

Module 2 Mechanics of Machining

Lesson

5

Mechanism of chip formation

Instructional Objectives

At the end of this lesson, the student would be able to

- (i) describe with illustration the mechanism of chip formation in machining
 - ductile materials and
 - brittle materials
- (ii) illustrate and assess geometrical characteristics of ductile chips :
 - chip reduction coefficient & cutting ratio
 - shear angle and cutting strain
- (iii) Identify and state the causes, characteristics and effects of built – up – edge (BUE) formation.
- (iv) Classify chips and identify the condition for different chip forms.

(i) 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.

- **Mechanism of chip formation in machining ductile materials**

During continuous machining the uncut layer of the work material just ahead of the cutting tool (edge) is subjected to almost all sided compression as indicated in Fig. 5.1.

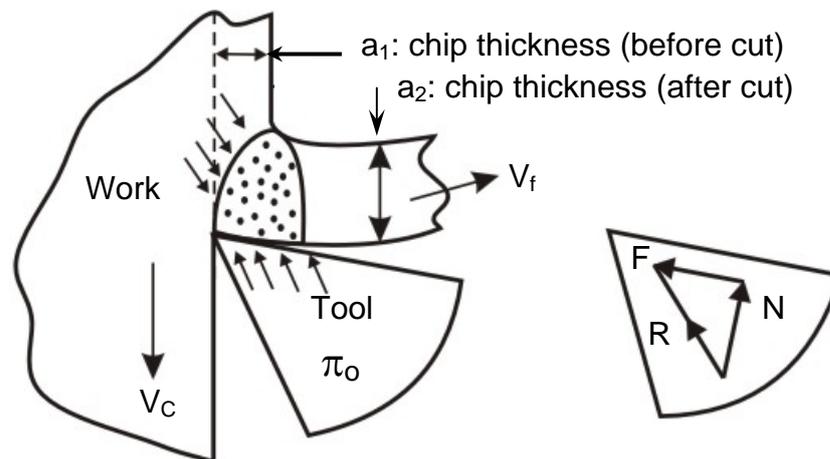


Fig. 5.1 Compression of work material (layer) ahead of the tool tip

The force exerted by the tool on the chip arises out of the normal force, N and frictional force, F as indicated in Fig. 5.1.

Due to such compression, shear stress develops, within that compressed region, in different magnitude, in different directions and rapidly increases in magnitude. Whenever and wherever the value of the shear stress reaches or exceeds the shear strength of that work material in the deformation region, yielding or slip takes place resulting shear deformation in that region and the plane of maximum shear stress. But the forces causing the shear stresses in the region of the chip quickly diminishes and finally disappears while that region moves along the tool rake surface towards and then goes beyond the point of chip-tool engagement. As a result the slip or shear stops propagating long before total separation takes place. In the mean time the succeeding portion of the chip starts undergoing compression followed by yielding and shear. This phenomenon repeats rapidly resulting in formation and removal of chips in thin layer by layer. This phenomenon has been explained in a simple way by Piispanen [1] using a card analogy as shown in Fig. 5.2.

