

ENR212 Lecture 8 Slides and Notes

Slide 1

Manufacturing Processes
Lecture 8

University of
South Australia

THEORY OF METAL MACHINING

Dr. Jun Ma

1. Overview of Machining Technology
2. Theory of Chip Formation in Metal Machining
3. Force Relationships and the Merchant Equation
4. Power and Energy Relationships in Machining
5. Cutting Temperature

Hello everyone, and welcome to Lecture Summary 8 for Manufacturing Processes. (This lecture works through material covered in Chap 21 of the textbook.)

In this lecture, we will introduce the theory of metal machining, and address the following topics:

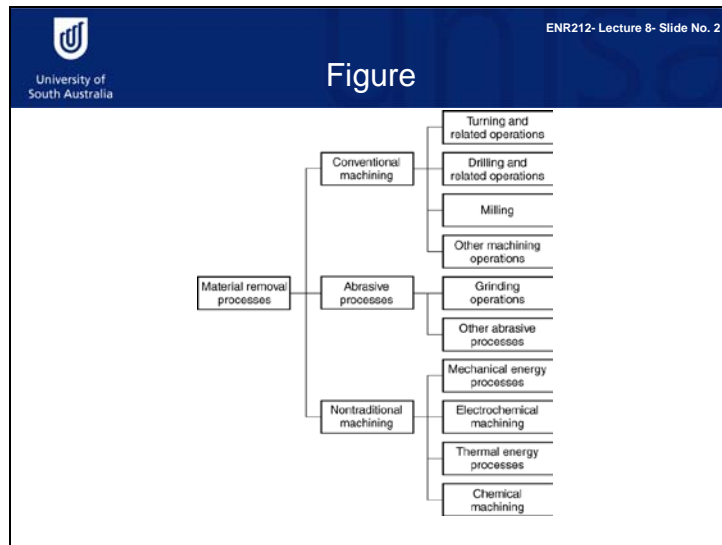
Overview of Machining Technology.

Theory of Chip Formation in Metal Machining.

Force Relationships and the Merchant Equation.

Power and Energy Relationships in Machining.

Cutting Temperature.

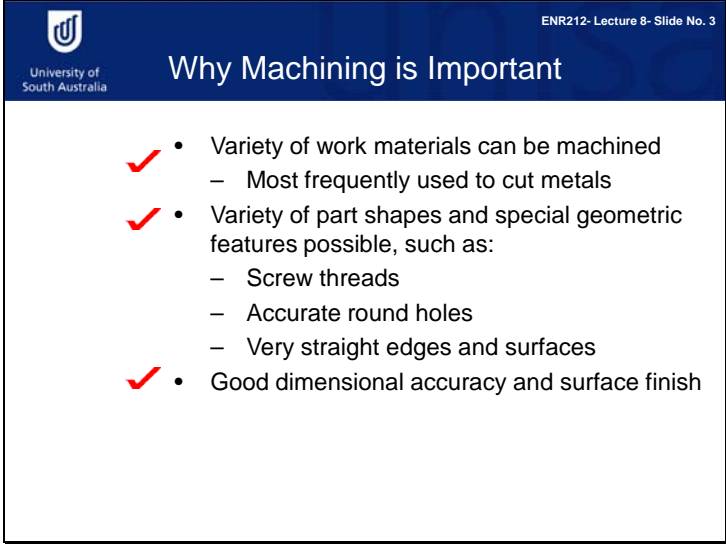


The Shaping operations include material removal processes. The common feature of these processes is that they remove material from a starting workpiece so that the remaining part has the desired geometry. Material removal processes include machining processes, abrasive processes and nontraditional machining processes.

*In machining processes, materials are removed by a sharp cutting tool (for example, through turning, milling and drilling).

*In abrasive processes, materials are removed by hard, abrasive particles (for example, through grinding).

* Nontraditional processes use various energy forms other than sharp cutting tools to remove materials, such as high velocity streams of abrasives or fluids.



The slide features a dark blue header with the University of South Australia logo on the left and the text 'ENR212- Lecture 8- Slide No. 3' on the right. The main title 'Why Machining is Important' is centered in the header. The content area is white with a black border and contains a bulleted list of three main points, each preceded by a red checkmark. The first point is 'Variety of work materials can be machined', with a sub-point 'Most frequently used to cut metals'. The second point is 'Variety of part shapes and special geometric features possible, such as:', with sub-points 'Screw threads', 'Accurate round holes', and 'Very straight edges and surfaces'. The third point is 'Good dimensional accuracy and surface finish'.

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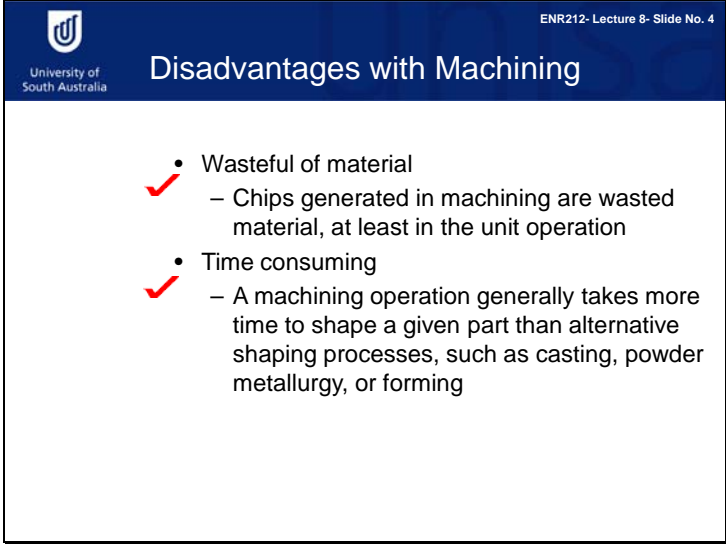
Why Machining is Important

- ✓ • Variety of work materials can be machined
 - Most frequently used to cut metals
- ✓ • Variety of part shapes and special geometric features possible, such as:
 - Screw threads
 - Accurate round holes
 - Very straight edges and surfaces
- ✓ • Good dimensional accuracy and surface finish

Machining is important because it has three main strengths. It can be applied to a wide variety of work materials, including metals, plastics, thermosets, composites and even ceramics. In fact, it is the most frequently used method to cut materials. It can be used to create any special geometries, such as screw threads. Finally, it can produce good dimensional accuracy and surface finish.

