Chapter 5 Metal-Forging Processes and Equipment
（金属锻造/锻压工艺及设备）

- 5.1 Introduction
- 5.2 Open-Die Forging
- 5.3 Impression-Die and Closed-Die Forging
- 5.4 Various Forging Operations
- 5.5 Forgeability of Metals; Forging Defects
- 5.6 Die Design, Die Materials and Lubrication
- 5.7 Die Manufacturing Methods and Die Failures
- 5.8 Forging Machines
- 5.9 The Economics of Forging

Preface（前言）:

- **This chapter describes the fundamentals of forging and related processes, including design and economic considerations.**
- **Open-die forging operations for producing simple shapes are discussed first, followed by impression-die and closed-die forging operations for producing more intricated shapes.**
- **Various forging operations, such as heading, piercing, coining, swaging, and cold extrusion, are then introduced.**
- **Factors involved in forging defects and die failures are explained.**
- **The economics of forging, as it relates to process selection, is also discussed.**
- **The chapter ends with a review of the design of forged parts, die design and manufacturing, and selection of die materials and lubricants in forging operations.**

Typical products made by forging and related processes: Shafts, gears, bolts, turbine blades, hand tools, dies, and components for machinery, transportations, and farm equipment.

Alternative processes: Casting, powder metallurgy, machining, and fabrication.

5.1 Introduction

Outline

- **Important factors:**
  - process
  - products:
    - discrete（*离散的/独立的*） parts
- **Characteristics of forged part**
- **Classification:**
  - by temperature:
    - hot forging（*热锻*）
    - warm forging（*温锻*）
    - cold forging（*冷锻*）
  - by tools:
    - open-die forging（*自由锻造*） § 5.2
    - impression-die forging（*模锻*）
    - closed-die forging（*闭式模锻/闭模锻造*）
    - precision forging （*精密锻造*）

§ 5.3

- **Forging（锻造/锻压）**
  - A **workpiece is shaped (formed)** by **compressive forces** applied through various **dies**（模具） and **tooling**（工具）.

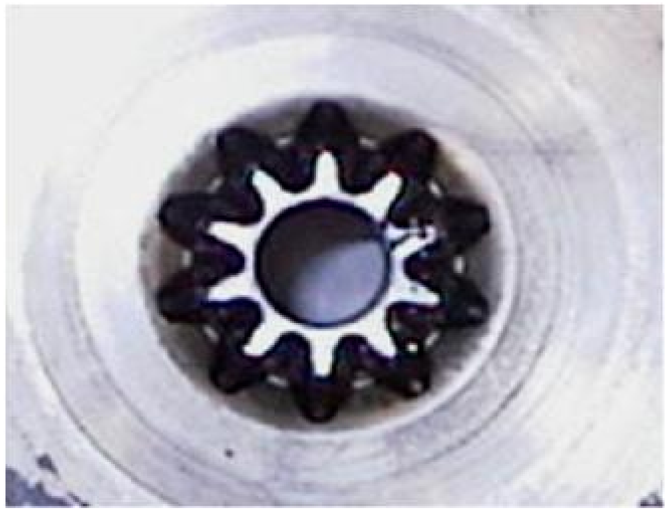
Ø one of the **oldest** metal working processes – 4000bc

Ø traditionally be performed with a heavy **hammer**（锤） and **anvil** （砧/平砧）by blacksmith

Ø mostly require a set of **dies** and such **equipment** as a **press**（压力机） or a **forging hammer**（锻锤/锤锻机）

discrete （离散的/独立的）parts

- **Typical forged products:**
  - large rotors for turbines（*涡轮机转子*）
  - bolts（*螺栓*）
  - rivets（*铆钉*）
  - cutlery（*刀具*）
  - connecting rods（*连杆*）
  - gears（*齿轮*）
  - shafts （*轴*）
  - hand tools（*手工具*）
  - structural components （*结构组件*）



Forging（锻件）

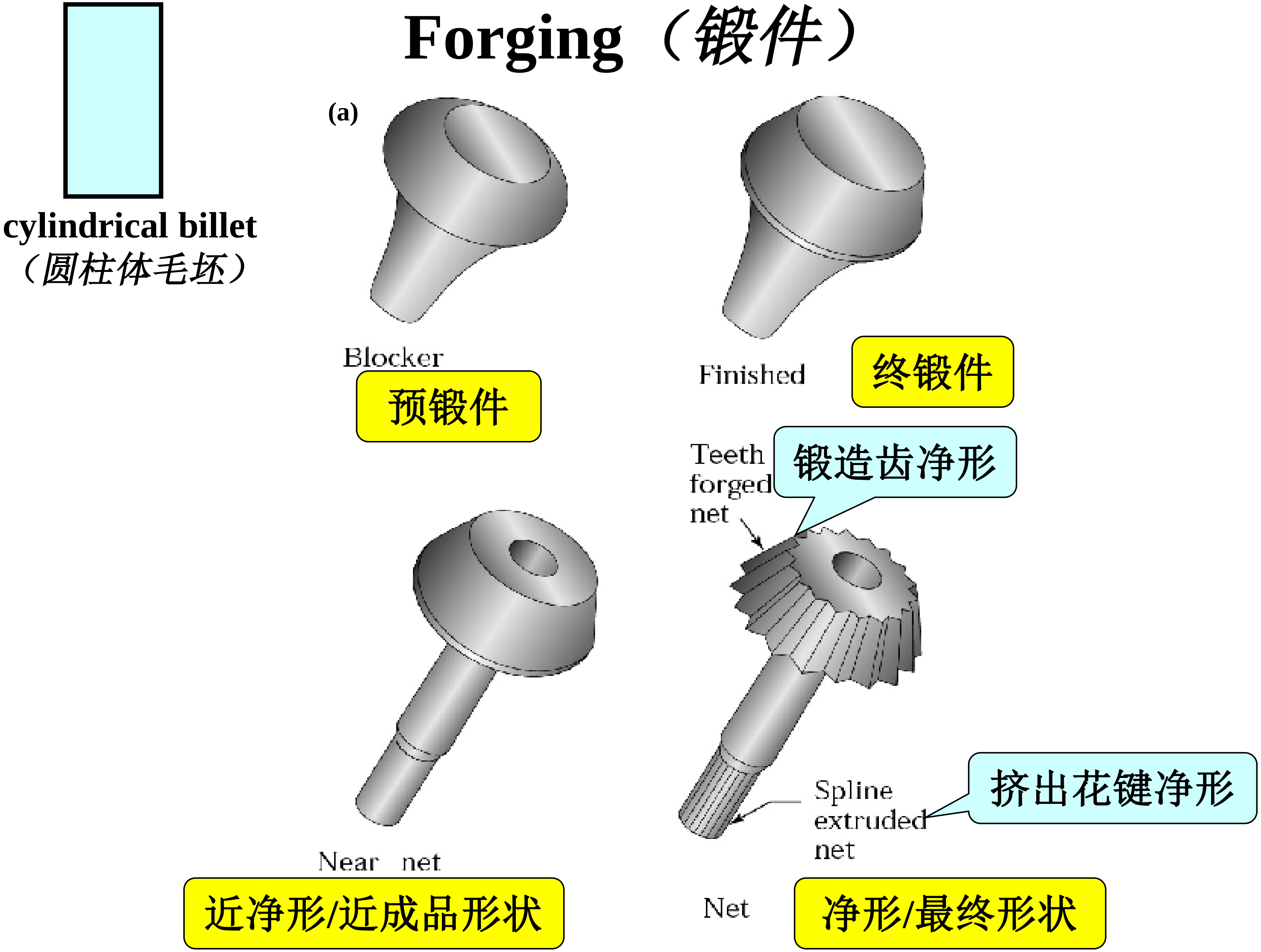
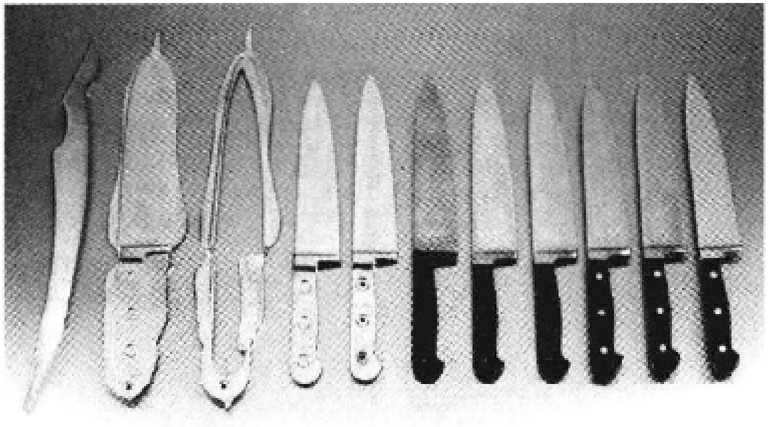


Figure 5.1 (a) Schematic illustration of the steps involved in forging a bevel gear with a shaft. ***Source*****: Forging Industry Association.** （带轴伞齿轮）

Forging（锻件）



(a)

