

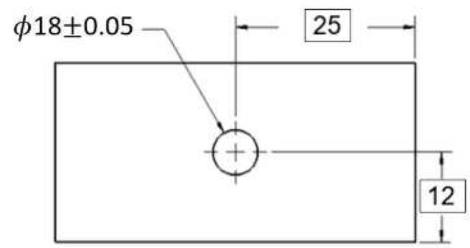
- __________ Dimension

: ______________ __________ 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.

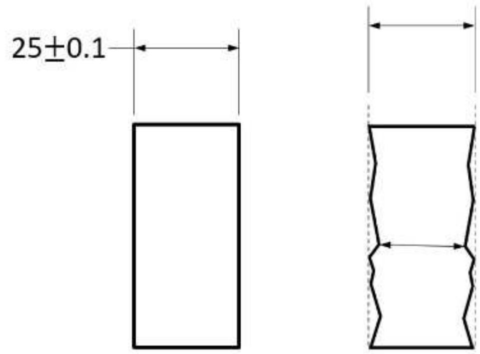
: The size of the feature must ______ violate the size tolerance.

- 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.



- __________ 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 (   )

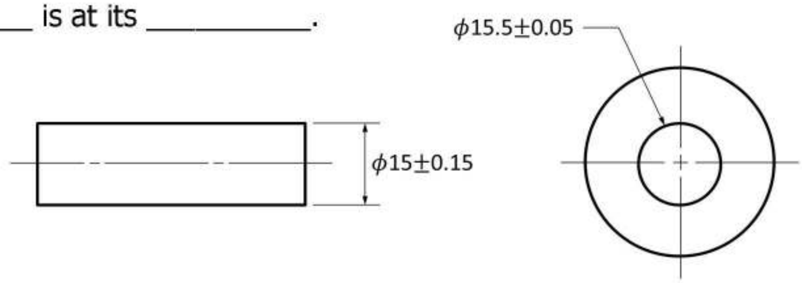
: condition of a feature or part where the ______ amount of _________ _______ within its dimensional tolerance.

: _________ 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 __________.

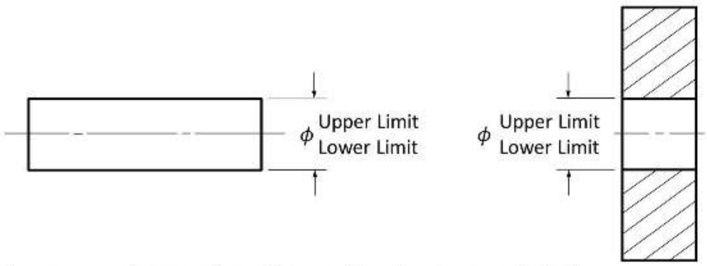


-

: 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.

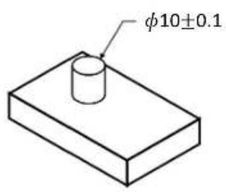
: Always ______ in a clearance fit.

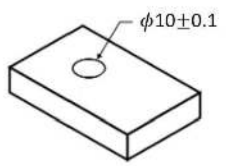
: to allow the mating parts to move freely relative to each other, enabling easy assembly and disassembly _________ need for force.

1. In a drawing, the size dimension is given as .750±.005.

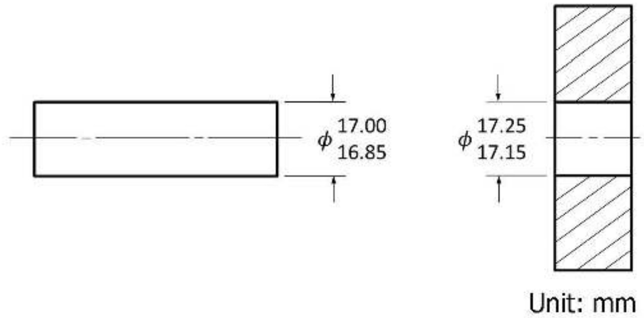
(1) Identify the basic size.
(2) Determine the limits of size.

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





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



Recall:

Allowance = ternal Feature ternal Feature

Tolerance

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.

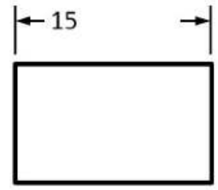
Types of Tolerance

____lateral Tolerance

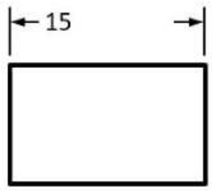
: most common tolerancing method.

: varies in ________ directions from the basic size.

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



(2) ____equal Bilateral Tolerance:

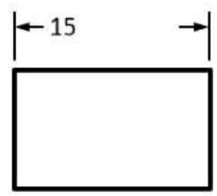


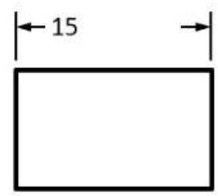
______lateral Tolerance

: 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.





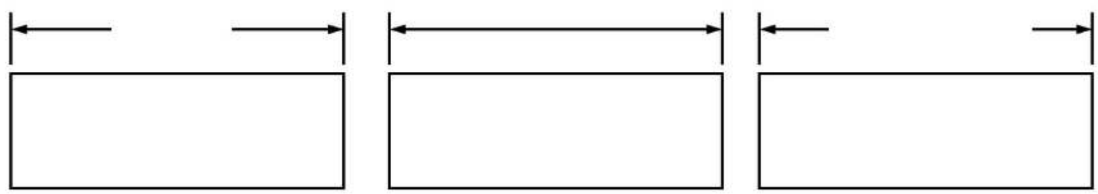
_______ Dimensioning

: 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.



Types of Tolerance

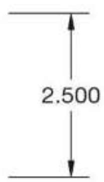
Specified Tolerance

: 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 ±.1
2 PLACE ±.01 3 PLACE ±.005

or

3 PLACE DECIMALS ARE ±.005

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.	• 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.
• When using unilateral tolerance, a single 0 is used without a + or – sign for the 0 part of the value.	• 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:

- **Tolerance Stacking/**

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

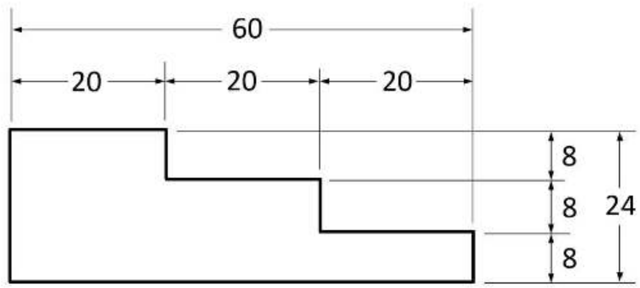
- **Effect of Dimension Types on Tolerance Stacking**

- 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.

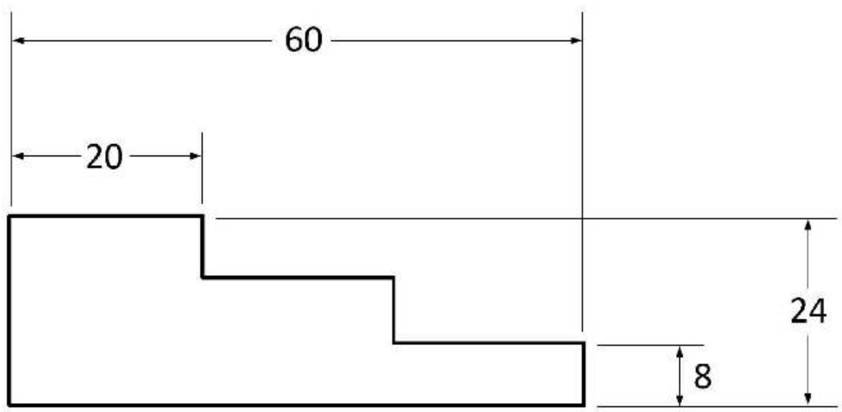
- **Effect of Dimension Types on Tolerance Stacking: How To Resolve**

- 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 __________.



Practice Problems

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.

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

(1) $24.00^{+0.45}_{-0.2}$

(4) $.75^{+.005}_{-.0}$

(2) 24.45
24.2

(5) .5
.498

(3) $24^{+0.0}_{-0.2}$

(6) $.5 \pm .002$

Manufacturing

Topic 04:

Fundamentals of Machining & Chip Morphology

Prof. J Lee

Objectives

1. Cutting Operation

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

2. Rake Angle

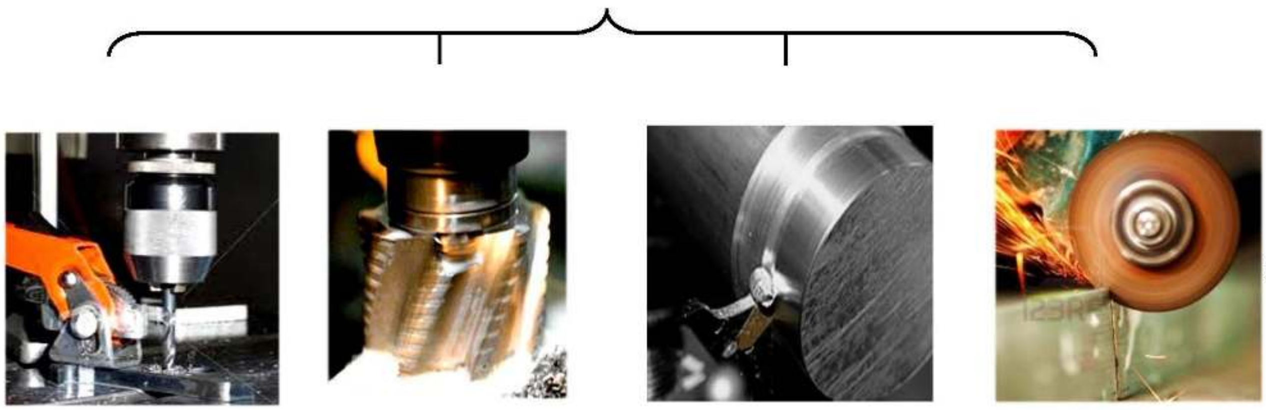
- Define the rake angle of the tool
- Identify the effect of the rake angle to the machining operation.

3. Chip Morphology

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

Applications

Cutting Operation



etc.

Cutting Operation

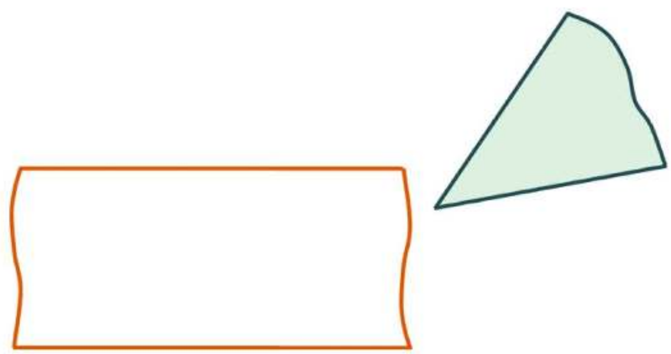
: Machining ______________ to ___________ material from the ________________

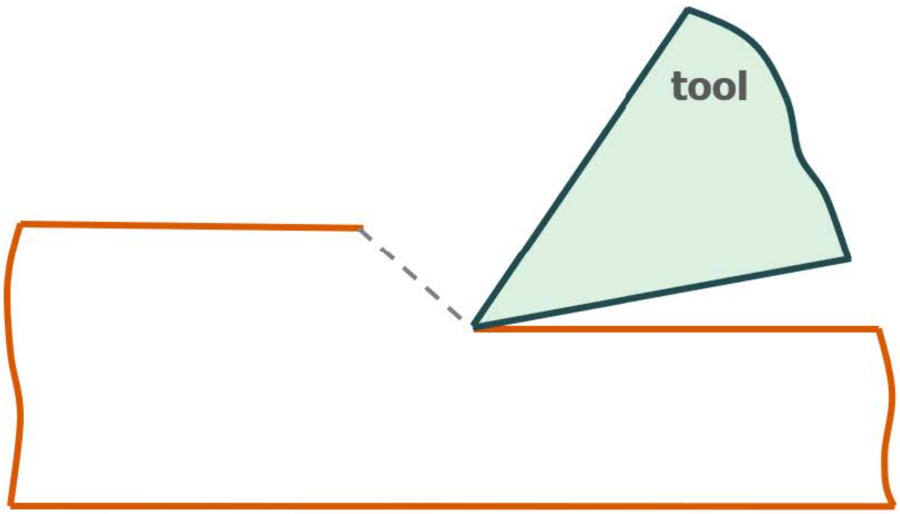
: Key components in cutting operation

(1) __________ ( ): a piece of _________ to _____ ______

(2) ______ : to _____ the _______

(3) _______________ ( ) : for _______________



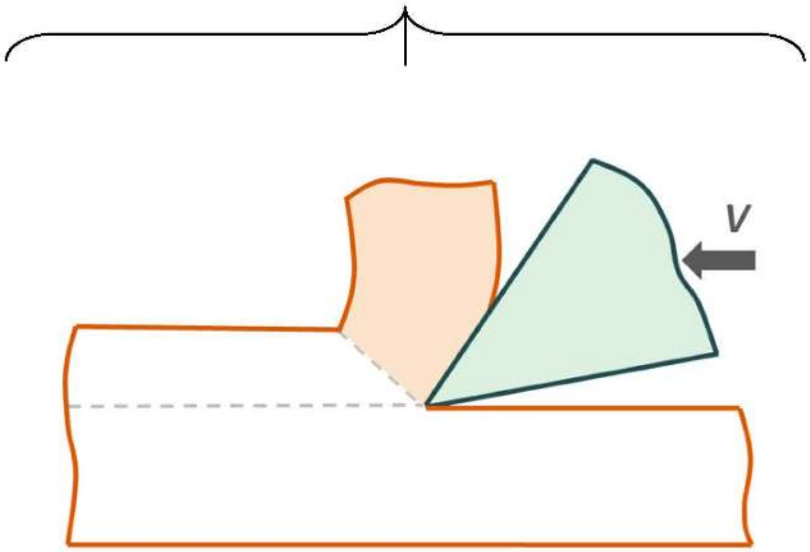

tool

Rake Angle

___________ (   )

: an angle between the tool ________ face and ____ the _________.

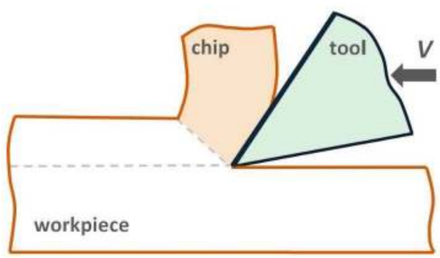
: affects (1) tool _____________, (2) ________ morphology (formation), (3) overall machining processes.



Manufacturing | Prof. J Lee, Copyright.

Rake Angle

___________ Rake Angle (   )



If tool rake face is

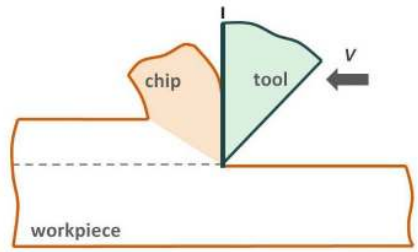
- Steeper: ______ ; __________
- Lower slope: _____ ; __________

+ : ____ cutting force and temperature

  : __________ cutting operation

− : premature tool ___________

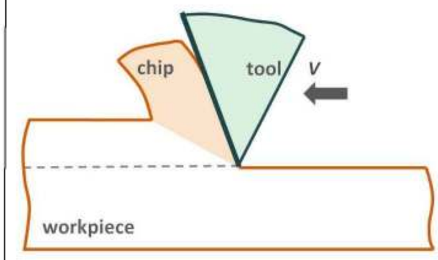
_______ Rake Angle (   )



+ : simple to _________ and

  ______________ of the cutting tool

__________ Rake Angle (   )



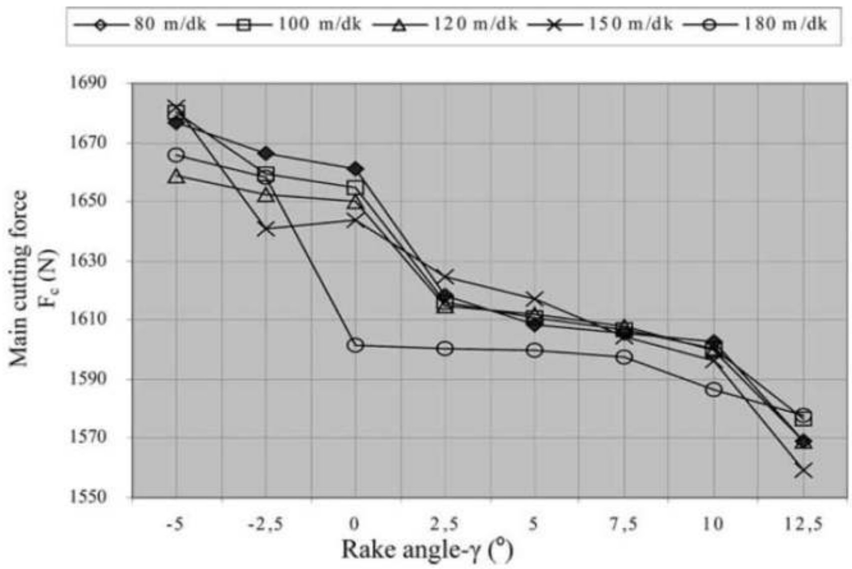
+ : creates ________________ chip

  : increase tool _________

− : _____ cutting force and temp.