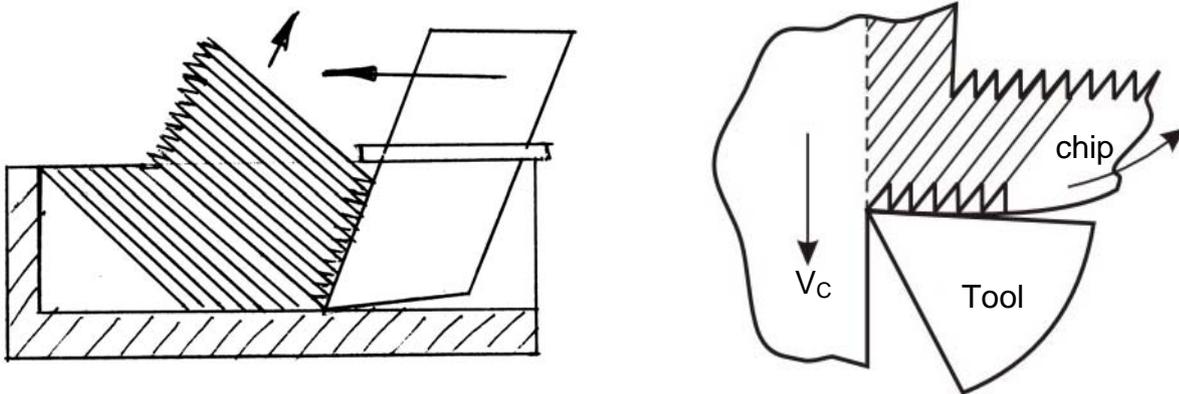
In actual machining chips also, such serrations are visible at their upper surface as indicated in Fig. 5.2. The lower surface becomes smooth due to further plastic deformation due to intensive rubbing with the tool at high pressure and temperature. The pattern of shear deformation by lamellar sliding, indicated in the model, can also be seen in actual chips by proper mounting, etching and polishing the side surface of the machining chip and observing under microscope.

The pattern and extent of total deformation of the chips due to the primary and the secondary shear deformations of the chips ahead and along the tool face,

as indicated in Fig. 5.3, depend upon

[1] Piispanen V., "Theory of formation of metal chips", J. Applied Physics, Vol. 19, No. 10, 1948, pp. 876.

- work material
- tool; material and geometry
- the machining speed (V_c) and feed (s_o)
- cutting fluid application



(a) Shifting of the postcards by partial sliding against each other

(b) Chip formation by shear in lamella.

Fig. 5.2 Piispanen model of card analogy to explain chip formation in machining ductile materials

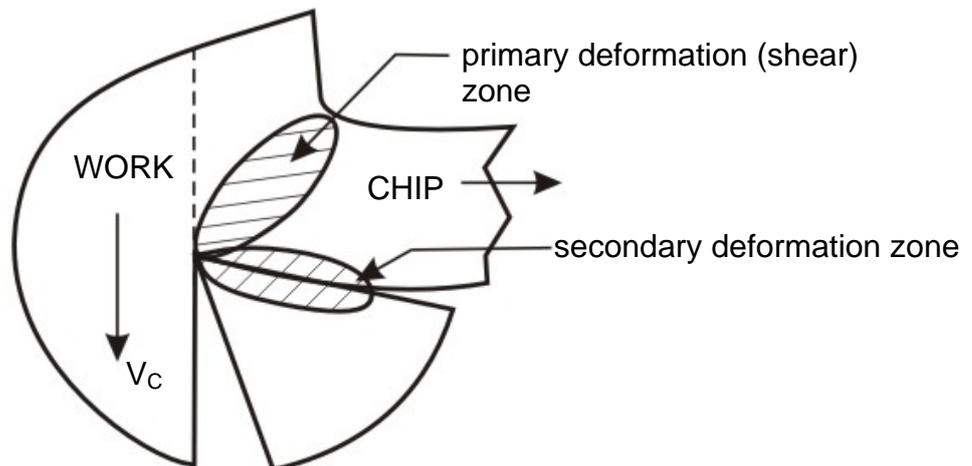
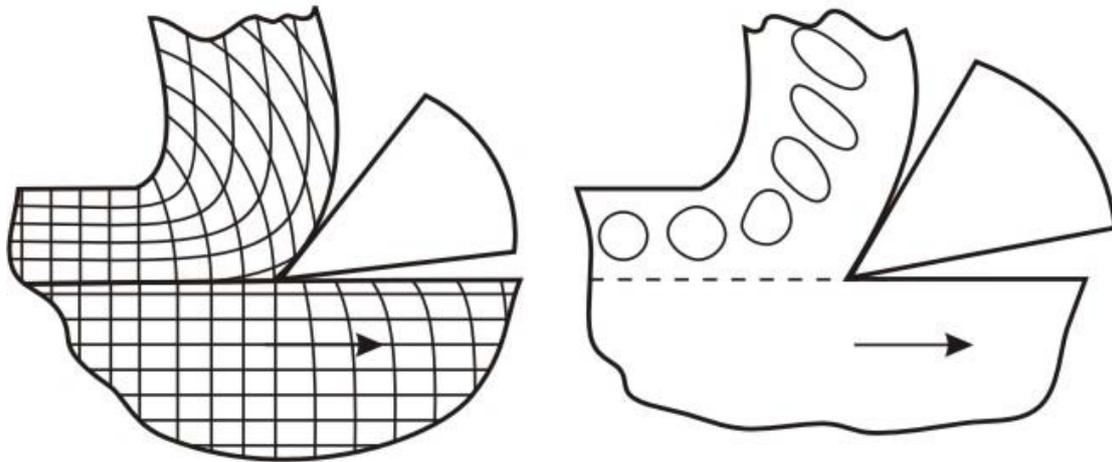