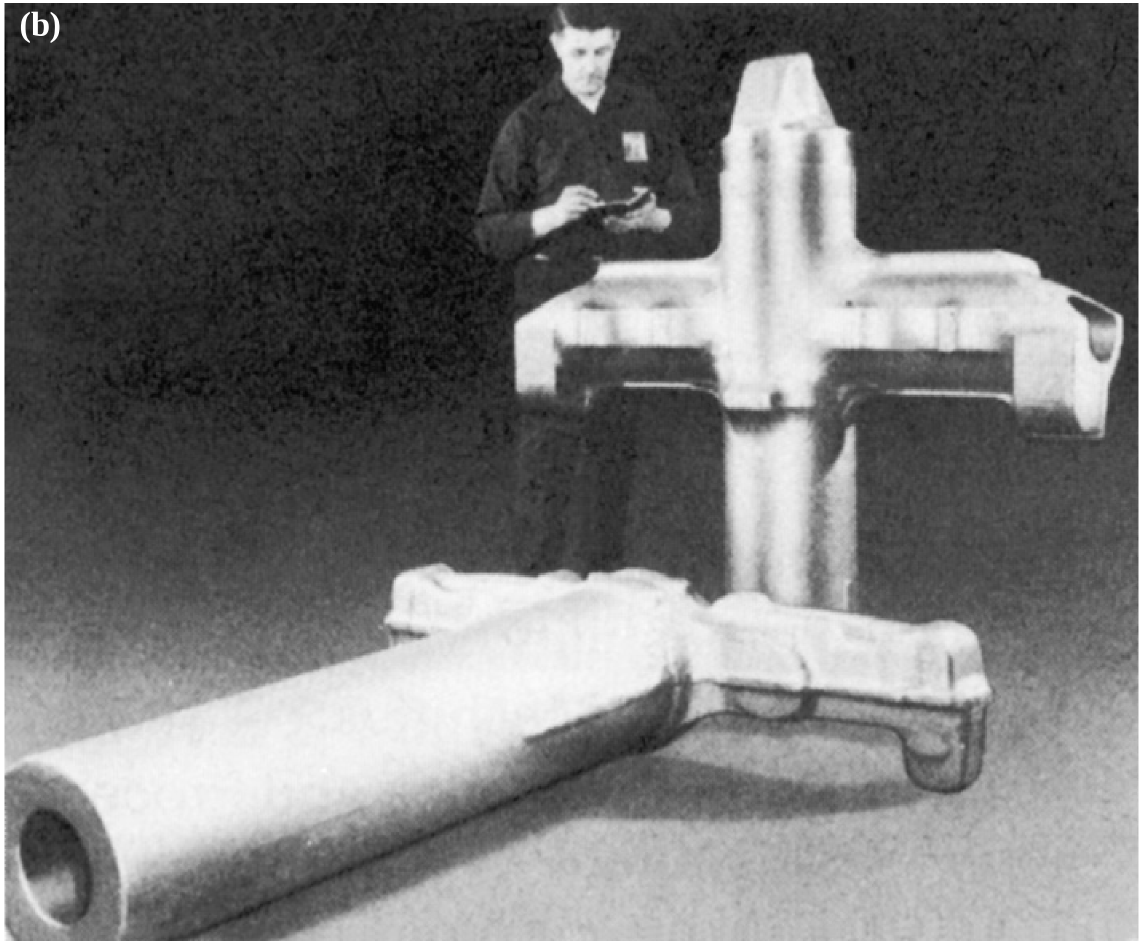


Figure 5.1 (a) Illustration of the steps involved in forging a knife. (b) Landing-gear*（起落架/着陆装置）*
components for the C5A and C5B transport aircraft, made by forging. ***Source*****: Wyman-Gordon Company.**

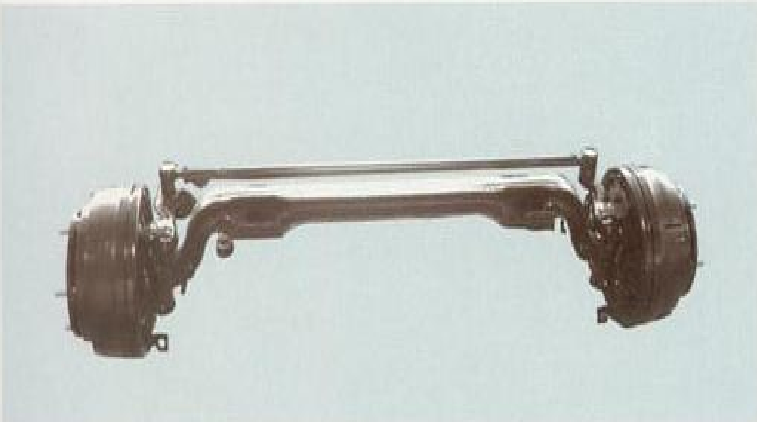
Typical Forged Parts

变速箱总成
Gear-Box Assembly

中间轴
Counter Shaft

二轴
Secondary Shaft

车桥机加产品
Machined Axle Parts



车桥总成
Axle Assembly

转向节
Knuckle

半轴套管
End tube

Hydraulic Press（液压机）

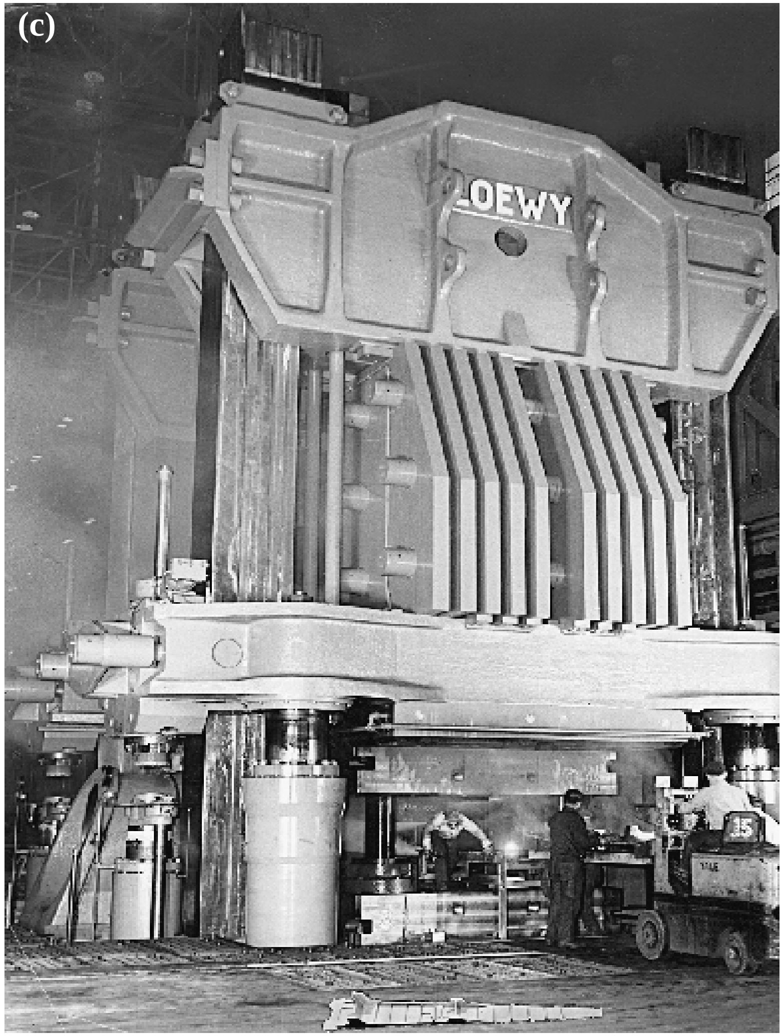
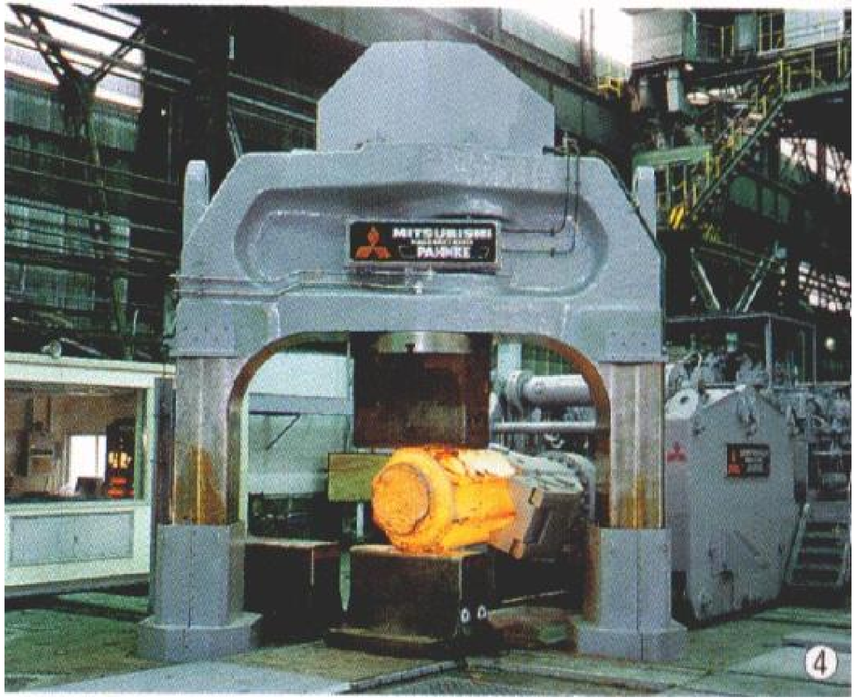


Figure 5.1 (c) general view of a 445 MN (50,000 ton) hydraulic press. *Source*: Wyman-Gordon Company.

Forging Hammer（锤锻机）

Forging Process
（锻压/锻造工艺）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锻造在制坯中的应用

- 一般机器或机械上的金属零件的传统生产过程是：

  冶炼——制坯——切削加工——热处理。

- 制坯是为切削加工零件提供毛坯的。
- 制坯的方法通常有三种：铸造、轧制和锻造。
- 铸造坯料结构具有很多缺陷，轧制只能生产截面简单的型材。
- 因此，机械制造业中，重要的机械零件，如齿轮、轴、汽车万向节、摇臂、前叉、前桥、连杆等，凡是受力恶劣且性能要求高的零件都是用锻造方法加工毛坯的。

Grain Flow Comparison

- **Characteristics of forged part:**
  - **metal flow and grain structure can be controlled**
  - **have good strength and toughness*（强度与刚度）*；**
  - **can be used reliably for highly stressed*（高应力）* and critical*（关键的）* applications.**

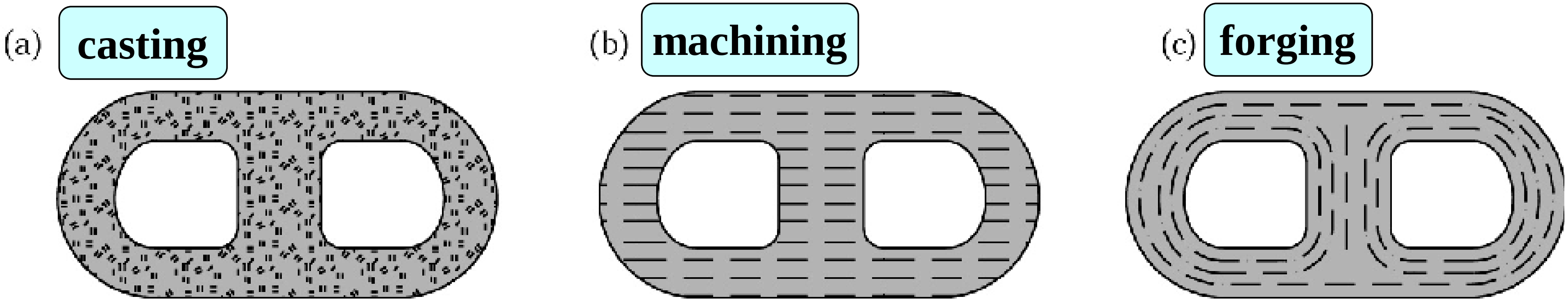


Figure 5.2 A part made by three different processes, showing grain flow. (a) casting, (b) machining, (c) forging. *Source*: Forging Industry Association.

