Metal cutting, commonly called machining, is the removal of unwanted portions from a block of material in the form of chips so as to obtain a finished product of desired size, shape, and finish.
There are seven *basic* chip formation processes

- **Shaping**
- **Drilling**
- **Turning**
- **Milling**
- **Sawing**
- **Broaching**
- **Abrasive machining**
Oblique Cutting: The cutting edge is set at an angle (the tool cutting edge inclination $\lambda_s$). This is the case of three-dimensional stress and strain conditions.
Orthogonal cutting: The cutting edge is straight and is set in a position that is perpendicular to the direction of primary motion.

This allows us to deal with stresses and strains that act in a plane.
In order to better understand this complex process, the tool geometry is simplified from the three-dimensional (oblique) geometry, to a two-dimensional (orthogonal) geometry.
Chip formation is a localized shear deformation resulting in the failure of the workpiece material immediately ahead of the cutting edges of the tool due to the force applied to the workpiece by the cutting tool, and relative motion between the tool and the workpiece.
During orthogonal machining, shearing takes place along a plane making an angle, which is called the shear angle $\phi$, with the horizontal.

This action transforms a volume of metal with thickness $t$ and $w$ (undeformed chip thickness and width, respectively) into a chip with thickness $t_c$ and width $w$. 

Orthogonal Cutting
Important observations during metal cutting are:

1. **Distortion** of the workpiece and the cutting tool due to the cutting force applied by the cutting tool.

2. **Generation of heat** due to the
   - work required to deform the workpiece and the chip,
   - friction between the face of the tool and the chip,
   - friction between the flank of the tool and the workpiece.
Temperature Distribution

[Diagram showing temperature distribution in a machining process, highlighting different zones such as the primary shear zone, secondary shear zone, and heat-affected zone in the workpiece.]
Strength

High-strength materials require larger forces than do materials of lower strength, causing greater tool and workpiece deflections; increased friction force and heat generation, and temperature; and requirement of greater work input.

On the other hand, hard and abrasive constituents such as carbides in steel accelerate tool wear.
Ductility

Ductility is an important factor.

*Highly ductile materials not only permit extensive plastic deformation of the chip during cutting, which increases work, heat generation, and temperature; but they also result in continuous chips which remain in contact longer with the tool face, thus causing more frictional heat generation.*

Chips of this type are severely deformed and have a characteristic curl.

*(Continuous chips)*
**Effects of Work Material Properties**

**Ductility**

*Brittle* materials cause *small segments of chips* due to the brittle failure along the shear zone.

Such chips are called *discontinuous* or *segmented* chips, and provide fairly *good surface finish*.

Are also observed when cutting with:
- Small rake angle
- Large depth of cut
- Machining *ductile* materials at
  - *low cutting speed*
  - *large feed*
Continuous Chip with Built-up Edge

When cutting ductile materials with a high coefficient of friction, the local high temperature and extreme pressure in the cutting zone cause the work material to adhere or weld to the cutting edge of the tool forming a built-up edge.

When the chip breaks down, the broken pieces are carried away by the underside of the chip and stick on the machined surface.
Continuous Chip with Built-up Edge

This type of chip is called **continuous chip with built-up edge**.

This undesirable occurrence causes vibration, poor surface finish, and shorter tool life.

Formation of built-up edge can be eliminated or minimized by 1) reducing the depth of cut; 2) increasing the cutting speed (while decreasing the depth of cut or/and feed); 3) increasing the rake angle; 4) using a cutting fluid (coolant).
Types of Chips

- Discontinuous (Segmented)
- Continuous
- Continuous with built-up edge
The geometry of a single-point cutting tool is critical to the performance of the tool during metal removal. Important surfaces and angles on a typical HSS single-point cutting tool used in shaping or turning operations are:

- **Face** is surface of the tool over which the chip flows.
- **Flank** is the surface of the tool which is in contact with the workpiece.
Rake angles are used to define the inclination of the face. The face is inclined backwards with respect to the cutting edge, so that the chip is directed upward from the machined surface.

