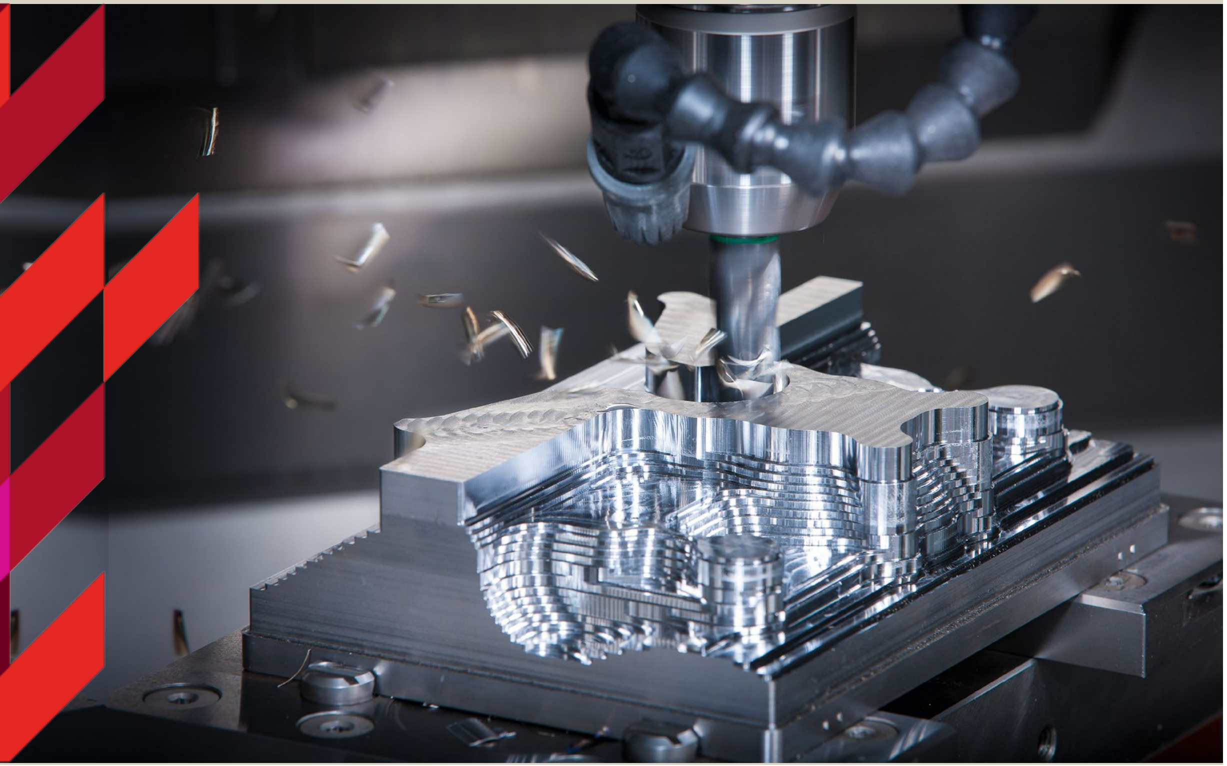
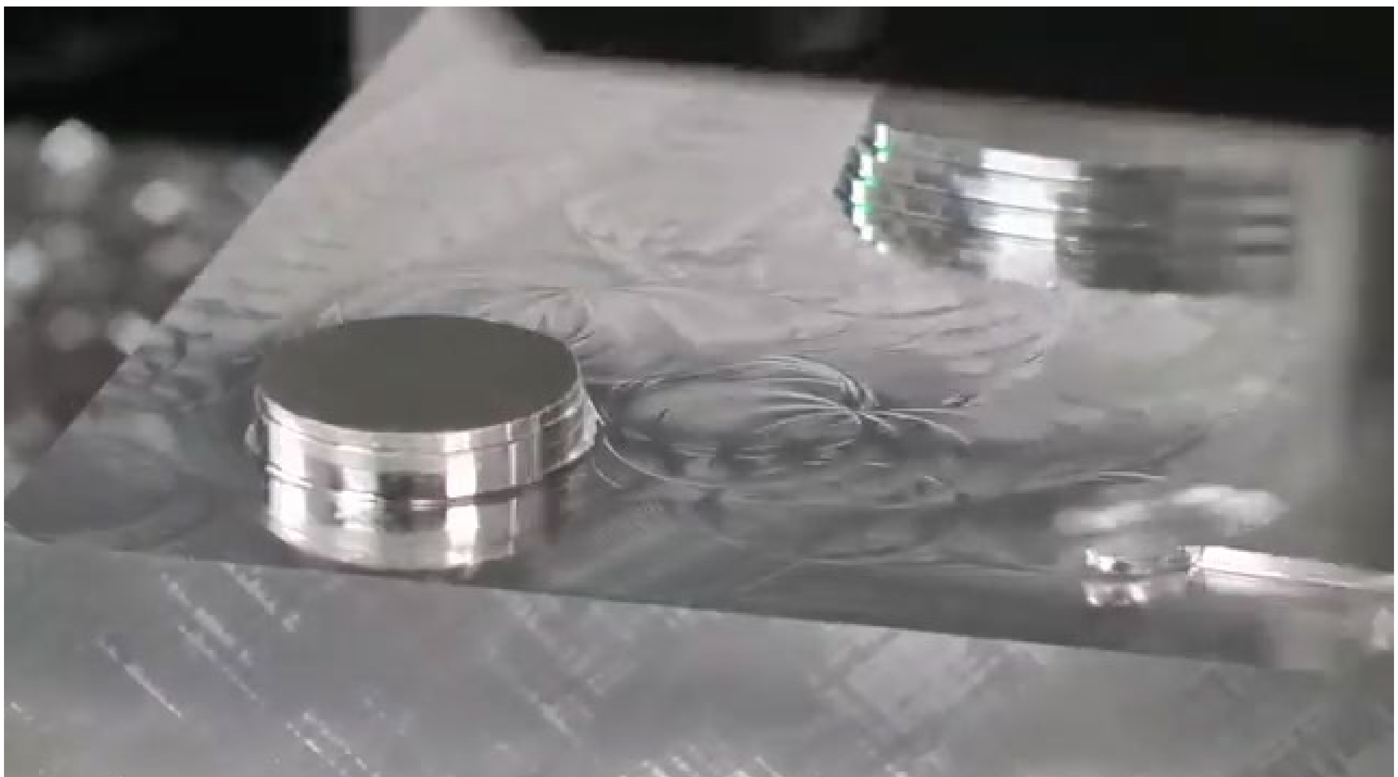
MECH2003 – Mechanical Design 2
Material Removal Methods



Material Removal Methods

Introduction

Last week we discussed the methods in which computer numerically controlled machines function. Most of these machines were being used to remove material to produce components such as this 3-axis CNC mill.



Material Removal Methods

Introduction

There is a large variety of machines that exist including this 5 axis CNC mill which was being used to machine a helmet from a solid billet of aluminium.

Material Removal Methods

Introduction

There was also this CNC lathe which had multiple cutting tools that could be interchanged allowing for a variety of operations to be undertaken.

Material Removal Methods

Introduction

Today we are going to learn about:

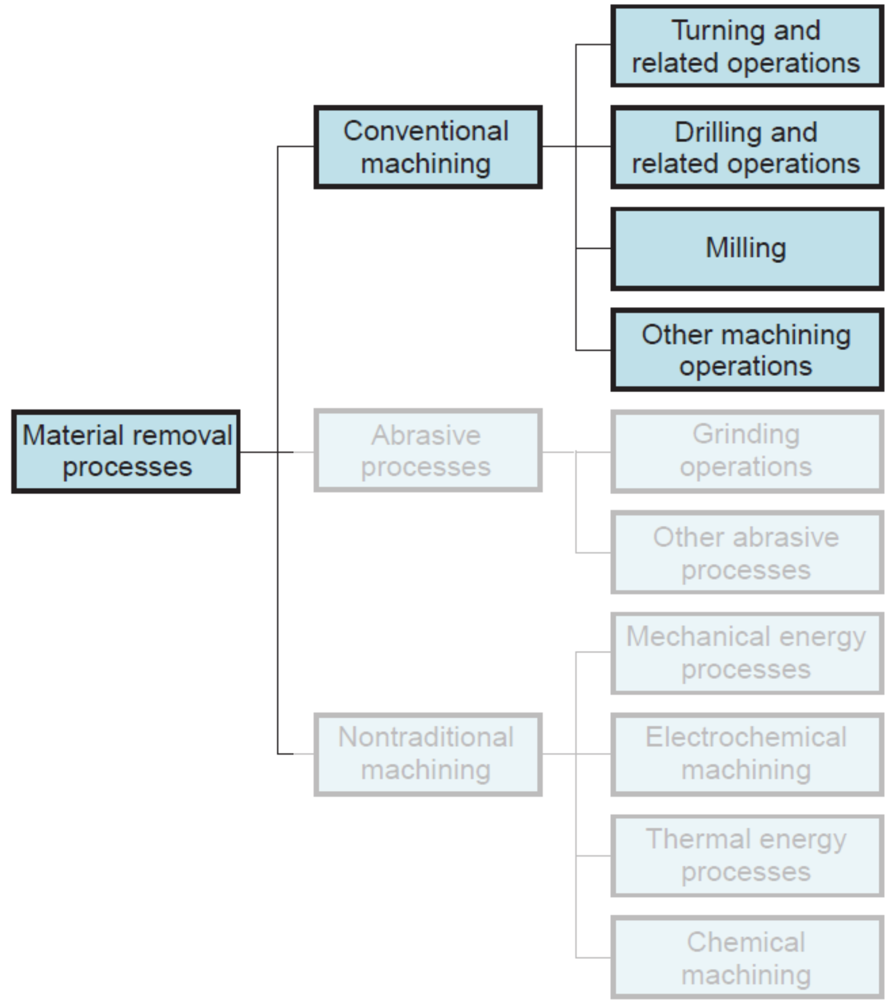
- Non machining material removal techniques
- Types of different conventional machining operations
- The theory associated with producing chips in the machining operation
- How to determine the forces associated with machining operations
- How to determine the power required to conduct machining operations
- The temperature increases that result from machining operations

Material Removal Methods

Non machining material removal techniques

Material removal processors can be categorised into a number of families depending on the technique used to remove material.

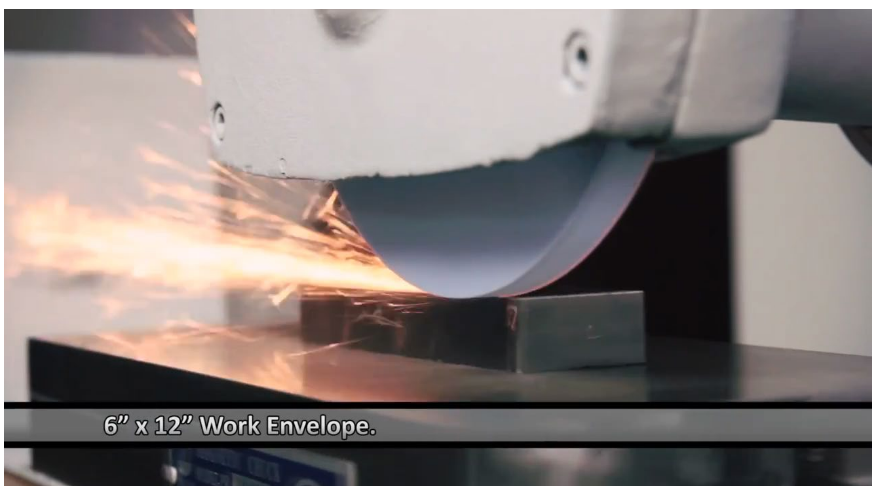
Later slides will be focusing the conventional machining processors, but it is important for you to be aware of what the other process are.

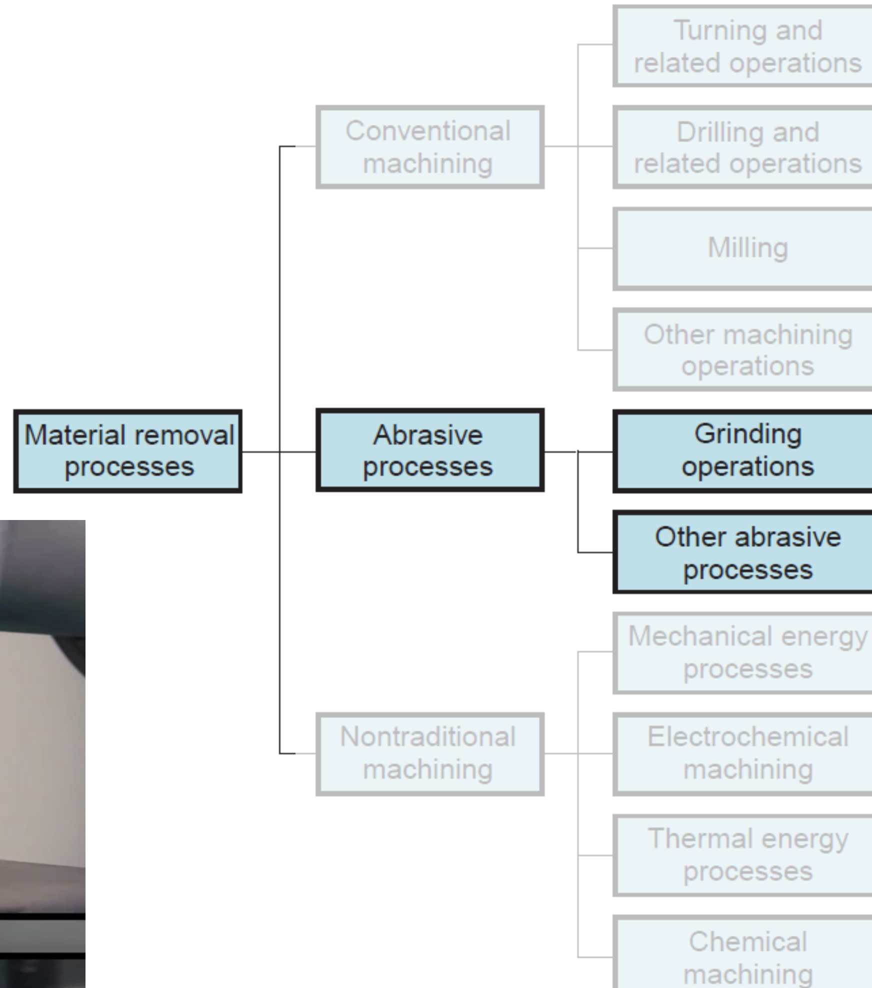


Material Removal Methods

Non machining material removal techniques

Abrasive processes are undertaken when hard, abrasive particles are utilised to remove material. They are usually used as part of a finishing operation to improve the surface finish of a component. This may include operations such as – *Grinding*

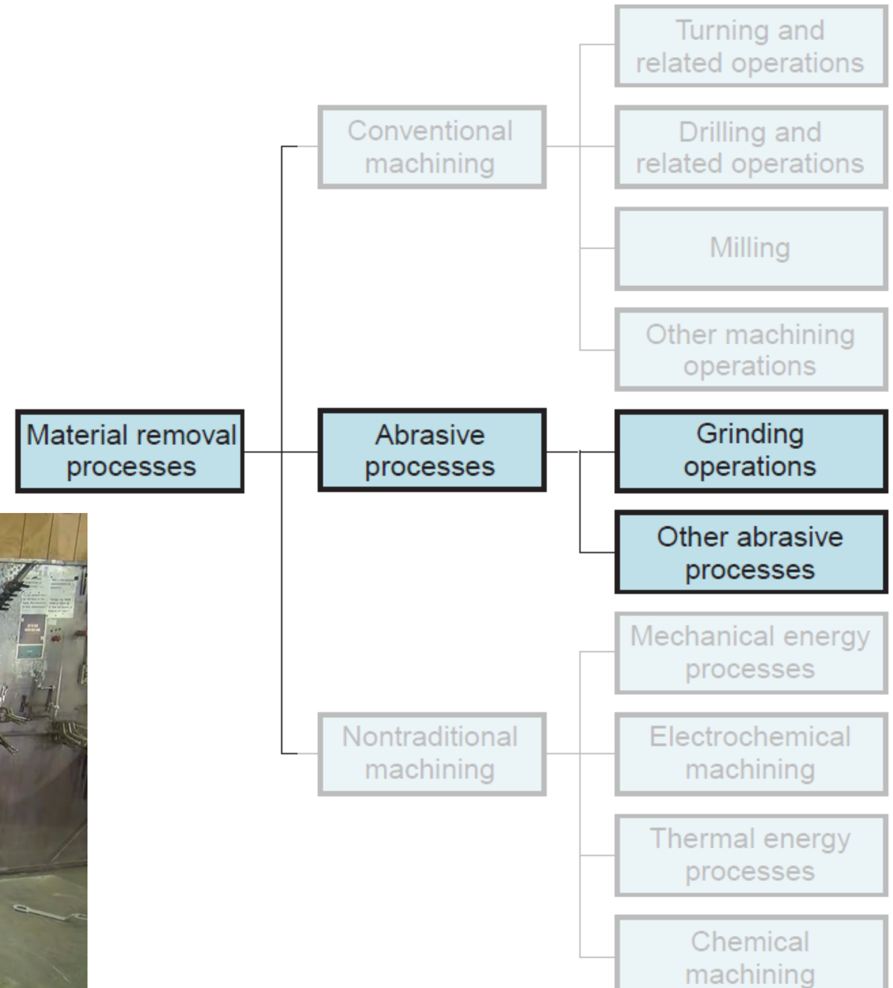




Material Removal Methods

Non machining material removal techniques

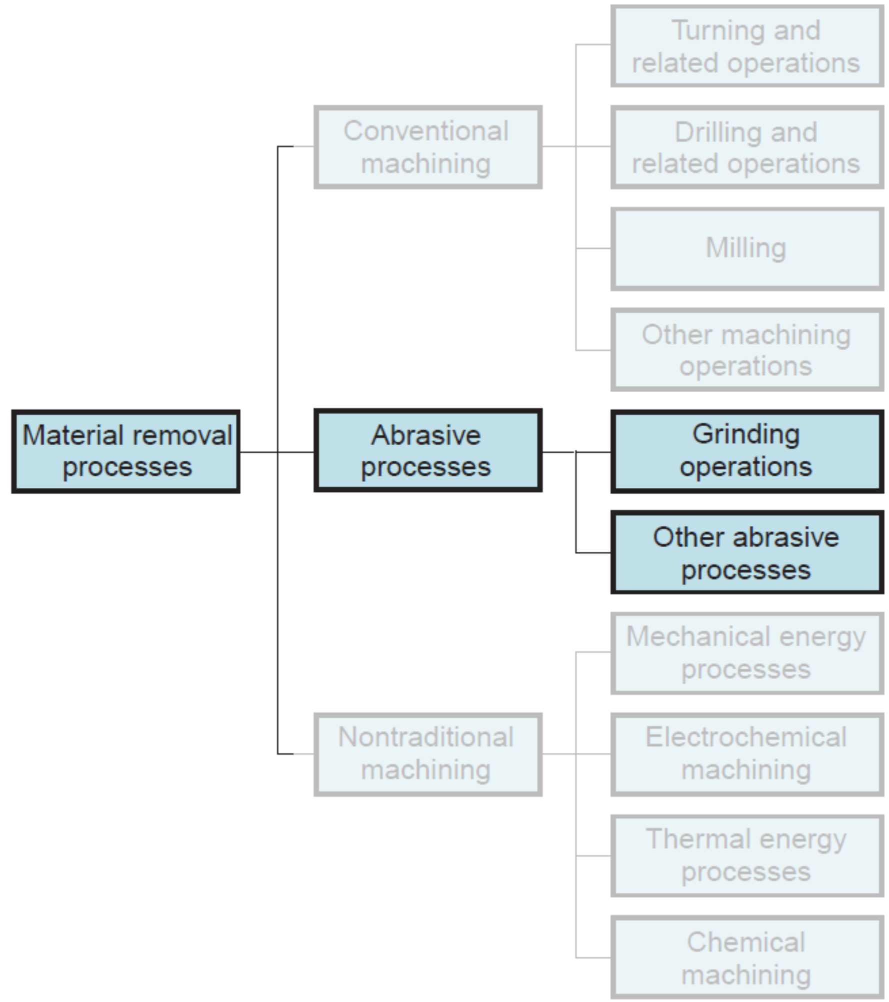
Abrasive processes are undertaken when hard, abrasive particles are utilised to remove material. They are usually used as part of a finishing operation to improve the surface finish of a component. This may include operations such as – *Polishing*