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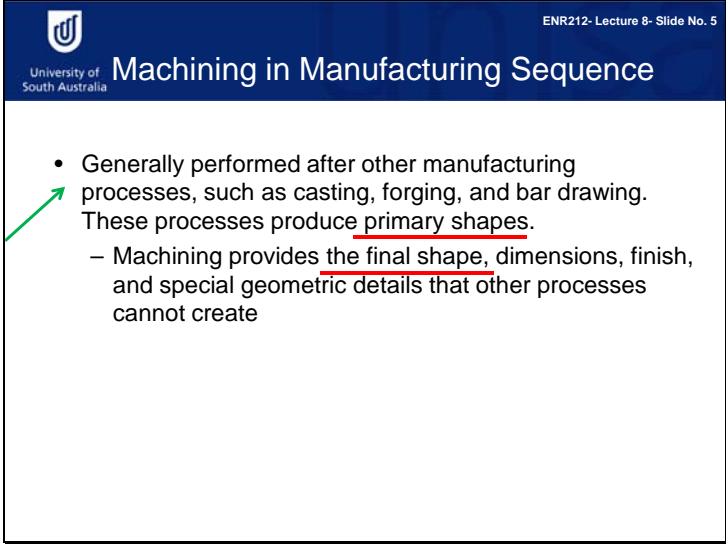
Disadvantages with Machining

- ✓ • Wasteful of material
 - Chips generated in machining are wasted material, at least in the unit operation
- ✓ • Time consuming
 - A machining operation generally takes more time to shape a given part than alternative shaping processes, such as casting, powder metallurgy, or forming

However, machining has two weaknesses. First, it is inherently wasteful of materials, because it removes materials from a starting workpiece. Second, a machining operation generally takes more time to shape a given part than alternative shaping processes such as casting or moulding.

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The slide features a dark blue header with the University of South Australia logo on the left and the text 'ENR212- Lecture 8- Slide No. 5' on the right. The main title 'Machining in Manufacturing Sequence' is centered in the header. The content area is white with a black border. A green arrow points from the left edge to the first bullet point. The text 'primary shapes' and 'the final shape' are underlined in red.

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Machining in Manufacturing Sequence

- Generally performed after other manufacturing processes, such as casting, forging, and bar drawing. These processes produce primary shapes.
 - Machining provides the final shape, dimensions, finish, and special geometric details that other processes cannot create

The weaknesses of machining can be overcome to some extent if the machining is performed after other manufacturing processes, such as casting or bulk deformation. These processes create the primary shapes of the starting workpiece, and these primary shapes are subsequently machined to produce the final geometry, dimensions, and finish.

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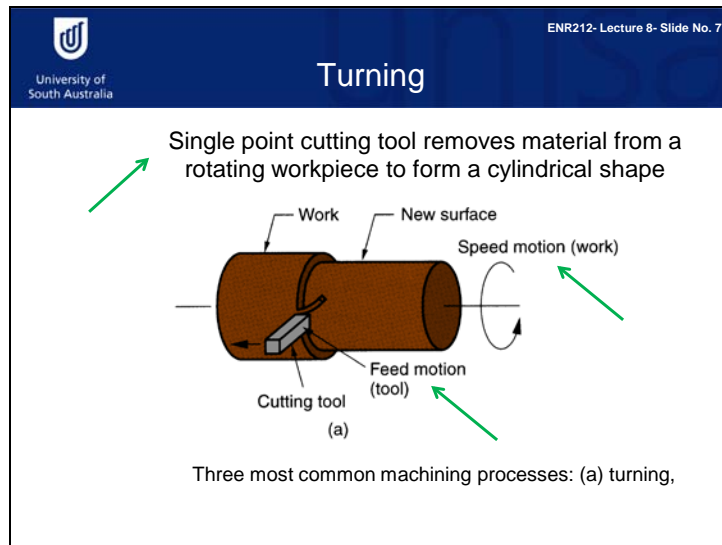
Machining Operations

- Most important machining operations:
 - Turning
 - Drilling
 - Milling
- Other machining operations:
 - Shaping and planing
 - Broaching
 - Sawing

There are three most commonly used machining operations. They are turning, drilling and milling. However, other machining operations include shaping and planing, broaching, and sawing.

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In turning, a cutting tool with a single cutting edge is used to remove material from a rotating workpiece to generate a cylindrical shape. There are two types of relative motion. The first is speed motion provided by the rotating workpiece, and the second is feed motion, achieved by moving the cutting tool slowly in a direction parallel to the axis of rotation of the workpiece. This figure shows you a typical turning operation.

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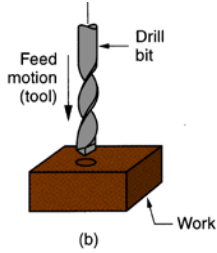
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Drilling

Drilling is usually performed with a rotating cylindrical tool that has two cutting edges on its working end. The tool is called a drill or drill bit. The rotating drill feeds into the stationary workpiece to form a hole whose diameter is equal to the drill diameter. Drilling is customarily performed on a drill press.

(b) drilling,



The diagram illustrates the drilling process. A grey drill bit is shown being fed into a brown rectangular workpiece. A downward arrow labeled 'Feed motion (tool)' indicates the direction of the drill's movement. The workpiece is labeled 'Work' and the drill bit is labeled 'Drill bit'. The diagram is labeled '(b)' at the bottom.

Drilling is a machining process which is usually performed with a rotating cylindrical tool that has two cutting edges on its working end. The tool is called a drill or drill bit. The rotating drill feeds into the stationary workpiece to form a hole whose diameter is equal to the drill diameter. Drilling is customarily performed on a drill press. This figure shows you a drilling process.

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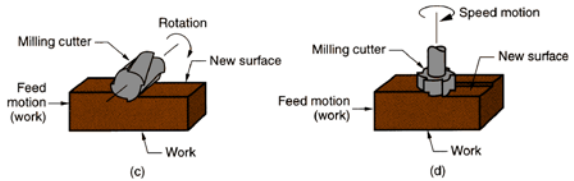
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Milling

Rotating multiple-cutting-edge tool is moved slowly relative to the material to generate a plane or straight surface.

Two forms: peripheral milling and face milling



(c) peripheral milling, and (d) face milling.

The diagram consists of two parts, (c) and (d). Part (c) shows a cylindrical milling cutter rotating around its vertical axis, indicated by a curved arrow labeled 'Rotation'. The cutter is moving along the length of a rectangular workpiece, indicated by an arrow labeled 'Feed motion (work)'. The top surface of the workpiece is labeled 'New surface'. Part (d) shows a cylindrical milling cutter rotating around its vertical axis, indicated by a curved arrow labeled 'Speed motion'. The cutter is moving across the width of a rectangular workpiece, indicated by an arrow labeled 'Feed motion (work)'. The top surface of the workpiece is labeled 'New surface'. Both diagrams label the 'Milling cutter' and 'Work'.