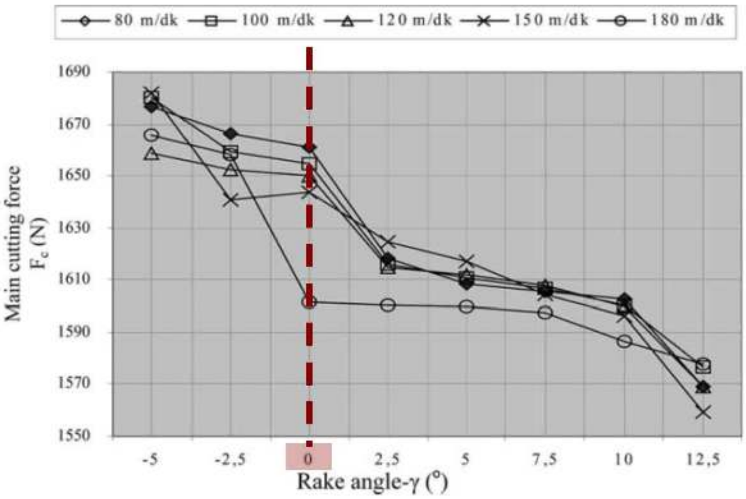
Practice Problem

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

Practice Problem



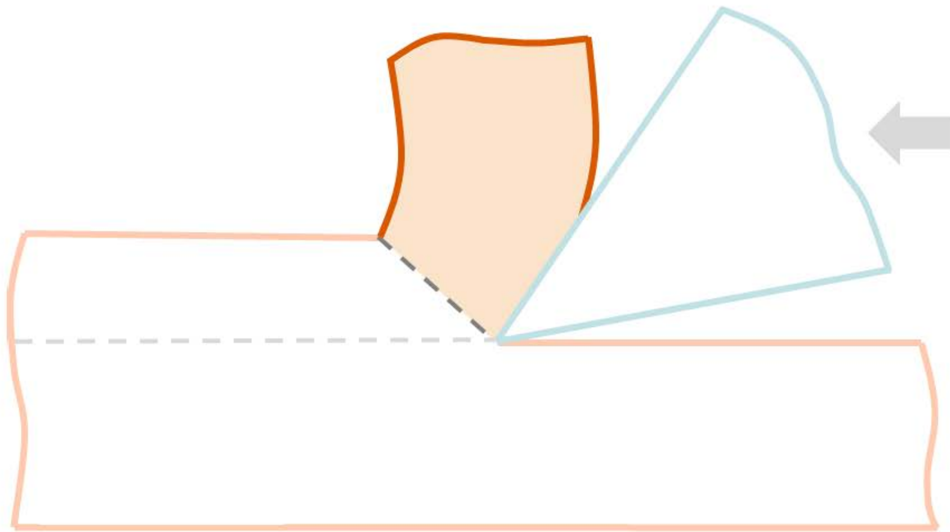
Gunay *et al.*, 2004, International J of Machine Tools & Manufacture, 44, 953-959

Key Findings Summary

- Cutting ______ ________ with tool ______ in different cutting _________
- Cutting Force ____ w/ _____ in ______
- Biggest decrease in cutting force was observed when ≤ ≤
- 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.



Chip Morphology: Chip Formation

- **Chip formation** depends on:

  (1) ______________________

  : e.g., _______ or _________

  (2) Cutting ____________

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

  (3) Cutting ______________: e.g, _____

Cutting Operation

- **Chip formation** indicates:

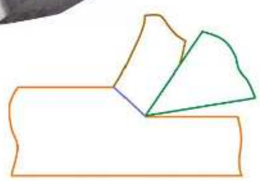
  (1) Characteristics of the ________ ___________

  (2) Amount of __________ ____ required to remove the workpiece material

  (3) Nature of interaction at the ________ - _______ ___________

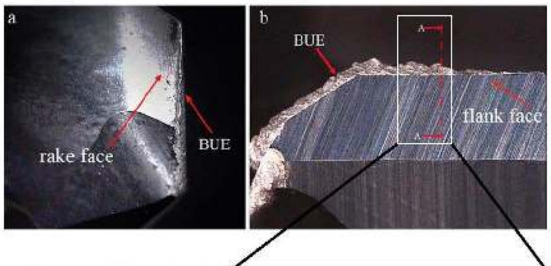
Manufacturing | Prof. J Lee, Copyright.

Chip Morphology

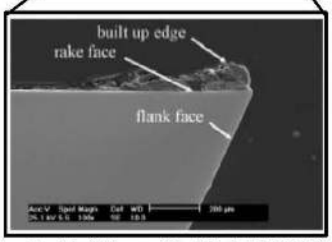
Types of Chips	W.P. Material	Cutting Conditions	Tool Geometry	Pros/Cons
				+ : Good for
				+ : Good for – : Not good for
 				– : Not good for : Not good for : Change tool

Chip Morphology: Built Up Edge (   )

- **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

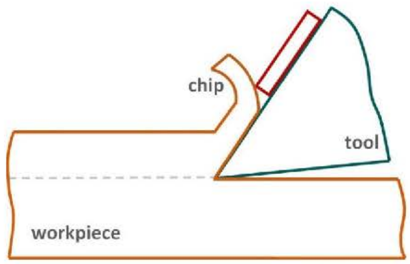
- **BUE**: is ____________ than the workpiece material due to the ____________ effect.
  - : causes a _____________edge.
  - : causes the formation of an ____regular cutting edge and ____even chip formation.

- **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

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.



____

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.

Practice Problems

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.

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

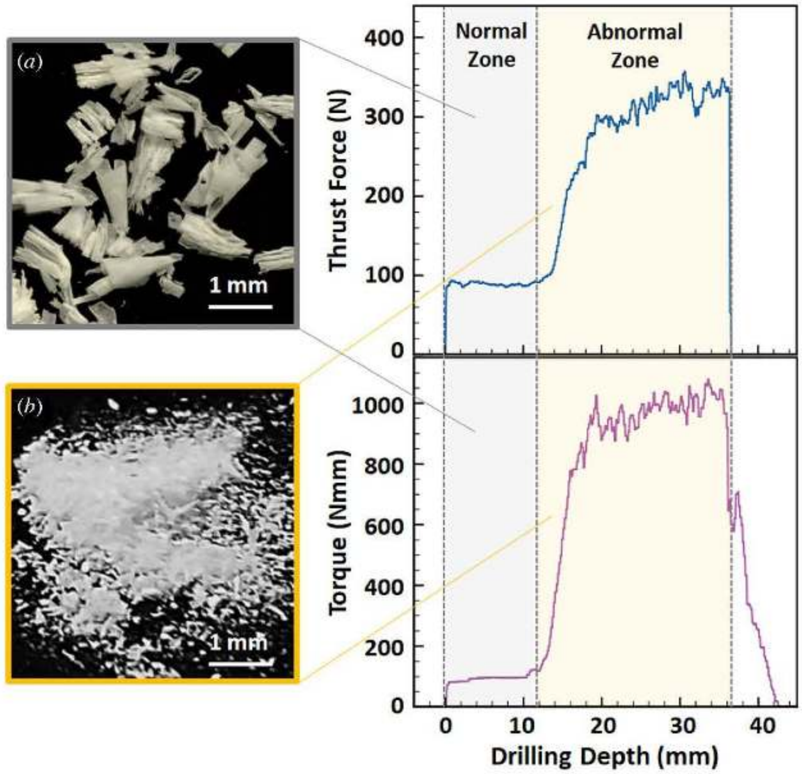


Fig. 1 Typical thrust force and torque profiles during deep-hole bone drilling, showing characteristic chip morphology variations with depth: (*a*) fragmented chips collected at 7 mm in the normal zone and (*b*) powdery chips collected at 20 mm in the abnormal zone

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 ($p\eta^2$) 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 $p\eta^2$ values of 0.97 for thrust force and 0.96 for torque. Feed rate followed closely, with $p\eta^2$ values of 0.91 and 0.89, respectively. In contrast, spindle speed showed a comparatively lower impact ($p\eta^2 = 0.29$ for thrust force and 0.15 for torque). The interaction between drill-bit diameter and feed rate also had a notable influence, with $p\eta^2 = 0.33$ 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 ($p\eta^2 < 0.14$) 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.

Manufacturing

Topic 05:

Cutting Mechanics

Prof. J Lee

Objectives

Orthogonal Cutting and Oblique Cutting

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

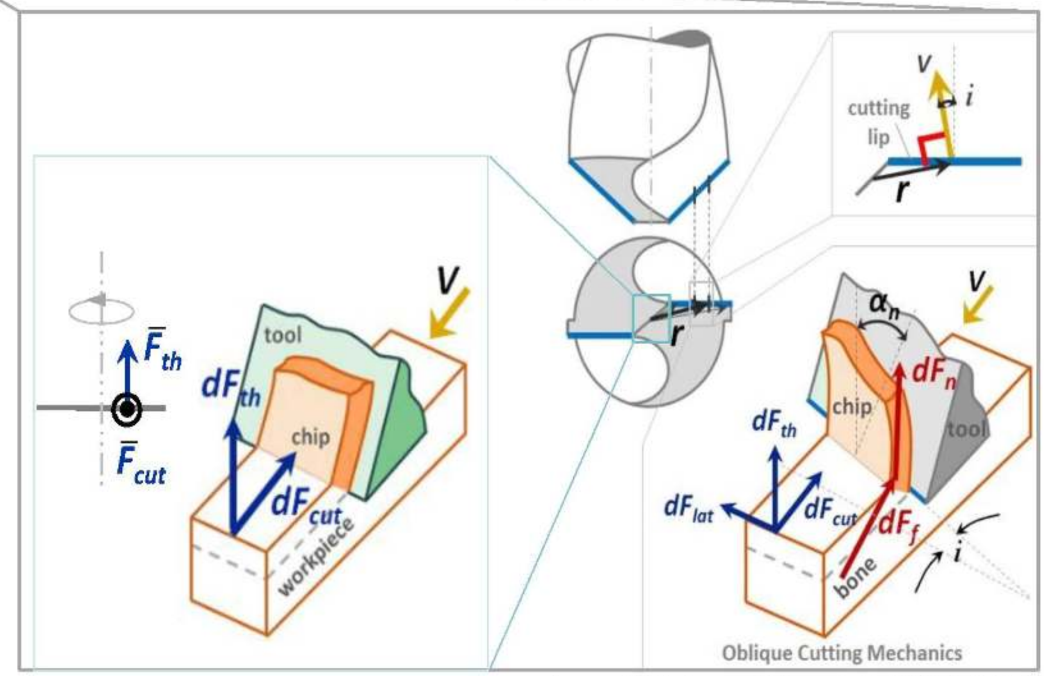
Oblique Cutting

- 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.

Applications



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

Why

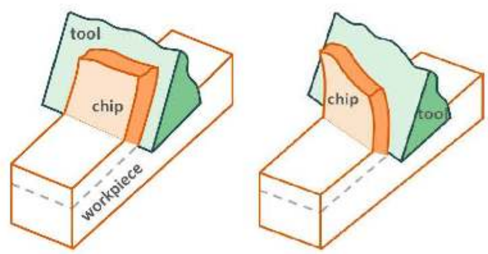
- **To understand the ________ ___________.**

- **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.



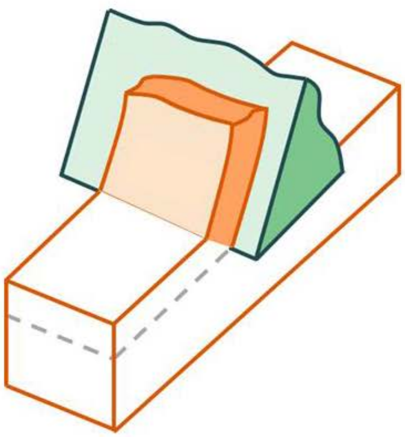
Cutting has _______ different types of cutting mechanisms in terms of the _____________ ___________

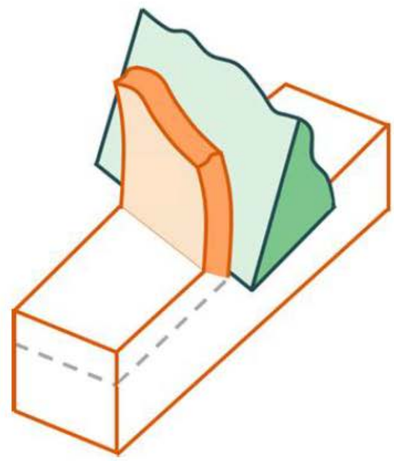
between ____________ _________ and ______.

____________ Cutting

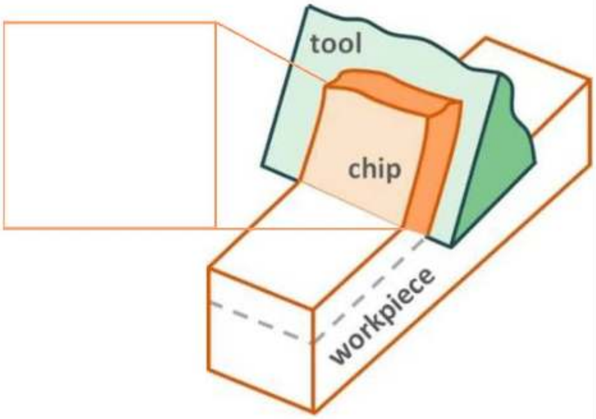
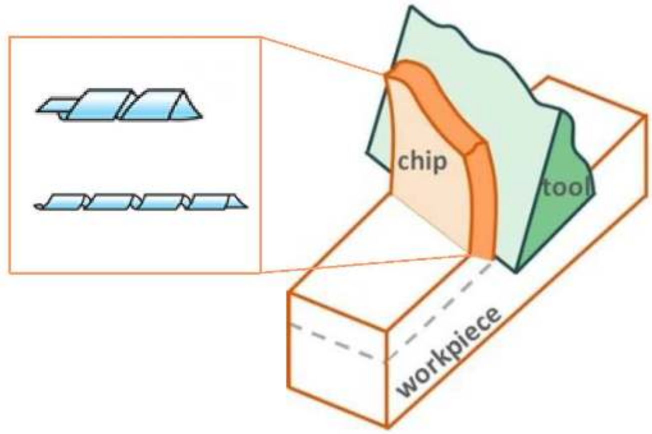
__________ Cutting

In ______:





Orthogonal vs Oblique Cutting

______________ Cutting	__________ Cutting
	
• Cutting ________ ____ Cutting ______.	• Cutting ________ ____ Cutting ______.
• ________ flows ______ the ________ ________.	• Chip flows _____ the rake face w/ an ______________ angle.
• Chip _________ in tight, and becomes __________.	• Chip flows _______ways in a ________ ________.
• Only ____ force components acting on the _____.	• ____ force components of the forces acting on the ______.
• Enough to describe with the _________________ angle.	• Defined by _________, ___________, _______________ angles.

To Define _________ Cutting Mechanics,

- _______________ angle ( )
- _____________ angle ( )
  - ____________________ ( )
  - __________________________ ( )
- ______________________
- __________________ angle ( )
- _____________________ angle ( )

} must be defined.

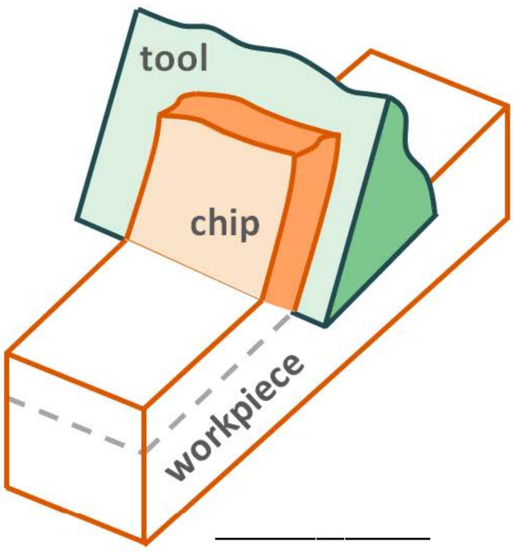
Oblique Cutting

____________ Angle (   )

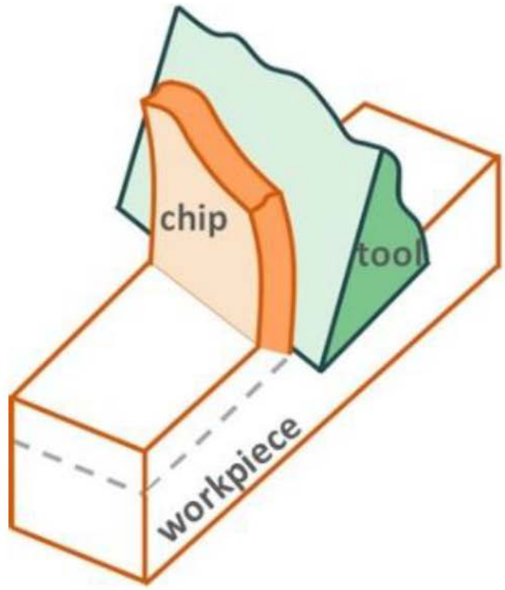
: Angle between the cutting _________ and the line ____ the line of action (LOA) of cutting ____

: _______ characteristic in ___________ cutting

: Known from the cutting ______________.



