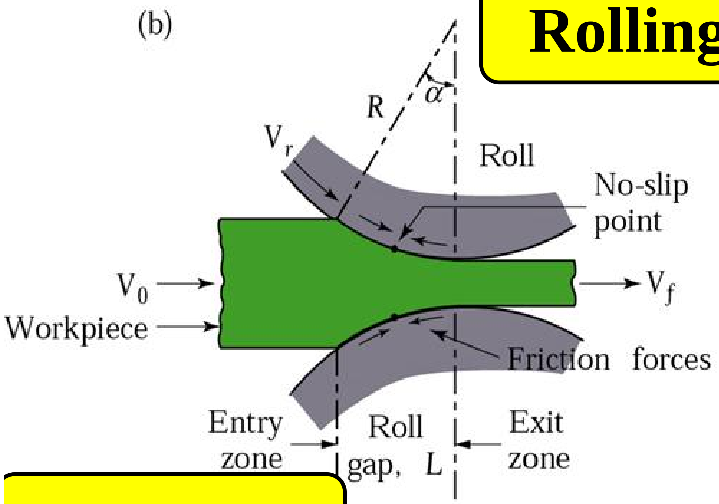
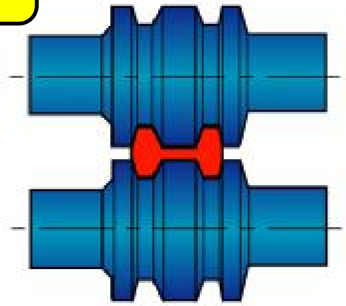
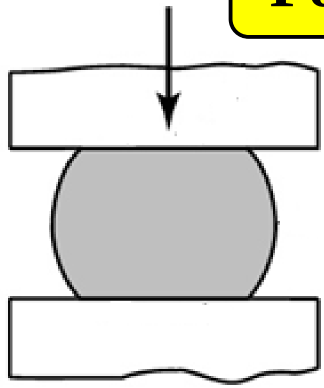
Summary of Chapter 4/5/6

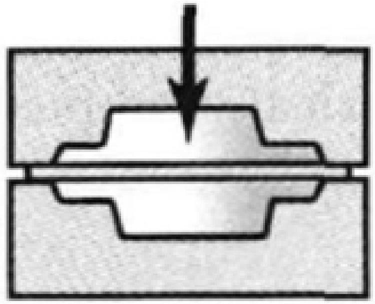
Rolling



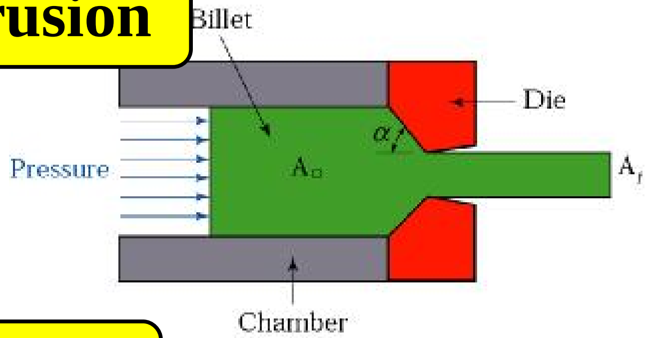


Forging

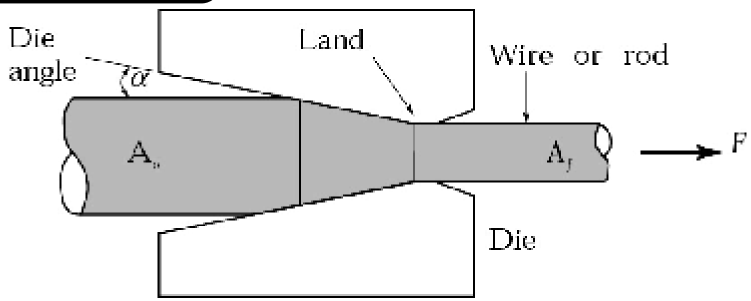




Extrusion



Drawing



Common of these processes:

- the thickness or cross-section of the billet is reduced or changed by compressive forces
- done at room or elevated temperature

冷/温/热

Bulk Deformation Processes
（体积成形工艺）

Chapter 7 Sheet-Metal Forming Processes and Equipment
（金属板料成形/钣金成形工艺及设备）

- 7.1 Introduction
- 7.2 Shearing
- 7.3 Sheet-metal Characteristics and Formability
- 7.4 Formability Tests for Sheet Metals
- 7.5 Bending Sheets，Plates and Tubes
- 7.6 Miscellaneous Bending and Related Operations
- 7.7 Deep Drawing
- 7.8 Rubber Forming and Hydroforming
- 7.9 Spinning
- 7.10 Superplastic Forming
- 7.11 Specialized Forming Processes
- 7.12 Manufacturing of Metal Honeycomb Structures
- 7.13 Design Considerations in Sheet-metal Forming
- 7.14 Equipment for Sheet-metal Forming
- 7.15 Economics of Sheet-forming Operations

Preface（前言）:

- This chapter describes the important characteristics of sheet metals and the forming processes employed to produce a wide variety of products.
- The chapter opens with a discussion of the shearing operation, a process that takes place to cut sheet metal into blanks of desired shapes or to remove portions of the material such as for holes or slots.
- A discussion of sheet-metal formability follows, with special emphasis on the specific metal properties that affect formability.
- The chapter then presents various bending operations for sheet, plates, and tubes, as well as operations such as stretch forming, rubber forming, spinning, peen forming, and superplastic forming.
- The important process of deep drawing is then described, along with deep drawability, as it relates to the production of containers with thin walls.
- The chapter ends with a discussion of part designs, equipment characteristics, and the economic considerations for all these operations.

Typical parts made by sheet-metal forming: Car bodies, aircraft fuselages, trailers, office furniture, appliances, fuel tanks, and cookware.

Alternative processes: Die casting, thermoforming, pultrusion, injection molding, blow molding.

7.1 INTRODUCTION

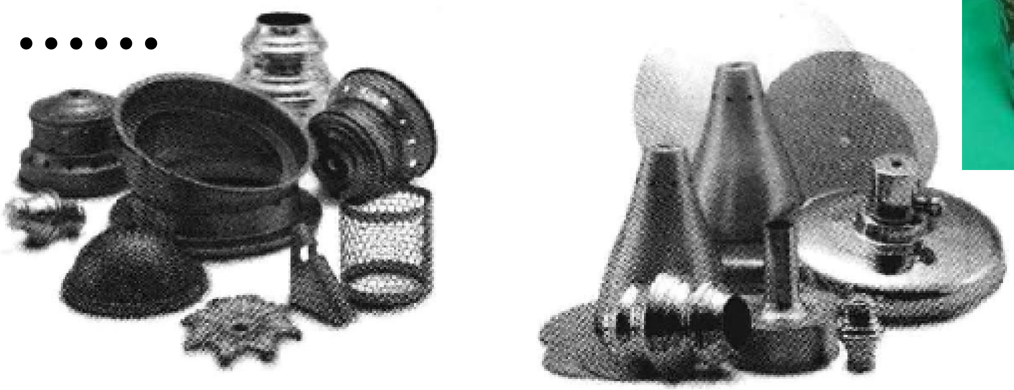
- **Sheet-metal forming** is a **plastic forming** *（塑性成形）* method, which causes **sheet** to **separate** *（分离）* or **deform** *（变形）* by using the **die and punch** *（凹模与凸模）* installed in the **press** *（压力机/冲床）*.
- also called **sheet stamping** *（板料冲压/钣金成形）*
- usually carried out at the **room temperature**, which is called **cold stamping** *（冷冲/冷冲压）*
- one of the oldest metal working processes – 5000B.C

- **There are numerous processes employed for making sheet-metal parts（钣金件）.**
- **The term pressworking（压力加工） or press forming（压力成形） is used commonly in industry to describe general sheet-forming operations, because they typically are performed on presses using a set of dies.**

Typical Sheet-Metal Products
（钣金件）

discrete parts

- **metal desks**
- **file cabinets（文件柜）**
- **appliances（器具）**
- **beverage cans**
- **car parts**
- **……**



(a) (b)

FIGURE 7.1 Examples of sheet-metal parts. (a) Stamped parts. (b) Parts produced by spinning. *Source*: (a) Courtesy of Williamsburg Metal Spinning & Stamping Corp.

car bodies

spaceflight products

- **sheet metal parts possess 60~75% in automobile's body components**

Ø **for the sake of light weight（轻量化）**

Advantages of Sheet-metal Parts

① light weight

for the thin thickness of sheet-metal

② versatile（*多样的/多用途的*） shape

③ material saving

④ high productivity

⑤ good surface finish, dimensional accuracy,

mechanical properties

Sheet- Metal Materials

- low-carbon steel（低碳钢）
  - low cost
  - generally good strength and formability（可成形性）
  - the most commonly used sheet metal
- TRIP and TWIP steels（相变诱发与孪生诱发塑性钢）
  - high strength and provide good crash protection（撞击保护）in a lightweight design（轻量化设计）
  - popular for automotive applications
- aluminium
  - commonly used for concern of corrosion resistance（耐腐蚀）
  - such as beverage cans, packaging, kitchen utensils
- aluminum and titanium
  - for aircraft and aerospace（航空航天） applications
- other metals
  - with various characteristics

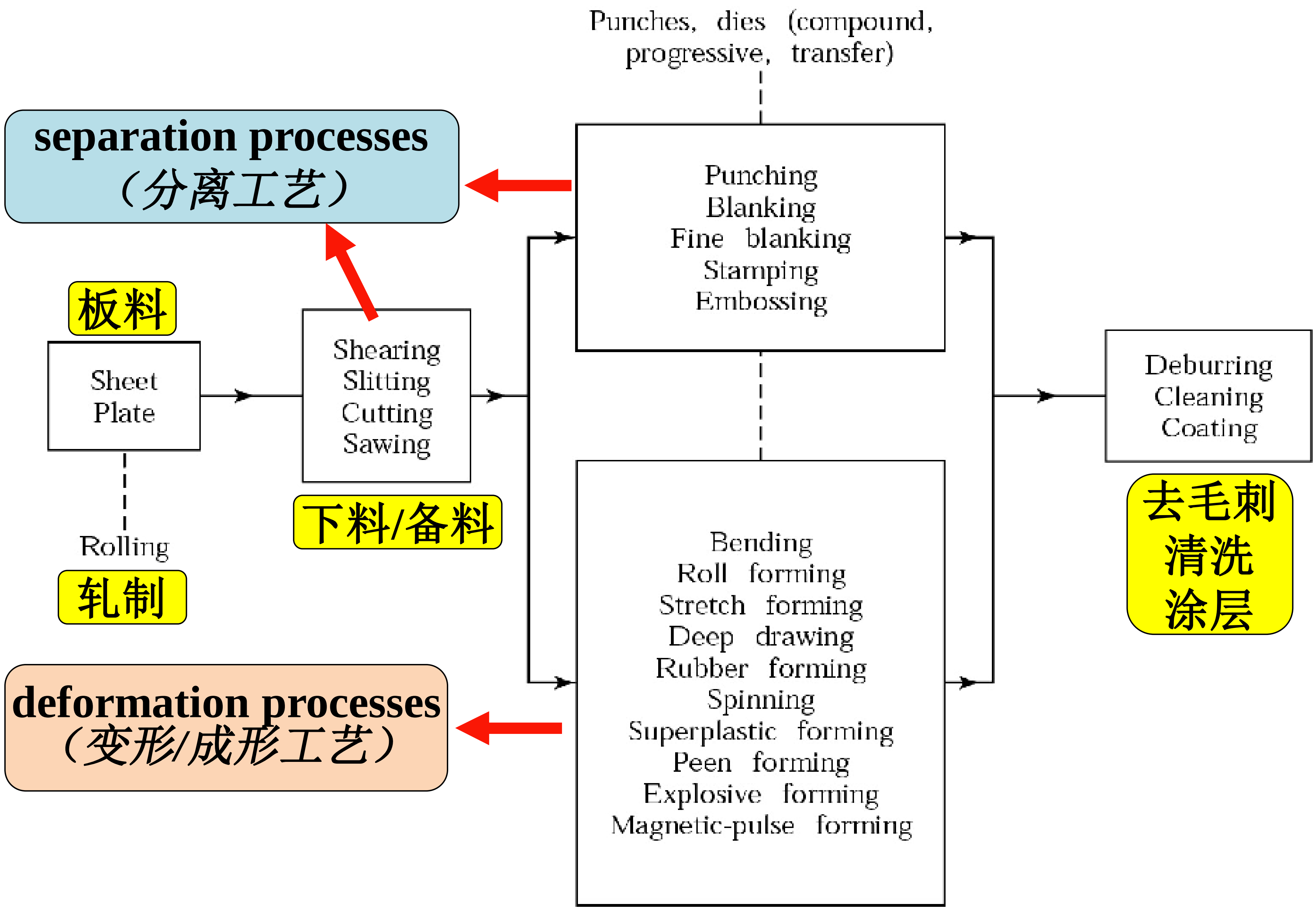
* 百度百科

- 汽车的轻量化是现代汽车工业的发展方向，因此，先进高强韧性钢应运而生，如双相钢，**TRIP steel**， **TWIP steel**
- **TRIP steel （Transformation Induced Plasticity steel）**
  - Ø 相变诱发塑性钢
  - Ø 是指由钢组织中逐步进行的马氏体相变过程导致的塑性升高的超高强度钢
- **TWIP steel (Twinning Induce Plasticity steel)**
  - Ø 孪生诱发塑性钢
  - Ø 高强韧性来自形变过程中孪晶的形成而不是**TRIP**钢中的相变
  - Ø 具有中等的抗拉强度(约**600MPa**)和极高的延伸率(大于**80%)**
  - Ø 具有高的能量吸收能力
  - Ø 没有低温脆性转变温度

Temperature of Sheet-metal Forming

- **Mostly room temperature**
- **Occasionally hot stamping**
  - **to increase formability**
  - **to decrease forming loads on machinery**
  - **typically used for titanium alloy and various high-strength steels**

Outline of Sheet-metal Forming Processes



- **sheet-metal forming**
  - **shearing procedure** *(冲裁工序)*
    - **punching** *(冲孔)*
    - **notching** *(切口)*
    - **blanking** *(落料）*
    - **slitting** *(切舌）*
    - **lancing** *(切缝)*
    - **parting** *(切断）*
    - **perforating** *(打孔)*
  - **deformation procedure** *(成形工序)*
    - **deep drawing** *(拉深)*
    - **bending** *(弯曲)*
    - **stretch forming** *(拉伸成形）*
    - ***spinning*** *(旋压)*
    - **explosive forming** *(爆炸成形)*
    - **rubber forming** *(橡胶模成形)*
    - **superplastic forming** *(超塑性成形)*

Characteristics of Sheet-Metal Forming Processes

TABLE 16.1

Process	Characteristics
Roll forming	Long parts with constant complex cross-sections; good surface finish; high production rates; high tooling costs.
Stretch forming	Large parts with shallow contours; suitable for low-quantity production; high labor costs; tooling and equipment costs depend on part size.
Drawing	Shallow or deep parts with relatively simple shapes; high production rates; high tooling and equipment costs.
Stamping	Includes a variety of operations, such as punching, blanking, embossing, bending, flanging, and coining; simple or complex shapes formed at high production rates; tooling and equipment costs can be high, but labor cost is low.
Rubber forming	Drawing and embossing of simple or complex shapes; sheet surface protected by rubber membranes; flexibility of operation; low tooling costs.
Spinning	Small or large axisymmetric parts; good surface finish; low tooling costs, but labor costs can be high unless operations are automated.
Superplastic forming	Complex shapes, fine detail and close tolerances; forming times are long, hence production rates are low; parts not suitable for high-temperature use.
Peen forming	Shallow contours on large sheets; flexibility of operation; equipment costs can be high; process is also used for straightening parts.
Explosive forming	Very large sheets with relatively complex shapes, although usually axisymmetric; low tooling costs, but high labor cost; suitable for low-quantity production; long cycle times.
Magnetic-pulse forming	Shallow forming, bulging, and embossing operations on relatively low-strength sheets; most suitable for tubular shapes; high production rates; requires special tooling.

TABLE 7.1

General Characteristics of Sheet-metal Forming Processes (in alphabetic order)

Forming process	Characteristics
Drawing	Shallow or deep parts with relatively simple shapes, high production rates, high tooling and equipment costs
Explosive	Large sheets with relatively simple shapes, low tooling costs but high labor cost, low-quantity production, long cycle times
Incremental	Simple to moderately complex shapes with good surface finish; low production rates, but no dedicated tooling required; limited materials
Magnetic-pulse	Shallow forming, bulging, and embossing operations on relatively low strength sheets, requires special tooling
Peen	Shallow contours on large sheets, flexibility of operation, generally high equipment costs, process also used for straightening formed parts
Roll	Long parts with constant simple or complex cross sections, good surface finish, high production rates, high tooling costs
Rubber	Drawing and embossing of simple or relatively complex shapes, sheet surface protected by rubber membranes, flexibility of operation, low tooling costs
Spinning	Small or large axisymmetric parts; good surface finish; low tooling costs, but labor costs can be high unless operations are automated
Stamping	Includes a wide variety of operations, such as punching, blanking, embossing, bending, flanging, and coining; simple or complex shapes formed at high production rates; tooling and equipment costs can be high, but labor cost is low
Stretch	Large parts with shallow contours, low-quantity production, high labor costs, tooling and equipment costs increase with part size
Superplastic	Complex shapes, fine detail and close dimensional tolerances, long forming times (hence production rates are low), parts not suitable for high-temperature use

7.2 Shearing（冲裁）

Outline

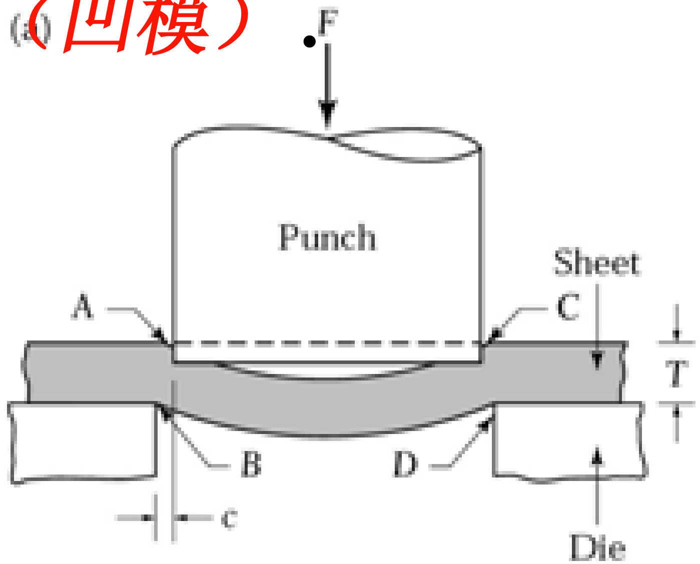
- Shearing process and major process parameters
- Features of the sheared edges and influence factors
- Punch force（冲裁力）
- Typical shearing operations:
  - punching （冲孔）
  - blanking（落料）
  - fine blanking（精密冲裁）
- Shearing dies:
  - clearance（模具间隙）
  - punch and die shapes
  - types of shearing dies:
    - single die （简单模）
    - compound die （复合模）
    - progressive die （级进模/连续模）
    - transfer die （传递模/移步模）

Shearing（冲裁）

– a blank（毛坯）of suitable dimensions is removed from a large rolled sheet (usually from a coil（卷料）)

– the sheet is cut by subjecting sheet metal to shear stresses（剪切应力）, typically ones developed between a punch（凸模/冲头） and a die（凹模）.

卷料

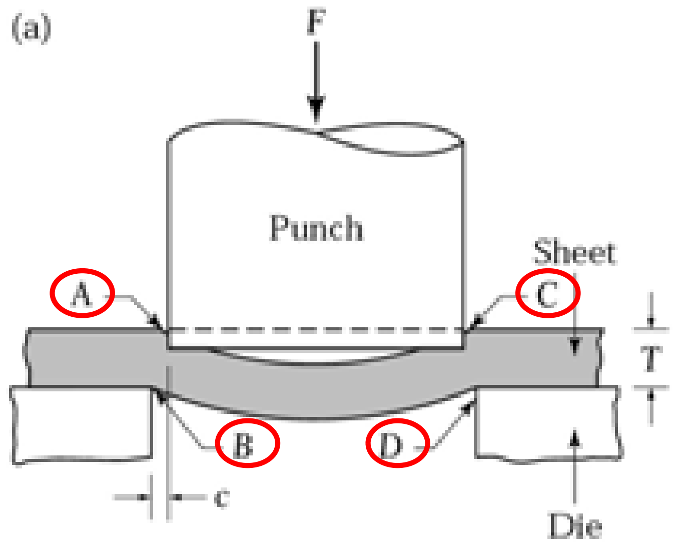


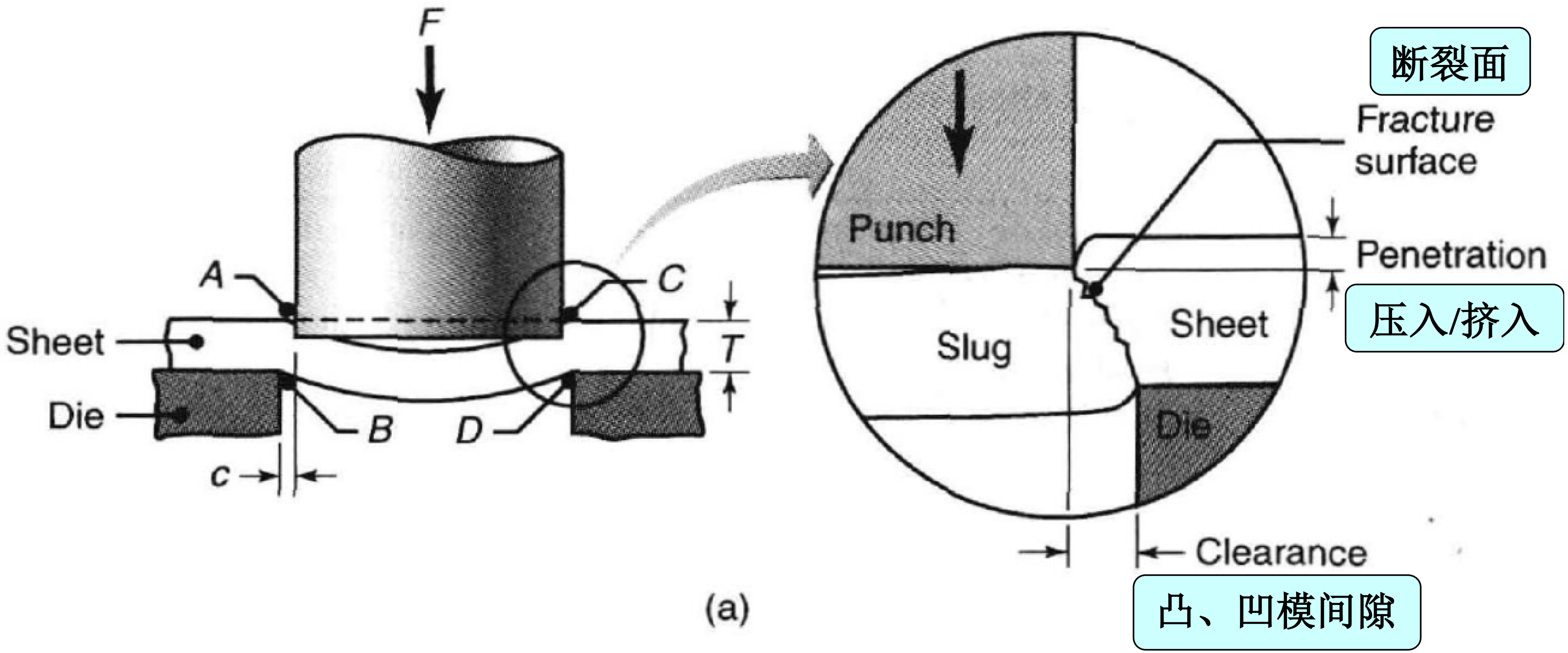
schematic illustration of shearing

Shearing Process

Three stages in shearing process:

- elastic deformation（弹性变形）
- plastic deformation（塑性变形）
- fracture separation（断裂分离）
  – starts with the formation of cracks on both the top and bottom edges of the workpiece
  – these cracks eventually meet（相遇/重合） each other and separation occurs

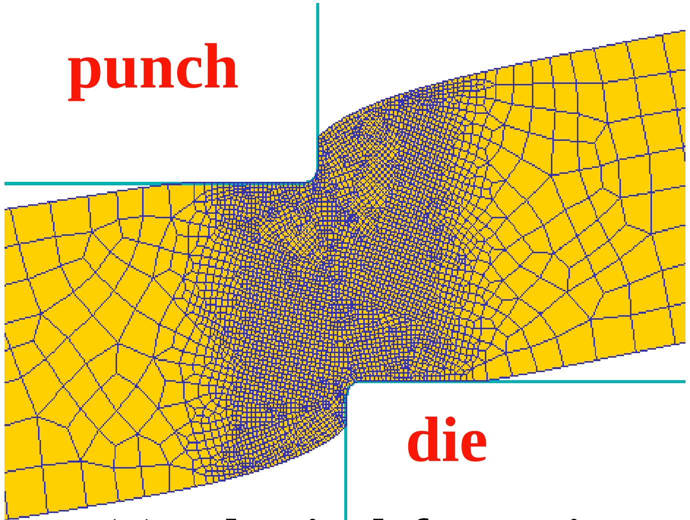




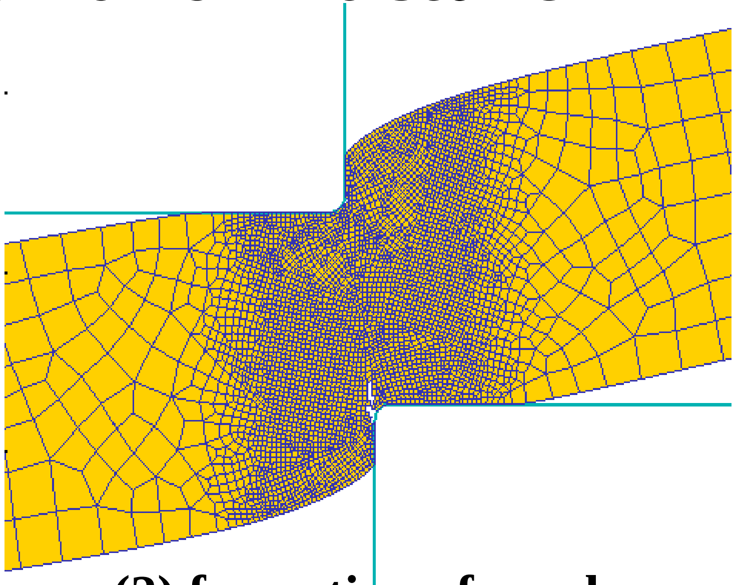
(a)

FIGURE 7.2 (a) Schematic illustration of shearing with a punch and die, indicating some of the process variables.

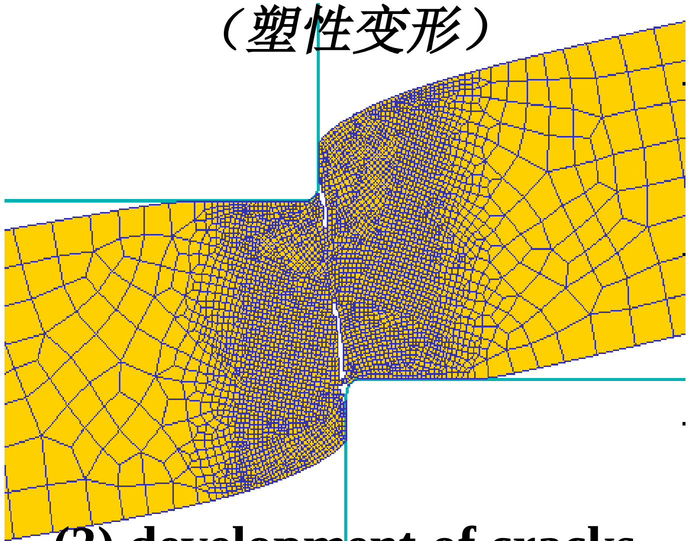
Crack Formation and Fracture



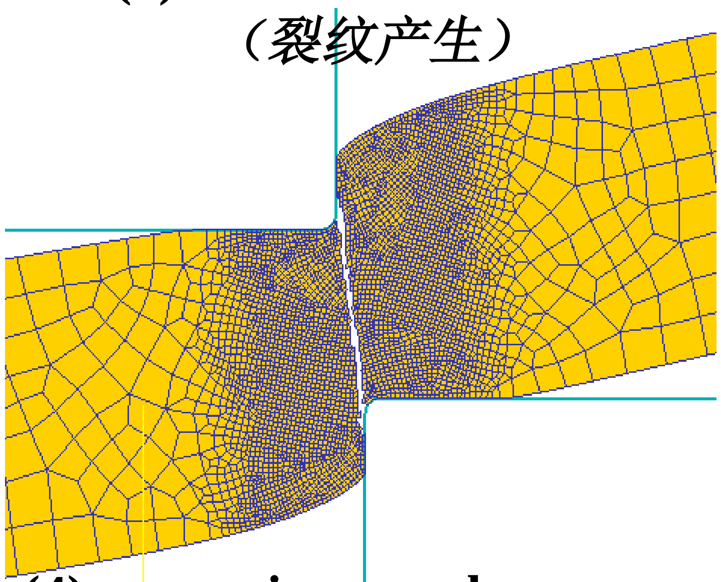
(1) plastic deformation
（塑性变形）



(2) formation of cracks
（裂纹产生）

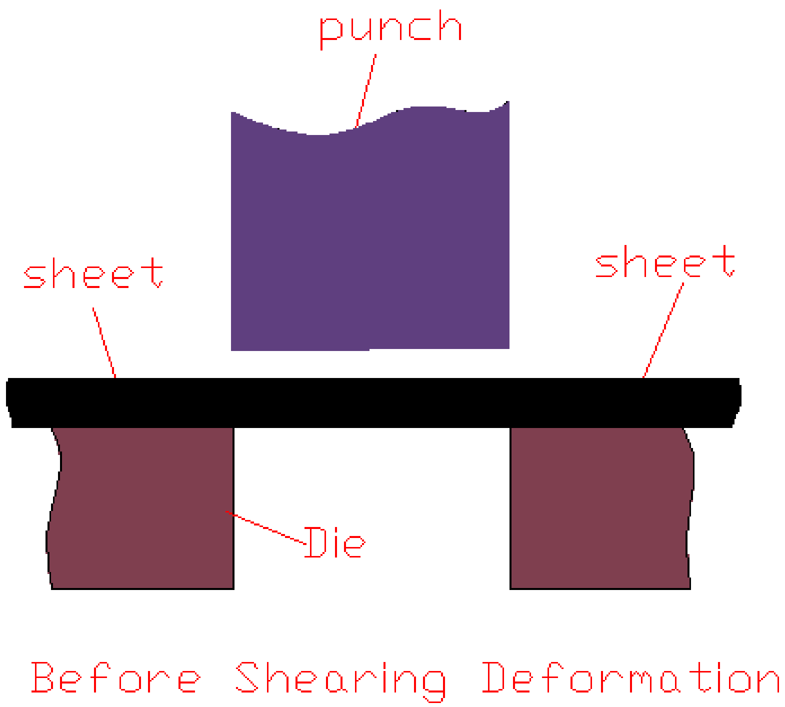


(3) development of cracks
（裂纹发展）

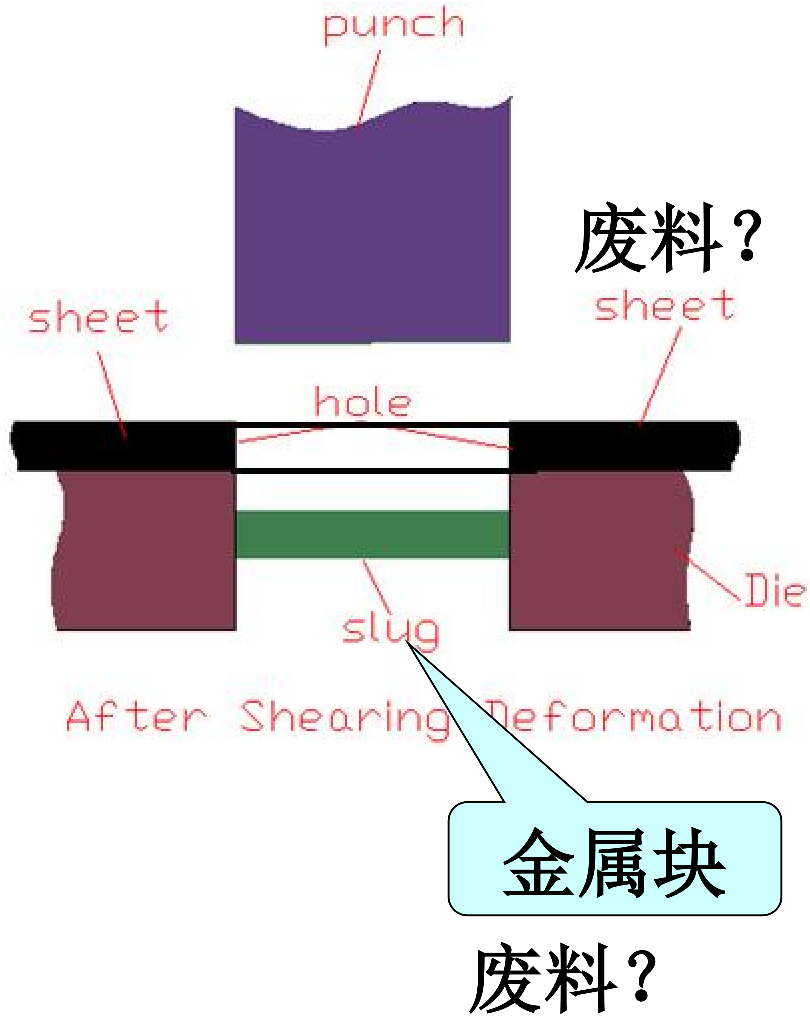


(4) separation: cracks meet each other
（断裂分离：裂纹重合）

冲裁前


punch
sheet
sheet
Die
Before Shearing Deformation

冲裁后


punch
废料？
sheet
sheet
hole
Die
slug
After Shearing Deformation
金属块
废料？

Major Process Parameters

① **shape** **of the punch and die**

② **speed** **of punching**（*冲裁速度*）

③ **clearance** （*模具间隙/凸凹模间隙*）

④ **lubrication**

Features of The Sheared Edges（冲裁边缘/断面特征）

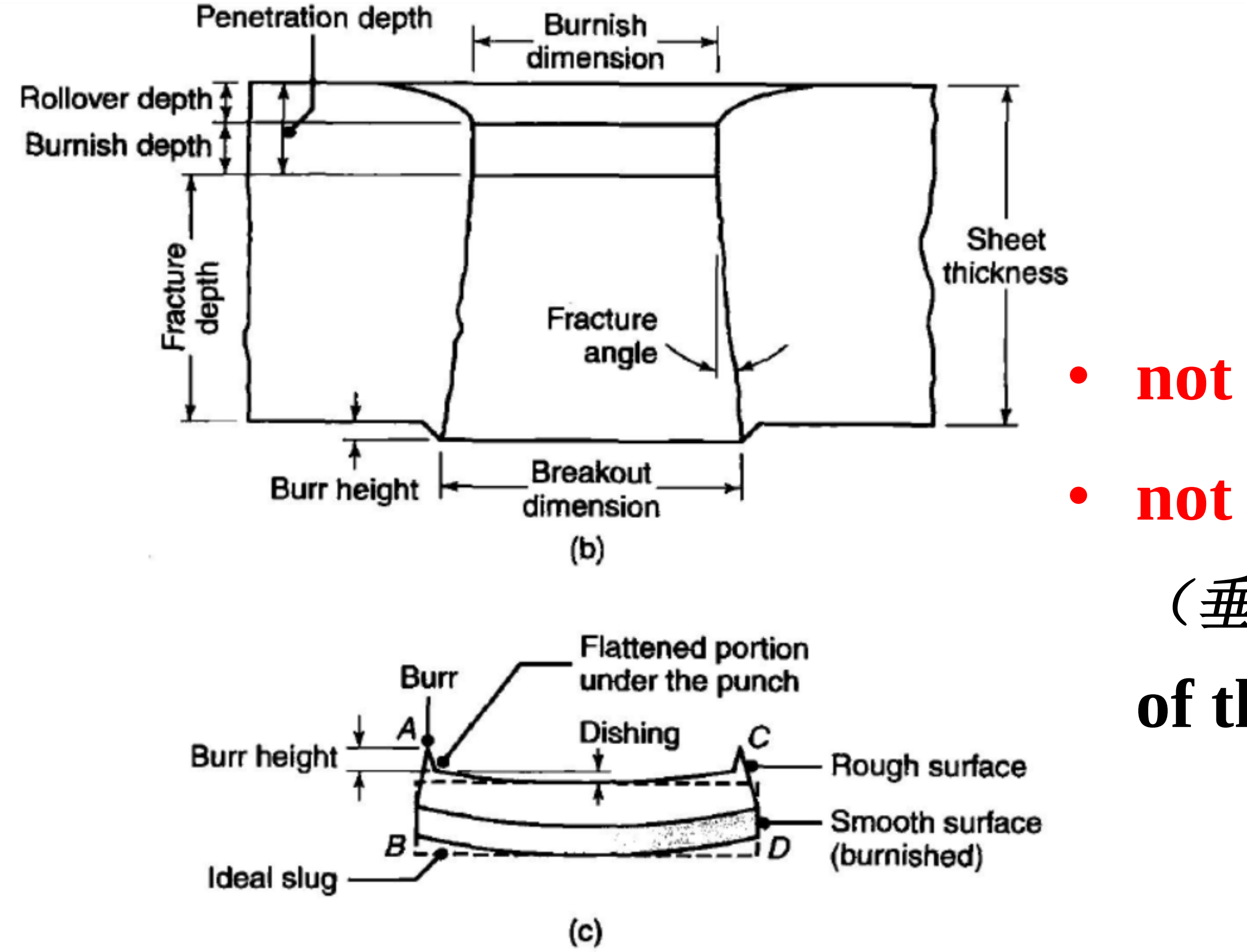
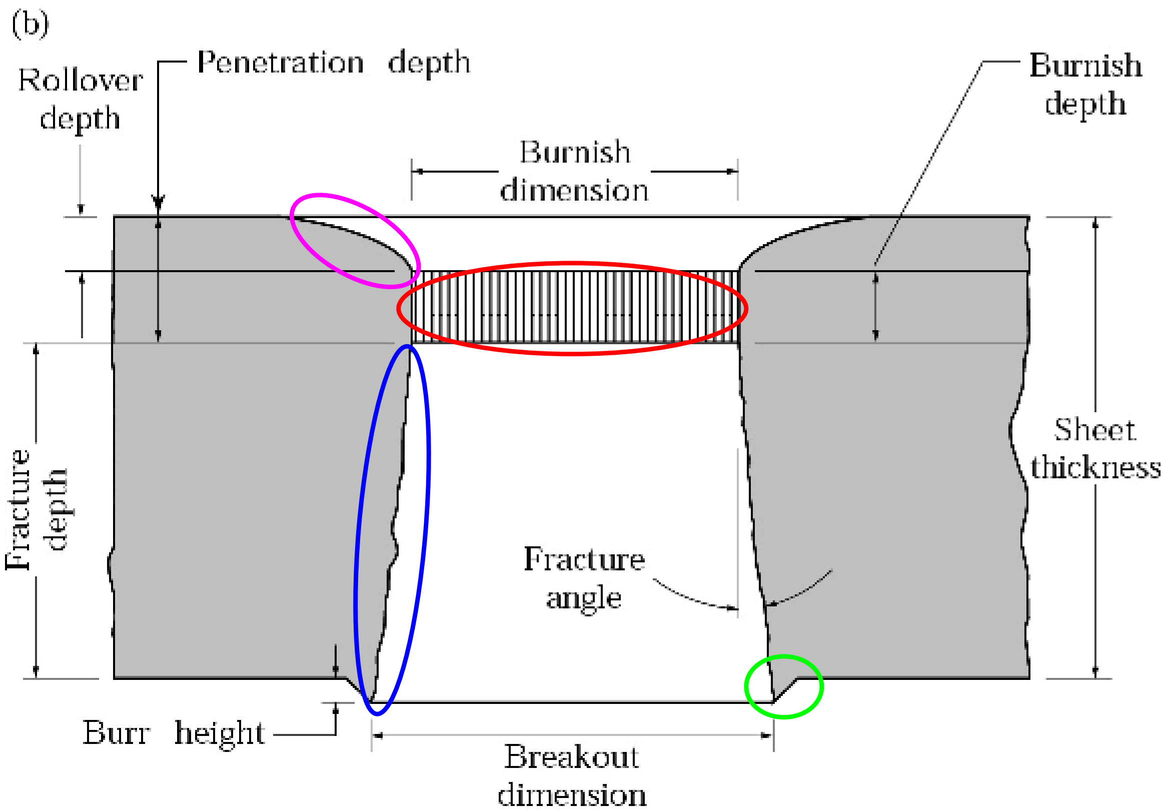


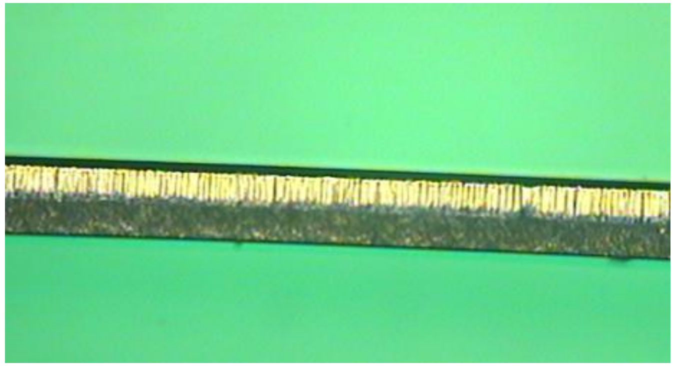
FIGURE 7.2 (a) Schematic illustration of shearing with a punch and die, indicating some of the process variables. Characteristic features of (b) a punched hole and (c) the slug. (Note that the scales of (b) and (c) are different.)