Material Removal Methods

Non machining material removal techniques

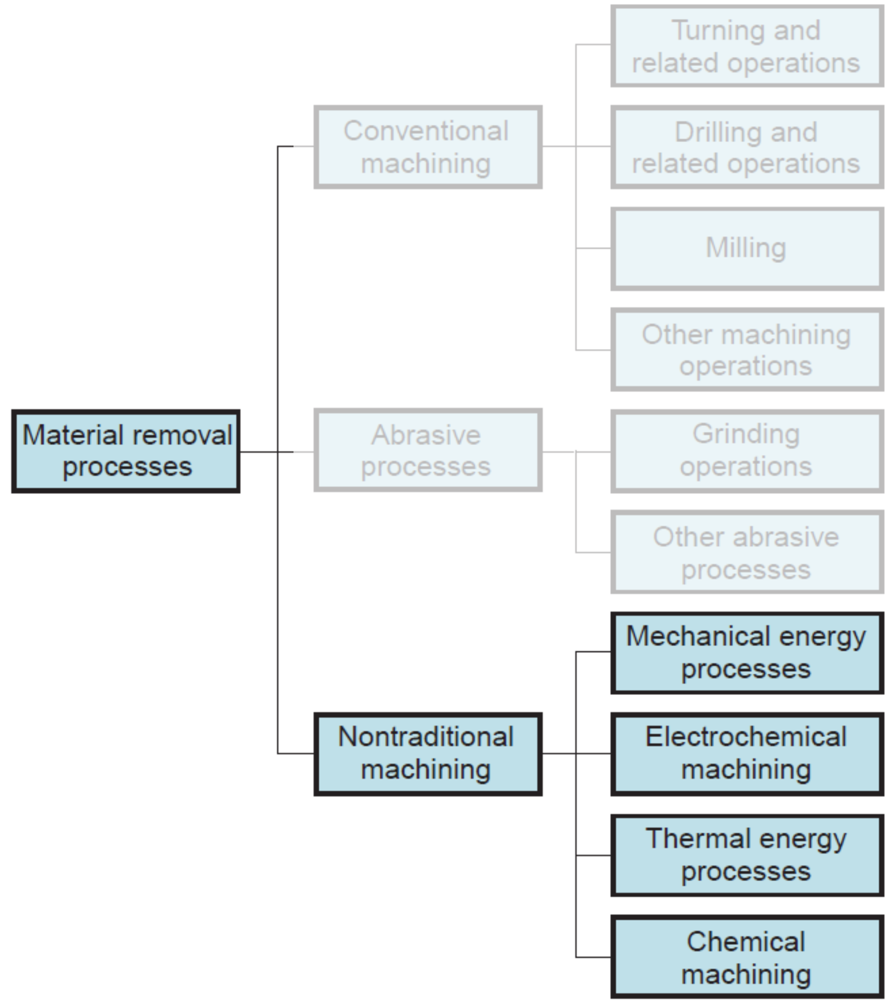
Abrasive processes are undertaken when hard, abrasive particles are utilised to remove material. They are usually used as part of a finishing operation to improve the surface finish of a component. This may include operations such as – *Sand blasting*



Material Removal Methods

Non-machining material removal techniques

Non-traditional machining techniques are any items that do not fall into either Conventional Machining or Abrasive processes. They remove material by using either; alternative mechanical, electrochemical, thermal or chemical processors.

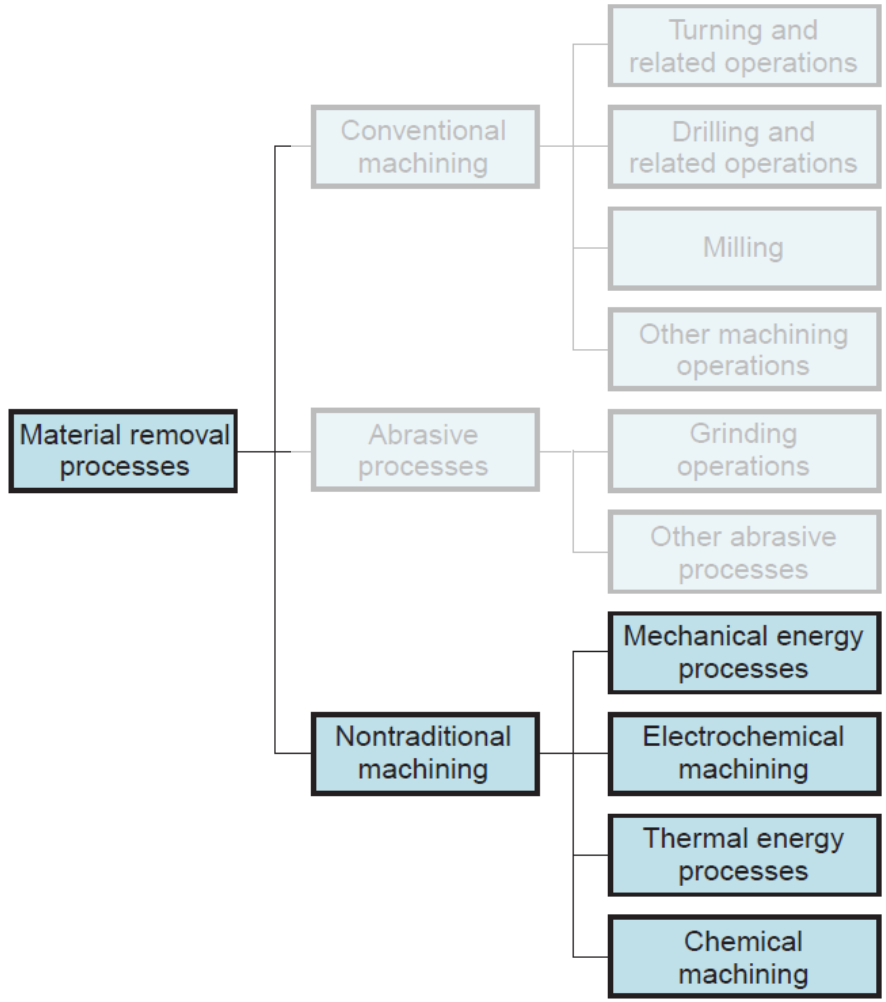


Material Removal Methods

Non-machining material removal techniques

These were developed during the World War II in response to a requirement to shape materials that either:

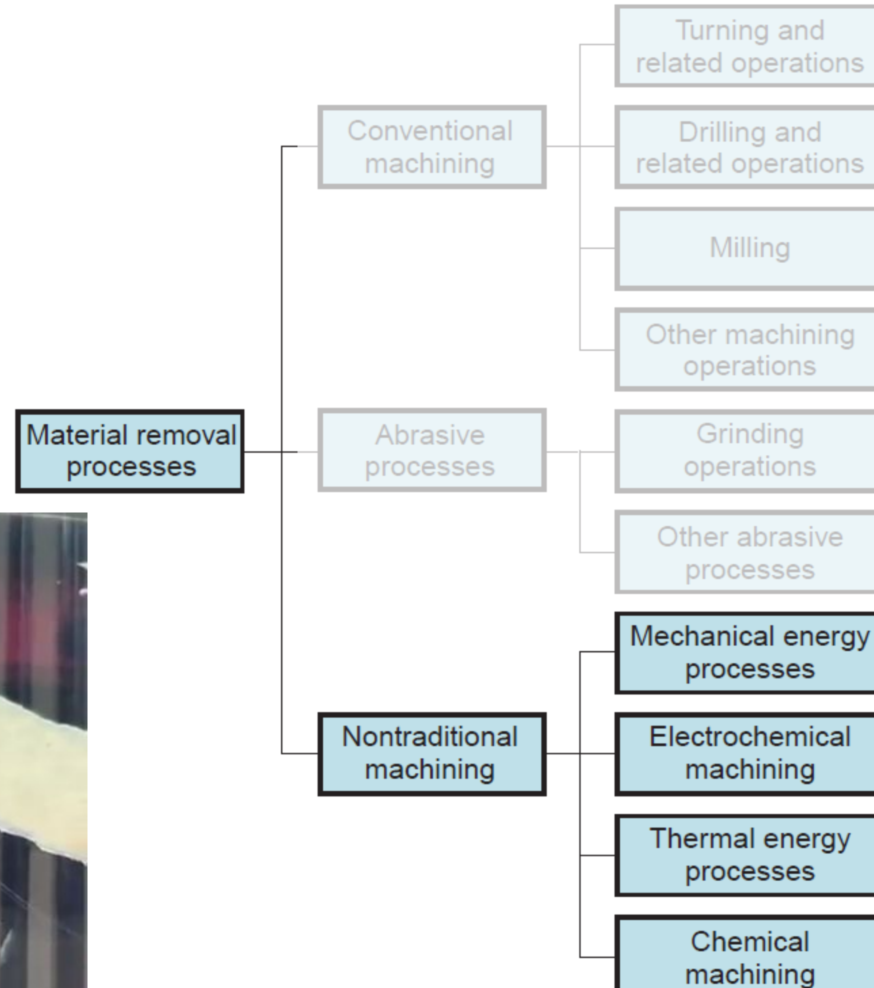
- Have special mechanical properties and are not suitable for traditional machining operations.
- The desired geometries are to complex for traditional machining operations..
- There is a requirement to avoid damage to the surface or place the material under the stress associated with traditional machining operations.



Material Removal Methods

Non-machining material removal techniques

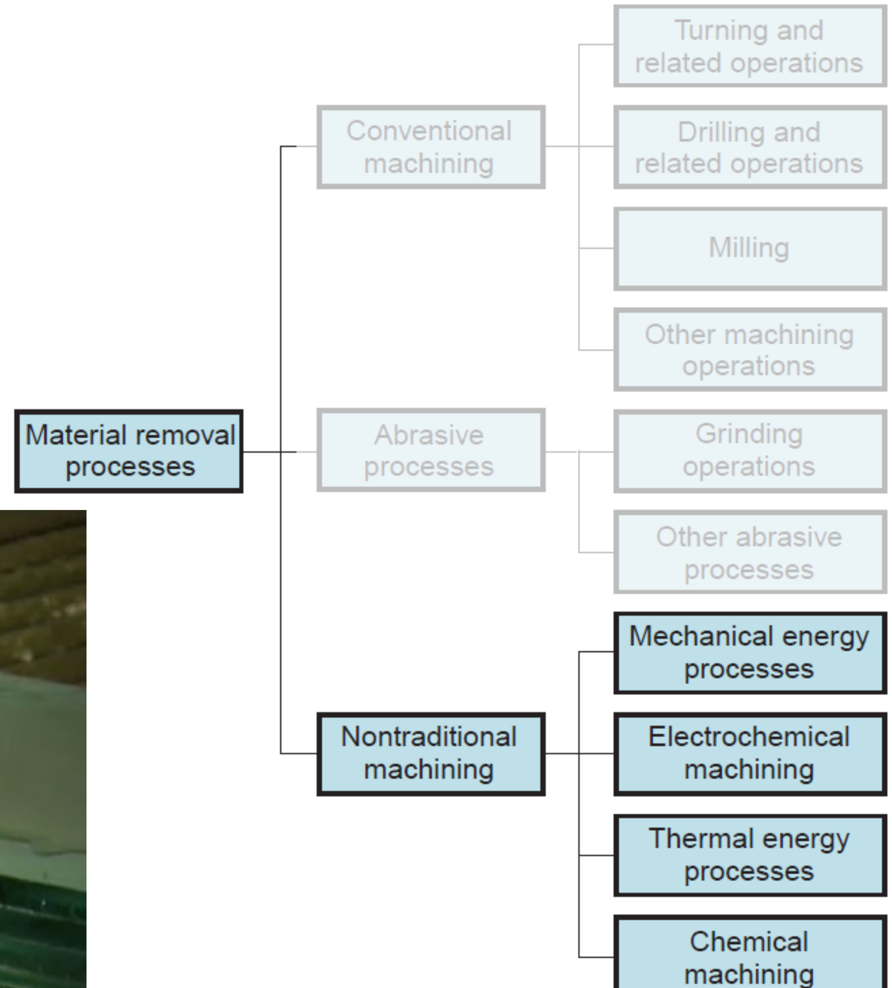
Non-traditional machining techniques may include – *Laser cutting*



Material Removal Methods

Non-machining material removal techniques

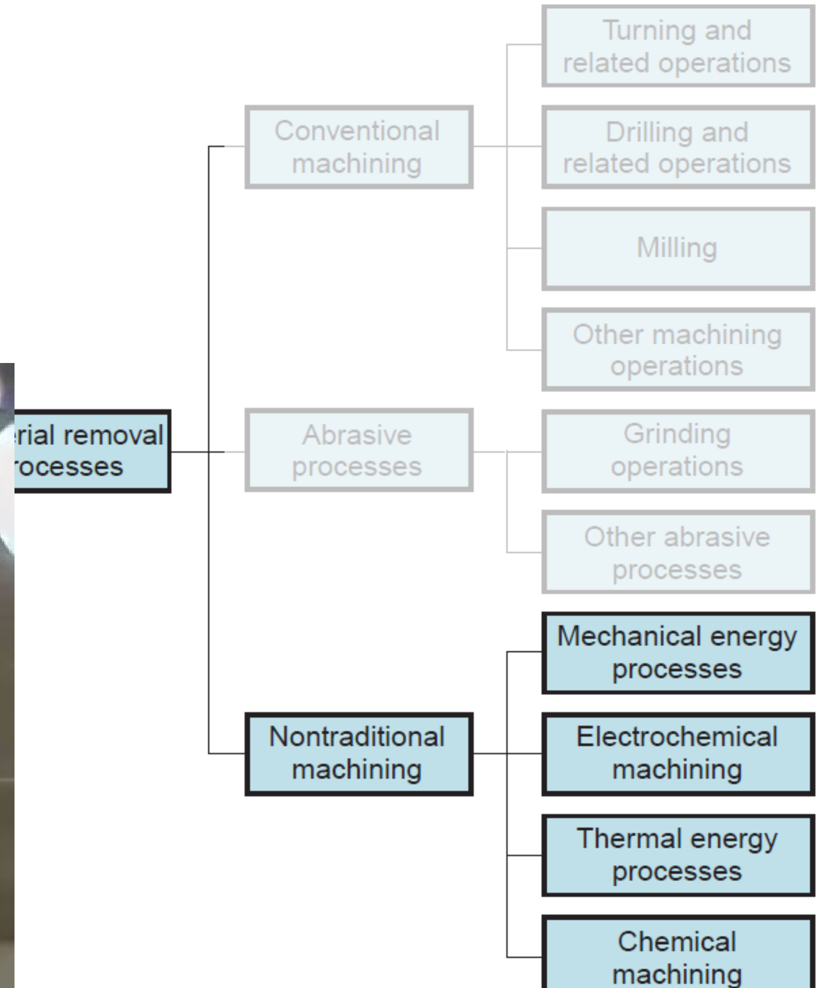
Non-traditional machining techniques may include – *Water jet cutting*



Material Removal Methods

Non-machining material removal techniques

Non-traditional machining techniques may include – *Electric discharge wiring*



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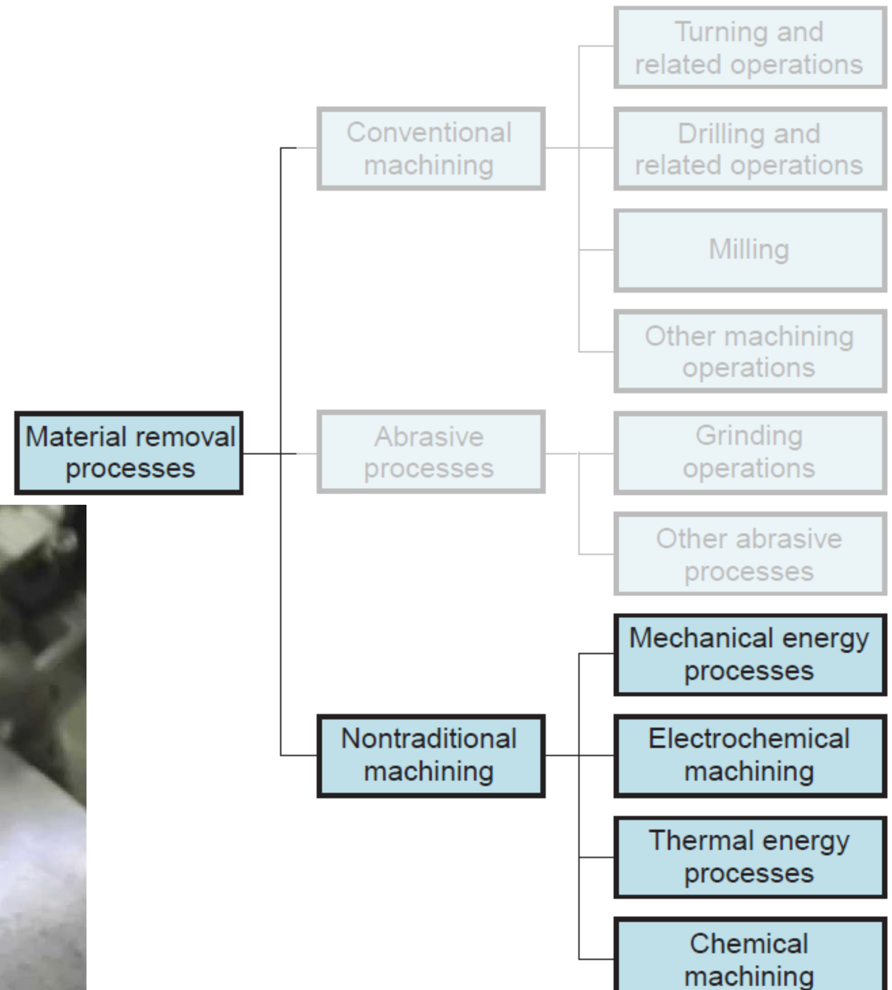
Non-machining material removal techniques

