Mechanism of Machining

3.3 Mechanism of chip formation in machining

Machining is a semi-finishing or finishing process essentially done to impart required or stipulated dimensional and form accuracy and surface finish to enable the product to

- fulfill its basic functional requirements
- provide better or improved performance
- render long service life.

Machining is a process of gradual removal of excess material from the preformed blanks in the form of chips.
The form of the chips is an important index of machining because it directly or indirectly indicates :

- Nature and behaviour of the work material under machining condition
- Specific energy requirement (amount of energy required to remove unit volume of work material) in machining work
- Nature and degree of interaction at the chip-tool interfaces.

The form of machined chips depend mainly upon :

- Work material
- Material and geometry of the cutting tool
- Levels of cutting velocity and feed and also to some extent on depth of cut
- Machining environment or cutting fluid that affects temperature and friction at the chip-tool and work-tool interfaces.

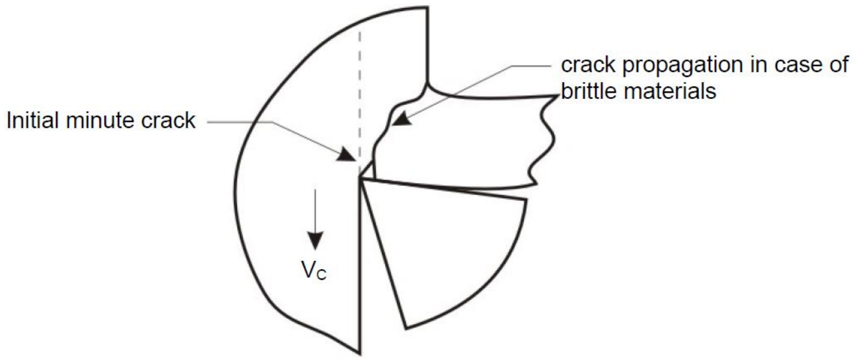
Knowledge of basic mechanism(s) of chip formation helps to understand the characteristics of chips and to attain favourable chip forms.

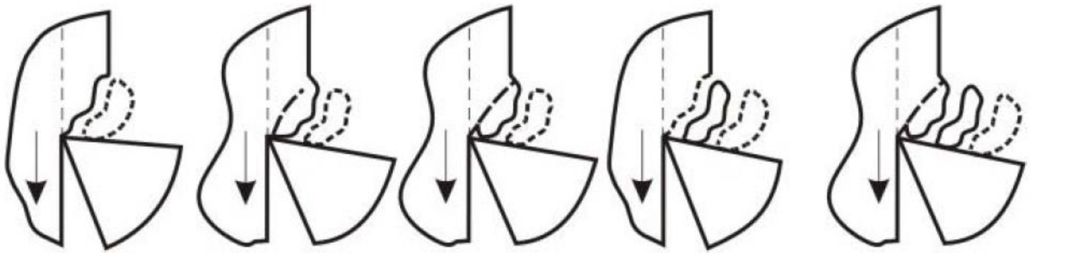
3.3.2 Mechanism of chip formation in machining brittle materials

The basic two mechanisms involved in chip formation are

- Yielding – generally for ductile materials
- Brittle fracture – generally for brittle materials

During machining, first a small crack develops at the tool tip as shown in Fig. 5.5 due to wedging action of the cutting edge. At the sharp crack-tip stress concentration takes place. In case of ductile materials immediately yielding takes place at the crack-tip and reduces the effect of stress concentration and prevents its propagation as crack. But in case of brittle materials the initiated crack quickly propagates, under stressing action, and total separation takes place from the parent workpiece through the minimum resistance path as indicated in Fig. 5.5.
Machining of brittle material produces discontinuous chips and mostly of irregular size and shape. The process of forming such chips is schematically shown in Fig.