- **not smooth**
- **not perpendicular to（垂直于） the plane of the sheet**

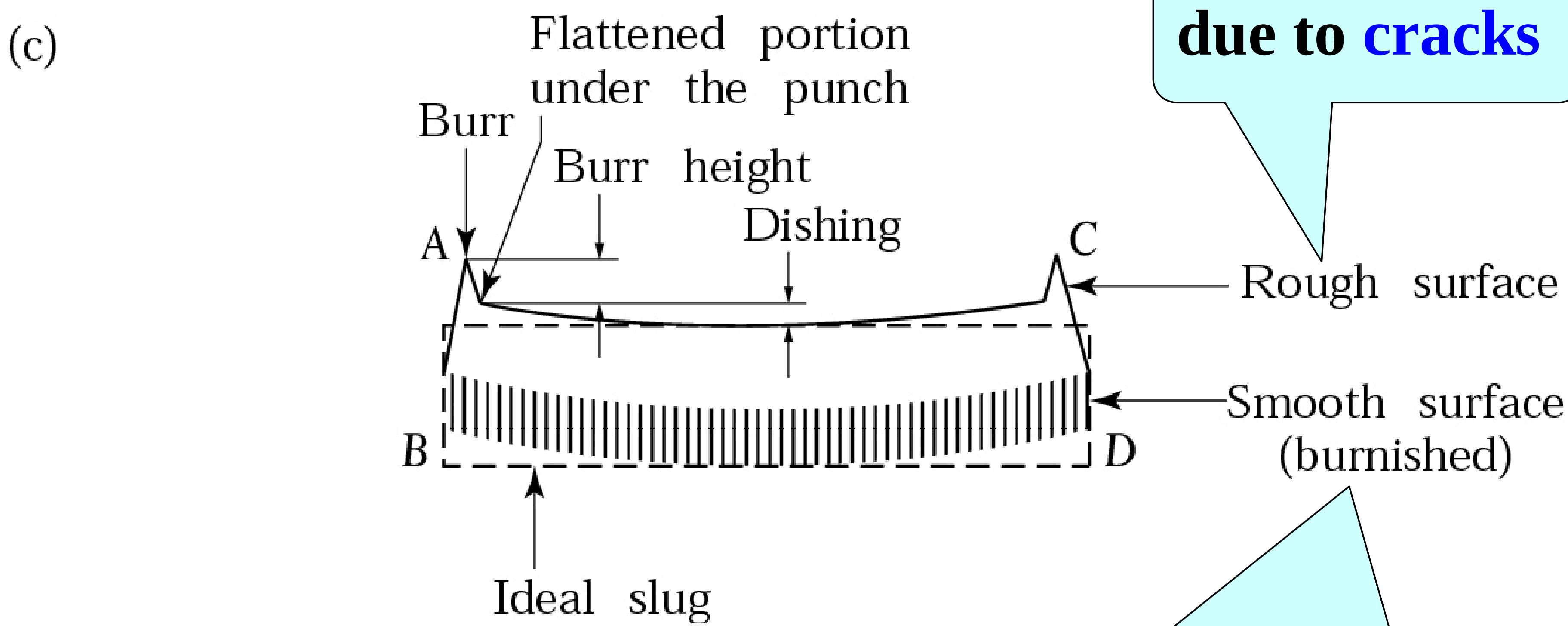
The whole fracture surfaces includes **four different zones**:

- rollover zone （圆角带）
- burnish zone（光亮带） → quality is the best
- fracture zone（断裂带/剪裂带）
- burr（毛刺）





Same Situation in Slug



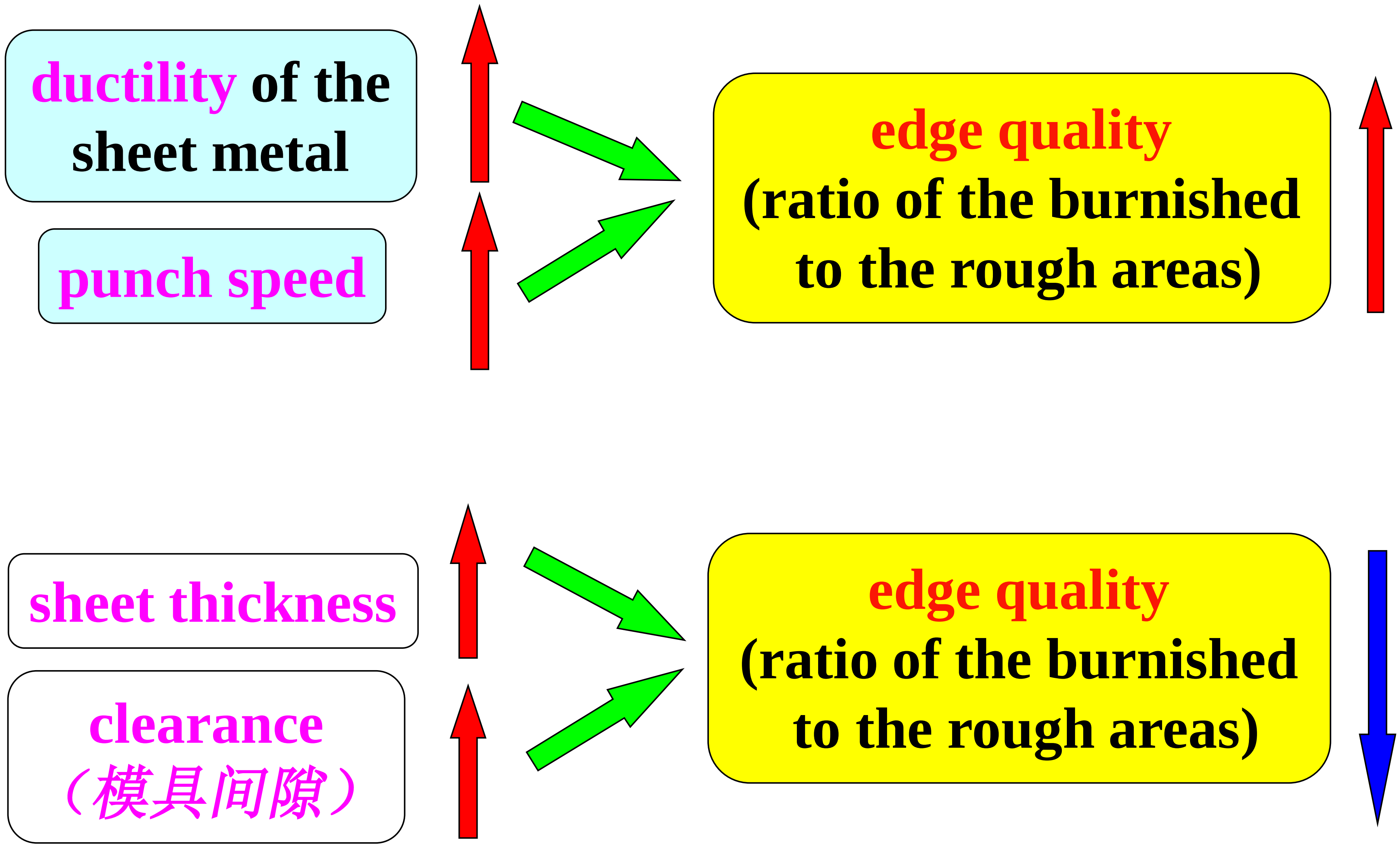
due to **cracks**

due to contact and rubbing *（接触与摩擦）* **of the sheared edge against the walls of the punch and die**

desirable sheared edge

- **depth of the burnish zone** ↑
- **depth of the rollover and fracture zone** ↓
- **height of the burr** ↓

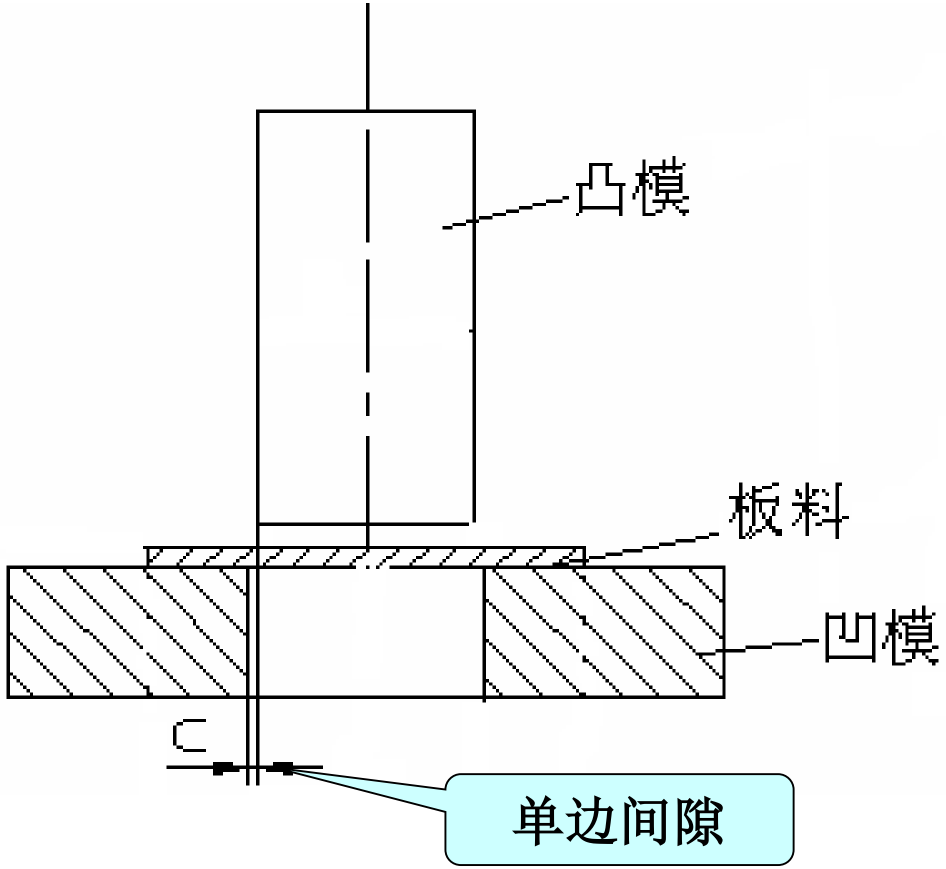
Factors Influence Sheared Edge Quality



1. Clearance（模具间隙）

$$c=(D_d-D_p)/2$$

- is the space or distance between die and punch.
- is a **major factor** in determining the **shape** and the **quality** of the sheared edge



c— clearance between die and punch;
D_d—diameter of die;
D_p—diameter of punch.

Effects of the Clearance

clearance ↑ → **roughness** of the edge ↑

clearance ↓ →
- **quality** of the edge ↑
- punch **forces** ↑

$c=(2\% \sim 10\%)T$

***T*: the thickness of the sheet**

Effects of the Clearance

间隙过小：冲裁件断面上下裂纹不重合，中间的部分材料随着冲裁的进行被第二次剪切，冲裁件外观质量较好，但摩擦大，冲裁力大，模具寿命降低

间隙合理：冲裁件断面上下裂纹重合，光亮带大，塌角（圆角）、毛刺小，表面较平整

冲裁间隙过大：冲裁件断面上下裂纹不重合，更多材料被撕裂拉断，断面粗糙、斜度大，光亮带小，塌角、毛刺锥度大

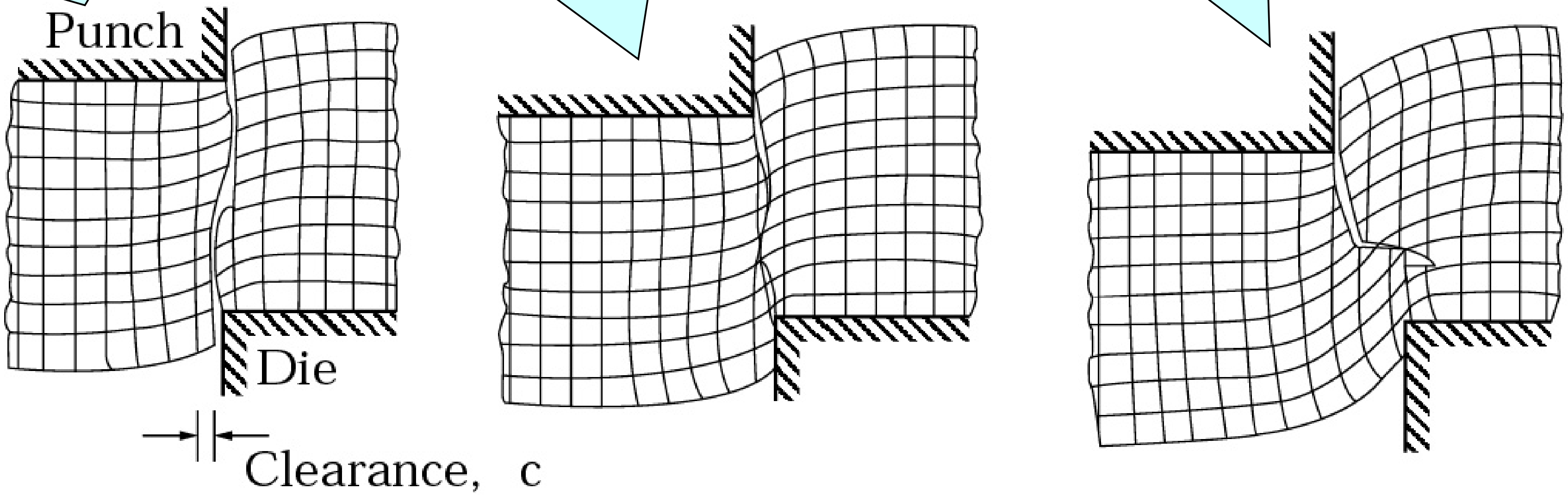


Figure 7.3 (a) Effect of the clearance, *c*, between punch and die on the deformation zone in shearing. As the clearance increases, the material tends to be pulled into the die rather than be sheared. In practice, clearances usually range between 2% and 10% of the thickness of the sheet.

Work Hardening（加工硬化） of Sheard Edges

– Adversely affect the formability of the sheet

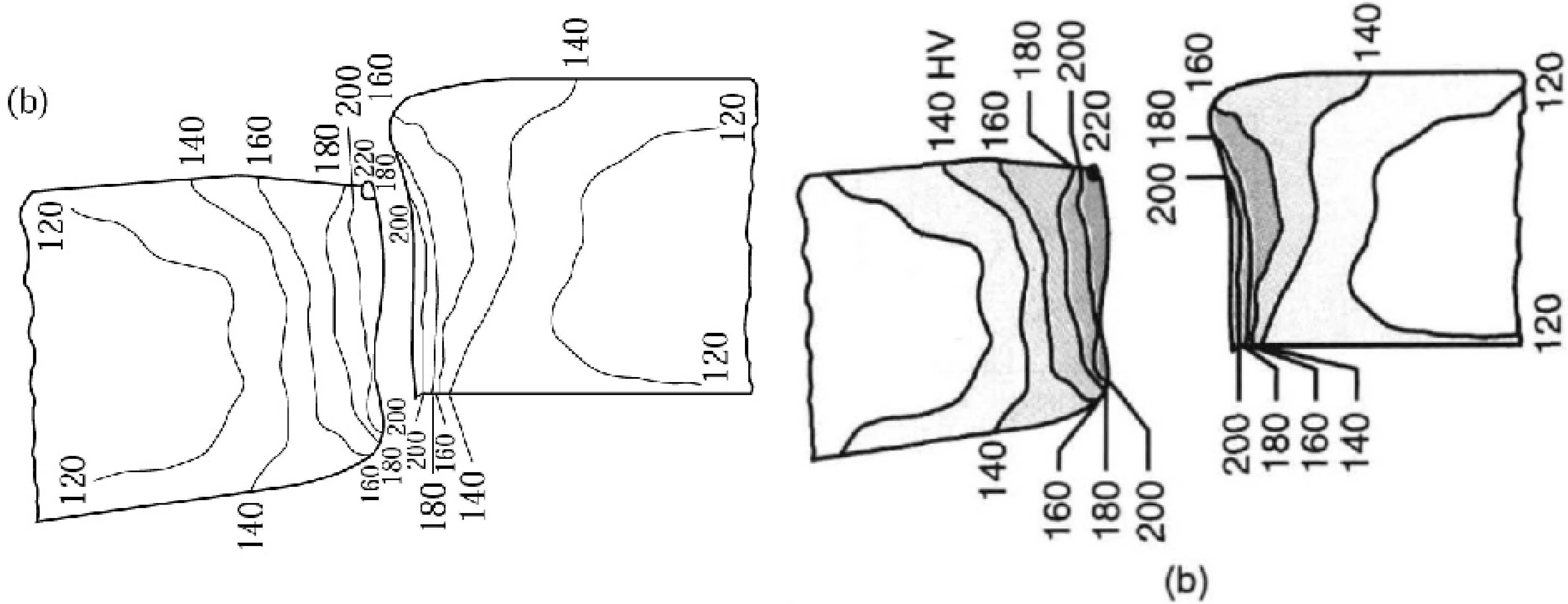


Figure 7.3 (b) Microhardness (HV) contours（维氏显微硬度等高线） for a 6.4-mm (0.25-in) thick AISI（*Acronym of American Iron and Steel Institute/美国钢铁学会标准*）1020 hot-rolled steel in the sheared region. *Source*: H. P. Weaver and K. J. Weinmann.

Shaving（修整）

– the extra material from a rough sheared edge is trimmed by cutting

– a secondary operation to make the sheared edge smoother and will add the production cost

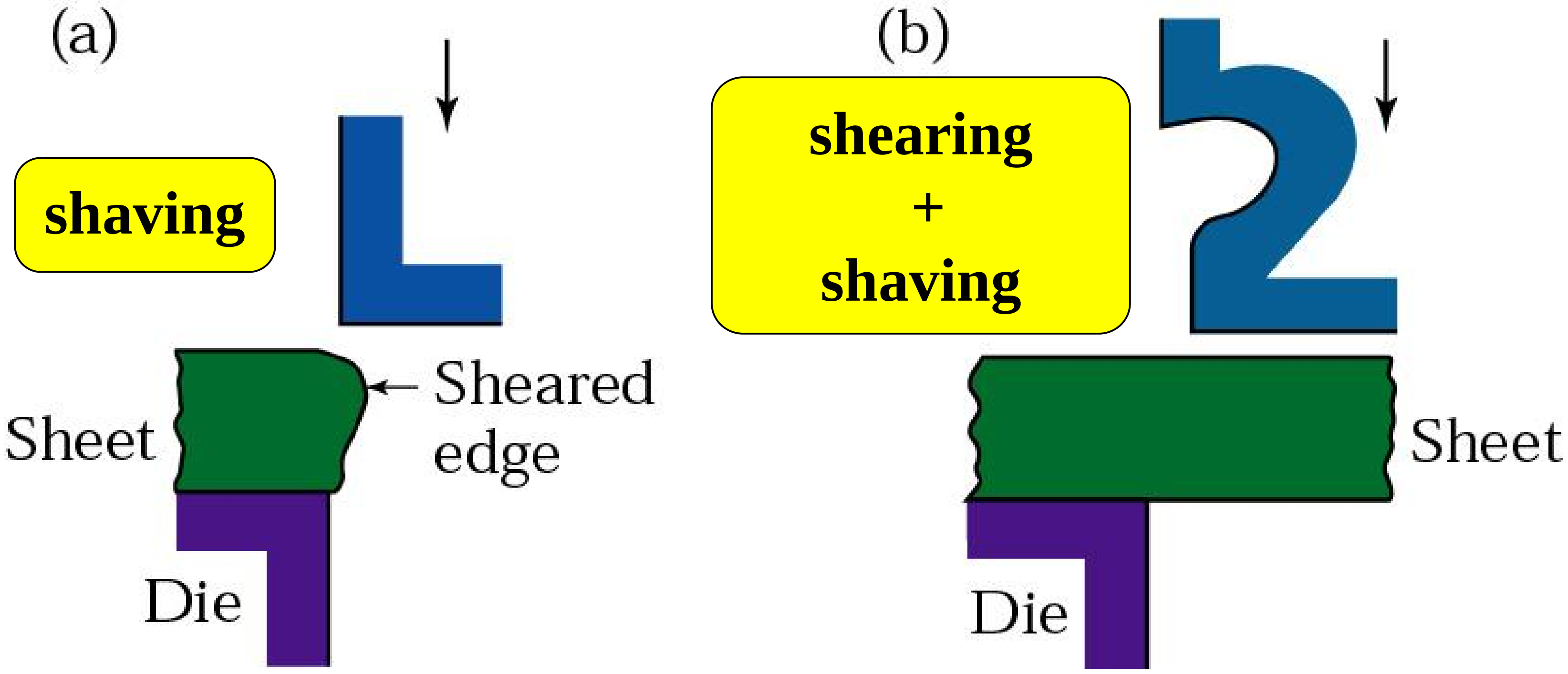


Figure 7.9 Schematic illustrations of the shaving of a sheared edge. (a) Shaving a sheared edge. (b) Shearing and shaving, combined in one stroke.

shaving

shearing
+
shaving

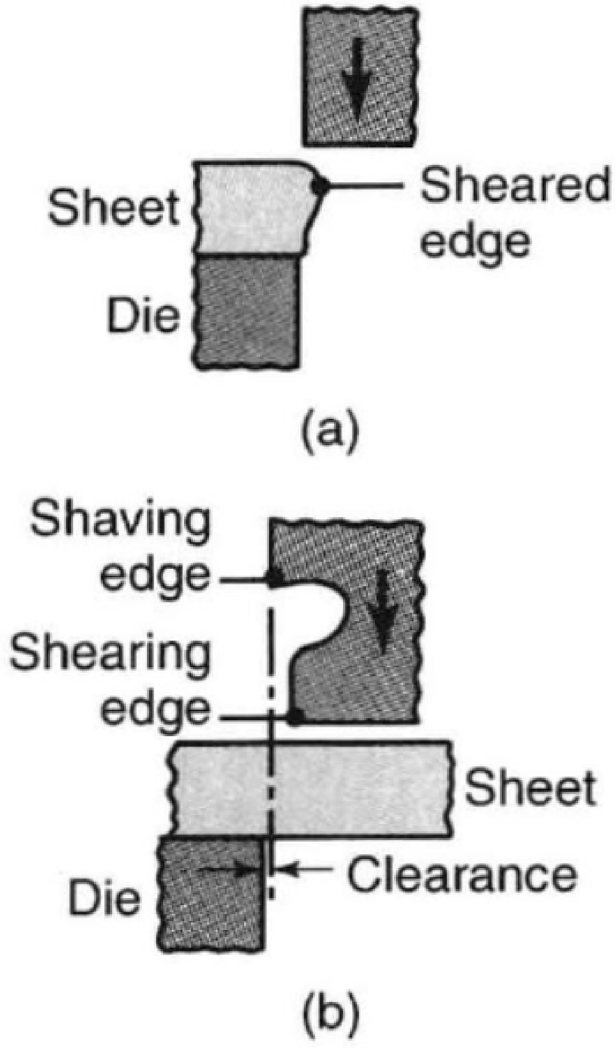


FIGURE 7.9 Schematic illustrations of the shaving process. (a) Shaving a sheared edge. (b) Shearing and shaving combined in one stroke.

2. Punch Speed（冲裁速度）

– **Edge quality improves with increasing punch speed**

– **May be as high as 10~12m/s**

– **With increasing speed, the heat generated by plastic deformation is confined to（限制于） a smaller and smaller zone**

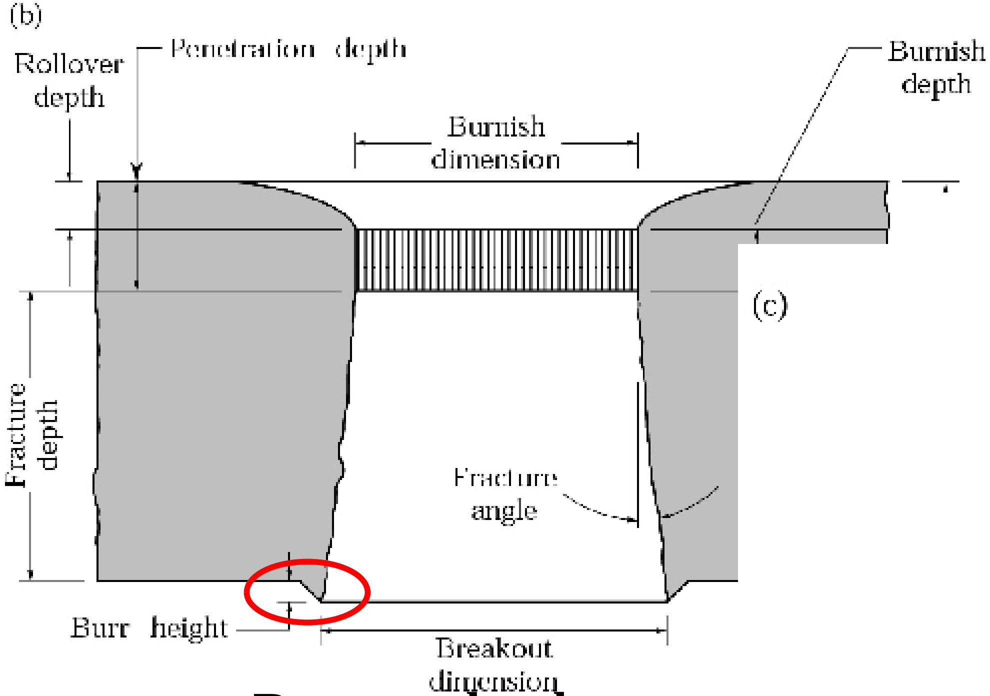
– **Consequently, the sheared zone in narrower and the sheared surface is smoother and exhibits less burr formation.**

3. Burr（毛刺）

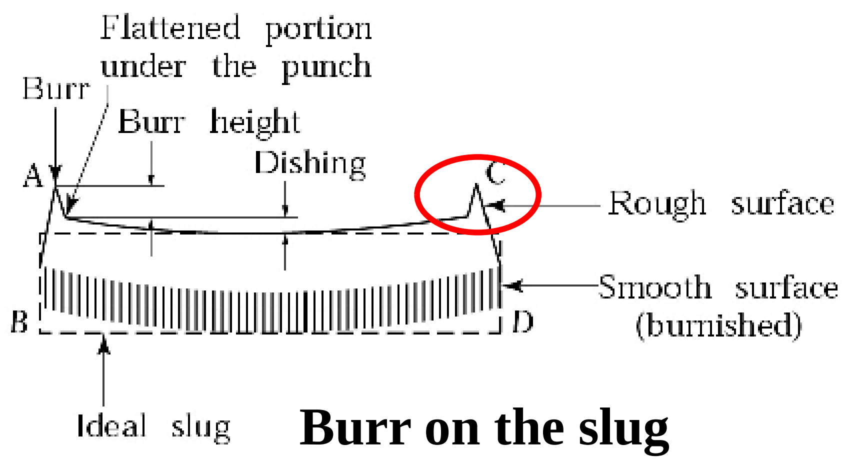
– is a thin edge or ridge（脊线/隆起）
– factors influence burr height:
  - ø clearance
  - ø ductility of the sheet metal
  - ø dull（钝的） tool edges（模具刃口）

burr height

– deburring（去毛刺）processes（ to remove burr ） is necessary



Burr on the sheet



Burr on the slug

* 热能去毛刺

- 原理：
  热能去毛刺方法，是利用高温清除零件的毛刺和飞边。被加工零件置于密封燃烧腔内，将可燃气体（天然气/甲烷/氢气）和氧气按一定比例、一定压力充入腔内，可燃气体包裹零件的里外以及毛刺、飞边，密密充斥零件内、外部、孔内，甚至盲孔里面。由火花塞点燃气体，瞬间产生燃点以上的高温。由于毛刺、飞边高于零部件表面，当温度急剧上升到毛刺、飞边自燃点以上时，小体积的毛刺、飞边燃烧。毛刺燃烧至工件主体，温度迅速降到自燃点以下时，腔里多余的氧气和毛刺混合化为氧化粉尘。这一过程很短，仅足以将毛刺、飞边烧掉，而不至于影响到工件本身。燃烧后，落在工件的所有表面上的毛刺和飞边的氧化残留物可以用溶剂清洗掉。
- 优点：
  热能去毛刺具有去除毛刺、飞边而又不影响和损伤工件的尺寸或金相结构的特点。热能方法可以去除零件任意部位的毛刺，包括手工无法到达的部位、零件内孔交接处，甚至盲孔里的毛刺。它优于手工去毛刺的是：
  加工后不需要检验是否有未去除和未除净的毛刺，效果可靠而且效率高；
- 可处理多种材料：锌、铝、铜、钢、不锈钢、铸铁，以及热熔塑料等零件；
- 相类似的零件，即使尺寸略有不同，也可以放在一起处理；对于尺寸不同的零件，只需稍微调整某些加工参数，甚至不用改变时间就能进行处理；
- 使生产成本大大降低，并保证了零件的质量和寿命。

Punch Force（冲裁力）

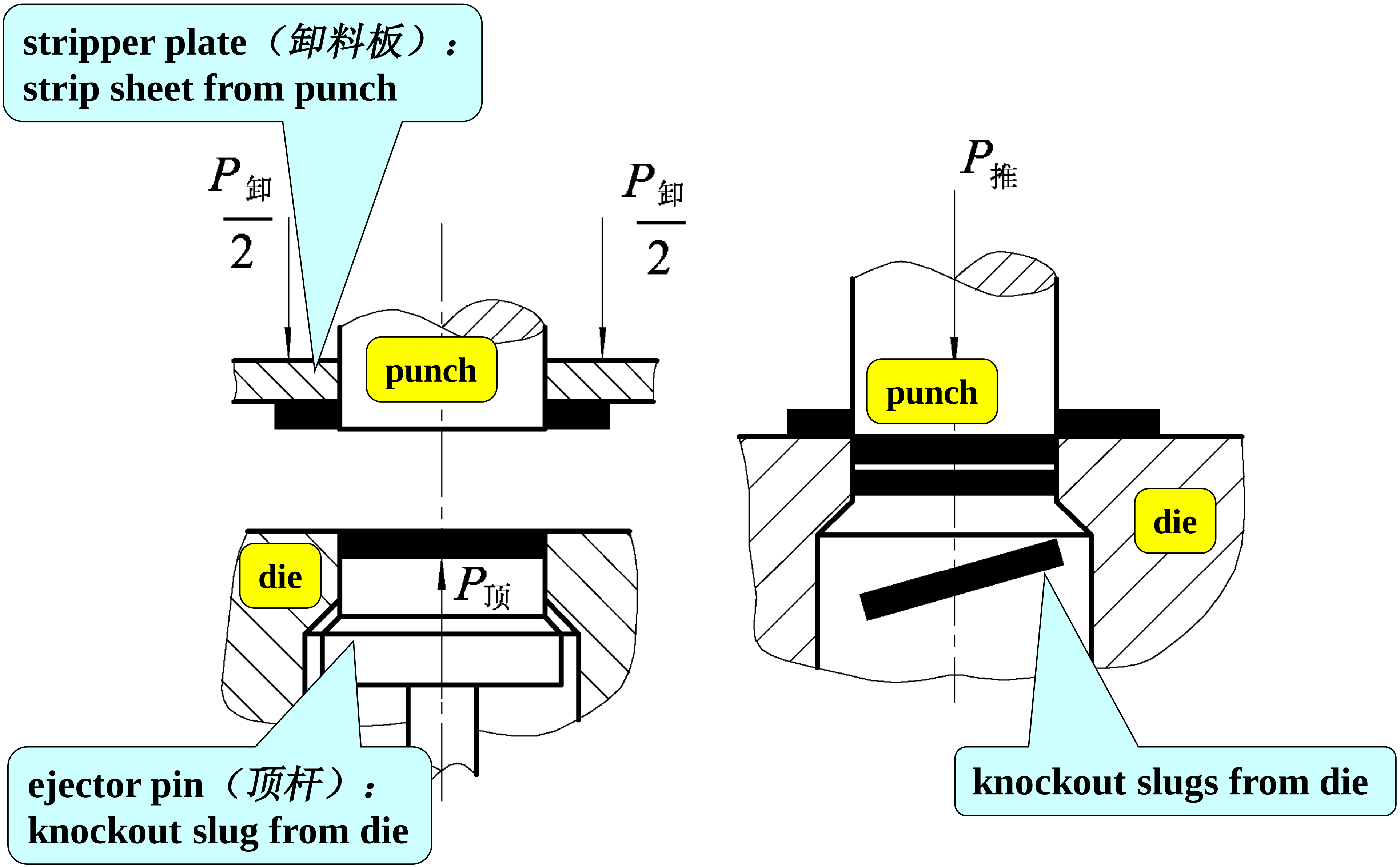
$$F = 0.7TL(UTS)$$

T: the thickness of the sheet
L: the total length sheared
UTS: the ultimate tensile strength （极限抗拉强度） of the material

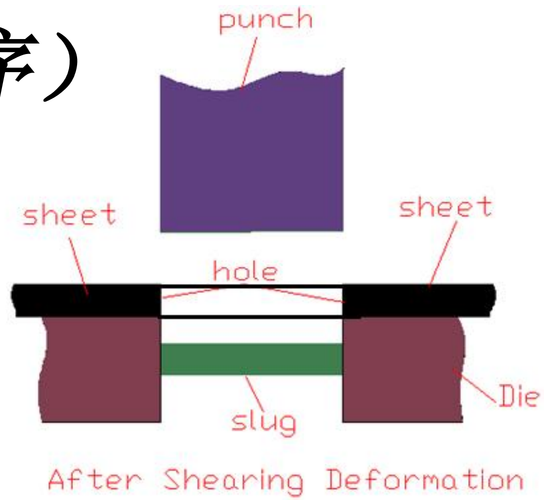
friction $\uparrow$ $\rightarrow$ **punch forces** $\uparrow$

clearance $\uparrow$ $\rightarrow$
- **punch forces** $\downarrow$
- **wear on the die &punch** $\downarrow$

Strip & Knockout
（卸料与顶件/推件）



7.2.1 Shearing Operations（冲裁工序）



1. Punching（冲孔） and Blanking（落料）

- **the most common shearing operations**
- **punching： the sheet with hole is the final part and the sheared slug is discarded（废弃的）**
- **blanking： the sheared slug is the final part and the rest is scrap（废料）**

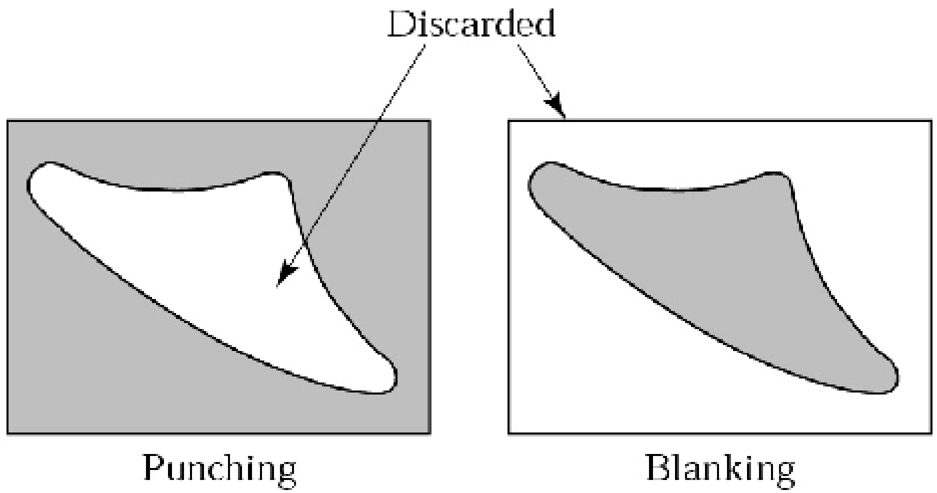
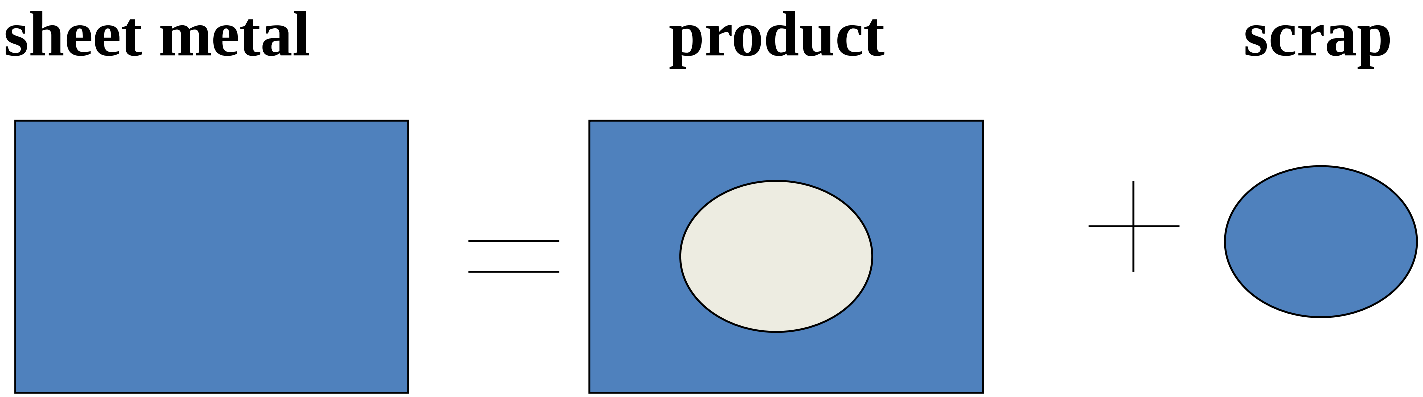
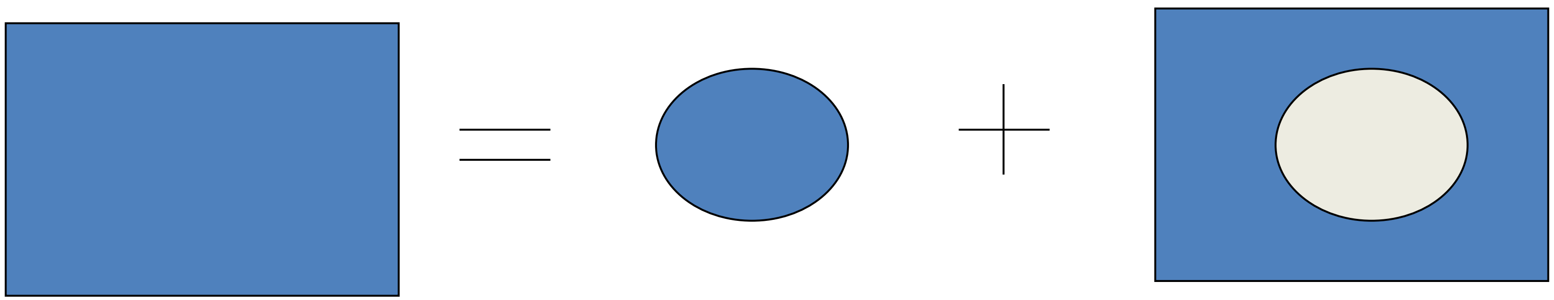


Figure 7.4 (a) Punching (piercing) and blanking.

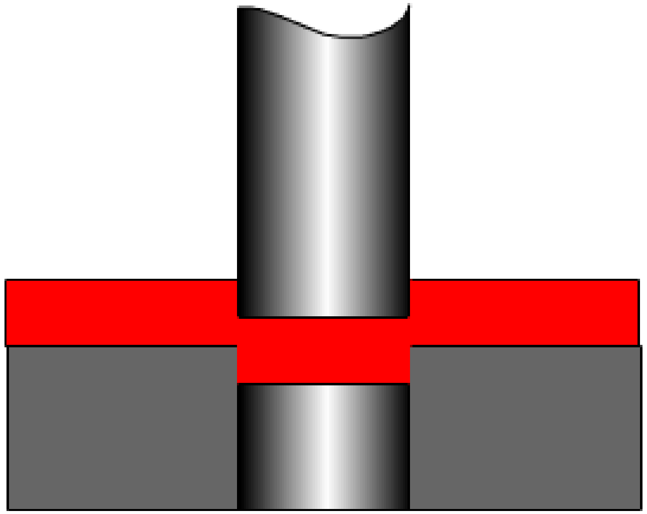
Punching（冲孔） and Blanking（落料）



For Punching



For Blanking



[shearing]

[blanking]

Punching（*冲孔*） and Blanking（*落料*）

- **They generally are carried out on computer-numerical-controlled machines with quick-change toolholders**（*具有快速换模装置的计算机数控设备*）
- **such machines are useful, particularly in making prototypes**（*模型/原型/样件*）**of sheet-metal part requiring several operations to produce.**

* 2. Die Cutting（模切/冲切）

a. perforating （打孔/穿孔）

– punching a number of holes in a sheet

- hole diameter：1 mm ～ 75 mm
- use as filter（过滤器）, screens（筛板）, in ventilation（通风）, guard for machinery, in weight reduction.
- punched in crank presses（曲柄压力机） at rates high as 300,000 holes per minute, using special dies and equipment.

b. parting（切断）- shearing the sheet into two or more pieces（一切为二或剪切成多件）

c. notching（切口）- removing pieces from the edges

d. lancing（切缝）- leaving a tab（凸起/凸耳） without removing any material

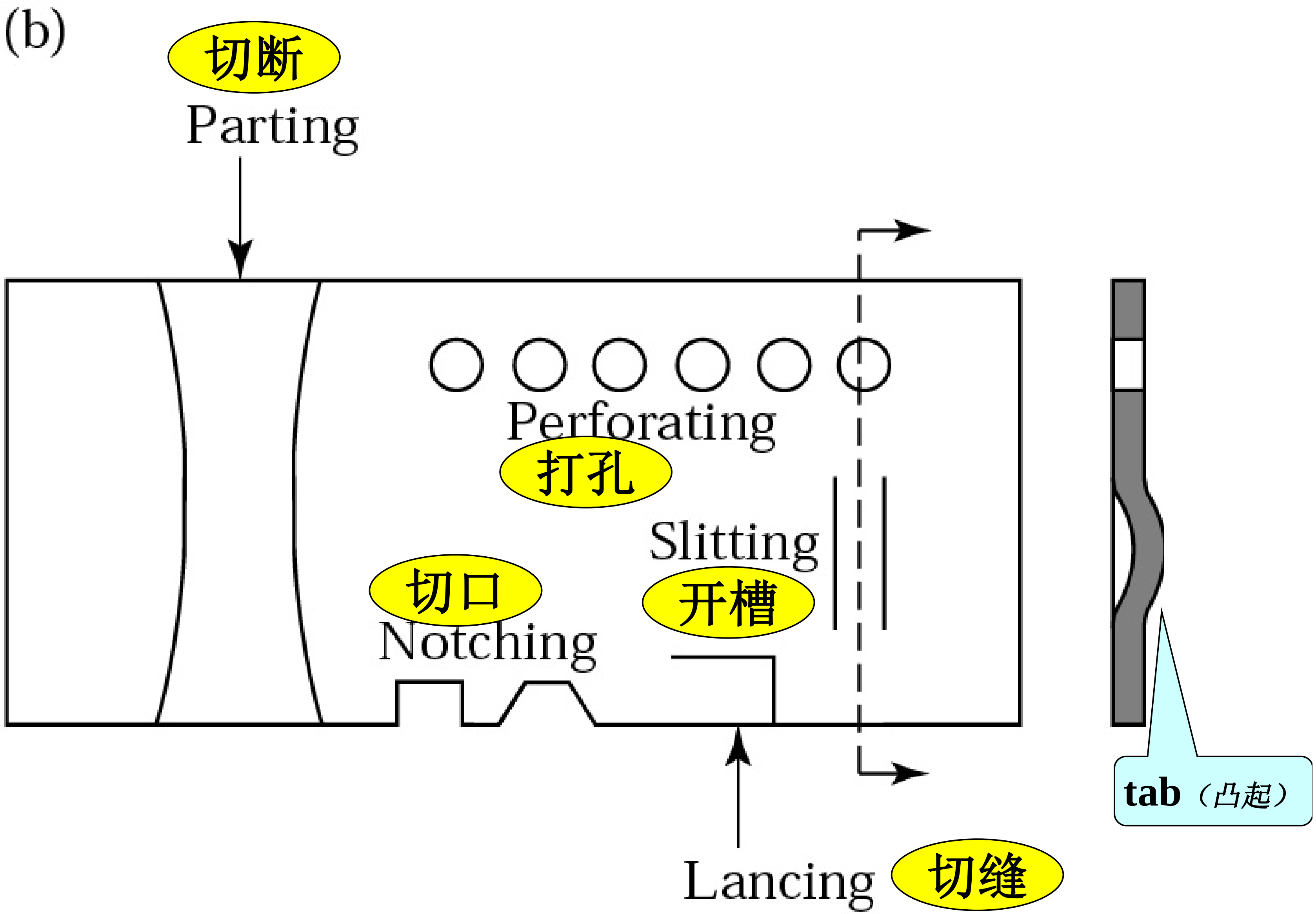


Figure 7.4 (b) Examples of various shearing operations on sheet metal.

3. Fine Blanking（精密落料/精密冲裁）

– to produce very smooth and square（平直的） edges

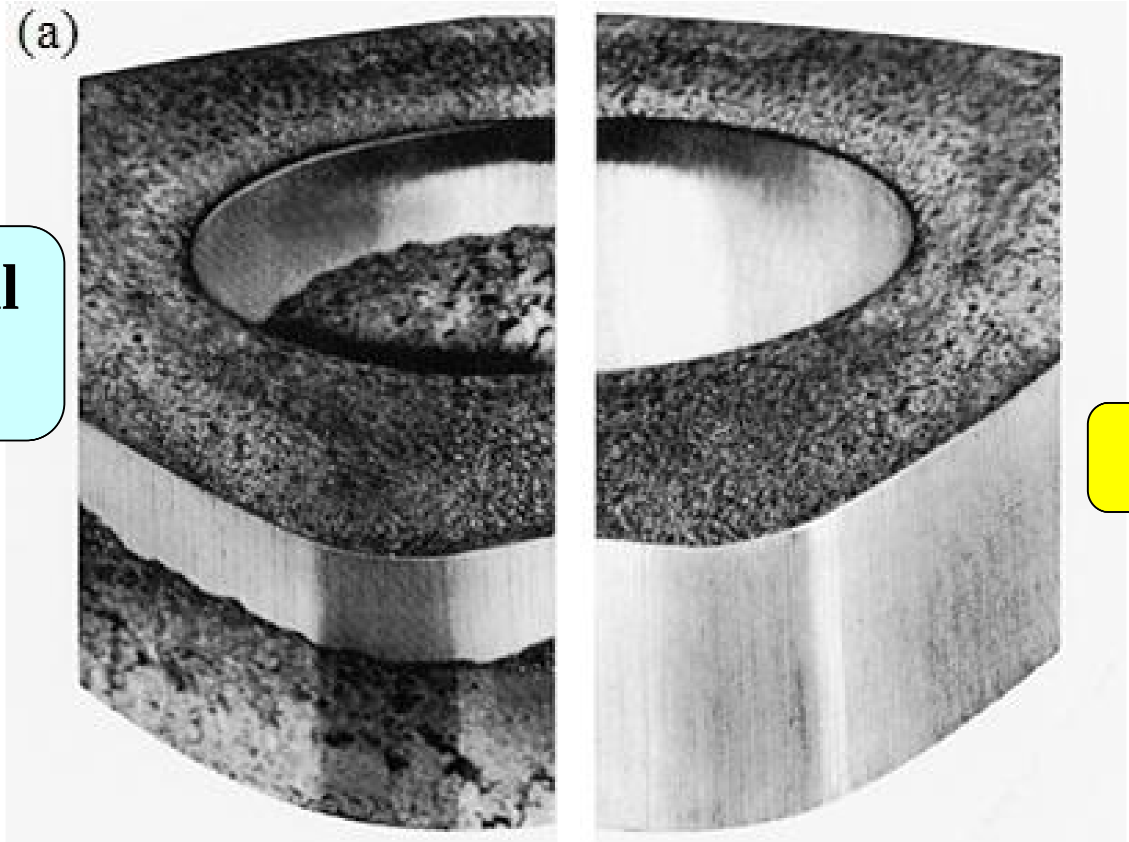


Figure 7.5 (a) Comparison of sheared edges produced by conventional (left) and by fine-blanking (right) techniques.