____



____

___________ Angle (   )

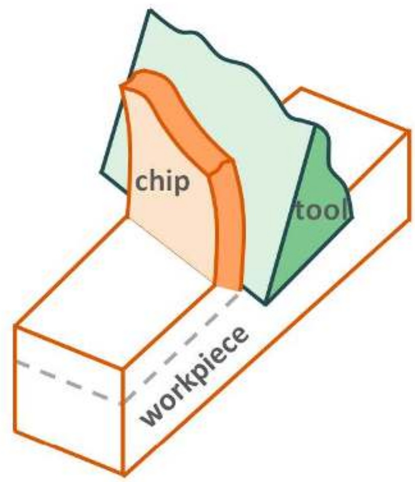
: Angle between the _________________ (   ), which is in the direction ____ to the ________________,

and the _______________ (   )

: Chip has a _______ with _____.

: More _____________ cutting mechanism for material removal

: Better __________ _________ and _______ _________.



How to find:

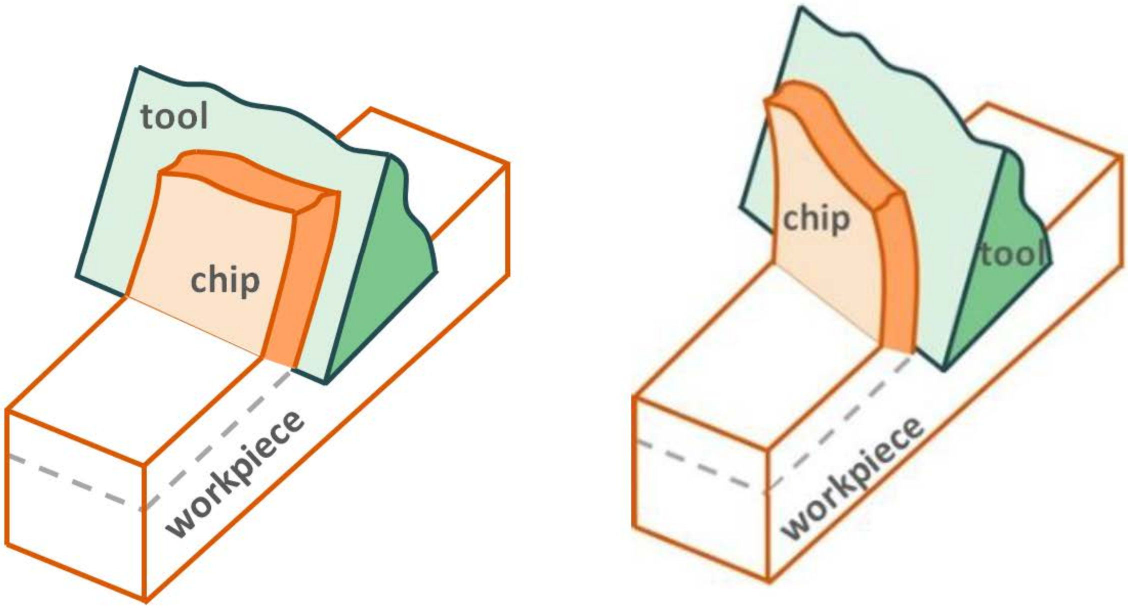
According to the ______________________,

_____________ Angle ( )	_______________ Angle ( )

→ Hence, ____ is ________ from the cutting _____________.

Rake Angle

________ Rake Angle (   )   ________ Rake Angle (   )



Normal Plane

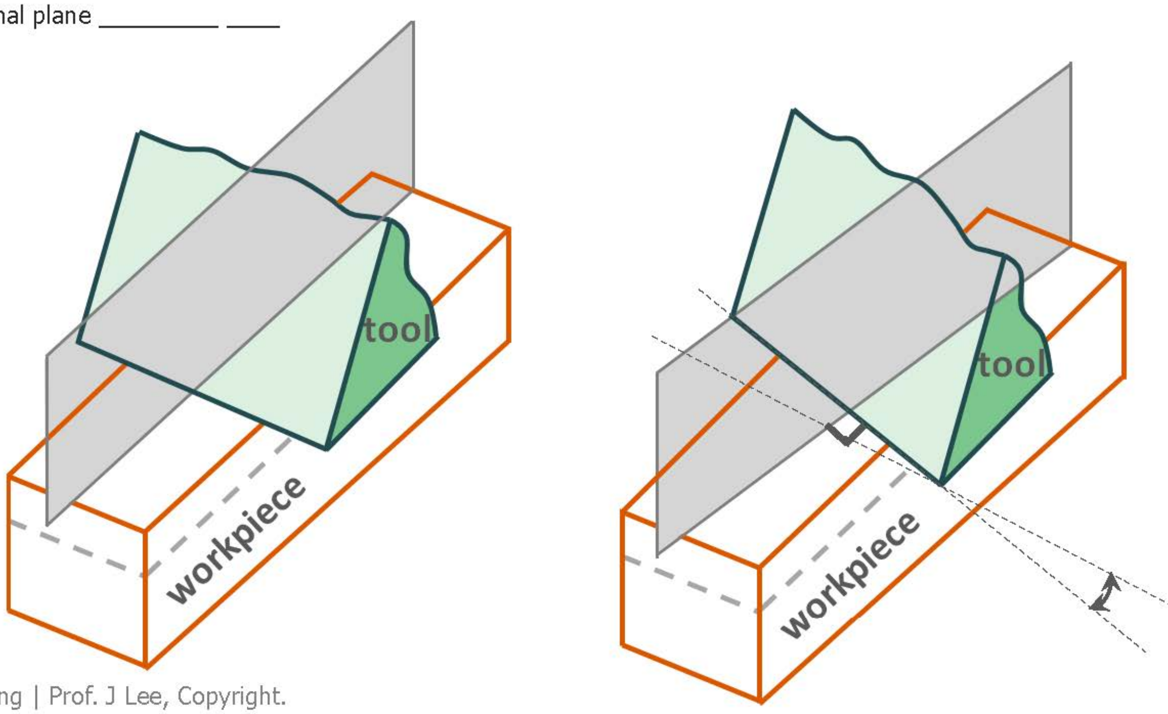
____________________ : Plane ____ the Cutting _______ (   ) & ____ the Machined Surface (   )

In orthogonal cutting:

- the normal plane ____ ____
- the normal plane _________ ____

In oblique cutting:

- the normal plane does ____ _______ ___ due to ____



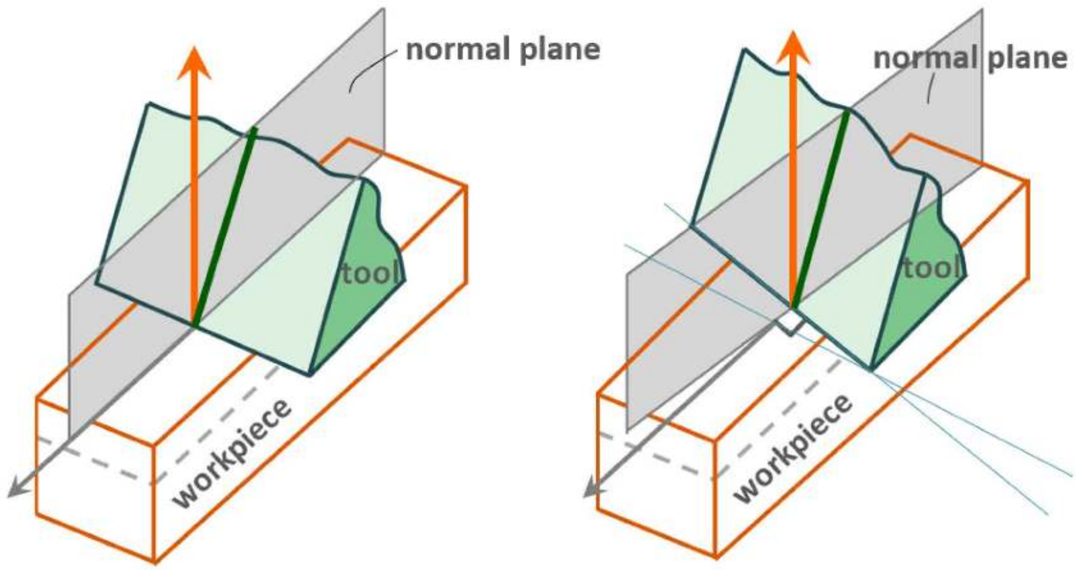
Normal Rake Angle

_______ Rake Angle (   ) : w.r.t ______

: Angle between ____ and ____

: on the ________________.

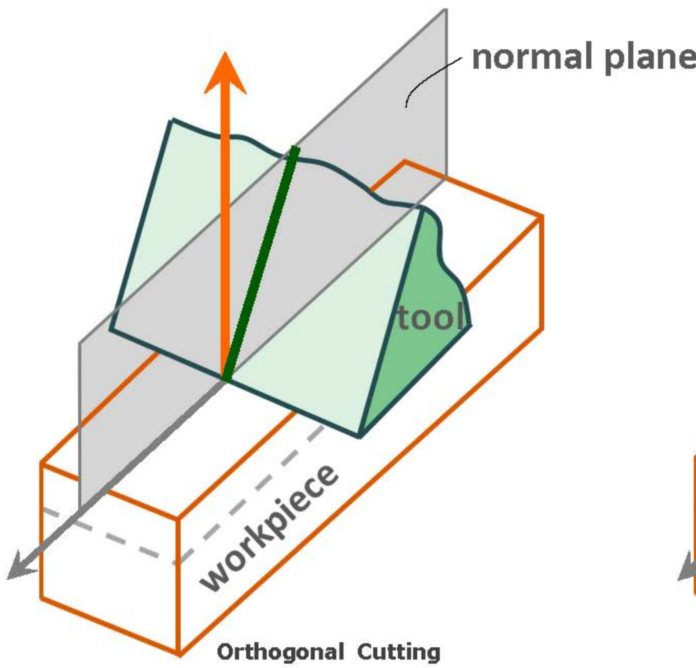
: Known from the __________________.



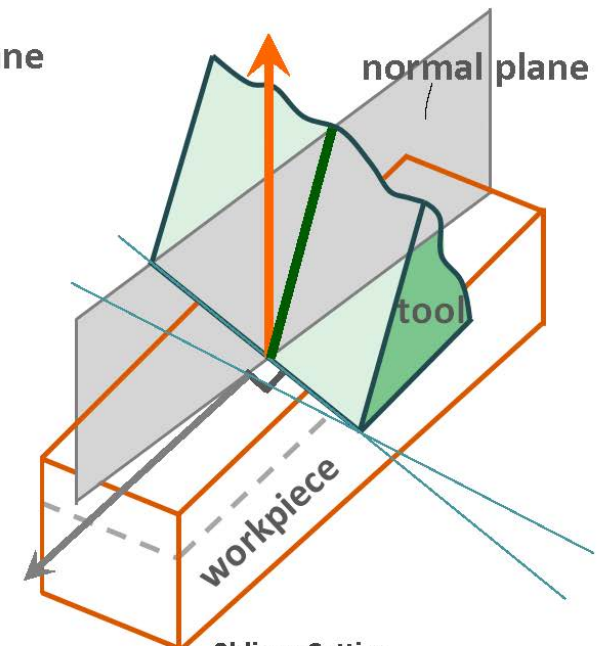
Normal Rake Angle

Topic 05 – 12

cutting edge workpiece	w.r.t the **Tool**	an angle between and



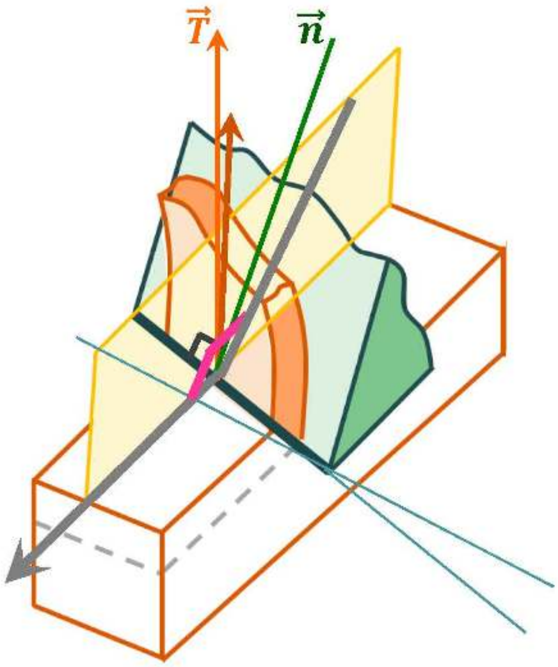
Orthogonal Cutting



Oblique Cutting

_________ **Rake Angle (   ):** w.r.t _______ _______ =

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



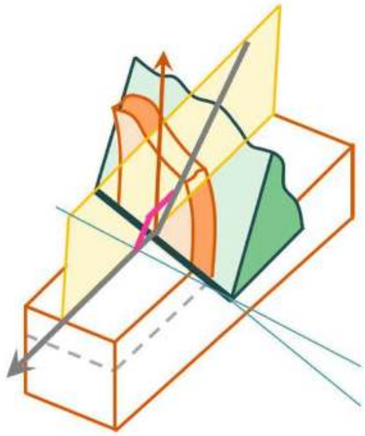
$\alpha_e =$

$=$

According to *Stabler's Rule,*

$=$

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



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

By ____________________

$= f(\qquad\qquad)$

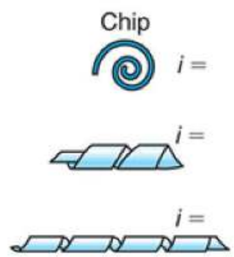
$$\alpha_e = \sin^{-1}(\sin^2 i + \cos^2 i \ \sin \alpha_n)$$

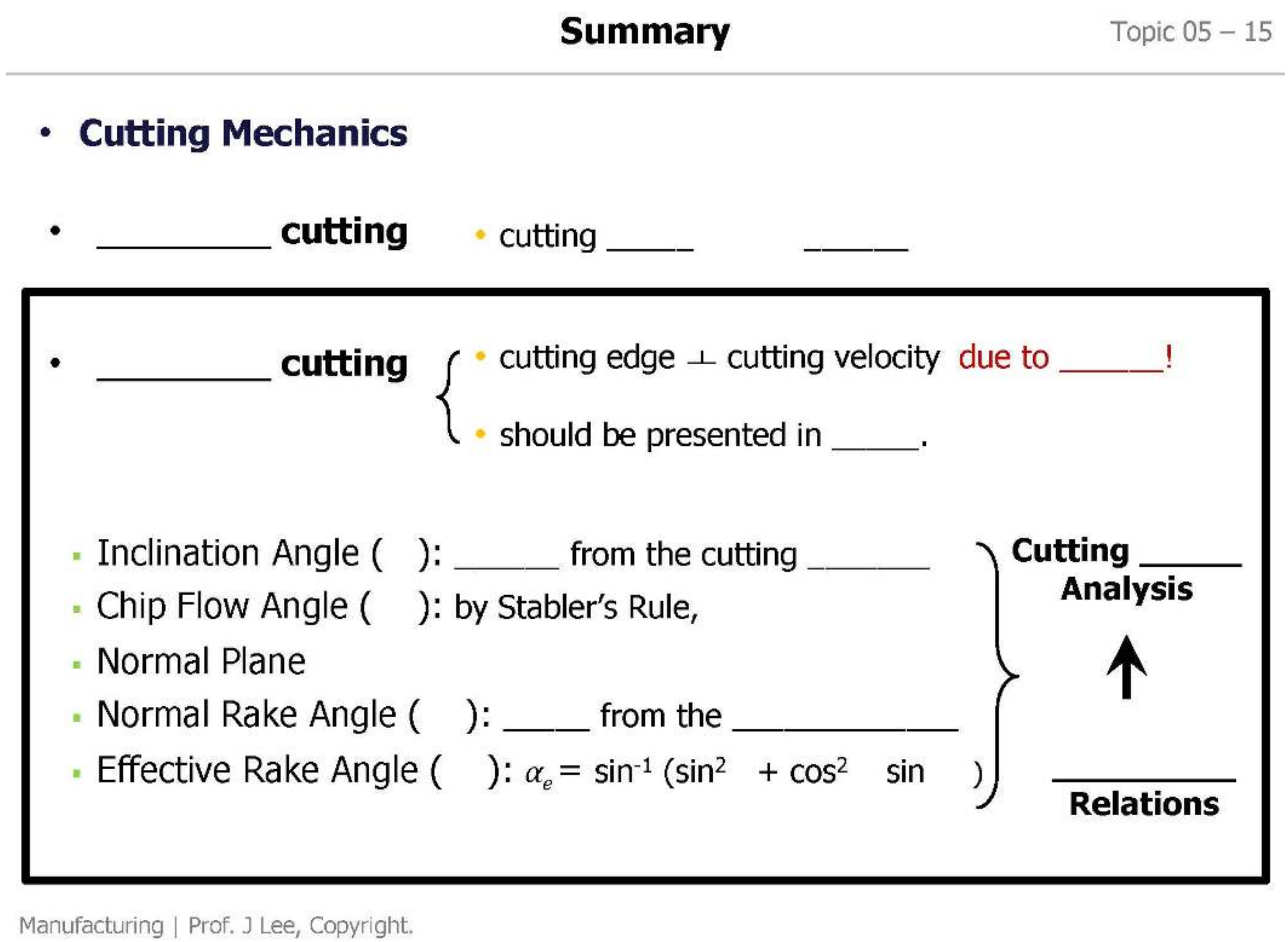
Effects of the Effective Rake Angle

- As _____ increases, ___ increases.
- If ____ ___, the chip becomes ________ and ________.

→ Consequently, the cutting ________ _____.

- If i = ___ : __________ →





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.

