2. Theory of Chip Formation in Metal Machining

The geometry of most practical machining operations is somewhat complex. A simplified model of machining is available that neglects many of the geometric complexities, yet describes the mechanics of the process quite well. It is called the orthogonal cutting model, Figure 7. Although an actual machining process is three-dimensional, the orthogonal model has only two dimensions that play active roles in the analysis.

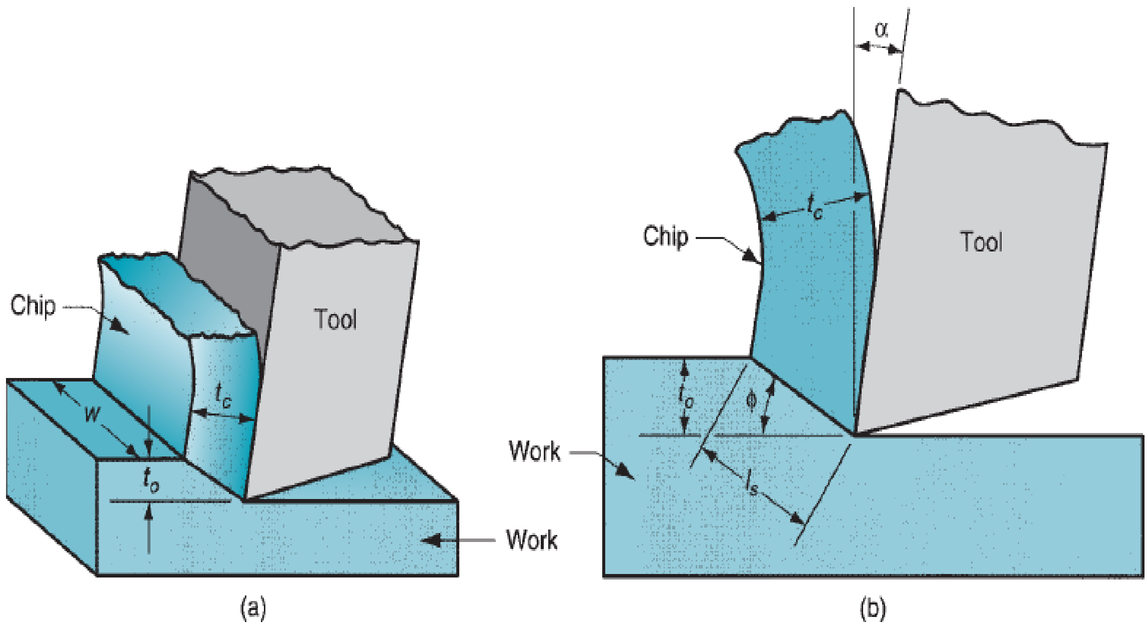


Figure 7: Orthogonal cutting: (a) as a three-dimensional process, and (b) how it reduces to two dimensions in the side view.

2.1 Types of Cutting

As shown in Figure (8), the metal cutting processes are mainly classified into two types.

(i) Orthogonal cutting process (Two-dimensional cutting).

(ii) Oblique cutting process (Three-dimensional cutting).

- ***Orthogonal Cutting*** (2-D Cutting): Cutting edge is

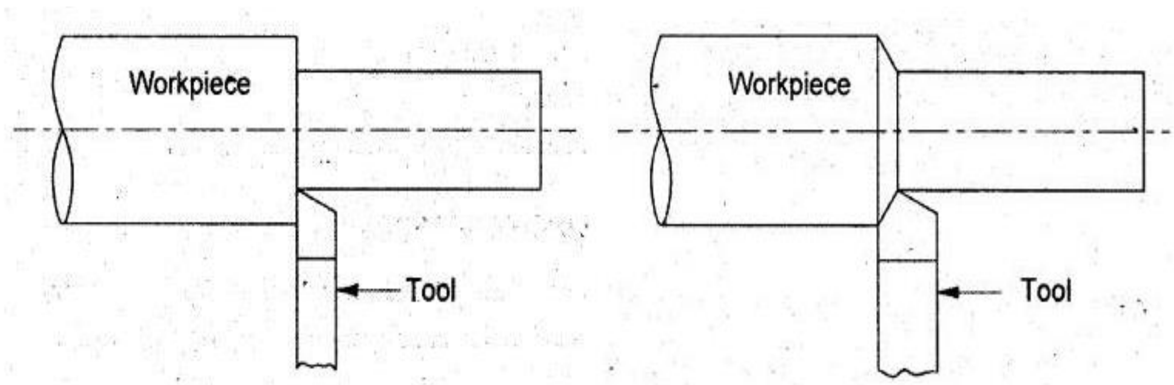
(1) Straight,

(2) Parallel to the original plane surface on the work piece.