Basic Die Setup（模具装置）of Fine Blanking

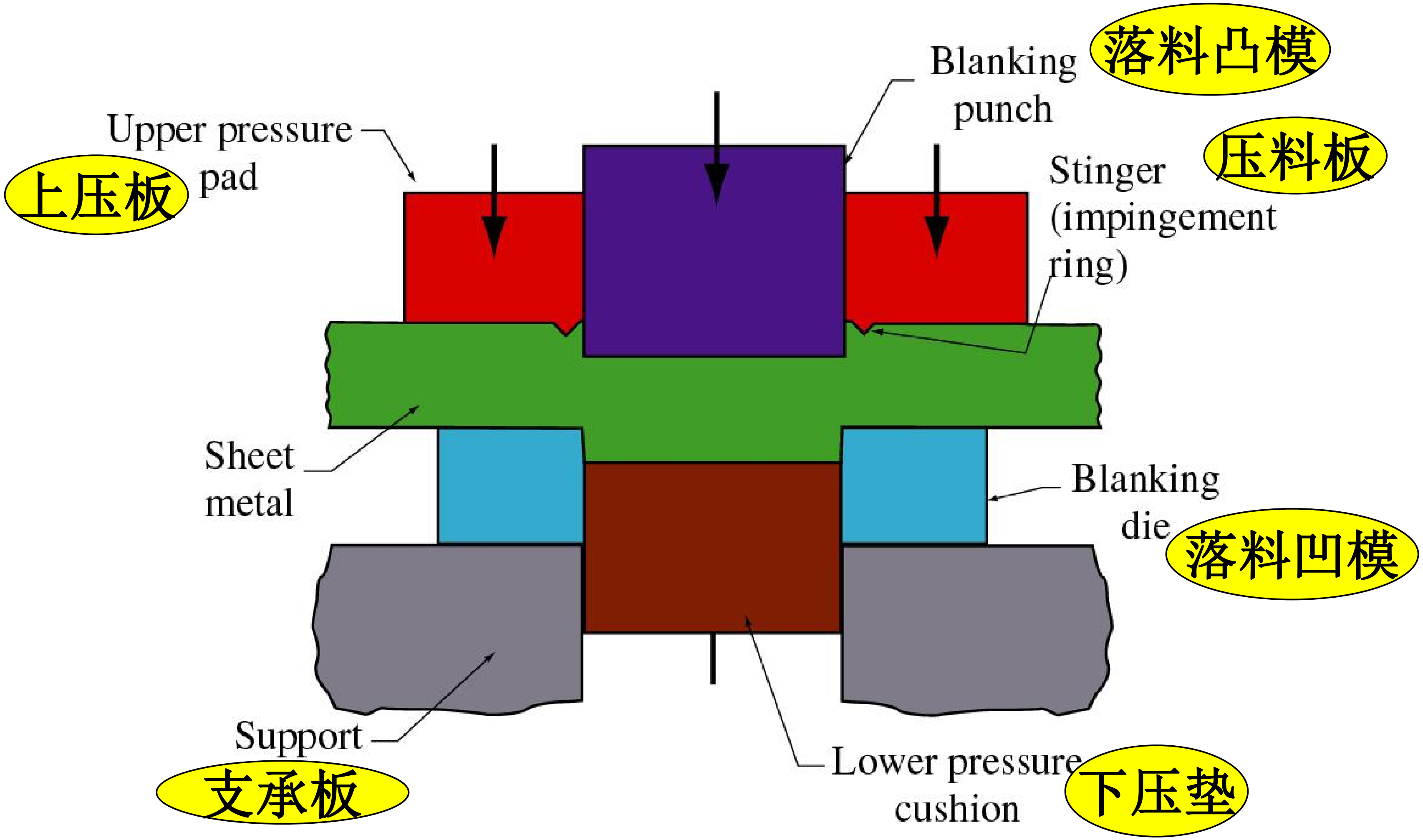


Figure 7.5 (b) Schematic illustration of one setup for fine blanking.
***Source*: Feintool U.S. Operations.**

Basic Die Setup of Fine Blanking

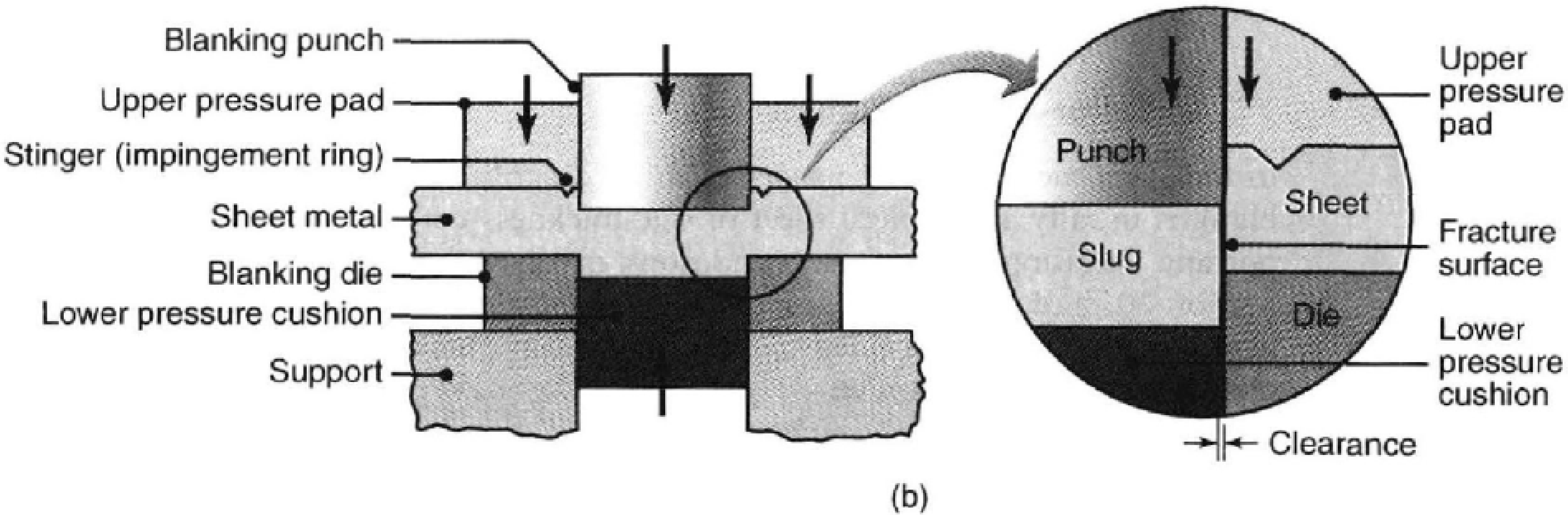


FIGURE 7.5 (a) Comparison of sheared edges produced by conventional (left) and by fine-blanking (right) techniques. (b) Schematic illustration of one setup for fine blanking. *Source*: Courtesy of Feintool U.S. Operations.

* Characteristics of Fine Blanking

① a V-shaped stinger, or impingement locks the sheet tightly

② usually carried out on triple-action hydraulic presses （三动液压机）, where the movement of the punch, of the pressure pad（压料板）, and of the die are separately controlled.

③ clearances: on the order of 1% T(T: 0.5mm ～ 13mm).

④ dimensional tolerances: ±0.05mm(± 0.025mm)

⑤ suitable sheet hardness: 50 ～ 90 HRB.

⑥ usually involves punching and blank simultaneously （同时地）

7. Scrap in Shearing（冲裁废料）

– the amount of scrap (the trim loss/切边损耗) produced in shearing operation can be significant

– can be as high as 30% on large stampings（冲压件）

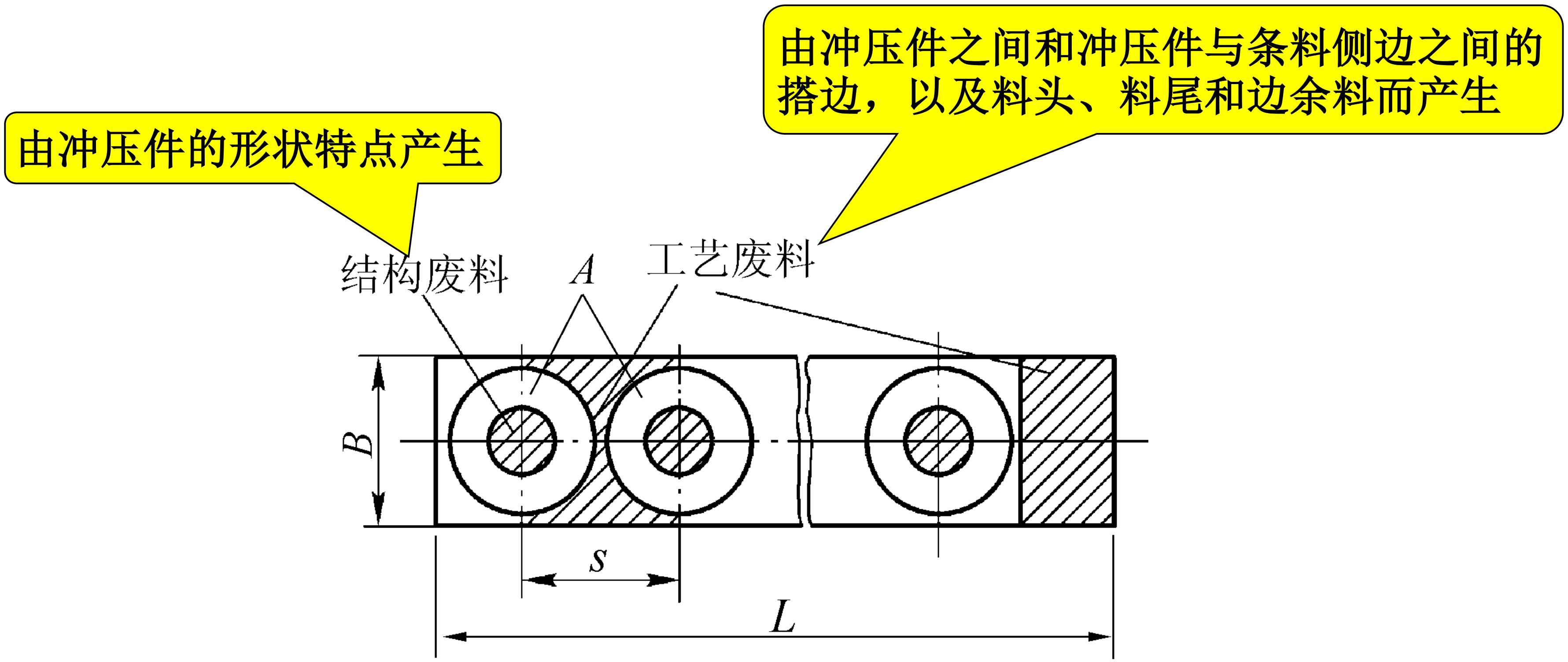
– is a significant factor in manufacturing cost

– can be reduced substantially by proper arrangement of the shape on the sheet to be cut

nesting(排样)

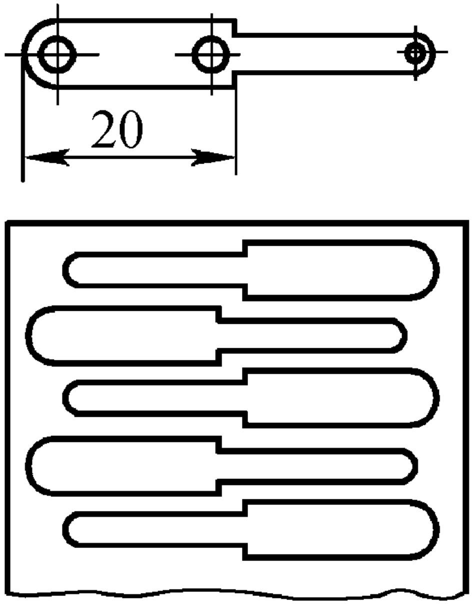
– Computer-aided design(CAD) techniques have been developed to minimize the scrap from shearing operations.

* Scrap（冲裁废料）

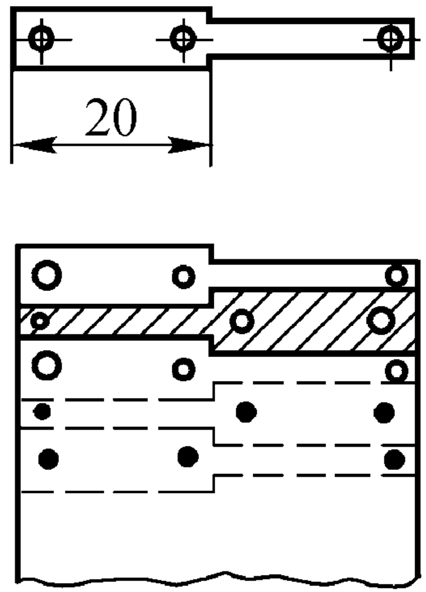


由冲压件的形状特点产生
由冲压件之间和冲压件与条料侧边之间的搭边，以及料头、料尾和边余料而产生
结构废料
A
工艺废料
B
s
L

* Scrap（冲裁废料）



(a) 修改前

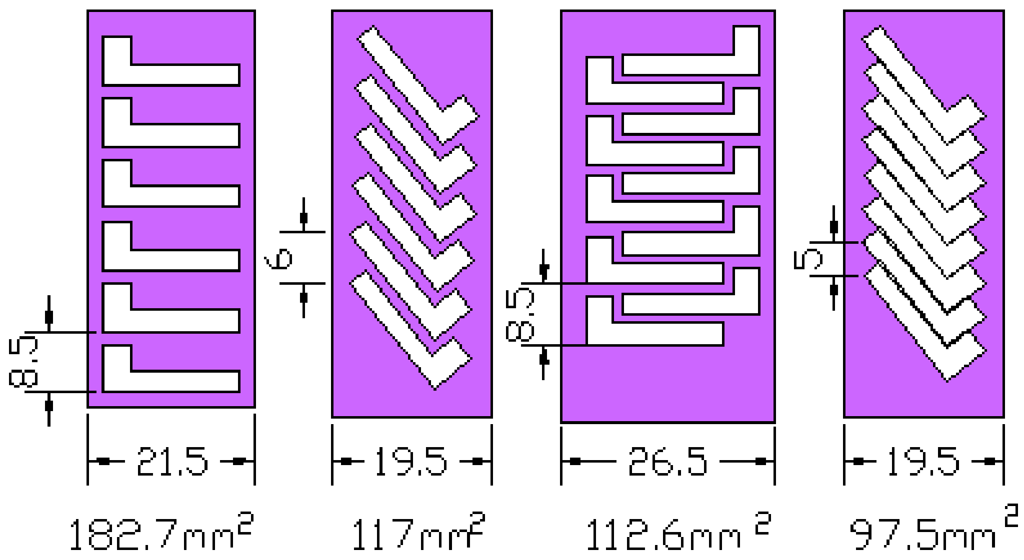


(b) 修改后

在满足使用的条件下，改变零件的结构形状，优化排样方案，提高材料利用率

* Nesting（排样）

不改变零件的结构形状，
优化排样方案，提高材料
利用率



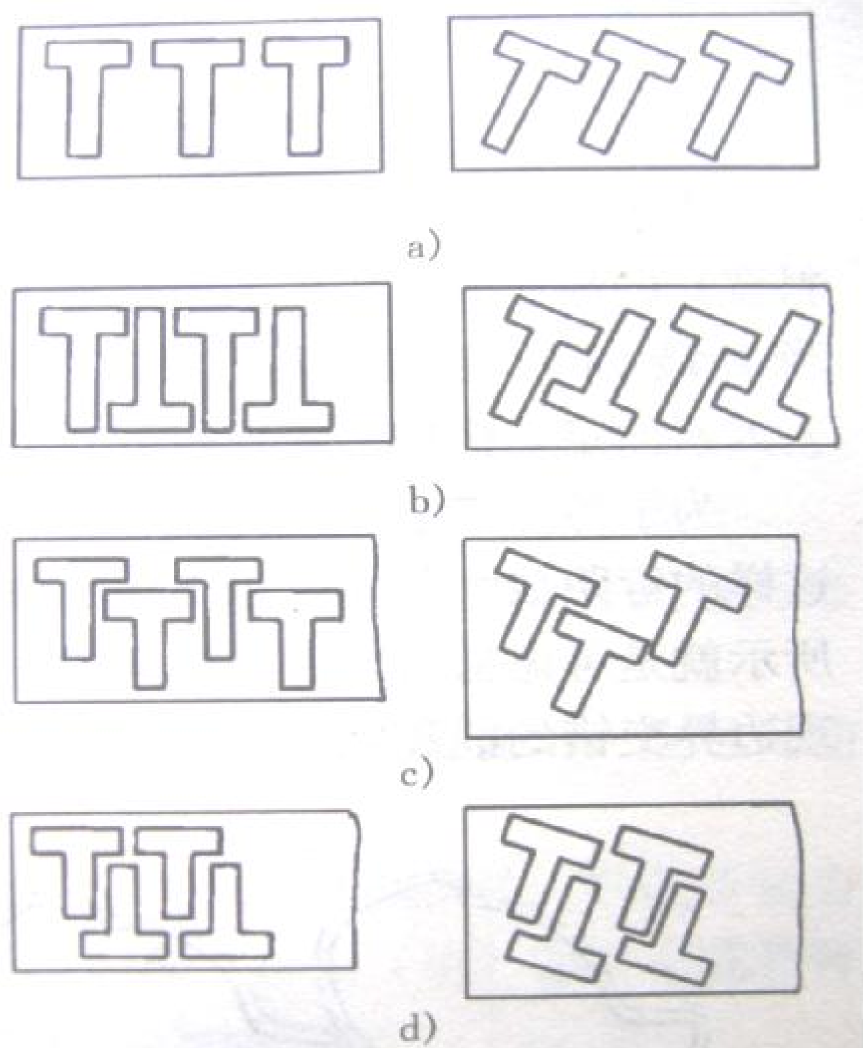
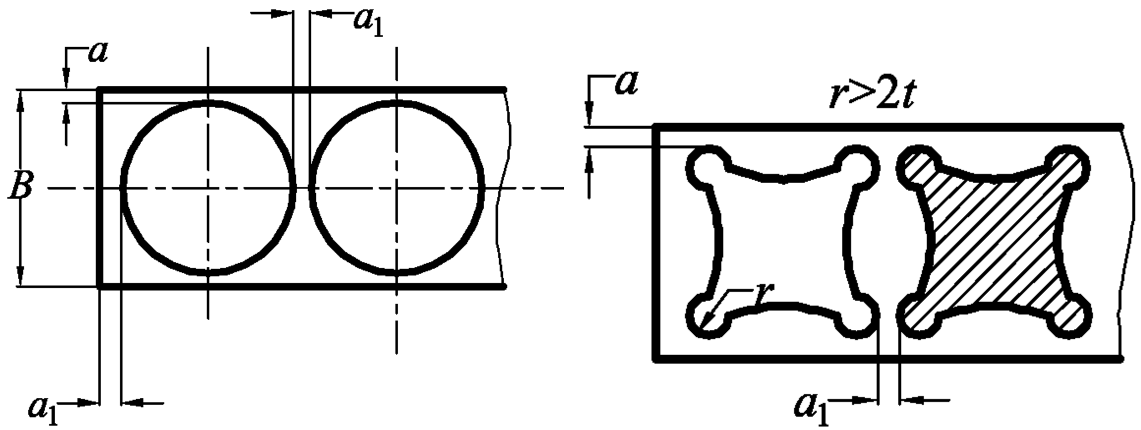


图 3-7 冲裁件排样形式
a）普通单排 b）对头单排
c）普通双排 d）对头双排

7.2.3 Characteristics and Type of Shearing Dies
（冲裁模/冲模特性与种类）

1. Clearances

- clearance control is important to ensure the **quality** of sheared edges and the **formability** of the sheared part
- the appropriate（适当的/合理的）clearance depend on:
  - Ø The **type of material** and its **temper**（硬度）
  - Ø The **thickness** and of the **size** of the blank
  - Ø Its **proximity**（接近性） to the edge of other sheared edges or the edges of the original sheet （即：搭边值,冲裁排样图中a, a1所示）



* General Guideline of Clearances

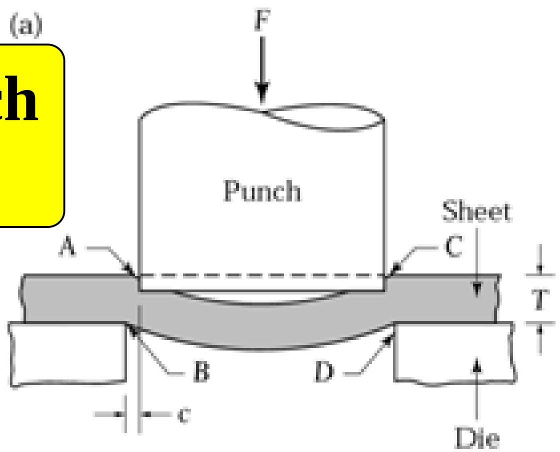
- clearance for soft material are less than those for harden grades
- the thicker the sheet is, the larger the clearance must be
- small ratio of hole diameter to sheet thickness requires greater clearance
- In using larger clearance, attention must be paid to the rigidity（*刚性*） and the alignment of the presses, the dies, and their setup

为保证冲模平衡地工作，模具的压力中心应与压力机滑块的中心线重合，以防止模具工作时发生歪斜、间隙不均匀，导致磨损

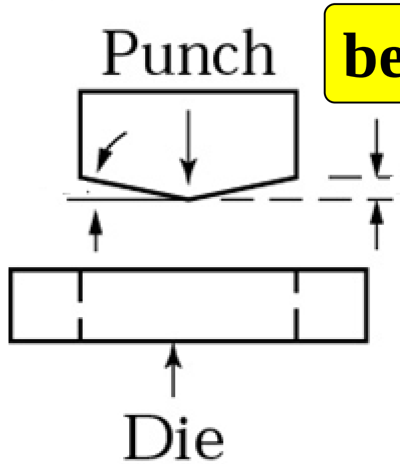
2. Punch and die shapes

- For **flat punch and die（平刃凸模与凹模）**, the punch force builds up rapidly during shearing, because the entire thickness is sheared at the same time.
- For **beveling the punch and die surface （斜刃凸模与凹模）**, the location of the region being sheared at any particular instant can be controlled
  - ø particular **suitable for** the shearing of **thick blanks**
  - ø also **reduces** the operation's **noise** level.

flat punch and die



bevel punch



(b):

- **single taper**（*单边锥形*）
- **lateral force**（*侧向力*） **does act on the punch**
- **sufficient lateral rigidity**（*刚度*） **is necessary**

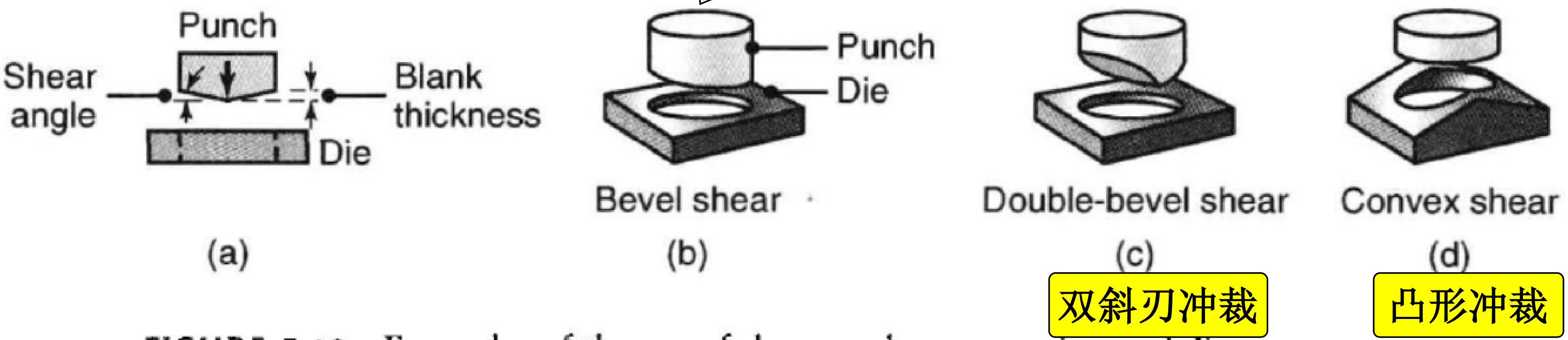


FIGURE 7.10 Examples of the use of shear angles on punches and dies.

(a), (c), (d):

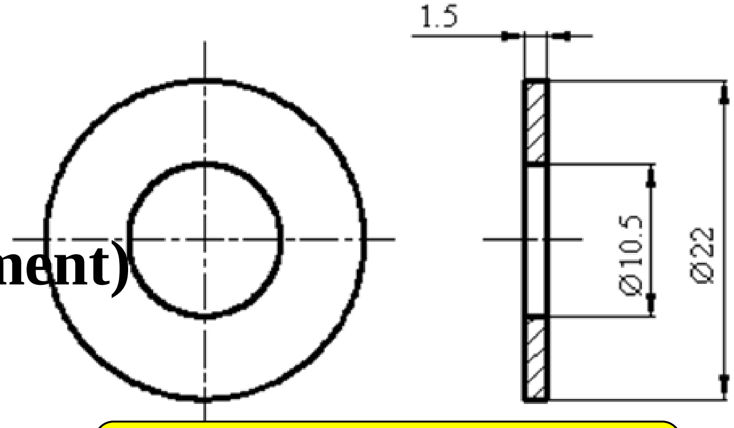
- **symmetry**（*对称的*） **shape**
- **no lateral forces**（*侧向力*）

3. Types of shearing dies

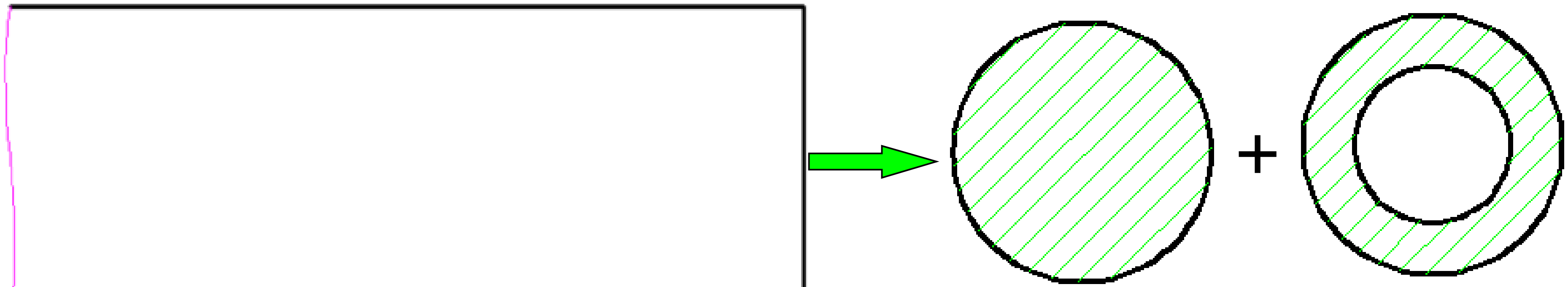
- **According to the die's structure, there are four types:**
  - **① single die** *（简单模）*
  - **② compound die** *（复合模）*
  - **③ progressive die** *（级进模/连续模）*
  - **④ transfer die** *（传递模/移步模）*

Basic Concepts

- **operation: 工序**
- **station：工位（position on equipment)**
- **stroke: 冲程**



part：washer（垫圈）



cold-rolled strip

blanking

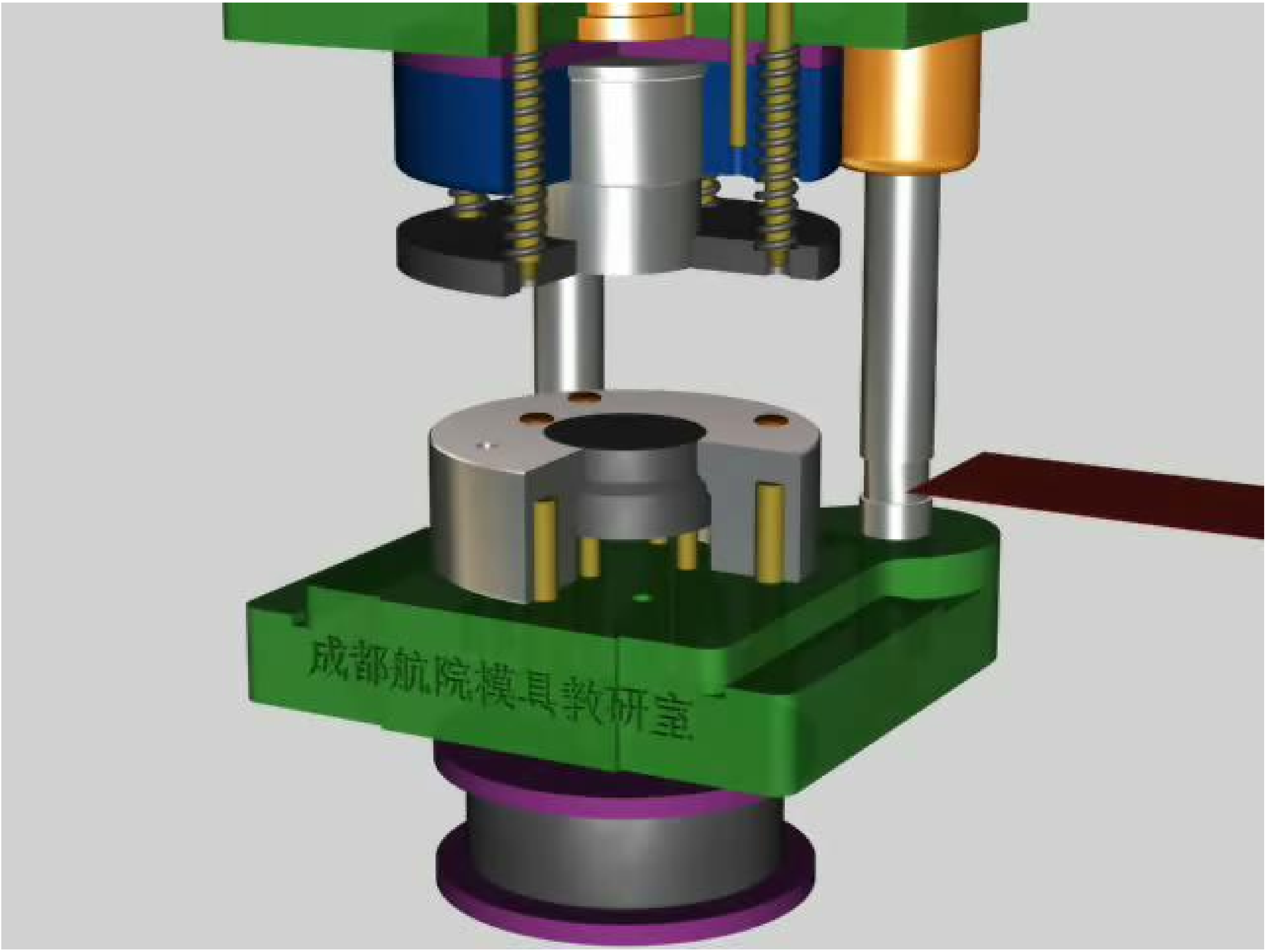
punching

operations

① Single die（简单模/单工序模）

- **Only one operation（工序） on the same strip（条料） is performed in one stroke（冲程） at one station（工位） with a single die.**

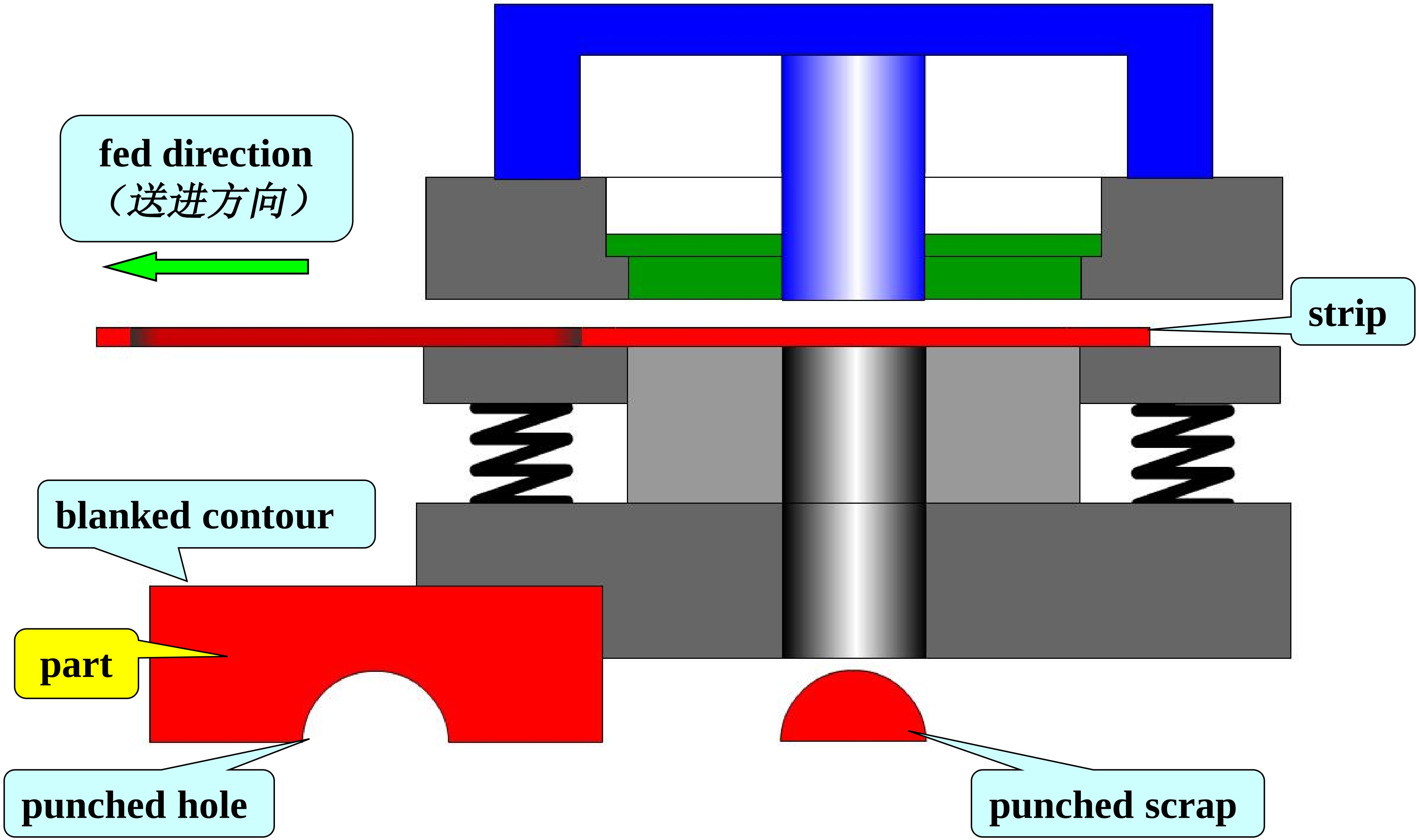
Single Die for Blanking
（*落料模*）



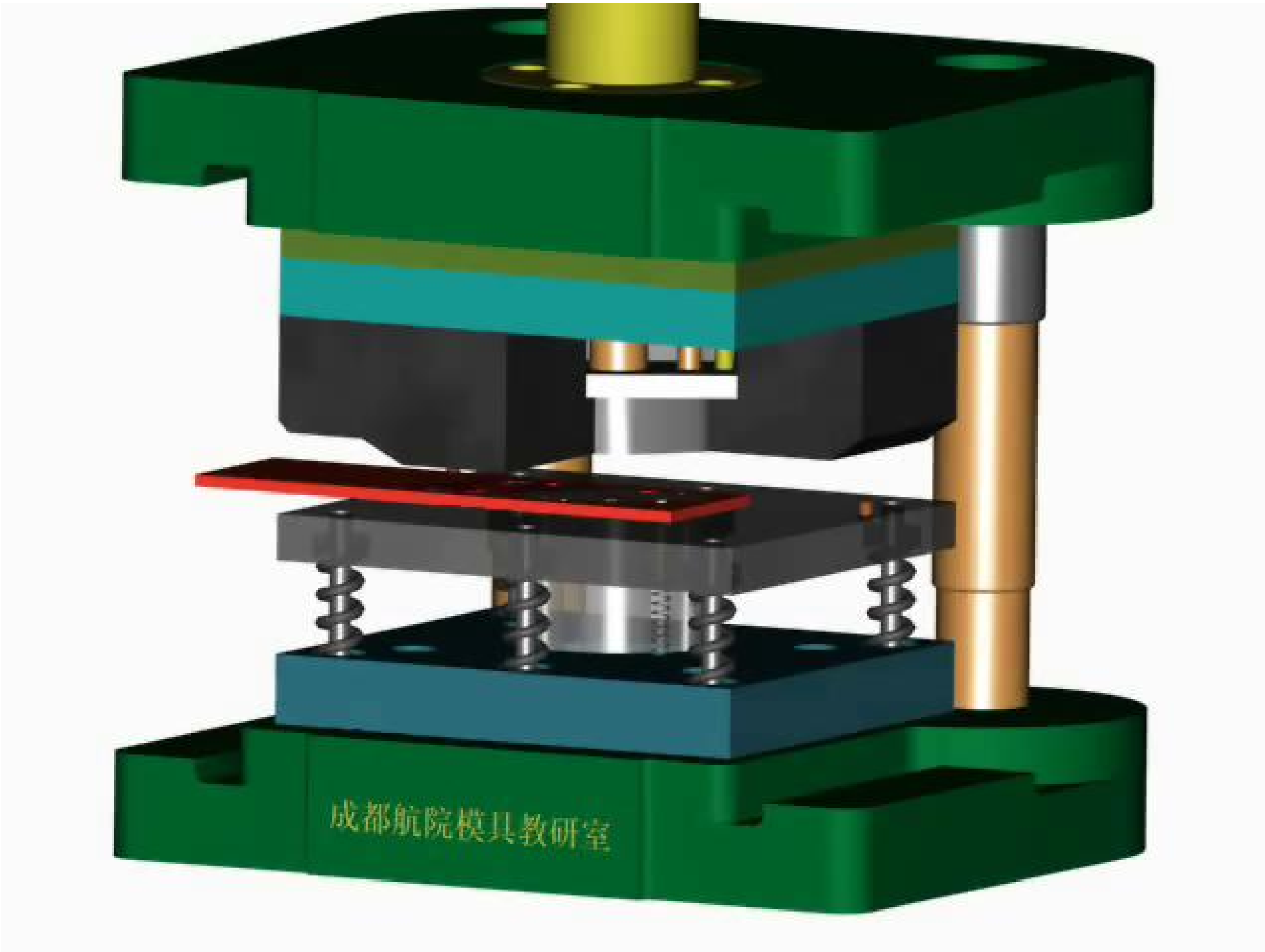
② Compound Dies （复合模）

- **Several operations on the same strip are performed in one stroke at one station with a compound die.**
- **Such combined operations are usually limited to relatively simple shapes, because：**
  - **（1）slow**
  - **（2）dies are much more expensive to produce than those for individual shearing operations.**

Compound Dies for Blanking & Punching
（落料冲孔复合模）



Compound Dies for Blanking & Punching
（落料冲孔复合模）



Schematic illustration before and after blanking a common washer（垫圈） in a compound die

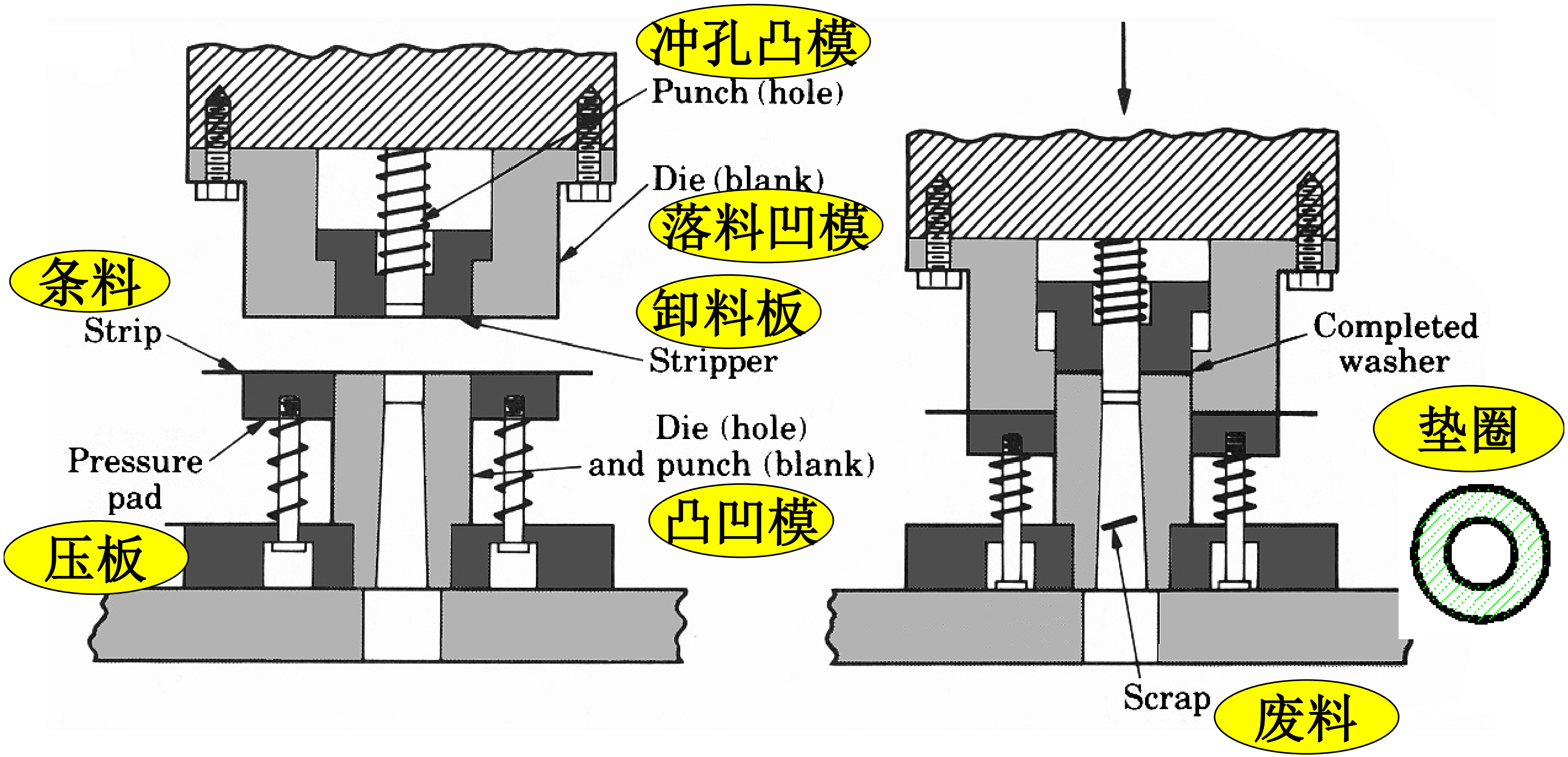
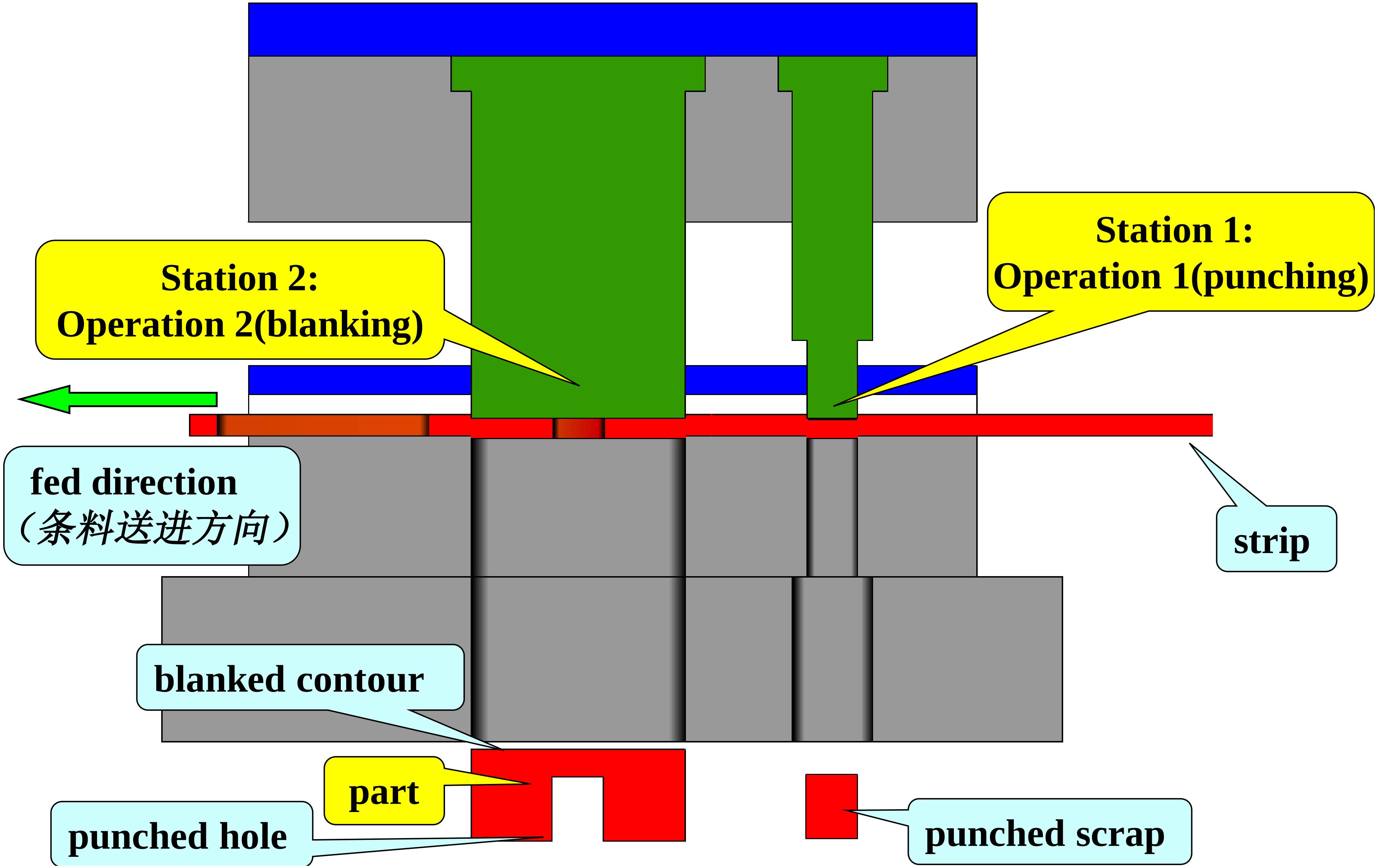


Figure 7.11 Schematic illustrations: (a) before and (b) after blanking a common washer in a compound die. Note the separate movements of the die (for blanking) and the punch (for punching the hole in the washer).