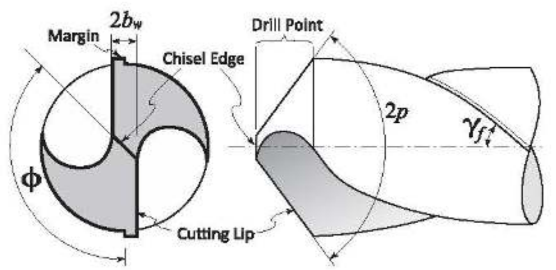


Fig. 1. Geometry of a twist drill-bit.

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,

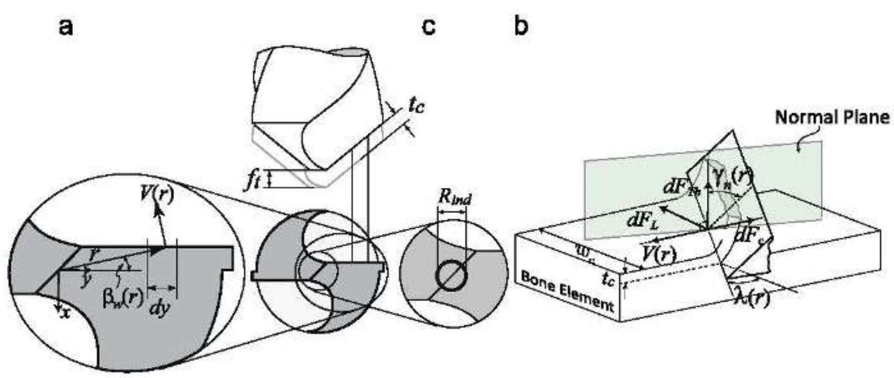


Fig. 2. Cutting geometry during drilling: (a) kinematic parameters for a cutting-lip element, (b) oblique cutting geometry and cutting forces, and (c) the indentation radius on the chisel edge.

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

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

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

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

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

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

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 $V(r) = 2\pi r n_s/60$, 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)

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

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

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

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 kth cutting element of the cutting lips to the global thrust force and torque can then be written as

$$dF_T = dF_{Th}(r_k)\frac{\cos(\beta_w(r_k))\sin(p)}{\cos(\lambda(r_k))} - dF_L(r_k)\frac{\cos(p)}{\cos(\lambda(r_k))}$$

and

$$dM_Z = r_k\, dF_T(r_k), \tag{6}$$

respectively, where $\beta_w(r_k) = \sin^{-1}(w/r_k)$ is the web-offset angle (see Fig. 2(a)). The total contribution F_{Tlip} and M_{Zlip} 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)

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

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)

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

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

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

where the normal rake angle α_n is

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

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

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

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)

Manufacturing

Topic 06:

Plastic Deformation in Cutting

Prof. J Lee

Objectives

1. Plastic Deformation in Metals

- Understand the crystal structure of metals and its behavior under loading.
- Understand why ductile materials are preferred in machining.

2. Plastic Deformation in Cutting

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

• Understanding the Structure of Metals

Why?

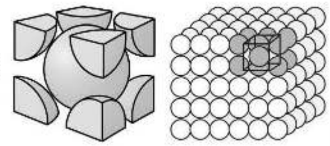
- Atomic structure influences the ____________ and _____________ of metals.
- serves as a guide to controlling and predicting the metals' _____________ and performance in various manufacturing processes.
- allows to __________ and evaluate their ___________ (strength and stiffness) and thus help us to make appropriate _____________ for specific applications.

▪ **___________ Structure of __________**

: ___________ have ___________ __________ arrangement

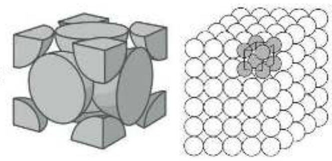
___________: when _______ solidify from a molten state, the _________ arrange themselves into various orderly configuration

▪ _________:



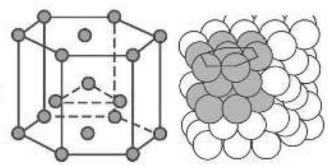
e.g.

▪ _________:



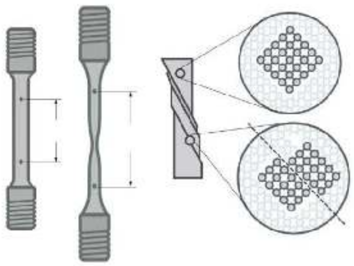
e.g.

▪ _________:



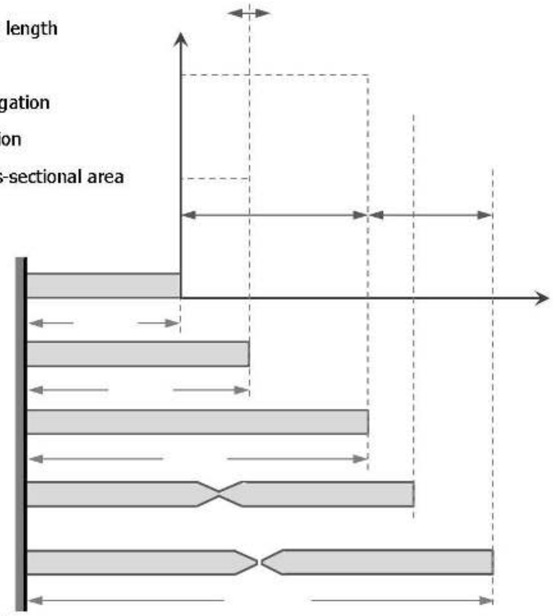
e.g.

- **Metal Behavior under the Loading**



Engineering Stress

Engineering Strain



(1) ________ _________ Behavior: when the load is first applied,
the specimen _______________ in ___ to the load.

(2) _______________ Limit (   ): the point on a stress-strain curve where the linear, elastic deformation region transitions into a non-linear, plastic deformation.

(3) __________ Deformation: when the yield stress ___ of the material is reached, plastic deformation occurs.

: as the load is increased, the specimen begins to undergo ____________ elastic deformation.

(4) ________: as the load is increased further, _____ reaches _____________ and then begins to _____.

(5) _________: if the specimen is loaded ____________ its ________, the cross-sectional ____ of the specimen is smaller in the necked region.

(6) ___________: as the test progresses, _____ drops further, and the specimen finally fractures at the necked region.

• Why Ductile Materials are Preferred in Machining

- In terms of the workpiece, _______________; integrity, _____________, _________; ________ , and _______ control,

  ____________ of a material directly affects the _________ of _______ produced.

  → the ______ directly affects ___________________, and the nature of ___________ involved.

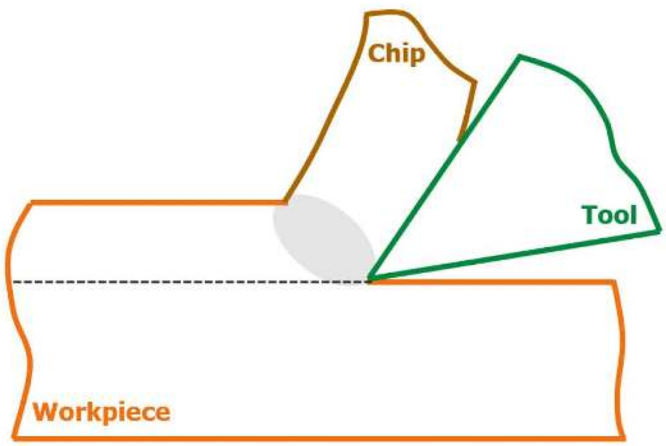
- _______ ductile materials may lead to ________ ____________.

Why ____ and _____ are generally considered to be easy to machine:

- relatively ________: cutting __________ and _________ are _______ compared to other materials.
-
- ____________: can withstand the ___________ in cutting.
- these materials do _____ generally form a ______ depending on cutting parameters.

Plastic Deformation in Cutting

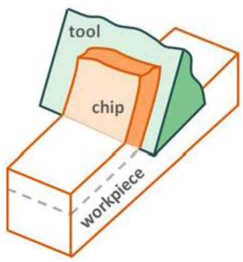
- __________: a process of extensive ______________________ to ________ a _______ which is removed afterward
  - Chip formation in metal cutting is accompanied by substantial __________________________ in the ________________.
  - ___________ takes place within a _____________, which is also called a ____________ zone.



Assumptions

Actual Orthogonal Cutting

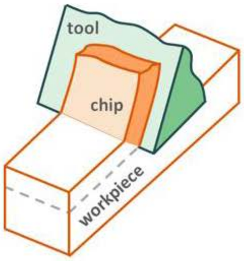
Idealized Orthogonal Cutting

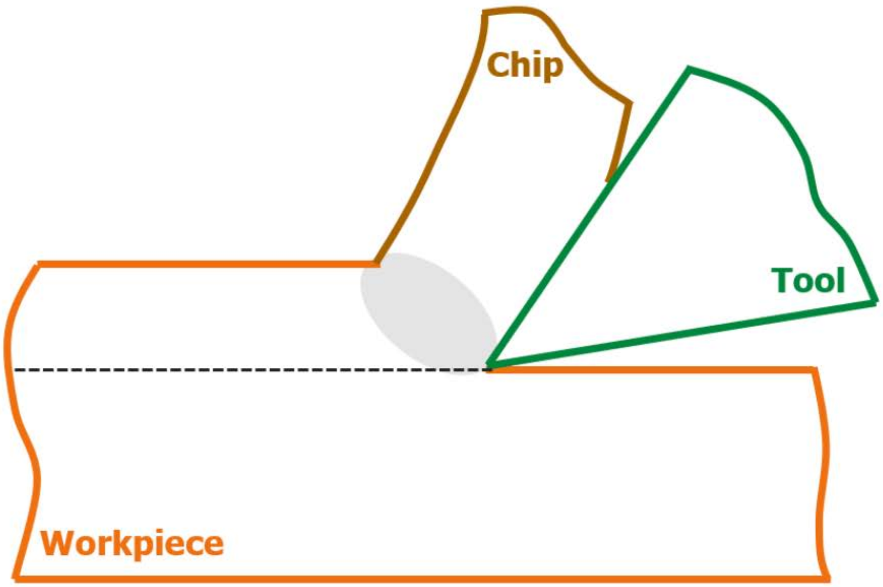


Assumptions:

- 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 ____________.
-

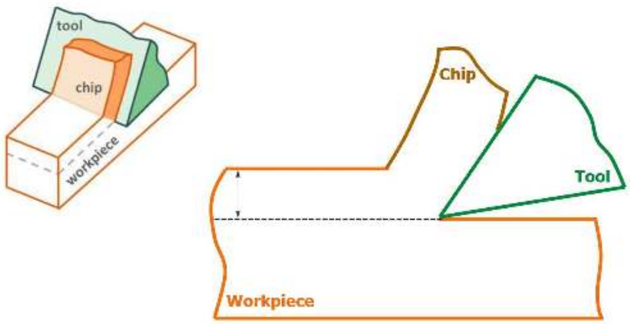
Important Parameters

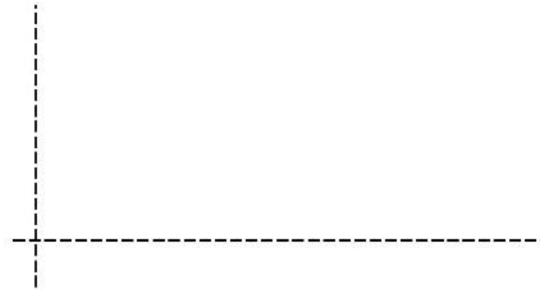




Cutting Ratio

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





Cutting Ratio, r = ——— = —————— = —————

_____________ thickness (   ) :

_______ thickness (   ) :

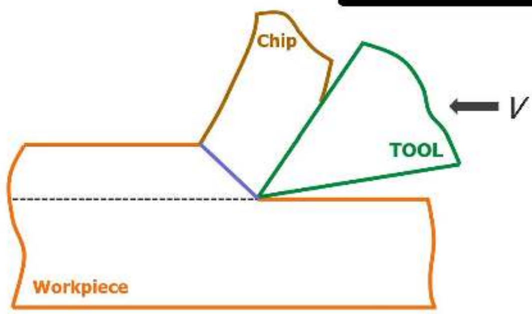
- Chip thickness (   ) can be determined from (1) ______ (2) ______ (3) ______.
- Cutting ratio is related to the two angles _____ and ______.
- Cutting ratio is important and useful parameter to evaluate cutting ________________.
- Cutting ratio can be used to calculate _____ : i) _____ is set; ii)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

  iii) ____ is known from ___________________.

Shear Strain

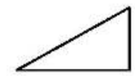
__________ (   ) : = __________ = ______ = ______ ______

Recall:
cot = ______
tan = ______

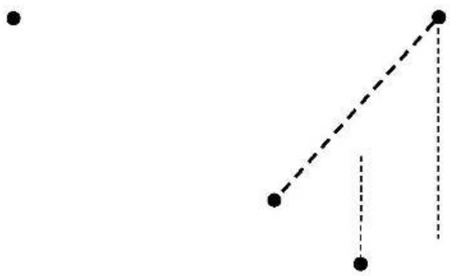


= ______ ______

= ________ __________



Shear Strain (   ) =



- **Characteristics of the Shear Strain**

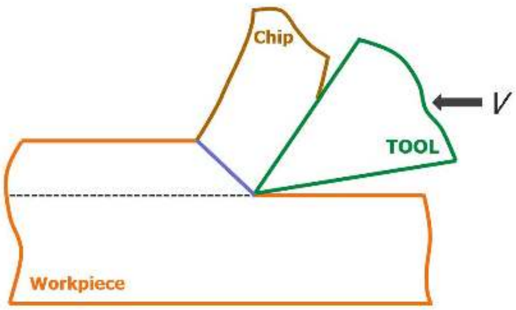
- Large shear strains associated with (1) __________

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 _________.

Shear Angle Model



- **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 (   ) = ______ = ______ ______

where β: __________ __________ at the tool–chip interface

μ: ____________ of __________ at the tool–chip interface

Note: In metal cutting, < <

- **Lee-Shaffer Model**

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

Shear Angle (   ) = = ______

Shear Angle

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

Why: influences (1) Cutting __________ and ___________

(2) ___________________________

(3) _________________

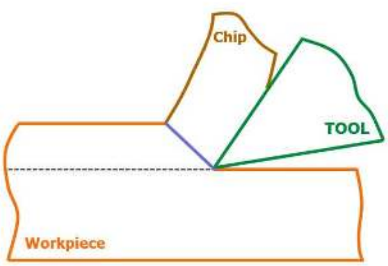
Message from Shear Angle Model

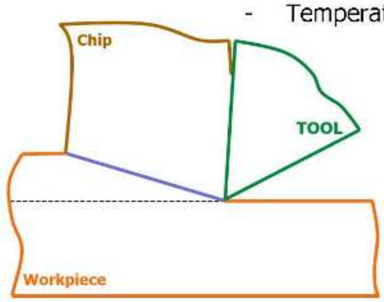
$$\phi = 45° + \frac{\alpha - \beta}{2} \quad \text{or} \quad \phi = 45° + \alpha - \beta$$

means:

If α or β

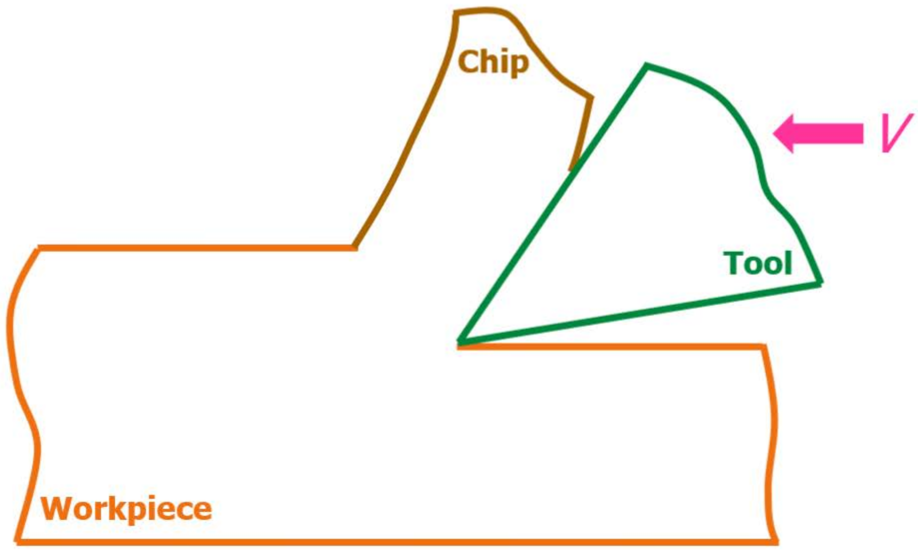
- ϕ ____ → chip becomes ______________.
- ________ chips → ________ → more _____ dissipation
- Temperature rise _____ since the work done during cutting is converted into ________.