Fig. 5.3 Primary and secondary deformation zones in the chip.

The overall deformation process causing chip formation is quite complex and hence needs thorough experimental studies for clear understanding the phenomena and its dependence on the affecting parameters. The feasible and popular experimental methods [2] for this purpose are:

- Study of deformation of rectangular or circular grids marked on the side surface as shown in Fig. 5.4

- Microscopic study of chips frozen by drop tool or quick stop apparatus
- Study of running chips by high speed camera fitted with low magnification microscope.



(a) rectangular grids

(b) circular grids

Fig. 5.4 Pattern of grid deformation during chip formation.

It has been established by several analytical and experimental methods including circular grid deformation that though the chips are initially compressed ahead of the tool tip, the final deformation is accomplished mostly by shear in machining ductile materials.

However, machining of ductile materials generally produces flat, curved or coiled continuous chips.

- **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. 5.6.

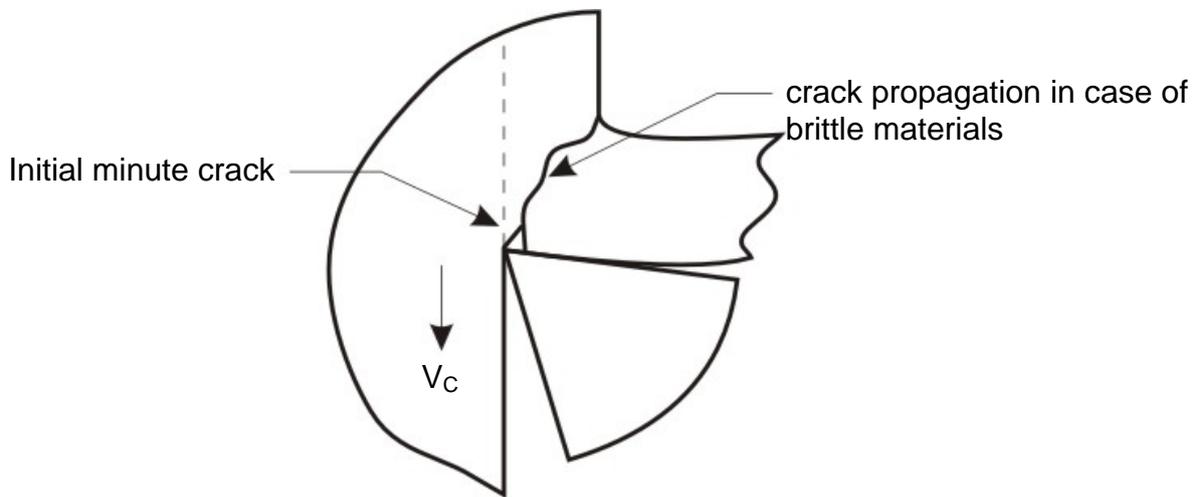
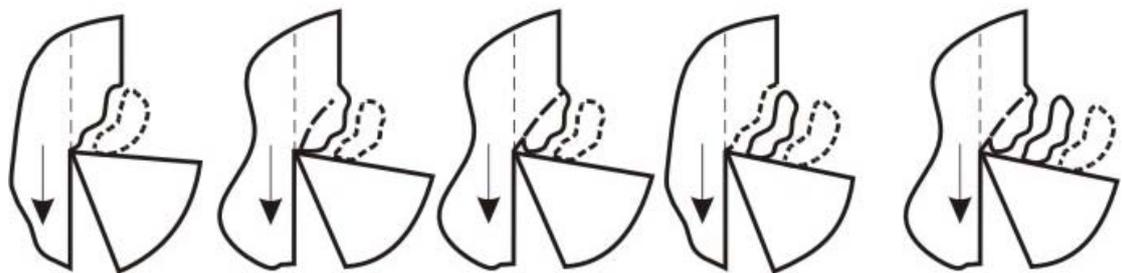


