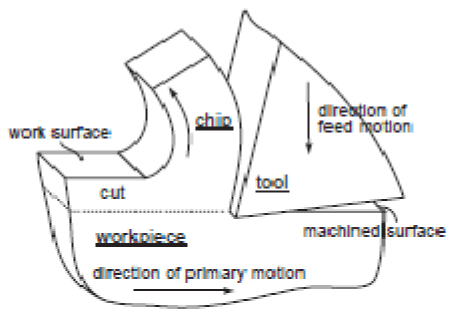
DESIGN AND MANUFACTURE OF CUTTING TOOLS, MECHANICS OF METAL CUTTING. TOOL LIFE AND TOOL WEAR

METAL CUTTING

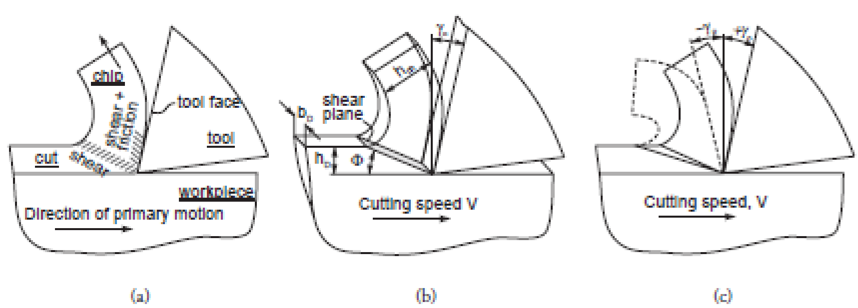
Metal cutting or Machining is the process of producing work piece by removing unwanted material from a block of metal, in form of chips. This process is most important since almost all the products get their final shape and size by metal removal, either directly or indirectly. The major drawback of the process is loss of material in the form of chips.



Schematics of metal cutting process showing the basic terminology.

MECHANICS OF CHIP FORMATION

Cutting is a process of extensive plastic deformation to form a chip that is removed afterward. The basic mechanism of chip formation is essentially the same for all machining operations. Assuming that the cutting action is continuous, we can develop so-called continuous model of cutting process.



(a) Chip formation in metal cutting is accompanied by substantial shear and frictional deformations in the shear plane and along the tool face; (b) Schematic illustration of the two-dimensional cutting process (also called *orthogonal cutting*), h_D and b_D are the *thickness of cut* and *width of cut* respectively, h_{ch} is the *chip thickness*, γ_o is the *tool orthogonal rake* angle, and Φ is the *shear plane angle*; (c) Cutting with positive and negative rake angles. Note the change in the shear plane angle and chip thickness.

Cutting is performed with a cutting tool moving at a cutting speed **v** in the direction of primary motion. The cutting tool is inclined at the rake angle γ_o. The rake angle can be positive, zero, or negative, typically taking values from +15^0 to -6^0. The rake angle influences significantly the process of plastic deformation in cutting and therefore the chip thickness, cutting forces and temperatures.

The tool is set to remove a cut with thickness h_D and width b_D. In the simplest model of orthogonal cutting shown in the figure, the plastic deformation takes place by shearing in a single shear plane inclined at the angle Φ (shear plane angle). The produced chip has a thickness of h_{ch} (chip thickness), width b_D and moves at speed V_{ch} (chip speed).