比较：

- 铸造件(Casting)有不可避免的缺陷，如晶粒粗大、结构疏松、具有多孔，其组织和性能均较差。
- 切削件(Machining)的内部晶粒大小和结构不改变，且其金属纤维组织被切断了，使得零件强度下降。
- 锻造件(Forging)经受了塑性变形和再结晶，粗大的树枝状结晶组织被破碎，疏松和孔隙被压实、焊合，内部组织和性能都得到了提高。

Outline of Forging and Related Operations

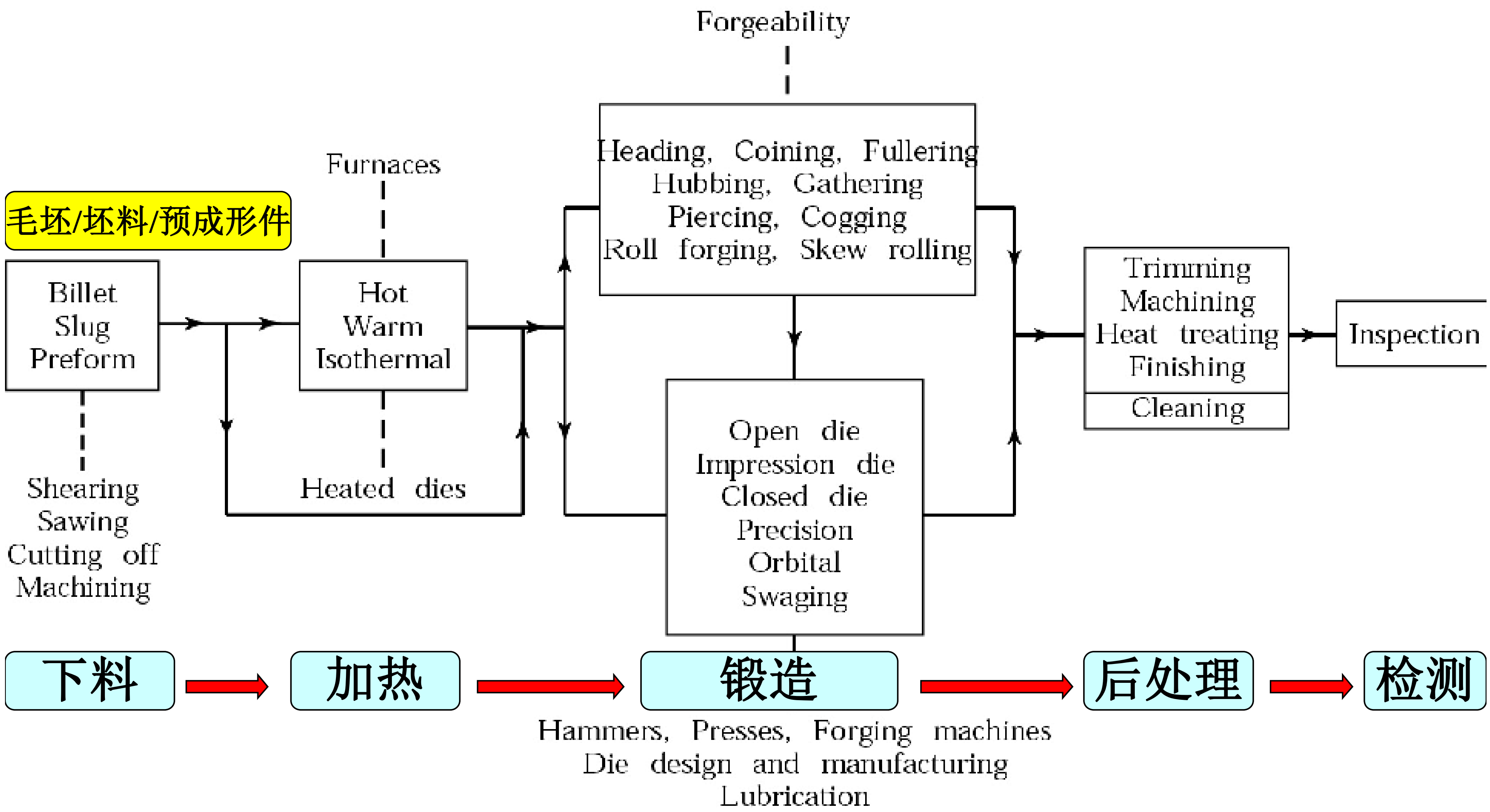


Figure 5.2

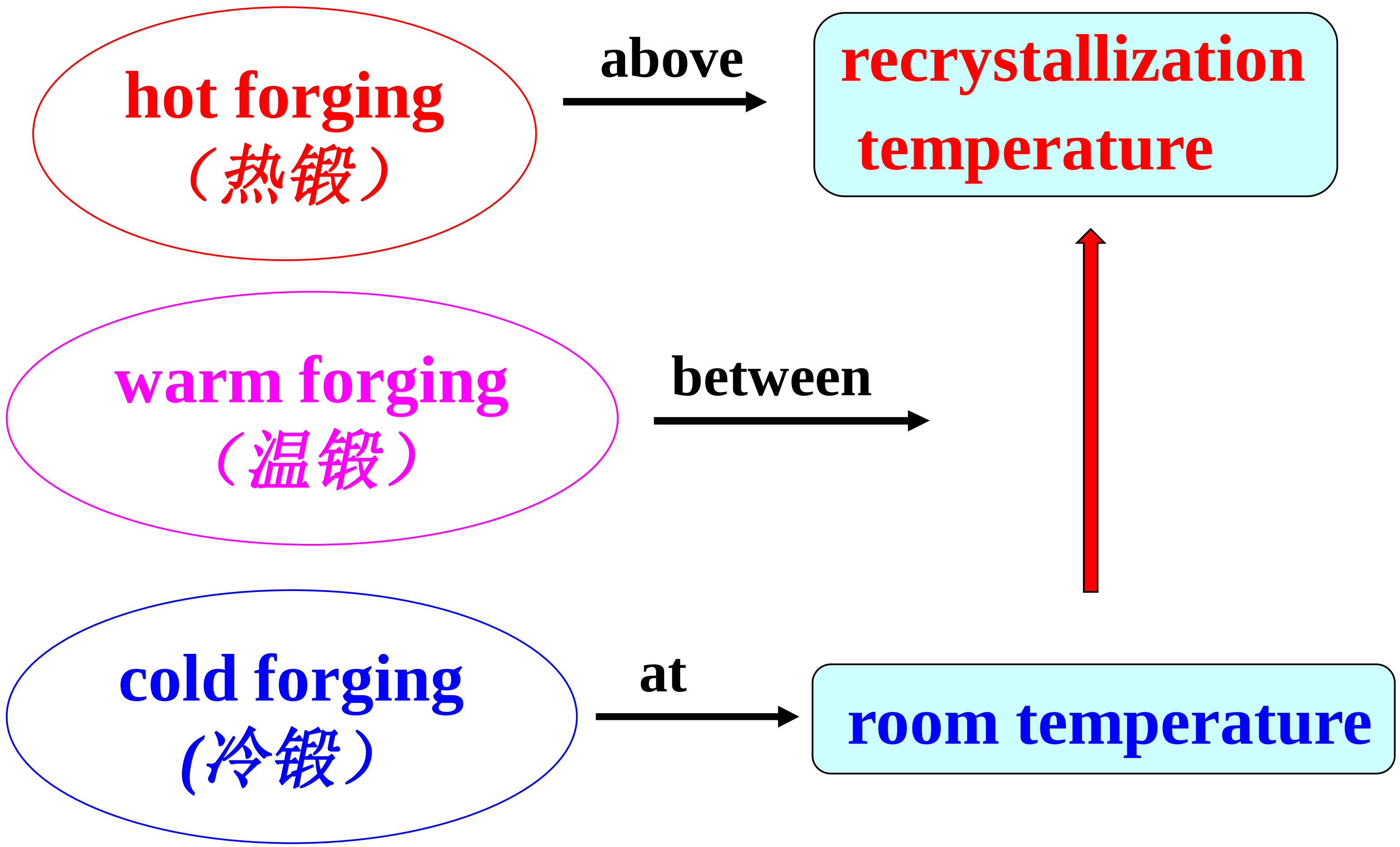
Characteristics of Forging Processes

TABLE 14.1

Process	Advantages	Limitations
Open die	Simple, inexpensive dies; useful for small quantities; wide range of sizes available; good strength characteristics	Limited to simple shapes; difficult to hold close tolerances; machining to final shape necessary; low production rate; relatively poor utilization of material; high degree of skill required
Closed die	Relatively good utilization of material; generally better properties than open-die forgings; good dimensional accuracy; high production rates; good reproducibility	High die cost for small quantities; machining often necessary
Blocker type	Low die costs; high production rates	Machining to final shape necessary; thick webs and large fillets necessary
Conventional type	Requires much less machining than blocker type; high production rates; good utilization of material	Somewhat higher die cost than blocker type
Precision type	Close tolerances; machining often unnecessary; very good material utilization; very thin webs and flanges possible	Requires high forces, intricate dies, and provision for removing forging from dies

Classification of Forging

a. By temperature



- “Forging can be carried out at room temperature (*cold forging*) or at elevated temperature (*warm* or *hot* forging) depending on the homologous（*相应的*）temperature.”