Fig. 5.5 Development and propagation of crack causing chip separation.



(a) separation (b) swelling (c) further swelling (d) separation (e) swelling again

Fig. 5.6 Schematic view of chip formation in machining brittle materials.

(ii) Geometry and characteristics of chip forms

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.

- **Chip reduction coefficient or cutting ratio**

The usual geometrical features of formation of continuous chips are schematically shown in Fig. 5.7.

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 Piispanen

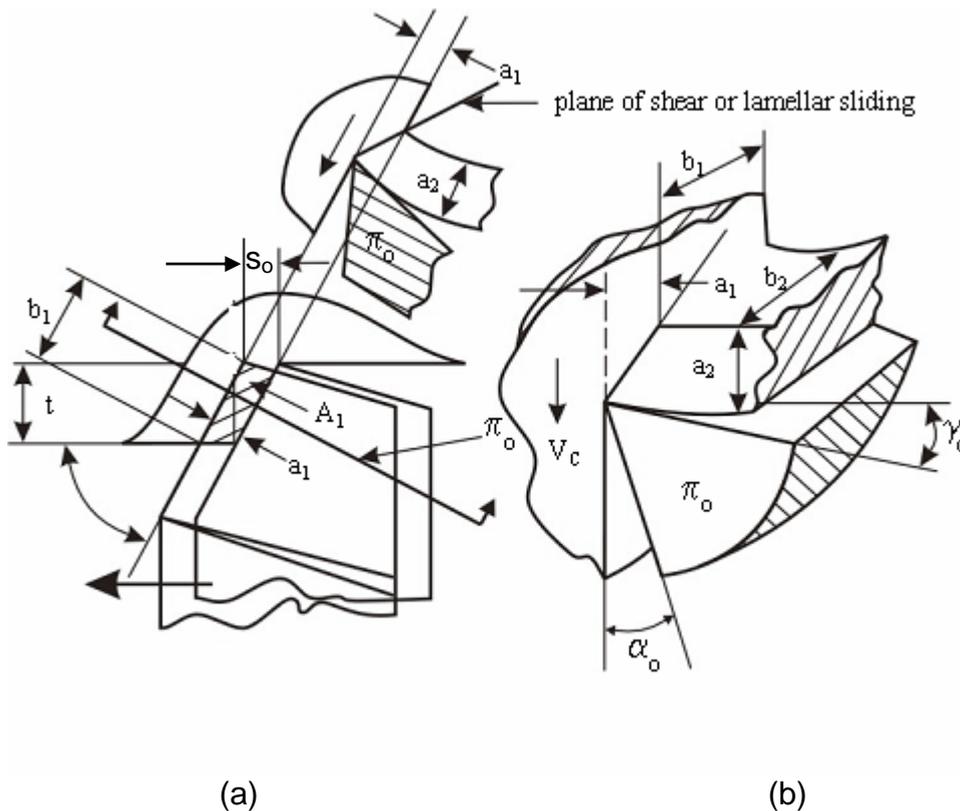


Fig. 5.7 Geometrical features of continuous chips' formation.

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_0 = 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

$$\zeta = \frac{a_2}{a_1} > 1.00 \text{ (since } a_2 > a_1 \text{)} \quad (5.1)$$

where, ζ = chip reduction coefficient

$$a_1 = s_o \sin \phi \quad (5.2)$$

where ϕ = 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,

$$\frac{1}{\zeta} = r = \frac{a_1}{a_2} \quad (5.3)$$

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]

$$\zeta = e^{\mu \left(\frac{\pi}{2} - \gamma_o \right)} \quad \text{[for orthogonal cutting]} \quad (5.4)$$

$\pi/2$ 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 schematically shown in Fig. 5.8.