③ Progressive Dies （级进模/连续模）

- The sheet metal is fed（送进/送料） through as a coil strip, and a different operation is performed at the same station at one stroke of a series of punches.
- Parts requiring multiple operations, such as punching, blanking, and notching（切口）, can be made as high production rates in progressive dies.

Progressive Die
（冲孔落料级进模）



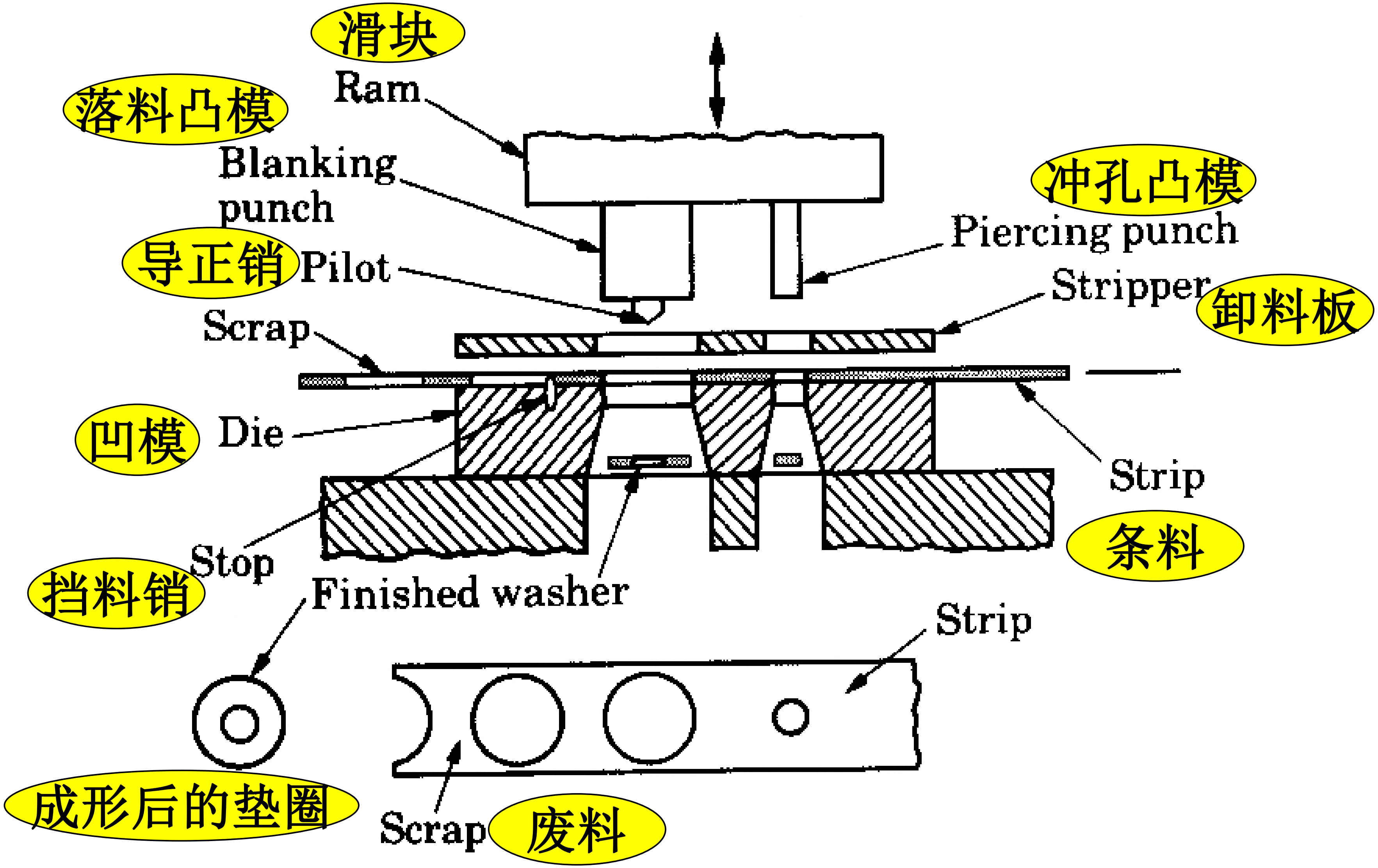


Figure 7.11 (c) Schematic illustration of making a washer in a progressive die.

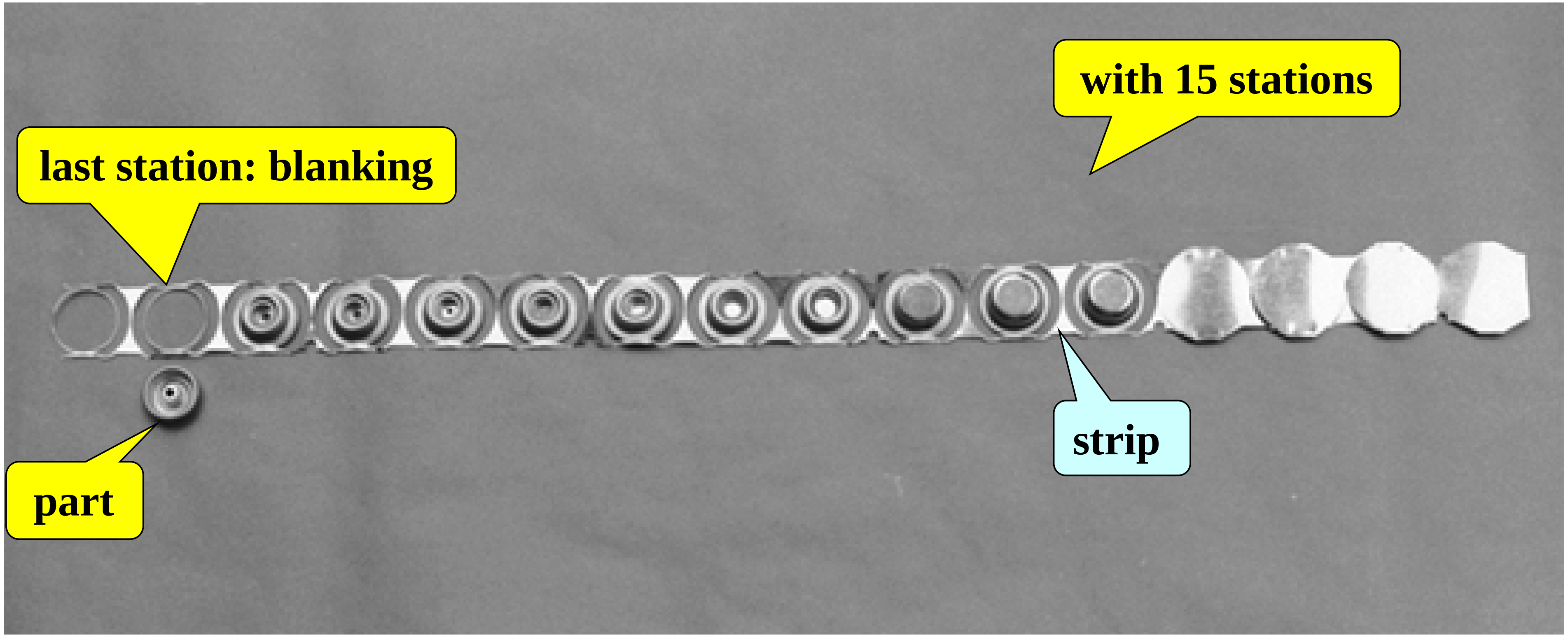
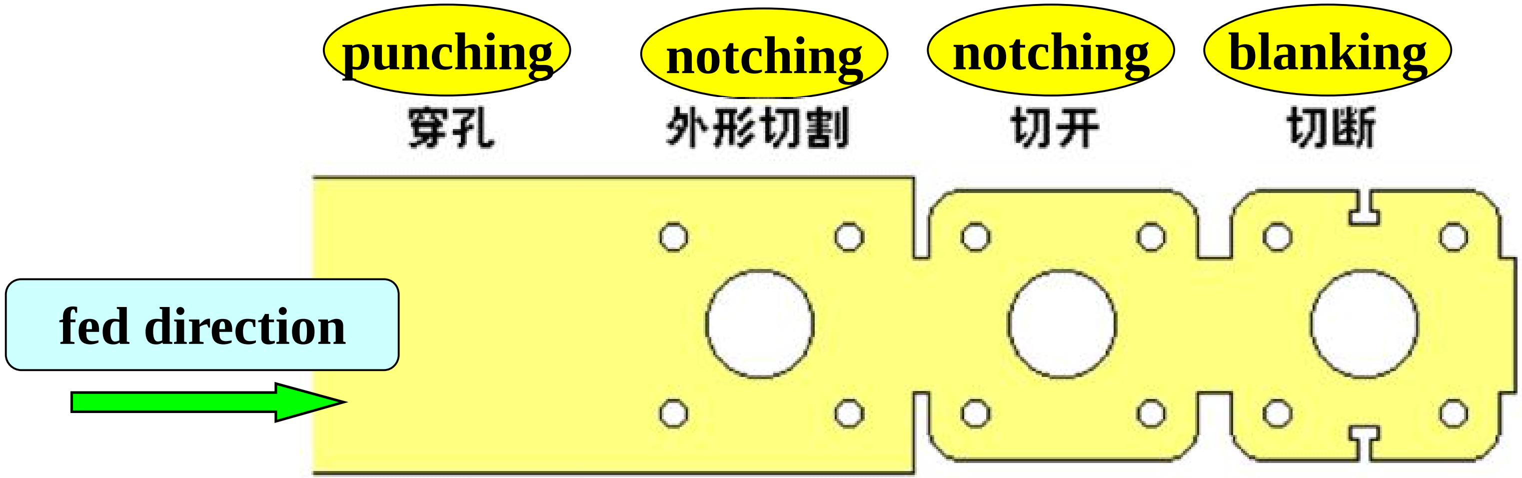
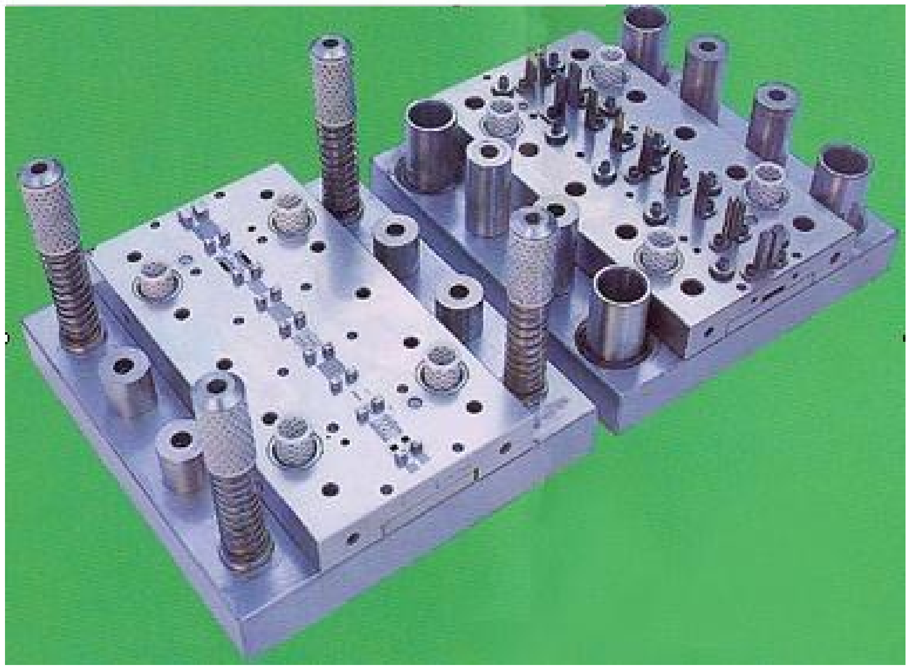


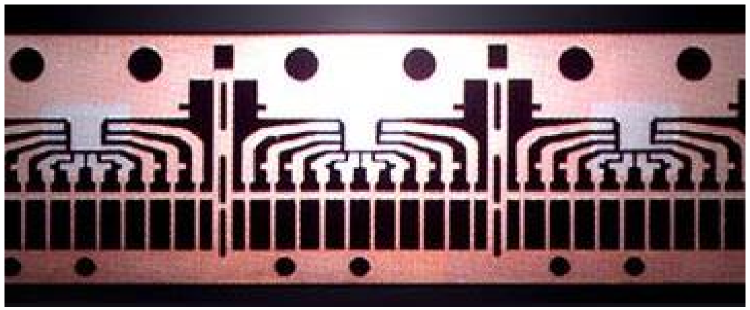
Figure 7.11 (d) Forming of the top piece of an aerosol spray can（气雾喷雾罐上盖） in a progressive die. Note that the part is attached to the strip until the last operation is completed.

Parts Formed in Progressive Dies





Parts Formed in Progressive Dies

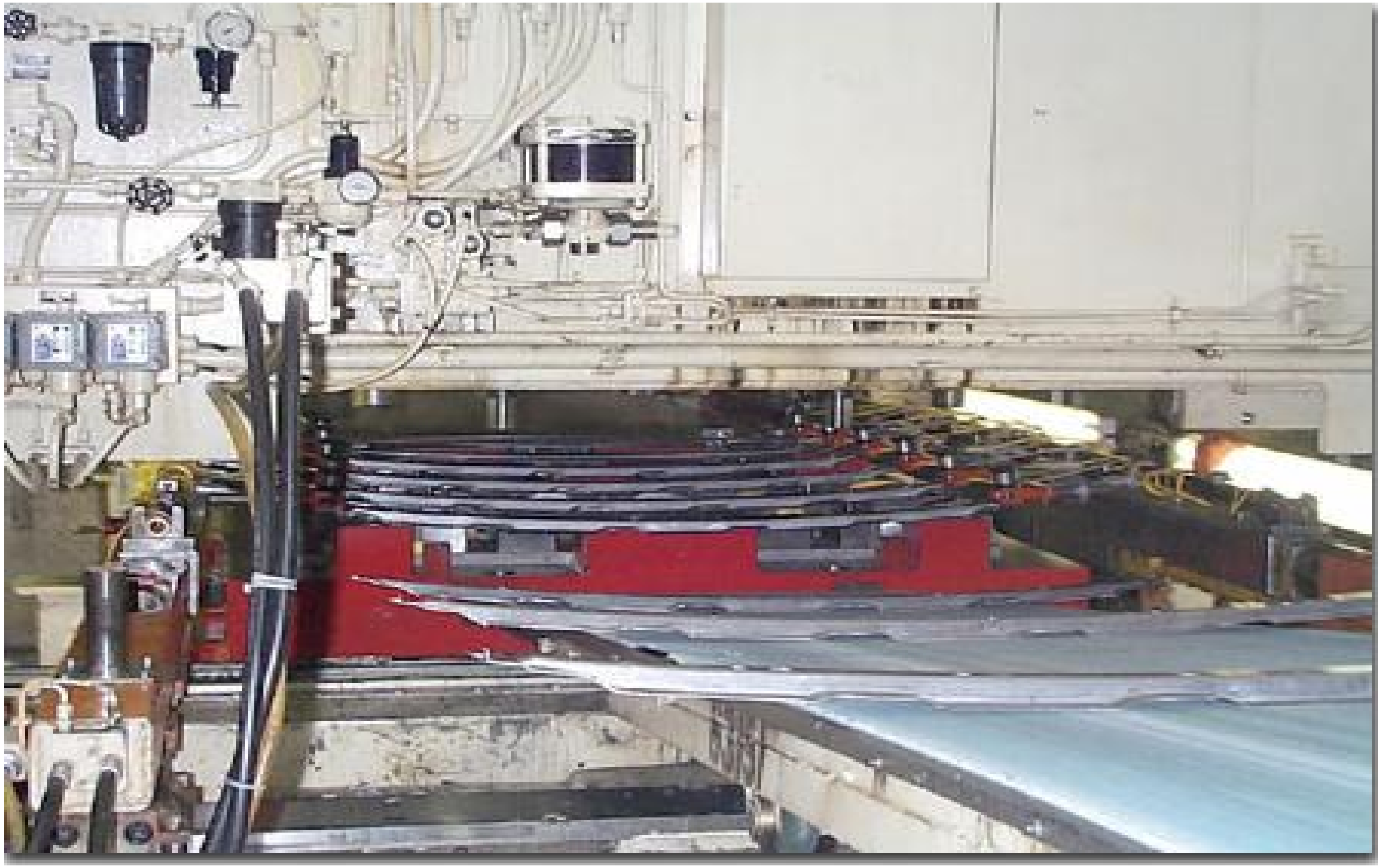


Automation of Sheet-metal Forming

④ Transfer Dies （传递模/移步模）

- In a transfer die setup, the sheet metal undergoes different operations at different stations of the machine that are arranged along a straight line or a circular path.
- After each step（工序）, the part is transferred to the next station for further operation.

- **Sheet metal part undergoes different operations at different stations in a straight line or circular path.**



Summary

- **single die**
  - Ø **one operation, one station**
- **compound die**
  - Ø **multiple operations, one station**
- **progressive die**
  - Ø **different operations, strip is fed through different stations on one equipment, series of punches**
- **transfer dies**
  - Ø **different operations, part is transferred to different stations or different equipments**

4. Tool and die material

- generally tool steels（*工具钢*）
- carbides（*硬质合金*） for high production rates

5. Lubrication

- important for reducing tool and die wear
- improving edge quality

7.3 Sheet-metal Characteristics and Formability （金属板料特性与可成形性）

- The **characteristics** of sheet metals have important **effects** on the overall **forming operations**（成形/变形工序）, which employ various dies, punches, and tooling to **stretch**（拉伸） and **bend**（弯曲） the sheet.
- Includes:
  - elongation（伸长率/延伸率）
  - yield-point elongation（屈服点伸长）
  - anisotropy（各向异性）
  - grain size（晶粒大小）
  - dent resistance of sheet metal（抗压痕性/耐冲击性）

TABLE 7.2

Important Metal Characteristics for Sheet-forming Operations

Characteristic	Importance
Elongation	Determines the capability of the sheet metal to stretch without necking and failure; high strain-hardening exponent (n) and strain-rate sensitivity exponent (m) are desirable
Yield-point elongation	Typically observed with mild-steel sheets (also called Lüder's bands or stretcher strains); results in depressions on the sheet surface; can be eliminated by temper rolling, but sheet must be formed within a certain time after rolling
Anisotropy (planar)	Exhibits different behavior in different planar directions, present in cold-rolled sheets because of preferred orientation or mechanical fibering, causes earing in deep drawing, can be reduced or eliminated by annealing but at lowered strength
Anisotropy (normal)	Determines thinning behavior of sheet metals during stretching, important in deep drawing
Grain size	Determines surface roughness on stretched sheet metal; the coarser the grain, the rougher is the appearance (like an orange peel); also affects material strength and ductility
Residual stresses	Typically caused by nonuniform deformation during forming, results in part distortion when sectioned, can lead to stress-corrosion cracking, reduced or eliminated by stress relieving
Springback	Due to elastic recovery of the plastically deformed sheet after unloading, causes distortion of part and loss of dimensional accuracy, can be controlled by techniques such as overbending and bottoming of the punch
Wrinkling	Caused by compressive stresses in the plane of the sheet; can be objectionable; depending on its extent, can be useful in imparting stiffness to parts by increasing their section modulus; can be controlled by proper tool and die design
Quality of sheared edges	Depends on process used; edges can be rough, not square, and contain cracks, residual stresses, and a work-hardened layer, which are all detrimental to the formability of the sheet; edge quality can be improved by fine blanking, reducing the clearance, shaving, and improvements in tool and die design and lubrication
Surface condition of sheet	Depends on sheet-rolling practice; important in sheet forming, as it can cause tearing and poor surface quality

1. Elongation（*伸长率/延伸率*）

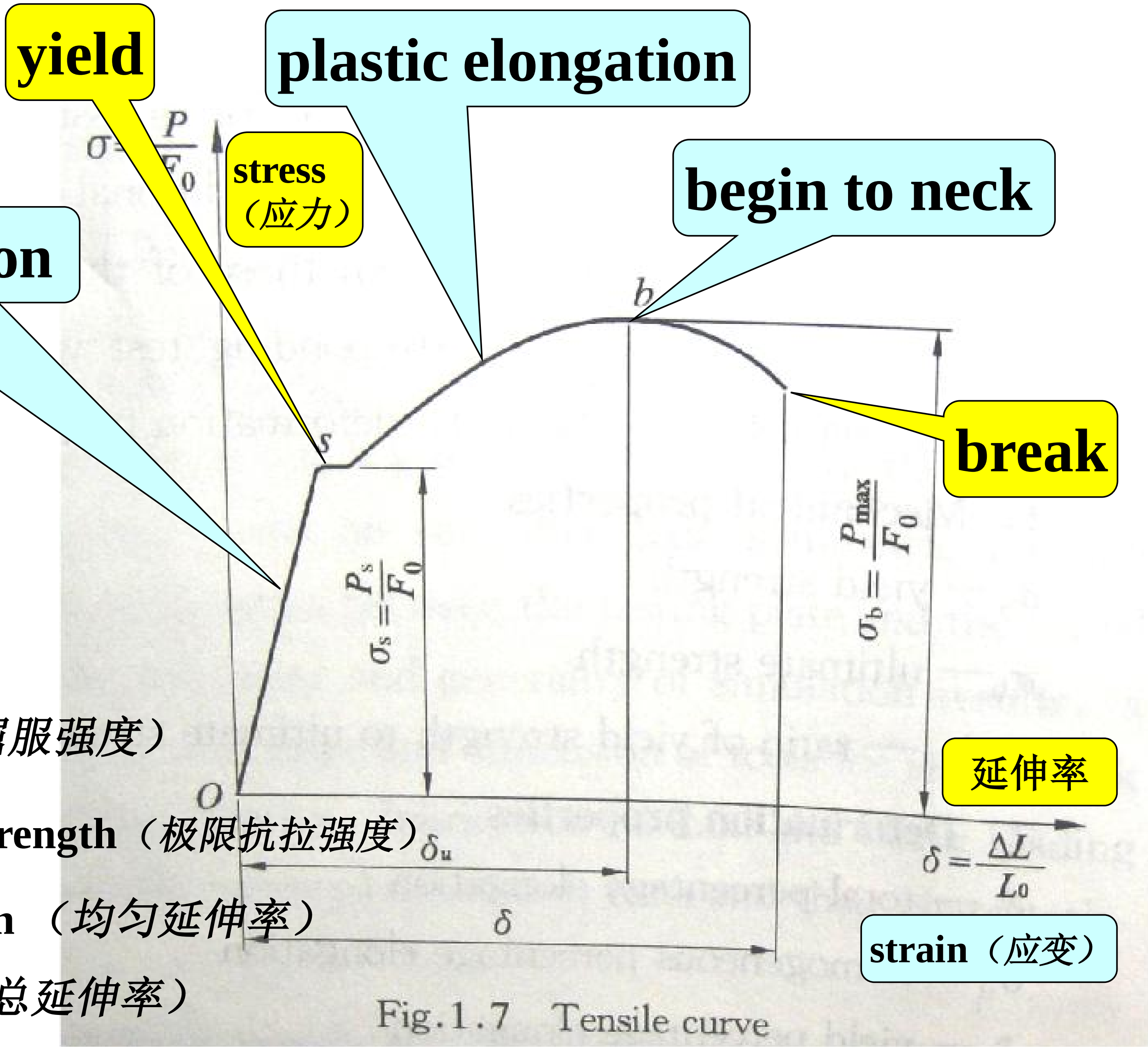


Fig.1.7 Tensile curve

屈强比： σ_s/σ_b

$\sigma_{s:}$: yield strength（*屈服强度*）

$\sigma_{b:}$: ultimate tensile strength（*极限抗拉强度*）

δ_u: uniform elongation （*均匀延伸率*）

δ: total elongation （*总延伸率*）

Elongation

- **Observations concerning tensile testing（*拉伸试验*） can be useful for understanding the behavior of sheet metal**
  - **a specimen subjected to tension first undergoes uniform elongation（*均匀伸长*）**
  - **only when the load exceeds（*超过*） the ultimate tensile strength（*极限抗拉强度*） does the specimen begin to neck（*缩颈/颈缩*）**
  - **eventually, break（*断裂*）**

- **Because the material is usually being stretched in sheet forming, high uniform elongation is desirable for good formability** *（可成形性）*.

- **The true strain at which necking begins is numerically equal to the strain-hardening exponent, *n*.** *（缩颈时的真实应变数值上等于应变硬化指数n）*

$n \uparrow \rightarrow$ uniform elongation $\uparrow \rightarrow$ formability $\uparrow$

Necking（缩颈/颈缩）

- **Necking may be localized（集中） or it may be diffuse（扩散）**
- **Depending on the strain-rate sensitivity（应变速率敏感性/*m*） of the material.**
- **Diffuseness is desirable in sheet-forming operations**

$m \uparrow \longrightarrow$ diffuseness $\uparrow \longrightarrow$ formability $\uparrow$

- **Total elongation（总伸长率）is also a significant factor in the formability of sheet metals.**

$$\left.\begin{array}{l} n \uparrow \\ m \uparrow \end{array}\right\} \Longrightarrow \text{total elongation} \uparrow \Longrightarrow \text{formability} \uparrow$$

2. Yield-Point Elongation（屈服点延伸）

- **Having upper and lower yield （上屈服点与下屈服点）.**
- **Stretches further in certain regions**
- **While other regions have not yet yielded.**

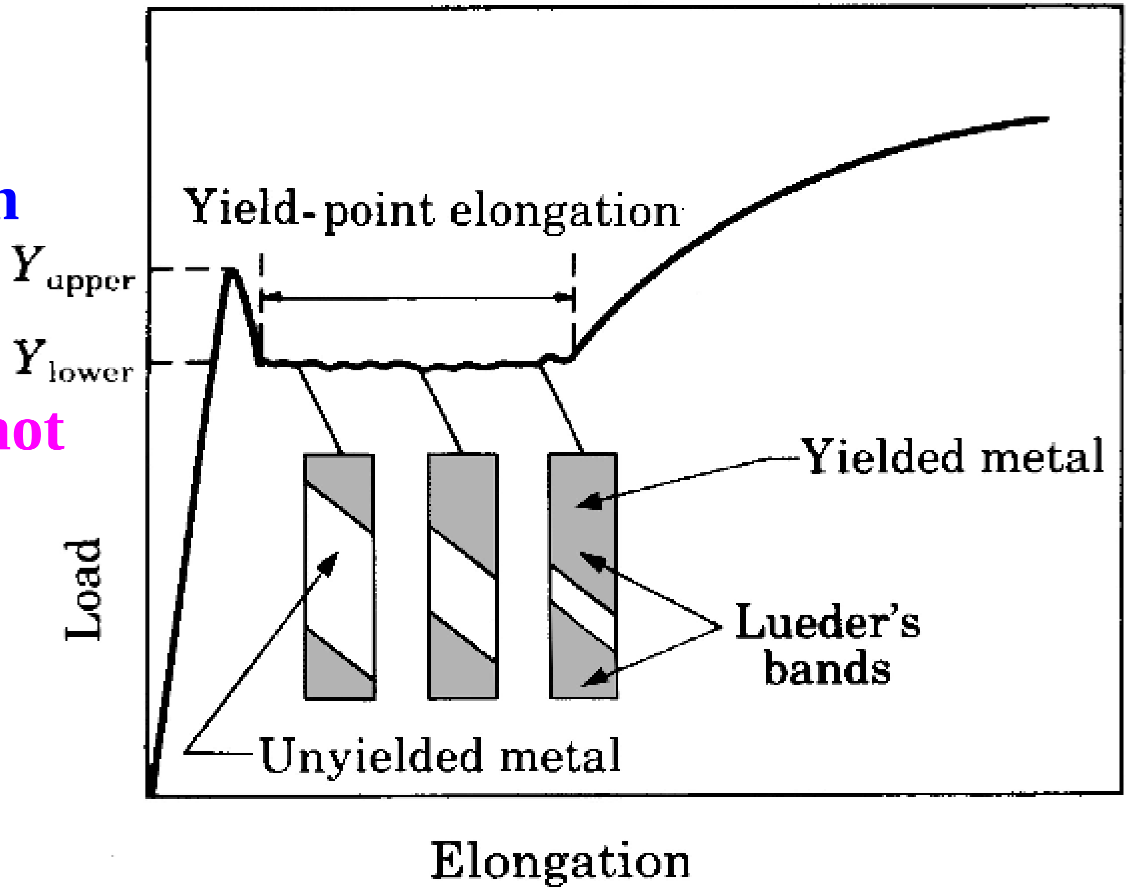
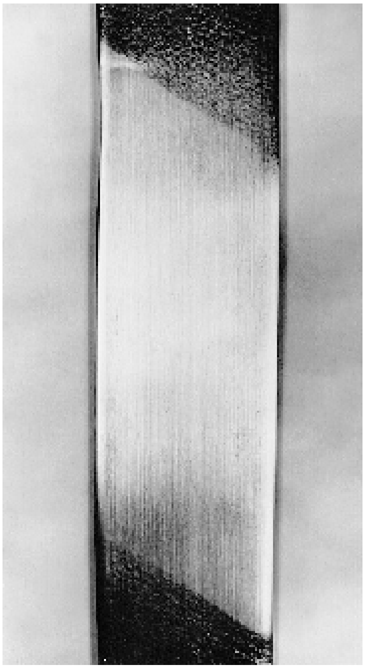


Figure 7.12 (a) Yield-point elongation in a sheet-metal specimen

Materials to exhibit yield-point elongation :

- low-carbon steels
- aluminum-magnesium alloys



coarseness（粗糙） in the surface

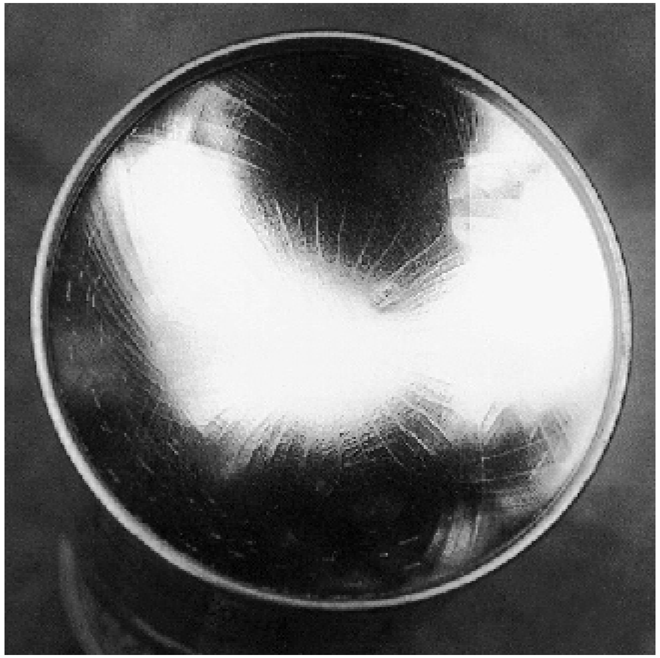


Figure 7.12 (b) Lueder's bands in a low-carbon steel sheet. *Source*: Courtesy of Caterpillar Inc. (c) Stretcher strains at the bottom of a steel can for household products.

Lueder's Bands（吕德斯带）

- Elongated depression（压痕/凹陷）caused by yield-point elongation
- Also called stretcher-strain marks or worms （拉伸应变纹）
- May be objectionable （不允许的）in the final product.
  - Coarseness（粗糙）in the surface degrades appearance
  - Causes difficulties in subsequent coating （涂覆/喷涂）and painting（喷漆）operations.

Methods to Eliminate（*消除*） or to Reduce Yield-point Elongation

- To reduce the thickness of the sheet 0.5% to 1.5% by cold rolling - temper rolling or skin rolling（*硬化冷轧或表面光轧*）
- Because of strain aging（*应变时效/弥散硬化*）, however, the yield-point elongation reappears after a few days at room temperature – or after a few hours at higher temperature.
- Should form the material within a certain time limit (which depends on the type of the steel).

Review

Temper Rolling or Skin Pass （硬化冷轧或表面光轧）

- The sheet metal is subjected to a **final light rolling pass** （轧制工步） of 0.5% to 1.5% **reduction** shortly before stretching（拉伸）
- Produce **compressive residual stress**（残余压应力） on the surface

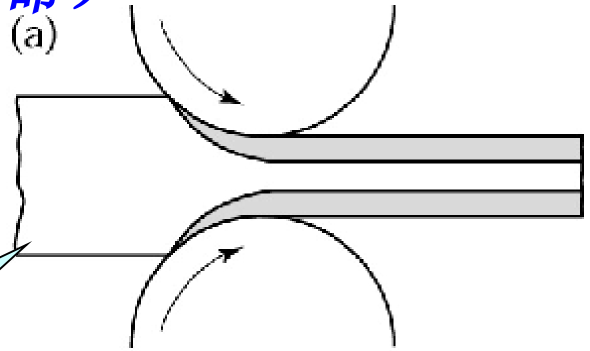
Application:

- For mild steel（低碳钢/软钢）, when stretched during sheet-forming operations, undergoes yield-point elongation（屈服点延伸）, a phenomenon that causes surface irregularities（不整齐/不规则） called stretcher strains（拉伸应变纹）or Lueder's bands（吕德斯带）.

Review

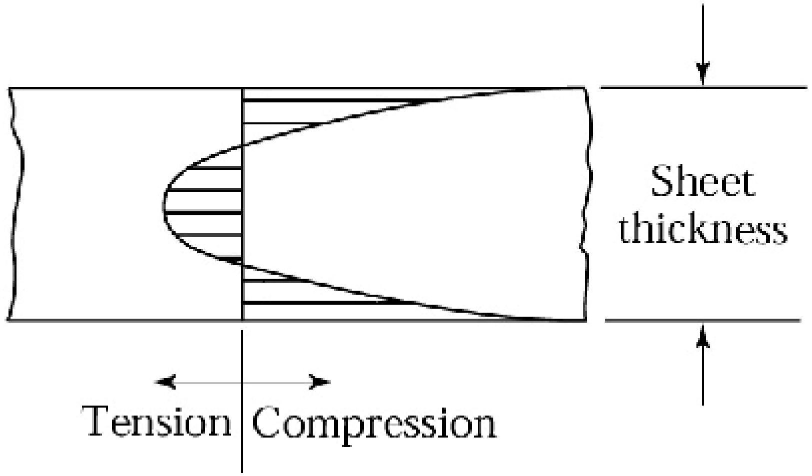
– To produce **compressive residual stress（残余压应力）on the surface**

– To improve **fatigue life（疲劳寿命）**



For small rolls and small reduction:

- compressive on surface
- tensile stress in the middle



* 屈服点延伸（屈服效应）

- 在拉伸曲线上出现上屈服点、下屈服点和屈服延伸区的现象称为屈服效应；
- 屈服效应在变形金属表面上会产生吕德斯带缺陷，因为在外应力作用下，某些地方位错钉扎不牢，它们首先摆脱溶质原子的气团开始运动位错源开动。位错向前运动时，在晶界前受阻堆积，产生很大的应力集中，再迭加上外应力就会使相邻的晶粒内的位错源开动，位错得以继续传播下去，这一过程进行的很快，所以就形成了不均匀的变形区，在金属外观上反映是一种带状的表面粗糙的缺陷；
- 在钢板冲压前进行小量的预变形，使被溶质原子钉扎的位错大部分基本摆脱气团包围，然后加工则不会出现吕德斯带了；
- 或在钢中加入少量的**Al**、**Ti**等强氮、碳化物形成元素，它们同**C**、**N**结合成化合物把**C**、**N**固定住了，使之不能有效的钉扎住位错，因而消除屈服效应现象。

3. Anisotropy（*各向异性*）

- An important factor that influences sheet-metal forming
- Is acquired during **thermo-mechanical processing**（*机械热加工工艺/热成形工艺*） of sheet
- Two types of anisotropy（directionality（*取向/方向性*））:
  - crystallographic anisotropy（*结晶学各向异性/变形织构*）(preferred orientation of the grains)
  - <u>mechanical fibering（*机械纤维*）</u>(alignment of impurities（*杂质*）, inclusions（*内含物*）, and voids（*空位*） throughout the thickness of the sheet).

主要影响材料弹性变形及塑性变形的特性

主要影响材料断裂的特性

4. Grain Size（晶粒大小）

- The grain size of the sheet metal is important for two reasons:

  ① affects mechanical properties

  ② influences the surface appearance（表观质量） of the formed part（orange peel（橘皮纹））

- The smaller the grain size, the stronger is the metal;
- The coarser（粗大） the grain, the rougher is the surface appearance.
- An ASTM（美国材料实验协会） grain size of 7 or finer is preferred（首选的） for general sheet-metal forming operations.

5. Dent Resistance *（抗压痕性/耐冲击性）*of Sheet Metal

- **Dent commonly are found on cars, appliances, and office furniture.**
- **Dents usually are caused by dynamic*（动态的）* forces from moving objects that hit the sheet metal.**
- **In typical automotive panels*（汽车车身）*, for example, velocities at impact range up to 45m/s.**
- **Thus, it is dynamic yield stress (yield stress under high rates of deformation),rather than the static*（静态的）* yield stress, that is the significant strength parameter.**

- **Dynamic forces tend to cause localized dents, whereas static forces tend to diffuse the dented area.**
- **This phenomenon may be demonstrated（*演示*） by trying to dent a piece of flat sheet metals, first by pushing a ball-peen hammer（*圆头锤*） against it and then by striking（*击打*） it with the hammer. Note how localized the dent will be in the latter case.**
- **Dent resistance of sheet-metal parts has been found to:**

a) **increase as the sheet thickness and its yield stress increase**

b) **decrease as its elastic modulus（*弹性模量*） and its overall panel stiffness（*刚度*） increase**

c) **Consequently, panels rigidly held at their edges have lower dent resistance because of their higher stiffness.**

7.4 Formability Tests for Sheet Metals

- **Formability:** the ability of the sheet metal to undergo the desired shape change without **failure**, such as necking, cracking, or tearing（*撕裂*）.
- Has great **technological** and **economic interest.**
- Sheet metal undergoes two forms of deformation:
  - **stretching**（*拉伸*） 侧重于长度的伸长
  - **drawing**（*拉深/拉延*） 侧重于深度的增加

Review

workability（可加工性）

the workpieces and products have a relatively high ratio of volume to surface area（体积与表面积比值）or of volume to thickness（体积与厚度比值）

- Applied to bulk deformation processes（体积成形/体积变形工艺）, such as rolling, forging, extrusion and drawing

Chapter 4/5/6

- Material mainly undergoes compressive forces（压力）

Cupping Tests（杯突试验）

- The earliest tests development to predict formability
  - the sheet-metal specimen is clamped（压紧/夹紧）between two circular flat dies
  - a steel ball or round punch is pushed into the sheet metal until a crack begins to appear on the stretched specimen.