Comparison of Cold Forging to Hot Forging

- **Cold forging:**
  - good dimensional accuracy
  - good surface finish
  - enhanced mechanical properties
  - requires greater forces
  - workpiece materials must have sufficient ductility

- **Hot forging:**
  - requires smaller forces
  - poor dimensional tolerance
  - rough surface finish

Classification of Forging

b. By tools

- **Open-Die Forging**（*自由锻造*）
- **Impression-Die Forging**（*模锻*）
- **Closed-Die Forging**（*闭式模锻/闭模锻造*）
- **Precision Forging** （*精密锻造*）

- Forgings（*锻件*） generally require additional finishing operations（*精加工工序*）:
  - heat treating to modify properties
  - machining to obtain accurate finished dimensions and good surface finish
- These additional operations can be minimized by precision forging（*精密锻造*）
  - a important example net-shape or near-net shape forming processes（*净成形或近净成形工艺*）
  - can reduce the number of operations required
  - reduce the manufacturing cost

- **Production methods of a component:**
  - by **forging**
  - by **casting**
  - by **powder metallurgy***（粉末冶金）*
  - by **machining***（机加工/切削加工）*
- **Production process used for a component is decided by:**
  - **economical requirement**
  - **properties requirement**
    - **strength** *（强度）*
    - **toughness** *（刚度/韧性）*
    - **dimensional accuracy** *（尺寸精度）*
    - **surface finish** *（表面光洁度）*
    - **internal or external defects** *（内部或外部缺陷）*

5.2 Open-Die Forging（*开模锻造/自由锻*）

Outline

- **Characteristics of open-die forging**
- **Two types of open-die forging:**
  - **upsetting（*镦粗*）**
    - basic concept
    - barreling（*鼓形*） in upsetting: reasons and solutions
  - **cogging（*拔长*）**
    - basic concept
    - advantages
- **Forging Force**

Open-Die Forging（*开模锻造*）

- the simplest forging process
- also called free forging（*自由锻*）
- forgings generally weigh 15 to 500kg (can make forgings as heavy as 275 metric tons)
- part sizes can vary from very small to very large

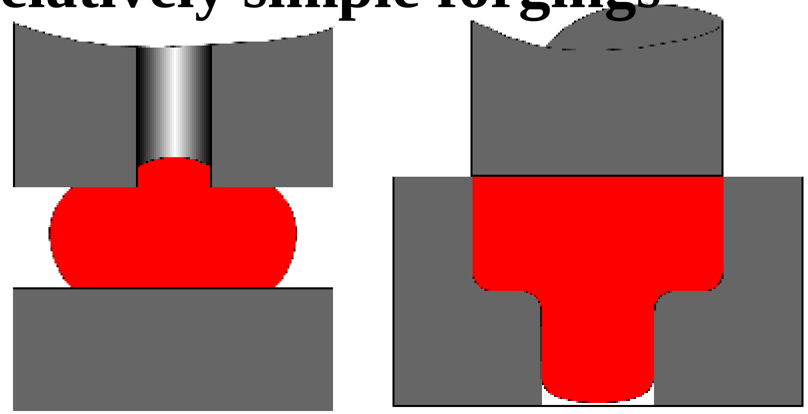
nails, pins, bolts

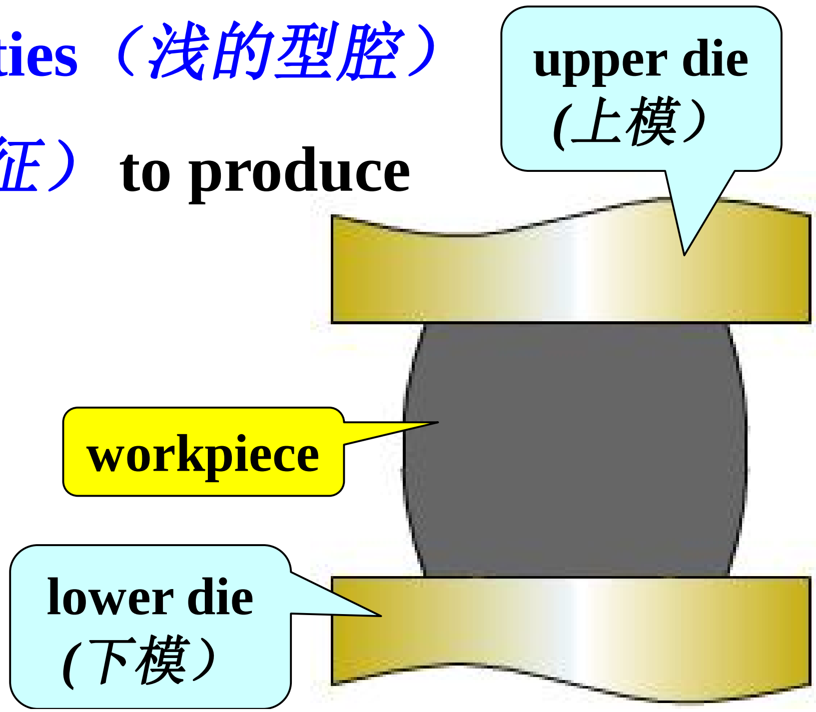
long shafts for ship propellers（*螺旋桨*）

5.2.1 Upsetting（镦粗）

– a solid（实心的）workpiece placed between **two flat dies** and **reduced in height** by **compressing** it.

- also called **flat-die forging**（平模锻造）
- **reduction in height increases the diameter** of the forged part
- die surfaces may have **shallow cavities**（浅的型腔）or **incorporate features**（合并的特征）to produce relatively simple forgings





Barreling in Upsetting

Reasons & Solutions:

- caused by **frictional forces** at the die-workpiece interface can be minimized if an **effective lubricant** is used
- caused by **thermal effects （热效应）** in hot forging can be minimized by using **heated dies**

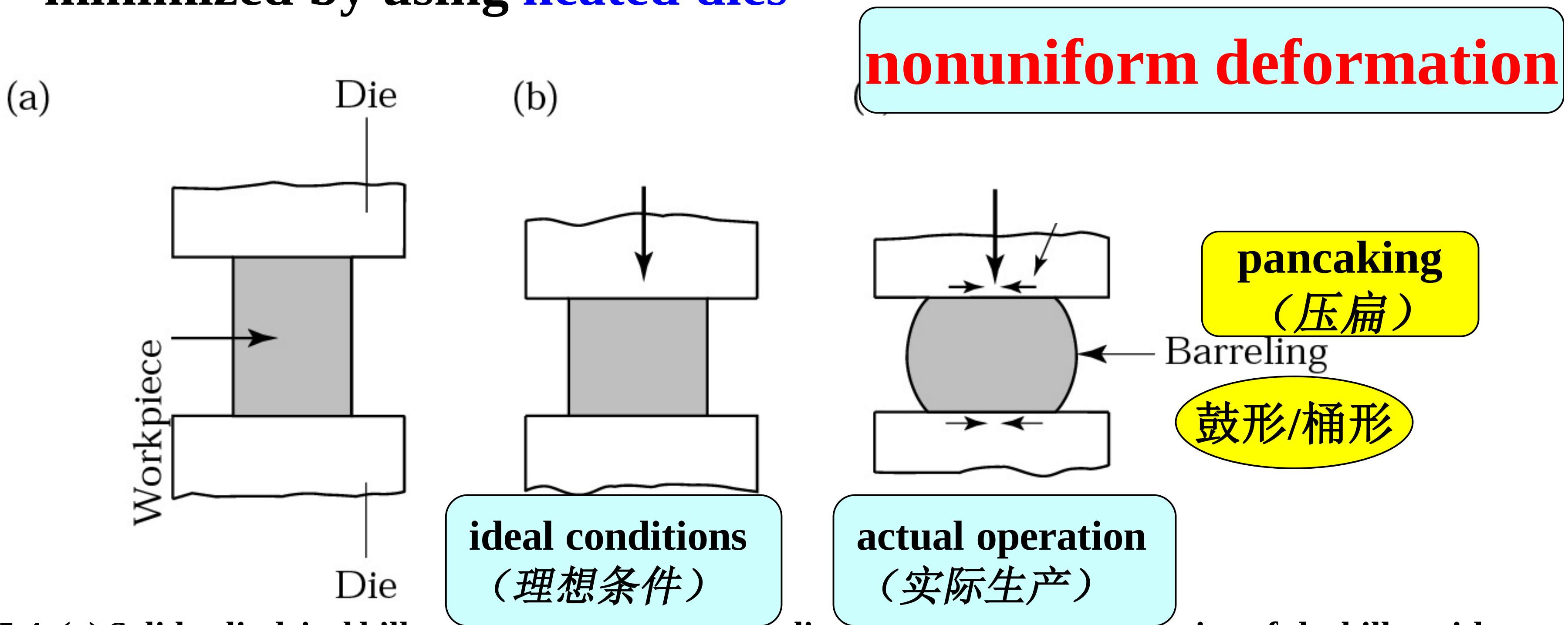


Figure 5.4 (a) Solid cylindrical billet upset between two flat dies. (b) Uniform deformation of the billet without friction. (c) Deformation with friction. Note barreling of the billet caused by friction forces at the billet-die interfaces.

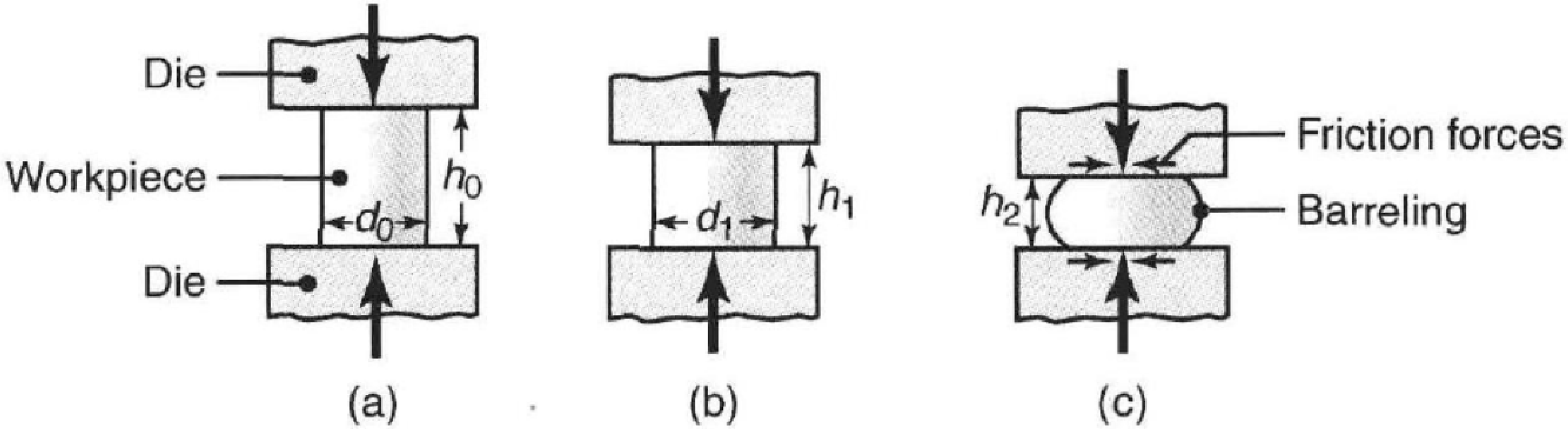


FIGURE 5.3 (a) Solid cylindrical billet upset between two flat dies. (b) Uniform deformation of the billet without friction. (c) Deformation with friction. Note barreling of the billet caused by friction forces at the billet–die interfaces.