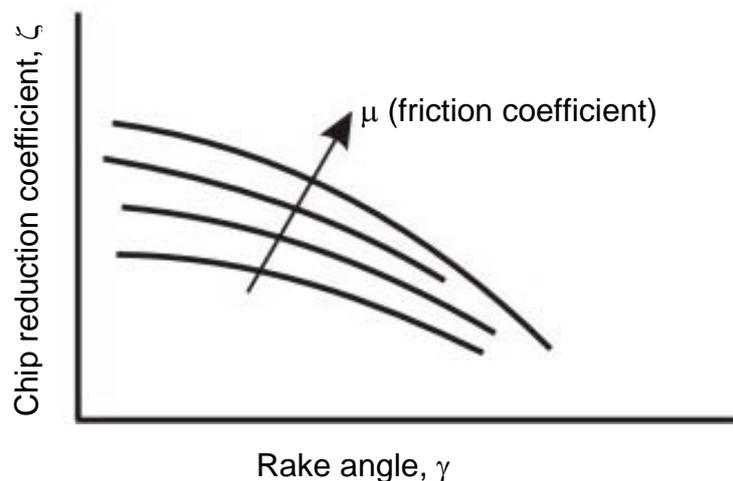


Fig. 5.8 Role of rake angle and friction on chip reduction coefficient

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,

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

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

Therefore assuming, $b_1=b_2$ in equation (5.5), ζ comes up to be,

$$\zeta \left(= \frac{a_2}{a_1} \right) = \frac{L_1}{L_2} \quad (5.6)$$

Again considering unchanged material flow (volume) ratio, Q

$$Q = (a_1 b_1) V_C = (a_2 b_2) V_f \quad (5.7)$$

Taking $b_1=b_2$,

$$\zeta \left(= \frac{a_2}{a_1} \right) = \frac{V_C}{V_f} \quad (5.8)$$

Equation (5.8) reveals that the chip velocity, V_f will be lesser than the cutting velocity, V_C and the ratio is equal to the cutting ratio, $r \left(= \frac{1}{\zeta} \right)$

• 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 and is schematically shown in Fig. 5.9.

Shear plane: Shear plane is the plane of separation of work material layer in the form of chip from the parent body due to shear along that plane.

Shear angle: Angle of inclination of the shear plane from the direction of cutting velocity [as shown in Fig. 5.9].

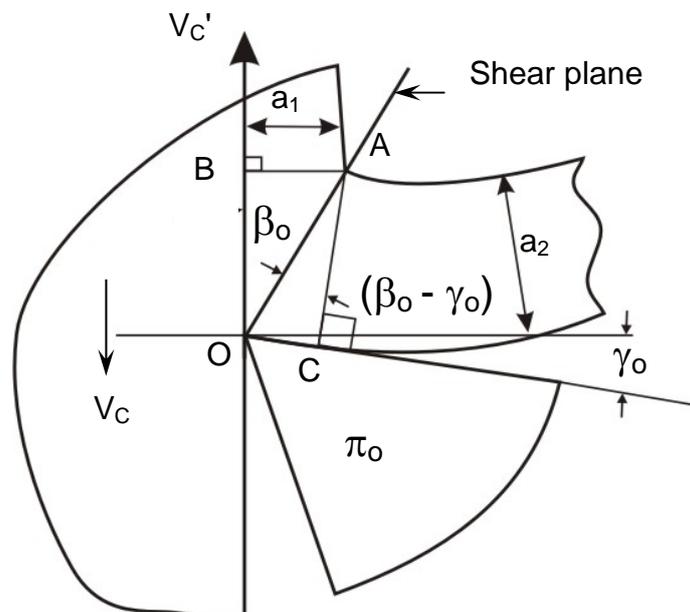


Fig. 5.9 Shear plane and shear angle in chip formation

The value of shear angle, denoted by β_o (taken in orthogonal plane) depends upon