In milling, a rotating tool with multiple cutting edges is moved slowly across the material to generate a plane or straight surface. There are two forms of milling, peripheral milling and face milling.

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Cutting Tool Classification

1. Single-Point Tools
 - One dominant cutting edge
 - Point is usually rounded to form a nose radius
 - Turning uses single point tools
2. Multiple Cutting Edge Tools
 - More than one cutting edge
 - Motion relative to work achieved by rotating
 - Drilling and milling use rotating multiple cutting edge tools

(a) (b)

There are two basic classifications of cutting tools, single-point and multiple-cutting-edge. A single-point tool has one cutting edge and is used for operations such as turning. A multiple-cutting-edge tool has more than one cutting edge and usually achieves its motion relative to the workpiece by rotating. These tools are used for drilling and milling operations.

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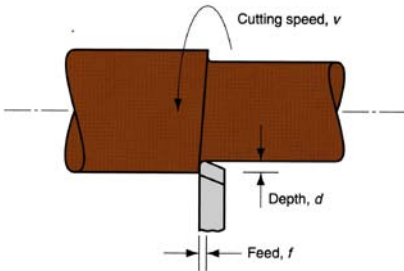
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Cutting Conditions in Turning

- Three dimensions of a machining process:
 - ✓ - Cutting speed v – primary motion
 - ✓ - Feed f – secondary motion
 - ✓ - Depth of cut d – penetration of tool below original work surface

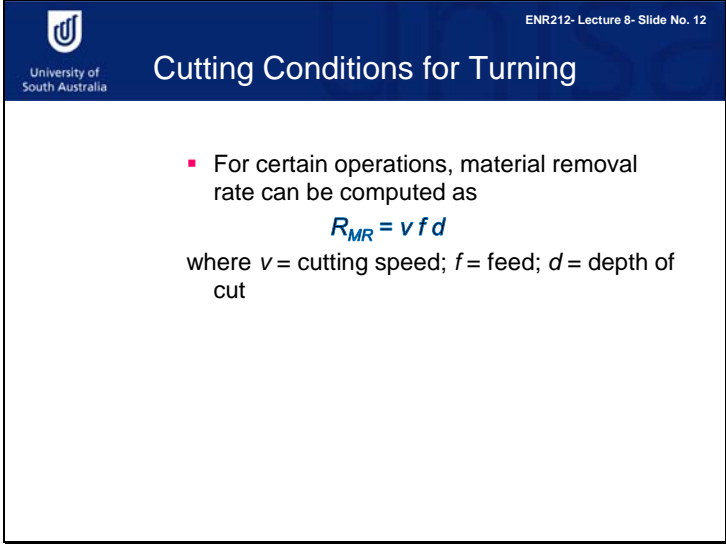


The diagram illustrates a turning operation on a lathe. A cylindrical workpiece is shown rotating, with a curved arrow labeled 'Cutting speed, v ' indicating the primary motion. A cutting tool is positioned against the workpiece, moving along its length, with a horizontal arrow labeled 'Feed, f ' indicating the secondary motion. The depth of the cut is shown as the distance the tool has penetrated below the original surface, indicated by a vertical arrow labeled 'Depth, d '.

We have looked at two types of relative motions in a turning operation, speed motion and feed motion. This slide shows you the three dimensions which must be considered in a machining process. They are the cutting motion, the feed motion and the depth of the cut.

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The slide features a dark blue header with the University of South Australia logo on the left and the text 'ENR212- Lecture 8- Slide No. 12' on the right. The main title 'Cutting Conditions for Turning' is centered in the header. The body of the slide contains a bulleted point and an equation.


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Cutting Conditions for Turning

- For certain operations, material removal rate can be computed as
$$R_{MR} = v f d$$
where v = cutting speed; f = feed; d = depth of cut

For most single-point tool operations, the material removal rate can be calculated using this equation. The Material Removal Rate is equal to the cutting speed multiplied by the feed multiplied by the depth of the cut.

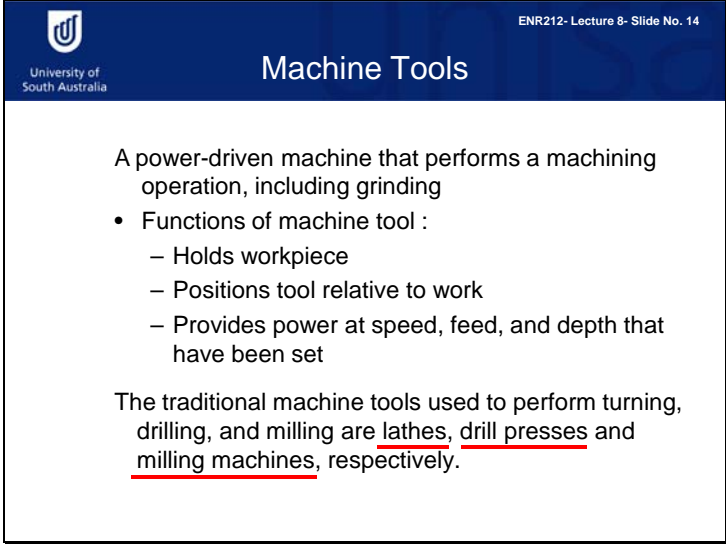
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Roughing vs. Finishing

In production, several roughing cuts are usually taken on the part, followed by one or two finishing cuts

- Roughing cuts - remove large amounts of material from starting workpiece
 - Creates shape close to desired geometry, but leaves some material for finish cutting
 - High feeds and depths, low speeds
- Finishing cuts - complete part geometry
 - Final dimensions, tolerances, and finish
 - Low feeds and depths, high cutting speeds

Machining operations are usually divided into two categories, depending on their purpose and the cutting conditions. Roughing cuts remove large amounts of material from the starting workpiece as rapidly as possible, in order to produce a shape close to the desired form, but they leave some material on the piece for a subsequent finishing operation. Roughing cuts are characterised by low speeds, high feed and large depth. Finishing cuts are used to complete the part and achieve the final dimensions, tolerances, and surface finish. They are characterised by low feeds and depth, and high cutting speeds.