Non-traditional machining techniques may include –
Electron beam machining

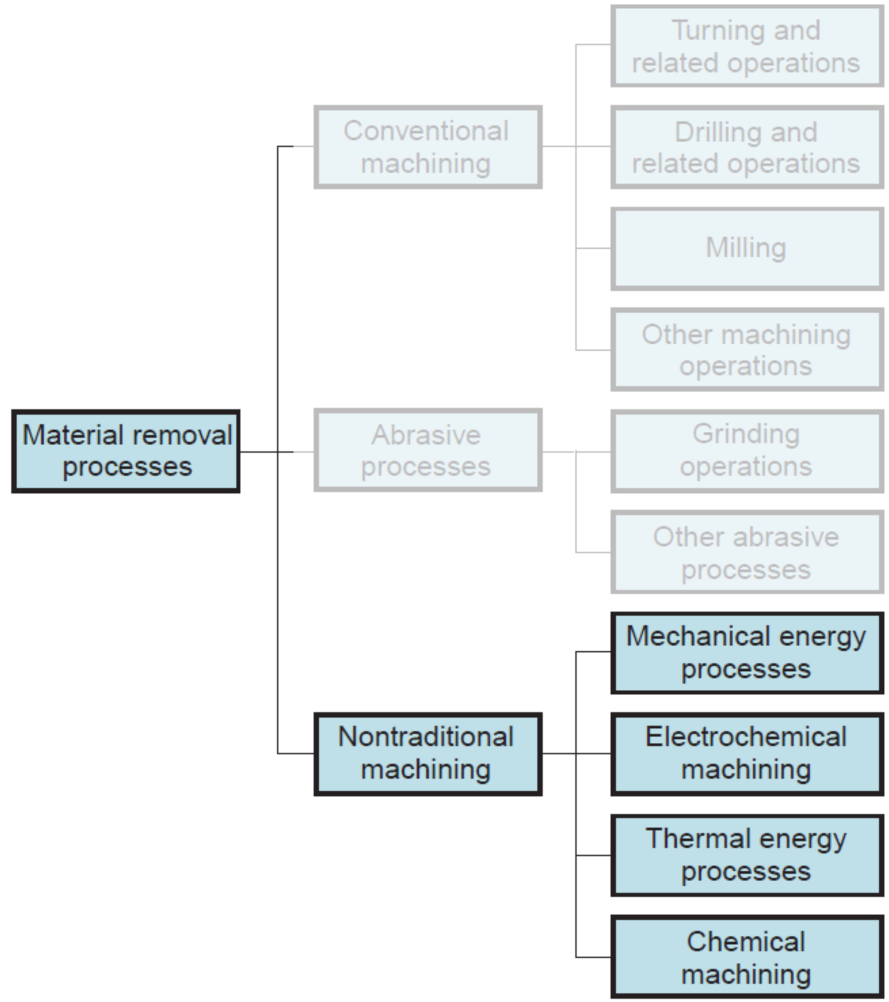


Material Removal Methods

Non-machining material removal techniques

The manufacture of semi conductors utilises chemical machining. This requires a four step process which is:

1. Cleaning
2. Masking
3. Etching
4. Demasking



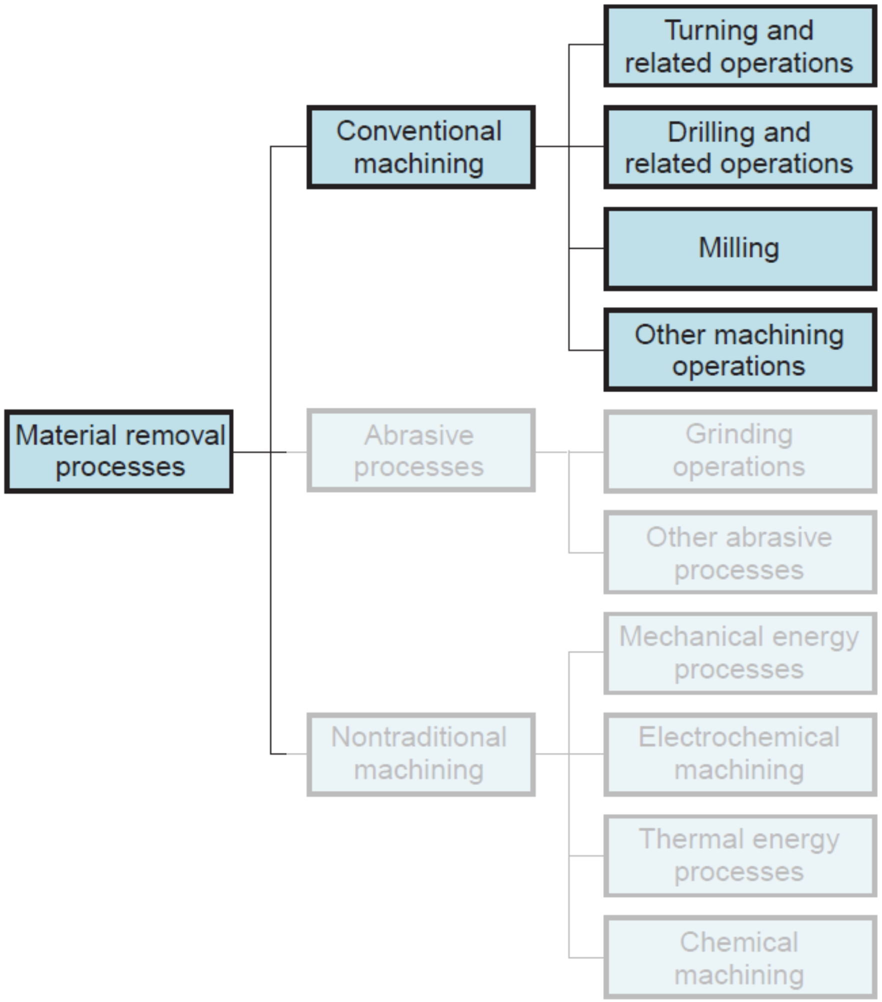
Material Removal Methods

Types of different machining operations

But the process of greatest interest to us today is conventional machining.

Conventional Machining operations belong to one of three categories:

- Turning
- Drilling
- Milling



Material Removal Methods

Types of different machining operations

All the previously mentioned operations remove material to produce a component by using the relative motion of the material and a sharp cutting tool.

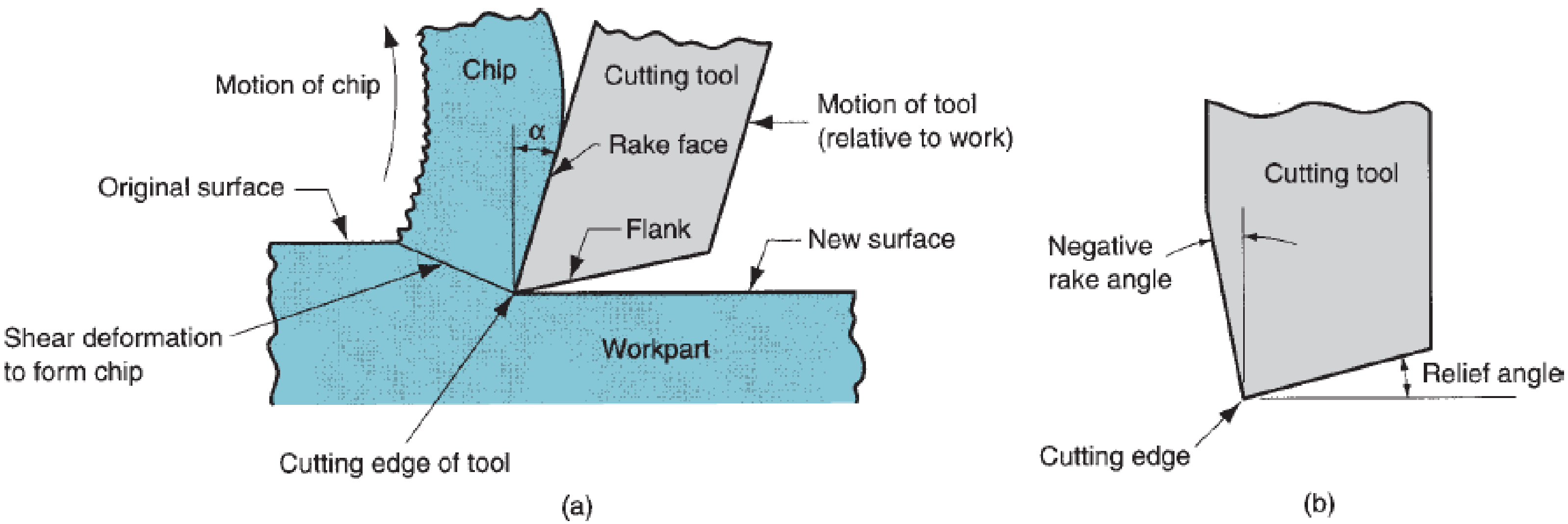


FIGURE 21.2 (a) A cross-sectional view of the machining process. (b) Tool with negative rake angle; compare with positive rake angle in (a).

Material Removal Methods

Types of different machining operations

Machining was a significant contribution to the industrial revolution and continues to be an important part of manufacturing because:

- Variety of Work Materials. Machining can be applied to a wide variety of work materials. Virtually all solid metals can be machined. Plastics and plastic composites can also be cut by machining. Ceramics pose difficulties because of their high hardness and brittleness; however, most ceramics can be successfully cut by the abrasive machining processes discussed in Chapter 25.
- Variety of part shapes and geometric features. Machining can be used to create any regular geometries, such as flat planes, round holes, and cylinders. By introducing variations in tool shapes and tool paths, irregular geometries can be created, such as screw threads and T-slots. By combining several machining operations in sequence, shapes of almost unlimited complexity and variety can be produced.

Material Removal Methods

Types of different machining operations

Machining was a significant contribution to the industrial revolution and continues to be an important part of manufacturing because:

- Dimensional accuracy. Machining can produce dimensions to very close tolerances. Some machining processes can achieve tolerances of ±0.025mm, much more accurate than most other processes.
- Good surface finishes. Machining is capable of creating very smooth surface finishes. Roughness values less than 0.4 microns (16 m-in.) can be achieved in conventional machining operations. To improve on this it is required to employ abrasive processes.

Material Removal Methods

Types of different machining operations

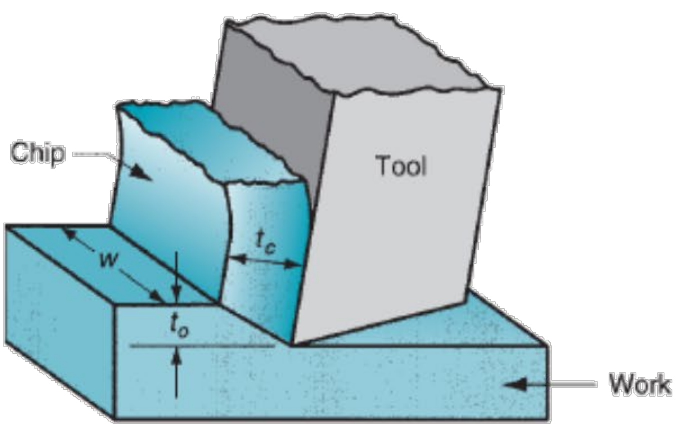
There are some negatives associated with machining, this includes:

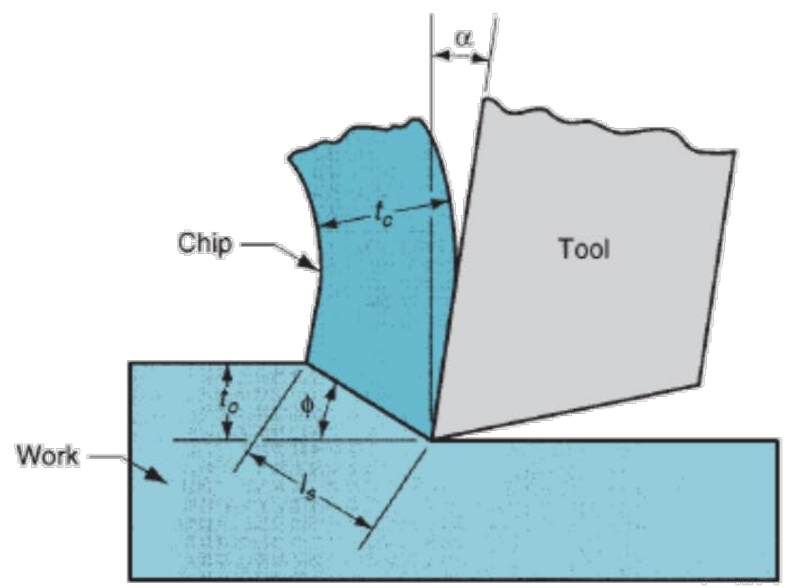
- Wasteful of material. Machining is inherently wasteful of material. The chips generated in a machining operation are wasted material. Although these chips can usually be recycled, they represent waste in terms of the unit operation.
- Time consuming. A machining operation generally takes more time to shape a given part than alternative shaping processes such as casting or forging.

Material Removal Methods

Theory of producing chips in the machining operation

Machining is a complex three dimensional model that can be simplified to a two dimensional representation. This technique is called the **orthogonal cutting model** and is represented below by the two diagrams. It uses a wedge-shaped **tool** in which the cutting edge is perpendicular to the direction of **cutting speed**.

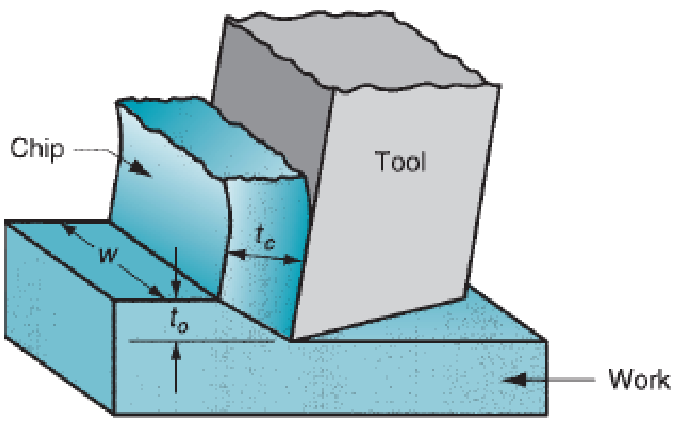


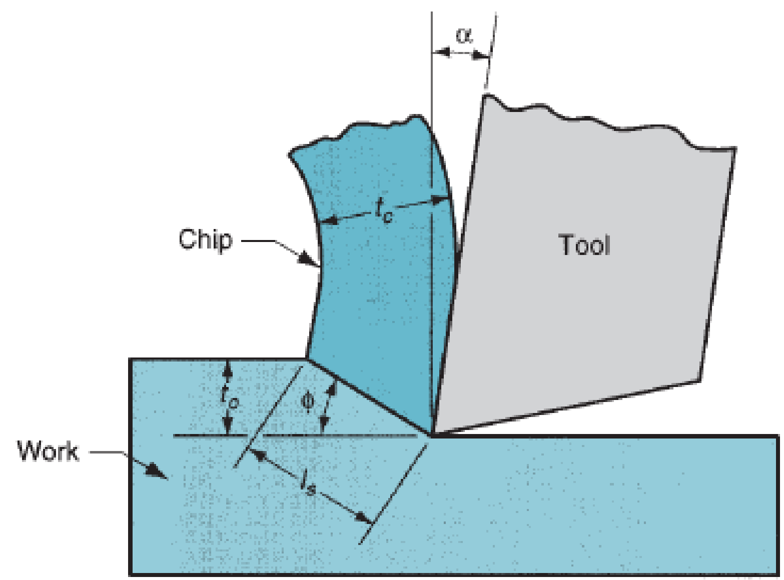


Material Removal Methods

Theory of producing chips in the machining operation

As the tool is forced into the material, the **chip** is formed by shear deformation along a plane called the **shear plane**, which is oriented at an angle φ with the surface of the work. Only at the sharp cutting edge of the tool does failure of the material occur, resulting in separation of the chip from the parent material. Along the shear plane, where the bulk of the mechanical energy is consumed in machining, the material is plastically deformed.





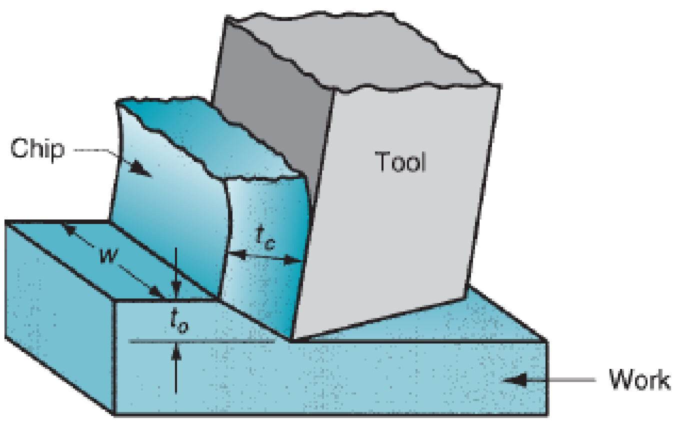
Material Removal Methods

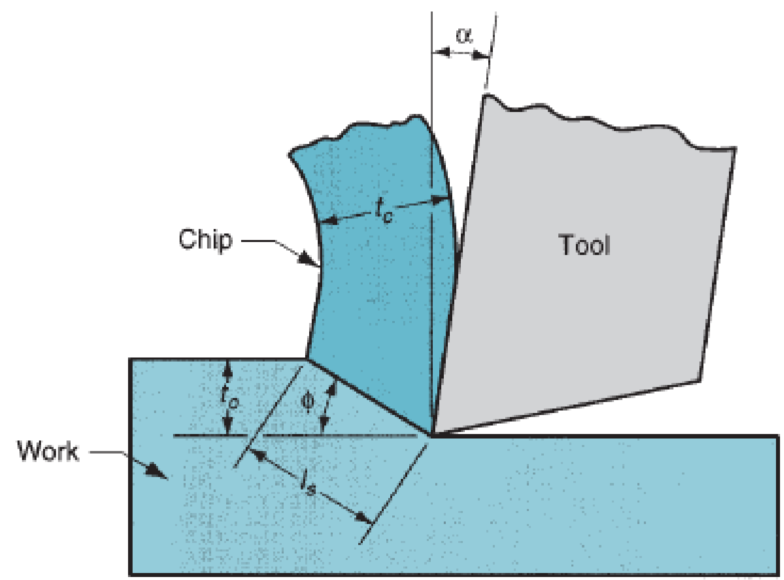
Theory of producing chips in the machining operation

The tool in orthogonal cutting has only two elements of geometry:

Rake angle - determines the direction that the chip flows as it is formed from the work part (α).