- Chip thickness before and after cut i.e. ζ
- Rake angle, γ_o (in orthogonal plane)

From Fig. 5.9,

$$AC = a_2 = OA \cos(\beta_o - \gamma_o)$$

$$\text{And } AB = a_1 = OA \sin \beta_o$$

Dividing a_2 by a_1

$$\frac{a_2}{a_1} = \zeta = \frac{\cos(\beta_o - \gamma_o)}{\sin \beta_o} \quad (5.9)$$

$$\text{or, } \tan \beta_o = \frac{\cos \gamma_o}{\zeta - \sin \gamma_o} \quad (5.10)$$

Replacing chip reduction coefficient, ζ by cutting ratio, r , the equation (5.10) changes to

$$\tan \beta_o = \frac{r \cos \gamma_o}{1 - r \sin \gamma_o} \quad (5.11)$$

Equation 5.10 depicts that with the increase in ζ , shear angle decreases and vice-versa. It is also evident from equation (5.10) as well as equation (5.4) that shear angle increases both directly and indirectly with the increase in tool rake angle. Increase in shear angle means more favourable machining condition requiring lesser specific energy.

• 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 from Fig. 5.10.

Due to presence of the tool as an obstruction the layer 1 has been shifted to position 2 by sliding along the shear plane.

From Fig. 5.10,

$$\text{Cutting strain (average), } \varepsilon = \frac{\Delta s}{Y} = \frac{PM}{ON}$$

$$\text{or, } \varepsilon = \frac{PN + NM}{ON} = \frac{PN}{ON} + \frac{NM}{ON}$$

$$\text{or, } \varepsilon = \cot \beta_o + \tan(\beta_o - \gamma_o) \quad (5.12)$$

(iii) 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. 5.11.