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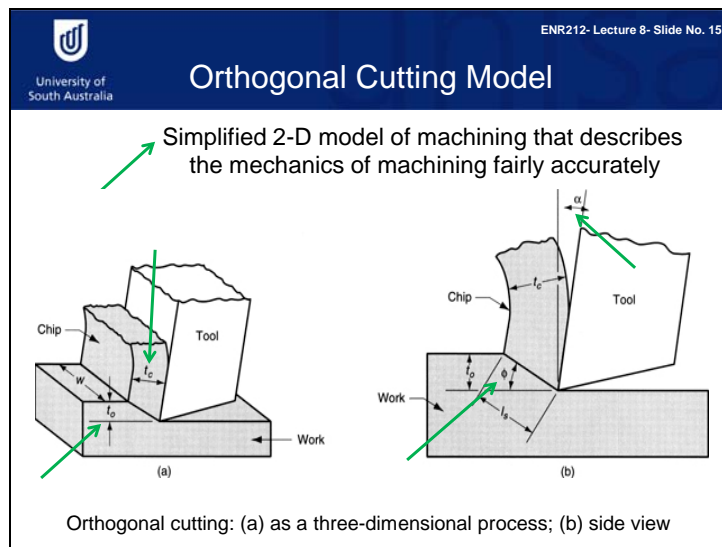
Machine Tools

A power-driven machine that performs a machining operation, including grinding


- Functions of machine tool :
 - Holds workpiece
 - Positions tool relative to work
 - Provides power at speed, feed, and depth that have been set

The traditional machine tools used to perform turning, drilling, and milling are lathes, drill presses and milling machines, respectively.

Machine tools are just the machines that accomplish the material removal processes. The machine tool for turning is called a lathe, and the machine tool for drilling is called a drill press. The machine tool for milling is called a milling machine.



The geometry of most workpieces in machining is complex. To describe the mechanics of the process, a simple two-dimensional orthogonal cutting model has been introduced. This model has only two dimensions which play an active role in the analysis. The cutting edge is perpendicular to the direction of the cutting speed, and the two elements of tool geometry are rake and shear plane angle. In this figure, as the tool is forced into the material, a chip is formed by shear deformation along a plane called the shear plane. In this case, the shear angle is an angle between the shear plane and the horizontal plane. The rake angle is an angle between the tool front plane and the vertical plane. Chips are produced in machining operations. The T_o represents the original chip thickness, and the T_c represents the thickness of a cut chip.

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Chip Thickness Ratio

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

where r = *chip thickness ratio*; t_o = thickness of the chip prior to chip formation; and t_c = chip thickness after separation

- Chip thickness after cut always greater than before, so chip ratio always less than 1.0

To calculate the chip thickness ratio, divide the chip thickness before chip formation by the chip thickness after separation. The thickness after the cutting is always greater than the thickness before, so the chip ratio is always less than 1.0.

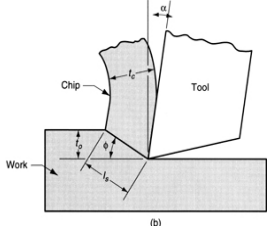
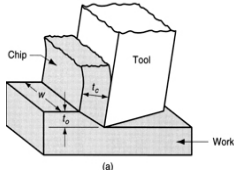
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Determining Shear Plane Angle

- Based on the geometric parameters of the orthogonal model, the shear plane angle ϕ can be determined as:

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


where r = chip ratio, and α = rake angle



In a chip formation process, the shear plane angle is the angle between the horizontal plane and the shear plane. It is calculated by this equation: Tan angle is equal to chip ratio cosine rake angle divided by 1 minus chip ratio sine rake angle.

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Shear Strain

Shear strain in machining can be computed from the following equation:

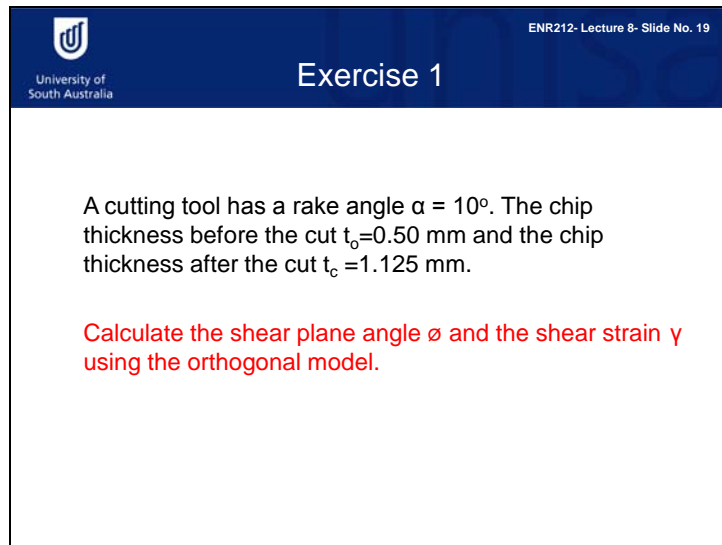
$$\gamma = \tan(\phi - \alpha) + \cos \phi$$

where γ = shear strain, ϕ = shear plane angle, and α = rake angle of cutting tool

We have looked at strain in previous lectures. Strain is relative to the deformation of a material. Shear strain is relative to the deformation of material in shearing. The shear strain in machining is calculated by \tan shear plane angle minus rake angle, plus \cos shear plane angle.

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The slide features a dark blue header with the University of South Australia logo on the left and the text 'ENR212- Lecture 8- Slide No. 19' on the right. The title 'Exercise 1' is centered in the header. The main content area is white and contains a problem statement and a red instruction.

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Exercise 1

A cutting tool has a rake angle $\alpha = 10^\circ$. The chip thickness before the cut $t_o = 0.50$ mm and the chip thickness after the cut $t_c = 1.125$ mm.

Calculate the shear plane angle ϕ and the shear strain γ using the orthogonal model.

Now it is the time to use the equations you have learnt to solve a practical problem. Pause the presentation here and work out this problem. An important task in manufacturing is to use theories to estimate and predict cutting forces, so that you can choose appropriate facilities and tools for your manufacturing processes. Suppose a cutting tool has a rake angle of 10° . The chip thickness before the cut is 0.50 mm and the chip thickness after the cut is 1.125 mm. Calculate the shear plane angle ϕ and the shear strain γ using the orthogonal model. The solution is on the next slide. (Note this kind of question will appear in the assessment activities for this unit.)


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Exercise 1 Solution

- rake angle $\alpha = 10^\circ$.
- chip thickness before the cut $t_o = 0.50$ mm
- chip thickness after the cut $t_c = 1.125$ mm.