Clearance angle - the clearance angle provides a small clearance between the tool flank and the newly generated work surface.



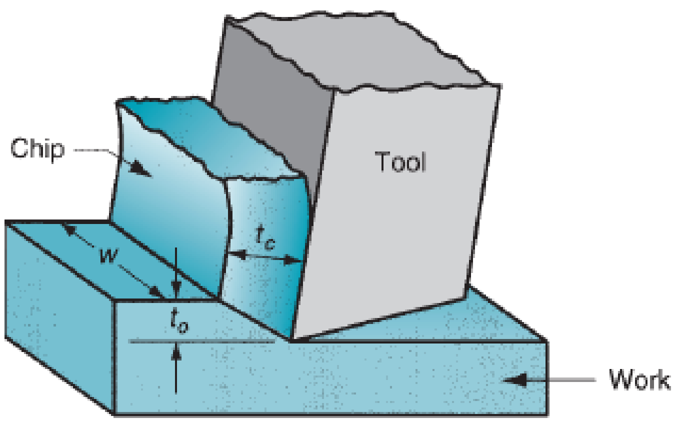


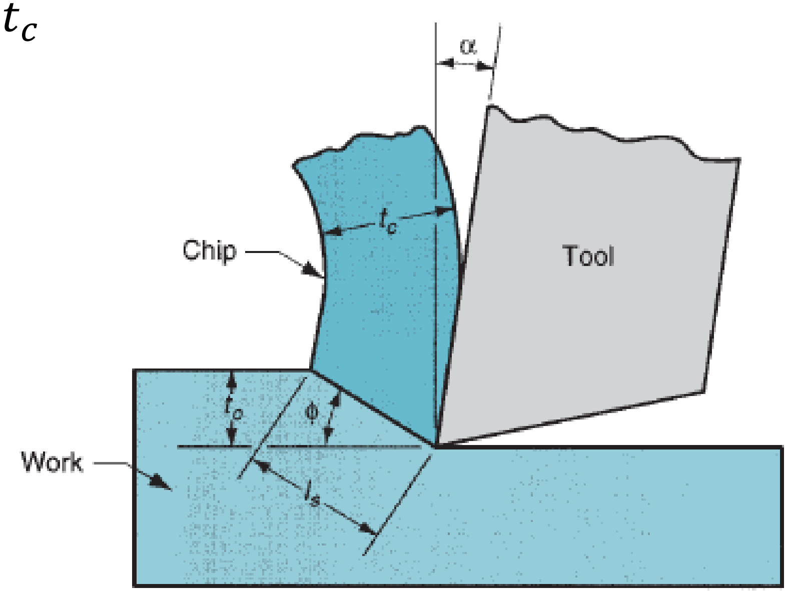
Material Removal Methods

Theory of producing chips in the machining operation

During cutting, the cutting edge of the tool is positioned a certain distance below the original work surface. This corresponds to the thickness of the chip prior to chip formation, t_o. As the chip is formed along the shear plane, its thickness increases to t_c. The ratio of to t_o t_c is called the chip thickness ratio (or simply the chip ratio) r :

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



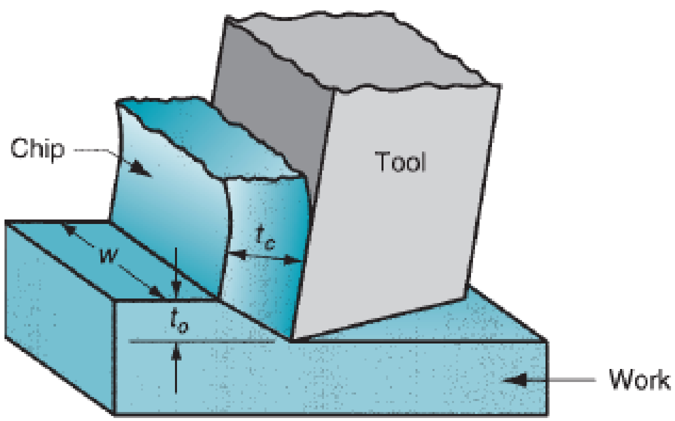


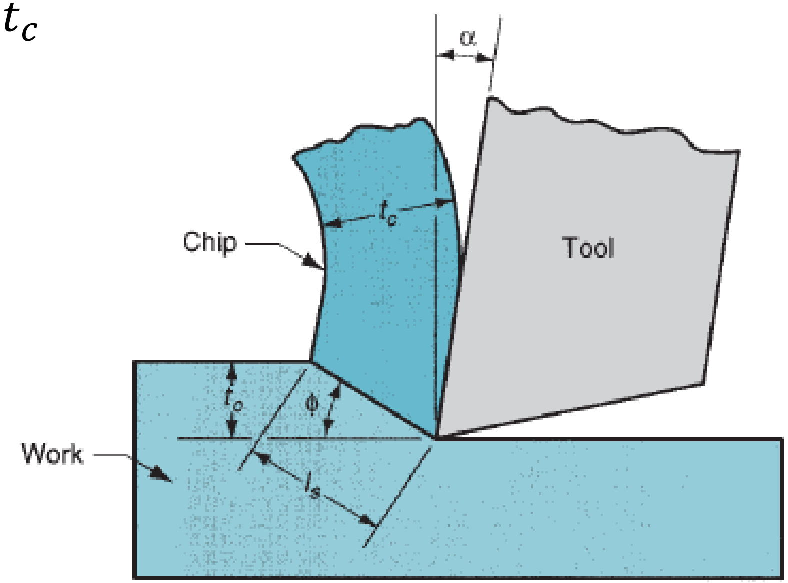
Material Removal Methods

Theory of producing chips in the machining operation

Since the chip thickness after cutting is always greater than the corresponding thickness before cutting, the chip ratio will always be less than 1.0. In addition, the orthogonal cut has a width dimension w, even though this dimension does not contribute much to the analysis in orthogonal cutting.

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





Material Removal Methods

Theory of producing chips in the machining operation

The geometry of the orthogonal cutting model allows us to establish an important relationship between the chip thickness ratio, the rake angle, and the shear plane angle. Let l_s be the length of the shear plane.

$$r = \frac{l_s \sin\varphi}{l_s \cos(\varphi - \alpha)} = \frac{\sin\varphi}{\cos(\varphi - \alpha)}$$

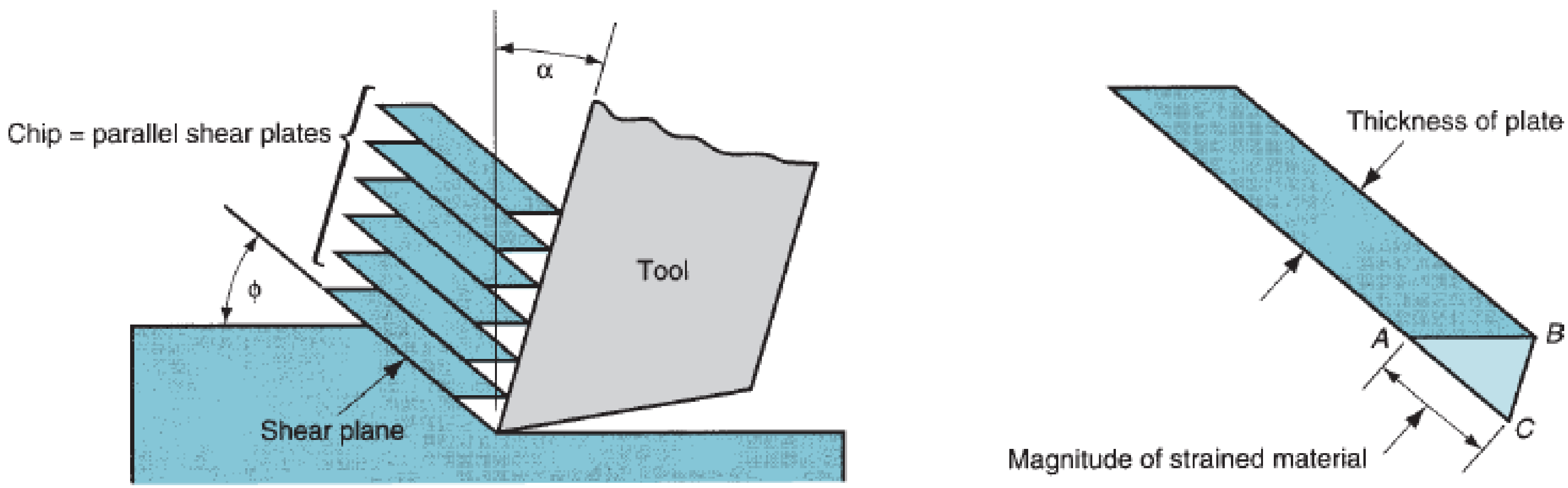
This can be rearranged to determine φ as follows:

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

Material Removal Methods

Theory of producing chips in the machining operation

The shear strain that occurs along the shear plane can be estimated by examining the figure below. The left figure shows shear deformation approximated by a series of parallel plates sliding against one another to form the chip. Consistent with our definition of shear strain each plate experiences the shear strain shown on the right.

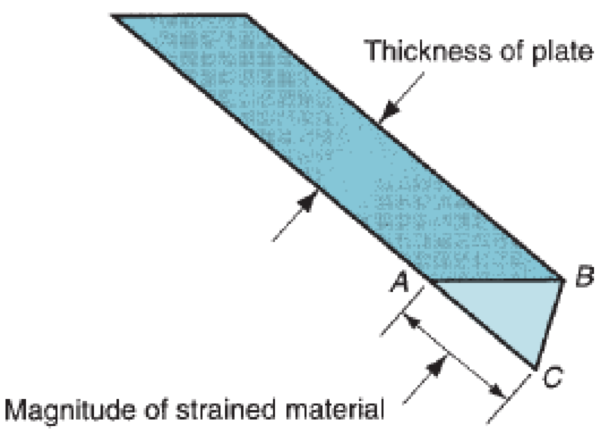


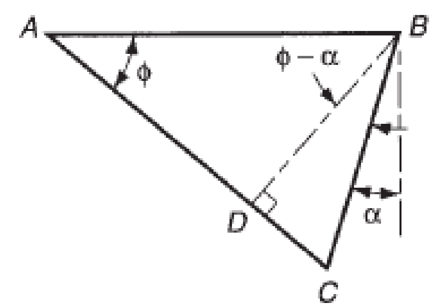
Material Removal Methods

Theory of producing chips in the machining operation

Referring to the small portion at the base of each plate (left) and analysing this shear strain triangle which is shown on the right, it is possible to determine an expression for the shear strain which is:

$$\gamma = \tan(\varphi - \alpha) + \cot \varphi$$





Material Removal Methods

Theory of producing chips in the machining operation

Example 1

In a machining operation that approximates orthogonal cutting, the cutting tool has a rake angle = 10^{O}. 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 and the shear strain in the operation.

Material Removal Methods

Theory of producing chips in the machining operation

Example 1

In a machining operation that approximates orthogonal cutting, the cutting tool has a rake angle = 10°. 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 and the shear strain in the operation.

Shear Plane Angle

$$\tan\phi = \frac{r\cos\alpha}{1 - r\sin\alpha} \text{ and } r = \frac{t_0}{t_c}$$

$$\tan\phi = \frac{\frac{0.5}{1.125}\cos 10}{1 - \frac{0.5}{1.125}\sin 10}$$

$$\phi = 25.4°$$

Material Removal Methods

Theory of producing chips in the machining operation

Example 1

In a machining operation that approximates orthogonal cutting, the cutting tool has a rake angle = 10^{O}. 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 and the shear strain in the operation.

Shear Strain

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

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

$$\gamma = 2.386$$

Material Removal Methods

Theory of producing chips in the machining operation

As was mentioned previously, machining is any operation that requires the relative motion between the material and a sharp cutting tool. The relative motion is referred to as the cutting speed and the secondary motion is the feed.

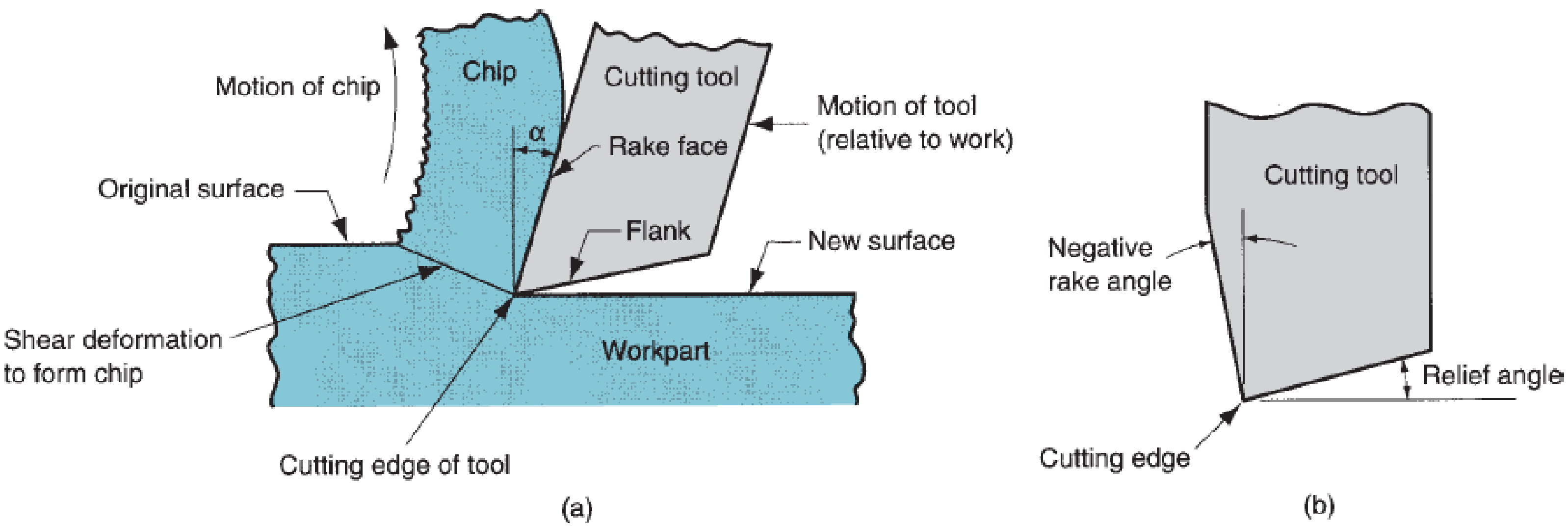
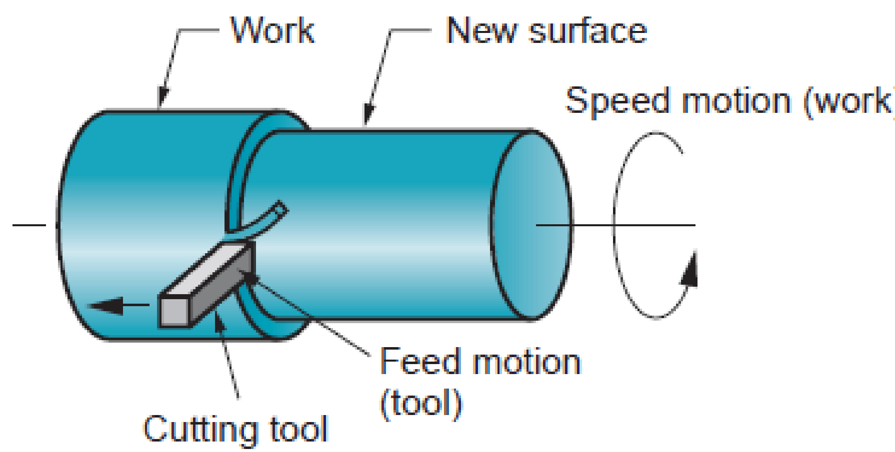


FIGURE 21.2 (a) A cross-sectional view of the machining process. (b) Tool with negative rake angle; compare with positive rake angle in (a).

Material Removal Methods

Theory of producing chips in the machining operation

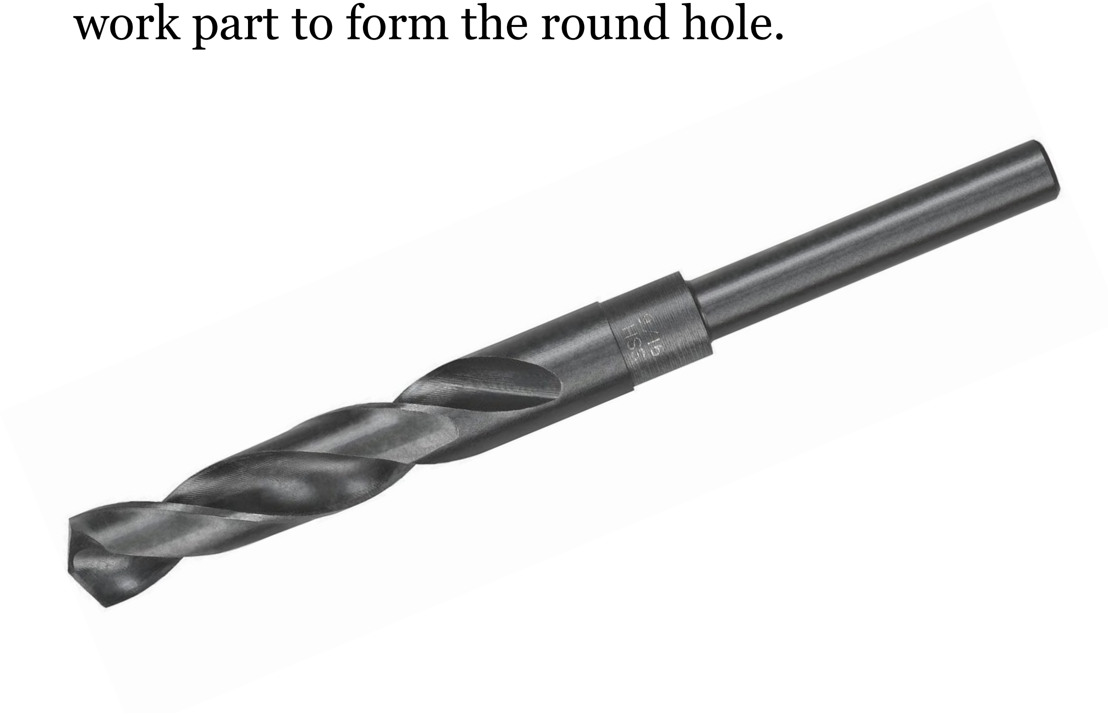
In **turning**, a cutting tool with a single cutting edge is used to remove material from a rotating work piece to generate a cylindrical shape. The speed motion in turning is provided by the rotating work part, and the feed motion is achieved by the cutting tool moving slowly in a direction parallel to the axis of rotation of the work piece.