5.2.2 Cogging （拔长）

– the thickness of a long bar is reduced by successive（连续的） forging steps at specific intervals（间隔/间距）.

- a basic open-die forging operation
- also called drawing out
- small contact area between die and workpiece
- no requiring large forces or heavy machinery

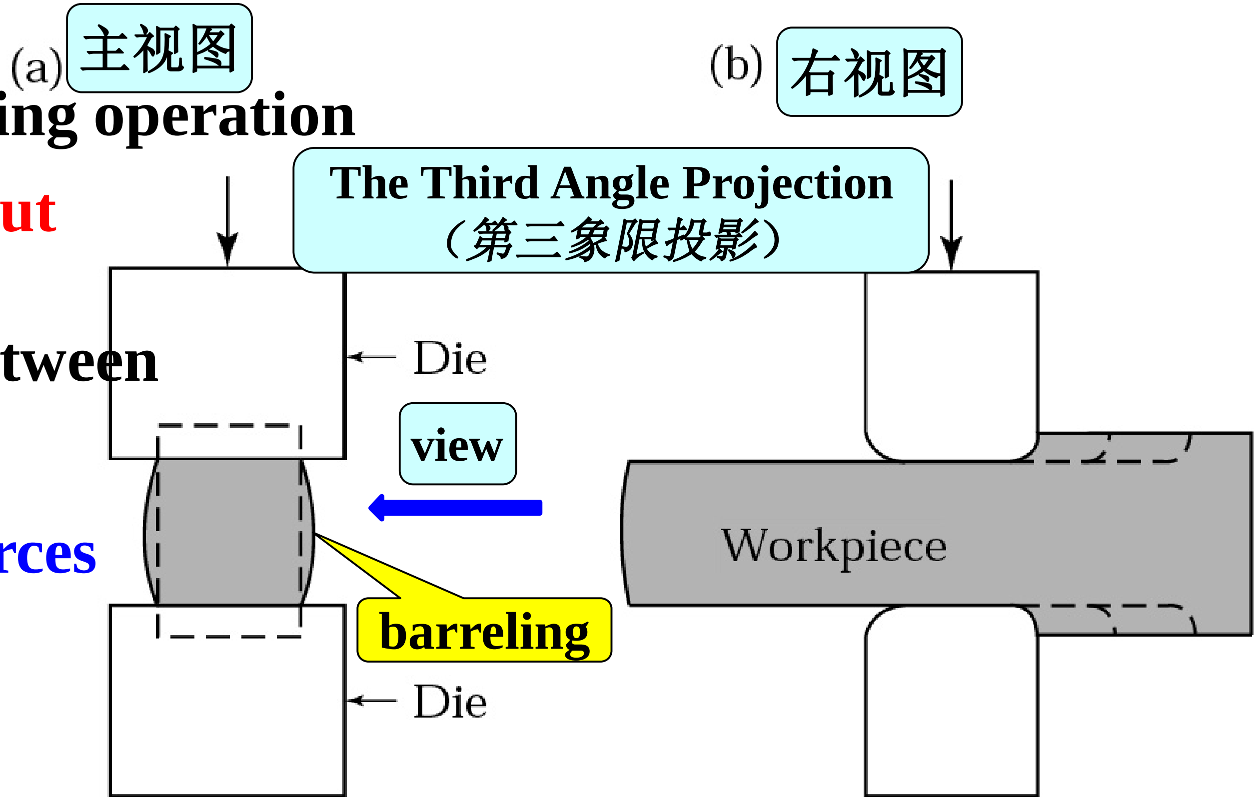


Figure 5.5 Two views of a cogging operation on a rectangular bar. Blacksmiths use this process to reduce the thickness of bars by hammering the part on an anvil. Note the barreling of the workpiece.

Cogging Practice

dimensional control and surface finish are not as good as in ring rolling

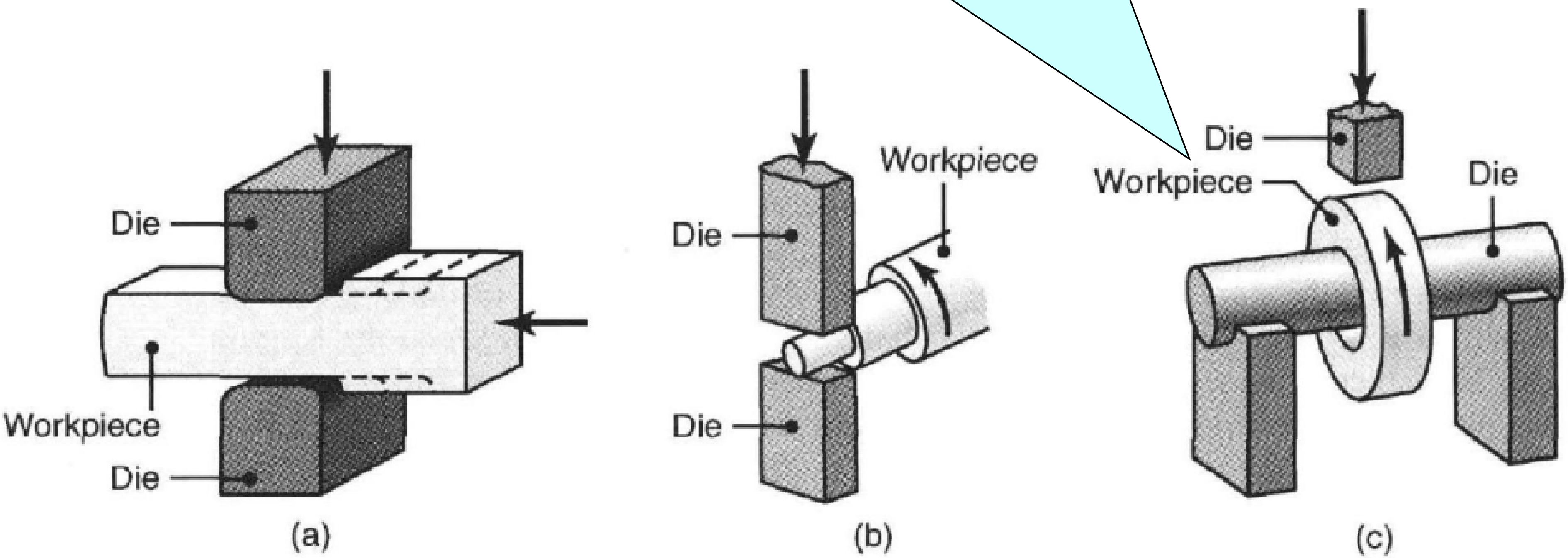


FIGURE 5.4 (a) Schematic illustration of a cogging operation on a rectangular bar. Blacksmiths use this process to reduce the thickness of bars by hammering the part on an anvil. Reduction in thickness is accompanied by barreling, as in Fig. 5.3c. (b) Reducing the diameter of a bar by open-die forging; note the movements of the dies and the workpiece. (c) The thickness of a ring being reduced by open-die forging.

Cogging Parts

- Blacksmiths perform such operations with a hammer and an anvil using hot pieces of metal.

- Cogging of larger workpieces usually is done using mechanized equipment（机械化设备） and computer controls in which lateral（侧向的/横向的） and vertical movements are coordinated（协调/配合） to produce the desired part.

iron fences

* Forging Force

- **The forging force, *F*, in an open-die forging operation on a solid cylindrical workpiece can be estimated from the formula:**

$$F = Y_f p\, r^2 \left(1 + \frac{2mr}{3h}\right)$$

***Y_f*: the flow stress of the material at the forging temperature**
***μ*: the coefficient of friction between the workpiece and the die**
***r*: the instantaneous（*即时的/瞬时的*）radius of the workpiece**
***h*: the instantaneous height of the workpiece**

5.3 Impression-die and Closed-die Forging

Outline

- **Impression-die forging（模锻）:**
  - process
  - flash（飞边）： concept and its importance
  - forging die（锻模）
  - stages in impression-die forging
- **Closed-die forging（闭式模锻/闭模锻造）**
- **Precision forging（精密锻造）**
- **Forging Practice and Product Quality**

5.3.1 Impression-die Forging （模锻）

- the workpiece acquires the shape of the die cavities (impressions)（型腔/模腔） while being forged between two shaped dies .
- usually is carried out at elevated temperatures to lower the required forces and attain enhanced ductility in the workpiece