Relief angles are used to define the inclination of the surfaces of the tool which are in contact with the workpiece (e.g. flank).

These surfaces are inclined, so that the rubbing of the tool on to the workpiece is prevented.

True rake is defined as the inclination of the tool face at the cutting edge as measured in the direction of actual chip flow.
Cutting Tool Geometry - Single Point Cutting Tool

- End cutting edge angle, ECEA
- Nose radius, NR
- Side cutting edge angle, $\kappa$
- Side rake angle, $\gamma_s$
- Side relief angle, SRA
- Back rake angle, $\gamma_b$
- End relief angle, ERA

Diagram showing:
- Work
- Chip
- Tool
- Turning single point tool process
- $D_1$
- $D_2$
- $f_r$
- $N_g$
Rake Angle

For cutting mild steel, the best rake angle is 10 - 20 degrees.

Positive rake angle:
- Increased strength
- Increased heat conduction capacity
- Easy cutting

Negative rake angle:
- Reduced strength at tool neck and cutting edge

End relief angle, ERA

Back rake angle, $\gamma_b$
Small rake angles cause high compression, tool forces, and friction which result in a thick, highly deformed, hot chip. Large rake angles reduce compression, the forces, and the friction resulting in a thinner, less deformed, and cooler chip.

On the other hand larger positive rake angles cause reduced strength of the cutting tool due to the reduced tool section and reduced capacity to conduct heat away from the cutting edge.

In order to provide greater strength at the cutting edge and better heat conductivity, zero or negative rake angles are used on sintered carbide or ceramic cutting tools.
Shear Plane

Angle between tool face and shear plane is about 90 degrees.

For the same depth of cut, increased rake angle increases the shear angle $\phi$ and decreases the shear plane edge length.

Thus it becomes possible to remove the chip with less power.
As a chip breaker, a **groove on the tool face** is employed for deflection of the chip at a **sharp angle** and **causing it to break** into short pieces that are easier to remove and are not so likely to become **tangled** (dolaşma, karışma) **in the machine** and possibly cause damage to personnel.
Solid chip breakers are available in various lengths and angles to suit each metal cutting application.

The adjustable chip breaker can eliminate the need for stocking various sizes of solid chip breakers.
Cutting Tool Materials

Cutting tool materials should have:

1. Strength,
2. Toughness to resist fracture,
3. Hardness and wear resistance at high temperatures,
4. Low coefficient of friction.

(5. Favorable cost.)
2. High Speed Steel (HSS) (1900)

Typical composition of this high alloy steel is 18-4-1 (tungsten 18%, chromium 4%, vanadium 1%).

Retains its hardness at temperatures up to 600°C.

Compared with tool steel, it can operate at about double the cutting speed with equal life, resulting in its name high-speed steel.

HSS is widely used for drills and many types of general-purpose milling cutters and in single-point tools used in general machining.

For high-production machining it has been almost completely replaced by carbides and coated tools.
Cutting Tool Materials

3. TiN Coated High Speed Steel (HSS) (1980)

Coated HSS provides significant improvements in cutting speeds, with increases of 10 to 20% being typical.

In addition to hobs, gear-shaper cutters, and drills; HSS tooling coated by TiN includes reamers, taps, chasers, spade-drill blades, broaches, band saw and circular saw blades, insert tooling, form tools, end mills, and an assortment of other milling cutters.

Physical vapor deposition has proved to be the most viable process for coating.
4. Cemented Carbide (Sintered Carbide) (1947)

Nonferrous alloys produced by powder metallurgy.

The early versions, which are still widely used, had tungsten carbide as the major constituent and cobalt as a binder.

Recent types of carbides utilize very fine micro particles dispersed (cemented) in the carbide structure (approx. 10% TiC and TaC) for improving toughness and tool life.