(3) Perpendicular to the direction of cutting.

For example: Operations: Lathe cut-off operation, Straight milling, etc.

- ***Oblique Cutting*** (3-D Cutting): Cutting edge of the tool is inclined to the line normal to the cutting direction. In actual machining, Turning, Milling etc.



Orthogonal Cutting **Oblique Cutting**

Figure 8: Orthogonal and Oblique cutting

The tool in orthogonal cutting has only two elements of geometry: (1) ***Rake angle*** (2) ***Clearance angle***.

As indicated previously, the rake angle α determines the direction that the chip flows as it is formed from the workpart; and the clearance angle γ provides a small clearance between the tool flank and the newly generated work surface.

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 t_o to t_c is called the ***chip thickness ratio*** (or ***cutting ratio*** or ***chip ratio***) $\boldsymbol{r_c}$:

$$r_c = \frac{t_o}{t_c} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

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 to t_o, the orthogonal cut has a width dimension w, as shown in Figure 7 (a), even though this dimension does not contribute much to the analysis in orthogonal cutting. 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 (ϕ). Let (***h***) be the length of the shear plane. We can make the substitutions: $t_o = h \sin f$, and $t_c = h \cos(\phi - \alpha)$. Thus,

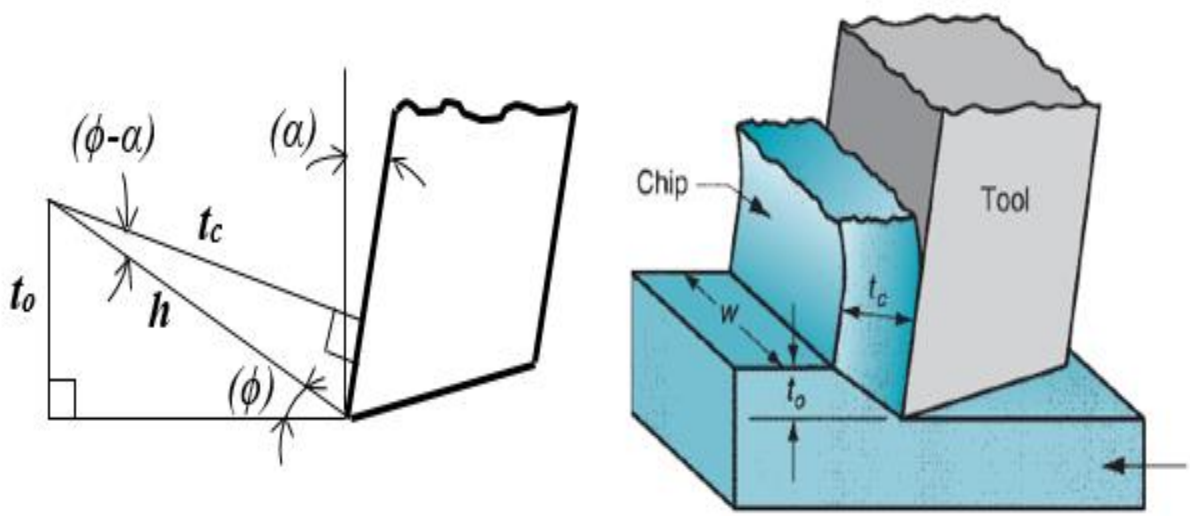


Figure 9: Calculation of shear angle.

$$\sin\emptyset = \frac{t_o}{h} \Rightarrow t_o = h\sin\emptyset \quad \ldots\ldots\ldots.\ldots\ldots\ldots\ldots.\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

$$\cos(\emptyset - \alpha) = \frac{t_c}{h} \Rightarrow t_c = h\cos(\emptyset - \alpha) \ldots\ldots\ldots.\ldots\ldots\ldots\ldots\ldots.\ldots.. (4)$$

$$r_c = \frac{t_o}{t_c} = \frac{h\sin\emptyset}{h\cos(\emptyset - \alpha)} = \frac{\sin\emptyset}{\cos\emptyset\cos\alpha + \sin\emptyset\sin\alpha} \ldots\ldots\ldots\ldots\ldots\ldots. (5)$$

$$r_c\cos\emptyset\cos\alpha + r_c\sin\emptyset\sin\alpha = \sin\emptyset \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (6)$$

$$\frac{r_c\cos\emptyset\cos\alpha}{\sin\emptyset} + \frac{r_c\sin\emptyset\sin\alpha}{\sin\emptyset} = 1 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (7)$$

$$\frac{r_c\cos\alpha}{\tan\emptyset} = 1 - r_c\sin\alpha \ldots\ldots\ldots\ldots\ldots\ldots\ldots.\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (8)$$

$$\tan\emptyset = \frac{r_c\cos\alpha}{1 - r_c\sin\alpha} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