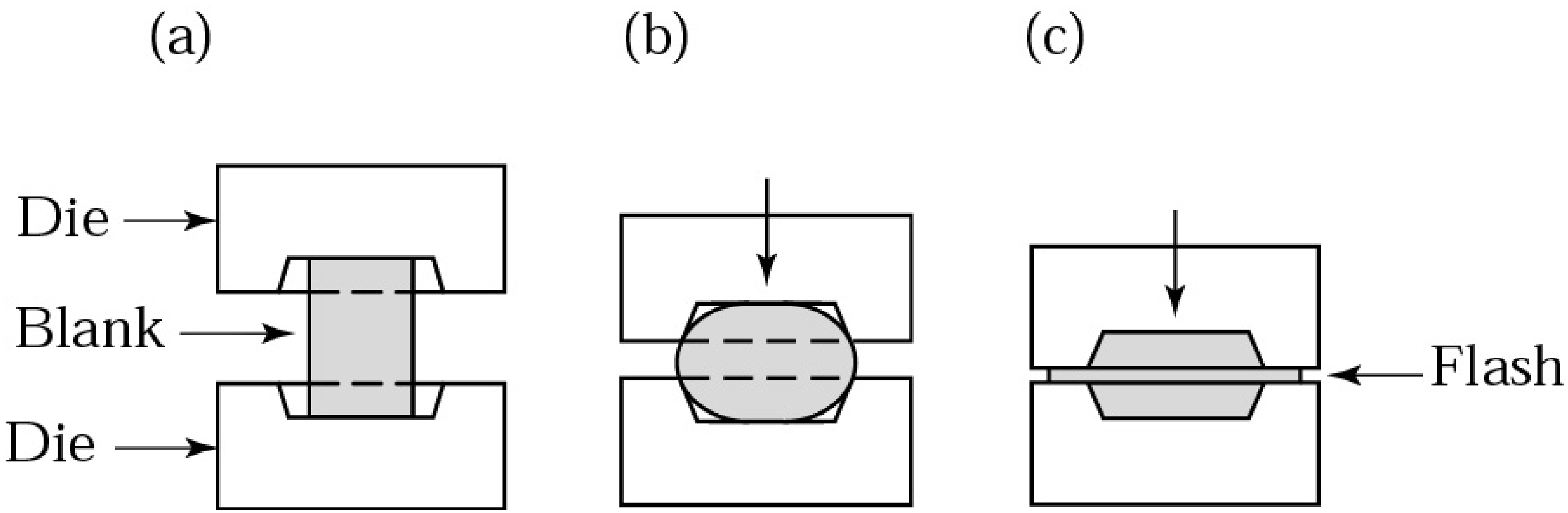
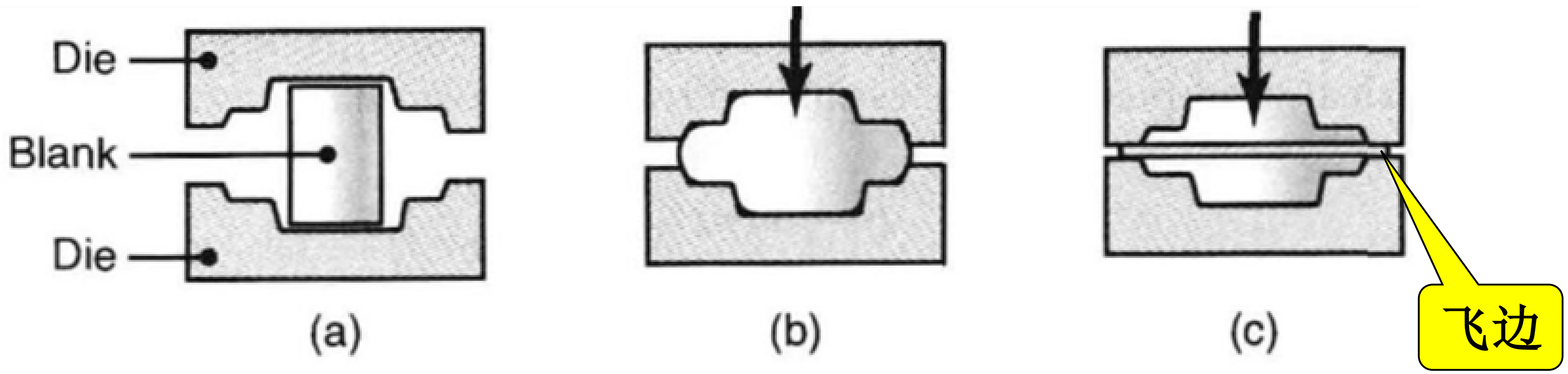


Figure 5.5 Stages in impression-die forging of a solid round billet. Note the formation of flash, which is excess metal that is subsequently trimmed off (see Fig. 5.8).



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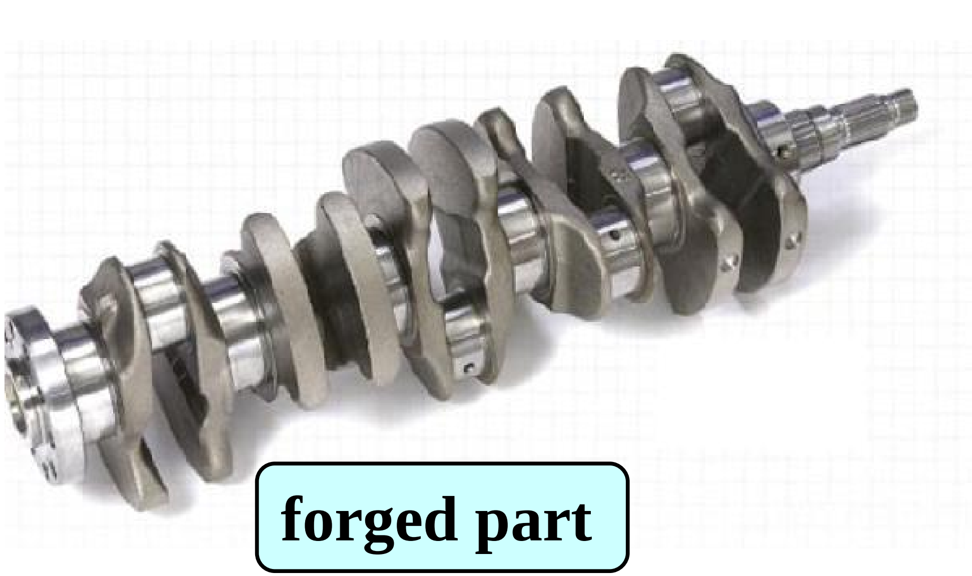
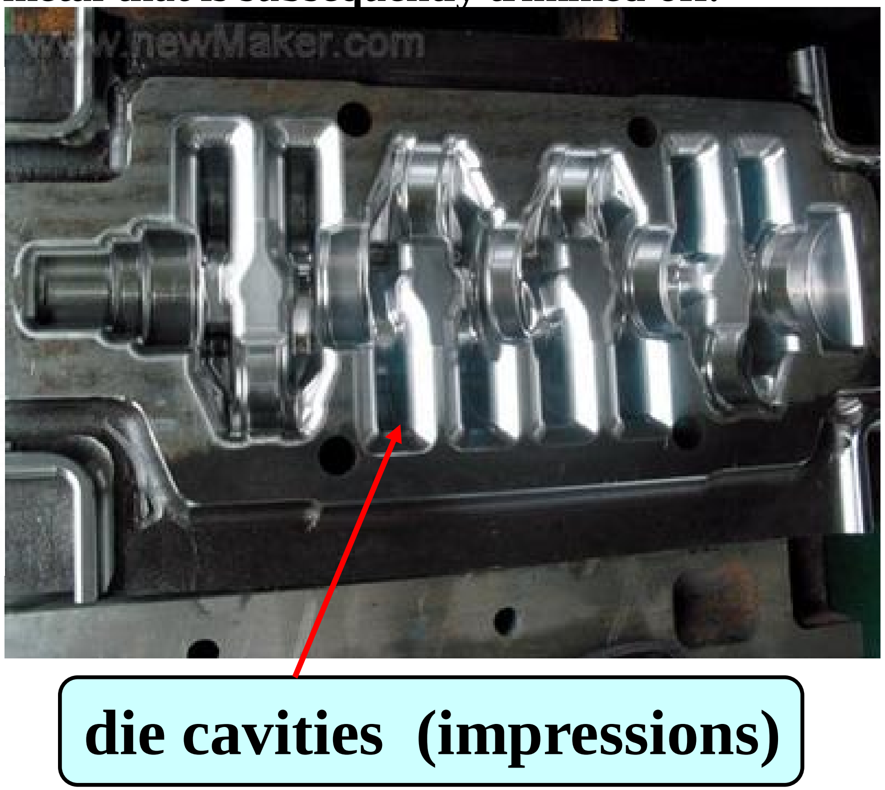
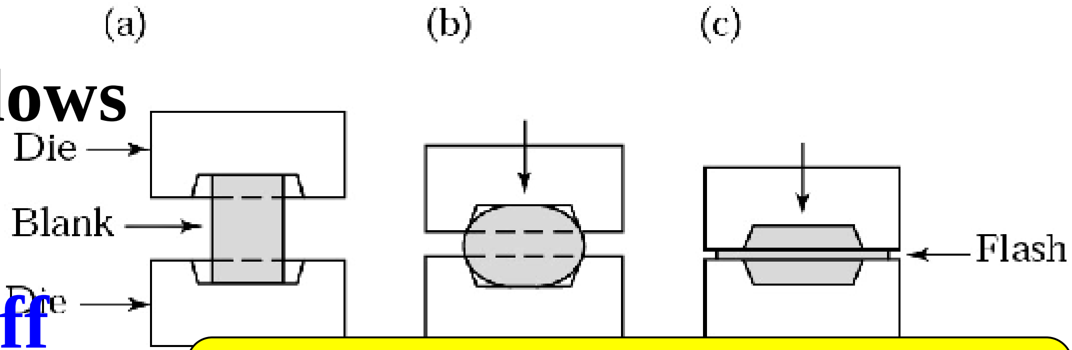




Crankshaft（曲轴/机轴） and Its Die

Flash（飞边）

- excess（多余的） metal flows outward of the cavity
- subsequently trimmed off（切边）



Law of Minimum Resistance（最小阻力定律）

- Significance（重要性/意义） of the flash
  - thin flash cools rapidly
  - has higher pressure and frictional resistance（摩擦阻力）
  - subjects the material in the die cavity to high pressures
  - encouraging the filling of the die cavity.

Significance（重要性/意义） of Flash

- The flash has an important role in impression-die forging.
- The high pressure and the resulting high frictional resistance in the flash presents a sever constraint（严格的限制） on any outward flow of the material in the die.
- Thus, base on the principle that in plastic deformation the material flows in the direction of least resistance (because it requires less energy), the material flows preferentially（优先地） into the die cavity, ultimately（最终） filling it completely.