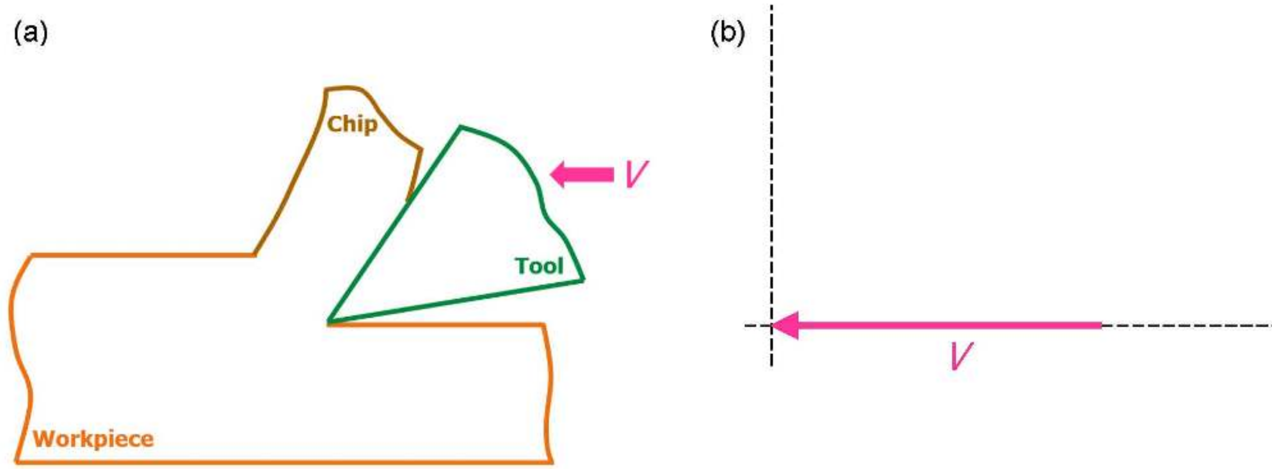
Practice Problems

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



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

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
$\emptyset$: the shear angle
α: the rake angle



Practice Problems

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:

$\mu =$ $\rightarrow$

Recall:

Cutting Ratio, $r = \frac{\quad}{\quad} = \frac{\quad}{\quad}$

Find: % increase of ______ when

Solution:

% increase = $\frac{\quad}{\quad}$

i) Original μ = ______:

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

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

ii) When doubled μ = ______:

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

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

iii) % increase = $\frac{\quad}{\quad}$ $= \frac{(1.3468 - 1.1645)\, t_o}{1.1645\, t_o}$ $= 15.6587$

Answer:

Manufacturing

Topic 07:

Forces in Cutting

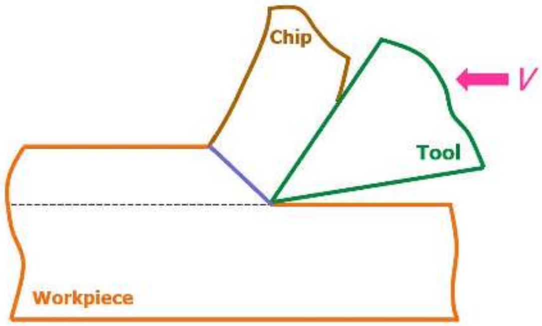
Prof. J Lee

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.

Velocity Relations in the Cutting Zone

- **Express the chip and shear velocities in terms of the known parameters, ___, ___, ___**



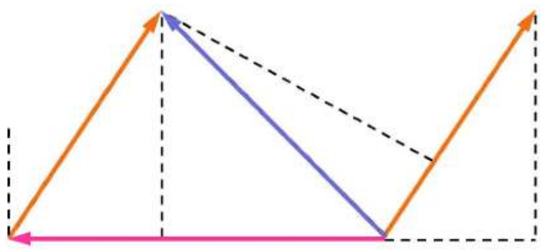
- According to the Mass Continuity, [ ]

Recall the cutting ratio: = ______ = ____________ = ______

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

= ____________

Velocity Diagram



In the velocity diagram, t_o = =

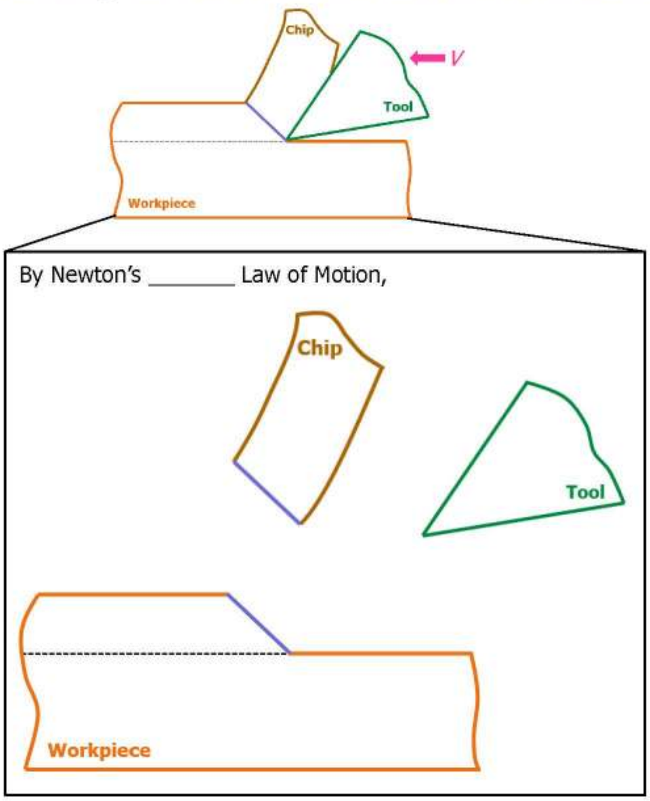
→ = ______

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

= ____________

Cutting Forces

- **Identify the forces in the interfaces in cutting**



I. "Workpiece – Tool" Interface

______ : _________ force, or primary force

: acts in the ______ direction.

: supplies the ______ required for cutting.

______ : _________ force

: acts in a direction _____ ____.

II. "Tool – Chip" Interface

______ : ___________ force

: acts along the ______ - _______ interface.

______ : ___________ force

: acts ______ to the tool-chip interface.

III. "Shear Plane – Workpiece" Interface

______ : ________ force

: acts along the ___________________.

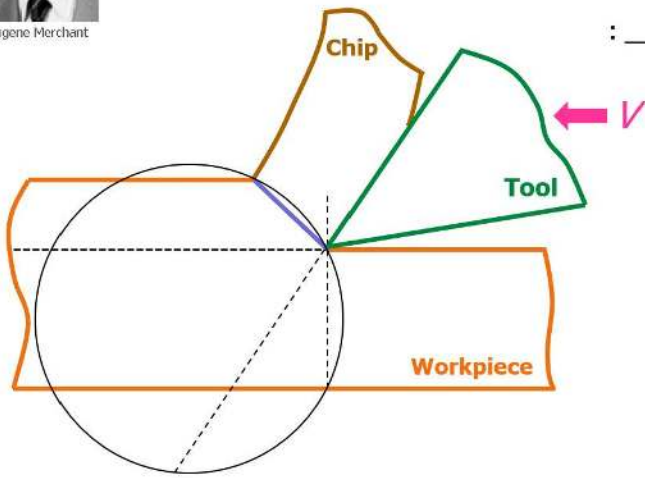
______ : ________ _________ force

: acts ______ to the shear plane.

M. Eugene Merchant

Merchant's Force Circle Diagram

- **Merchant's Force Circle Diagram (   )**



: _________ circle to determine forces acting in the cutting zone

- **Determine   using the force vectors**

I. "Workpiece – Tool" Interface

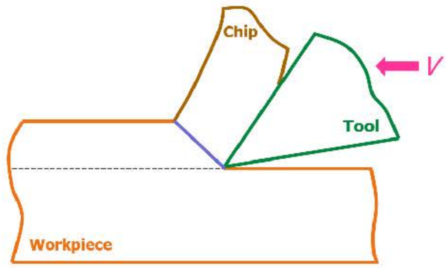
II. "Tool – Chip" Interface

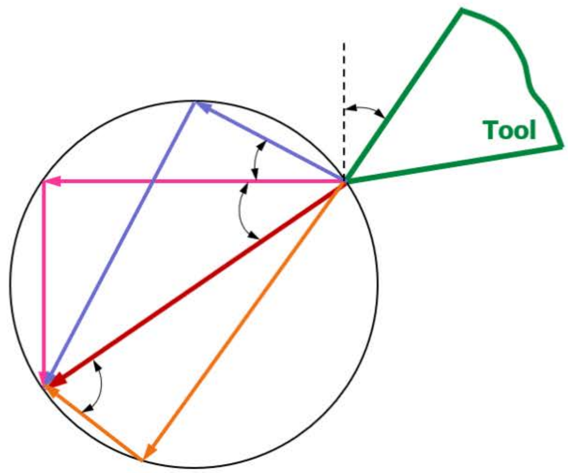
III. "Shear Plane – Workpiece" Interface

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

Merchant's Force Circle Diagram

- **Resultant Force (   )**





Recall:

$\tan\theta = \underline{\qquad}$

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

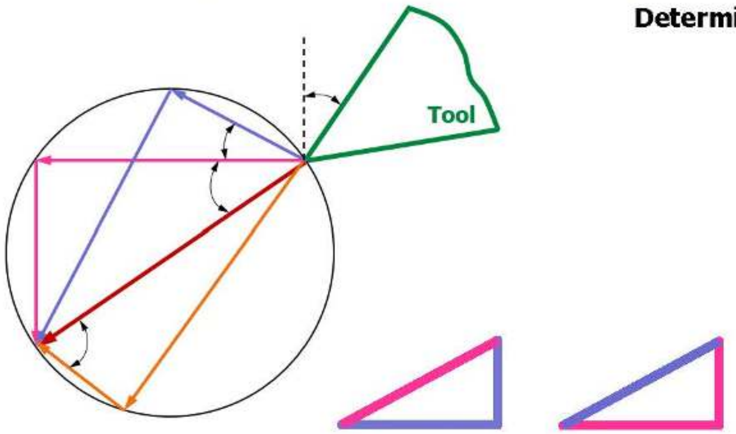
I. Cutting Forces at "Workpiece – Tool" Interface

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

$$F_s = F_c \cos\emptyset - F_t \sin\emptyset$$
$$F_{sn} = F_c \sin\emptyset + F_t \cos\emptyset$$

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

= ———— → F_s = (Eq 1) and = ———— → = (Eq 2)

Substituting Eq 2 into Eq 1,

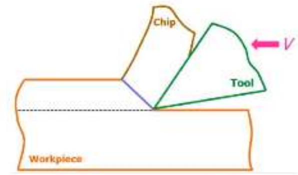
F_s =

= , where $\tan\emptyset$ = ————

$\therefore F_s =$

Cutting Forces

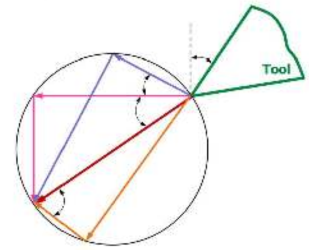
- **Messages in Cutting Forces**



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

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

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



- 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 = $= \text{———} = \dfrac{(F_c \sin\alpha + F_t \cos\alpha)}{(F_c \cos\alpha - F_t \sin\alpha)} = \text{—————————}$

Recall:

$\tan\alpha =$ ________

- In the shear zone, the local shear stresses and the pressure on the cutting tool are _________ __________.

∵ the contact areas are very __________.

- Consequently, the tool ______ is subjected to very ________ stresses

→ lead to (1) ______________; (2) ____________ of the tool; and (3) _____________ of the tool.

3. Cutting Forces at "Workpiece – Tool" Interface:

- Thrust Force ______ can be determined by:

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

  : If ____ is too ________, the tool will be __________ _________ ________ the workpiece surface being machined.

  → __________ → _______ dimensional accuracy.

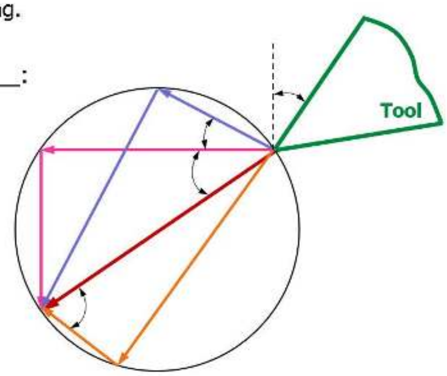
  : hence, the work-___________ devices and machine ______ must be sufficiently _________ to support that force with ______________________.

- Magnitude of _____ is always _______: ∵ _____ supplies the _____ required in cutting.

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

  e.g. if β α : _____ acts ______ ( )

  if β α : _____ acts ______ ( )



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

  i) ____________

  ii) __________: _______ ____________ at the tool-chip interface

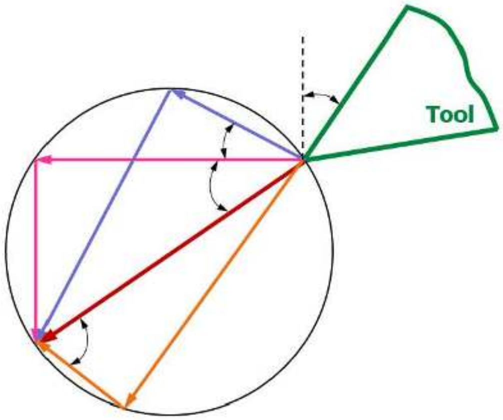
  iii) or ________

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.

Practice Problems

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

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.



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

Manufacturing

Topic 08:

Mechanical and Thermal Energy in Machining

Prof. J Lee

Objectives

1. Mechanical Energy in Machining

- Determine the power and specific energy required for machining processes.

2. Thermal Energy in Machining

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

3. Force and Temperature Measurement in Machining

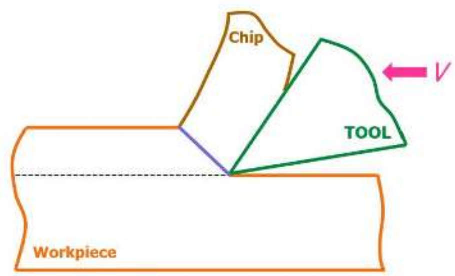
- Explore techniques for measuring forces and temperatures in real-time during machining processes.

Power in Machining

- **Power (   ):** - ________ at which _________ is done.
  - amount of _____ consumed ______ ________________
  - Unit: [   ] = [   ]   or   [   ]
  - Recall: ____ hp = ______ [   ] =   [   ]
  - mainly dissipated   in the ________ zone due to the E required to ________ the ______________
  - and   on the ______________________ due to _____________ at the tool-chip interface.

How to determine the Total Power Input in Cutting

= ____________ = __________ =   =



(1) Power for ______________

=

where V_s: __________ velocity

(2) Power for ______________

=

where V_c: __________ velocity

Specific Energy

• Specific Energy (   )

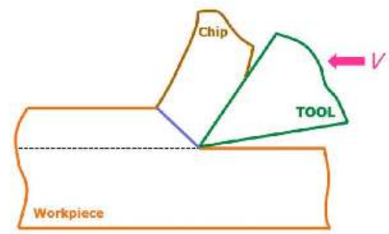
- the amount of ____ required to __________ a unit ___________ of material
- provides insight into the efficiency of the cutting process by indicating

  how much ______ is ____________ ______ the __________ of material removed.
- helps in comparing the machinability of different materials and optimizing machining parameters.

- Unit: [   ] = [   ] = [   ]

How to determine the Total Specific Energy in Cutting

= __________ = ____________ = _______ = _____________



where P_t:

A_c: cross-sectional area of the

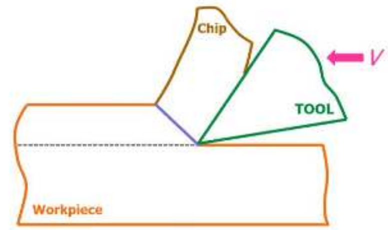
V:

Chip Area =

where w:

How to determine the Total Specific Energy in Cutting

= ______ = ______ = ______ =



(1) Specific Energy for ______

= ______ = ______

where $F_s =$

Recall

Chip Area $A_c =$

(2) Specific Energy for ______

= ______ = ______ = ______

where $F_f =$

Recall

$r =$ ______ = ______

According to the Mass Continuity,

Specific Energy

Experimental Data of Orthogonal Cutting in 4130 Steel

α (°)	ϕ (°)	β (°)	μ	γ	F_c (N)	F_t (N)	u_t (MNm/m³)	u_s (MNm/m³)	u_f (MNm/m³)	u_f/u_t (%)
25.0	20.9	56.0	1.46	2.55	1,690	996	2,206	1,441	765	35
35.0	31.6	57.0	1.53	1.56	1,130	454	1,475	772	703	48
40.0	35.7	57.0	1.54	1.32	1,030	316	1,344	650	696	52
45.0	41.9	62.0	1.83	1.06	1,030	302	1,344	517	827	62

- **Messages from the Experimental Data:**

- _______ ____ → _______ rapidly _______.

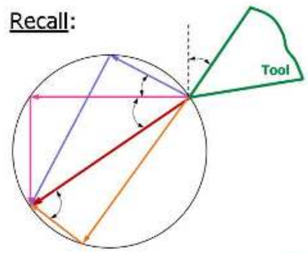
→ the ratio _________ ______ significantly.

- _____ _____ → both _____ and _____ ______.

- This trend can be predicted by developing an expression for the energy ratio:

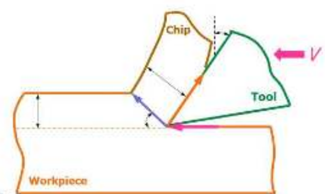
_____ = ________ = ________________ _____ = __________ __________

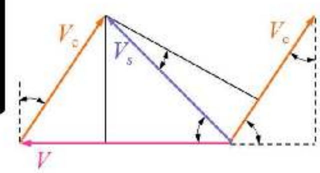
Recall:



$\therefore F_f =$

$F_c =$





- **Heat Generation in Machining**
  - In all ________working processes where __________ _______________ is involved,

    the ____ dissipated in cutting is ______________ into _________

    → __________ the _________________ in the ___________ ________ and the _______ _____________.