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

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

Calculations

$$r = \frac{0.50\text{mm}}{1.125\text{mm}} = 0.444$$

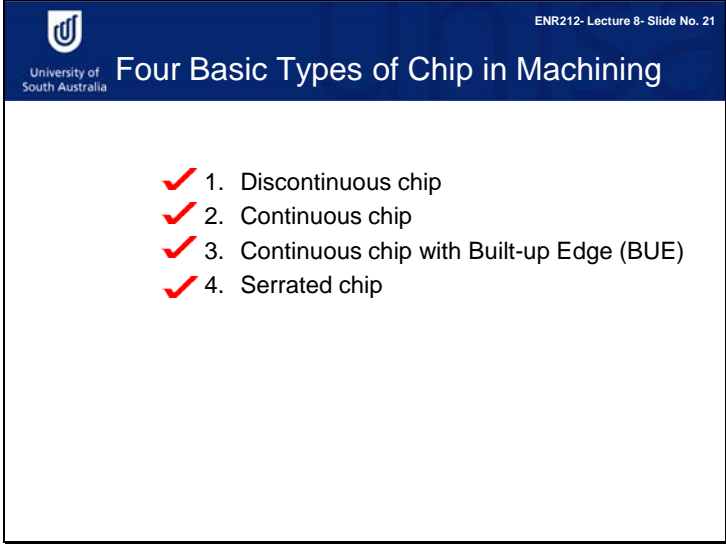
$$\tan \phi = \frac{0.444 \cos 10}{1 - 0.444 \sin 10} = 0.4738 \quad \phi = 25.4^\circ$$

$$\gamma = \tan(25.4 - 10) + \cot 25.4 = 0.275 + 2.111 = 2.386$$

First of all, you need to find the chip thickness ratio, by dividing the chip thickness before chip formation by the chip thickness after separation, which gives you a chip thickness ratio of 0.444. Now let's look at the shear plane angle. You should have worked this out by using the equation Tan angle is equal to chip ratio cosine rake angle divided by 1 minus chip ratio sine rake angle. The answer for this scenario is that Tan angle is 0.4738, which means that the shear plane angle is 25.4 degrees. Finally, calculate the shear strain using the formula tan shear plane angle minus rake angle, plus cosine shear plane angle. The answer is 2.386.

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Four Basic Types of Chip in Machining

- ✓ 1. Discontinuous chip
- ✓ 2. Continuous chip
- ✓ 3. Continuous chip with Built-up Edge (BUE)
- ✓ 4. Serrated chip

A chip is produced by shear deformation when a single-edge cutting tool is forced into a rotating part. Depending on the type of material being machined and the cutting conditions of the operation, four basic types of chips can be distinguished: discontinuous chip, continuous chip, continuous chip with a built-up edge, and serrated chip.

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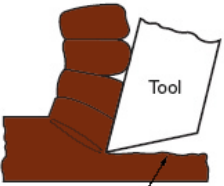
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Discontinuous Chip

- ✓ Brittle work materials
- ✓ Low cutting speeds
- ✓ High tool-chip friction
- ✓ Large feed and depth of cut

Discontinuous chip



Irregular surface due to chip discontinuities (a)

Discontinuous chips are produced by brittle materials, such as cast iron, at low cutting speeds. High tool-chip friction and large feed and depth of cut can cause this type of chip to form.

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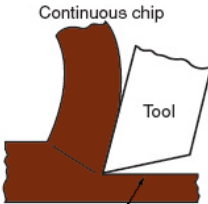
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Continuous Chip

- ✓ • Ductile work materials
- ✓ • High cutting speeds
- ✓ • Small feeds and depths
- ✓ • Sharp cutting edge
- ✓ • Low tool-chip friction



The diagram shows a cross-section of a cutting process. A tool is shown cutting a workpiece, forming a continuous chip. The chip is labeled 'Continuous chip' and the tool is labeled 'Tool'. The surface of the workpiece is labeled 'Good finish typical'.

(b)

Continuous chips are formed by ductile materials at high speeds with relatively small feeds and depth. They are caused by sharp cutting edges on the tools and low tool-chip friction.

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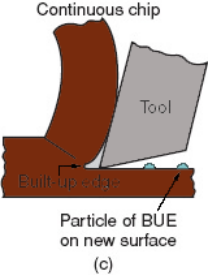
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Continuous chip with build-up edge

- ✓ • Ductile materials
- ✓ • Low-to-medium cutting speeds
- ✓ • Tool-chip friction causes portions of chip to adhere to rake face
- ✓ • BUE forms, then breaks off, cyclically



Continuous chip

Tool

Built-up edge

Particle of BUE on new surface (c)

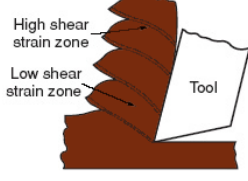
When ductile materials are being machined at low-to-medium cutting speeds, friction between the tool and the chip tends to cause portions of the work material to adhere to the rake face of the tool near the cutting edge. This can form a continuous chip with a built up edge (BUE). The formation of a BUE is cyclical; it forms and grows, then becomes unstable and breaks off.

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Serrated Chip

- Semicontinuous - saw-tooth appearance
- Cyclical chip forms with alternating high shear strain then low shear strain
- Associated with difficult-to-machine metals at high cutting speeds



The diagram illustrates a serrated chip being removed by a tool. The chip has a saw-tooth appearance. Labels indicate 'High shear strain zone' and 'Low shear strain zone' alternating along the length of the chip. The tool is labeled 'Tool'.

(d)

(d) serrated.

Serrated chips possess a saw-tooth appearance. They are the result of alternating high shear strain and then low shear strain. This type of chip is most closely associated with certain difficult-to-machine metals being machined at high cutting speeds, such as titanium alloys.

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Forces Acting on Chip

- Friction force F and Normal force to friction N
- Shear force F_s and Normal force to shear F_n

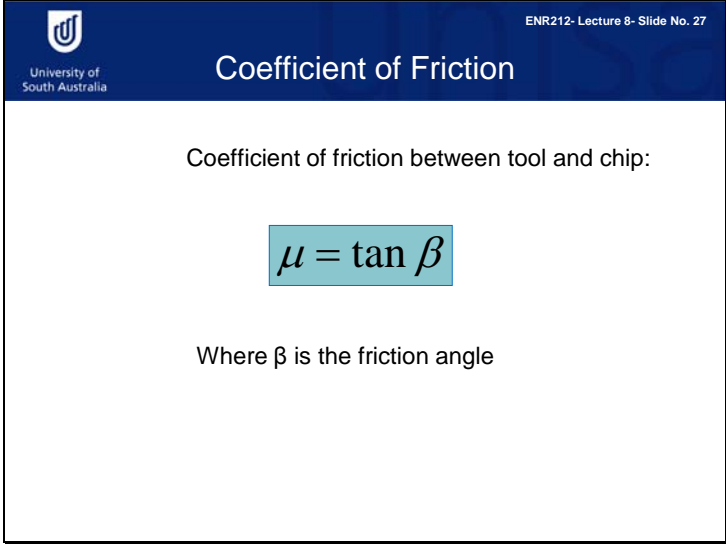
Forces in metal cutting: (a) forces acting on the chip in orthogonal cutting

(a)

As shown in this figure, there are four forces in total in a typical machining process. The friction force is the frictional force which resists the flow of the chip along the rake face of the tool. The normal force to friction is perpendicular to the friction force. The shear force is the force that causes shear deformation to occur in the shear plane, and the normal force to shear is perpendicular to the shear force.