They can be operated at cutting speeds 200 to 500% greater than those used for HSS, and they have replaced HSS in many processes.
Many carbide tools are made in the form of **throwaway** inserts, having **three to eight cutting edges**, and are held mechanically in tool holders.

When one cutting edge becomes dull, the insert is repositioned to a new edge; when all the edges become dull, it is thrown away.
5. **Ceramic** *(1950s)*

Ceramics are made of pure aluminum oxide by powder metallurgy techniques.

They can be operated at from two or three times the cutting speed of tungsten carbide, usually requiring no coolant. Usually they are in the form of disposable *(throwaway)* tips.

Ceramics are usually as hard as carbides but are more brittle, and require more rigid tool holders and machine tools.
Cermets are best suited for finishing. Approximately 70 percent ceramic and 30 percent titanium carbide, are pressed into billets under extremely high pressure and temperature. After sintering, the billets are sliced to the desired tool shapes. Subsequent grinding operations for final size and edge preparation, complete the manufacturing process.
6. **Diamond**

Hardest material known.

Diamond is pure carbon, and carbon has a strong affinity for iron, forming iron oxide or carbide; which results in removal of carbon, thus rapid wear of the tool during machining of ferrous workpieces.

Therefore, they should only be used on non-ferrous metals.

Has limited but important application in machining operations such as in boring.

Diamond machining is done at high speeds with fine feeds for finishing, and produces excellent finishes.

Diamond particles are used in grinding wheels.

Diamond tools are used for truing the grinding wheels.
Some diamond cutting tools are made of a diamond crystal compaction (many small crystals pressed together) bonded to a carbide base.

These diamond cutting tools should only be used for light finishing cuts of precision surfaces.

Feeds should be very light and speeds are usually high.

Rigidity in the machine tool and the setup is very critical because of the extreme hardness and brittleness of diamond.
7. **Cubic Boron Nitride (CBN)** *(1965s)*

Man-made tool material.

Similar to diamond in its polycrystalline structure and is also bonded to a carbide base.

Hardest material known other than diamond.

Retains it hardness at elevated temperatures *(~ 1000°C)*.

Still, CBN should mainly be considered as a finishing tool material because of its extreme hardness and brittleness.

Can be used to machine hard aerospace materials.
A tough, shock-resistant carbide tool is coated with a thin, hard, crater resistant surface material. 

- **TiC-coated tools** have two or three times the wear resistance of the best uncoated tool with the same breakage resistance. This results in 50 to 100% increase in the speed for the same tool life.

- **Ceramic (Al₂O₃)-coating** permits 90% speed increase in machining of steel. Gives excellent crater wear resistance.
Titanium carbide remains as the basic material covering the substrate for strength and wear resistance. The second layer is aluminium oxide which has proven chemical stability at high temperatures and resists abrasive wear. The third layer is a thin coating of titanium nitride to give the insert a lower coefficient of friction and to reduce edge build-up.

FIGURE 22-6 Triple-coated carbide tools provide resistance to wear and plastic deformation in machining of steel, abrasive wear in cast iron, and built-up edge formation.
Hardness - Strength - Toughness
Cutting Tool Materials

FIGURE 21-1 Improvements in cutting tool materials have led to significant increases in cutting speeds (and productivity) over the years.
*** MACHINING/cutting tool materials (SME/Wiley’s video)***
A tool may be said to reach end of its life when a further wear causes one, some or all of the followings:

1. Loss of dimensional **accuracy** of the workpiece,
2. Excessive **surface roughness** on the workpiece,
3. Increased **power requirement** of the machine tool,
4. Physical **loss of the cutting edge** of the cutting tool.

The cutting time accumulated before failure is termed as **tool life**.
Tool wear, which is increased by high temperatures which cause the tool material to lose its hardness and thus make it more subjected to wear, occurs mainly in two areas.

1. On tool face, causing formation of craters due to the severe abrasion between the chip and the tool face, being more common on HSS tools in machining ductile materials.
2. On the **flank** below the cutting edge, resulting from contact with the abrasive machined surface both in rough and finishing operations.