  - In machining, **temperature rise is a very important factor. Why?**

    In terms of

    (1) __________ _______: Excessive temperate __________ the ____________, ______________, _____________ and __________ _____________ of the cutting tool

    : Tools may __________ and undergo plastic deformation → _________ the tool _________

    (2) _______________ ____________ and tolerances: Increased heat causes uneven dimensional changes in the part being machined depending on the physical properties of the material.

    (3) __________ ___________: An excessive temperature rise can induce thermal damage in the ___________ __________, adversely affecting its properties

  - Almost all (about _____%) of the _____________ ______ consumed in a machining operation _____________ into ________.
  - ________ elevates ________ in (1) _______ ; (2) ________ __________ ; (3) _________

- **How To:**

(1) _________ _____________: Design of Experiments (   )

: a systematic method to _____________ the relationship between ___________ _____________a process (   ) and the _________.

: allows for multiple _______ factors to be manipulated determining their _________ on a desired _________.

(2) Design ________________ __________

: set up appropriate cutting ________ , _______ , __________, _____________ to measure the outcomes, , and _______ system to __________ the ________.

(3) ___________ experiments

: ensures the _________________ within the _________________ of the equipment and machine used.

(4) Perform _____________________

: identify the influences of the input parameters to the outcomes.

• **Design of Experiments ( )**

________ Parameters
(______________ Variables)

• Cutting ________:

- __________; ____________; _________

• ______ ___________

• Cutting ____________:

- cutting ________ ( ); ______ or _____

• Cutting ____________

Experiment →

________ Parameters
(_____________ Variables)

• Cutting ________ and _____

• __________ in ______, _____ and/or _____

• ____________________

• ____________ ; _____________

• _________ _________ of the workpiece

- Example of ______

- **Experimental Setup**

: Cutting forces can be measured using ________________.

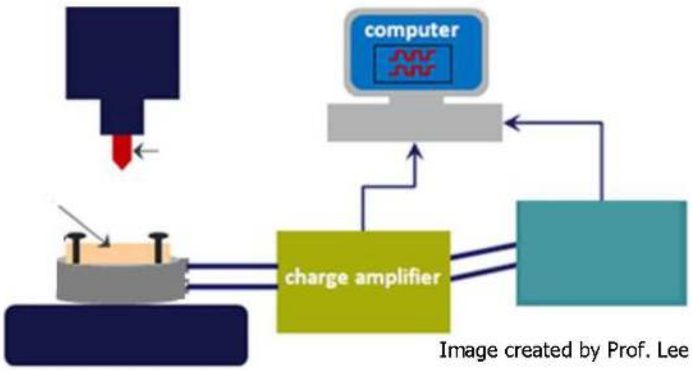
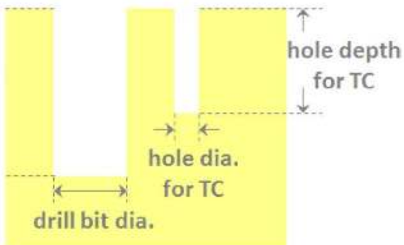
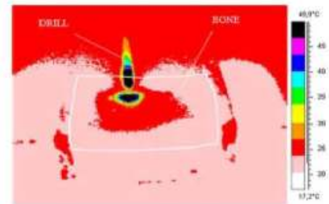


Image created by Prof. Lee

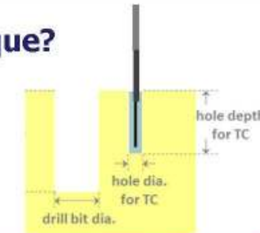
Lee *et al.* 2020, J. Eng. Sci. Med. Diagn. Ther., 3, 031006-1-7.

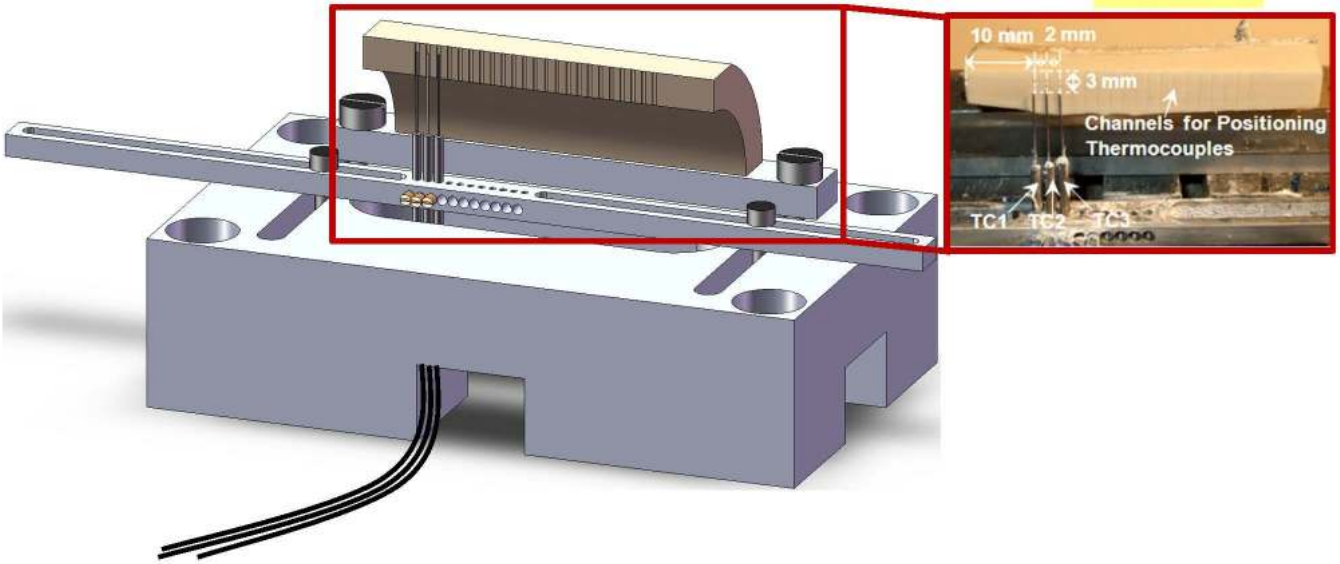
- **Experimental Setup**

: temperature can be measured using ____________________ or __________ __________.

________________	________________
 Ref. Lee *et al.* 2012. Med. Eng. Phys., 34(1), 1510-1520.	 
___ : can measure the temperature at the _________ where we want to know.	___ : _______ to measure
___ : uncertainty issues from _____ ___________ and/or from _________ ____________	___ : only allows the ________ temperature measurement.

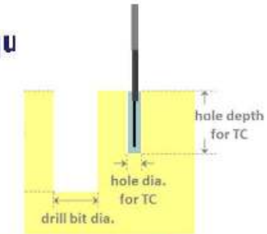
- **How to Resolve the Uncertainty Issues from TC Measurement Technique?**
  - Uncertainty from the _____ ___________ from the Top-to-Bottom Insertion

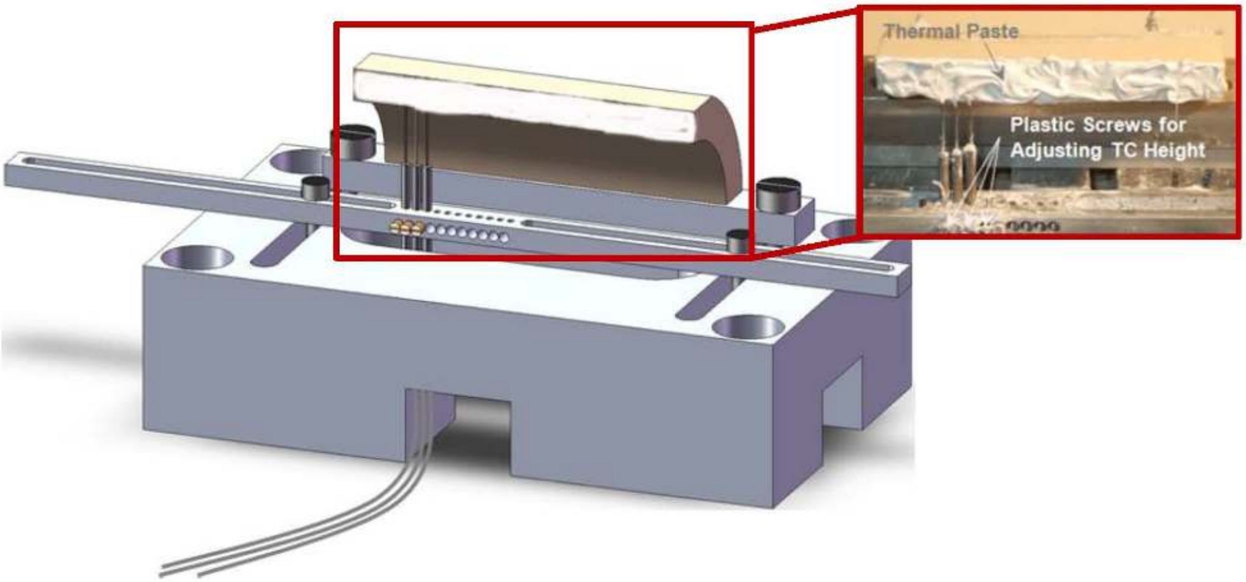




Lee *et al.* 2012, An experimental investigation on thermal exposure during bone drilling, Medical Engineering and Physics, 34 (10), 1510-1520.

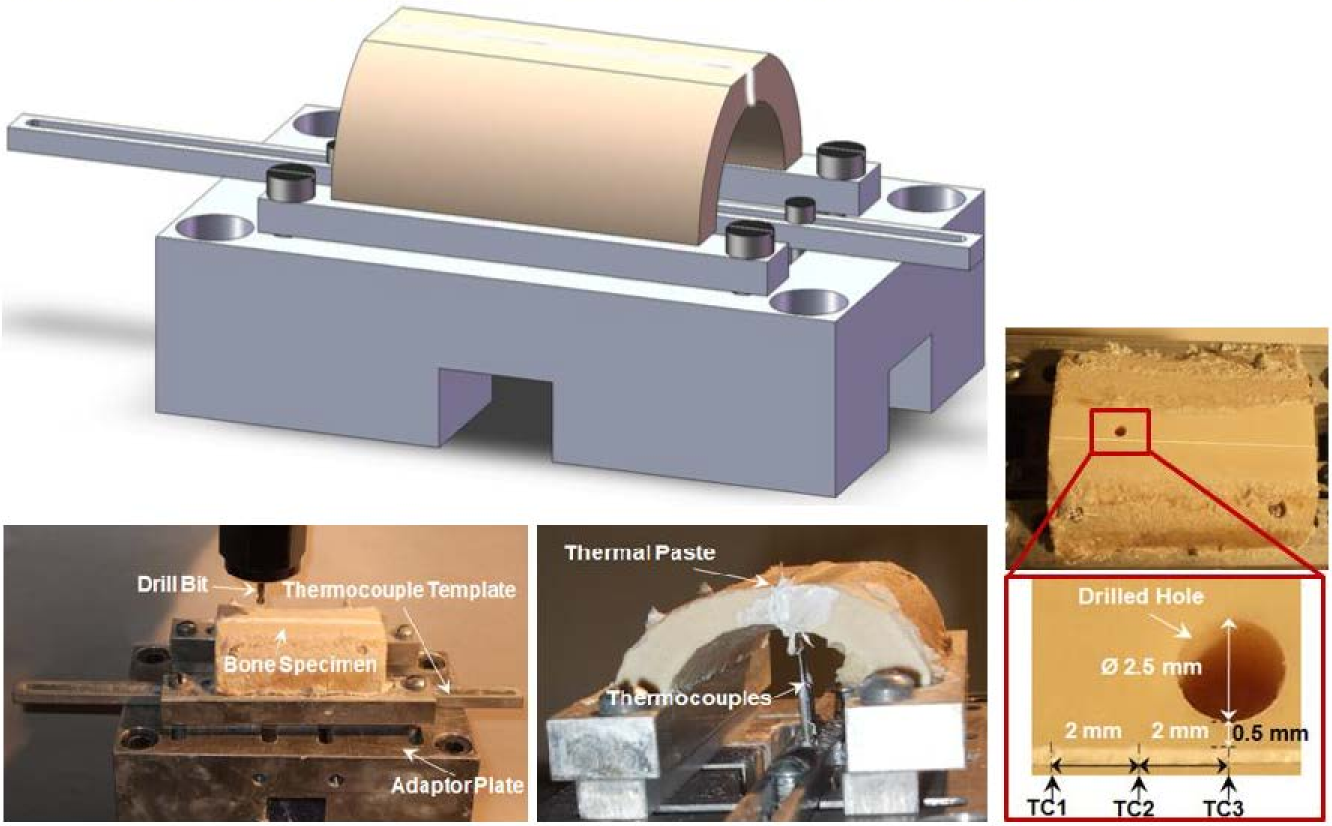
- **How to Resolve the Uncertainty Issues from TC Measurement Techniqu**
  - Uncertainty from the __________ ___________ due to the ______ filled in the _______





Lee *et al.* 2012, An experimental investigation on thermal exposure during bone drilling, Medical Engineering and Physics, 34 (10), 1510-1520.

- **How to Resolve the Uncertainty Issues from TC Measurement Technique?**



Lee *et al.* 2012, An experimental investigation on thermal exposure during bone drilling, Medical Engineering and Physics, 34 (10), 1510-1520.


Manufacturing
Topic 11:
Drilling Operations
Prof. J Lee

Objectives

- 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.

Drilling

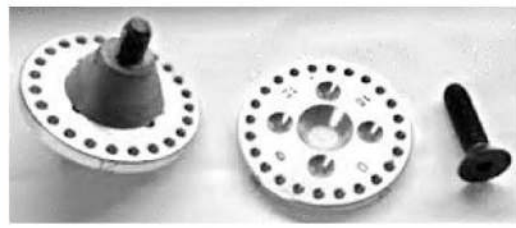
• What

- 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

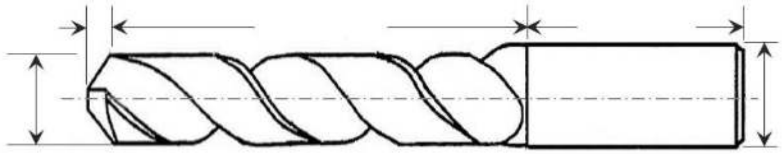
Applications in Drilling Process



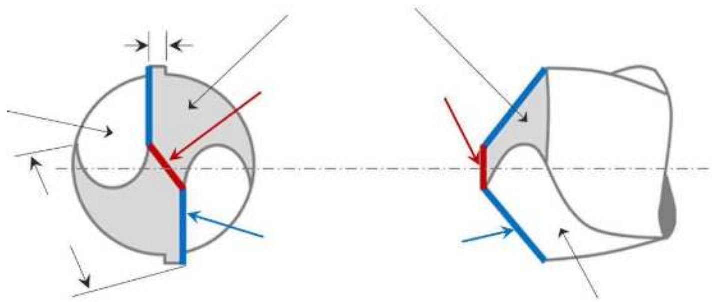
Drilling

- **Tool** : ___________

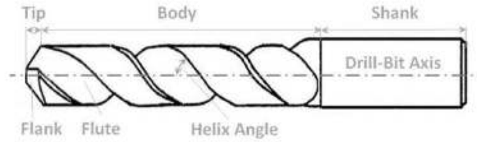
Geometry of a _________ drill bit



_______ of a drill bit



• Features of Twist Drill Bit



__________: to ________ the drill bit from the _____________

__________: to ______________ ________ during drilling

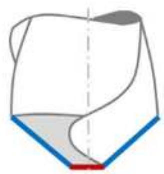
__________: to __________ chips

: 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 __________

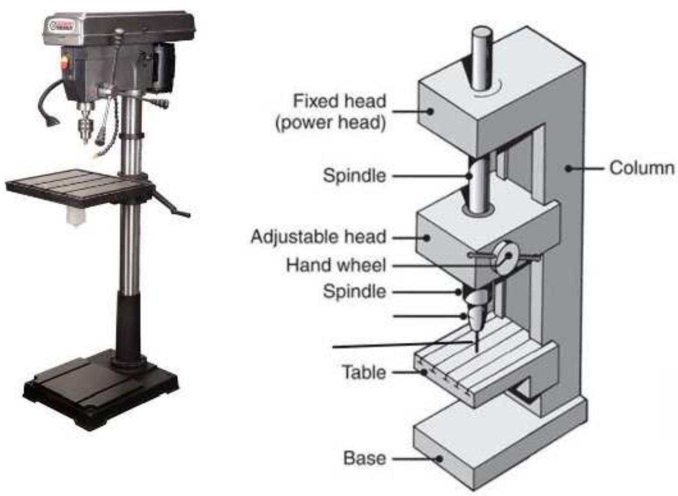
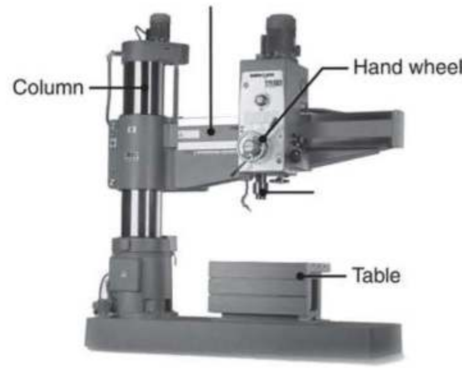
: ________ __________ defines the inclination of the cutting lips

_________ _________: to _______________ into the workpiece

: formed by the intersection of the ___________

: __________ ________ ___________ defines the chisel edge.