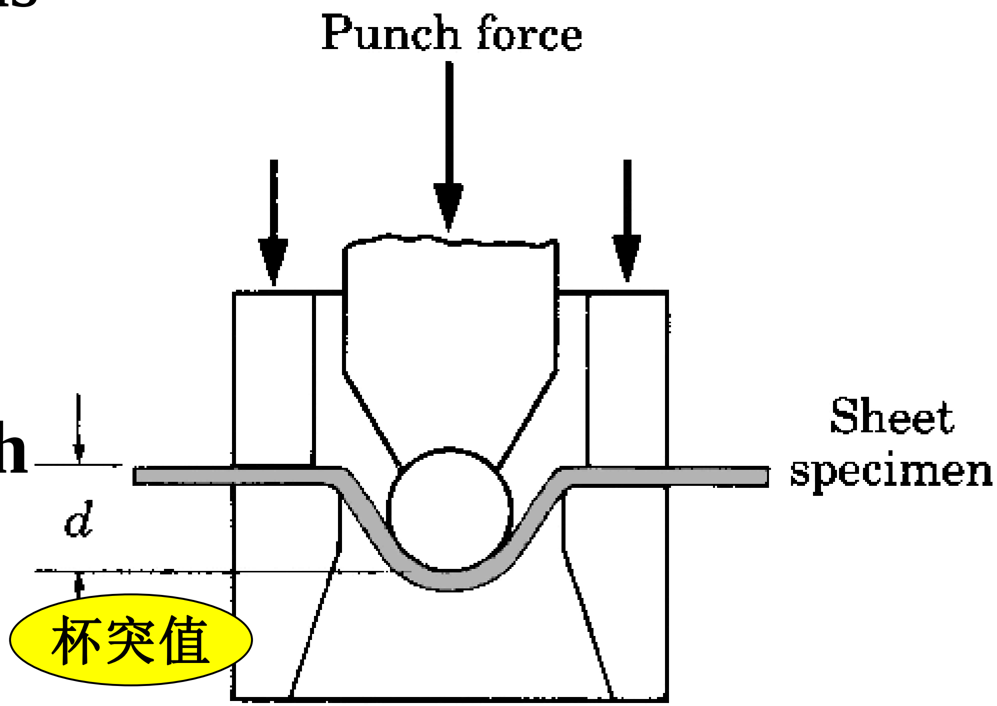
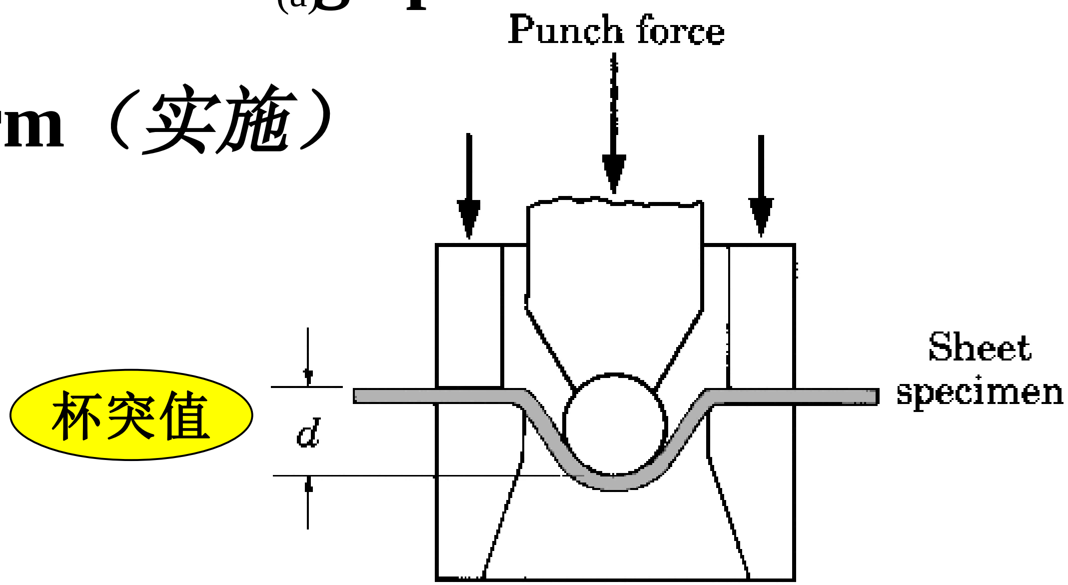


Figure 7.13 (a) A cupping test (the Erichsen test) to determine the formability of sheet metals

d ↑ ⟶ formability ↑

- ***d*** **is an approximate（*近似的*） indicators（*指标*） of formability**
- **Do not simulate（*模拟*） the exact（*精确的/确切的*） conditions of actual sheet-forming operations**
- **Tests are easy to perform（*实施*）**

(a)



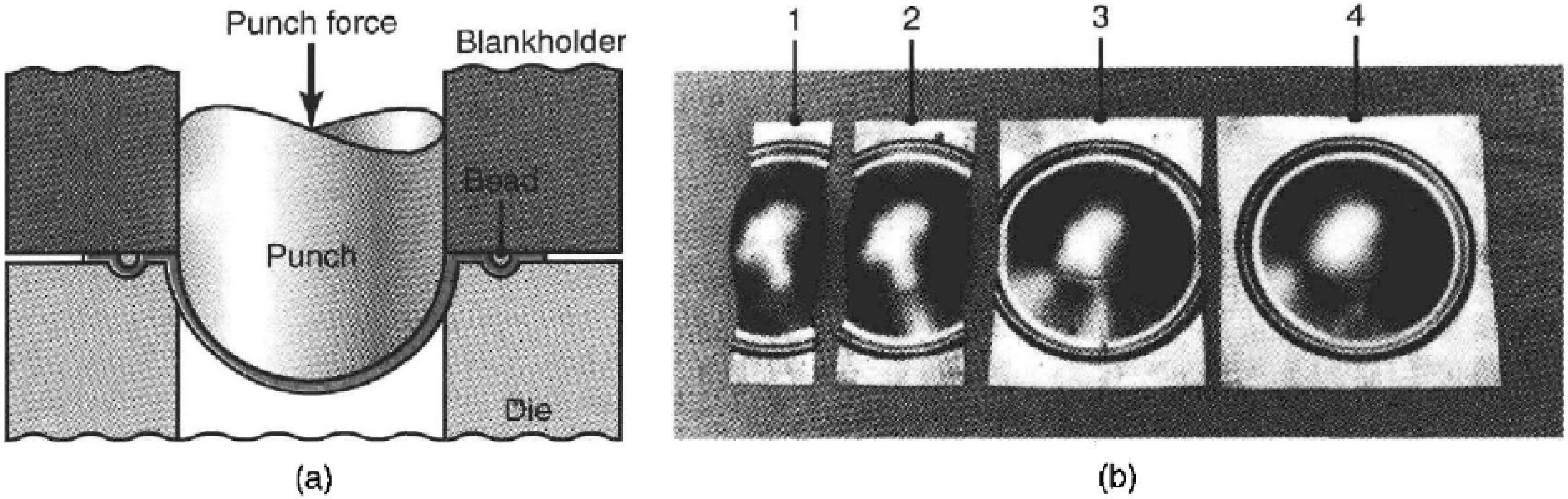
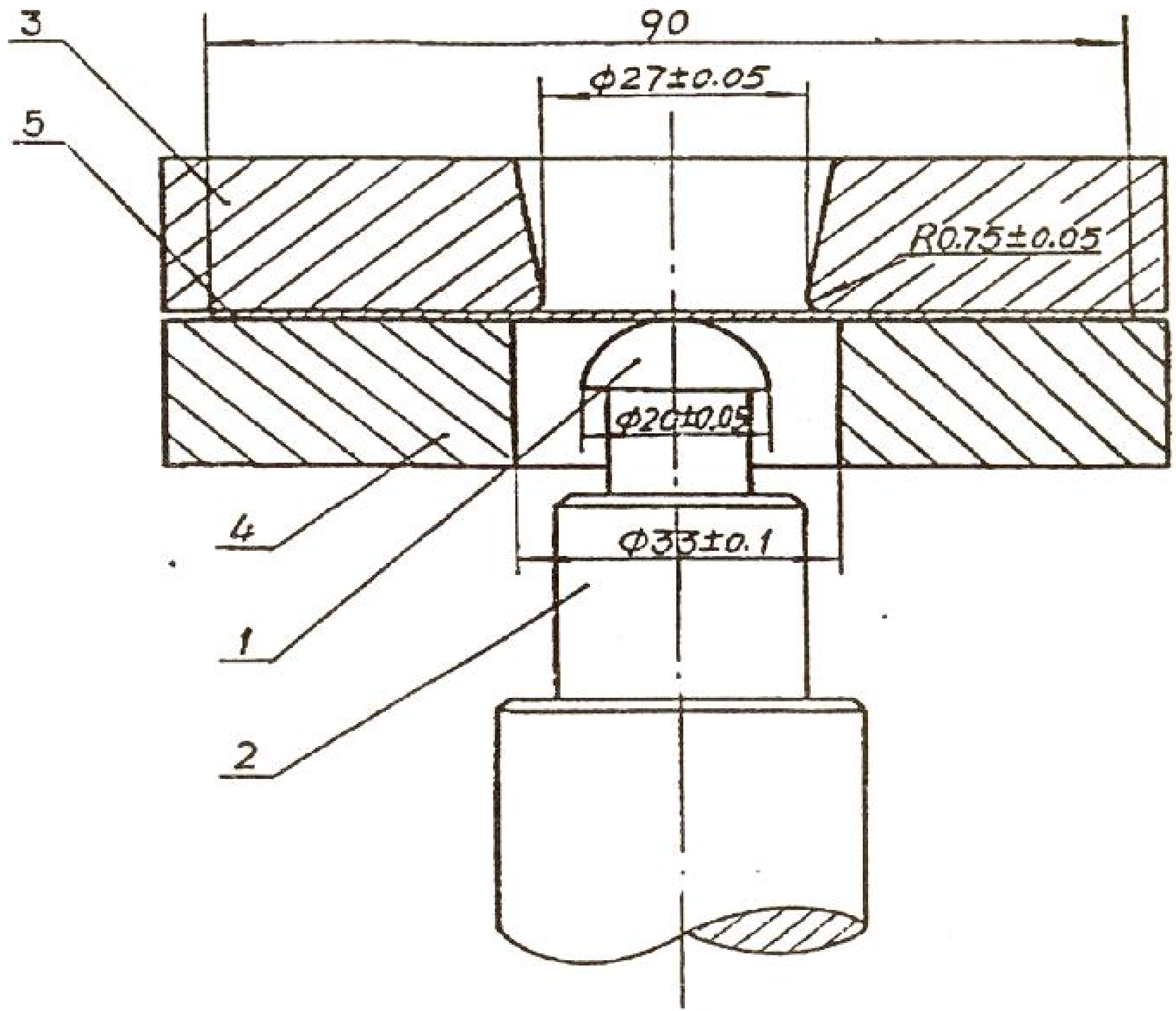


FIGURE 7.13 (a) A cupping test (the Erichsen test) to determine the formability of sheet metals. (b) Bulge-test results on steel sheets of various widths. The specimen farthest left is subjected to, basically, simple tension. The specimen that is farthest right is subjected to equal biaxial stretching. *Source*: Courtesy of Inland Steel Company.



1. 凸模　2. 凸模座　3. 凹模　4. 压边圈　5. 试件

Die Setup Used in Cupping Test

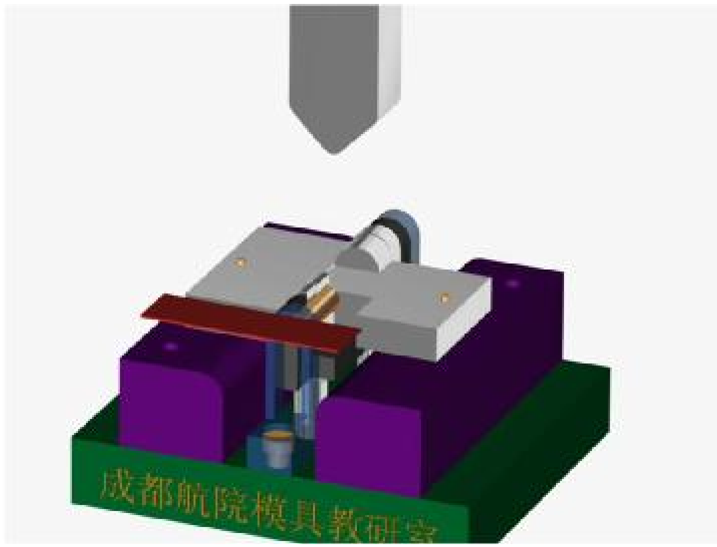
7.5 Bending Sheet and Plate（*板材的弯曲*）

Outline

- Bending process
- Typical bent part
- Major process parameters:
  - bend allowance and neutral axis（*弯曲余量与弯曲应变中性层*）
  - minimum bend radius（*最小弯曲半径*）
  - bendability（*可弯曲性*） and influence factors
- Springback（*回弹*） in bending and solutions

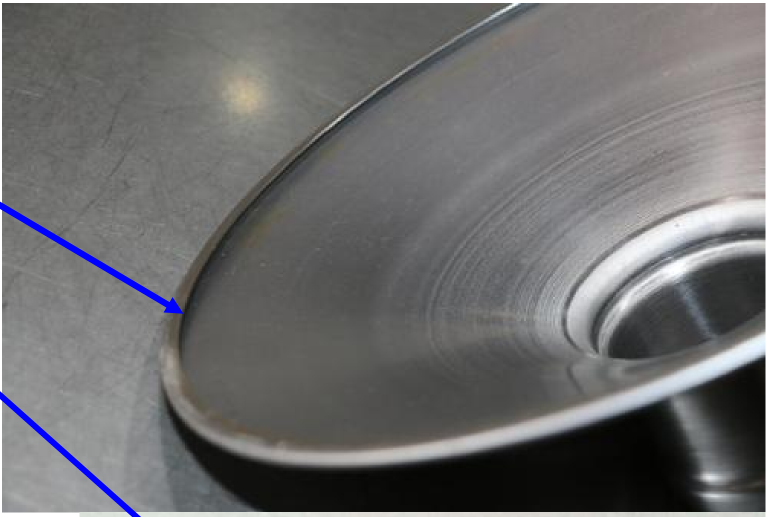
Bending Sheet and Plate

- One of the most common and important industrial forming operations.
- Used to form corrugations（波纹/皱褶）, flanges（凸缘）, beads（卷边）and seams（接缝）
- Also to impart stiffness（刚性/刚度）to the part (by increasing its moment of inertia（转动惯量）) without adding any weight

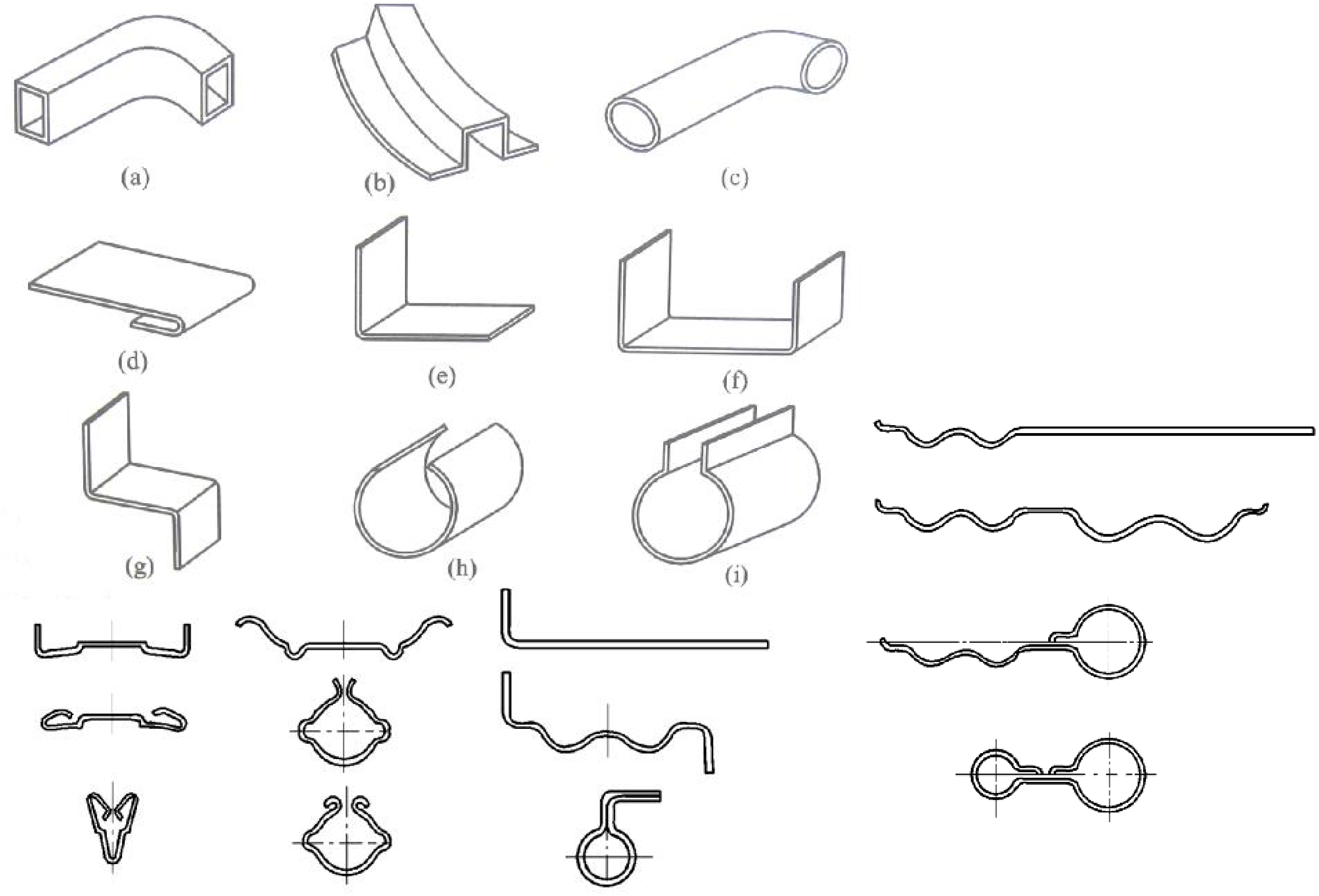


Specific Example

- **circumferential beads**（*周向卷边*） **to improve diametral stiffness**（*径向刚性*） **by using beading process**（*卷边*工艺）



Typical Bended Parts



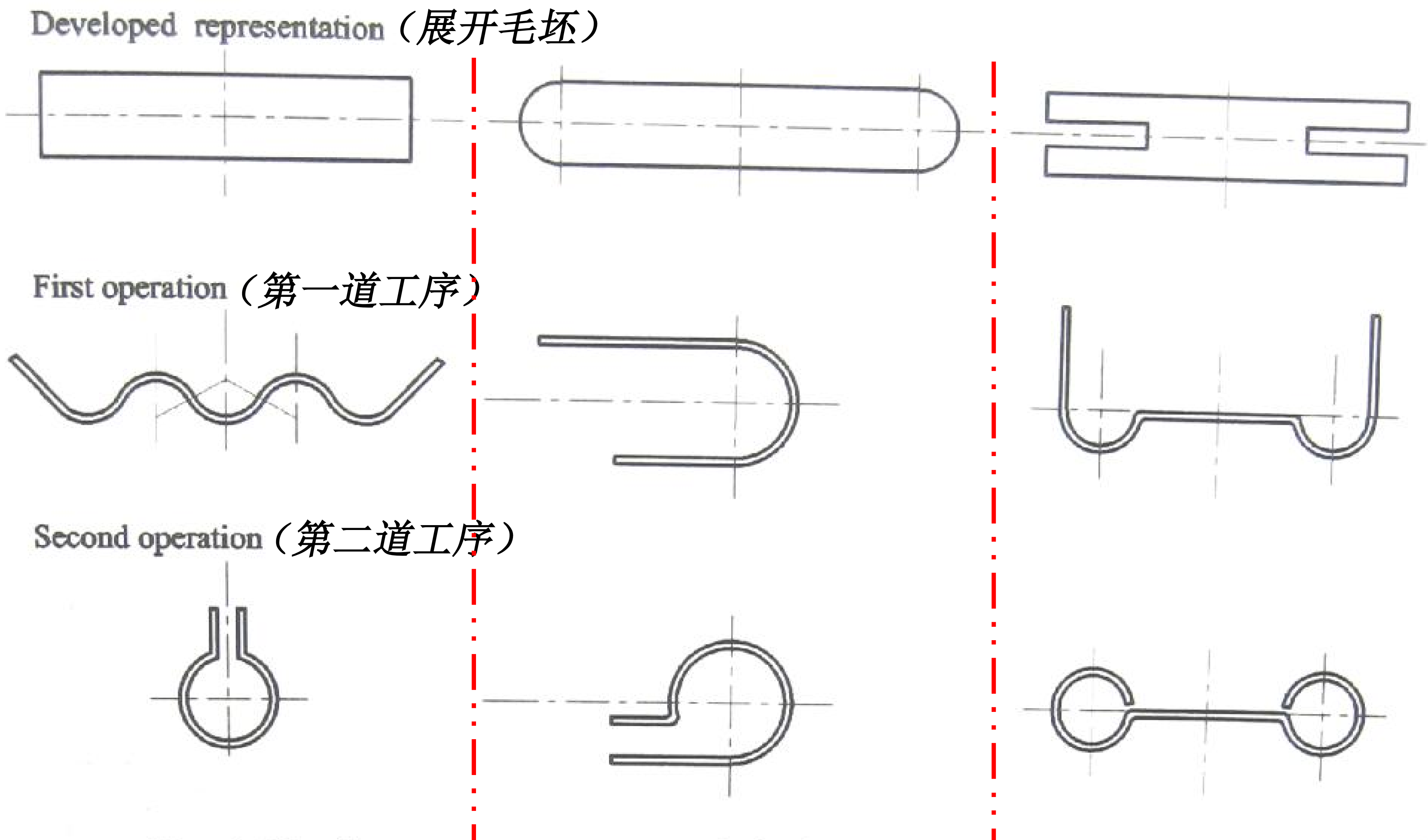


Fig.4.25　Sequence arrangement of the bended part（two operations）

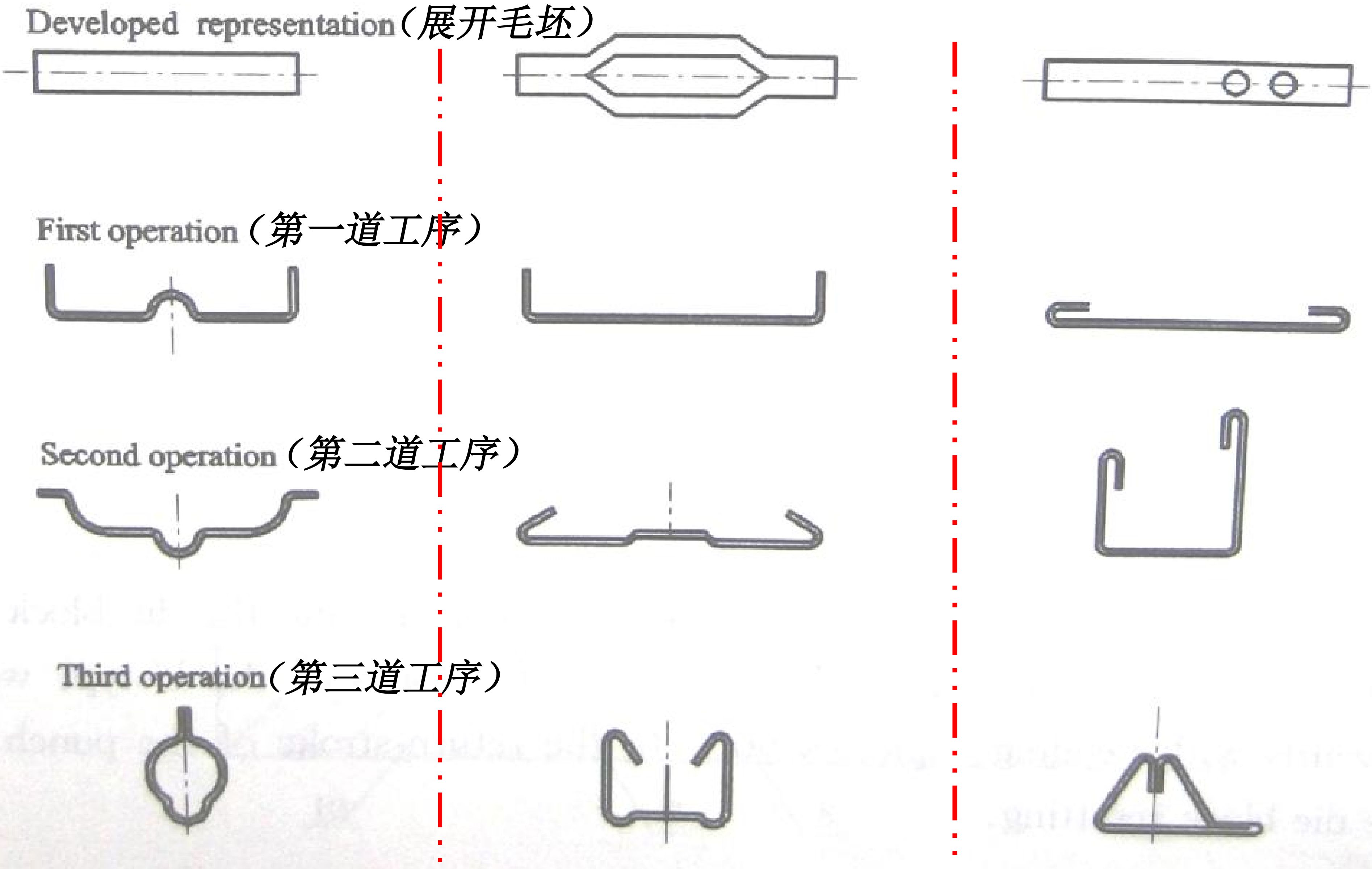
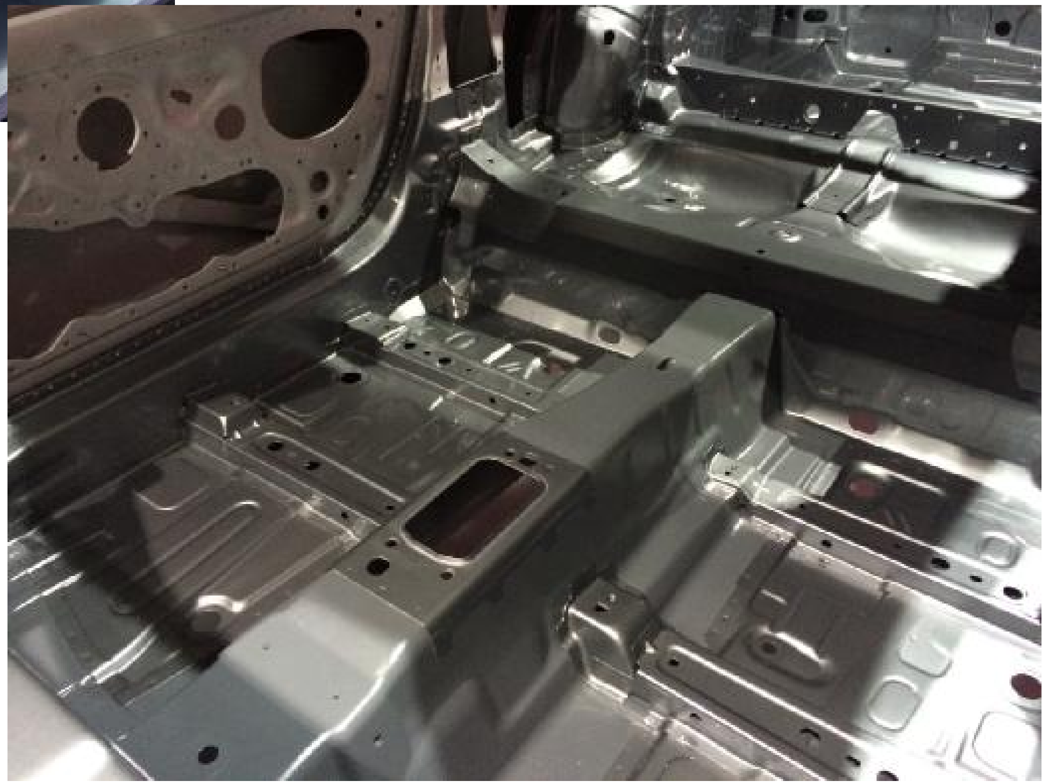
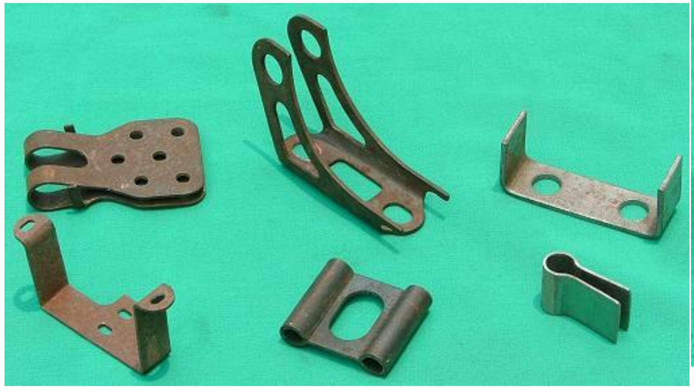


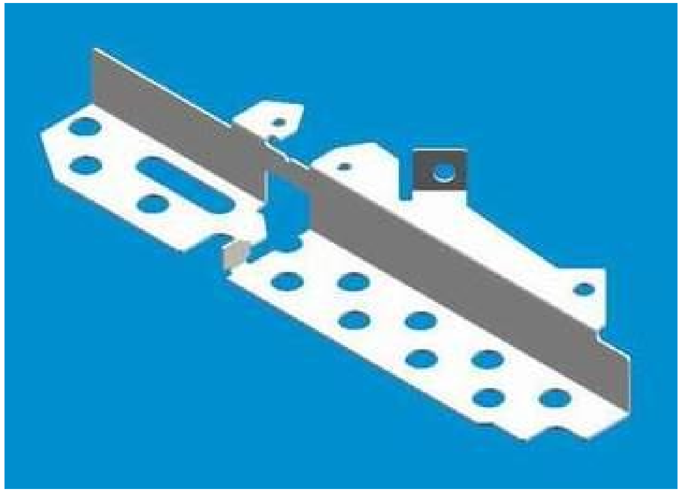
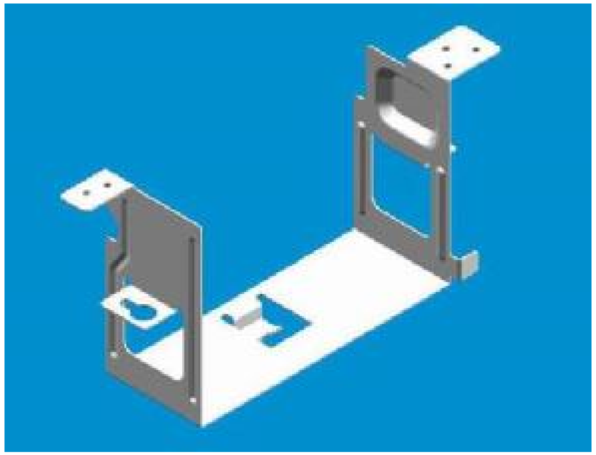
Fig.4.26 Sequence arrangement of the bended part (three operations)






Bending Process

- Outer fibers are in tension
- Inner fibers are in compression.

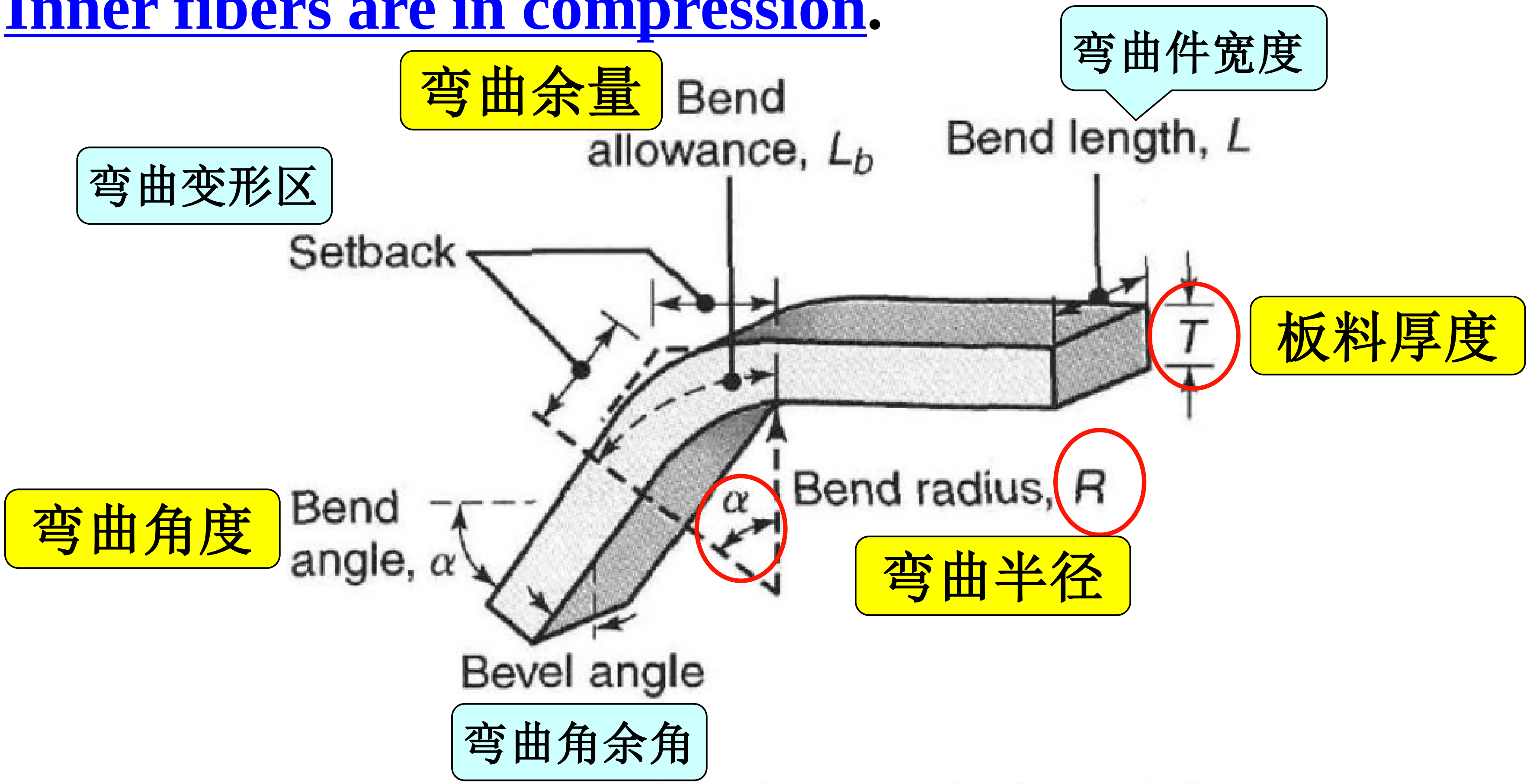
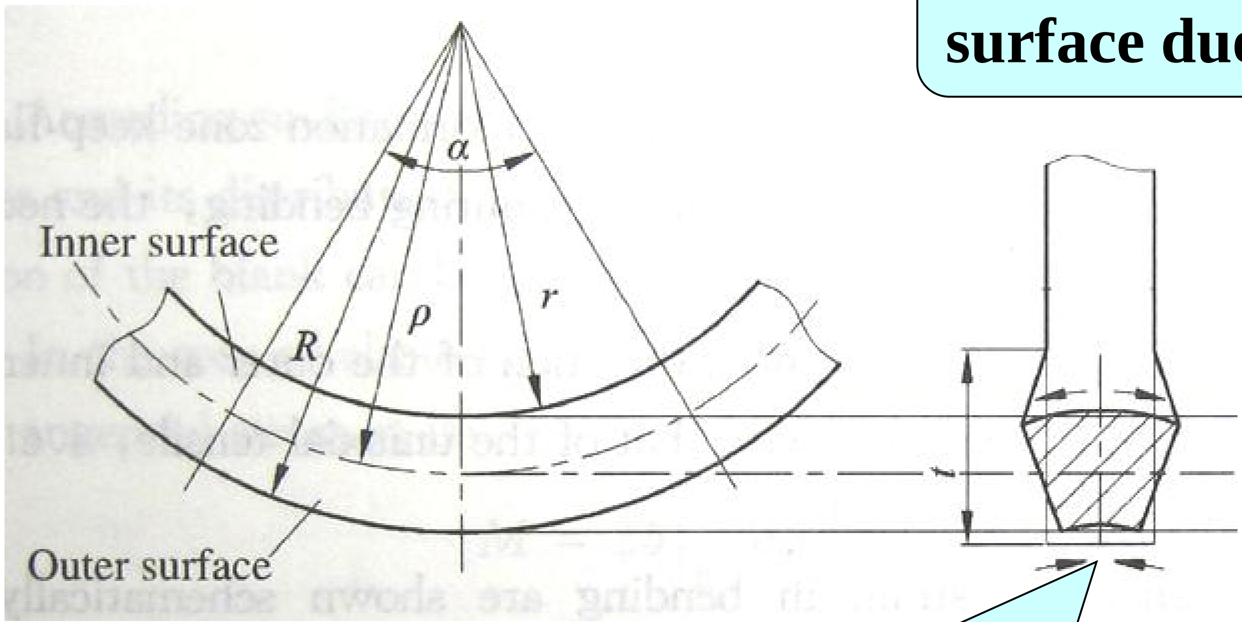
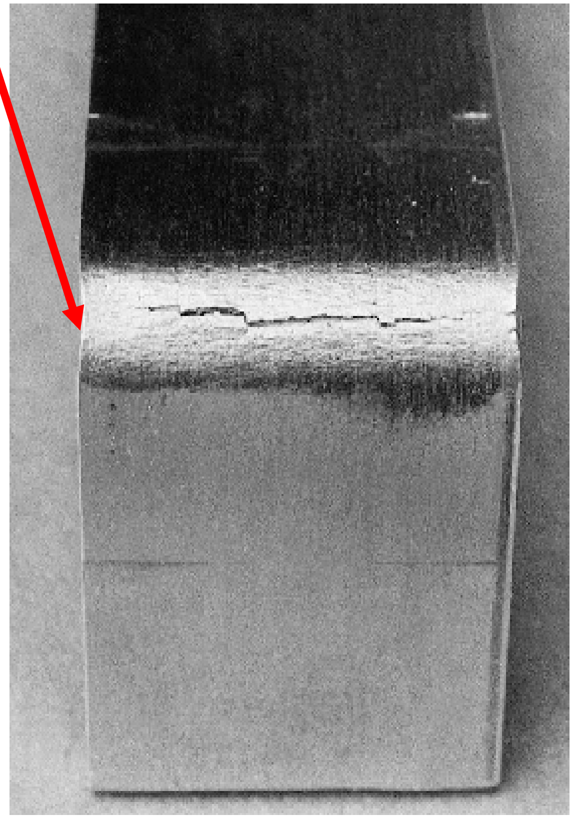


FIGURE 7.16 Bending terminology. Note that the bend radius is measured to the inner surface of the bent part.

Because of the Poisson effect（泊松效应）, the width of the part (bend length, *L*) in the outer region is smaller, and in the inner region is larger, than the original width.

the narrowing（变窄） of the top surface due to the Poisson effect.





This phenomenon may easily be observed by bending a rectangular rubber eraser（橡皮擦）

* Poisson Effect

- **Poisson’s Ratio （Simon Denis Poisson):** 材料在单向受拉或受压时，在材料的比例极限内，由均匀分布的纵向应力所引起的横向应变与相应的纵向应变之比的绝对值。
- 比如，一杆受拉伸时，其轴向伸长伴随着横向收缩(反之亦然)，而横向应变 e' 与轴向应变 e 之比称为泊松比 μ。
- 材料的泊松比一般通过试验方法测定。实验表明，对于某种材料，当应力不超过比例极限时，泊松比是个小于1的常数

$$m = \frac{Lateral\ Strain}{Axial\ Strain} = \frac{\text{横向应变}}{\text{轴向应变}}$$

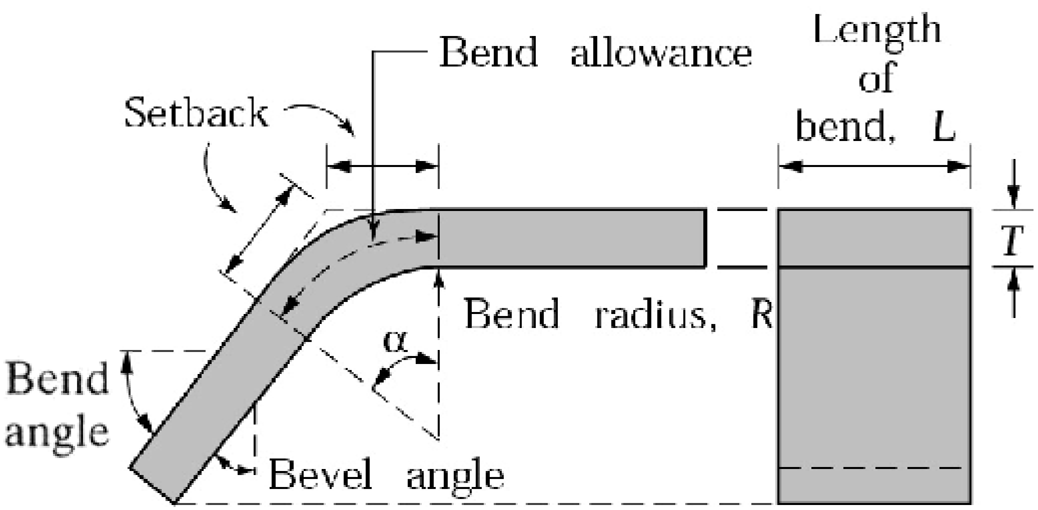
Bend allowance and Neutral axis

（弯曲余量与弯曲应变中性层）

- **Bend allowance is the length of the neutral axis（中性轴） in the bend**
- **used to determine the blank length for a bent part.**

$$L_b = \alpha\,(R + kT)$$

α: the bend angle, radians（弧度）
T: the sheet thickness
R: the bend radius
k: a constant（中性层内移系数/折弯系数）
- **for the ideal case: k=0.5;**
- **usually: 0.33 (for R<2T) ～ 0.5 (for R>2T).**



1. Minimum Bend Radius（最小弯曲半径）

– The radius at which a crack first appears at the outer fibers of a sheet being bent is referred to as the minimum bend radius.

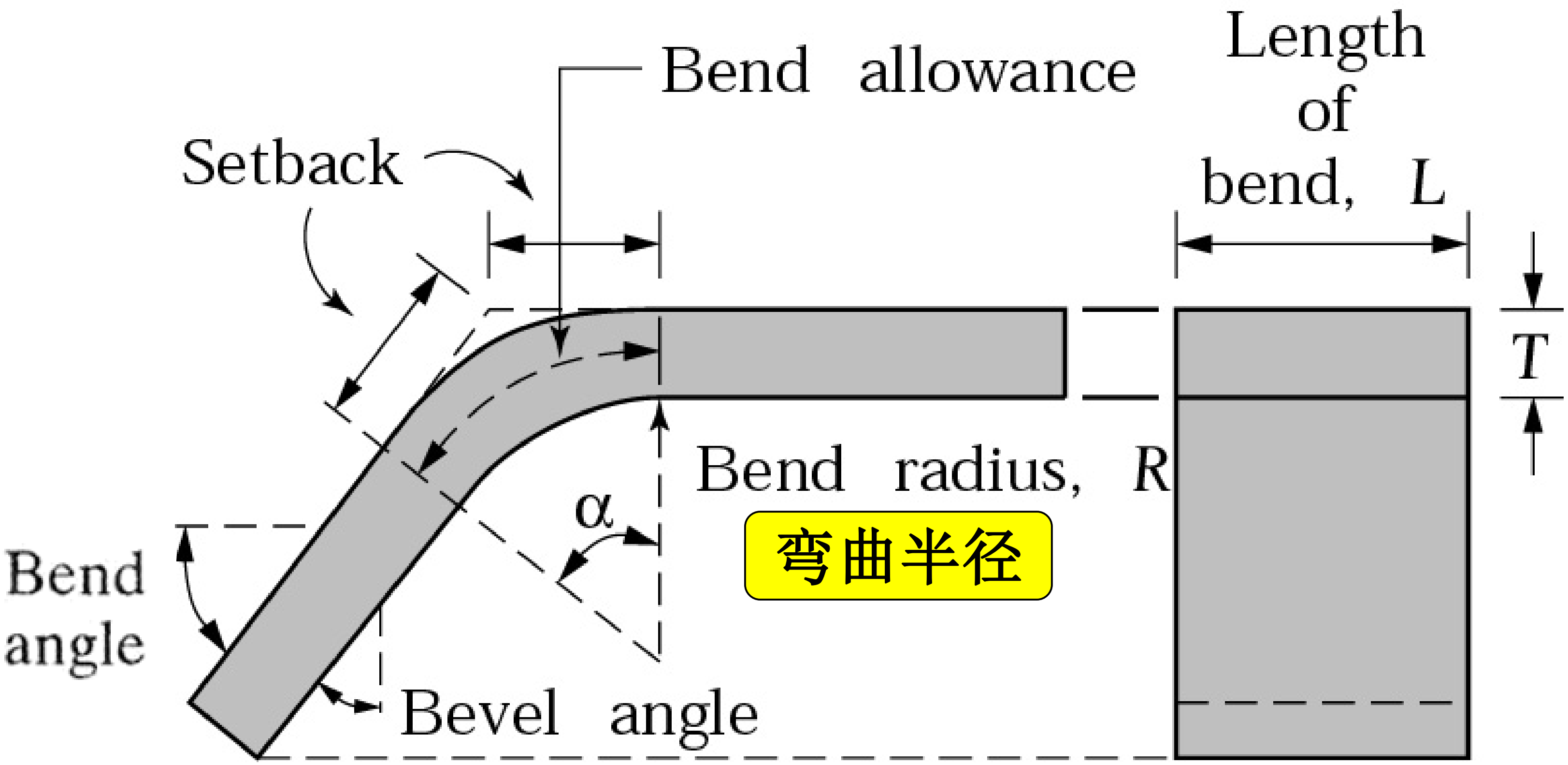


Figure 7.7 Bending terminology.
Note that the bend radius is measured to the inner surface of the bent part.