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The slide features a dark blue header with the University of South Australia logo on the left and the text "ENR212- Lecture 8- Slide No. 27" on the right. The main title "Coefficient of Friction" is centered in the header. Below the header, the text "Coefficient of friction between tool and chip:" is centered. The equation $\mu = \tan \beta$ is displayed in a light blue box, centered on the slide. Below the equation, the text "Where β is the friction angle" is centered.

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Coefficient of Friction

Coefficient of friction between tool and chip:

$$\mu = \tan \beta$$

Where β is the friction angle

The friction between tool and chip is important. The coefficient of friction between the tool and chip is tan friction angle.

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Shear Stress

Shear stress acting along the shear plane:

$$S = \frac{F_s}{A_s}$$

where A_s = area of the shear plane

$$A_s = \frac{t_o w}{\sin \phi}$$

t_o : original chip thickness (cut depth); w : width (feed)

Shear stress = shear strength of work material during cutting

In past lectures, we have looked at what stress and engineering stress are. Stress is equal to the load divided by the original cross-sectional area. So, what is shear stress? Shear stress is defined as a stress acting along the shear plane. Shear stress is equal to the load divided by the area of the shear plane.

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Cutting Force and Thrust Force

- F , N , F_s , and F_n cannot be directly measured
- Forces acting on the tool that can be measured:
 - Cutting force F_c and Thrust force F_t

(a) Forces acting on the chip that cannot be measured

(b) Forces acting on the tool that can be measured

When a cutting tool is forced into a working material, two forces are needed, and these are measurable. The cutting force is in the direction of cutting, the same direction as the cutting speed. The thrust force is perpendicular to the cutting force and is associated with the chip thickness before the cut.

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Forces in Metal Cutting

- Equations can be derived to relate the forces that cannot be measured to the forces that can be measured:
$$F = F_c \sin\alpha + F_t \cos\alpha$$
$$N = F_c \cos\alpha - F_t \sin\alpha$$
$$F_s = F_c \cos\phi - F_t \sin\phi$$
$$F_n = F_c \sin\phi + F_t \cos\phi$$
- Based on these calculated force, shear stress and coefficient of friction can be determined

Cutting force and thrust force are used to calculate shear force, friction force, and normal force to friction, by these four equations.

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Exercise 2


A cutting tool has a rake angle $\alpha = 10^\circ$. The chip thickness before the cut is 0.50 mm and the chip thickness after the cut is 1.125 mm. The shear plane angle is 25.4° . The cutting force is 1559 N and the thrust force is 1271N. The width is 3.0mm.

Determine the shear strength of the work materials (that is, work out the shear force and shear stress).

Now pause this presentation and use what you have learnt from the last few slides to solve this question. The solution is on the next slide.

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Exercise 2 Solution

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- rake angle $\alpha = 10^\circ$.
- chip thickness before the cut $t_c = 0.50$ mm
- chip thickness after the cut $t_c = 1.125$ mm
- shear plane angle $\phi = 25.4^\circ$
- A_s = area of the shear plane
- shear plane angle $\phi = 25.4^\circ$
- cutting force $F_c = 1559$ N
- thrust force $F_t = 1271$ N.
- width $w = 3.0$ mm.

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

$$A_s = \frac{t_c w}{\sin\phi}$$

$$S = \frac{F_s}{A_s}$$

Calculations

$$F_s = (1559N)\cos25.4^\circ - (1271N)\sin25.4^\circ = 863N$$
$$A_s = \frac{(0.5mm)(3.0mm)}{\sin25.4^\circ} = 3.497mm^2 \quad S = \frac{F_s}{A_s} = \frac{863N}{3.497mm^2} = 247MPa$$

To do this, we need to determine the shear force F_s and the shear stress S . You can see the three equations which you need, and the actual calculations, in this slide.

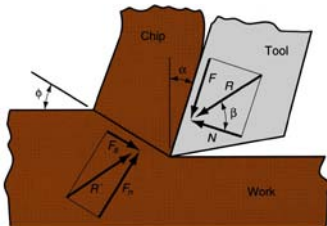
The shear force F_s equals the cutting force \cos shear plane angle minus the thrust force \sin shear plane angle, which equals 863 Newtons. To work out the shear stress, we need to know the shear plane area, which is the chip thickness prior to cutting multiplied by the width, all divided by sine shear plane angle. The area is 3.497 square mm. Now we find the shear stress by dividing the the shear force by the shear plane area, which is 247 MPa.

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The Merchant Equation

- Of all the possible angles at which shear deformation can occur, the work material will select a shear plane angle ϕ that minimizes energy, given by

$$\phi = 45 + \frac{\alpha}{2} - \frac{\beta}{2}$$


(a)

The diagram (a) illustrates the Merchant equation in the context of orthogonal cutting. It shows a tool cutting a workpiece, forming a chip. The shear plane angle is denoted by ϕ . The rake angle is α and the friction angle is β . Forces shown include the cutting force F_c , the shear force F_s , the normal force N , and the friction force F . The chip is shown being removed from the workpiece.

One of the most important equations in metal cutting is the merchant equation. This equation states that the shear plane angle is 45 plus rake angle divided by 2 minus friction angle divided by 2.

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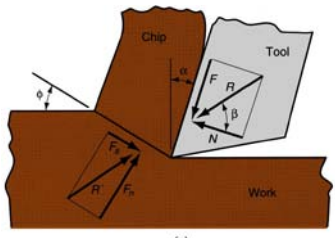
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What the Merchant Equation Tells Us

$$\phi = 45 + \frac{\alpha}{2} - \frac{\beta}{2}$$

- To increase shear plane angle
 - Increase the rake angle
 - Reduce the friction angle (or coefficient of friction)

Based on orthogonal cutting, but validity extends to 3-D machining



(a)

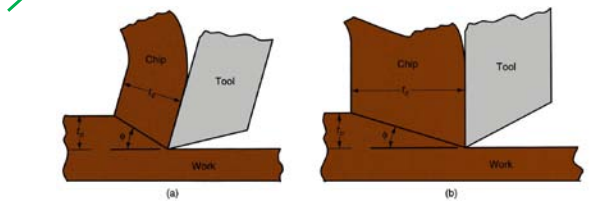
What does the merchant equation tell us? It tells us that to increase shear plane angle, we need to increase the rake angle, while reducing the friction angle.