- **Machine**

______________ Drill Press	____________ Drill Press
	

Drilling Operations

• 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

General Possible Problems in Drilling Operations

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

General Possible Problems in Drilling Operations

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

Procedures for Producing Accurate Holes

• 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.

Important Outcomes in Drilling Operations

- **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.

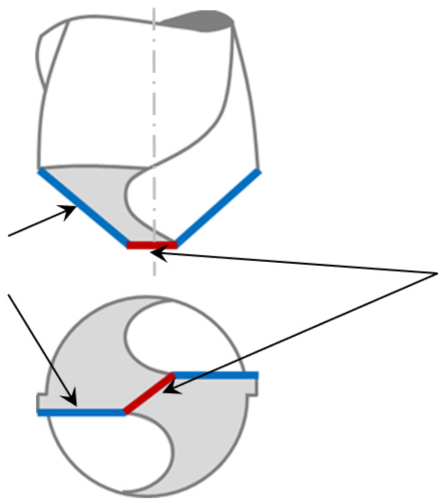
- **Torque**

: _____________ 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.

Analysis of Drilling Operations

- **Force Modeling**

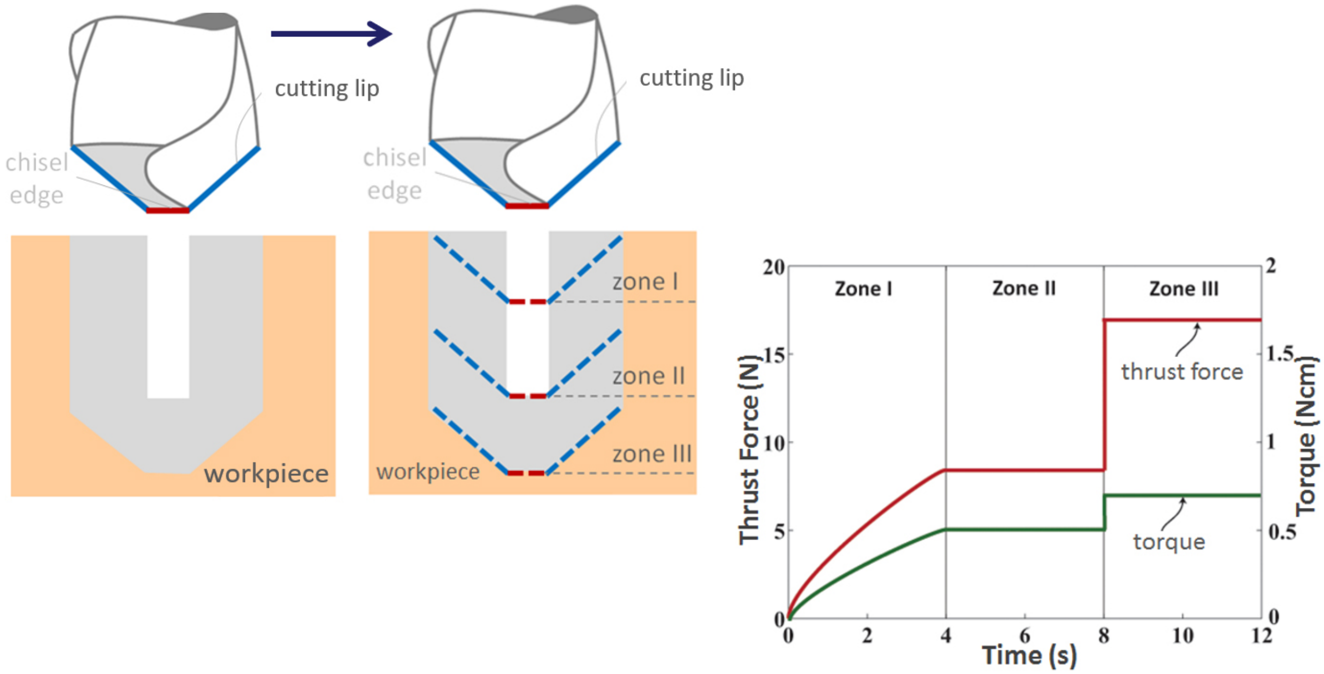


Source: J.E. Lee *et al*., 2012. Modeling and Experimentation of Bone Drilling Forces. J of Biomechanics, 45(6), 1076-1083.

Total Forces on a Drill Bit = Forces from

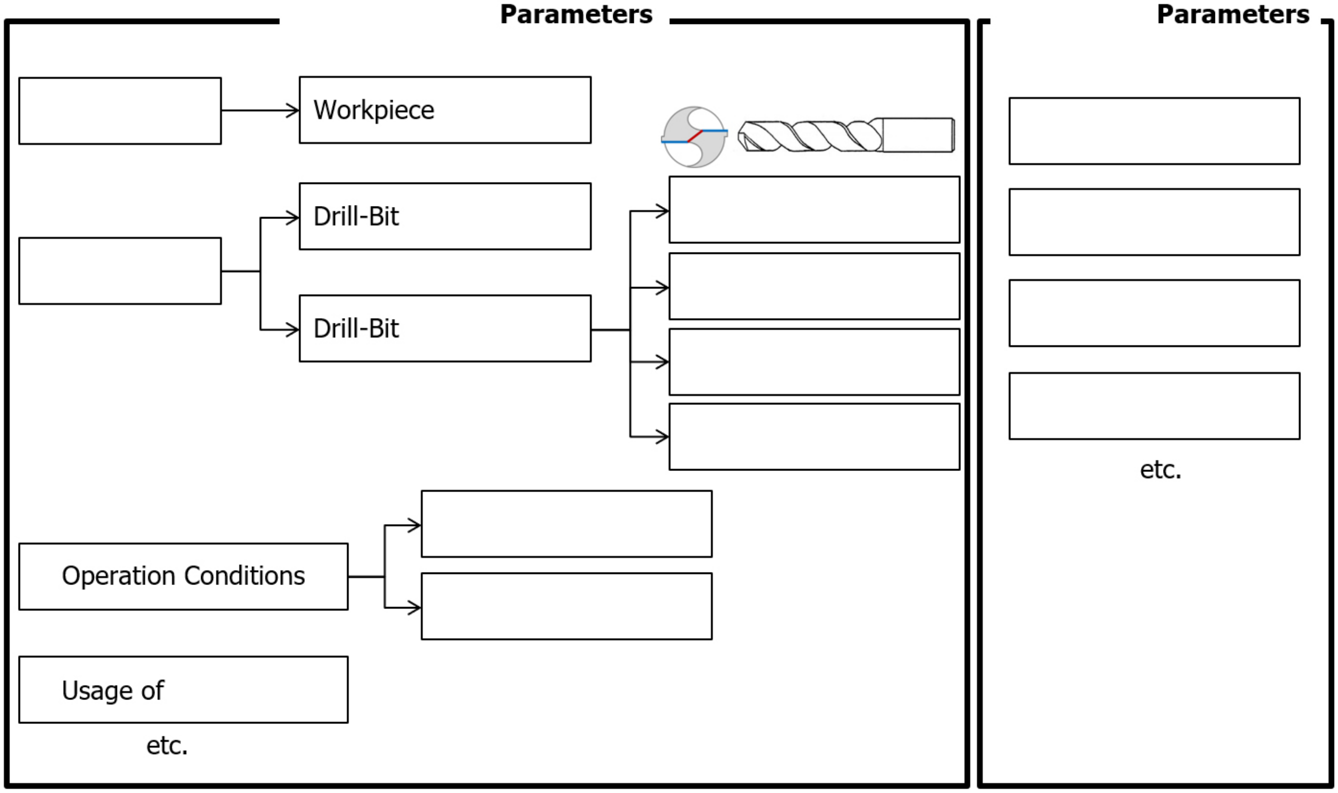
Forces from

• **Design of Experiments**

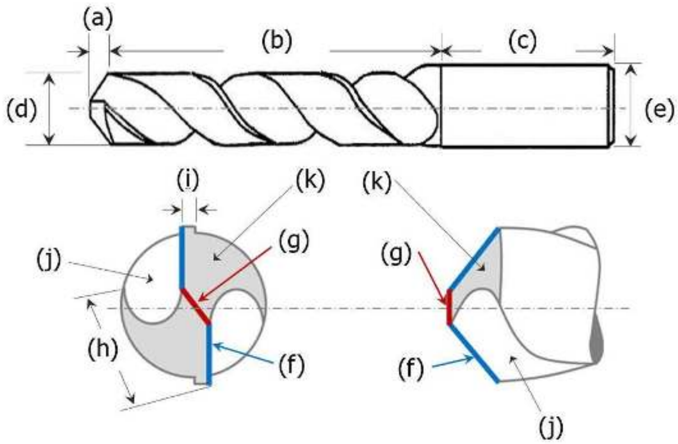


Source: J.E. Lee *et al.*, 2012. Modeling and Experimentation of Bone Drilling Forces. J of Biomechanics, 45(6), 1076-1083.

• Design of Experiments

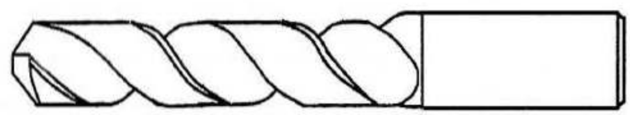


1. The figures show a twist drill in different views. Label the drill geometry features corresponding to (a) through (k).



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

(1) Helix angle
(2) Point angle




Manufacturing
Topic 12:
Milling Operations
Prof. J Lee

Objectives

- 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.

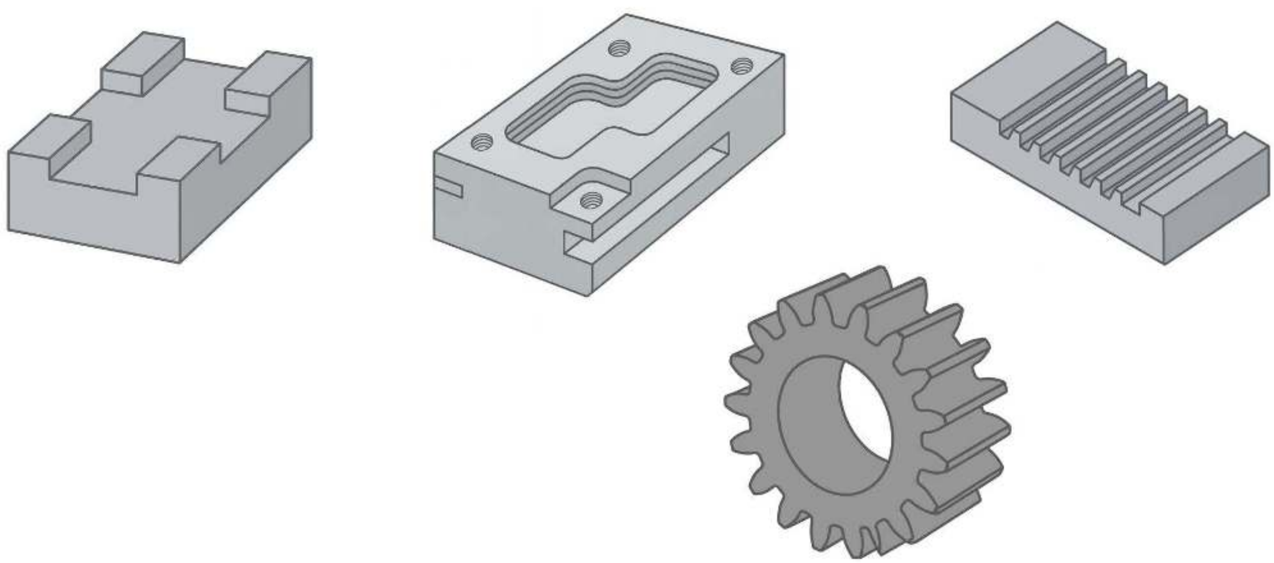
Milling

- **What**

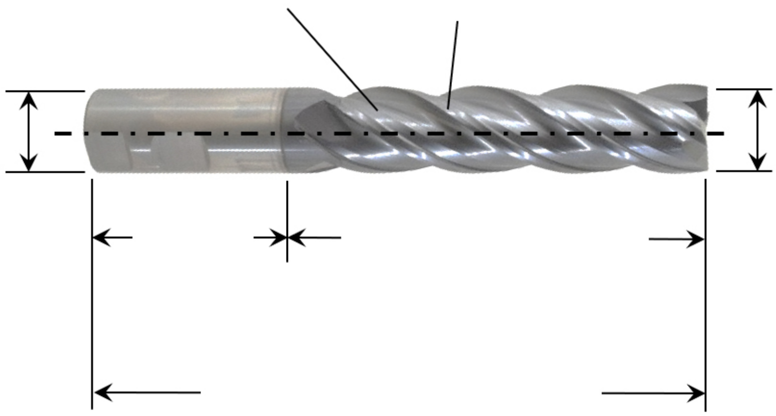
 - a material _______________ process using a ___________ cutter having cutting __________.

 - used to machine _______ surfaces; ___________; ________, etc.

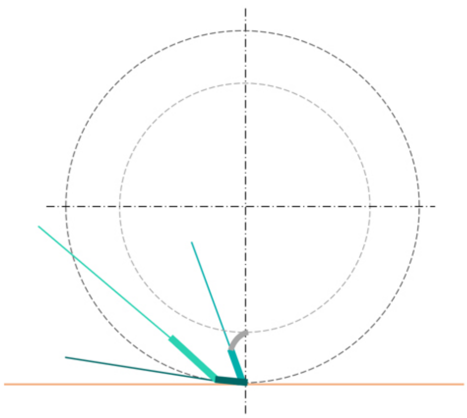
- **Typical Parts and Shapes by Milling Process**

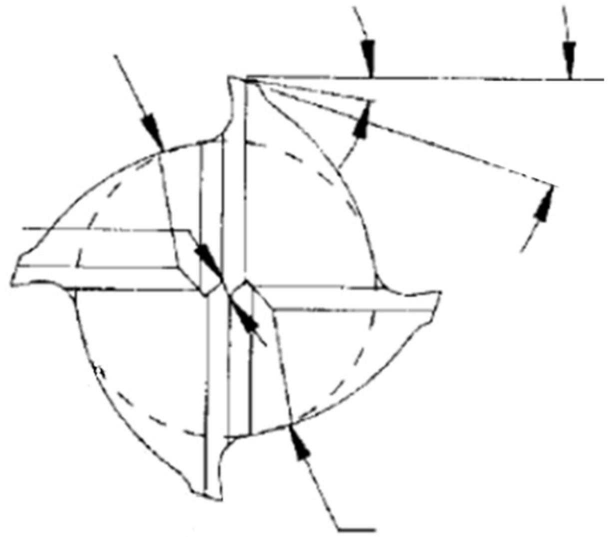


- **Tool**
  - ________________________
  - can be typically specified by ______, ___________ angle , _____ of ____________, material, coating, etc
- **Milling Cutter Geometry:**



- **Milling Cutter Geometry: Tip**





Milling Tool

• Tool - Milling Cutter

_______ ____ of _________: Pros _________ ___________

Cons _________ _______ ______________

" for _____________ material"

_____ ________ center-cutting

_________ flute center-cutting

_________ flute center-cutting

_________ flute center-cutting

_________ flute center-cutting

" provides ____________ ________ _____________"

_________ ____ of tooth: + _________ chip ejection

\- _______ tool rigidity

: The __________ will ___________________ engage and machine the workpiece.

- Milling is also called "_________________ _____________"

: ______ or more flutes provide a _________ finish and ________________ tool rigidity.

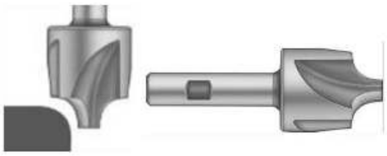
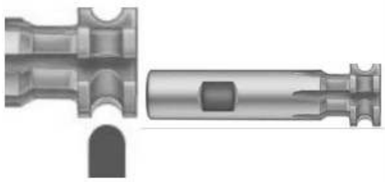
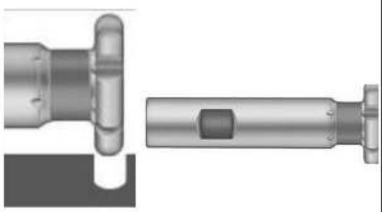
Milling Tool

• 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 ____________ ________

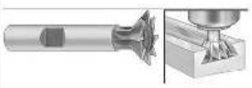
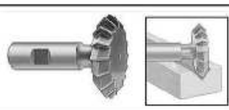
Milling Tool

• 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

Milling Tool

• Types of Milling Cutters

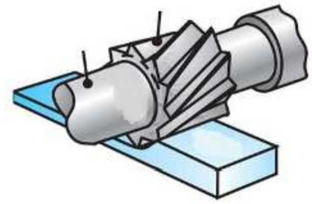
	__________ _______	: for ____________ cutting of large and _______ surfaces
	side and face cutter	: has cutting edges on the _____________ and ________ of the teeth : for cutting shoulders; __________
	slitting cutter	: for cutting a narrow slit into material : _____ used for removing lots of material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

- **Types of Milling Operations**

  - **w.r.t the Milling Cutter ______**
    - \- _____________ Milling (_______ Milling)
    - \- ________ Milling
  - **w.r.t the relation of the Cutter ____________ to the ________ Direction**
    - \- _____________ Milling (_____ Milling)
    - \- ________ Milling (_______ Milling)

Milling Operations

- **w.r.t the Milling ________ ________**



- ______________ Milling (________ Milling)

: the ______ of cutter rotation is ___ to the ______ surface

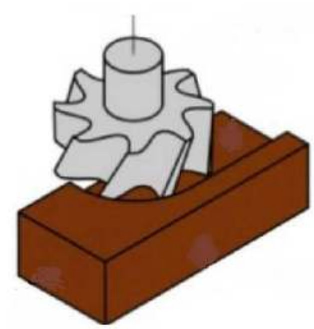
: the cutter _________ has a number of _________ along its circumference

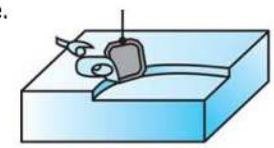
: each _________ acts like a __________- _________ cutting tool

: 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.