Engineering Strain（工程应变）

$$e = \frac{1}{(2R/T)+1}$$

for outer fibers, *e* is tensile strain（拉应变）

（相对弯曲半径）

$R \downarrow \rightarrow R/T \downarrow \rightarrow e \uparrow \rightarrow$ cracks

The minimum bend radius, R_{min}

– indicates that the smallest radius to which the sheet can be bent without cracking

– usually expressed in the term of thickness, as 2T, 3T, 4T…

TABLE 7.3

Minimum Bend Radius for Various Metals at Room Temperature

Material		Condition	
		Soft	Hard
Aluminum alloys	铝合金	0	$6T$
Beryllium copper	铍铜合金	0	$4T$
Brass (low-leaded)	低铅黄铜	0	$2T$
Magnesium	镁	$5T$	$13T$
Steels	钢		
Austenitic stainless	奥氏体不锈钢	$0.5T$	$6T$
Low-carbon, low-alloy, and HSLA	低碳钢，低合金，高强度低合金钢	$0.5T$	$4T$
Titanium	钛	$0.7T$	$3T$
Titanium alloys	钛合金	$2.6T$	$4T$

- R_{min} **=0, means the sheet can be folded（折叠） over itself, without cracking**

Bendability（可弯曲性）

- **Minimum bend radius, *R*:**

$$R = T\left(\frac{50}{r} - 1\right)$$

***r*: the tensile reduction in the area（拉伸断面缩减率） of the bent part, %**

$$r \uparrow \;\longrightarrow\; R \downarrow \;\longrightarrow\; \textbf{bendability} \uparrow$$

Methods to increase *r*:

- **heating the sheet;**
- **bending in a high-pressure environment**

$$R = T\left(\frac{50}{r} - 1\right)$$

P200 in Textbook Formula （7.5）

- r=50
- R_{min}=0
- can be **bent over** itself`

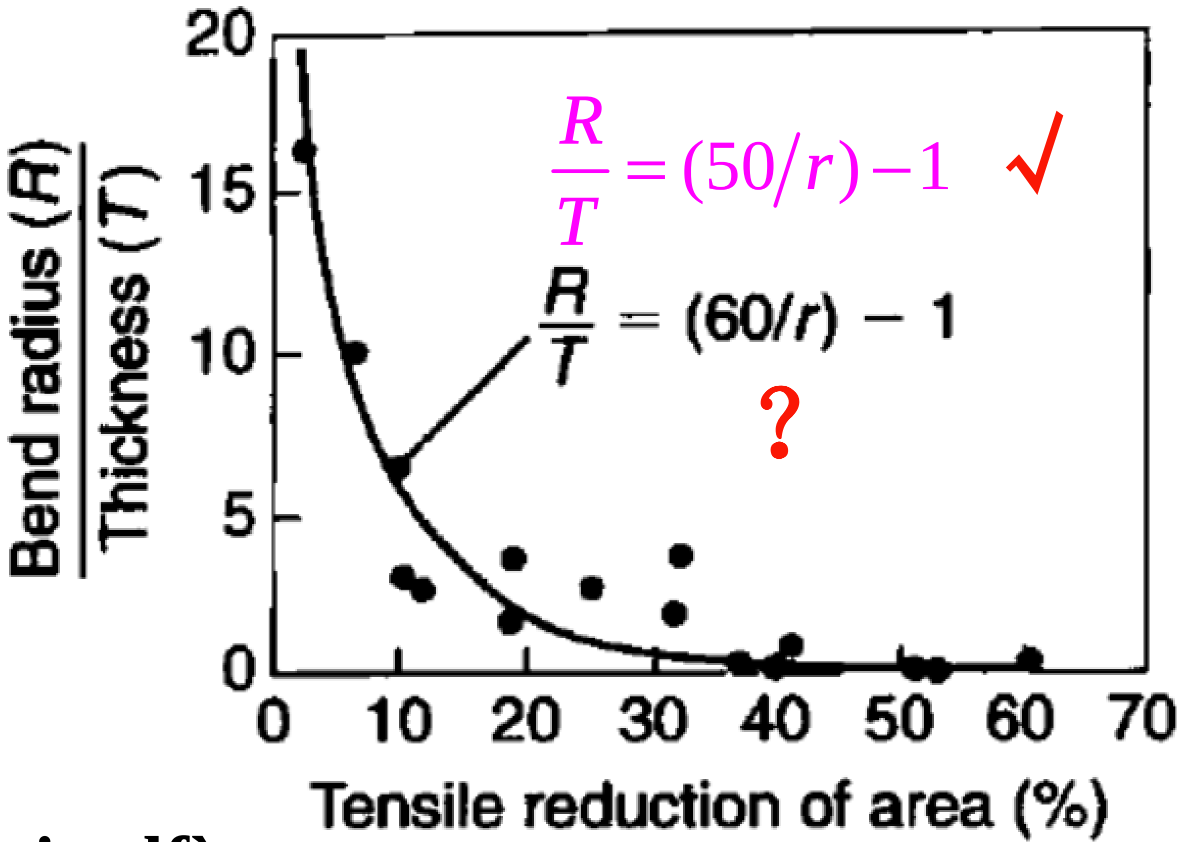


FIGURE 7.18 Relationship between R/T and tensile reduction of area for sheet metals. Note that sheet metal with a 50% tensile reduction of area can be bent over itself in a process like the folding of a piece of paper without cracking. *Source*: After J. Datsko and C.T. Yang.

Factors Affect Bendability

- **Edge condition:**
  - **rough edges are points of stress concentration**（应力集中）
  - **edge roughness↑, bendability↓**
- **The amount, shape and hardness of inclusions（夹杂物）:**
  - **inclusions in the form stringers（纵梁形） is detrimental（有害的） than globular-shaped （球形）**
- **The amount of cold working（冷作硬化）caused by shearing:**
  - **can be removed by shaving or machining the edges of the part or by annealing（退火） to improve its ductility**

Factors Affect Bendability

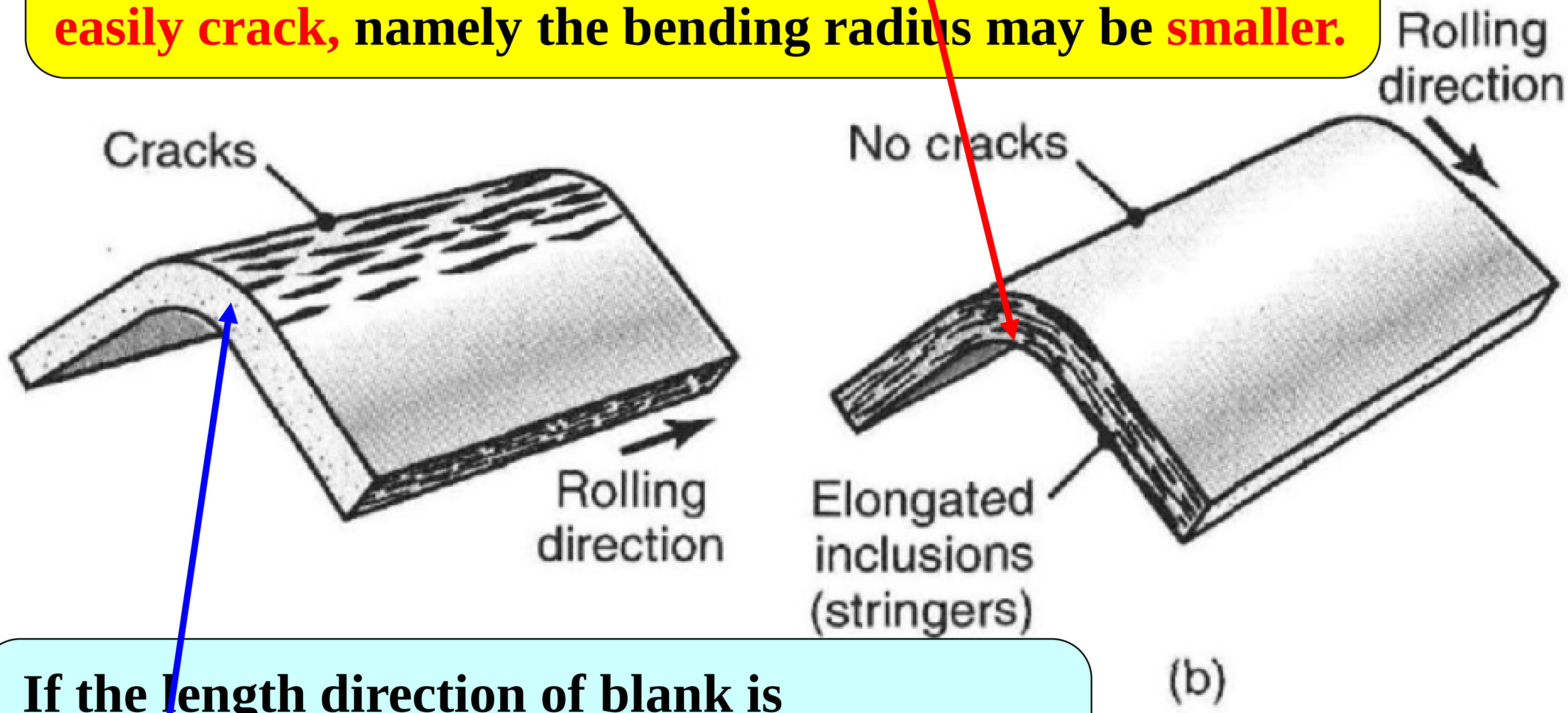
- Anisotropy（各向异性）:
  – produced by cold rolling
  – includes two types:
    - ø crystallographic anisotropy（结晶学各向异性/变形织构）(preferred orientation of the grains) ;
    - ø mechanical fibering（机械纤维）(alignment of impurities, inclusions, and voids throughout the thickness of the sheet).
  – can be determined by observing the direction of cracking in the cupping test

fiber direction or rolling direction

    - ø if the crack is circular, the sheet is isotropic（各向同性）

R_{min} Vs Direction of Bending and of Rolling

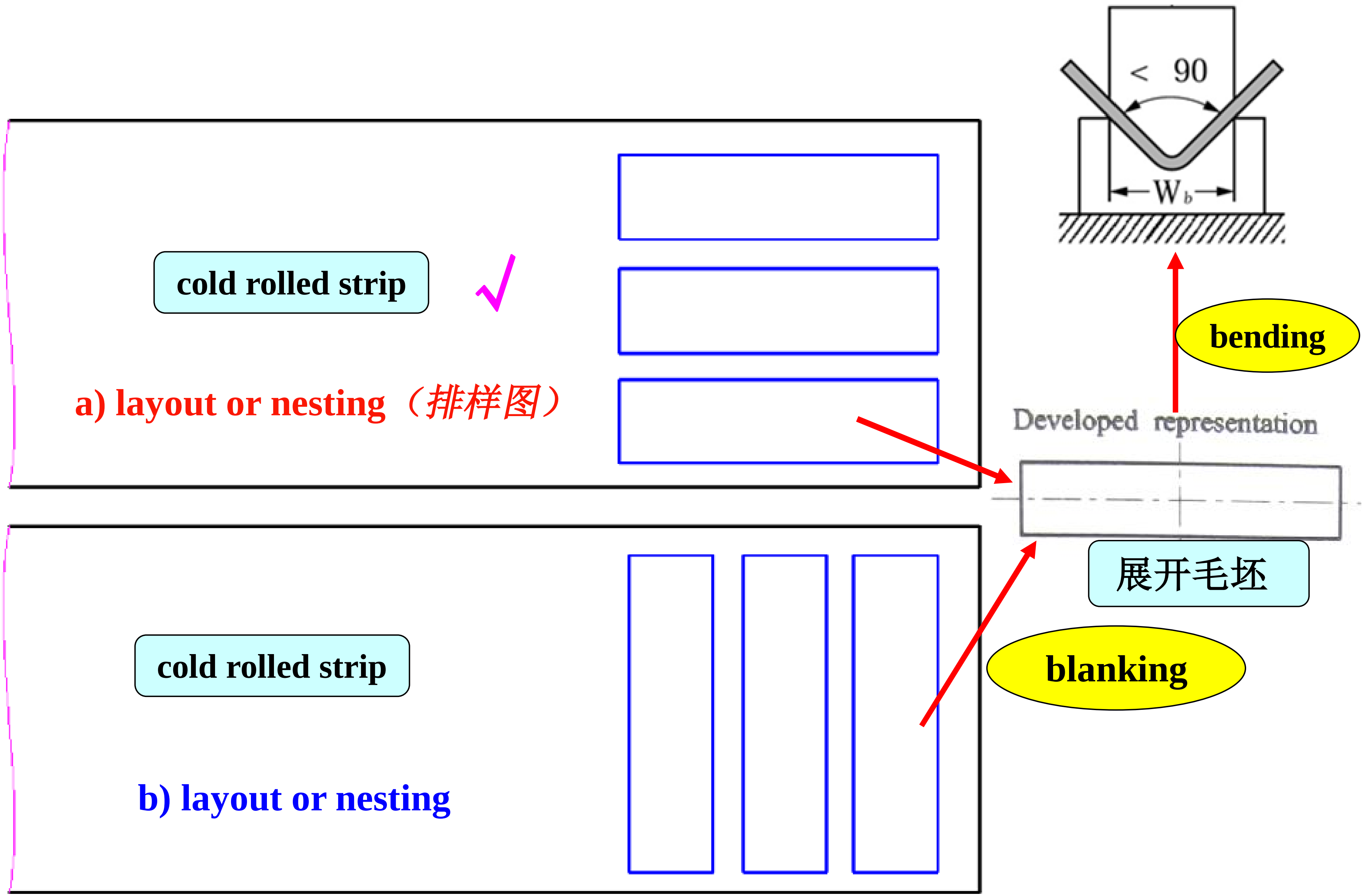
If the length direction of blank is parallel（平行）to its fiber direction (rolling direction), the blank doesn't easily crack, namely the bending radius may be smaller.



If the length direction of blank is perpendicular（垂直） to its fiber direction (rolling direction), it's easy to crack.

FIGURE 7.17 (a) and (b) The effect of elongated inclusions (stringers) on cracking as a function of the direction of bending with respect to the original rolling direction of the sheet.

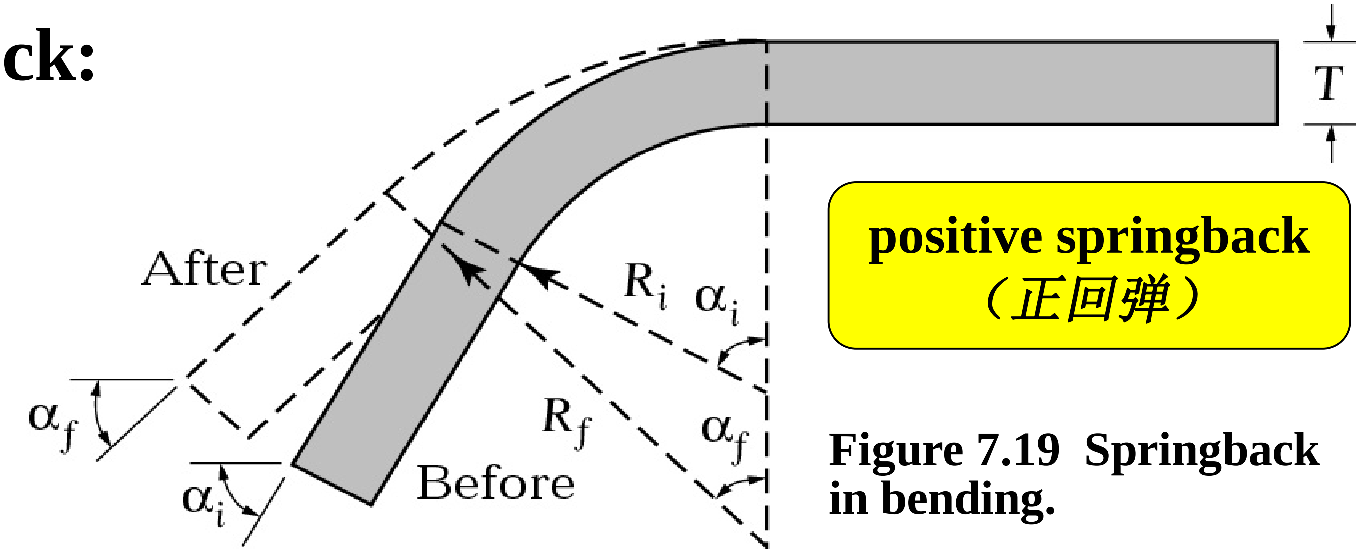
Example



弯曲件
< 90
W_b
bending
Developed representation
展开毛坯
blanking
cold rolled strip
√
a) layout or nesting（排样图）
cold rolled strip
b) layout or nesting

2. Springback（回弹）

- In bending, after plastic deformation there is always an elastic recovery（弹性回复）, called springback.
- Due to modulus of elasticity（弹性模量） for all materials
- After springback:
  - R ↑
  - α ↓



positive springback
（正回弹）

Figure 7.19 Springback in bending.

- Is a main defect（缺陷） affecting the quality of bended part

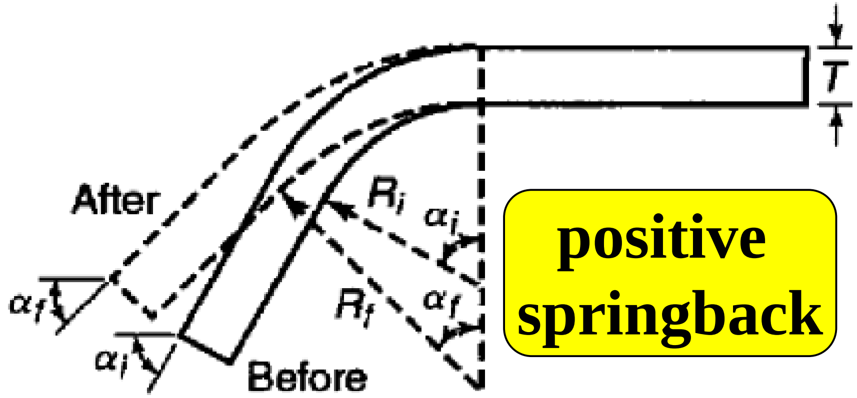
？ $$\frac{R_i}{R_f} = 4\left(\frac{R_i Y}{ET}\right)^3 - 3\left(\frac{R_i Y}{ET}\right) + 1$$

回弹量

R/T **: *相对弯曲半径***
Y**: yield strength*（屈服强度）***
E**: elastic moduluse *（弹性模量）***

R/T ↑
Y（σ_s） ↑
E ↓

springback ↑



positive springback

FIGURE 7.19 Springback in bending. The part tends to recover elastically after bending, and its bend radius becomes larger. Under certain conditions, it is possible for the final bend angle to be smaller than the original angle (negative springback).

Questions on Formula(7.6）in P201 of Textbook

回弹前

回弹后

?

$$\frac{R_i}{R_f} = 4\left(\frac{R_i Y}{ET}\right)^3 - 3\left(\frac{R_i Y}{ET}\right) + 1$$

< 1 $\neq$ > 1

$$\frac{R_i}{T} > 1$$

相对弯曲半径

屈服强度

$$\frac{Y}{E} > 1$$

弹性模量

√

$$\frac{R_f}{R_i} = 4\left(\frac{R_i Y}{ET}\right)^3 - 3\left(\frac{R_i Y}{ET}\right) + 1$$

回弹量

钢筋强度和弹性模量经验参考值

钢筋种类	钢筋直径 d (mm)	屈服强度 fsy (MPa)	弹性模量 Es (GPa)
R235(Q235)	8-20	235	210
HRB335	6-50	335	200
HRB400	6-50	400	200
KL400	8-40	400	200

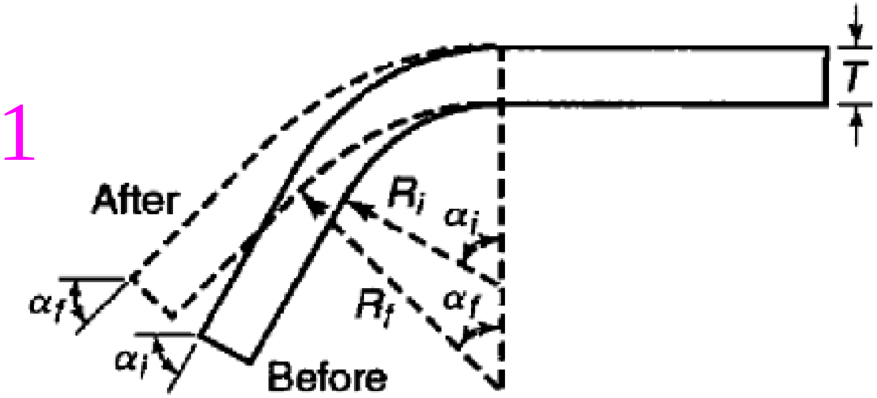


FIGURE 7.19 Springback in bending. The part tends to recover elastically after bending, and its bend radius becomes larger. Under certain conditions, it is possible for the final bend angle to be smaller than the original angle (negative springback).

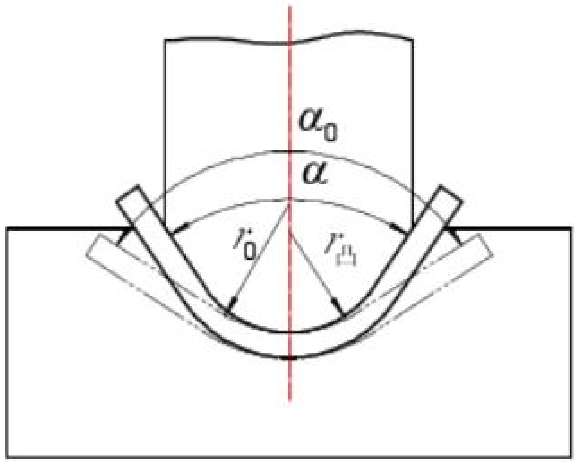
* 中文资料查到的回弹计算公式

相对弯曲半径较大时$\left(\frac{r}{t}\geq 10\right)$，不仅弹复角达到了相当大的数值，而且圆角半径也有较大的变化（下图所示）。这时的弹复主要决定于材料的机械性能。因此，凸模圆角半径和弹复角可按下式进行计算：

回弹后

凸模圆角半径为 $r_{凸}=\dfrac{r_0}{1+\dfrac{3\sigma_s}{E}\cdot\dfrac{r_0}{t}}$

回弹前



设 $\dfrac{3\sigma_s}{E}=K$

故 $r_{凸}=\dfrac{r_0}{1+K\dfrac{r_0}{t}}$

弹复角的数值为 $\Delta\alpha=(180^\circ-\alpha_0)\left(\dfrac{r_0}{r_{凸}}-1\right)$

式中 $r_{凸}$——凸模的圆角半径，$[r_{凸}]$为 mm ； r_0——工件的圆角半径，$[r_0]$为 mm ；

α_0——工件的弯曲角度，$[\alpha_0]$为（°）； σ_s——工件材料屈服强度，$[\sigma_s]$为 MPa;

E——工件材料弹性模数，$[E]$为 MPa； t——工件材料厚度，$[t]$为 mm ；

K——简化系数，见下表：

* 中文资料查到的回弹计算公式

弯曲成型是风机零件生产中最常用的加工方法。在弯曲模具的设计中,回弹计算是极其重要的,因为它关系到成型的质量和修模的次数。目前最常用的计算回弹值的公式是:

回弹后

$$R = \frac{R'}{1 + 3\frac{\sigma_s}{E}\frac{R'}{t}}$$

回弹前

式中 R ——回弹前的圆角半径

R' ——回弹后的圆角半径

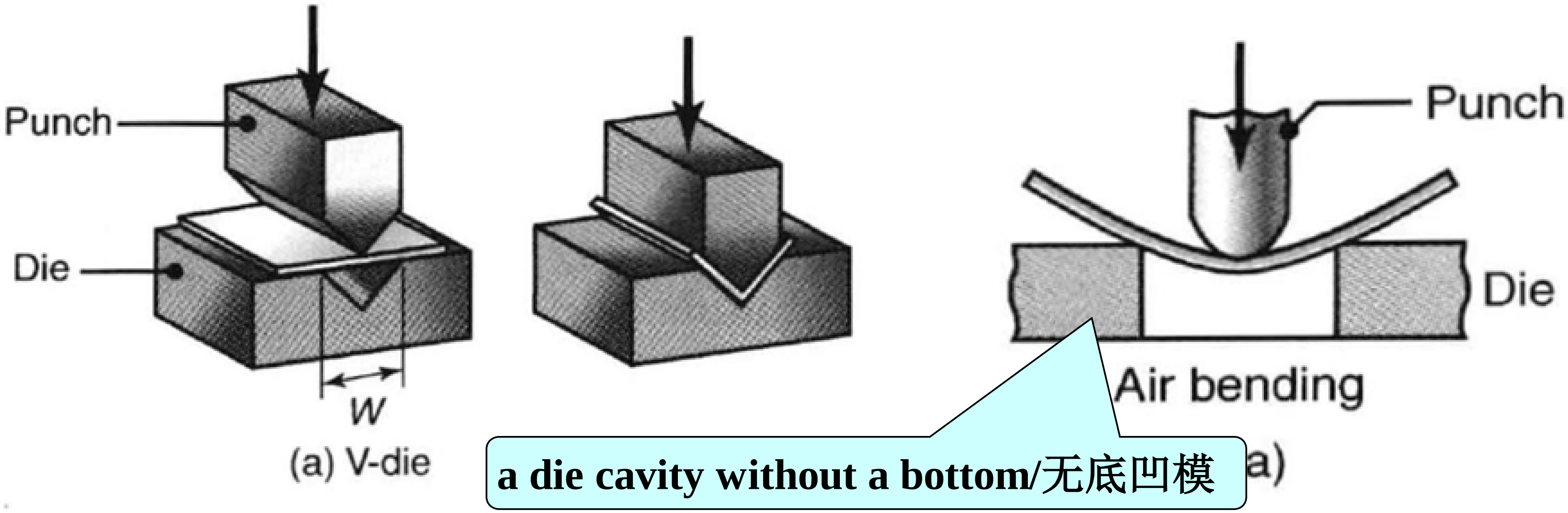
σ_s ——弯曲材料的屈服极限

t ——弯曲件的厚度

E ——弯曲材料的弹性模数

* Negative springback（*负回弹*）

- **Possibly happens in V-die bending （*V形模弯曲*）under certain conditions:**
  - **clearance is too small**
  - **the punch completes the bending operation at the end of the stroke**
- **Does not occur in air bending (free bending/*自由弯曲*）**



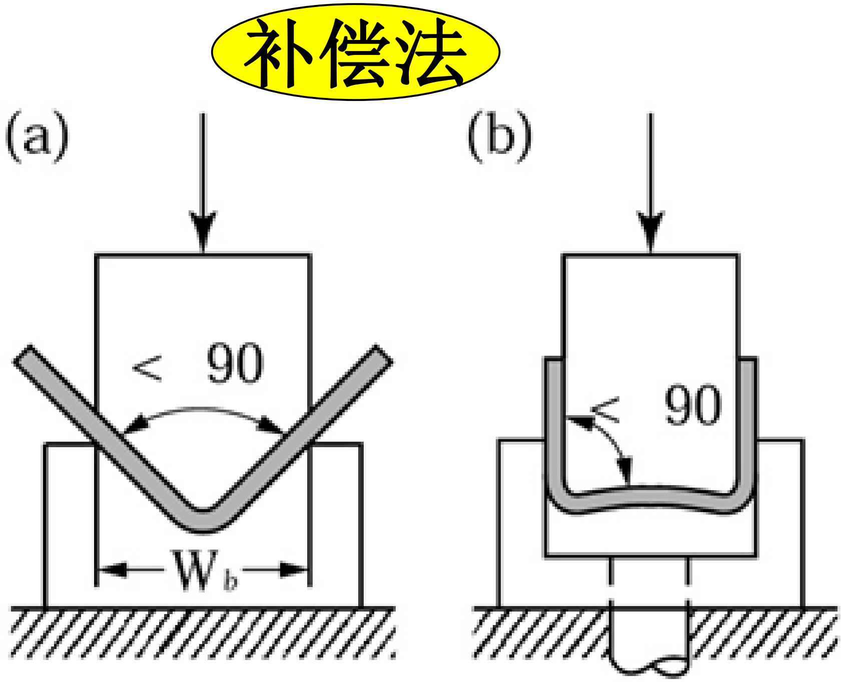
a die cavity without a bottom/无底凹模

* Negative springback（负回弹）

板材出现负回弹。出现负回弹的原因是：弯曲时，弯曲部位中性层内侧切向应力为压应力，外侧为拉应力，卸载后，内外层回弹的趋势都是使板料复直，因此回弹量较大。当压边力较大时，在凸模的作用下，板料受拉伸力增大，中性层内侧的切向应力的绝对值逐渐减小，甚至转变成拉应力，因此在卸载后内外层回弹趋势相互抵消，使回弹逐渐减小，当压边力增大到一定数值时，回弹将减小至零，并进而出现负回弹。因此，当压边力的选择适当时，回

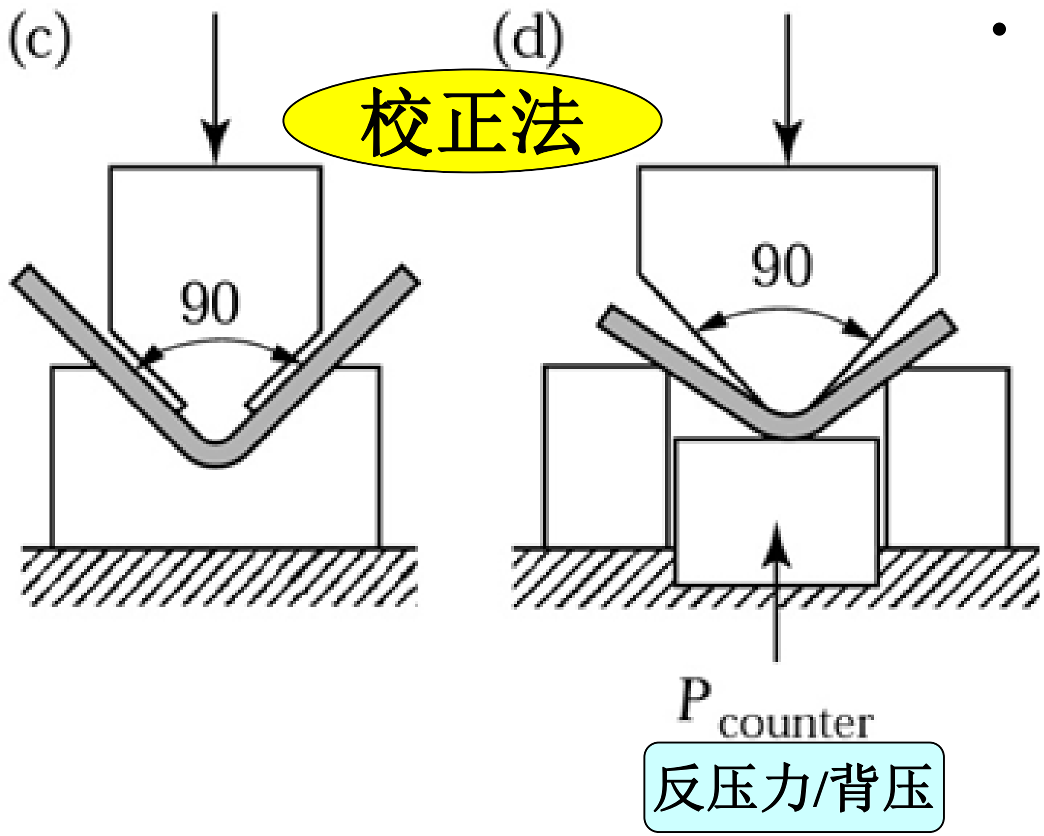
Compensation for Springback（回弹补偿）

- ① **Overbending（过度弯曲）**



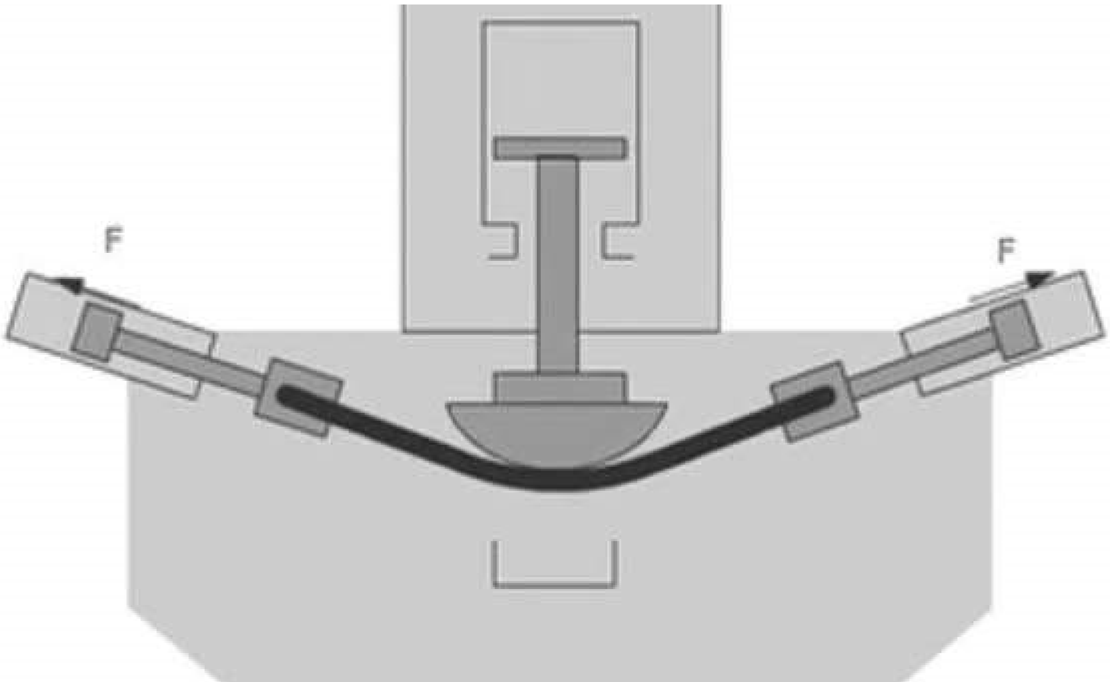
- 按照预先估算或试验或分析计算所得的回弹量，对弯曲模具工作部分的形状进行修正，从而使得出模回弹后的弯曲件获得所要求的形状和尺寸

- ② **Bottoming the punch**
  - **coin the bend area by subjecting it to high localized compressive stresses（*局部压应力*）between the technique tip of the punch and the die surface;**



- 将凸模做成局部突起的形状，使弯曲变形力集中作用在材料弯曲变形区，同时采用有底凹模，使得板厚方向承受很大的压应力，改善弯曲变形区内、外层应力状态，使其成为三向压应力状态，提高其塑性，从而减少弹性变形，减少回弹

- ③ Stretch bending（拉弯）
  - in which the part is subjected to tension while being bent.
- ④ Carried out at elevated temperatures （热弯）



拉弯成形

铝型材拉弯

弯管

* 拉弯成形为什么能减少回弹

- 拉弯是首先在平直状态下拉伸，使材料超过屈服点，然后开始弯曲，此时整个弯曲截面都处于塑性拉伸变形状态，弯曲件的内外层的应力方向一致，从而减小回弹。最后当弯曲结束时再补充加大拉力，以便更好地保持弯曲时所获得的弯曲度。
- 目前，一些飞机、汽车、拖拉机等大型制造厂都广泛采用拉弯工艺。

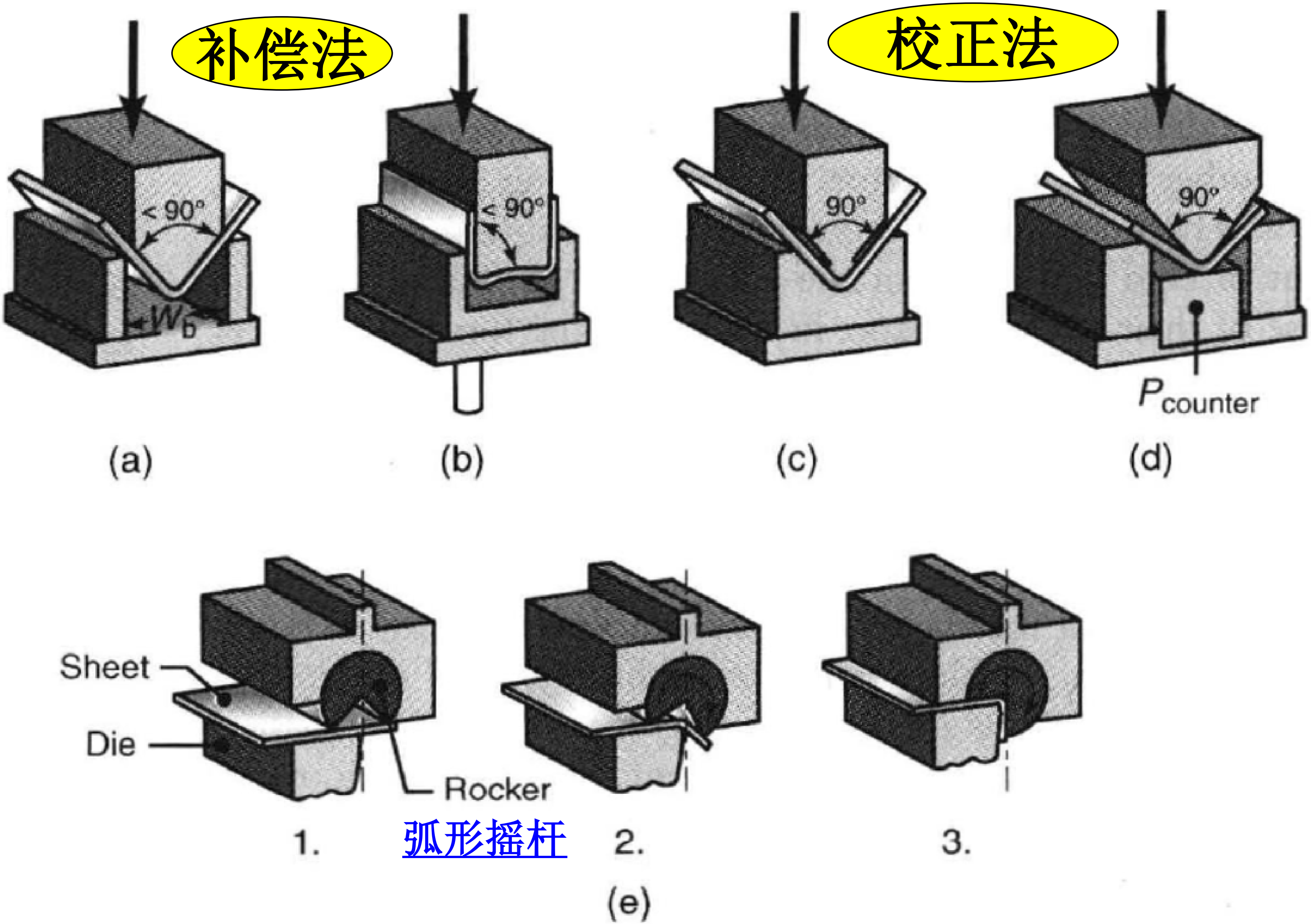


FIGURE 7.20 Methods of reducing or eliminating springback in bending operations.

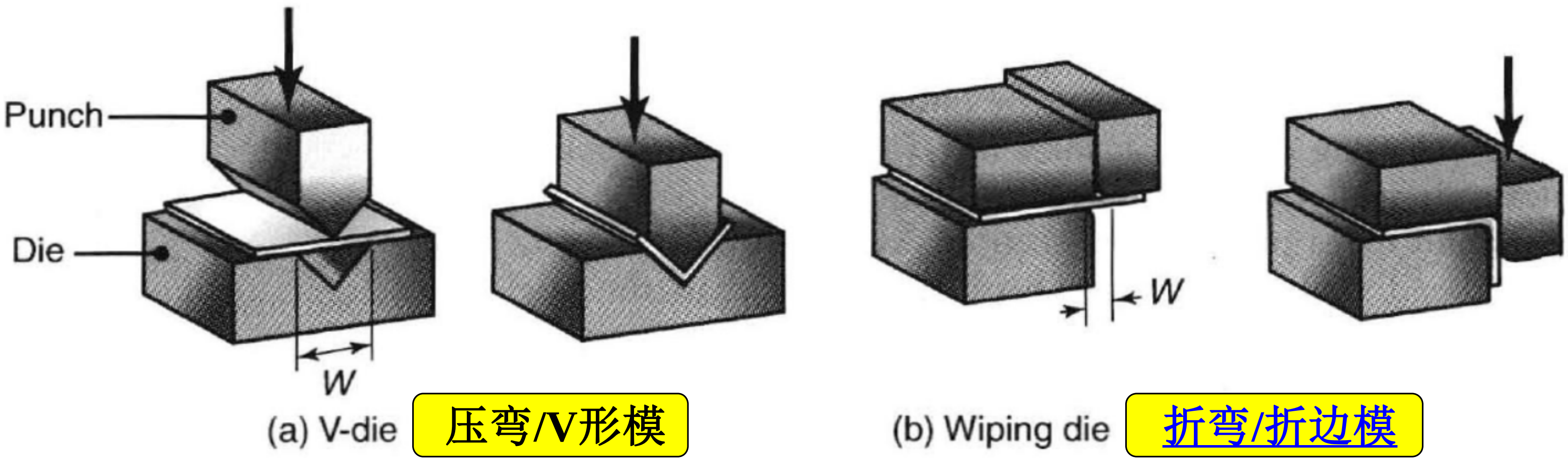


FIGURE 7.21 Common die-bending operations showing the die-opening dimension, W, used in calculating bending forces.