Forging Die Design Features（锻模特征）

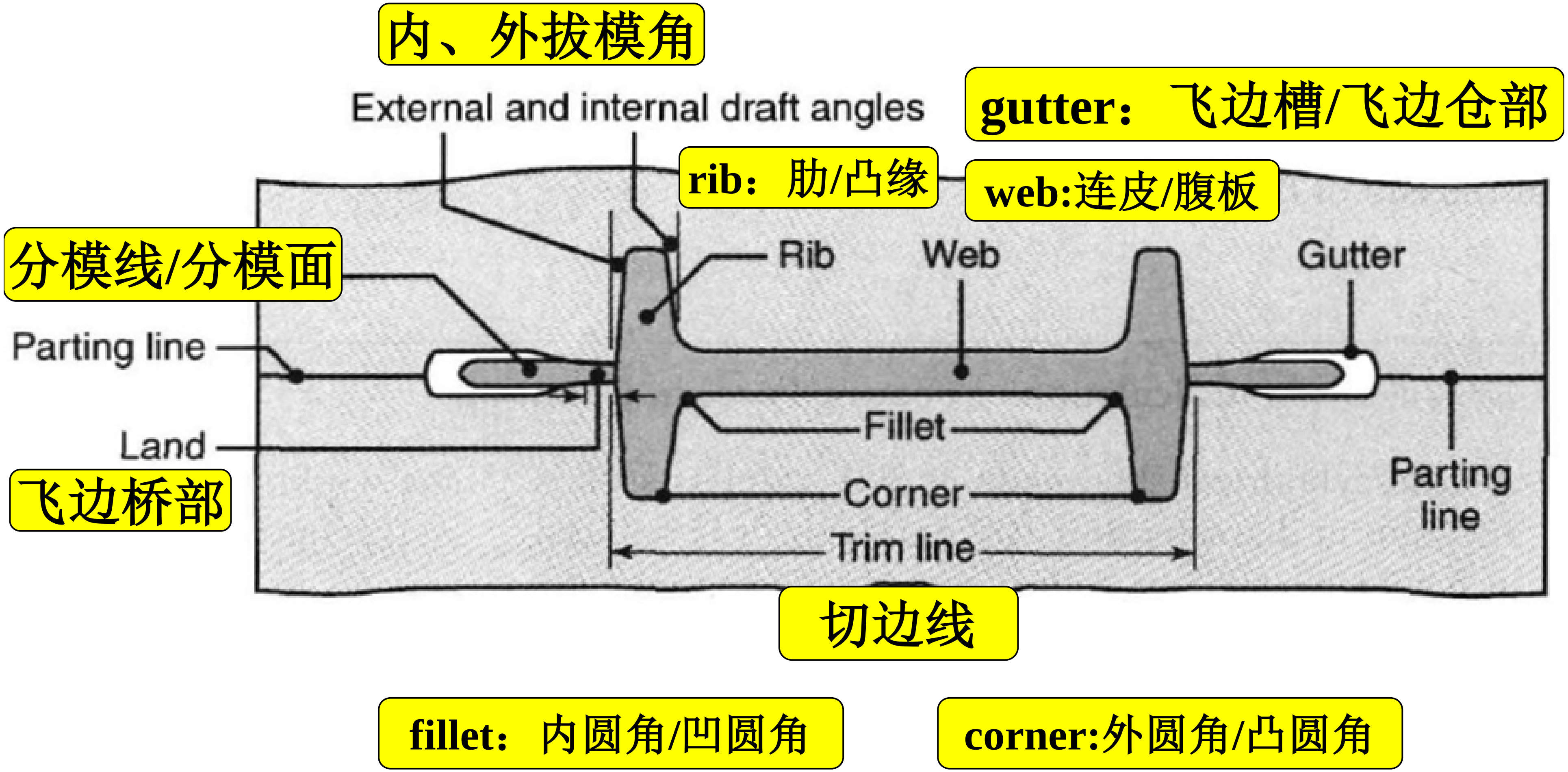


Figure 5.5 Standard terminology（*标准术语*）for various features of a typical impression-forging die.

Die Inserts (*模具镶件*)

- this alternative reduces the cost of making several similar dies, particularly for complex shapes;
- The inserts are usually made of stronger and harder materials
- and they can be replaced easily in the case of wear or failure in a particular section of the die

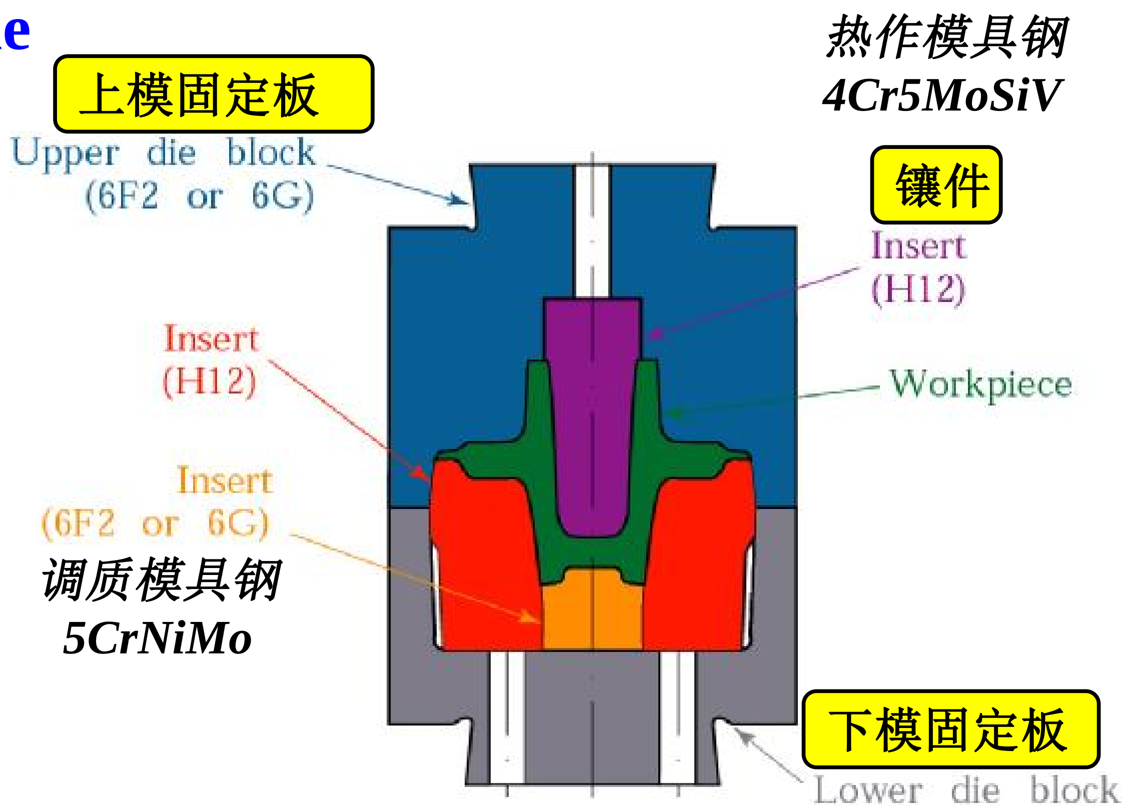


Figure 5.6 Die inserts used in dies for forging an automotive axle housing（汽车桥壳）. (See Tables 5.5 to 5.7 for die materials.) *Source*: *Metals Handbook, Desk Edition*. ASM International, Metals Park, Ohio, 1985. Used with permission.

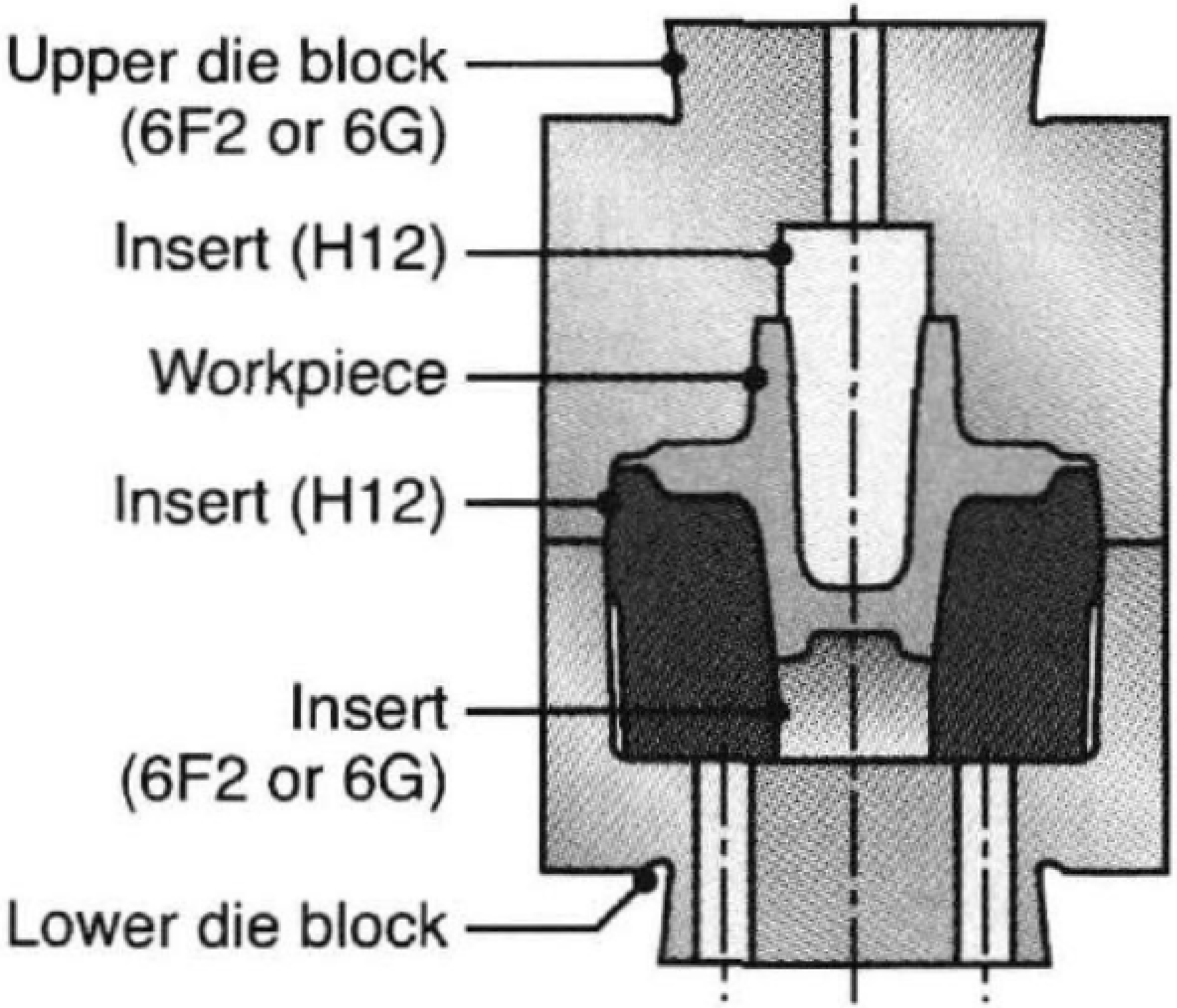


FIGURE 5.6 Die inserts used in forging an automotive axle housing.