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Effect of Higher Shear Plane Angle

- Higher shear plane angle means smaller shear plane which means lower shear force, cutting forces, power, and temperature

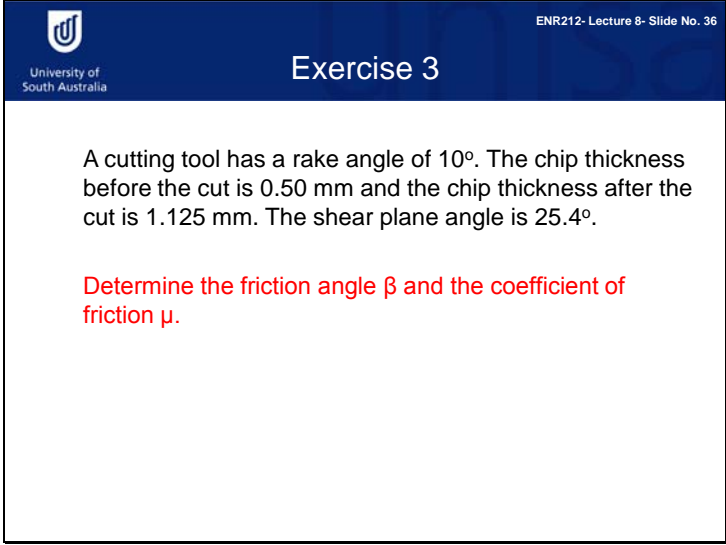


Effect of shear plane angle ϕ : (a) higher ϕ with a resulting lower shear plane area; (b) smaller ϕ with a corresponding larger shear plane area. Note that the rake angle is larger in (a), which tends to increase shear angle according to the Merchant equation

This slide shows you the relationship between the shear plane angle and the cutting force. A higher shear plane angle means a smaller shear plane, which means lower shear force, cutting forces, power, and temperature.

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Slide 36



The slide features a dark blue header with the University of South Australia logo on the left and the text 'ENR212- Lecture 8- Slide No. 36' on the right. The title 'Exercise 3' is centered in the header. The main content area is white with a black border and contains a text block and a red instruction.

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Exercise 3

A cutting tool has a rake angle of 10° . The chip thickness before the cut is 0.50 mm and the chip thickness after the cut is 1.125 mm. The shear plane angle is 25.4° .

Determine the friction angle β and the coefficient of friction μ .

Now, pause the presentation and use the Merchant equation to try to work out this problem. The solution is on the next slide.

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Exercise 3 Solution

- rake angle $\alpha = 10^\circ$
- chip thickness before the cut $t_o = 0.50$ mm
- chip thickness after the cut $t_c = 1.125$ mm
- shear plane angle $\phi = 25.4^\circ$


$$\phi = 45 + \frac{\alpha}{2} - \frac{\beta}{2}$$

$$\mu = \tan \beta$$

Calculations

$$\beta = 2(45) + 10^\circ - 2(25.4^\circ) = 49.2^\circ$$
$$\mu = \tan 49.2^\circ = 1.16$$

You can see the two equations which you need for this problem in this slide. The coefficient of friction between the tool and chip is \tan friction angle. The friction angle can be derived by rearranging the Merchant equation, because you know the shear plane angle and the rake angle. The solution is that the friction angle is 49.2 degrees and the coefficient of friction is 1.16.

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Power and Energy Relationships

- A machining operation requires power
- The power to perform machining can be computed from:

$$P_c = F_c v$$


where P_c = cutting power; F_c = cutting force; and v = cutting speed

Example: cutting speed, $v=100\text{m/min}$; depth of cut, $t_o=0.5\text{mm}$; width of cut, $w=3.0\text{mm}$; cutting force, $F_c=1557\text{N}$,

Determine the cutting power


$$P_c=(1557\text{N}) \times (100\text{m/min})=155,700\text{Nm/min}$$
$$=155,700\text{J/min}=2595\text{J/s}=2595\text{W}=2.6\text{kW}$$

A machining operation requires power, and you will need to work out the amount of power you require for specific operations. The equation for this is cutting power equals cutting force multiplied by cutting speed. For example, if we have an operation with a cutting speed of 100 meters per minute, and a cutting force of 1557 Newtons, then the power needed is 155,700 Newton meters per minute, which equals 2.6 kilo Watts.

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Power and Energy Relationships

- Gross power to operate the machine tool P_g or HP_g is given by



$$P_g = \frac{P_c}{E}$$

where E = mechanical efficiency of machine tool

- Typical E for machine tools ~ 90%

Example continued: $P_c=2.6\text{Kw}$,
Determine the gross power
 $P_g=2.6/0.9=2.9\text{kW}$

The gross power needed to operate the machine tool is calculated by dividing cutting power by the mechanical efficiency of the machine tool, which is typically 90%. So, to continue the last example, if we divide the cutting power by 90%, we get a gross power of 2.9 kilo Watts.


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Unit Power in Machining

- Useful to convert power into power per unit volume rate of metal cut
- Called *unit power*, P_u
- also known as the **specific energy** U

$$U = P_u = \frac{P_c}{R_{MR}} = \frac{F_c v}{vt_o W} = \frac{F_c}{t_o W}$$

where R_{MR} = material removal rate
N-m/mm³ or J/mm³ (in-lb/in³)

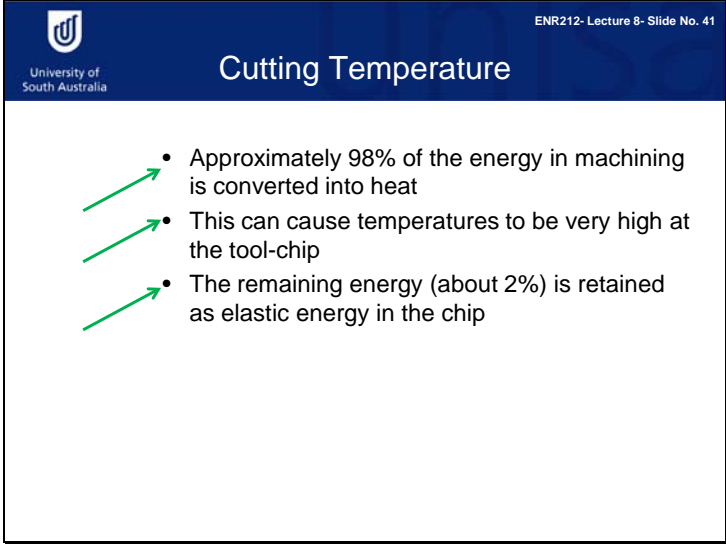
Example continued: $P_c=155.700\text{Nm/min}$
Determine specific energy

$$P_U = \frac{155.700\text{Nm/min}}{100\text{m/min} (3.0\text{mm})(0.5\text{mm})} = \frac{155,700}{150,000} = 1.038\text{Nm/mm}^3$$

The unit power is the amount of power required to remove per unit volume of cut metal. It is calculated by dividing the cutting power by the material removal rate. To continue the previous example, if the cutting power is 155.7 Nm per minute, and the material removal rate is 100 meters per minute, then the Unit power is 1.038 Nm per cubic mm.