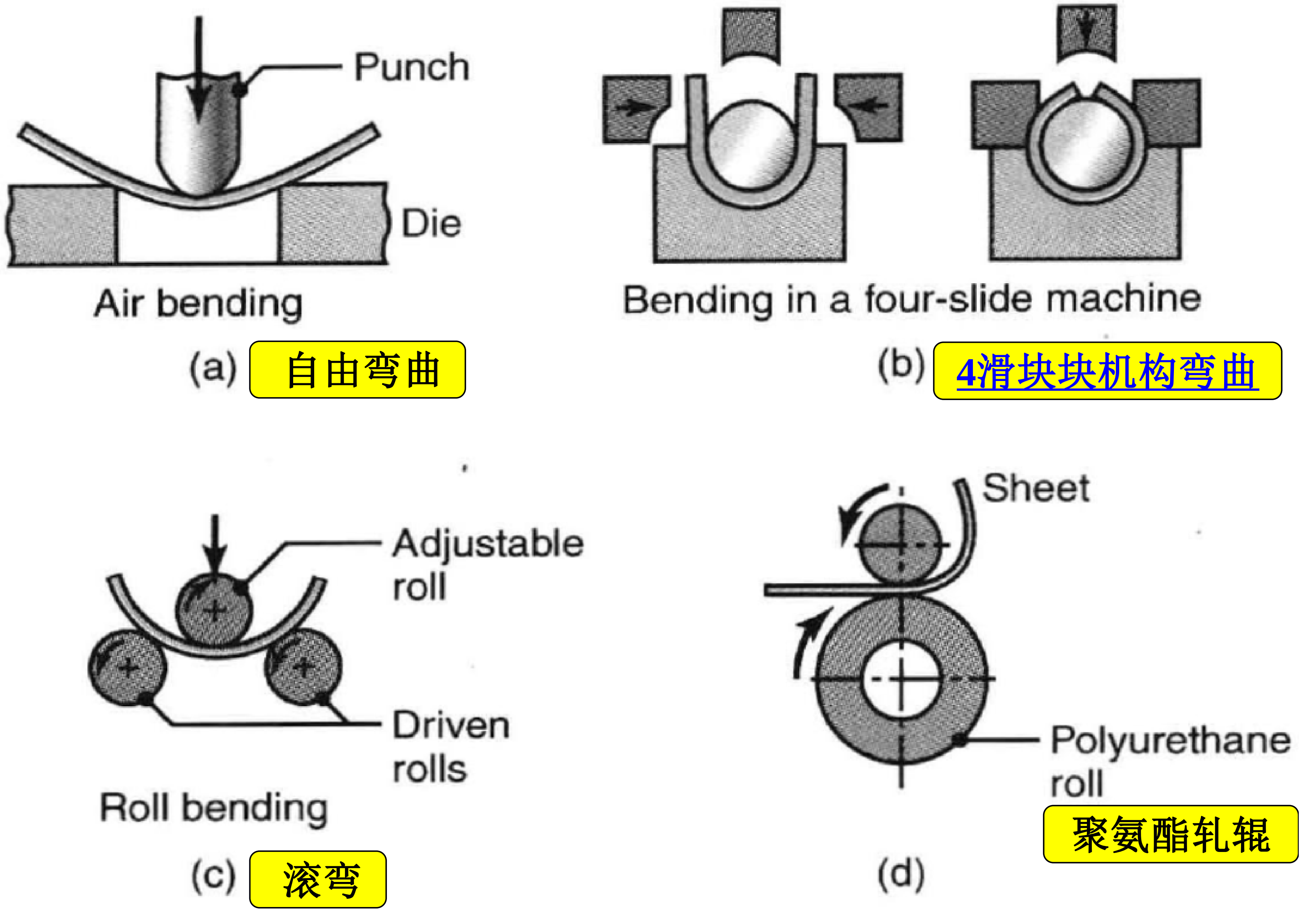
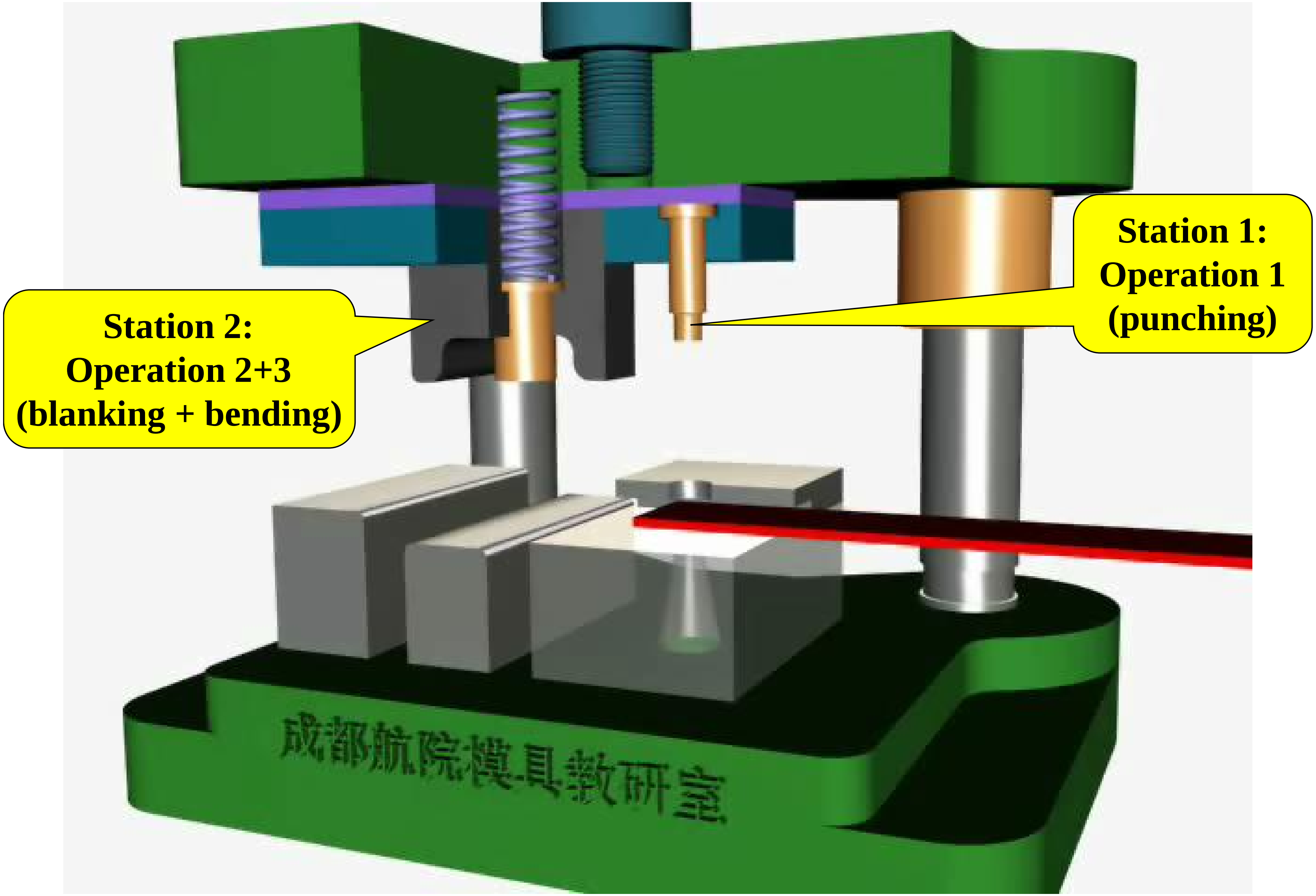


FIGURE 7.22 Examples of various bending operations.

Bending with Progressive Die



7.7 Deep Drawing（*拉深/拉延*）

deep drawing ≠ stretching

（*拉深 ≠拉伸*）

Outline

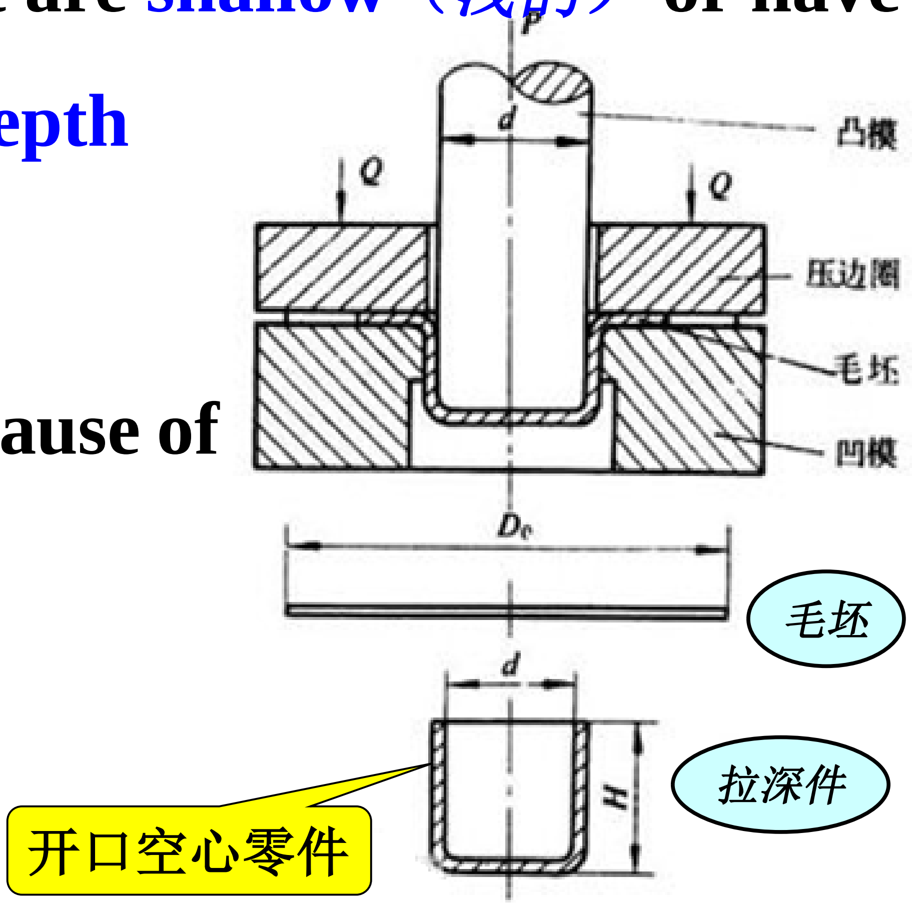
- **Deep-drawing process**
- **Typical deep-drawn products**
- **Important variables**
- **Defects in deep-drawing and solutions:**
  - **winkle（*起皱*）**
  - **tearing（*拉裂*）**
  - **earing（*凸耳*）**
- **Deep drawability（*可拉深性*） and influence factors:**
  - ***LDR*（*极限拉深比*）**
  - **normal anisotropy（*法向/厚向各向异性*）**
  - **planar anisotropy（*平面各向异性*）**

Deep Drawing（拉深）

- **Punch forces a flat sheet metal into a deep die cavity to produce cup-shaped or box-shaped parts（杯形件或盒形件）**

- **Also used to make parts that are shallow（浅的） or have moderate（适度的/中等的） depth**

- **One of the most important metalworking processes because of its widespread use.**



Typical Deep-drawn Products

- cylindrical（round cup-shaped）parts（*筒形件/杯形件*）or box-shaped parts（*盒形件*）
  - pot and pans
  - containers for food and beverages
  - kitchen sinks（*水槽/洗涤盆*）
  - automotive fuel tanks（*汽车油箱*）

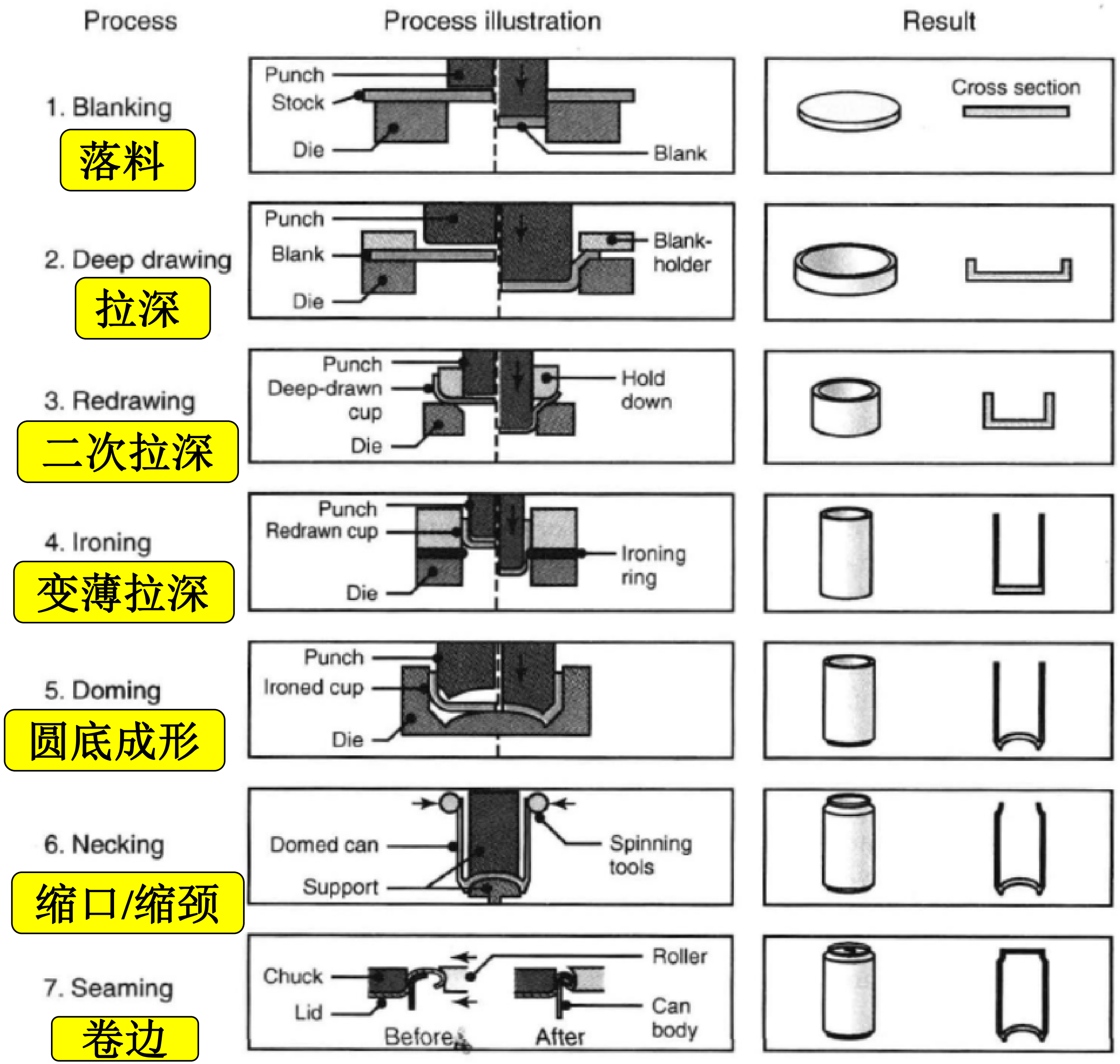
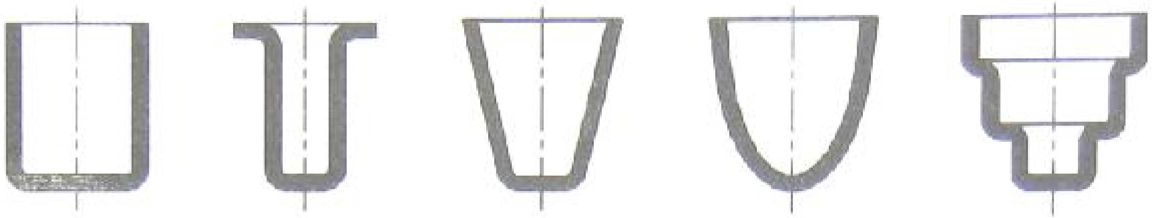
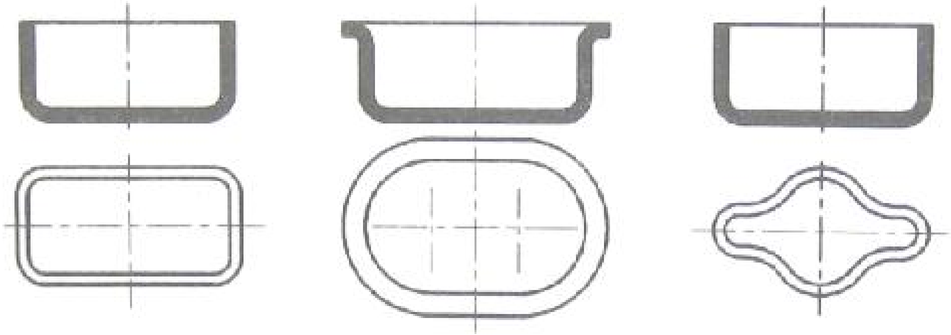


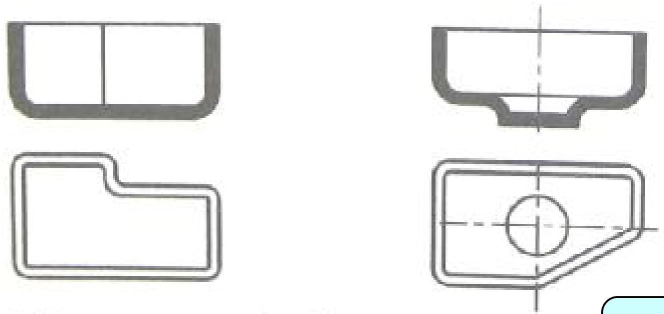
FIGURE 7.30 The metal-forming processes involved in manufacturing a two-piece aluminum beverage can.



(a) symmetrical rotational part 轴对称旋转体零件



(b) symmetrical rectangular part 轴对称盒形件



(c) asymmetrical complex part 不对称复杂件

Fig.5.1 Diagrammatic sketch of deep drawn parts

The Deep-Drawing Process

Basic operation:

– **a round sheet metal block is placed over a circular die opening and held in a place with blank holder （压料板/压边圈）**

– **punch forces it down into the die cavity to form a cup**

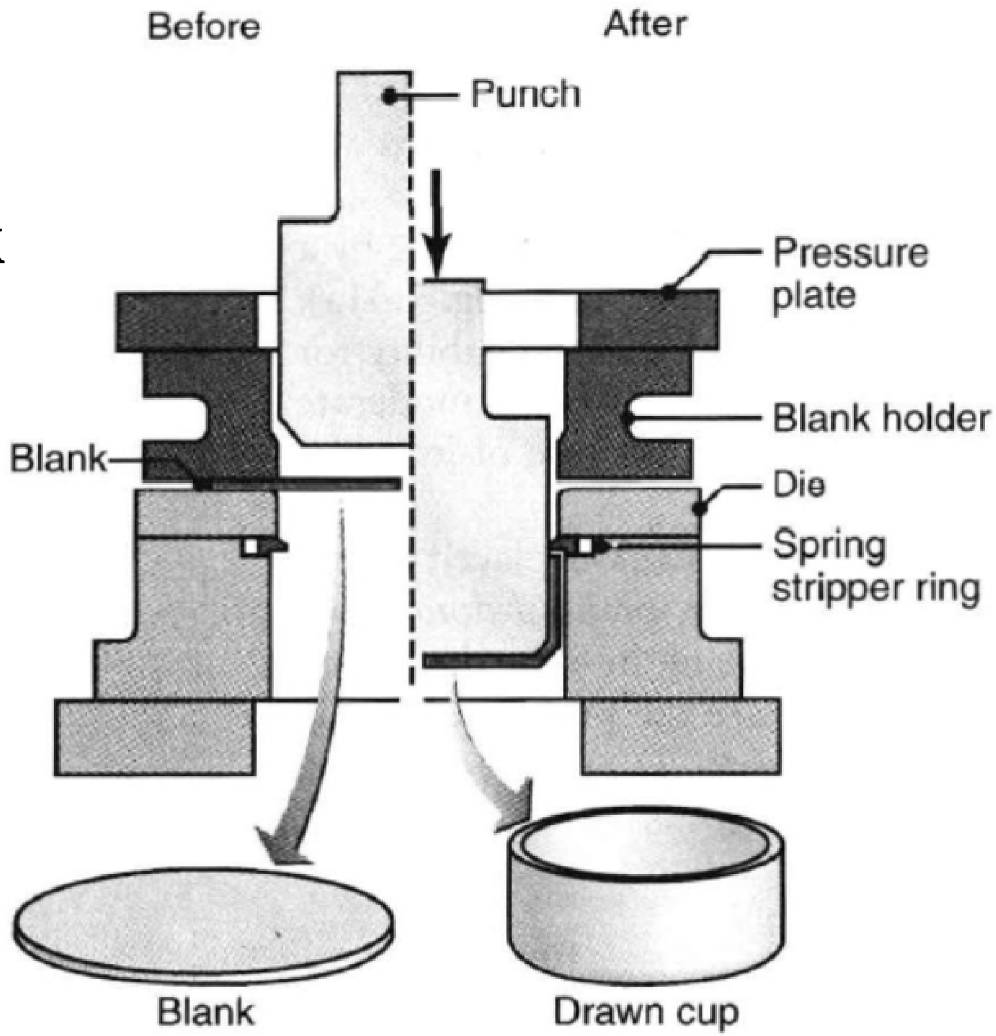


Figure 7.31 (a) schematic illustration of the deep-drawing process on a circular sheet-metal blank.

Basic Deep-Drawing Operation

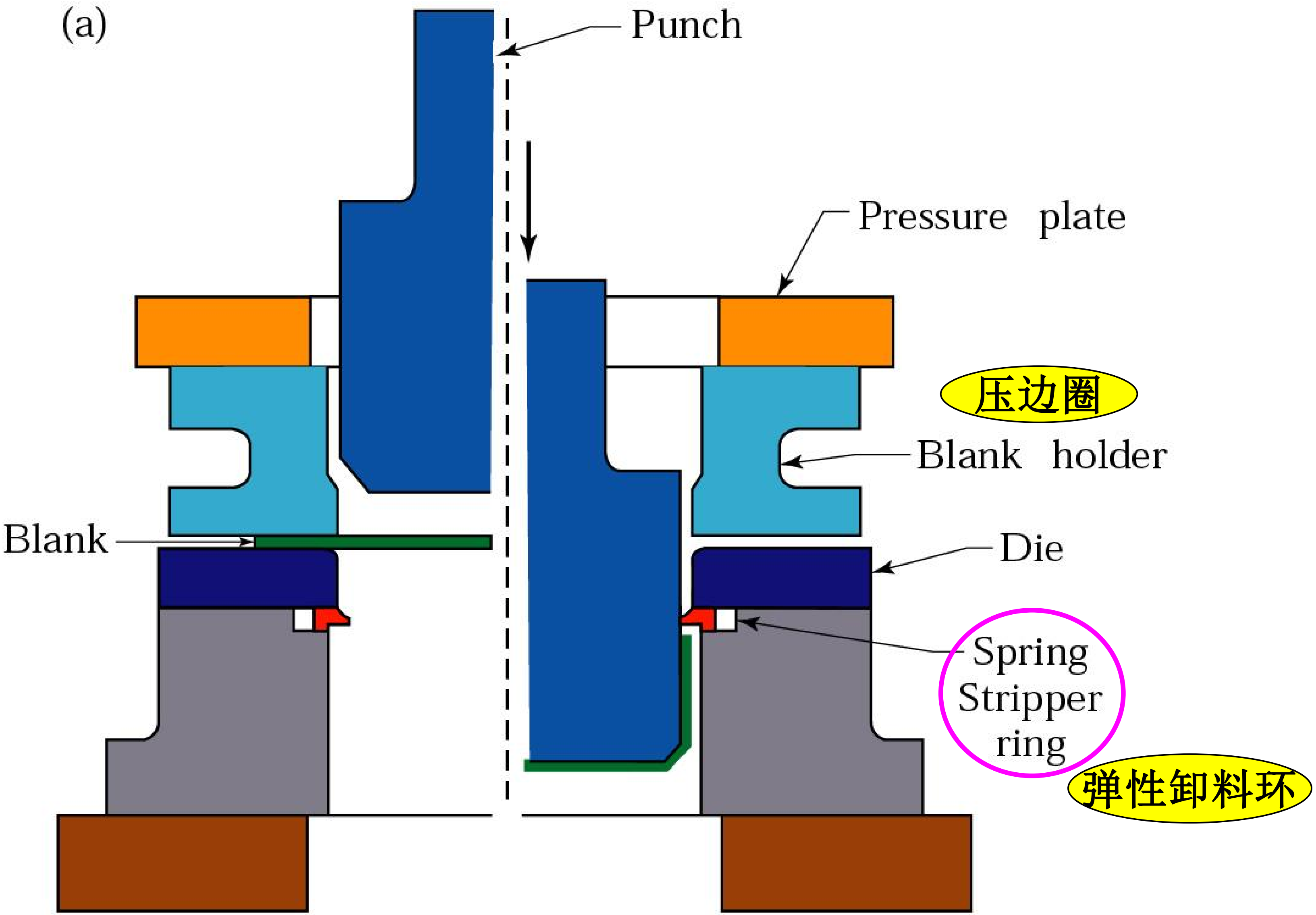
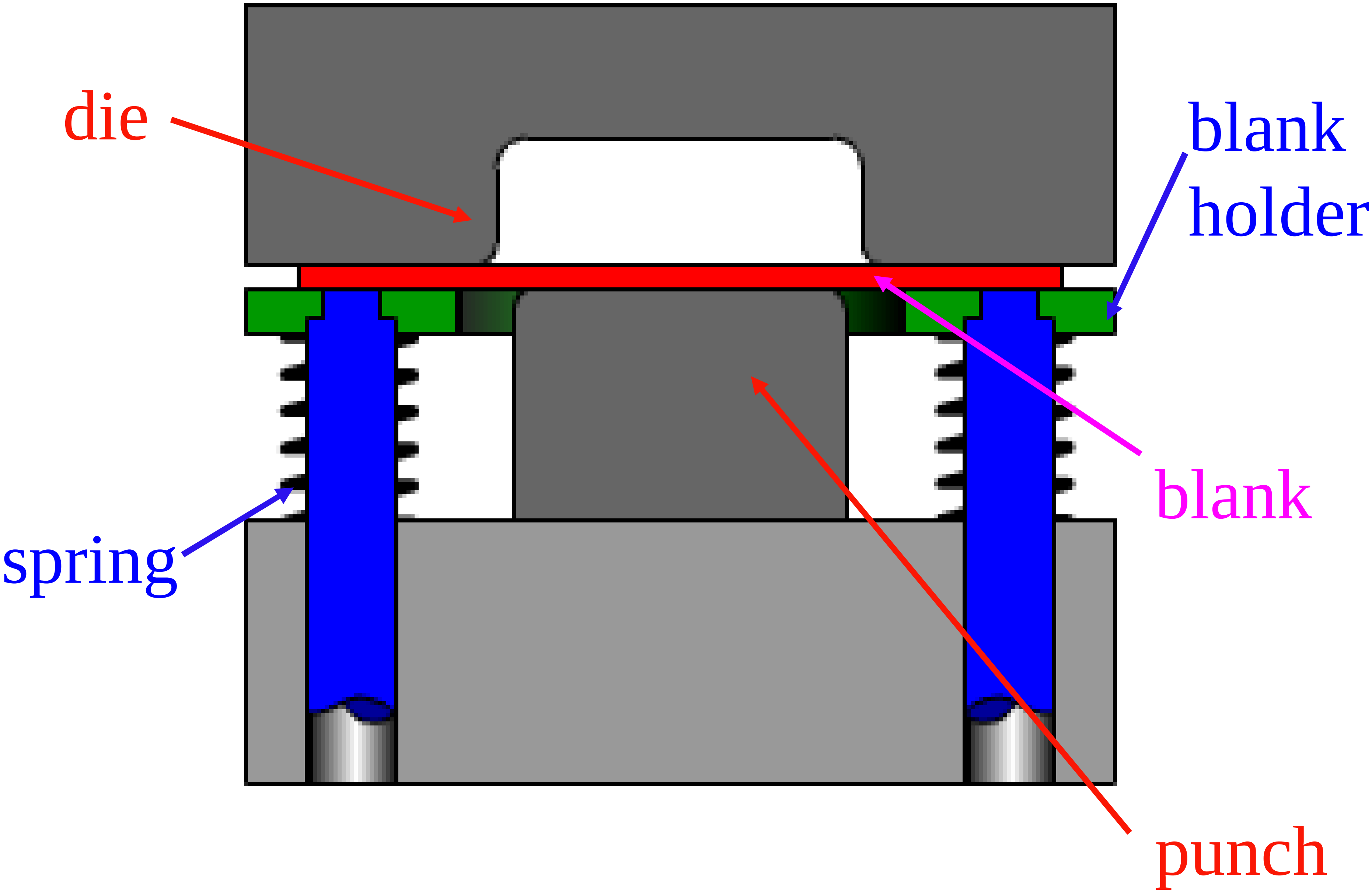
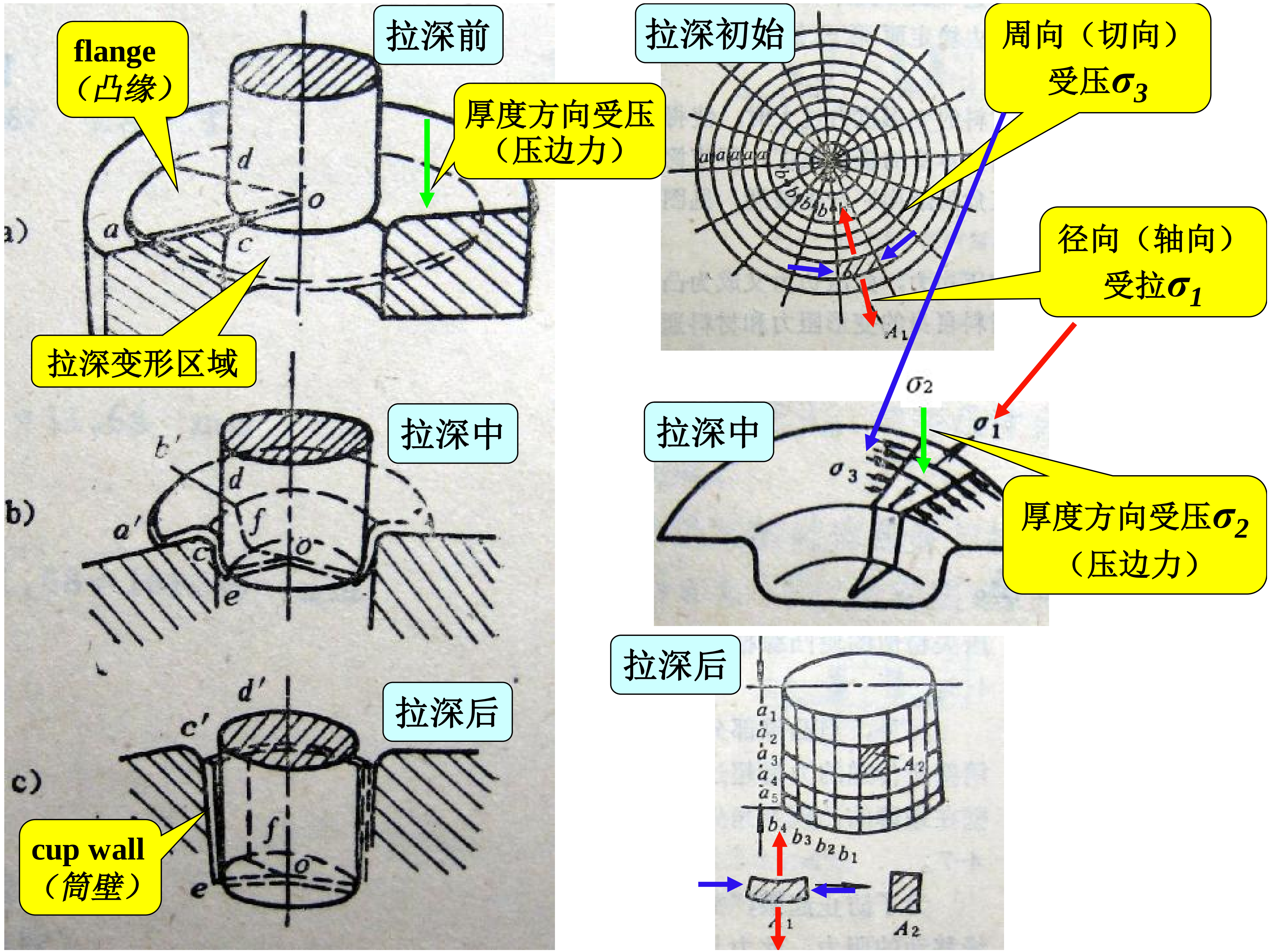


Figure 7.31 (a) Schematic illustration of the deep-drawing process on a circular sheet-metal blank. The stripper ring facilitates the removal of the formed cup from the punch.

倒装式拉深模




flange
（凸缘）
拉深前
厚度方向受压
（压边力）
拉深变形区域
a)
拉深中
b)
拉深后
c)
cup wall
（筒壁）
拉深初始
周向（切向）
受压σ_3
径向（轴向）
受拉σ_1
A_1
σ_2
σ_1
σ_3
拉深中
厚度方向受压σ_2
（压边力）
拉深后
A_2

Important Variables

① **properties of the sheet metal**

② $D_o/D_p > 1$

D_o: blank diameter
D_p: punch diameter

③ **clearance, c**

④ **punch corner radius, R_p**（凸模圆角半径）

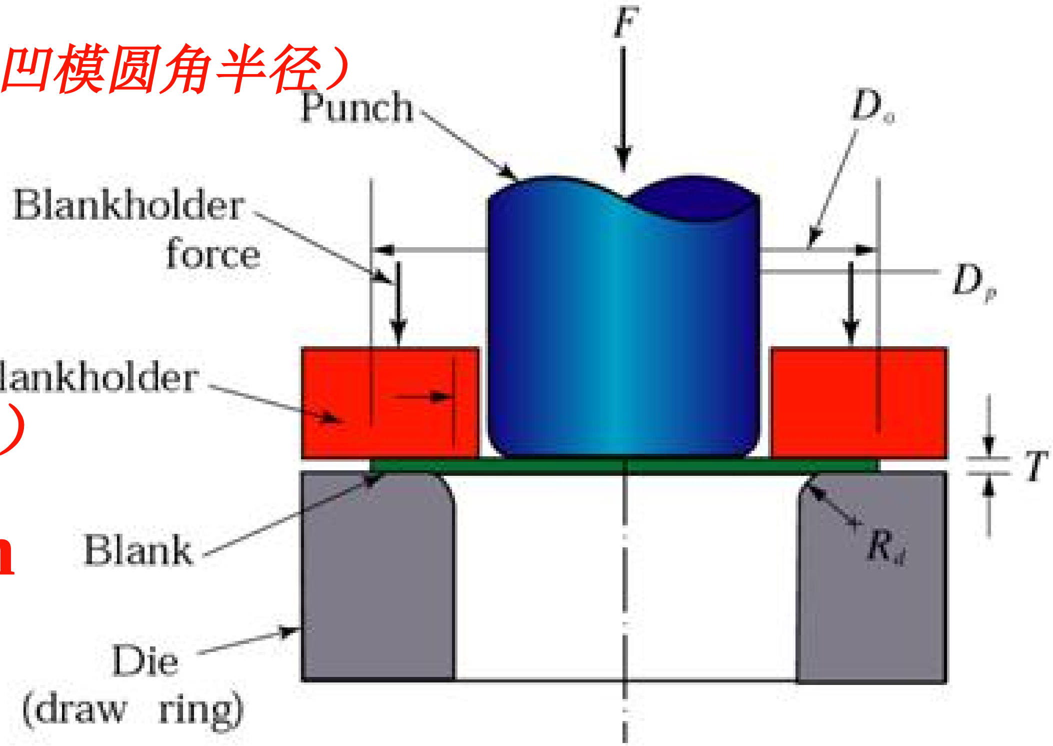
⑤ **die corner radius, R_d**（凹模圆角半径）

⑥ **blankholder force**

（压边力）

⑦ **punch force, F**（拉深力）

⑧ **friction and lubrication**



Defects in Deep-drawing

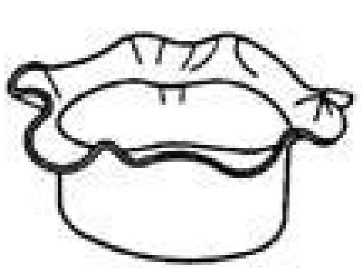
1. Wrinkle（起皱）

– due to **compressive circumferential (hoop) stresses** *（周向/切向压应力）* in the **flange** *（凸缘/法兰）*

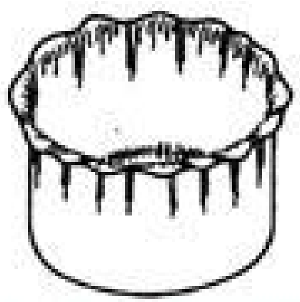
– tend to cause the flange to **wrinkle** during drawing

– can be reduced or eliminated if a **blank holder** is kept under the effect of a certain force

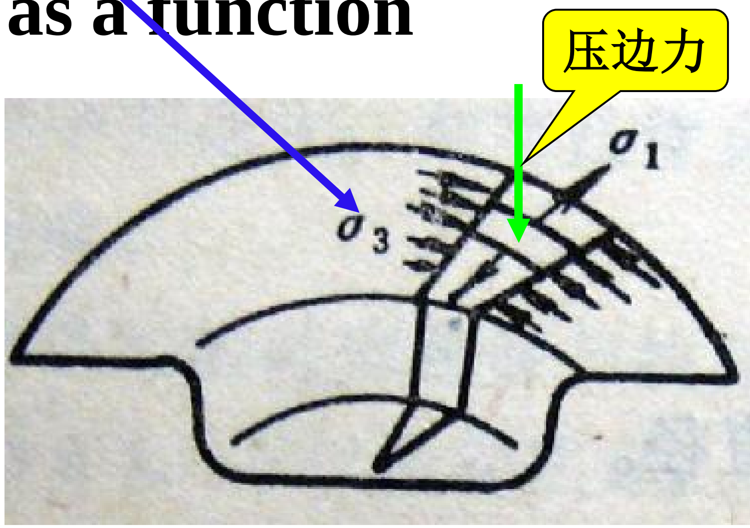
– in order to improve performance, the magnitude of this force can be controlled as a function of punch travel

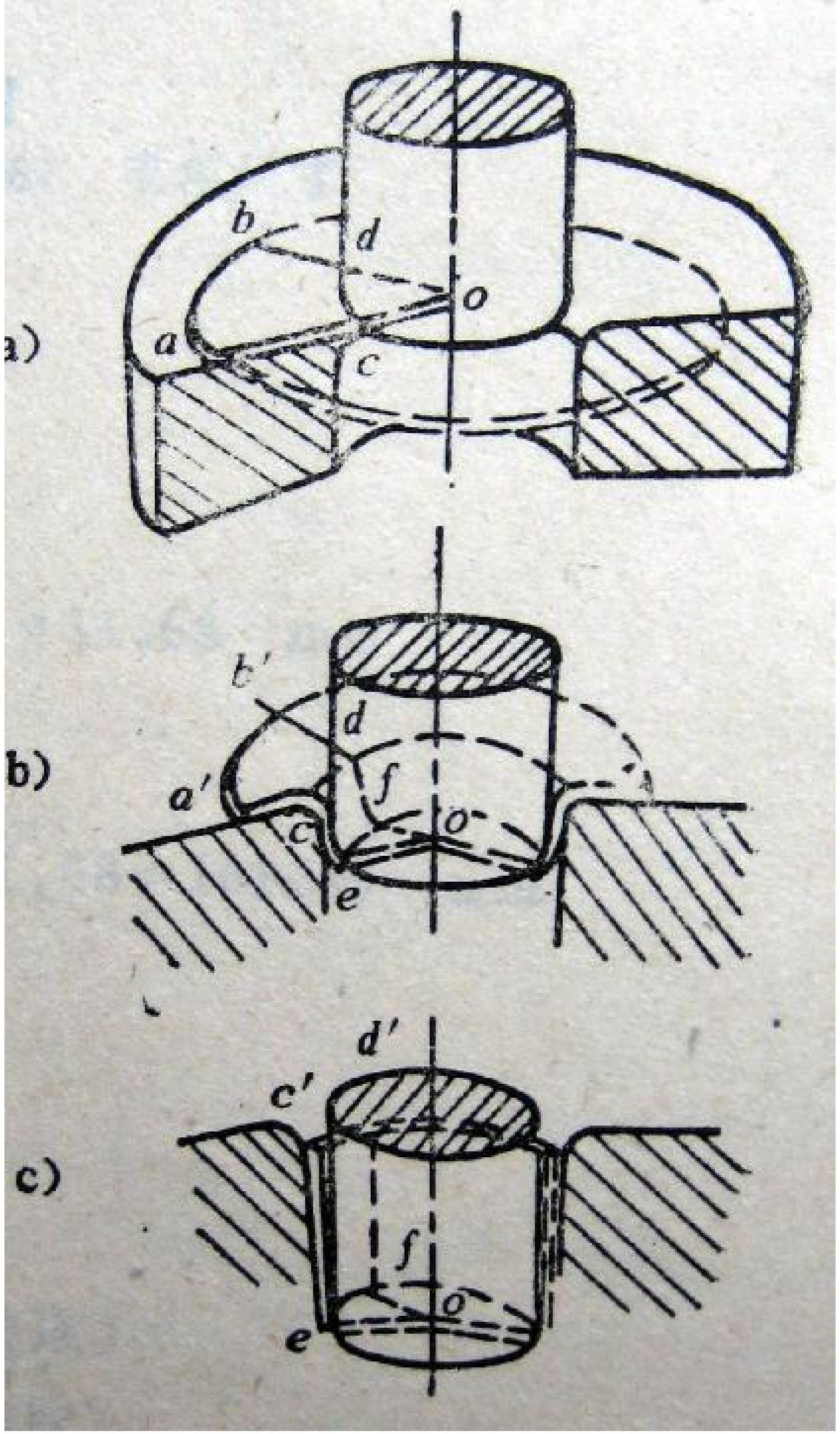
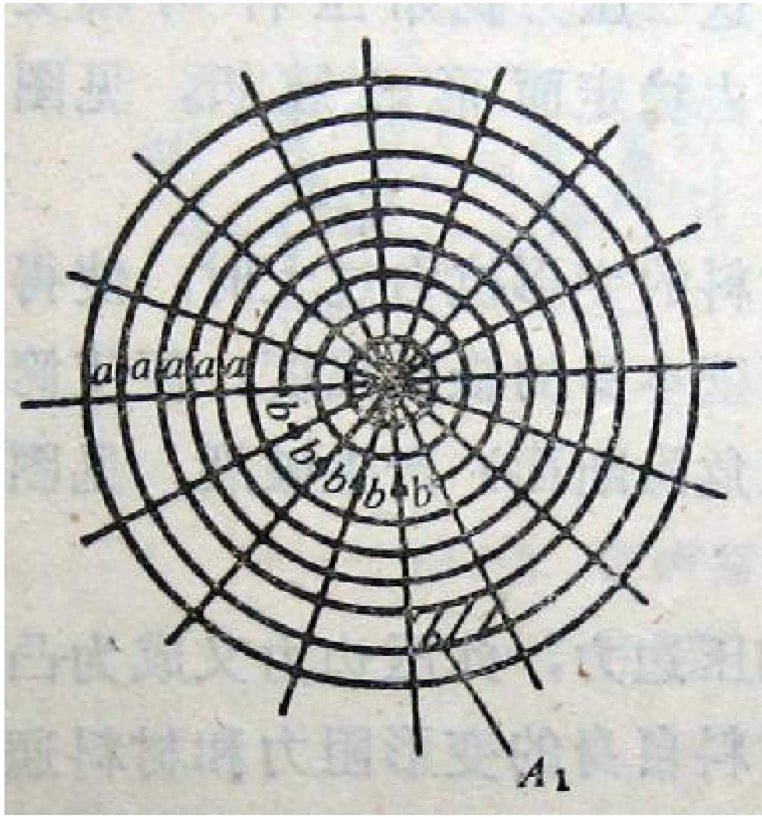
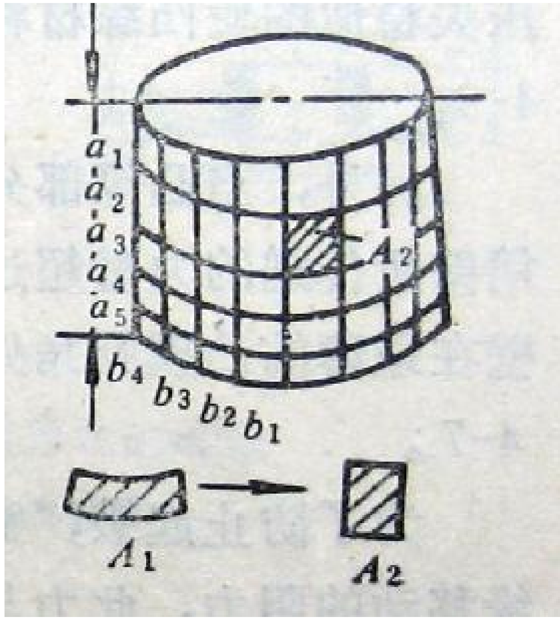


(a) 起皱现象



(b) 轻微起皱影响拉深件




a)
b
d
o
a
c
b)
b'
d
a'
f
c
o
e
c)
d'
c'
f
o
e

A_1

a_1
a_2
a_3
a_4
a_5
A_2
b_4 b_3 b_2 b_1
A_1
A_2

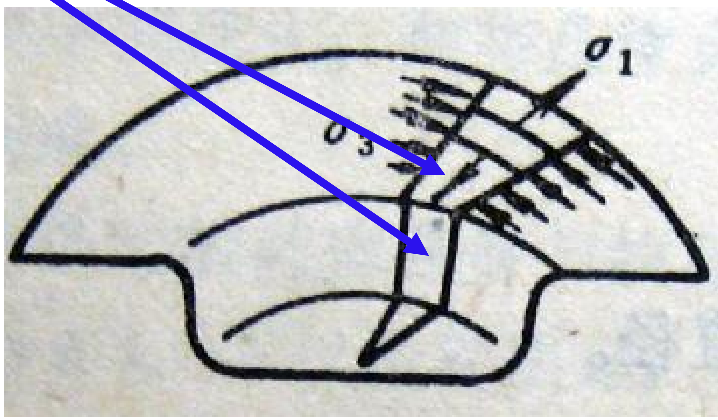
Defects in Deep-drawing

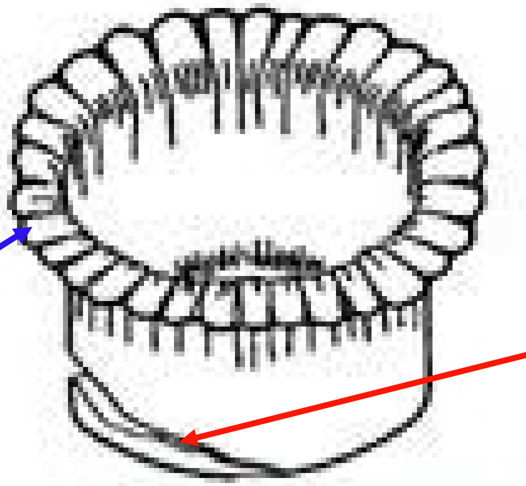
2. Tearing（拉裂/撕裂）

– the cup wall is subjected principally to a longitudinal tensile stress （纵向/轴向拉应力）