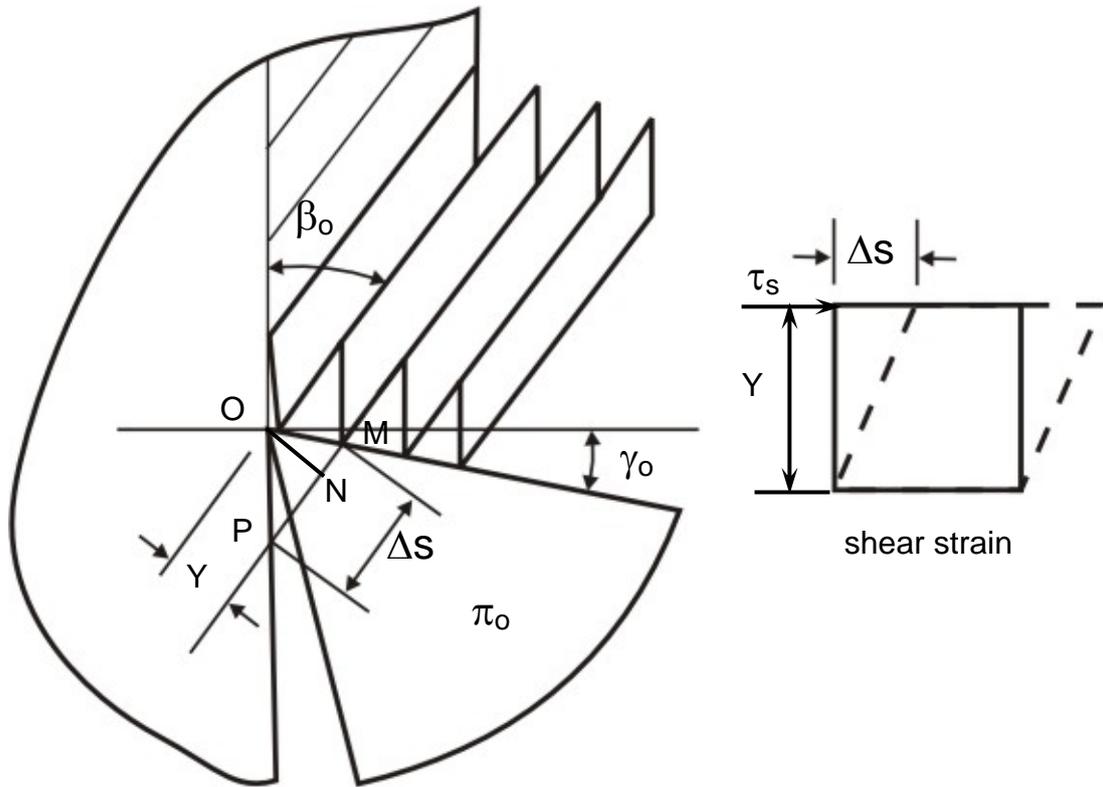


Fig. 5.10 Cutting strain in machining

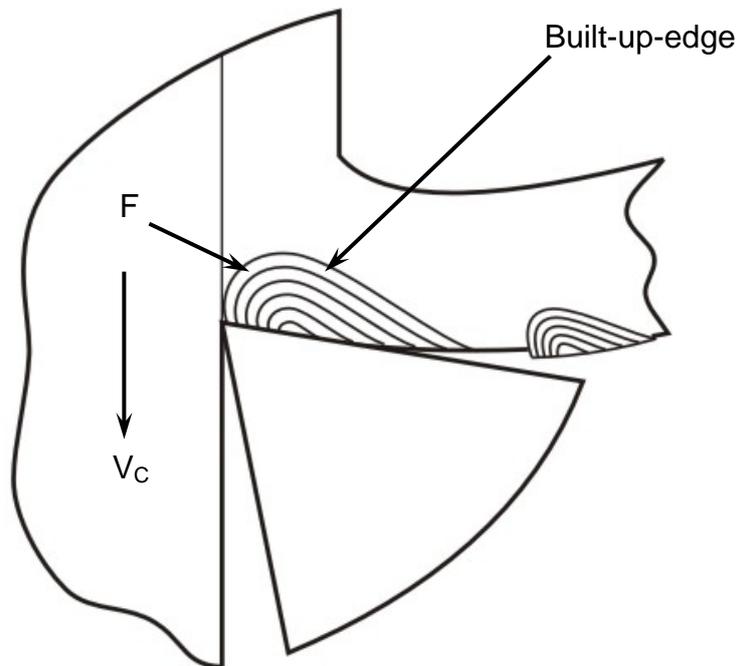


Fig. 5.11 Scheme of built-up-edge formation

With the growth of the BUE, the force, F (shown in Fig. 5.11) 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.

- **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. 5.12.

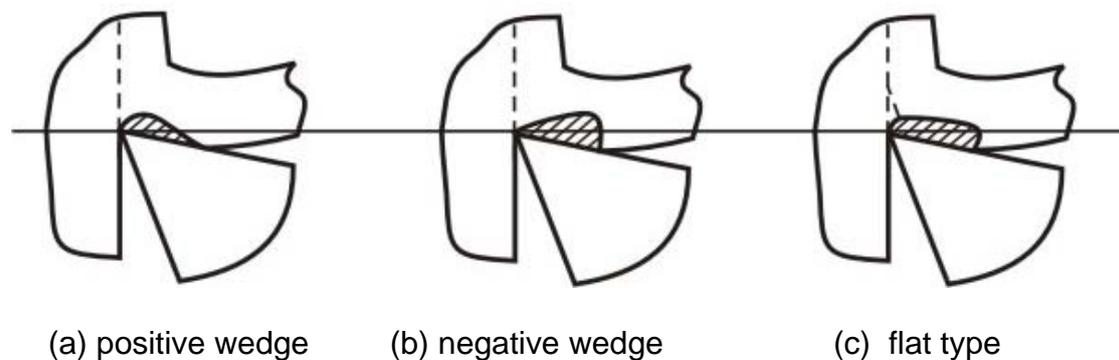


Fig. 5.12 Different forms of built-up-edge.