Milling Operations

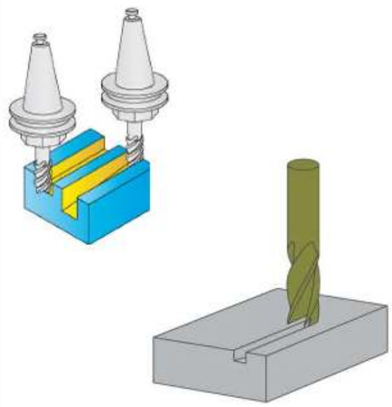
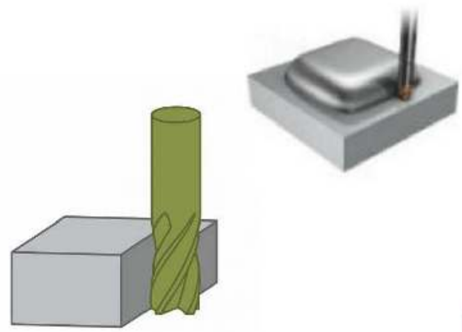
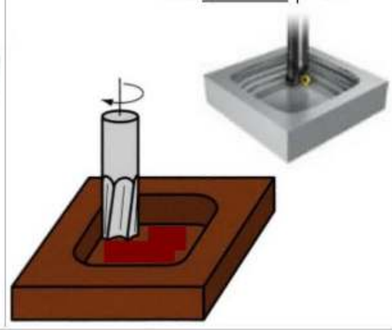
• **End Milling**

When Used?

: To produce both ______________ and ________ milling operations simultaneously.

: To produce ____________ , ____________ or ___________ surfaces

: commonly used for ____________ , _________ , ___________ , _________ milling

________ **Milling**	___________ **Milling**	________ **Milling**
	To cut _________ periphery of _______ part 	To mill __________ pockets into _______ parts 

Manufacturing | Prof. J Lee, Copyright.

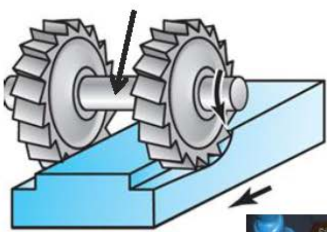
Milling Operations

- **Others**

____________ Milling

: ____ or more cutters are mounted on an __________

: To simultaneously machine _____ __________ surfaces



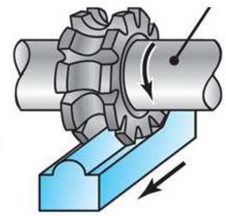
: _______________ milling

__________ Milling

: To produce ____________ surfaces or _____________

e.g. __________; ___________

______________ milling:

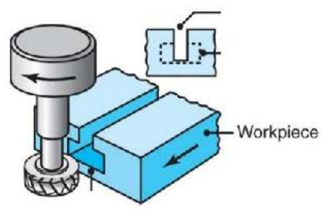


__________ Milling

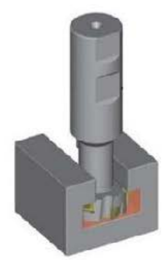
: ____ or ____ stages are required for ___-slots

(1) ______ _________ cutter for _______ slot

→ (2) __________ cutter



: ________ milling



Milling Operations

Topic 12 – 13

- **w.r.t the relation of the Cutter __________ to the ______ Direction**

- _____________ Milling (_____ Milling)

: The __________ rotates __________ the ________ direction.

: Tool ______ ________ at the beginning of the cut causing ________ **tool wear** and ___ **tool life.**

: **Chip thickness** starts from ______ and ___

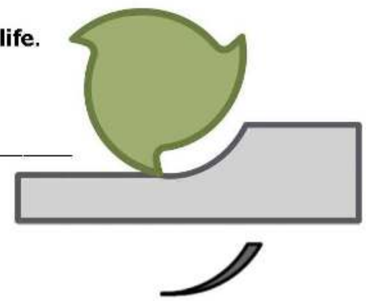
→ more ______ to diffuse ______ the ______ → workpiece _____________

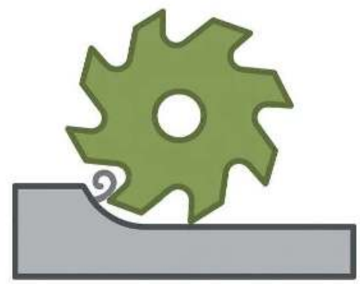
: Chips are carried ________ by the tooth and fall in front of cutter

→ __________ surface finish ; ______________ chips

: ________ **forces** created tend to _______ the workpiece

→ _______ expansive work __________ are required.





Milling Operations

• **w.r.t the relation of the Cutter __________ to the _______ Direction**

- _________ Milling (________ Milling)

: The __________ rotates ____ the ________ direction.

: _______ **tool rubbing** can ___ **tool life.**

: **Chip thickness** starts from _______ and ___

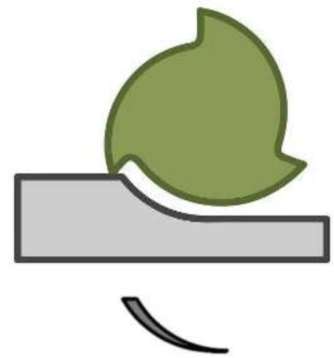
→ **heat generated** will more likely transfer to the _______ instead of the _______.

: Chips are removed _________ the cutter

→ ____ the chance of chip re-cutting

: _______________ **forces** created _______ to ________ the _______

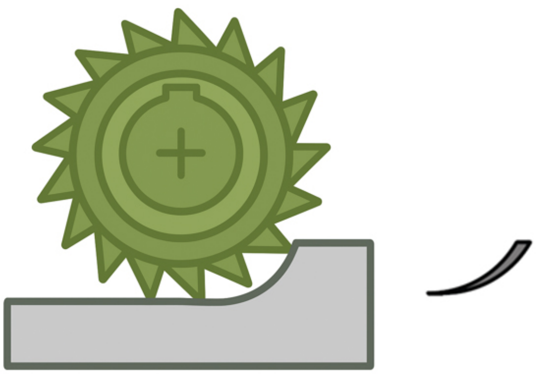
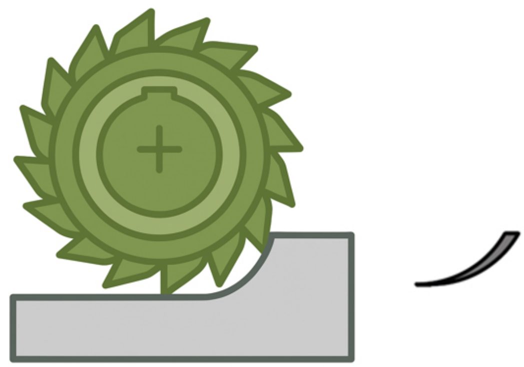
→ ________ complex work **holdings** are required.



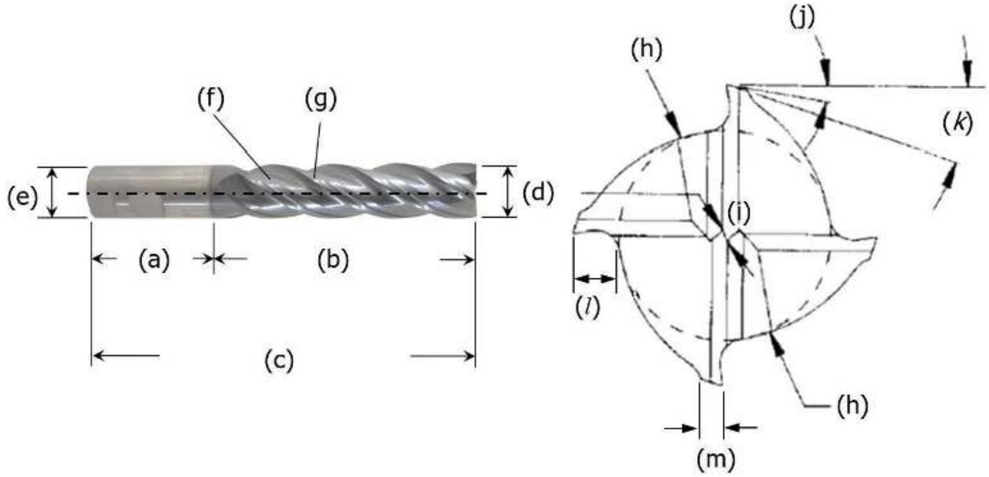
Milling Operations

- **Summary**

w.r.t the relation of the cutter _________ to the ______ direction

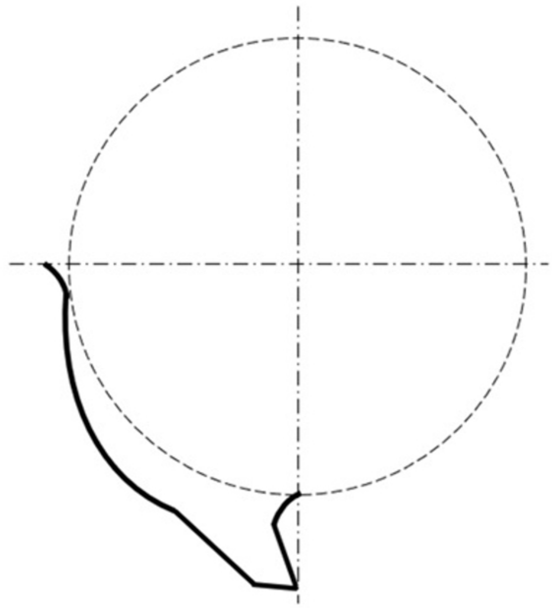
_____________ Milling (________ Milling)	_____________ Milling (________ Milling)
	
- undeformed chip thickness: chip thickness begins at (zero or max) and ____. - chips are carried _______ by the tooth and fall in front of the cutter - It can create (better or worse) surface finish and _____ re-cutting chips. - (upward or downward) forces created tending to ________ the workpiece.	- undeformed chip thickness: chip thickness begins at (zero or max) and ____. - chips are removed _________ the cutter - It can create (better or worse) surface finish and _____ re-cutting chips. - (upward or downward) forces created tending to __________ the workpiece.

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



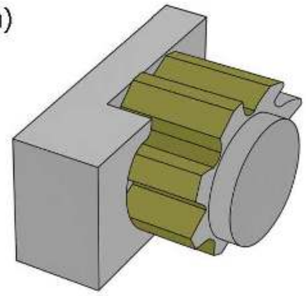
2. The figure shows one tooth of a four-flute milling cutter in cross-sectional tip view. Label the following geometric features on the figure:

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

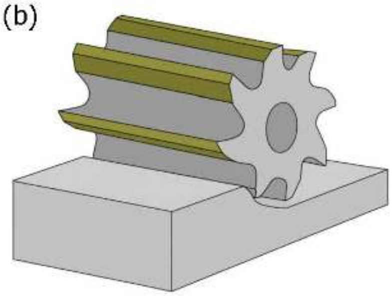


3. Identify the type of milling operation illustrated in the figure with respect to the milling cutter types.

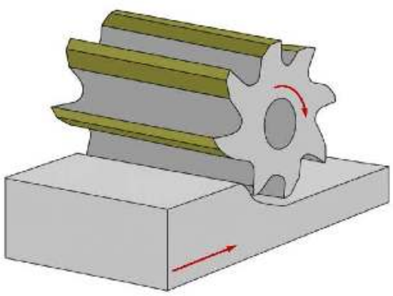
(a)



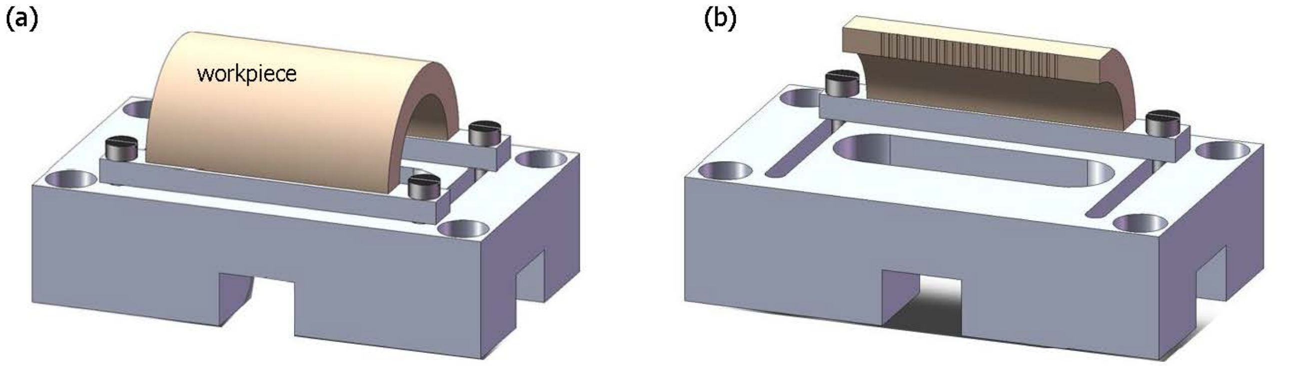
(b)



4. (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.



5. 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.



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

Index

D

Glossary

Sample Word 1 | Sample Definition 1

Detailed Licensing

Overview

Title: Manufacturing Processes

Webpages: 21

Applicable Restrictions: Noncommercial

All licenses found:

- CC BY-NC-SA 4.0: 90.5% (19 pages)
- Undeclared: 9.5% (2 pages)

By Page

- Manufacturing Processes - *CC BY-NC-SA 4.0*
  - Front Matter - *CC BY-NC-SA 4.0*
    - TitlePage - *CC BY-NC-SA 4.0*
    - InfoPage - *CC BY-NC-SA 4.0*
    - Table of Contents - *Undeclared*
    - Licensing - *CC BY-NC-SA 4.0*
  - Topic 01: Introduction to Manufacturing Processes - *CC BY-NC-SA 4.0*
  - Topic 02: Engineering Drawing Review - Dimensioning - *CC BY-NC-SA 4.0*
  - Topic 03. Dimensioning and Tolerancing - *CC BY-NC-SA 4.0*
  - Topic 04. Fundamentals of Machining and Chip Morphology - *CC BY-NC-SA 4.0*
  - Topic 05. Cutting Mechanics - *CC BY-NC-SA 4.0*
  - Topic 06. Plastic Deformation in Cutting - *CC BY-NC-SA 4.0*
  - Topic 07. Forces in Cutting - *CC BY-NC-SA 4.0*
  - Topic 08. Mechanical and Thermal Energy in Machining - *CC BY-NC-SA 4.0*
  - Topic 11. Drilling Operations - *CC BY-NC-SA 4.0*
  - Topic 12. Milling Operations - *CC BY-NC-SA 4.0*
  - Back Matter - *CC BY-NC-SA 4.0*
    - Index - *CC BY-NC-SA 4.0*
    - Glossary - *CC BY-NC-SA 4.0*
    - Detailed Licensing - *CC BY-NC-SA 4.0*
    - Detailed Licensing - *Undeclared*

Detailed Licensing

Overview

Title: Manufacturing Processes

Webpages: 21

Applicable Restrictions: Noncommercial

All licenses found:

- CC BY-NC-SA 4.0: 90.5% (19 pages)
- Undeclared: 9.5% (2 pages)

By Page

- Manufacturing Processes - *CC BY-NC-SA 4.0*
  - Front Matter - *CC BY-NC-SA 4.0*
    - TitlePage - *CC BY-NC-SA 4.0*
    - InfoPage - *CC BY-NC-SA 4.0*
    - Table of Contents - *Undeclared*
    - Licensing - *CC BY-NC-SA 4.0*
  - Topic 01: Introduction to Manufacturing Processes - *CC BY-NC-SA 4.0*
  - Topic 02: Engineering Drawing Review - Dimensioning - *CC BY-NC-SA 4.0*
  - Topic 03. Dimensioning and Tolerancing - *CC BY-NC-SA 4.0*
  - Topic 04. Fundamentals of Machining and Chip Morphology - *CC BY-NC-SA 4.0*
  - Topic 05. Cutting Mechanics - *CC BY-NC-SA 4.0*
  - Topic 06. Plastic Deformation in Cutting - *CC BY-NC-SA 4.0*
  - Topic 07. Forces in Cutting - *CC BY-NC-SA 4.0*
  - Topic 08. Mechanical and Thermal Energy in Machining - *CC BY-NC-SA 4.0*
  - Topic 11. Drilling Operations - *CC BY-NC-SA 4.0*
  - Topic 12. Milling Operations - *CC BY-NC-SA 4.0*
  - Back Matter - *CC BY-NC-SA 4.0*
    - Index - *CC BY-NC-SA 4.0*
    - Glossary - *CC BY-NC-SA 4.0*
    - Detailed Licensing - *CC BY-NC-SA 4.0*
    - Detailed Licensing - *Undeclared*