The chip thickness compression ratio Λ_h is defined by

$$\Lambda_h = {}^{h_{ch}}/_{h_D}$$

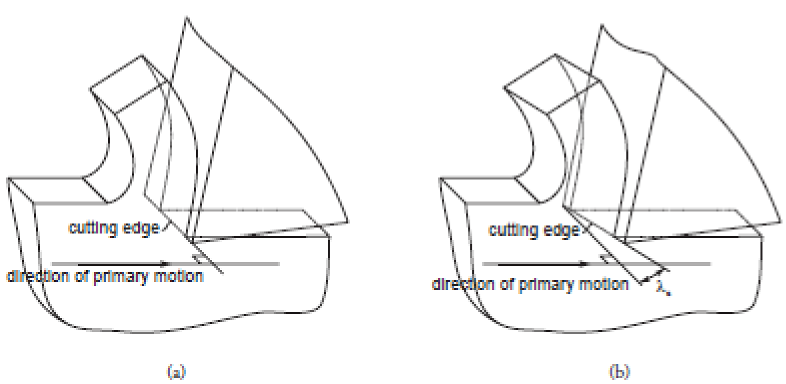
Chip thickness is always bigger than thickness of cut, therefore Λ_h is always greater than 1. The value of chip thickness compression ratio gives valuable information about the rate of plastic deformation in the chip formation zone.

In reality, chip formation occurs not in a plane but in so-called primary and secondary shear zones, the first one between the cut and chip and the second one along the cutting tool face.

TYPES OF CUTTING

Depending on whether the stress and deformation in cutting occur in a plane (two-dimensional case) or in the space (three-dimensional case), we consider two principle types of cutting:

1. **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.
2. **Oblique cutting**: The cutting edge is set at an angle (the tool cutting edge inclination). This is the case of three dimensional stress and strain condition.



(a) Orthogonal cutting with a cutting tool set normally to the direction of primary motion; (b) Oblique cutting with a cutting tool set at the tool cutting edge inclination angle λ_s to the direction of primary motion.

According to the number of active cutting edges engaged in cutting, we distinguish again two types of cutting:

1. **Single point cutting**: The cutting tool has only one major cutting edge. It consists of a sharpened cutting part called its point and the shank. Examples are turning, shaping, boring
2. **Multipoint cutting**: The cutting tool has more than one major cutting edge. Examples are drilling, milling, broaching, reaming.

CUTTING CONDITION

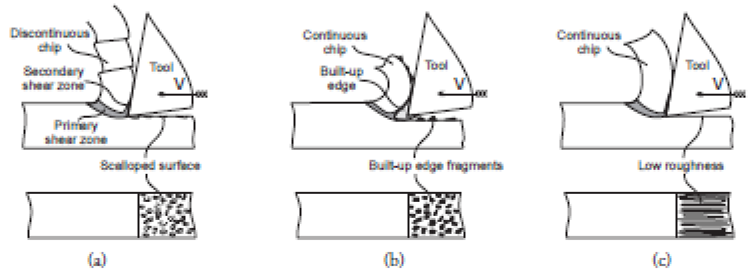
Each machining operation is characterized by cutting conditions, which comprises a set of three elements:

1. **Cutting velocity**: The traveling velocity of the tool relative to the work-piece. It is measured in m/s or m/min.
2. **Depth of cut**: The axial projection of the length of the active cutting tool edge, measured in mm. In orthogonal cutting, it is equal to the actual width of cut.
3. **Feed**: The relative movement of the tool in order to process the entire surface of the work-piece. In orthogonal cutting, it is equal to the thickness of cut.

CHIP FORMATION

There are three types of chips that are commonly produced in cutting

1. **Discontinuous chips**: A discontinuous chip comes off as small chunks or particles. When we get this chip, it may indicate brittle work material, small or negative rake angles and coarse feeds and low speed.
2. **Continuous chips**: It looks like a long ribbon with a smooth shinning surface. This chip type may indicate ductile work materials, large positive rake angle and fine feeds and high speeds.
3. **Continuous chips with built up edge**: It still look like a long ribbon, but the surface is no longer smooth and shining. Under some circumstances (low cutting speeds, small or negative rake angles), work materials like mild steel, aluminium, cast iron etc., tend to develop so-called built-up edge, a very hardened layer of work material attached to the tool face, which tends to acts as a cutting edge itself replacing the real cutting tool edge. The built-up edge tends to grow until it reaches a critical size and then passes off with the chip, leaving small fragments on the machining surface. Chip will break free and cutting forces are smaller, but the effect is a rough machined surface. The built-up edge disappears at high cutting speeds.



The type of chip changes with cutting speed. When cutting mild steel, the chip is discontinuous at low cutting velocity (a), forms with a built-up edge at about 0.5 m/s (b), and is continuous with well developed secondary shear zone at high velocity (c).