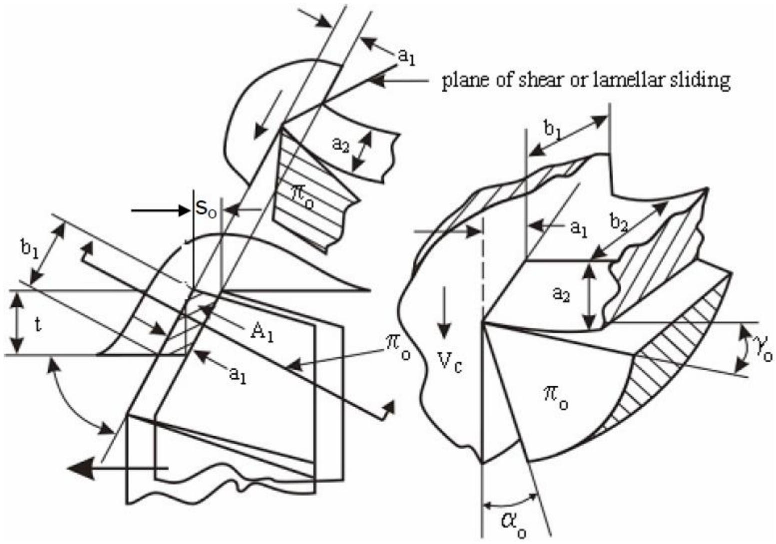


3.4 Geometry and characteristics of continuous chip formation

The geometry of the chips being formed at the cutting zone follow a particular pattern especially in machining ductile materials. The major section of the engineering materials being machined are ductile in nature, even some semi-ductile or semi-brittle materials behave ductile under the compressive forces at the cutting zone during machining.
The pattern and degree of deformation during chip formation are quantitatively assessed and expressed by some factors, the values of which indicate about the forces and energy required for a particular machining work.

3.4.1 Chip reduction coefficient and cutting ratio

The usual geometrical features of formation of continuous chips are schematically shown in Fig.



The chip thickness (a_2) usually becomes larger than the uncut chip thickness (a_1). The reason can be attributed to

- compression of the chip ahead of the tool
- frictional resistance to chip flow
- lamellar sliding according to Piispannen

The significant geometrical parameters involved in chip formation are shown in Fig. 5.7 and those parameters are defined (in respect of straight turning) as:

t = depth of cut (mm) – perpendicular penetration of the cutting tool tip in work surface

s_o = feed (mm/rev) – axial travel of the tool per revolution of the job

b_1 = width (mm) of chip before cut

b_2 = width (mm) of chip after cut

a_1 = thickness (mm) of uncut layer (or chip before cut)

a_2 = chip thickness (mm) – thickness of chip after cut

A_1 = cross section (area, mm^2) of chip before cut

The degree of thickening of the chip is expressed by

$_{12}aa=\zeta > 1.00$ (since $a_2 > a_1$) (5.1)

where, ζ = chip reduction coefficient

□□= principal cutting edge angle

Larger value of ζ means more thickening i.e., more effort in terms of forces or energy required to accomplish the machining work. Therefore it is always desirable to reduce a_2 or ζ without sacrificing productivity, i.e. metal removal rate (MRR).

Chip thickening is also often expressed by the reciprocal of ζ as,

$_{21}1aar==\zeta$ (5.3)

where, r = cutting ratio

The value of chip reduction coefficient, ζ (and hence cutting ratio) depends mainly upon

- tool rake angle, γ
- chip-tool interaction, mainly friction,μ

Roughly in the following way [3]

$\zeta = e^{\mu(\pi/2 - \gamma_o)}$ [for orthogonal cutting] (5.4)

$\pi/2$ and γ_o are in radians

The simple but very significant expression (5.4) clearly depicts that the value of ζ can be desirably reduced by

- Using tool having larger positive rake
- Reducing friction by using lubricant

The role of rake angle and friction at the chip-tool interface on chip reduction coefficient are also schematical.

Chip reduction coefficient, ζ is generally assessed and expressed by the ratio of the chip thickness, after (a_2) and before cut (a_1) as in equation 5.1.