– elongation causes the cup wall to thin（变薄）

– if excessive, it causes tearing





(c) 严重起皱导致破裂

tearing at cup wall

wrinkle at flange

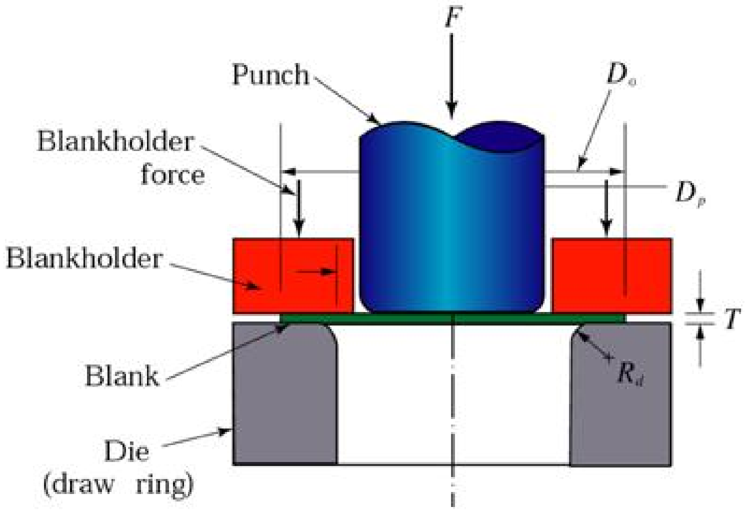
Defects in Deep-drawing

Guidelines for Deep Drawing Practice

① **blankholder pressure**
- **too low** → **wrinkle**
- **too high** → **tear**

② **clearance** **too small** → **tear**

③ **corner radius of punch and die**
- **too small** → **tear**
- **too large** → **wrinkle**



Methods to Avoid Tearing

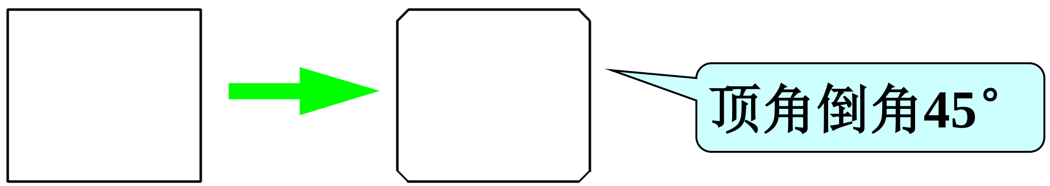
① Large die radii

② Effective lubrication

③ Proper design and location of draw beads（拉延筋）

④ Proper blank size and shape

⑤ Cutting off of corner of square or rectangular blanks at 45° to reduce tensile stresses during drawing



⑥ Using blanks free of internal and external defects

* Draw Beads（拉延筋）

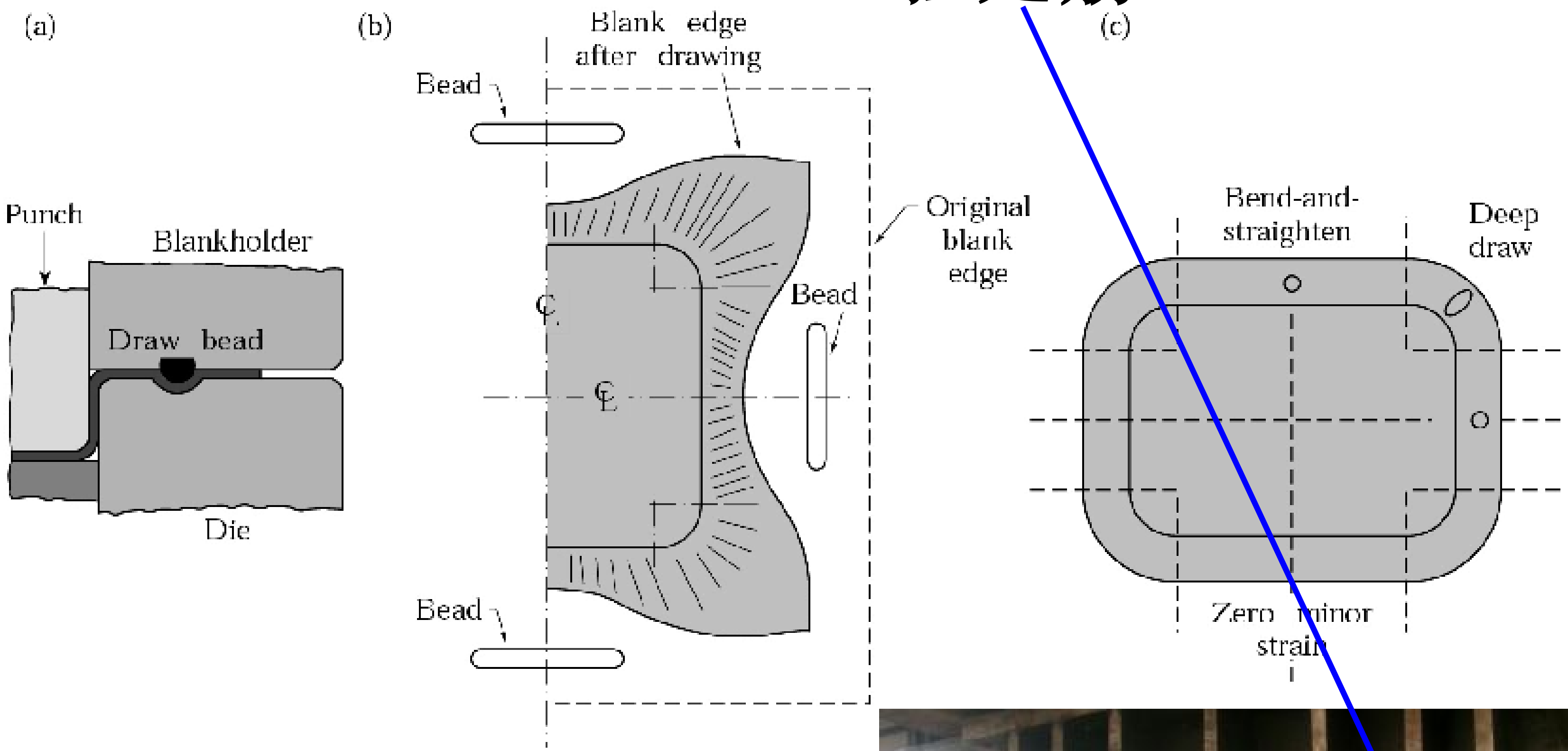


Figure 7.36 (a) Schematic illustration of a draw bead. (b) Metal flow during the drawing of a box- shaped part, while using beads to control the movement of the material. (c) Deformation of circular grids in the flange in deep drawing.

* 设置拉延筋的作用

板料在通过拉延筋时发生了弯曲、回复、反弯曲的反复变形，这些变形所需要的变形力加上板料与拉延筋之间的摩擦力构成了拉延筋的进料阻力

(1) 控制变形区材料的进料阻力，调节冲压变形区的拉力及其分布

(2) 通过对拉延筋各项参数的适当配置，能够通过均衡工件各部分的进料阻力来调节材料的流动情况，增加坯料流动的稳定性，得到变形均匀的冲压件;

(3) 使用拉延筋后，压料面间隙可适当加大，表面精度可适当降低，从而减少压料面的磨损，降低模具制造成本

(4) 通过增加径向拉应力，使材料的塑性变形程度、硬化程度得以提高，减少由于变形不足而产生的松弛回弹以及波纹等缺陷，

提高工件的刚度

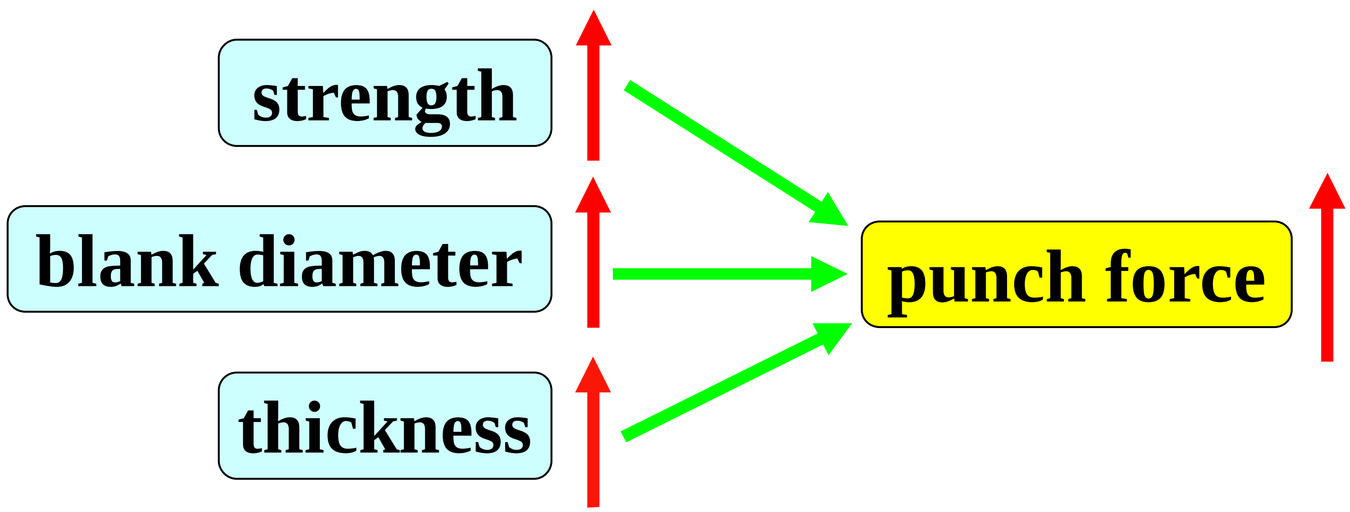
(5) 可防止因凸缘周边材料不均匀流动而不可避免产生的皱纹进入修边线内，减轻或消除复杂零件悬空部分因材料集中而发生的内皱现象

(6) 拉延筋提供的进料阻力，可以在一定程度上降低对压床吨位的需求;通过增加胀形成分和增大进料阻力，可减小板料外形尺寸，提高材料利用率。

* Punch Force（拉深力）

– Because of the many variables involved, the punch force, *F*, is **difficult to calculate**

– In general:



7.7.1 Deep Drawability（可拉深性）

- **Generally expressed by LDR （Limiting Drawing Ratio , *极限拉深比*）**

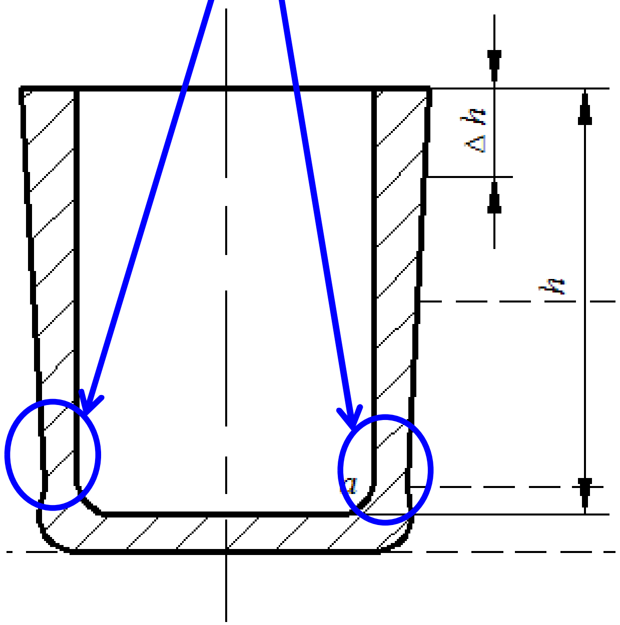
$$\mathrm{LDR} = \frac{\textit{Maximum blank diameter}}{\textit{Punch diameter}} = \frac{D_0}{D_p} > 1$$

thinning（变薄） of the cup wall under high longitudinal tensile stresses

LDR ↑ → **deep drawability** ↑

- **Determined by:**
  - **normal anisotropy, *R***

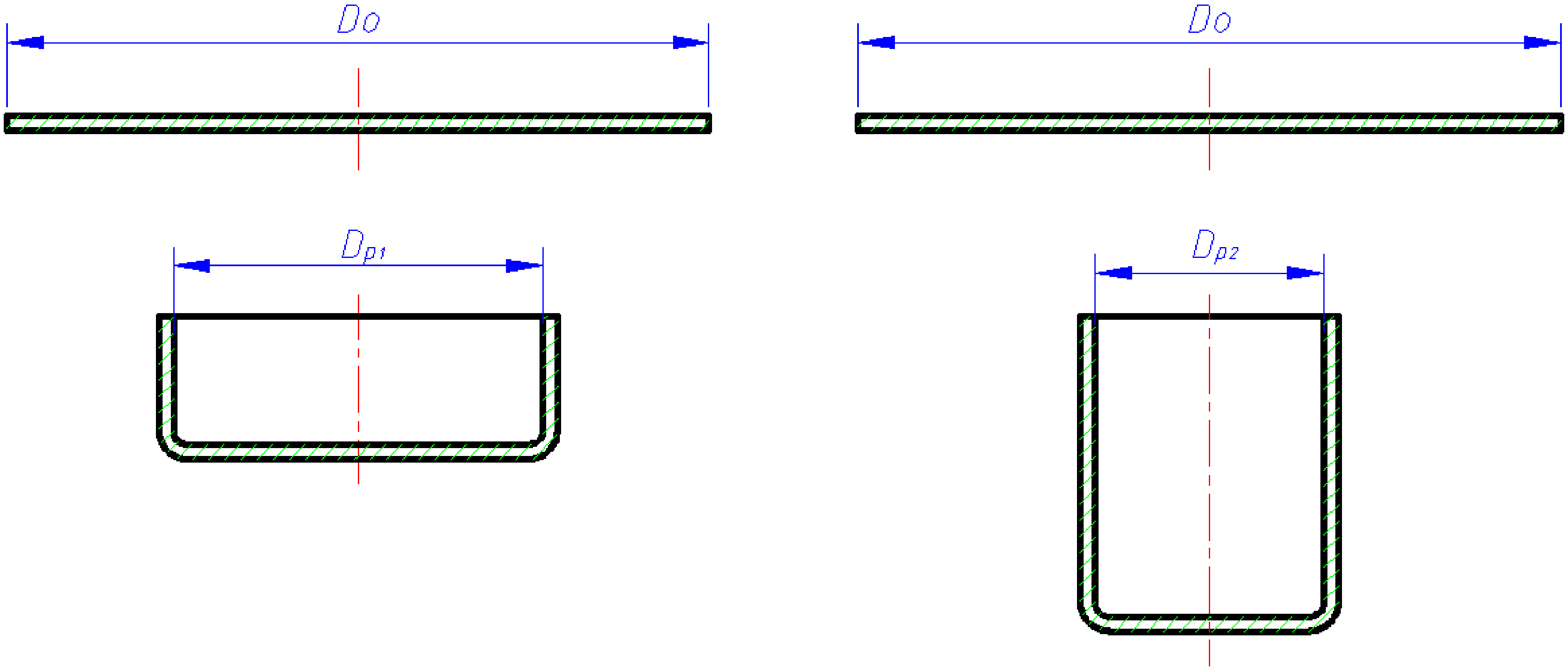
    (法向各向异性/厚向各向异性）



拉深件沿高度方向壁厚的变化

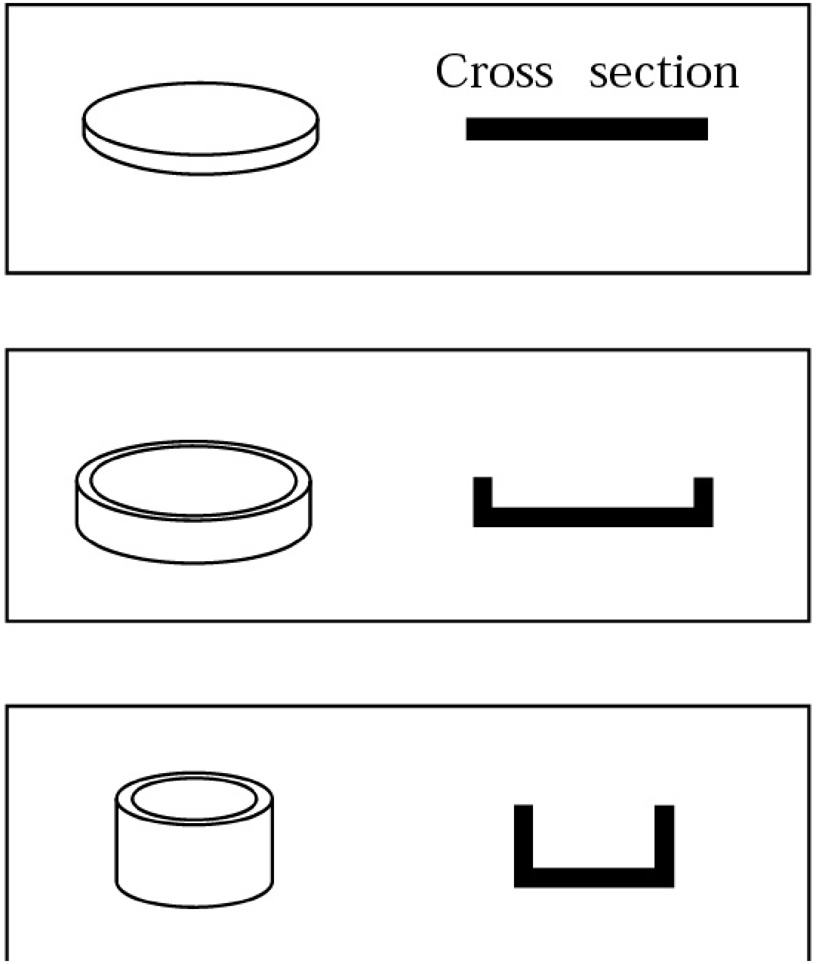
LDR

better deep drawability



$$LDR_1 = \frac{D_0}{D_{p1}} < LDR_2 = \frac{D_0}{D_{p2}}$$

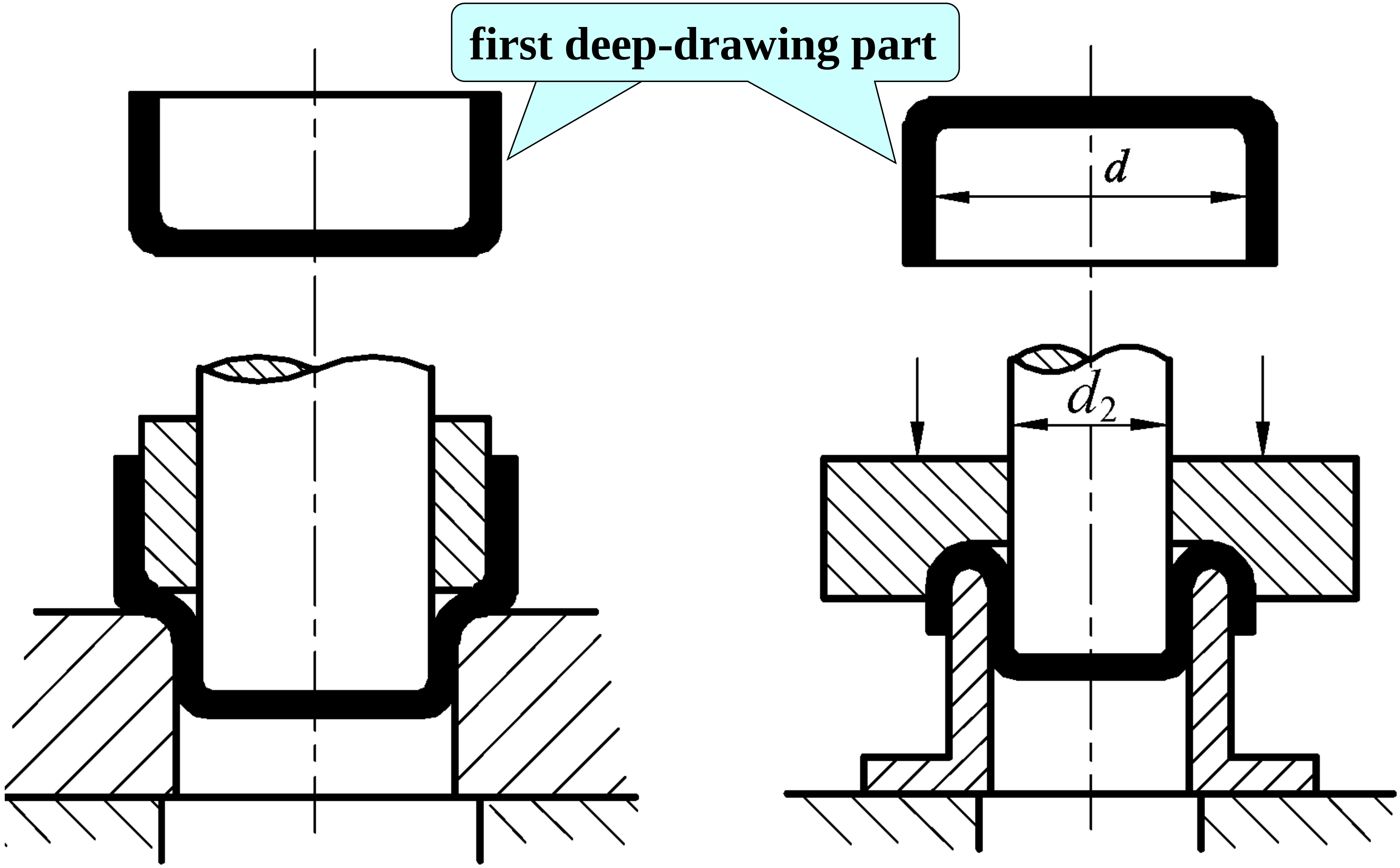
LDR



blanking

deep drawing

redrawing
（二次拉深）



(a) 正拉深 **redrawing**

(b) 反拉深 **reverse redrawing**

Normal Anisotropy
（法向/厚向各向异性）

- **Expressed in *R***

宽度应变

$$R = \frac{width\ strain}{thickness\ strain} = \frac{e_w}{e_t}$$

厚度应变

thinning（变薄）

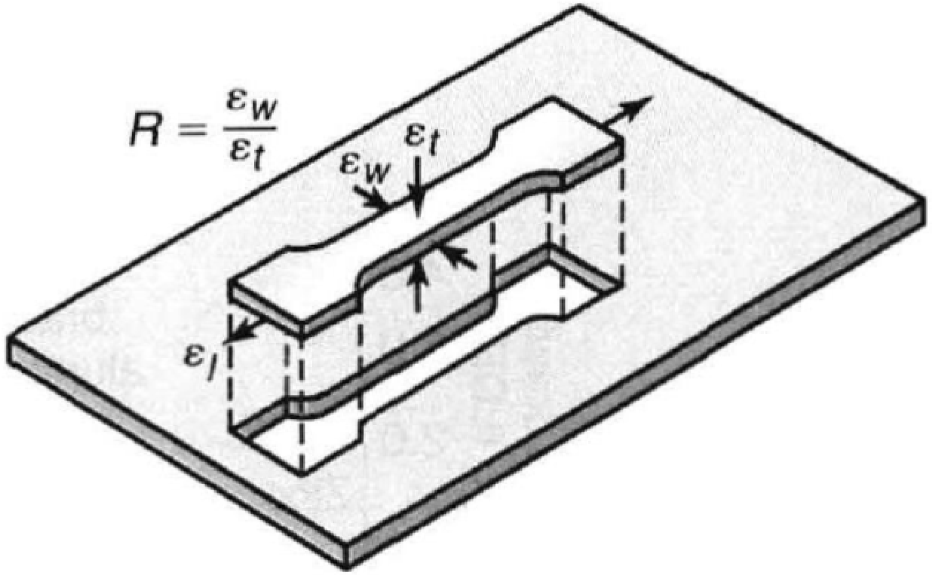


FIGURE 7.32 Strains on a tensile-test specimen removed from a piece of sheet metal. These strains are used in determining the normal and planar anisotropy of the sheet metal.

- **Also called plastic anisotropy**
  （塑性各向异性）

$e_t \downarrow$ → **R** $\uparrow$ → **difficulty to thinning** $\uparrow$ → **deep drawability** $\uparrow$

- **Because cold-rolled sheets generally have anisotropy in their planar direction（平面方向）, the *R* value of a specimen will depend on its orientation（方向/方位）**
- **In this case, a average value, R_{avg} （平均法向各向异性）, is necessary.**

$$R_{avg} = \frac{R_0 + 2R_{45} + R_{90}}{4}$$

the angles are relative to the rolling direction of the sheet

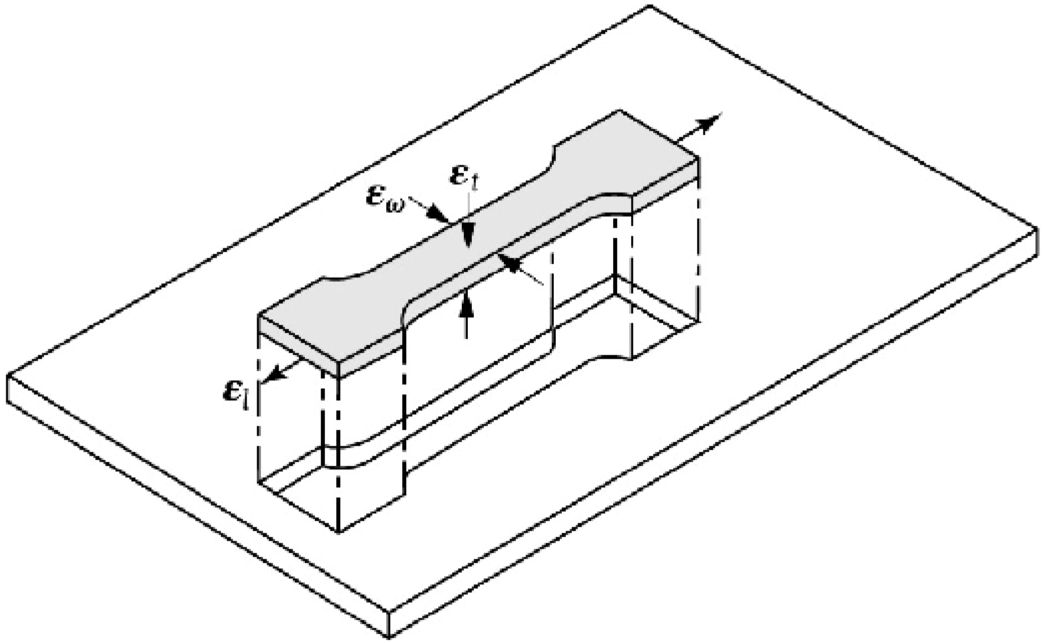


Figure 7.33 Strains on a tensile-test specimen removed from a piece of sheet metal. These strains are used in determining the normal and planar anisotropy of the sheet metal.

R_{avg} ↑ → LDR ↑ → deep drawability ↑

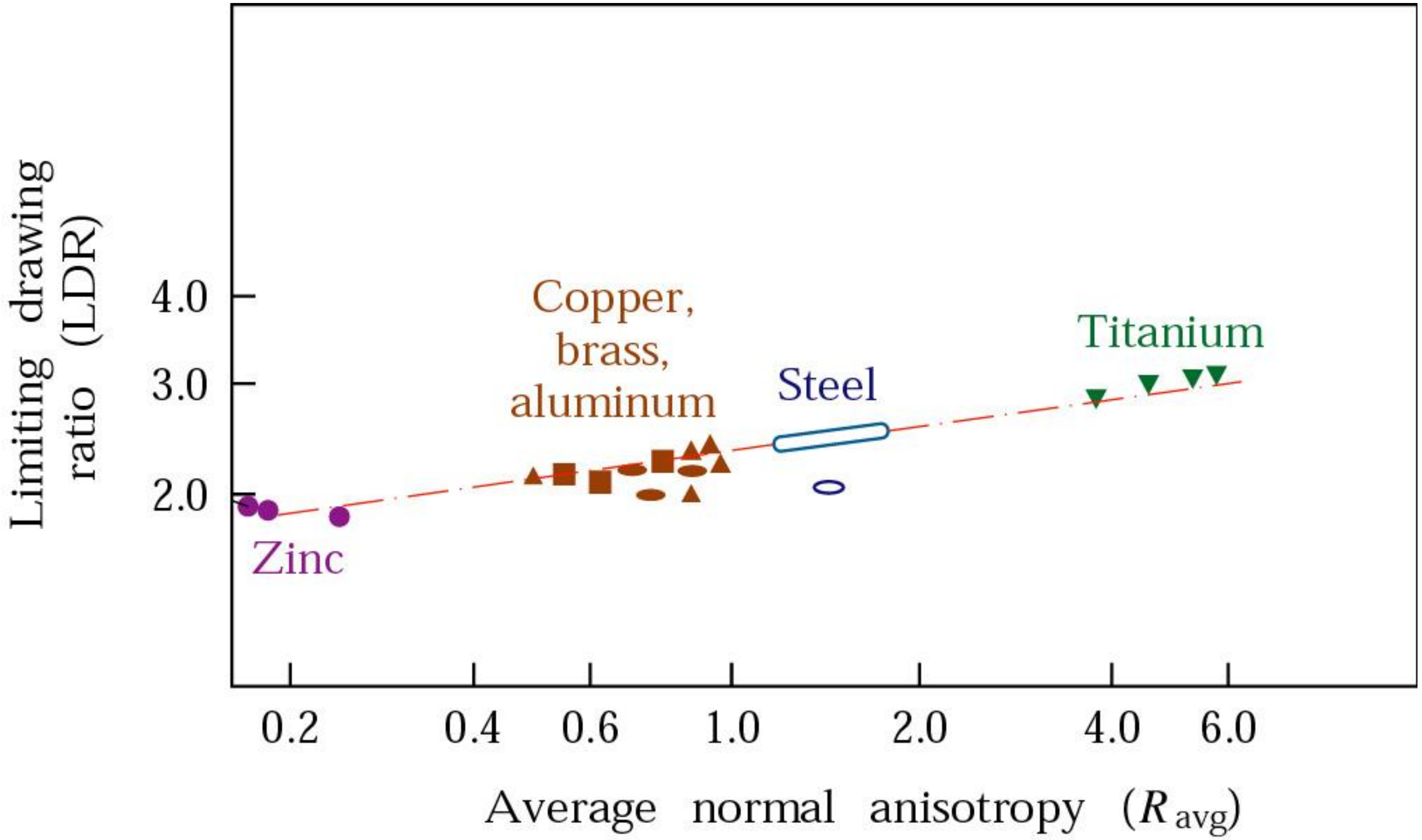


Figure 7.33 The experimentally determined relationship between average normal anisotropy and the limiting drawing ratio for various sheet metals. *Source*: M. Atkinson.

TABLE 7.4

Typical Ranges of Average Normal Anisotropy, R_{avg}, for Various Sheet Metals

锌合金	Zinc alloys	0.4–0.6
热轧钢	Hot-rolled steel	0.8–1.0
冷轧沸腾钢	Cold-rolled, rimmed steel	1.0–1.4
冷轧铝镇静钢	Cold-rolled, aluminum-killed steel	1.4–1.8
铝合金	Aluminum alloys	0.6–0.8
铜与黄铜	Copper and brass	0.6–0.9
*α*钛合金	Titanium alloys (α) — **best deep drawability**	3.0–5.0
不锈钢	Stainless steels	0.9–1.2
高强度低合金钢	High-strength, low-alloy steels	0.9–1.2

Defects in Deep-drawing

3. Earing （凸耳/制耳）

– a phenomenon（现象） that edges of deep-drawn cups become **wavy**

– number of ears may be 2, 4, 8.

– is a **defect** on deep-drawn parts, and have to be **trimmed off**

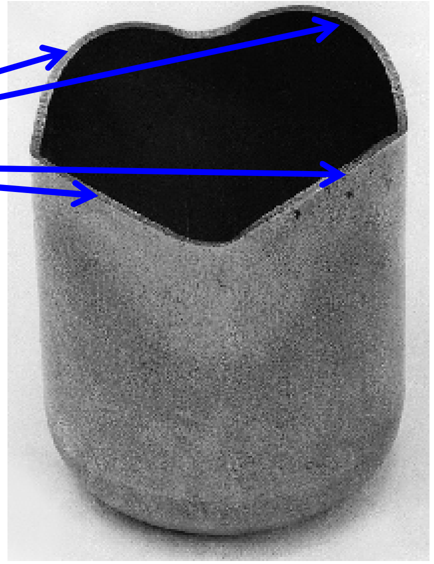


Figure 7.45 Earing in a drawn steel cup, caused by the planar anisotropy of the sheet metal.

- Earing is caused by **planar anisotropy** （平面各向异性）, ΔR

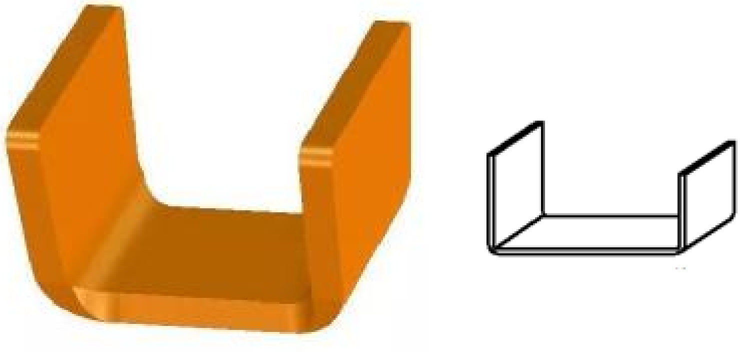
$$\Delta R = \frac{R_0 - 2R_{45} + R_{90}}{2}$$

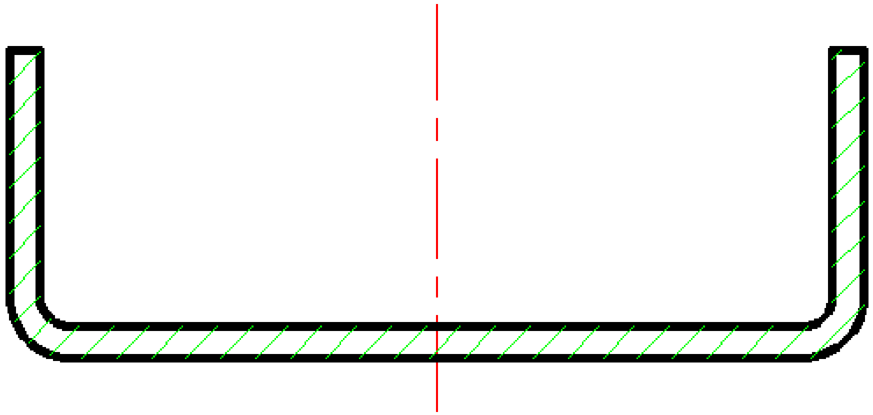
- $\Delta R = 0$, no ears form — isotropy（各向同性）

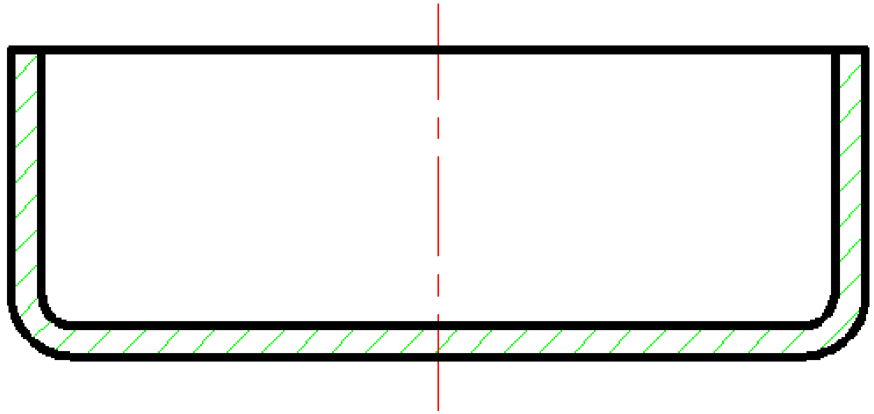
$\Delta R \uparrow$ → height of ears $\uparrow$ → deep drawability $\downarrow$

- **It can be seen that deep drawability is enhanced by high R_{avg} and a low ΔR.**
- **generally, however, sheet metals with high R_{avg} also have high ΔR.**
- **Sheet-metal textures**（*变形织构/各向异性*）**are being developed to improve drawability：**
  - **control the type of alloying elements in the material**
  - **control various processing parameters, during rolling of the sheet.**

Two Sheet-metal Parts







U形弯曲件

筒形拉深件

7.14 Equipment For Sheet-Metal Forming

- **For most general pressworking（*压力加工*） or press forming（*压力成形*） operations, the basic equipment consists of mechanical, hydraulic, pneumatic（*气动的/气压的*）, or pneumatic-hydraulic presses（*压力机/冲床*） with a wide variety of designs, features, capacities, and computer controls.**

- **The proper design, stiffness, and construction of such equipment is essential to the efficient operation of the system and to achieving a high production rate, good dimensional control, and high product quality.**

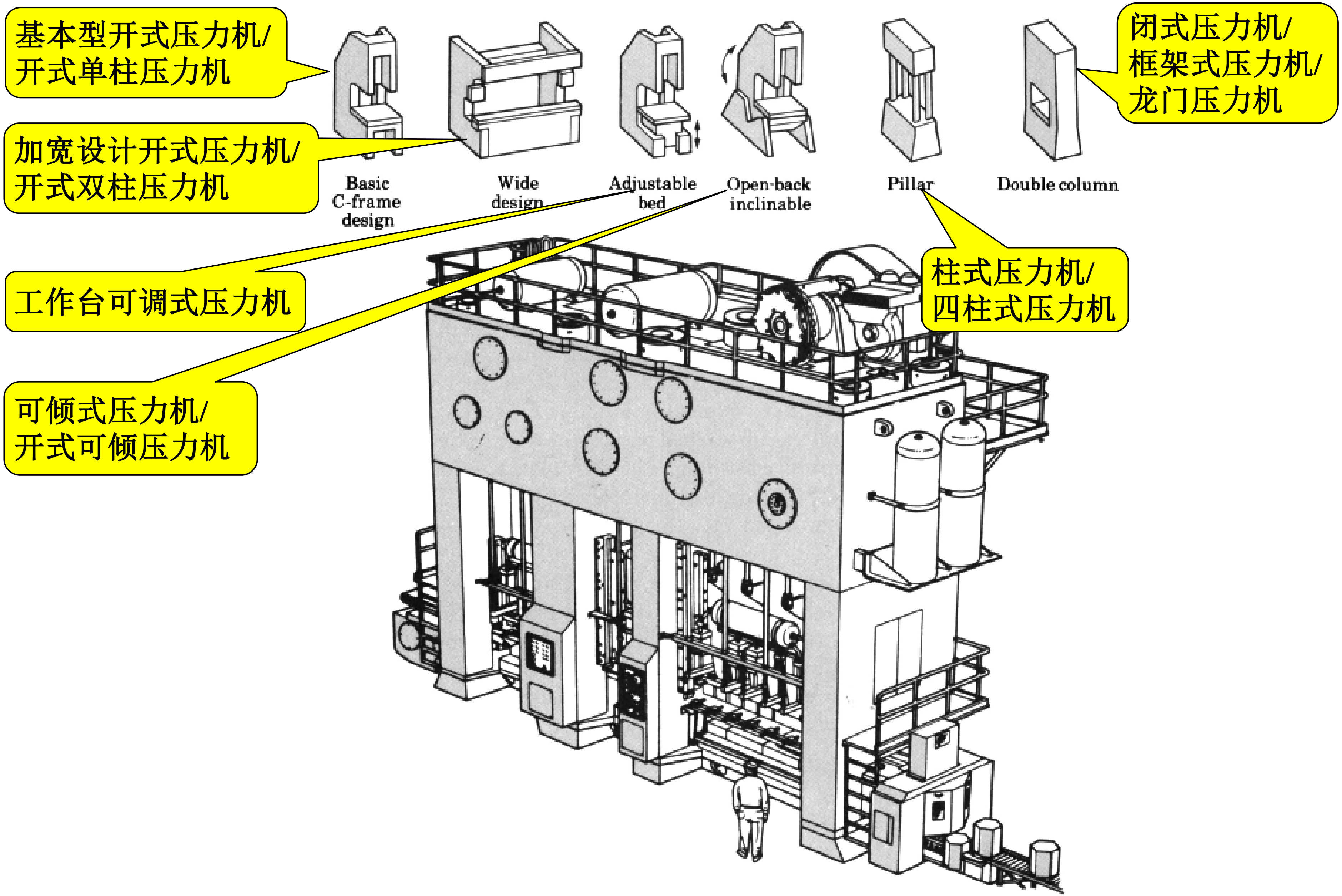


Figure 7.60 Schematic illustration of types of press frames（压力机机身） for sheet- forming operations. Each type has its own characteristics of stiffness, capacity, and accessibility. *Source*: *Engineer's Handbook*, VEB Fachbuchverlag, 1965. (c) A large stamping press. *Source*: Verson Allsteel Company.


CAF-45H


WORLD GROUP


XPS

KEY TERMS

sheet-metal forming- 金属板材成形

forming process- 成形工艺

shearing deformation- 冲裁成形，剪切成形

plastic deformation- 塑性成形

crack- 裂纹

sheared edges- 剪切边

rollover depth - 圆角带

burnish depth- 光亮带

fracture depth- 断裂带

slug- 废料

punch- 冲孔，凸模

clearances- 间隙

burr- 毛刺

punch speed- 冲模速度

punch force- 冲裁力

blanking- 落料

punching- 冲孔

single die- 简单模

compound die- 复合模

progressive die- 级进模

bendability 可弯曲性

bend allowance 弯曲中性层弧长

bending 弯曲

blankholder 压边圈

burnished surface 磨（抛，挤）光面

burr 毛刺，毛口

clearance （冲裁凸、凹模之间的）间隙

compound dies 复合模

deburring 去毛刺，清理毛口

deep drawing 深拉，深冲，拉延

drawbead 拉延筋

earing 凸耳，形成花边

flanging 折边，翻边

formability 可成形性

forming-limit diagram 成形极限图

hemming 折边，卷边

honeycomb process 蜂窝结构成形工艺

ironing 挤拉，变薄拉深

laser forming 激光成形

limiting drawing ratio 极限拉深比

lueder's bands 吕德斯带，滑移带

magnetic-pulse forming 磁脉冲成形

nesting 嵌套

nibbling 步冲，分段冲裁

normal anisotropy 法向异性

peen forming 锤击成形

planar anisotropy 平面各向异性

plastic anisotropy 塑性各向异性

press brake 弯板机

progressive dies 级进模，连续模

punching 冲孔

redrawing 二次拉深，再拉深

Planar anisotropy 平面各向异性

Plastic anisotropy 塑性各向异性

Press brake 弯板机

Progressive dies 级进模，连续模

Punching 冲孔

Redrawing 二次拉深，再拉深

roll forming 轧制成形

rubber forming 橡胶成形

shaving 修整，精整

shearing 冲裁，剪切

spinning 旋压

springback 回弹，弹复

steel rule 钢尺

stretch forming 拉伸成形

superplastic forming 超塑性成形

tailor-welded blanks 焊接坯料

transfer dies 传送模

wrinking 起皱

Review Questions

1. What are the advantages of sheet metal parts ?
2. What is the shearing ?
3. List the three phases in shearing process.
4. Describe the characteristics of sheared edges.
5. How does separation occur in shearing?
6. Describe the major process parameters in shearing.
7. What is the clearance ?
8. How to decide the appropriate clearance ?
9. What is burr ?
10. What is the difference between punching and blanking ?

11. What is the difference between single die, compound die, progressive die and transfer dies ?

12. List the characteristics of sheet metal that are important in sheet-forming operations.

13.What are the two basic modes of deformation that sheet metals may undergo ?

14. What is bend allowance and neutral axis?

15. What is bendability? How to improve the bendability of the sheet-metal?

16. What is the springback in bending ? What is the result of springback in bending ?

17. What are the major process problems in deep-drawing?

18. How to reduce or eliminate wrinkle and tearing ?

19. How to express drawability?

20. What is normal anisotropy? What is planar anisotropy?