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. 5.13

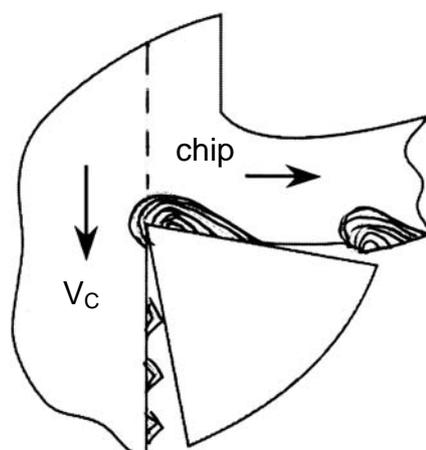


Fig. 5.13 Overgrowing and overflowing of BUE causing surface roughness

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.

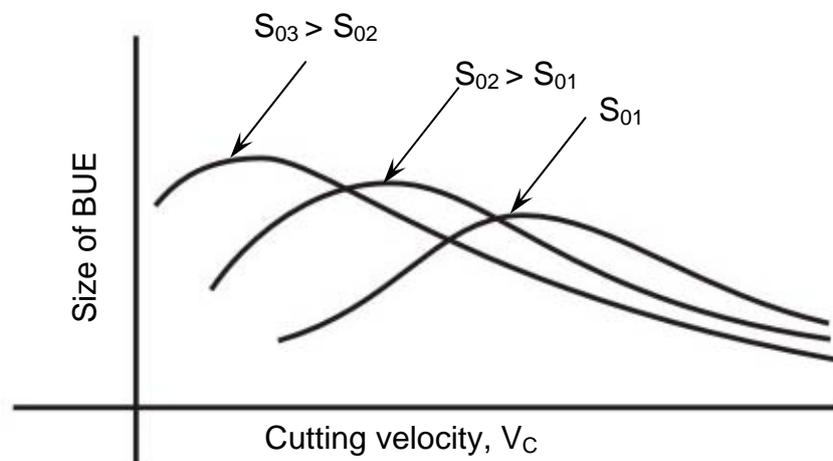


Fig. 5.14 Role of cutting velocity and feed on BUE formation.

- 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.

(iv) Types of chips and conditions for formation of those 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
- 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.
- 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.

Exercise - 5

A. Quiz Test

Identify the correct one out of the four given answers

1. In turning mild steel the value of ζ will be

- (a) > 1.0
- (b) < 1.0
- (c) $= 1.0$
- (d) none of the above

2. The value of shear angle, β_o depends upon

- (a) tool rake angle
- (b) friction at chip-tool interface
- (c) built – up – edge formation
- (d) all of the above

3. Shaping grey cast iron block will produce

- (a) continuous chip with BUE
- (b) continuous chip without BUE
- (c) discontinuous chip of irregular size & shape
- (d) discontinuous chip of regular size & shape

4. The value of chip reduction coefficient, ζ does not depend upon

- (a) cutting velocity
- (b) depth of cut
- (c) cutting tool material
- (d) tool rake angle

B. Numerical Problem

1. During plain turning mild steel by a tool of geometry, $0^\circ, 0^\circ, 8^\circ, 7^\circ, 15^\circ, 90^\circ, 0$ (mm) at $s_o = 0.2$ mm/rev, the chip thickness was found to be 0.5 mm. Determine the values of ζ and β_o in the above case.

Answers

A. Quiz Test

1 – (a)

2 – (d)

3 – (c)

4 – (b)

B. Numerical Problem

$$\zeta = \frac{a_2}{a_1} = \frac{a_2}{s_o \sin \phi} = \frac{0.5}{0.2 \times \sin 90^\circ} = 2.5$$

$$\tan \beta_o = \frac{\cos \gamma_o}{\zeta - \sin \gamma_o} = \frac{\cos 0^\circ}{2.5 - \sin 0^\circ} [\because \gamma_o = 0^\circ]$$

$$= \frac{1}{\zeta} = \frac{1}{2.5} = 0.4$$

$$\therefore \beta_o = \tan^{-1}(0.4) = 21.8^\circ$$