But ζ can also be expressed or assessed by the ratio of • Total length of the chip before (L_1) and after cut (L_2)

- Cutting velocity, V_C and chip velocity, V_f

Considering total volume of chip produced in a given time,

$a_1 b_1 L_1 = a_2 b_2 L_2$ (5.5)

The width of chip, b generally does not change significantly during machining unless there is side flow for some adverse situation.

3.4.2 Shear angle

It has been observed that during machining, particularly ductile materials, the chip sharply changes its direction of flow (relative to the tool) from the direction of the cutting velocity, V_C to that along the tool rake surface after thickening by shear deformation or slip or lamellar sliding along a plane. This plane is called shear plane.

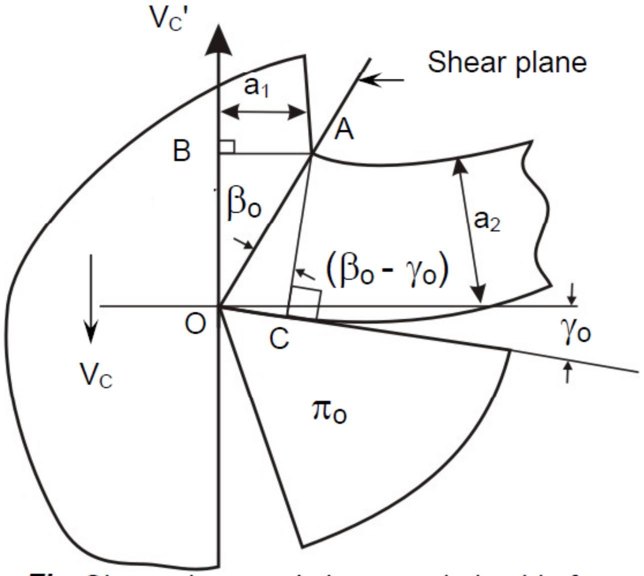


Fig. *Shear plane and shear angle in chip formation*

3.4.3 Cutting strain

The magnitude of strain, that develops along the shear plane due to machining action, is called cutting strain (shear). The relationship of this cutting strain, ε with the governing parameters can be derived.
Due to presence of the tool as an obstruction the layer 1 has been shifted to position 2 by sliding along the shear plane.

3.4.4 Built-up-edge (BUE) formation

Causes of formation
In machining ductile metals like steels with long chip-tool contact length, lot of stress and temperature develops in the secondary deformation zone at the chip-tool interface. Under such high stress and temperature in between two clean surfaces of metals, strong bonding may locally take place due to adhesion similar to welding. Such bonding will be encouraged and accelerated if the chip tool materials have mutual affinity or solubility. The weldment starts forming as an embryo at the most favourable location and thus gradually grows as schematically shown in Fig.

With the growth of the BUE, the force, F (shown in Fig) also gradually increases due to wedging action of the tool tip along with the BUE formed on it. Whenever the force, F exceeds the bonding force of the BUE, the BUE is broken or sheared off and taken away by the flowing chip. Then again BUE starts forming and growing. This goes on repeatedly.

3.4.4.2 Characteristics of BUE

Built-up-edges are characterized by its shape, size and bond strength, which depend upon:
- work tool materials
- stress and temperature, i.e., cutting velocity and feed
- cutting fluid application governing cooling and lubrication.

BUE may develop basically in three different shapes as schematically shown in Fig.

In machining too soft and ductile metals by tools like high speed steel or uncoated carbide the BUE may grow larger and overflow towards the finished surface through the flank as shown in Fig.

While the major part of the detached BUE goes away along the flowing chip, a small part of the BUE may remain stuck on the machined surface and spoils the surface finish. BUE formation needs certain level of temperature at the interface depending upon the mutual affinity of the work-tool materials. With the increase in V_C and s_o the cutting temperature rises and favours BUE formation. But if V_C is raised too high beyond certain limit, BUE will be squashed out by the flowing chip before the BUE grows. Fig. 5.14 shows schematically the role of increasing V_C and s_o on BUE formation (size). But sometime the BUE may adhere so strongly that it remains strongly bonded at the tool tip and does not break or shear off even after reasonably long time of machining. Such detrimental situation occurs in case of certain tool-work materials and at speed-feed conditions which strongly favour adhesion and welding.