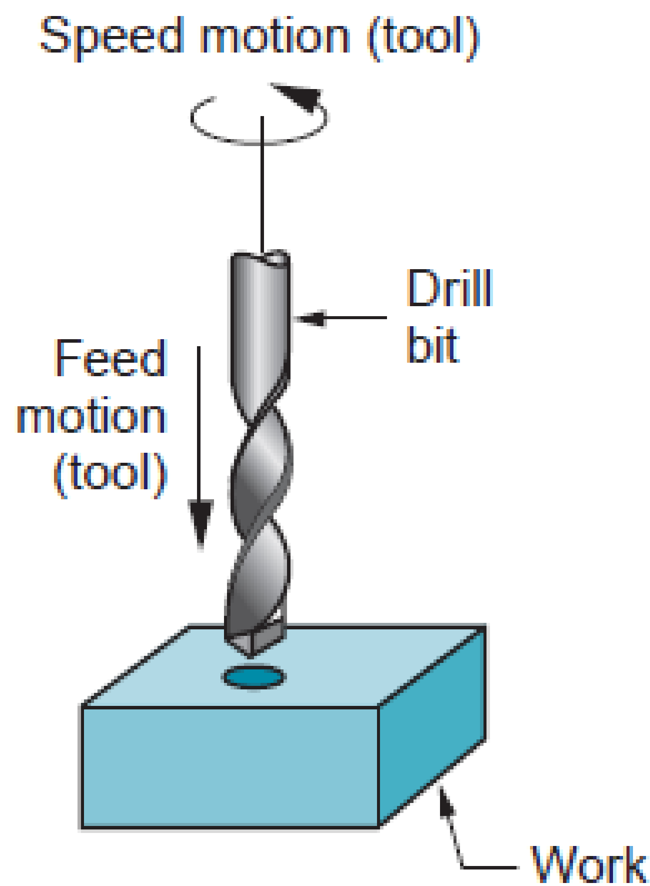


Material Removal Methods

Theory of producing chips in the machining operation

Drilling is used to create a round hole. It is accomplished by a rotating tool that typically has two cutting edges. The tool is fed in a direction parallel to its axis of rotation into the work part to form the round hole.

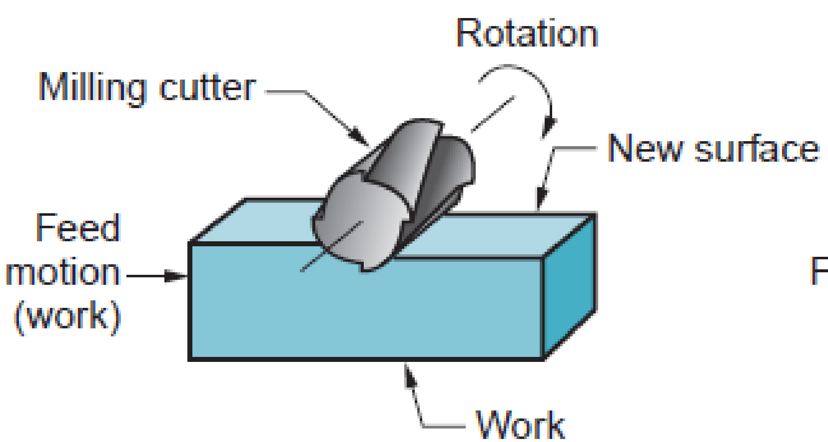


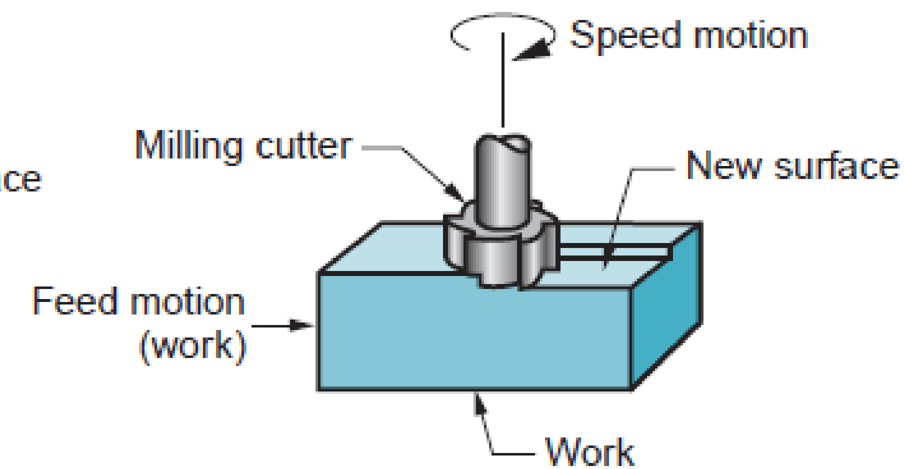


Material Removal Methods

Theory of producing chips in the machining operation

In milling, a rotating tool with multiple cutting edges is fed slowly across the work material to generate a plane or straight surface. The direction of the feed motion is perpendicular to the tool's axis of rotation. The speed motion is provided by the rotating milling cutter. The two basic forms of milling are peripheral milling (left) and face milling (right).





Material Removal Methods

Theory of producing chips in the machining operation

A cutting tool has one or more sharp cutting edges and is made of a material that is harder than the work material. The cutting edge serves to separate a chip from the parent work material. Connected to the cutting edge are two surfaces of the tool: the rake face and the flank.

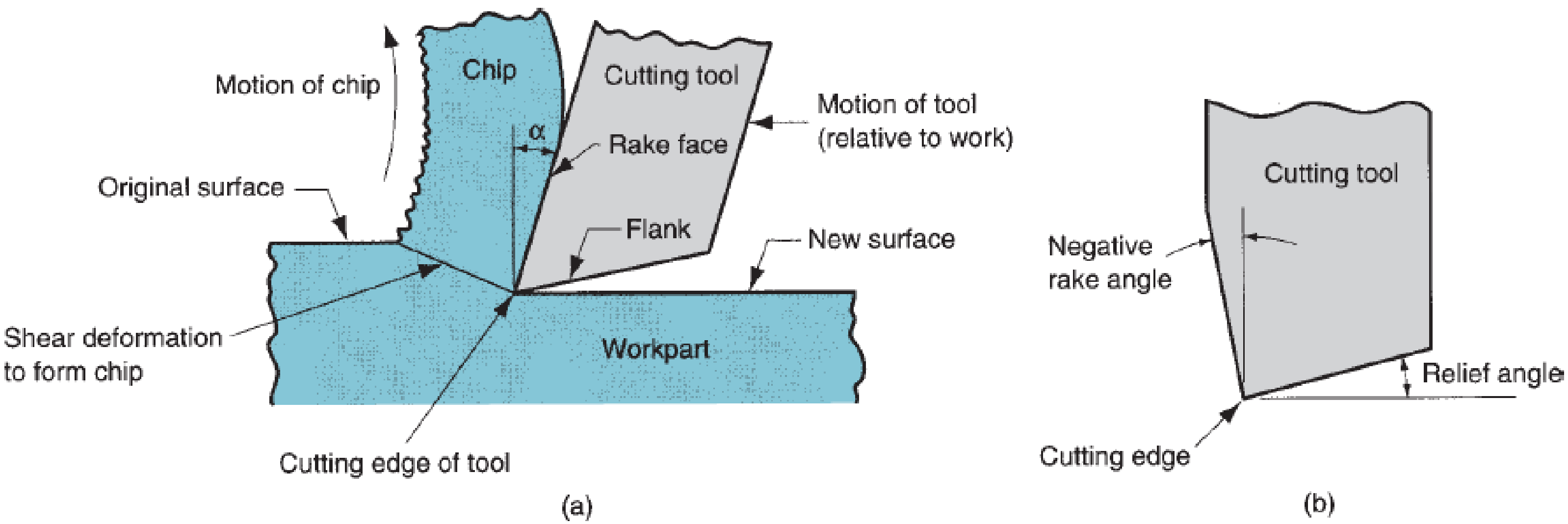


FIGURE 21.2 (a) A cross-sectional view of the machining process. (b) Tool with negative rake angle; compare with positive rake angle in (a).

Material Removal Methods

Theory of producing chips in the machining operation

The **rake** face, which deflects the chip, is oriented at a certain angle called the **rake angle** α. It is measured relative to a plane perpendicular to the work surface.

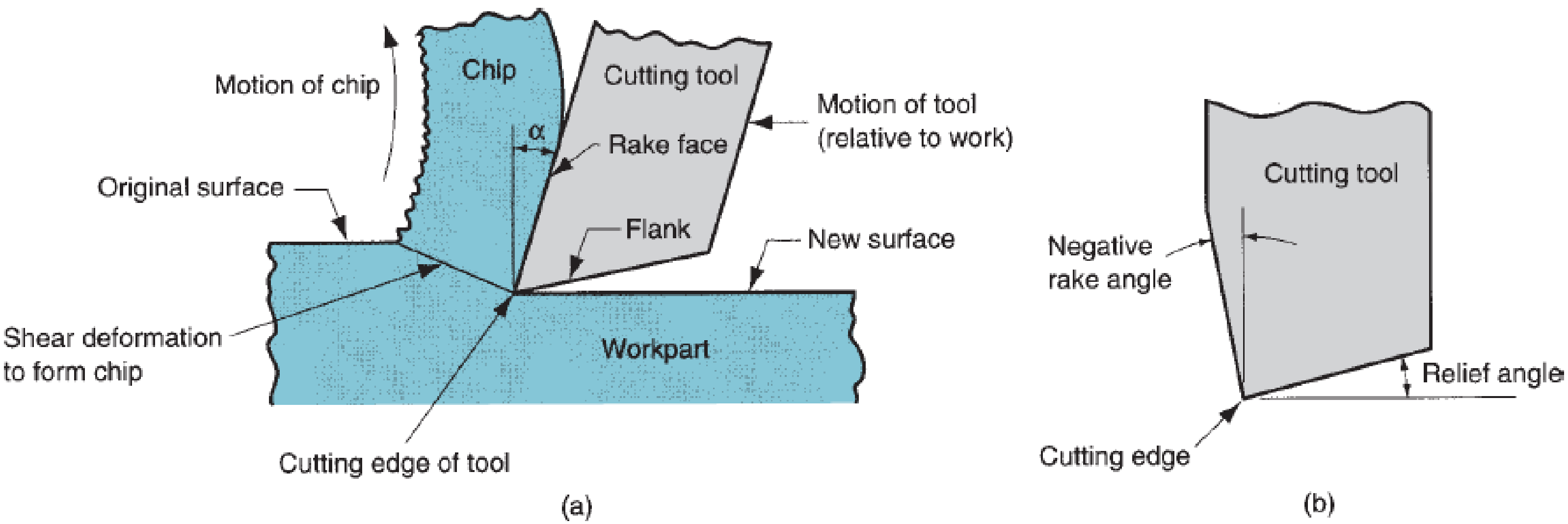


FIGURE 21.2 (a) A cross-sectional view of the machining process. (b) Tool with negative rake angle; compare with positive rake angle in (a).

Material Removal Methods

Theory of producing chips in the machining operation

The **flank** of the tool provides a clearance between the tool and the newly generated work surface, thus protecting the surface from abrasion, which would degrade the finish. This flank surface is oriented at an angle called the **relief angle**.

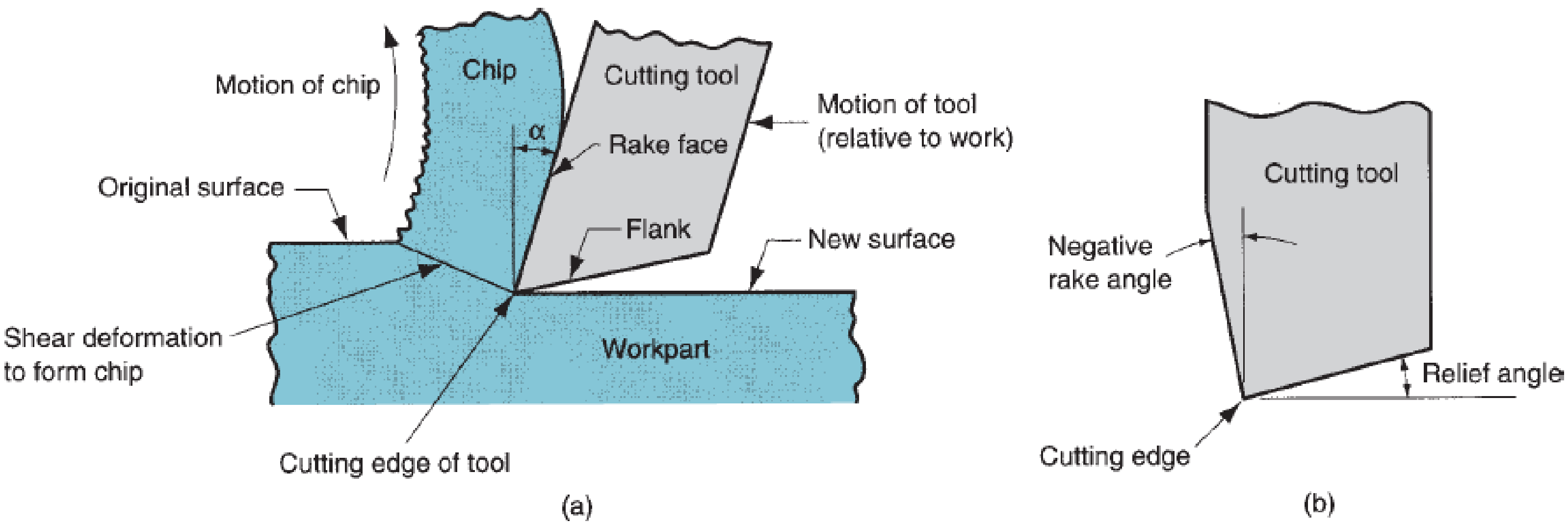
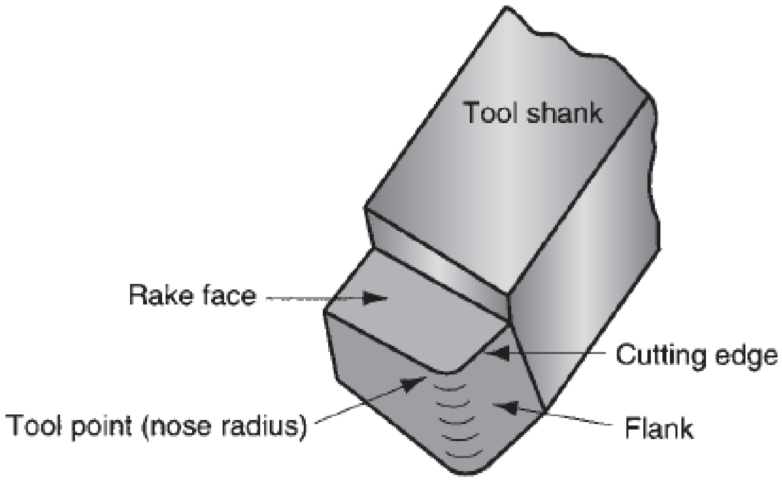


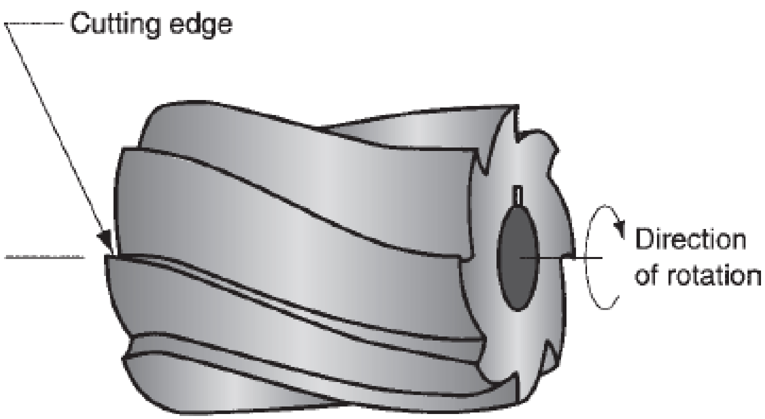
FIGURE 21.2 (a) A cross-sectional view of the machining process. (b) Tool with negative rake angle; compare with positive rake angle in (a).

Material Removal Methods

Theory of producing chips in the machining operation

Cutting tools can have a single cutting edge (left) are typically used in turning operations. Multiple cutting tools (right) are used when the relative motion is achieved through the use of spinning the tool such as drilling and/or milling.