The shear strain that occurs along the shear plane can be estimated by examining Figure 10. Part (a) 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 in Figure 10(b). Referring to part (c), this can be expressed as:

$$\tau = \frac{AC}{BD} = \frac{AD + DC}{BD}$$

Which can be reduced to the following definition of shear strain in metal cutting:

$$\tau = \tan(\emptyset - \alpha) + \cot\emptyset \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots... (10)$$

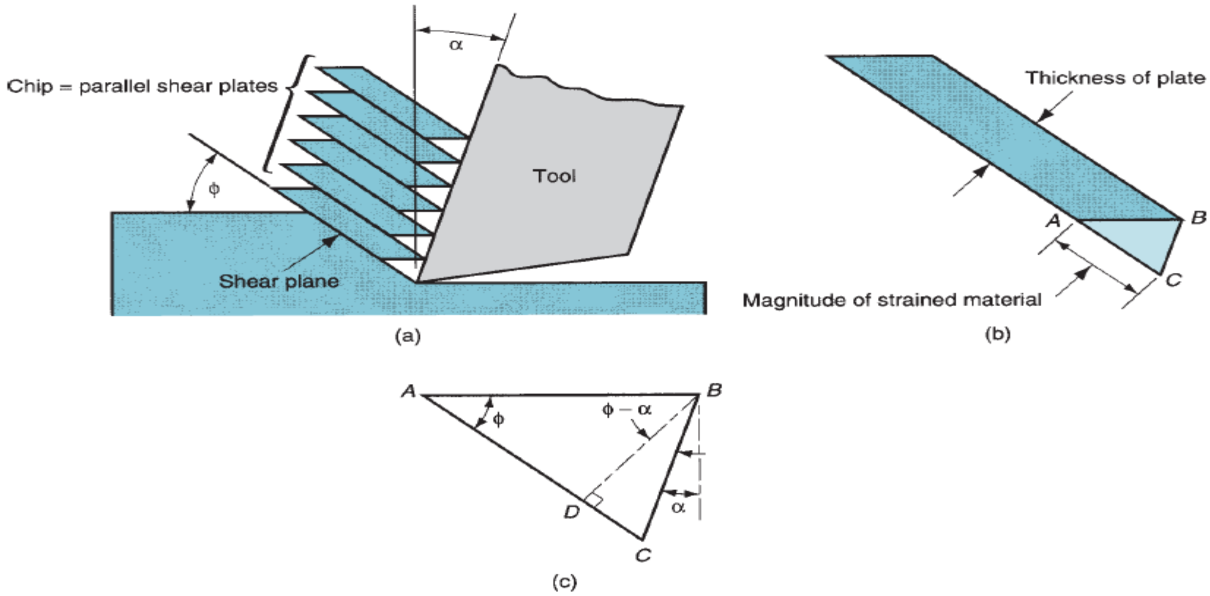


Figure 10: Shear strain during chip formation: (a) chip formation depicted as a series of parallel plates sliding relative to each other; (b) one of the plate isolated to illustrate the definition of shear strain based on this parallel plate model; and (c) shear strain triangle used to derive Eq. (10).

2.2 Actual Chip Formation

Formation of the chip depends on the type of material being machined and the cutting conditions of the operation. Four basic types of chip can be distinguished, illustrated in Figure 11:

- ***Discontinuous chip***. The conditions below support its formation.
  1. The workpiece is relatively brittle material (e.g., cast iron).
  2. Low cutting speeds are used.
  3. Low rake angle.
- ***Continuous chip***. The conditions below support its formation.
  1. The workpiece is ductile material.
  2. High cutting speeds are used.
  3. Relatively small feed rate and depth of cut.

4. A sharp cutting edge on the tool.
5. Low tool–chip friction encourage the formation of continuous chips.
6. High rake angle.
7. Cutting fluid is effective.

- ***Continuous chip with built-up edge*** (***BUE***). The conditions below support its formation.

1. The workpiece is ductile material.
2. Low-to medium cutting speeds are used.
3. Friction on the tool surface is high.
4. Cutting fluid is ineffective.
5. Low rake angle.
6. High feed rate.

Note: 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). The formation of a BUE is cyclical; it forms and grows, then becomes unstable and breaks off. 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. Portions of the detached BUE that are not carried off with the chip become imbedded in the newly created work surface, causing the surface to become rough.

- ***Serrated chips.*** The conditions below support its formation.
    1. The workpiece is difficult-to-machine metals such as titanium alloys, nickel-base superalloys, and austenitic stainless steels.
    2. High cutting speeds are used.