3.4.4.3 Effects of BUE formation

Formation of BUE causes several harmful effects, such as:

- It unfavourably changes the rake angle at the tool tip causing increase in cutting forces and power consumption
- Repeated formation and dislodgement of the BUE causes fluctuation in cutting forces and thus induces vibration which is harmful for the tool, job and the machine tool.
- Surface finish gets deteriorated
- May reduce tool life by accelerating tool-wear at its rake surface by adhesion and flaking

Occasionally, formation of thin flat type stable BUE may reduce tool wear at the rake face.

3.4.5 Broad classification of machining chips

Different types of chips of various shape, size, colour etc. are produced by machining depending upon

- type of cut, i.e., continuous (turning, boring etc.) or intermittent cut (milling)
- work material (brittle or ductile etc.)
- cutting tool geometry (rake, cutting angles etc.)
- levels of the cutting velocity and feed (low, medium or high)
- cutting fluid (type of fluid and method of application)

The basic major types of chips and the conditions generally under which such types of chips form are given below:

Discontinuous type
• of irregular size and shape : - work material – brittle like grey cast iron
• of regular size and shape : - work material ductile but hard and work hardenable
- feed – large
- tool rake – negative
- cutting fluid – absent or inadequate

o Continuous type
• Without BUE : work material – ductile
Cutting velocity – high
Feed – low
Rake angle – positive and large
Cutting fluid – both cooling and lubricating
• With BUE : - work material – ductile
- cutting velocity – medium
- feed – medium or large
- cutting fluid – inadequate or absent.

o Jointed or segmented type

- work material – semi-ductile
- cutting velocity – low to medium
- feed – medium to large
- tool rake – negative
- cutting fluid – absent

Often in machining ductile metals at high speed, the chips are deliberately broken into small segments of regular size and shape by using chip breakers mainly for convenience and reduction of chip-tool contact length.

3.4.7 Orthogonal and oblique cutting

It is appears from the diagram in Fig. 6.1 that while turning ductile material by a sharp tool, the continuous chip would flow over the tool's rake surface and in the direction apparently perpendicular to the principal cutting edge, i.e., along orthogonal plane which is normal to the cutting plane containing the principal cutting edge. But practically, the chip may not flow along the orthogonal plane for several factors like presence of inclination angle, λ, etc.

The role of inclination angle, λ on the direction of chip flow is schematically shown in Fig. which visualises that,

- when λ=0, the chip flows along orthogonal plane, i.e, $\rho_c = 0$
- when λ≠0, the chip flow is deviated from π_o and $\rho_c = \lambda$ where ρ_c is chip flow deviation (from π_o) angle

V_C Y_o X_o t s_o π_C Orthogonal plane π_o chip flow direction

The role of inclination angle, λ on the direction of chip flow is schematically shown in Fig. which visualises that,

- when λ=0, the chip flows along orthogonal plane, i.e, $\rho_c = 0$

- when $\lambda \neq 0$, the chip flow is deviated from π_o and $\rho_c = \lambda$ where ρ_c is chip flow deviation (from π_o) angle

Orthogonal cutting: when chip flows along orthogonal plane, π_o, i.e., $\rho_c = 0$

Oblique cutting : when chip flow deviates from orthogonal plane, i.e. $\rho_c \neq 0$
But practically ρ_c may be zero even if $\lambda = 0$ and ρ_c may not be exactly equal to λ even if $\lambda \neq 0$. Because there are some other (than λ) factors also which may cause chip flow deviation.

Pure orthogonal cutting: This refers to chip flow along π_o and $\varphi = 90^o$ as typically shown in Fig. where a pipe like job of uniform thickness is turned (reduced in length) in a center lathe by a turning tool of geometry; $\lambda = 0$ and $\varphi = 90^o$ resulting chip flow along π_o which is also π_x in this case.