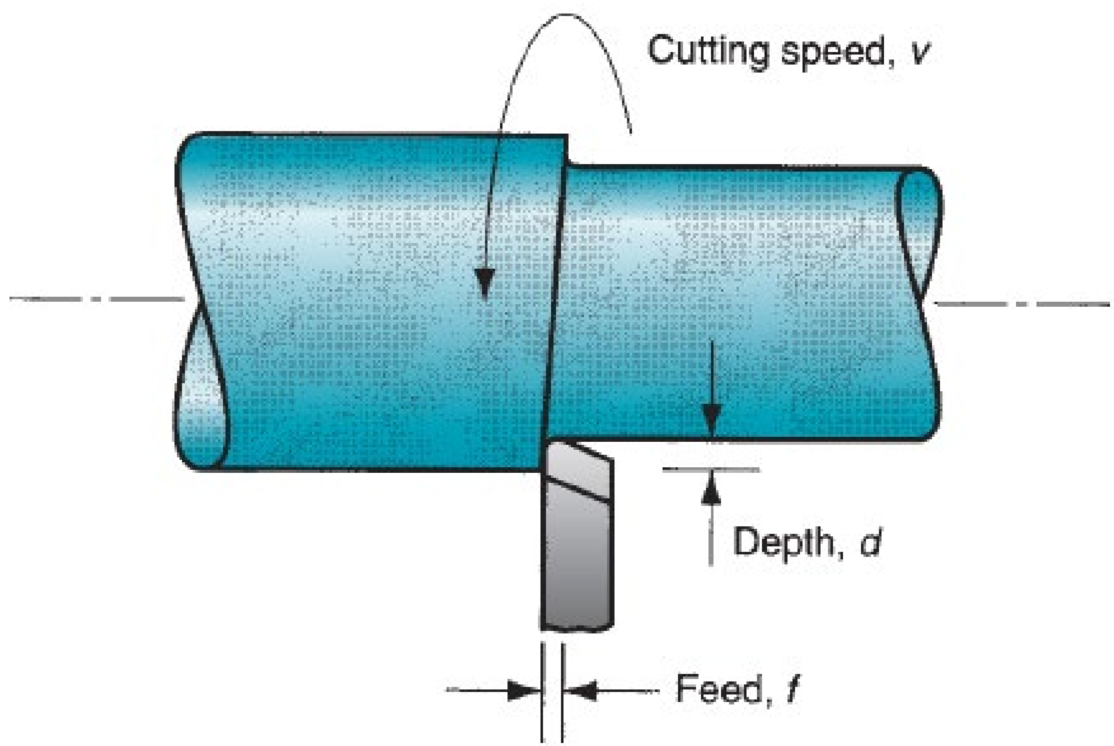




Material Removal Methods

Theory of producing chips in the machining operation

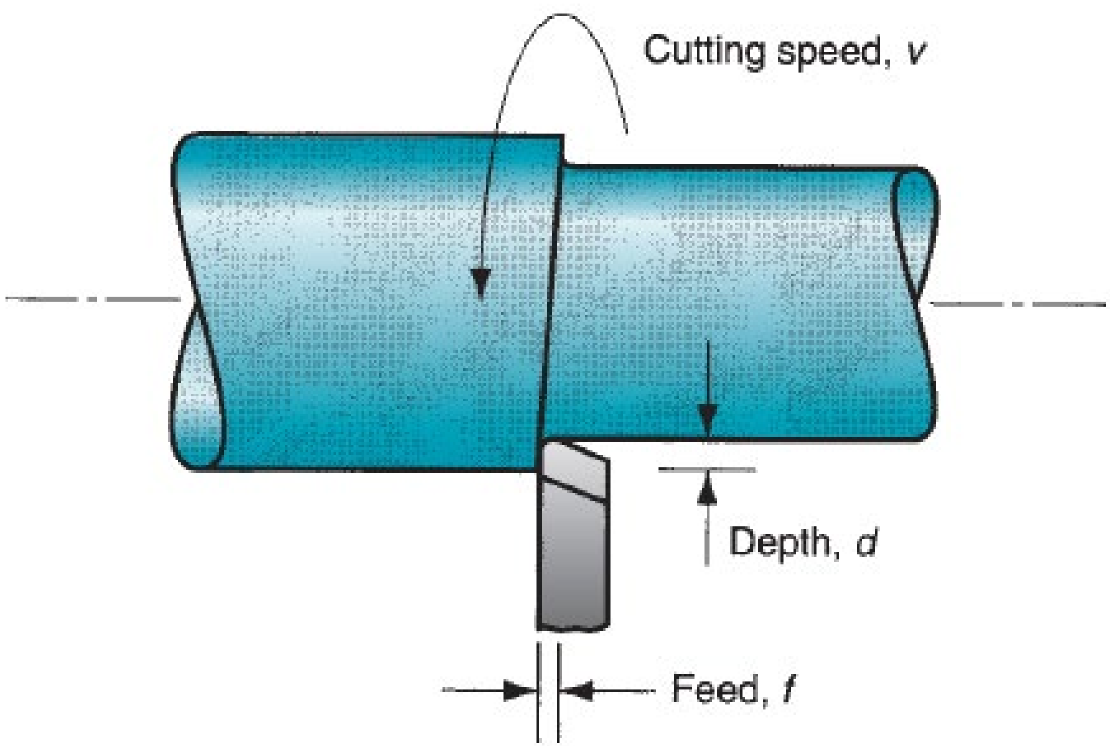
Regardless of the number of cutting edges, relative motion is required. The primary motion is accomplished at a certain cutting speed $\boldsymbol{v}$. In addition, the tool must be moved laterally across the work. This is a much lower motion, called the feed $\boldsymbol{f}$.



Material Removal Methods

Theory of producing chips in the machining operation

The remaining dimension of the cut is the penetration of the cutting tool below the original work surface, called the depth of cut ***d***. Collectively, speed, feed, and depth of cut are called the cutting conditions.



Material Removal Methods

Theory of producing chips in the machining operation

The material removal rate R_{MR} for a single cutting edge tool can be calculated using the following equation:

$$R_{MR} = vfd$$

Note that the SI units are not used for this equation, they should be:

R_{MR} = material removal rate (mm^3/s)
v = cutting speed (mm/s)
f = feed (mm)
d = depth (mm)

Material Removal Methods

Theory of producing chips in the machining operation

There are two types of cuts that can be made when machining, **roughing** and **finishing cuts**.

Roughing cuts are used to remove large amounts of material at any one time to obtain dimensions that are close to those desired quickly.

Finishing cuts are undertaken to more precisely achieve the desired dimensions and are done during the final stage. This is usually undertaken with higher cutting speeds and lower feed rates and cutting depths in comparison to roughing. This is critical particularly when tight tolerances are required.

Cutting fluid is frequently used in machining to keep both the tool and the component cool during the machining operation.

Material Removal Methods

Theory of producing chips in the machining operation

Machine tools are any piece of equipment that controls the relative position of the component being machined and the cutting tool. These machines are typically capable of producing components with dimensional accuracy of 0.025mm or better.

Accuracy in a machining operation is achieved when the deflection of the component and cutting tool are minimised. Therefore always ensure that both are extremely well supported as close to as possible the location that will be machined.

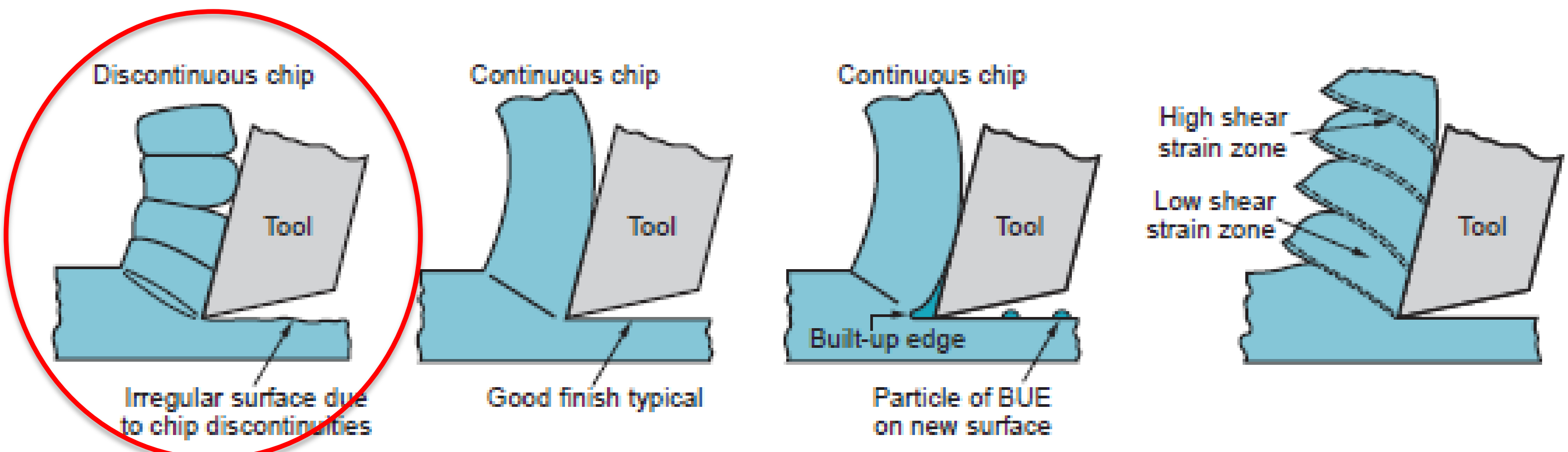
The conventional machine tools for turning, drilling and milling are lathes, drill presses and mills respectively, but other do exist as well.

Material Removal Methods

Theory of producing chips in the machining operation

The piece of material removed from the machined component is the chip. There are 4 different types of chips that can be generated;

- Discontinuous chip. When relatively brittle materials (e.g., cast irons) are machined at low cutting speeds, the chips often form into separate segments (sometimes the segments are loosely attached). This tends to impart an irregular texture to the machined surface. High tool–chip friction and large feed and depth of cut promote the formation of this chip type.

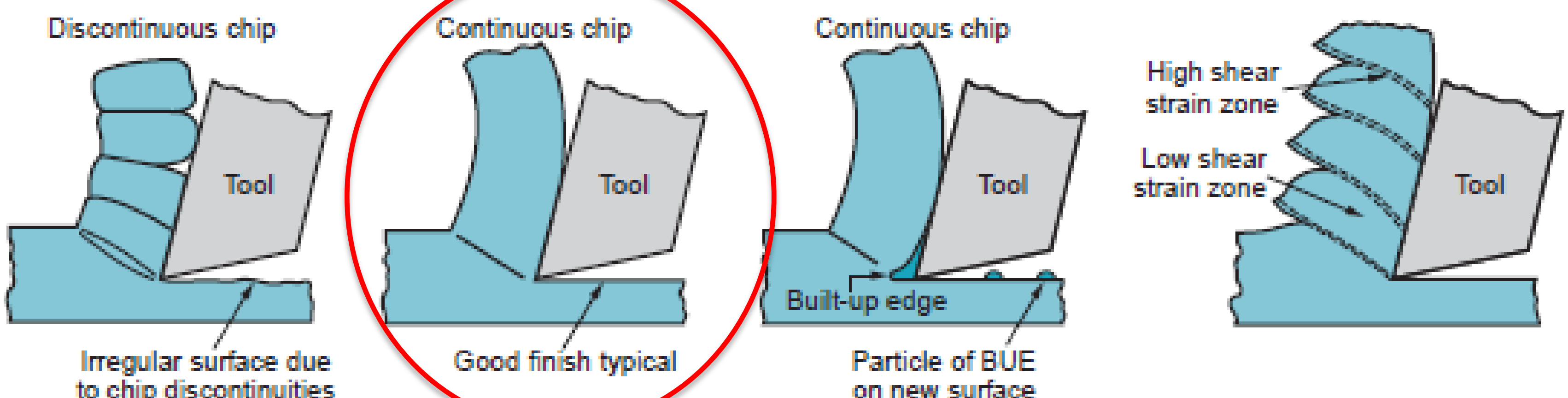


Material Removal Methods

Theory of producing chips in the machining operation

The piece of material removed from the machined component is the chip. There are 4 different types of chips that can be generated;

- Continuous chip. When ductile work materials are cut at high speeds and relatively small feeds and depths, long continuous chips are formed. A good surface finish typically results. A sharp cutting edge on the tool and low tool–chip friction encourage the formation of continuous chips, these can cause problems with regard to chip disposal and/or tangling about the tool. To solve these problems, turning tools are often equipped with chip breakers.

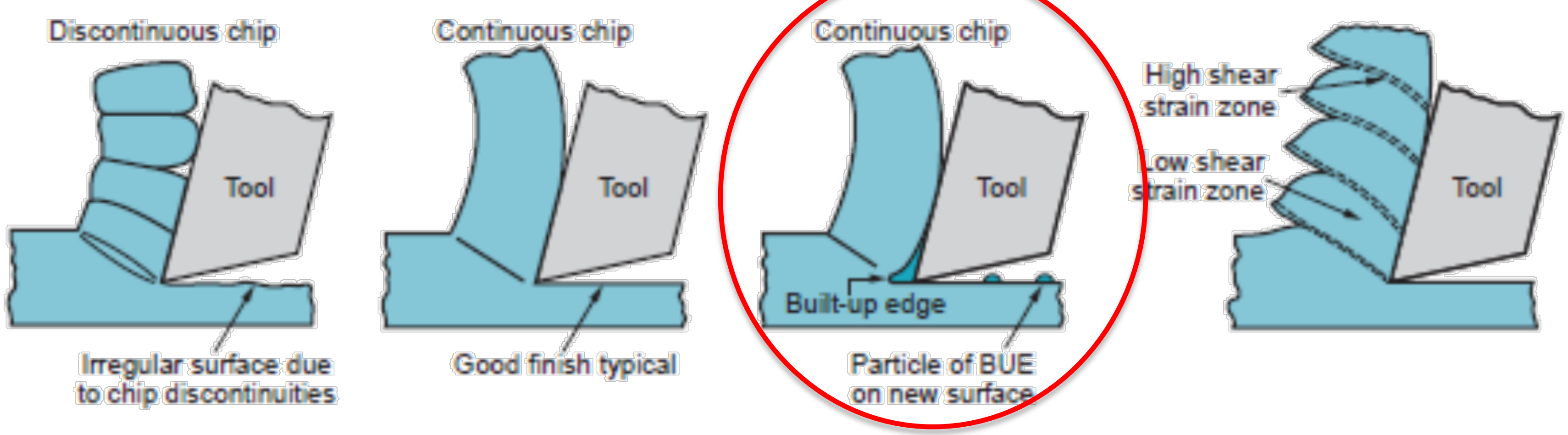


Material Removal Methods

Theory of producing chips in the machining operation

The piece of material removed from the machined component is the chip. There are 4 different types of chips that can be generated;

- Continuous chip with built-up edge. When machining ductile materials at low-to medium cutting speeds, friction between tool and chip tends to cause portions of the work material to adhere to the rake face of the tool near the cutting edge. This formation is called a built-up edge (BUE). Much of the detached BUE is carried away with the chip, sometimes taking portions of the tool rake face with it, which reduces the life of the cutting tool.

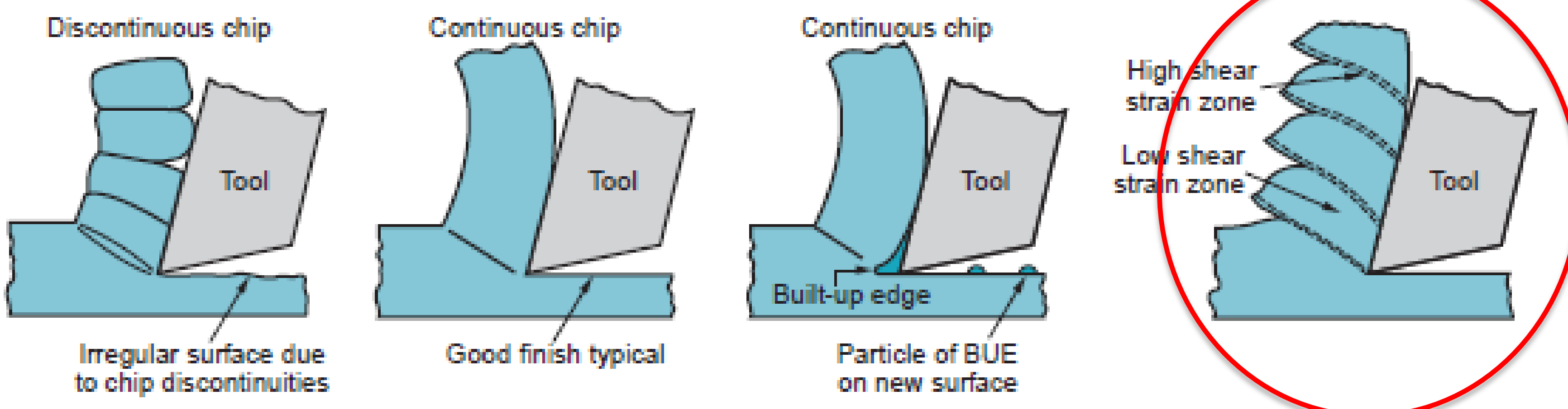


Material Removal Methods

Theory of producing chips in the machining operation

The piece of material removed from the machined component is the chip. There are 4 different types of chips that can be generated;

- Serrated chips. These chips are semi-continuous in the sense that they possess a saw-tooth appearance that is produced by a cyclical chip formation of alternating high shear strain followed by low shear strain. This fourth type of chip is most closely associated with certain difficult-to-machine metals such as titanium alloys, nickel-base superalloys, and austenitic stainless steels when they are machined at higher cutting speeds.