*For carbide and ceramic tools, flank wear is the most common type of wear.*
Tool wear is also observed at the edge and the nose of the tool areas.

3. **Edge wear** occurs on the clearance face of the tool and is mainly caused by the rubbing of the newly machined workpiece surface on the contact area of the tool edge. This type of wear occurs on all tools while cutting any type of work material.

4. **Nose wear (corner wear)** is usually observed after a considerable cutting time, nose wear appears when the tool has already exhibited land and/or crater wear. Wear on the nose of the cutting edge usually affects the quality of the surface finish on the workpiece.
Tool Wear

[Diagram showing parts of a tool with labels: Tool cutting part, Chip contact area, Crater wear, Corner wear, Major cutting edge, Flank wear, VB.]

- Tool cutting part
- Chip contact area
- Crater wear
- Corner wear
- Major cutting edge: perfectly sharp at the beginning of cutting, worn after cutting for some period of time
- Flank wear
- VB
Flank wear appears in the form of so-called wear land and is measured by the width of this wear land, $VB$.

Flank wear affects to the great extent the mechanics of cutting.

Cutting forces increase significantly with flank wear.

If the amount of flank wear exceeds some critical value ($VB > 0.5\sim0.6$ mm), the excessive cutting force may cause tool failure.
Corner wear (nose wear) actually shortens the cutting tool, thus increasing gradually the dimension of machined surface and introducing a significant dimensional error in machining, which can reach values of about 0.03~0.05 mm.
Tool Wear

Tool wear is affected by:

1) workpiece material properties,
2) cutting force - controlled by proper selection of feed and depth of cut.
3) Temperature - related to cutting speed (as cutting speed increase, the temperature of the cutting zone increases which causes a loss in tool properties and decreased tool life).
Typical tool wear curves for flank wear at different velocities.
The initial wear is very fast, then it evens out to a more gradual pattern until the limit is reached; after that, the wear substantially increases.
Taylor's Equation

A simple and easy-to-use analytical expression which gives the relationship between the cutting speed and the tool life is given below.

This expression is called **Taylor's Equation**.

\[ V T^n = C \]

- **V** - Cutting speed in m/min
- **T** - Tool life in minutes
- **C** - Cutting speed for 1 minute tool life
- **n** - Exponent
  
  *(Slope of the cutting speed versus tool life plot)*

Frederick W. Taylor  
*(1856 -1915)*
Taylor's Equation

C and n are found by conducting experiments at different cutting speeds and recording the tool life.

When plotted on log-log scale, cutting speed versus tool life relationship becomes a straight line, so that values of C and n can be determined easily.

\[ V T^n = C \]
Taylor's Equation

C - Cutting speed for 1 minute tool life

*Depends on all input parameters, including feed.*

\( n \) - Exponent

(Slope of the cutting speed versus tool life plot)

*Depends mostly on cutting tool material, but is effected by work material, cutting conditions, and environment.*

- 0.14 to 0.16 for HSS
- 0.25 for uncoated carbides,
- 0.30 for TiC-coated insert
- 0.40 for ceramic coated inserts.

\( = > n \) increases with increasing tool material quality
Coolants are used to decrease tool operating temperature and improve cutting performance. A good cutting fluid should act as a lubricant as well as removing the heat (coolant) from the cutting zone.

Water is a good coolant, but is a poor lubricant and presents corrosion (rust) hazard.

On the other hand, oil is a good lubricant but is less effective in cooling.

In practice, emulsion combinations of oil and water or wax and water are used as cutting fluids.
Advantages Gained by Using Cutting Fluids

1. Tool life is increased.
2. Surface finish of the workpiece is improved.
3. Built-up edge formation is prevented.
4. Power consumed by the machine tool is reduced.
5. Corrosion hazard is reduced.
6. Chips are washed away and the cutting zone is kept clear.