CHIP CONTROL

Discontinuous chips are generally desired because they:

i. Are less dangerous for the operator.
ii. Do not cause damage to work-piece surface and machine tool.
iii. Can be easily removed from the work-piece.
iv. Can be easily handled and disposed after machining.

Three principle methods to produce the favourable discontinuous chips are:

i. Proper selection of cutting condition
ii. Use of chip breakers
iii. Change in the work material properties.

CUTTING TOOL MATERIALS

The cutting tool materials must possess a number of important properties to avoid excessive wear, fracture failure and high temperatures in cutting. The following characteristics are essential for cutting materials to withstand the heavy conditions of the cutting process and to produce high quality and economical parts:

i. Hardness at elevated temperatures
ii. Toughness: ability of a material to absorb energy without failing.
iii. Wear resistance
iv. Chemical inertness
v. Thermal conductivity
vi. Surface finish on the tool

CUTTING TOOL MATERIALS

1. **Carbon steels**: The oldest of tool material. This material has low wear resistance and low hot hardness. The use of these materials now is very limited.
2. **High-speed steel (HSS)**: Highly alloyed with vanadium, cobalt, molybdenum, tungsten and chromium added to increase hot hardness and wear resistance. High toughness and good wear

resistance make HSS suitable for all type of cutting tools with complex shapes for relatively low to medium cutting speeds. The most widely used tool material today for taps, drills, reamers, gear tools, end cutters, slitting, broaches, etc

3. **Cemented carbides**: Most important too materials today because of their high hot hardness and wear resistance. However they are of low toughness. These materials are produced by powder metallurgy methods.
4. **Ceramics**: They have high wear resistance and low toughness; therefore they are suitable only for continuous operations such as finishing turning of cast iron and steel at very high speeds. There is no occurrence of built-up edge and coolants are not required.
5. **Cubic boron nitride (CBN) and synthetic diamonds**: Diamond is the hardest substance ever known of all materials. It is used as a coating material in its polycrystalline form, or as a single-crystal diamond tool for special applications, such as mirror finishing of non-ferrous materials. Next to diamond, CBN is the hardest tool material. CBN is used mainly as coating material because it is very brittle. In spite of diamond, CBN is suitable for cutting ferrous materials.

MACHINABILITY

Machinability is a term indicating how the work material responds to the cutting process. In most cases, machinability means that material is cut with good surface finish, long tool life, low force and power requirements, and low cost.

The higher the tool life, the better is the machinability of a work material.

The machinability rating or index of different materials is taken from relative to the index which is standardized. The machinability index K_M is defined by

$$K_M = {}^{V_{60}}/_{V_{60R}}$$

where V_{60} is the cutting speed for the target material that ensures tool life of 60 min, V_{60R} is the same for the reference material. Reference materials are selected for each group of work materials (Ferrous and non-ferrous) among the most popular and widely used brands.

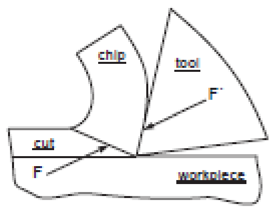
If K_M>1, the machinability of the target material is better than that of the reference material, and vice versa.

CUTTING FORCES

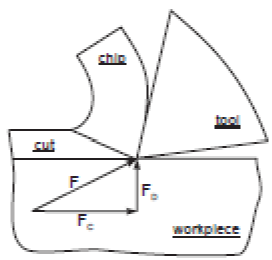
Cutting is a process of extensive stresses and plastic deformations. The high compressive and frictional contact stresses on the tool face result in a substantial cutting force F. The knowledge of cutting forces is essential because of proper design of the cutting tools, of proper design of the fixtures used to hold the workpiece and cutting tool, calculation of the machine tool power and selection of the cutting conditions to avoid an excessive distortion of the workpiece.

CUTTING FORCE COMPONENTS

In orthogonal cutting, the total cutting force F is conveniently resolved into two components in the horizontal and vertical direction, which can be directly measured using a force measuring device called a dynamometer.