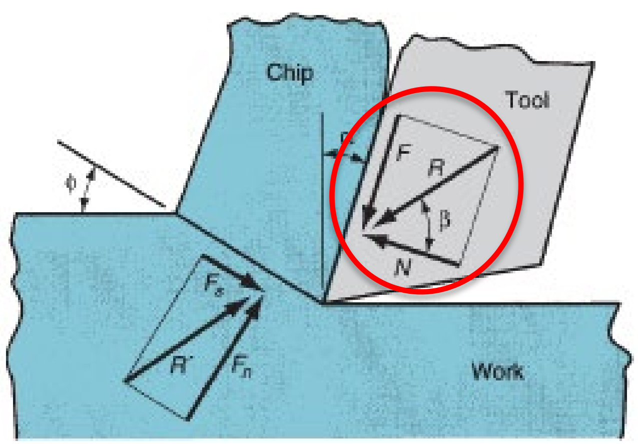


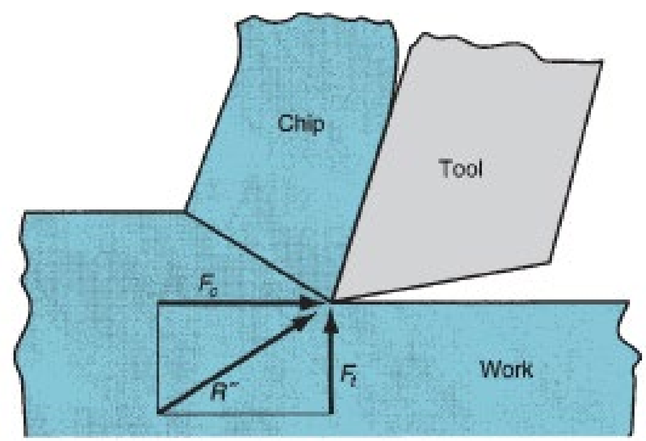
Material Removal Methods

Forces in Metal Cutting

The forces applied against the chip by the tool can be separated into two mutually perpendicular components: friction force and normal force to friction. The **friction force** F is the frictional force resisting the flow of the chip along the rake face of the tool. The **normal force** to friction N is perpendicular to the friction force. These two components can be used to define the **coefficient of friction,** μ between the tool and the chip:

$$\mu = \frac{F}{N}$$

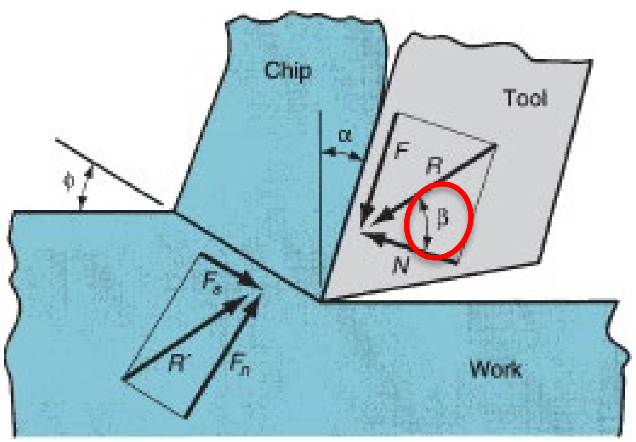


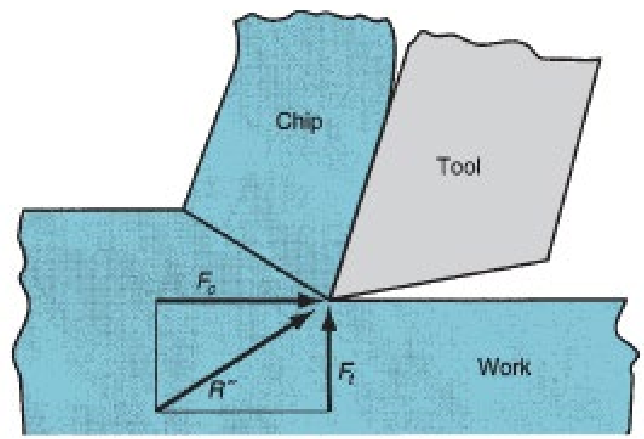


Forces in Metal Cutting

The friction force and its normal force can be added vectorially to form a **resultant force** R, which is oriented at an angle β, called the **friction angle**. The friction angle is related to the coefficient of friction as:

$$\mu = \tan\beta$$



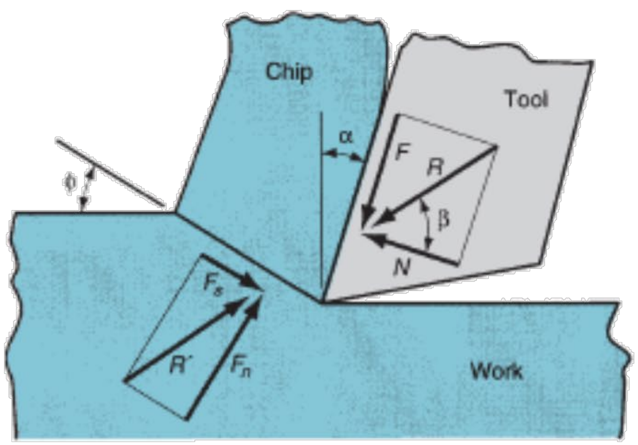


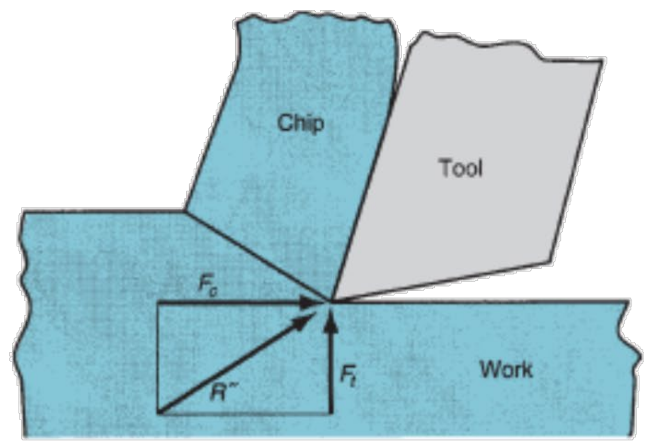
Material Removal Methods

Forces in Metal Cutting

In addition to the tool forces acting on the chip, there are two force components applied by the work piece on the chip: shear force and normal force to shear. The shear force F_s is the force that causes shear deformation to occur in the shear plane, and the normal force to shear F_n is perpendicular to the shear force. Based on the shear force, we can define the shear stress that acts along the shear plane between the work and the chip:

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



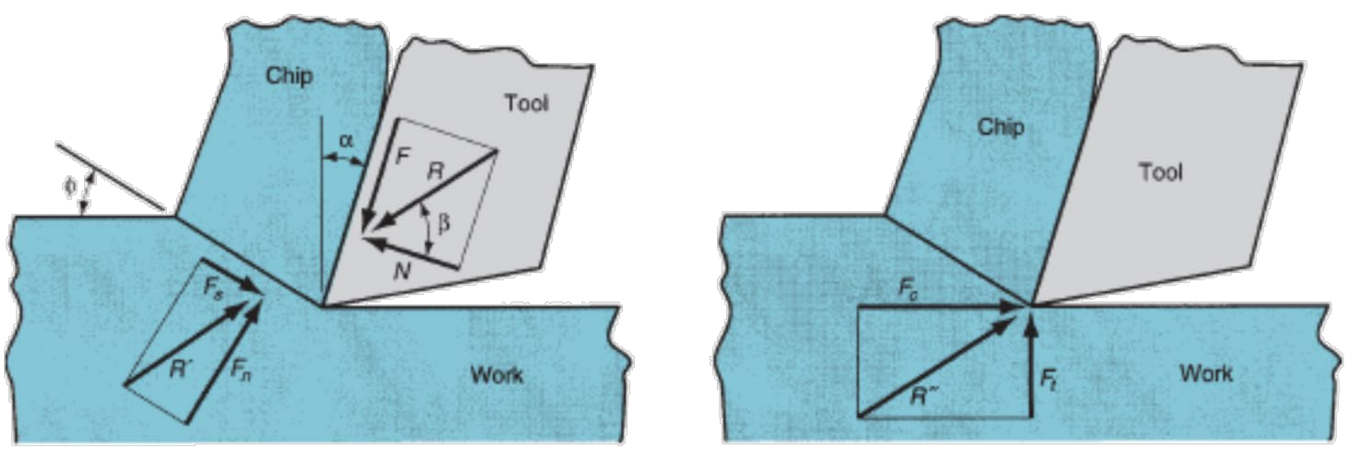


Material Removal Methods

Forces in Metal Cutting

The shear stress in this equation represents the level of stress required to perform the machining operation. Therefore, this stress is equal to the shear strength of the work material ($\tau = S$) under the conditions at which cutting occurs.

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

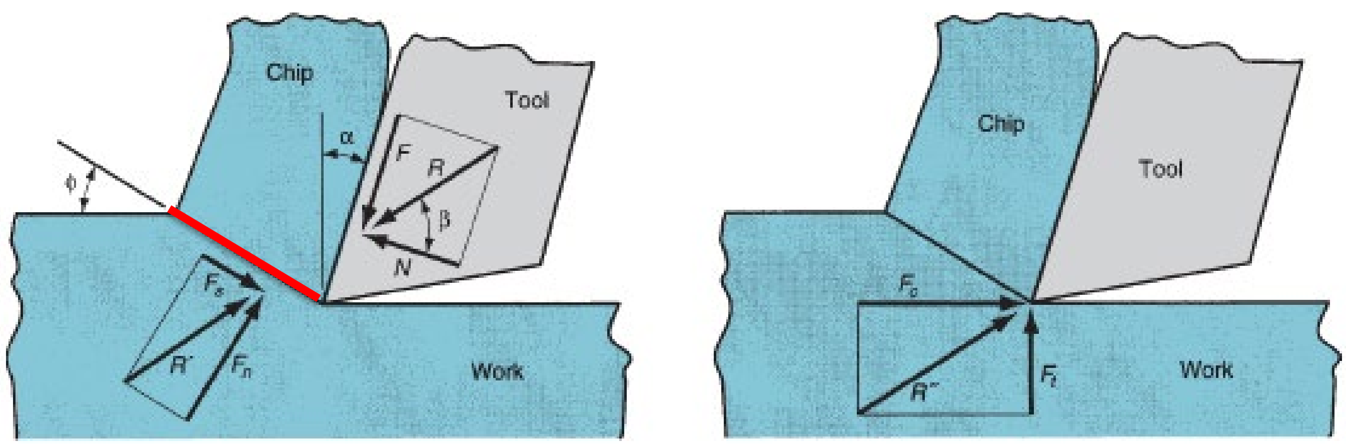


Material Removal Methods

Forces in Metal Cutting

A_s = area of the shear plane. This shear plane area can be calculated as:

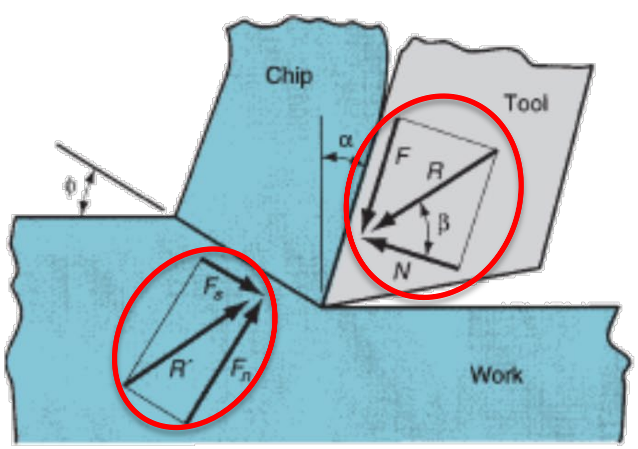
$$A_s = \frac{t_o w}{\sin \varphi}$$

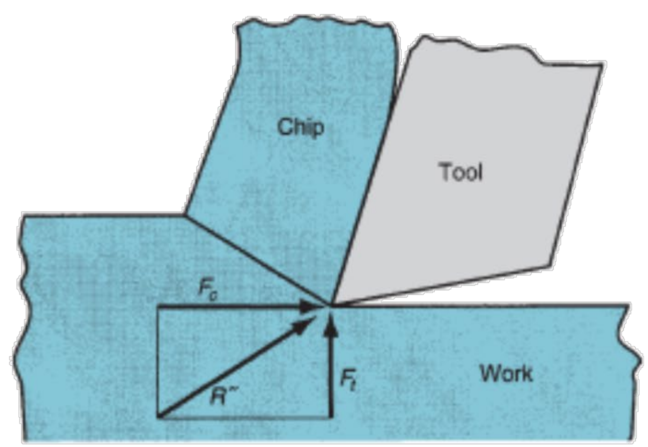


Material Removal Methods

Forces in Metal Cutting

None of the four force components F, N, F_s, and F_n can be directly measured in a machining operation, because the directions in which they are applied vary with different tool geometries and cutting conditions. However, it is possible for the cutting tool to be instrumented using a force measuring device called a dynamometer, so that two additional force components acting against the tool can be directly measured: cutting force and thrust force.

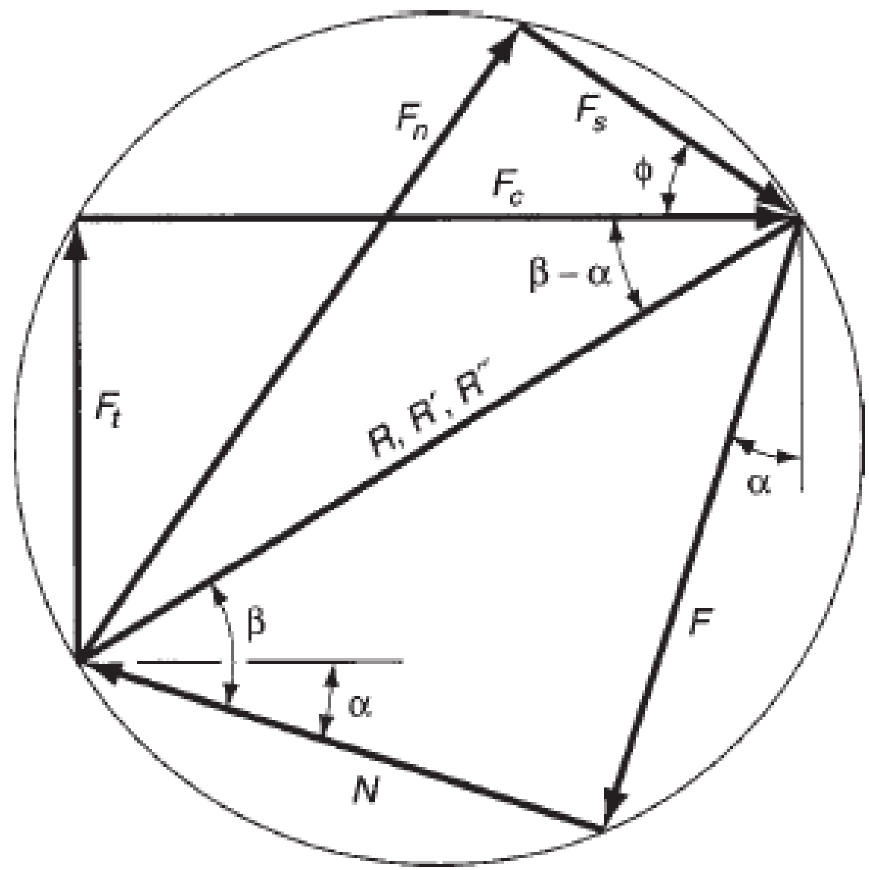




Material Removal Methods

Forces in Metal Cutting

The cutting force F_c is in the direction of cutting, the same direction as the cutting speed v, and the thrust force F_t is perpendicular to the cutting force and is associated with the chip thickness before the cut to. The cutting force and thrust force are shown on the right together with their resultant force R. The respective directions of these forces are known, so the force transducers in the dynamometer can be aligned accordingly.

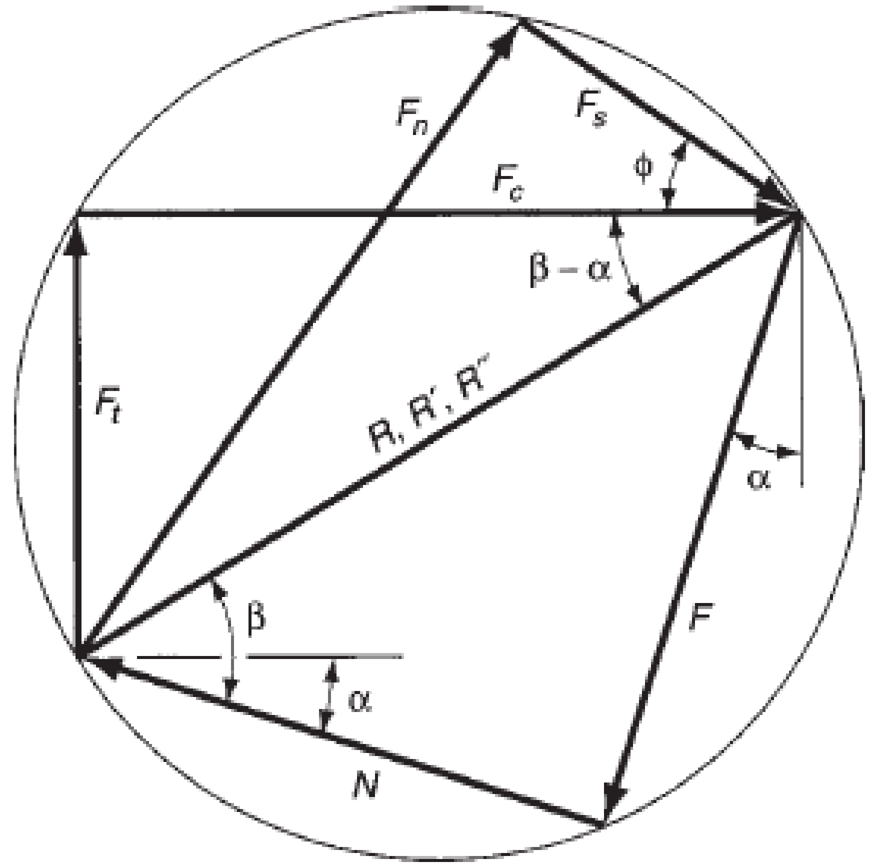


Material Removal Methods

Forces in Metal Cutting

Using the previous diagram and trigonometry, equations can be derived to relate the four force components that cannot be measured to the two forces that can be measured. These are:

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

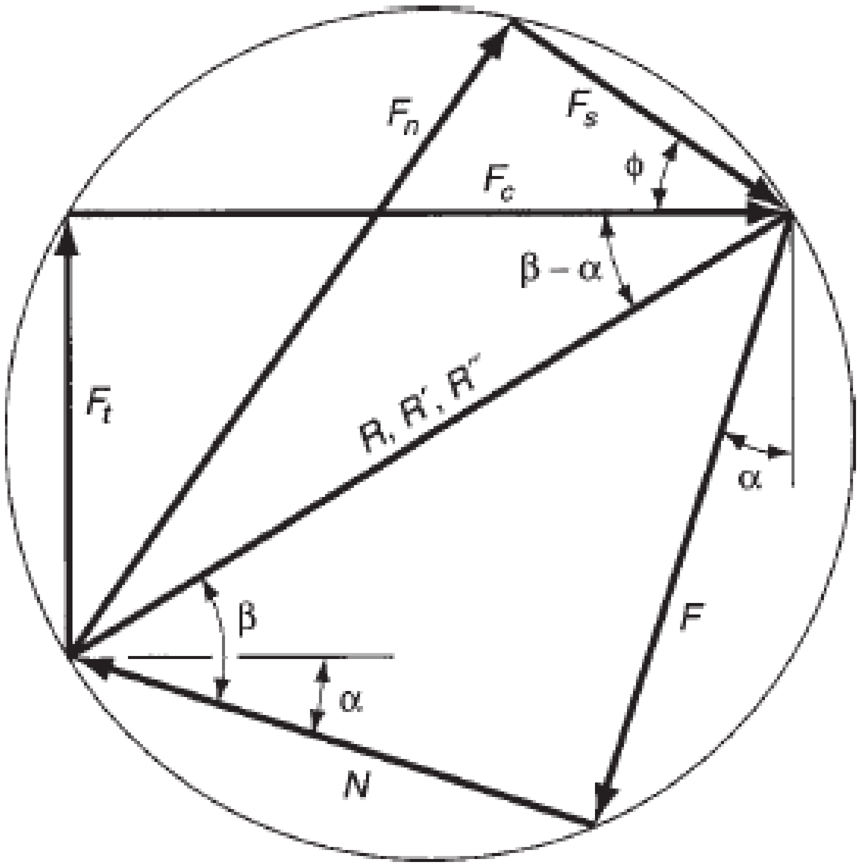


Material Removal Methods

Forces in Metal Cutting

If cutting force and thrust force are known, these four equations can be used to calculate estimates of shear force, friction force, and normal force to friction. Based on these force estimates, shear stress and coefficient of friction can be determined.