Note: the term shear-localized is also used for this fourth chip type).

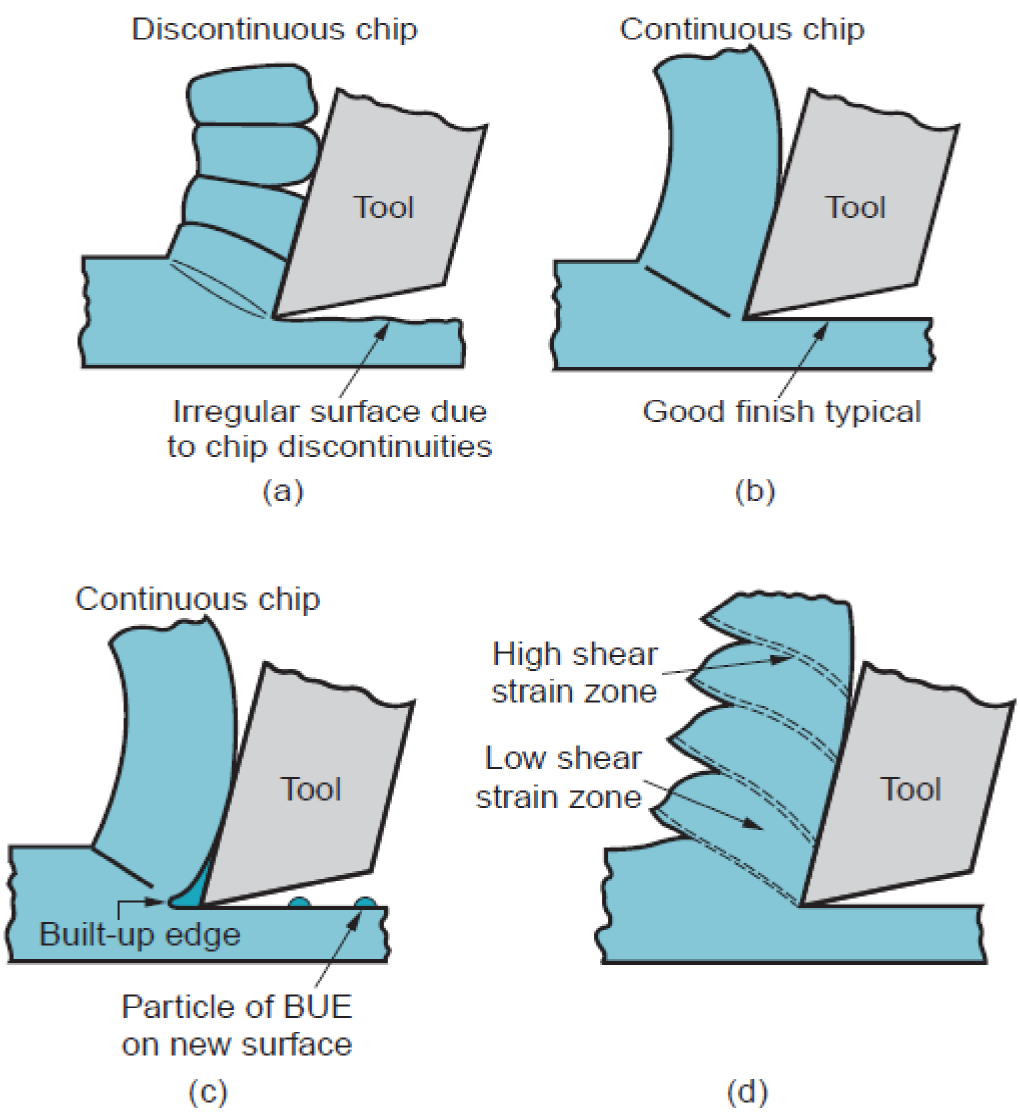


Figure 11: Four types of chip formation in metal cutting: (a) discontinuous, (b) continuous, (c) continuous with built-up edge, (d) serrated.

Example 1 Orthogonal Cutting

In a machining operation that approximates orthogonal cutting, the cutting tool has a rake angle (**10**°). The chip thickness before the cut (**0.50**) mm and the chip thickness after the cut (**1.125**) mm. Calculate the shear plane angle and the shear strain in the operation.

$$r_c = \frac{t_o}{t_c} = \frac{0.5}{1.125} = 0.444$$

$$\tan \emptyset = \frac{r_c \cos \alpha}{1 - r_c \sin \alpha} = \frac{0.444 \ \cos 10}{1 - 0.444 \sin 10} = 0.4738$$

$$\emptyset = 25.4°$$

$$\tau = \tan(\emptyset - \alpha) + \cot \emptyset$$

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

$$\tau = 0.275 + 2.111 = 2.386$$