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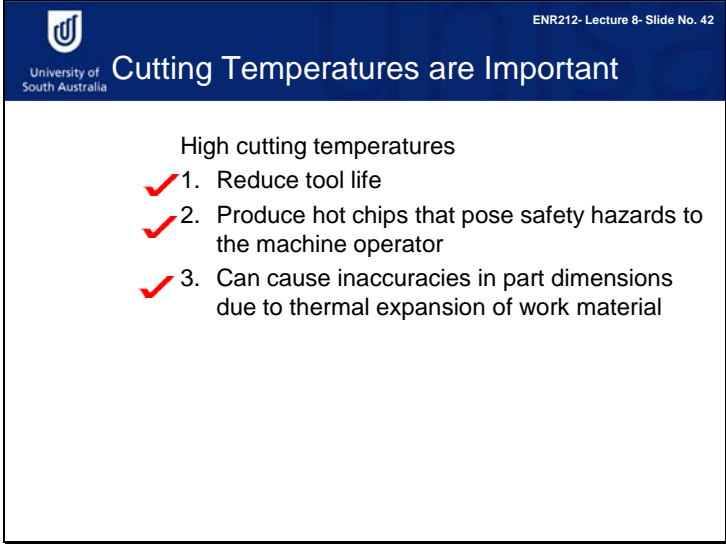
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Cutting Temperature

- Approximately 98% of the energy in machining is converted into heat
- This can cause temperatures to be very high at the tool-chip
- The remaining energy (about 2%) is retained as elastic energy in the chip

Approximately 98% of the energy in machining is converted into heat. This can cause very high temperatures at the tool-chip. The remaining energy (about 2%) is retained as elastic energy in the chip.



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Cutting Temperatures are Important

High cutting temperatures


- ✓ 1. Reduce tool life
- ✓ 2. Produce hot chips that pose safety hazards to the machine operator
- ✓ 3. Can cause inaccuracies in part dimensions due to thermal expansion of work material

High cutting temperatures are not good at all, for a number of reasons. They reduce tool life, they produce hot chips that pose safety hazards to the machine operator, and they can cause inaccuracies in part dimensions, due to the thermal expansion of work material.

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Cutting Temperature

- Analytical method derived by an engineer called Nathan Cook from dimensional analysis using experimental data for various work materials



$$T = \frac{0.4U}{\rho C} \left(\frac{vt_o}{K} \right)^{0.333}$$

where T = temperature rise at tool-chip interface; U = specific energy; v = cutting speed; t_o = chip thickness before cut; ρC = volumetric specific heat of work material; K = thermal diffusivity of work material

It is important to control the cutting temperature. Nathan Cook developed an equation for predicting cutting temperature.

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Exercise 4


Ambient temperature 20°C
Cutting speed, $v=1667\text{mm/s}$
Cutting depth, $t_o=0.5\text{mm}$
Specific energy, $U=1.038\text{Nm/mm}^3$
Specific heat for material, $\rho C=3.0(10^{-3})\text{J/mm}^3\text{-C}$
Thermal Diffusivity, $K=50\text{mm}^2/\text{s}$

Find the temperature for the tool chip interface

Now, you can use the Nathan's equation to predict the cutting temperature in this example. You have been given the ambient temperature, the cutting speed and depth, the specific energy, the specific heat for the material and the thermal diffusivity. Find the temperature rise for the tool chip interface. The solution is on the next slide.

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Exercise 4 Solution

Ambient temperature 20°C
Cutting speed, $v=1667\text{mm/s}$
Cutting depth, $t_o=0.5\text{mm}$
Specific energy, $U=1.038\text{Nm/mm}^3$
Specific heat for material, $\rho C=3.0(10^{-3})\text{J/mm}^3\cdot\text{C}$
Thermal Diffusivity, $K=50\text{mm}^2/\text{s}$

$$T = \frac{0.4U}{\rho C} \left(\frac{vt_o}{K} \right)^{0.333}$$

Calculations

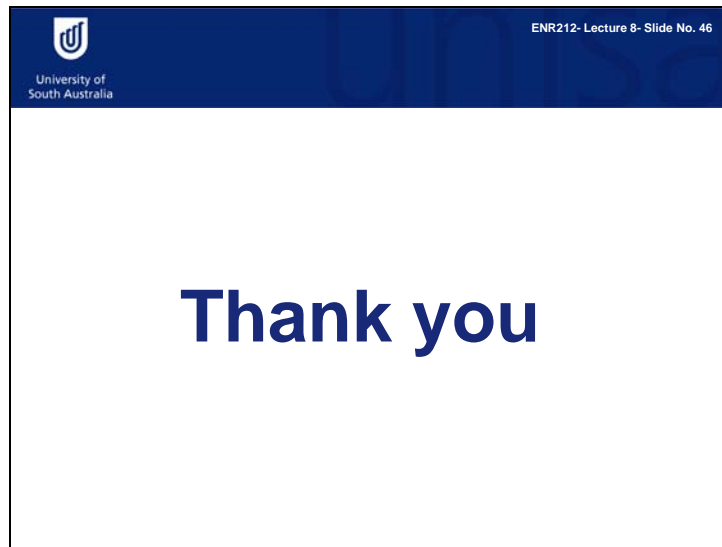
$$T = \frac{0.4 \times 1.038 \text{ Nm/mm}^3}{3.0(10^{-3}) \text{ J/mm}^3 \cdot \text{C}} \left[\frac{1667 \text{ mm/s} (0.5 \text{ mm})}{50 \text{ mm}^2/\text{s}} \right]^{0.333}$$
$$T = (138.4^\circ\text{C})(2.552) = 353^\circ\text{C}$$

Resulting cutting temperature = $20+353=373^\circ\text{C}$

Nathan Cook's equation is given here. You should have used this equation to work out that the cutting temperature rise is 353 degrees Celsius. Given the ambient temperature of 20 degrees, this means that the resultant cutting temperature is 373 degrees Celsius.

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Thank you for your attention.