Total cutting force F and reaction force F' in orthogonal cutting



Total cutting force F is conveniently resolved into horizontal component F_C and vertical component F_D

The two force components acts against the tool:

1. **Cutting force F_C**: This force is in the direction of primary motion. The cutting force constitutes about 70-80% of the total force F and is used to calculate the power P required to perform the machining operation.

$$P = VF_c$$

2. **Thrust force F_D**: This force is in direction of feed motion in orthogonal cutting. The thrust force is used to calculate the power of feed motion.

In three-dimensional oblique cutting, one more force component appears along the third axis. The thrust force F_D is further resolved into two more components, one in the direction of feed motion called feed force F_f and the other perpendicular to it and to the cutting force F_C called back force F_P, which is in the direction of the cutting tool axis.

The cutting force value is primarily affected by cutting conditions (cutting sped V, feed f, depth of cut d), cutting tool geometry (tool orthogonal rake angle) and properties of work material. The simplest way to control cutting forces is to change the cutting conditions.

TOOL WEAR AND TOOL LIFE

During any machining process, the tool is subjected to three distinct factors: forces, temperature and sliding action due to relative motion between tool and workpiece. Due to these factors, the cutting tool will start giving unsatisfactory performance after some time. They may include the following: loss of dimensional accuracy, increased surface roughness, and increased power requirements etc. The unsatisfactory performance results from tool wear due to its continued use. When the tool wears out, it is either replaced or reconditioned, usually by grinding. This will result in loss of production due to machine down time, in addition to the cost of replacing or reconditioning the tool. Thus the study of tool wear is very important from the stand point of performance and economics.

Tool wear or tool failure may be classified as follows:

a. Flank wear
b. Crater wear on tool face
c. Localized wear such as the rounding of the cutting edge
d. Chipping off of the cutting edge.

The total cutting time accumulated before tool failure occurs is termed **"tool life"**. Tool life can be defined as tool's useful life which has been expended when it can no longer produce satisfactory parts. The most commonly used criteria for measuring the tool life are:

i. Total destruction of the tool when it ceases to cut.
ii. A fixed size of wear land on tool flank.

Tool wear and hence tool life depends on many factors. The greatest variation of tool life is with the cutting speed and tool temperature which is closely related to the cutting speed.

REAMERS

A reamer is a rotary cutting tool generally of cylindrical shape, which is used to enlarge and finish holes to accurate dimensions to a previously formed hole. It is a multiple edge cutting tool, having the cutting edges on its periphery. It consists of three main parts: fluted section, neck and shank.

Types of reamers include hand reamers, machine reamers, chucking reamers, floating reamers, expanding reamers, adjustable reamers, taper reamers and shell reamers.

DRILLS

Drilling is a process of cutting or originating a round hole from the solid material. The tool (drill) and not the workpiece is revolved and is fed into the material along its axis. The most common type of drill is the fluted twist drill. It is made from a round bar of tool material, and has three principal parts: the point, the body and the shank.

BROACH

A broach is a multi-point cutting tool consisting of a bar having a surface containing of series of cutting teeth or edges which gradually increase in size from the starting or entering end to the rear end. Broaches are used for machining either internal or external surfaces. The surfaces produced may be flat, circular or of any intricate shape. In broaching, the broach is pushed or pulled over or through a surface of a workpiece. Each tooth of the tool takes a thin slice from the surface. Broaching of inside surface is called 'Internal or hole broaching' and outside surfaces as 'Surface broaching'.

REVIEW QUESTIONS

1. Discuss the various types of cutting tools
2. Briefly discuss reamers
3. Why is tool wear important in metal cutting?
4. Differentiate between orthogonal and oblique cutting
5. Explain tool wear and tool life
6. What are drills?
7. Differentiate between orthogonal and oblique cutting
8. Differentiate between single-point cutting and multi-point cutting

ASSIGNMENT

Draw and label the following cutting tools

i. Drill
ii. Reamers
iii. Broach