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



Material Removal Methods

Forces in Metal Cutting

Example 2

Suppose in Example 1 that cutting force and thrust force are measured during an orthogonal cutting operation: F_c = 1559 N and F_t = 1271 N. The width of the orthogonal cutting operation w = 3.0 mm. Based on these data, determine the shear strength of the work material.

Material Removal Methods

Forces in Metal Cutting

Example 2

Suppose in Example 1 that cutting force and thrust force are measured during an orthogonal cutting operation: F_c = 1559 N and F_t = 1271 N. The width of the orthogonal cutting operation w = 3.0 mm. Based on these data, determine the shear strength of the work material.

Remember, from Example 1:

$$\phi = 25.4°\,, t_0 = 0.5mm$$

Shear is given by:

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

But we need to determine F_s and A_s first

Example 2

Suppose in Example 1 that cutting force and thrust force are measured during an orthogonal cutting operation: F_c = 1559 N and F_t = 1271 N. The width of the orthogonal cutting operation w = 3.0 mm. Based on these data, determine the shear strength of the work material.

Determine F_s

$$F_s = F_c \cos\phi \ - F_t \sin\phi = 1559 \cos 25.4 - 1271 \sin 25.4 = 863.1\ N$$

Determine A_s

$$A_s = \frac{t_0 w}{\sin\phi} = \frac{0.5 \times 3}{\sin 25.4} = 3.497 mm^2$$

Sub back into the stress formula

$$\tau = 246.8 MPa$$

Material Removal Methods

Forces in Metal Cutting

Metal cutting was extensively researched by Eugene Merchant who determined that the angle φ is the angle where the shear stress is equal to the shear strength of the material. He demonstrate that the chip formation will occur in a way that minimises the energy required to create it.

Material Removal Methods

Forces in Metal Cutting

At any other angle, the shear stress of the material will exceed the shear stress being applied. By understanding this he was able to derive a mathematical expression relating the shear stress to the shear stress angle.

$$\tau = \frac{F_c \cos\varphi - F_t \sin\varphi}{t_o w / \sin\varphi}$$

He also found the relationship between the shear stress angle, the tool rake and the friction angle.

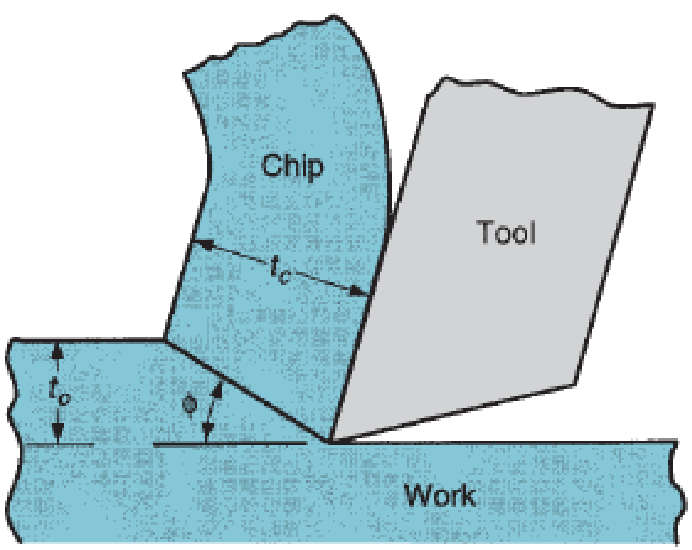
$$\varphi = 45 + \frac{\alpha}{2} - \frac{\beta}{2}$$

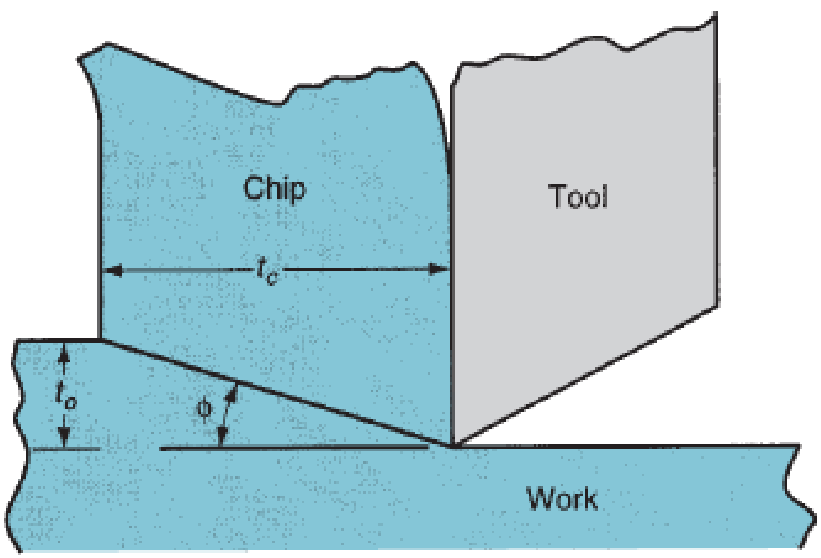
These equations should be considered as approximations as they do not consider the effect that temperature rises have on the material properties.

Material Removal Methods

Forces in Metal Cutting

With the aid of the previous equations and the following diagrams, it should be clear that the shear angle can be manipulated by the tool rake and friction angle. It controls the thickness of the chip and the greater this is, the greater the force will be required to cut into the material. Therefore tool rake and lubrication are important in machining.





Material Removal Methods

Forces in Metal Cutting

Example 3

Using the data and results from our previous examples, determine the friction angle (β) and the coefficient of friction (μ).

Using $\alpha = 10°$ and $\phi = 25.4°$

$$\varphi = 45 + \frac{\alpha}{2} - \frac{\beta}{2} \quad \rightarrow \quad \beta = 90 + \alpha - 2\phi$$

$$\beta = 90 + 10 - 2 \times 25.4 = 49.2°$$

$$\mu = \tan 49.2 = 1.159$$

Material Removal Methods

Power required for Machining Operations

The product of cutting force and speed gives the power (energy per unit time) required to perform a machining operation:

$$P_c = F_c v$$

Where:

P_c = cutting power (W)

F_c = cutting force (N)

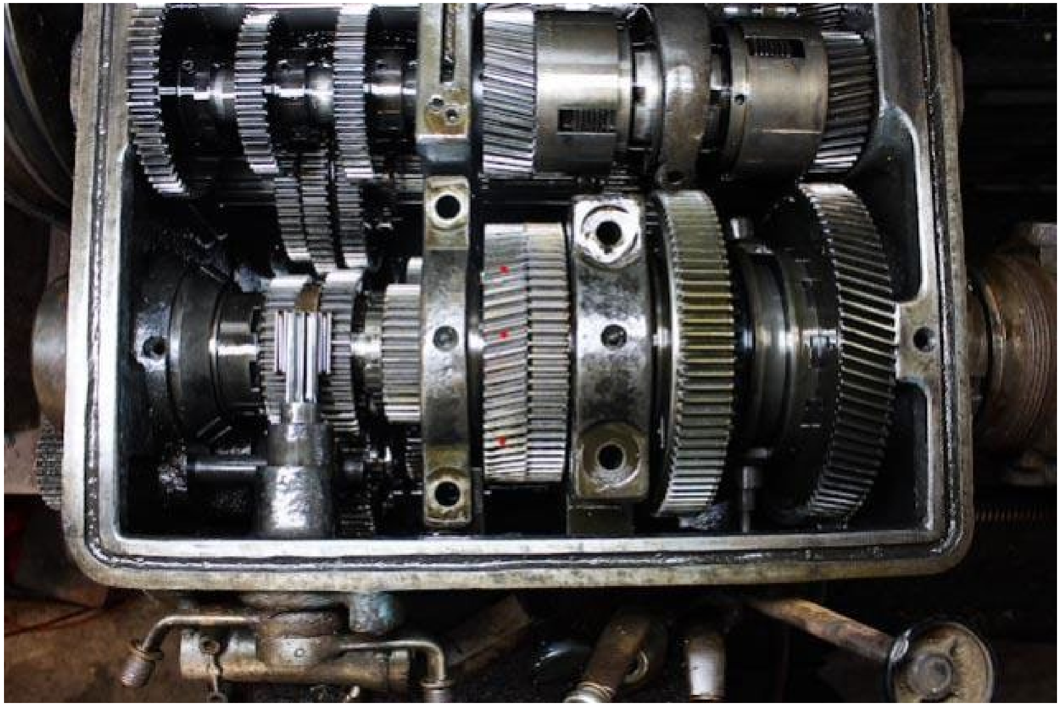
v = cutting speed (ms^{-1})

Note that this is the power required at the tool to complete the machining operation.

Material Removal Methods

Power required for Machining Operations

This does not take into account the losses associated with delivering the necessary power. Most machine tools are approximately 90% efficient with the majority of those losses associated with the gears used to reduce the motor speed and increase the torque required.



Material Removal Methods

Power required for Machining Operations

It is often useful to convert power into power per unit volume rate of metal cut. This allows comparison of the power required for different materials independent of what the suitable material removal rate might be for each.

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

Where:

P_u = power per unit volume rate

P_c = cutting power (W)

R_{MR} = cutting force (N)

Material Removal Methods

Power required for Machining Operations

The following table is a typical list of materials and the required power to remove per unit of volume. These values assume that the tool being used is sharp and the chi thickness = 0.25mm.

Material	Brinell Hardness	Specific Energy U or Unit Power P_u N-m/mm^3	Specific Energy U or Unit Power P_u in-lb/in^3	Unit Horsepower HP_u hp/(in^3/min)
Carbon steel	150–200	1.6	240,000	0.6
	201–250	2.2	320,000	0.8
	251–300	2.8	400,000	1.0
Alloy steels	200–250	2.2	320,000	0.8
	251–300	2.8	400,000	1.0
	301–350	3.6	520,000	1.3
	351–400	4.4	640,000	1.6
Cast irons	125–175	1.1	160,000	0.4
	175–250	1.6	240,000	0.6
Stainless steel	150–250	2.8	400,000	1.0
Aluminum	50–100	0.7	100,000	0.25
Aluminum alloys	100–150	0.8	120,000	0.3
Brass	100–150	2.2	320,000	0.8
Bronze	100–150	2.2	320,000	0.8
Magnesium alloys	50–100	0.4	60,000	0.15

Material Removal Methods

Power required for Machining Operations

If the tool is worn, the values provided here should be multiplied by a factor between 1 and 1.25, with the larger values in this range being used when the tool wear is greater.

Material	Brinell Hardness	Specific Energy U or Unit Power P_u N-m/mm^3	Specific Energy U or Unit Power P_u in-lb/in^3	Unit Horsepower HP_u hp/(in^3/min)
Carbon steel	150–200	1.6	240,000	0.6
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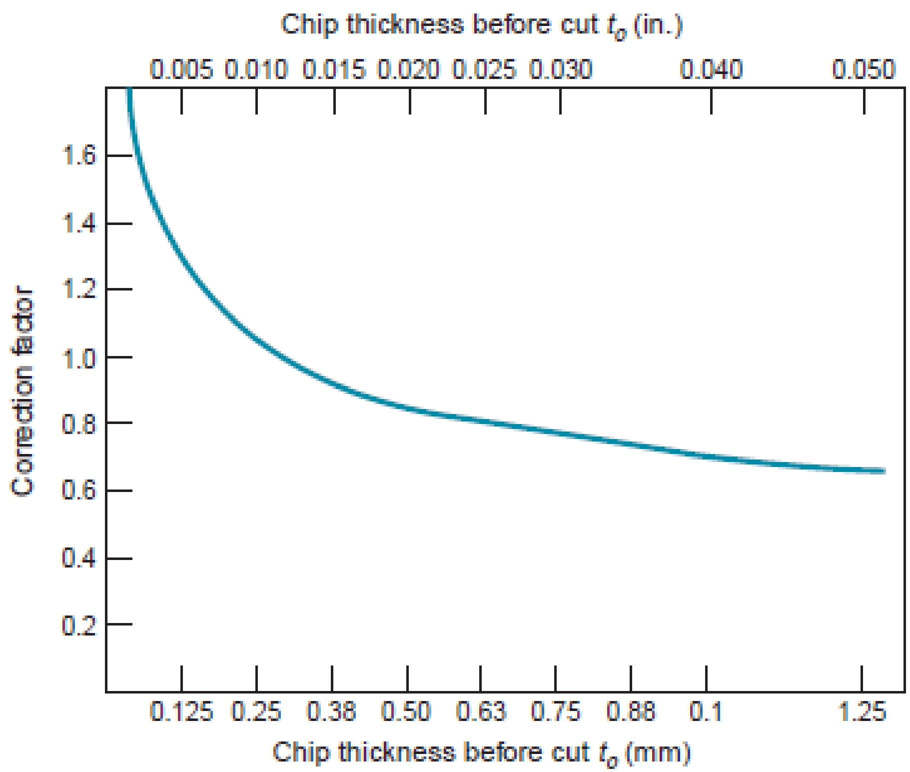
Stainless steel	150–250	2.8	400,000	1.0
Aluminum	50–100	0.7	100,000	0.25
Aluminum alloys	100–150	0.8	120,000	0.3
Brass	100–150	2.2	320,000	0.8
Bronze	100–150	2.2	320,000	0.8
Magnesium alloys	50–100	0.4	60,000	0.15

Material Removal Methods

Power required for Machining Operations

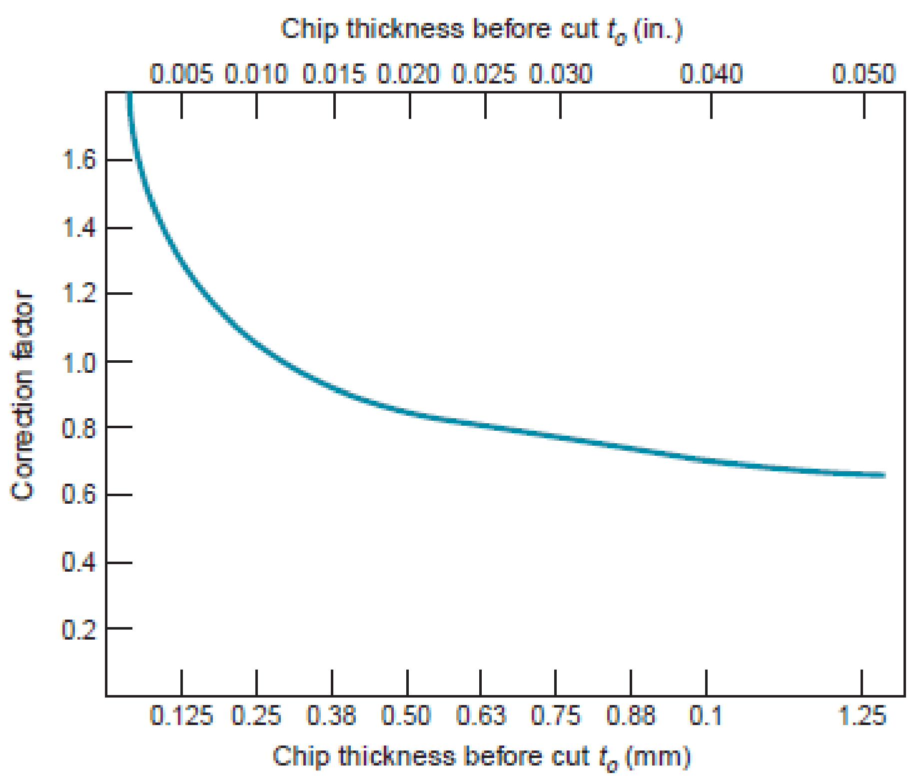
A correction factor can also be applied to values in the previous chart for the power per unit volume of each material if the it is desired to alter the chip thickness after selecting the appropriate value from the graph below.



Material Removal Methods

Power required for Machining Operations

Note that less power is used to remove more material per cut in comparison to less removing less. What are the consequences of doing this but?



Material Removal Methods

Power required for Machining Operations

Example 4

Continuing with our previous examples, let us determine cutting power and specific energy in the machining operation if the cutting speed = 100 m/min. Summarizing the data and results from previous examples, t_o = 0.50 mm, w = 3.0 mm, F_c = 1557 N.

Material Removal Methods

Power required for Machining Operations

Example 4

Continuing with our previous examples, let us determine cutting power and specific energy in the machining operation if the cutting speed = 100 m/min. Summarizing the data and results from previous examples, t_o = 0.50 mm, w = 3.0 mm, F_c = 1557 N.

Find cutting Power P_c

$$P_c = F_c v = 1557 \times \frac{100}{60} = 155700\,\frac{J}{min} = \ 2595\,W$$

Specific energy will be given by

$$U = \frac{F_c v}{v t_0 w} = \frac{155700}{100x10^3 \times 0.5 \times 3} = 1.038\ \frac{N.m}{mm^3}$$

Material Removal Methods

Cutting Temperatures

Of the total energy consumed in machining, nearly all of it (~98%) is converted into heat. This heat can cause temperatures to be very high at the tool – chip interface — over 600^{O}C is not unusual. The remaining energy (~2%) is retained as elastic energy in the chip.

Cutting temperatures are important because high temperatures;

1. reduce tool life
2. produce hot chips that pose safety hazards to the machine operator, and
3. can cause inaccuracies in work part dimensions due to thermal expansion of the work material.

Material Removal Methods

Cutting Temperatures

One method for determining the temperature increase associated with machining was derived by Cook by using experimental data for a variety of work materials to establish parameter values for the following equation:

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

Where:

ΔT = mean temperature rise at the tool-chip interface (C^O)

U = specific energy in the operation ($N.m/mm^3$)

v = cutting speed (ms^{-1})

t_o = chip thickness before cut (m)

ρC = volumetric specific heat of the work material, $J/mm^3.C$

K = thermal diffusivity of the work material (m^2/s)

Material Removal Methods

Cutting Temperatures

Example 5

For the specific energy obtained in Example 21.4, calculate the increase in temperature above ambient temperature of 20^{O}C. Use the given data from the previous examples in this lecture: v = 100 m/min, t_o = 0.50 mm. In addition, the volumetric specific heat for the work material = 3.0 (10^{-3}) J/mm^3.C, and thermal diffusivity = 50×10^{-6} m^2/s. The specific energy in the operation is 1.038 N.m/mm^3.

Material Removal Methods

Cutting Temperatures

Example 5

For the specific energy obtained in Example 21.4, calculate the increase in temperature above ambient temperature of $20^{O}C$. Use the given data from the previous examples in this lecture: v = 100 m/min, t_o = 0.50 mm. In addition, the volumetric specific heat for the work material = 3.0 (10^{-3}) J/mm^3.C, and thermal diffusivity = 50×10^{-6} m^2/s. The specific energy in the operation is 1.038 N.m/mm^3.

$$\Delta T = \frac{0.4 \times 1.038}{3 \times 10^{-3}} \left(\frac{\frac{100}{60} \times 0.0005}{50 \times 10^{-6}} \right)^{0.333} = 353°C$$