Steps of Impression-die Forging Process

a. preparing blank （备料）

b. preforming processes（预成形）

c. blocking（初锻）

d. finish forging（终锻）

e. removing flash（去飞边）

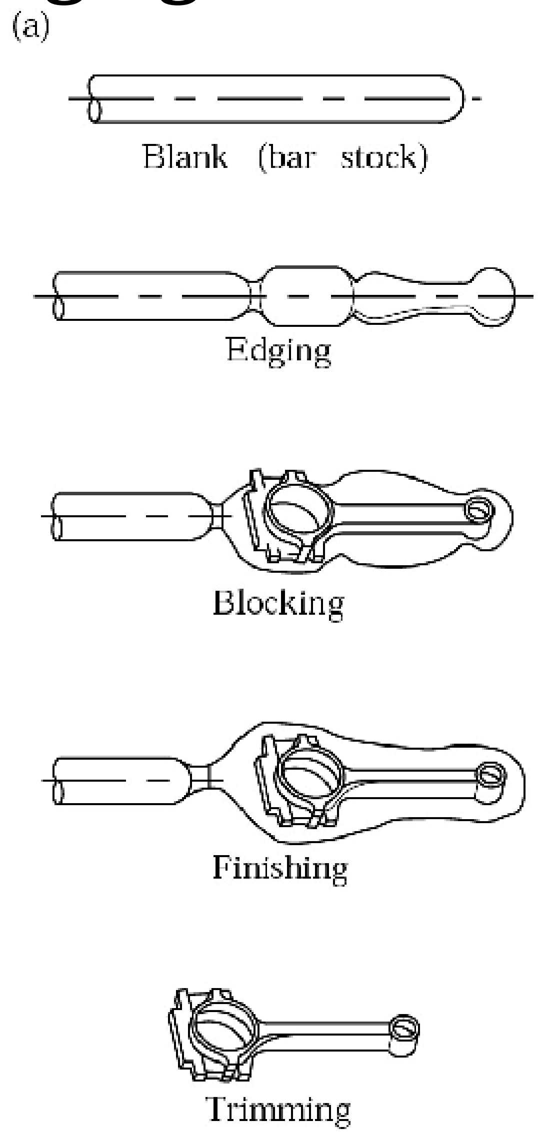


Figure 5.7 (a) Stages in forging a connecting rod （连杆） for an internal combustion engine（内燃机）. Note the amount of flash required to ensure proper filling of the die cavities. (b) Fullering, and (c) edging operations to distribute the material when preshaping（预成形） the blank for forging.

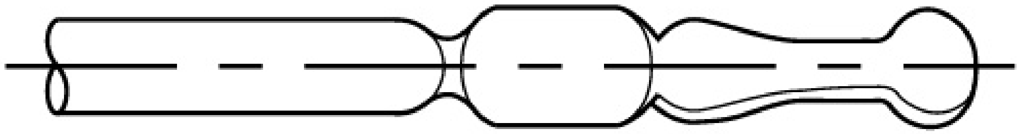
a. Preparing Blank（备料/下料)

- cutting（切割/切削） or cropping（剪切） from an extruded or drawn bar stock（挤出或拉拔棒料）
- a preform（预成形件） in operations such as powder metallurgy （粉末冶金）
- casting（铸造）
- a preform blank in a prior（先前的） forging operation

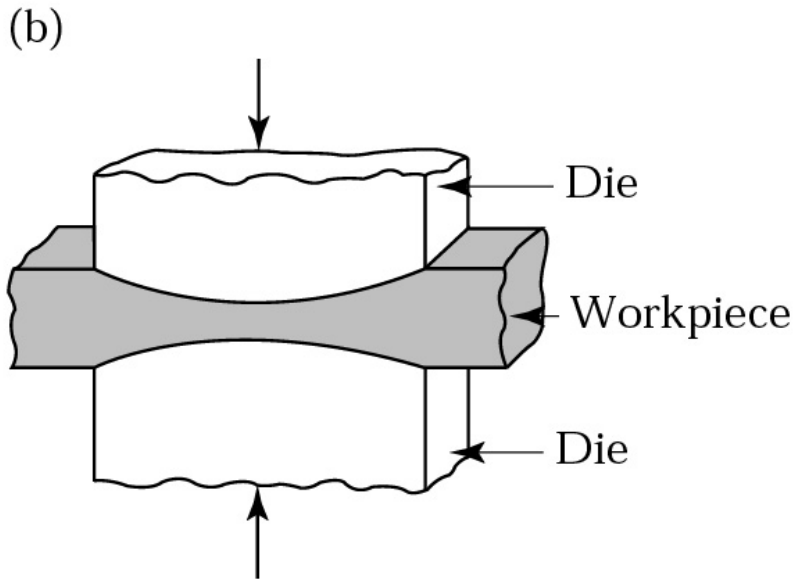
Blank (bar stock)

b. Preforming Processes（预成形工艺）

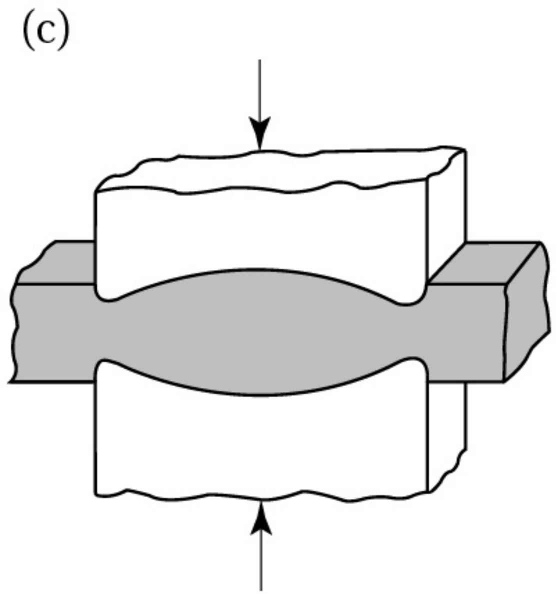
- used **to distribute**（分布/分配） the material into various regions of the blank
- using simple shaped dies of various contours（轮廓）
- such as **fullering**（压槽） and **edging**（压边）



Edging



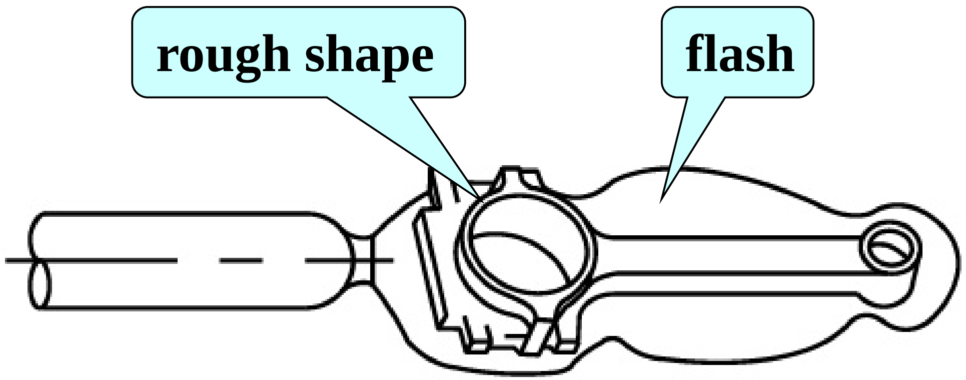
- **fullering （*压槽*）**
  - **material is distributed away（*分散*） from an area**



- **edging （*压边*）**
  - **material is gathered into（*聚集*） a localized area**

c. Blocking（*预锻/粗锻/初锻/胎膜锻*）

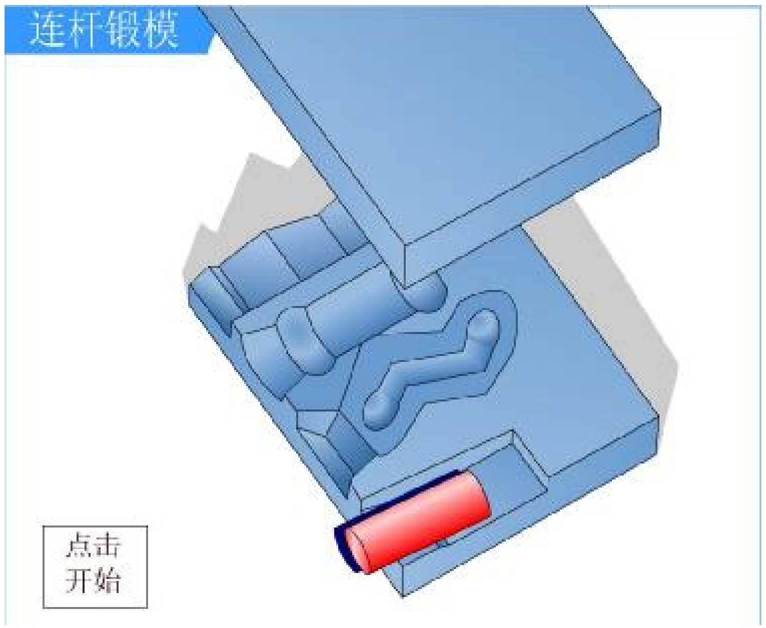
- formed into the rough shape of final part
- using blocker dies（*预锻模*）

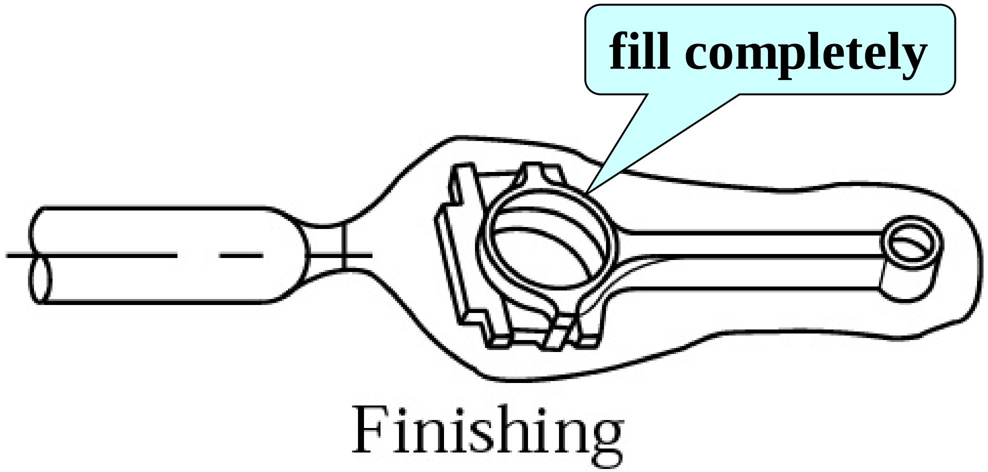


Blocking

d. Finishing Forging（终锻）

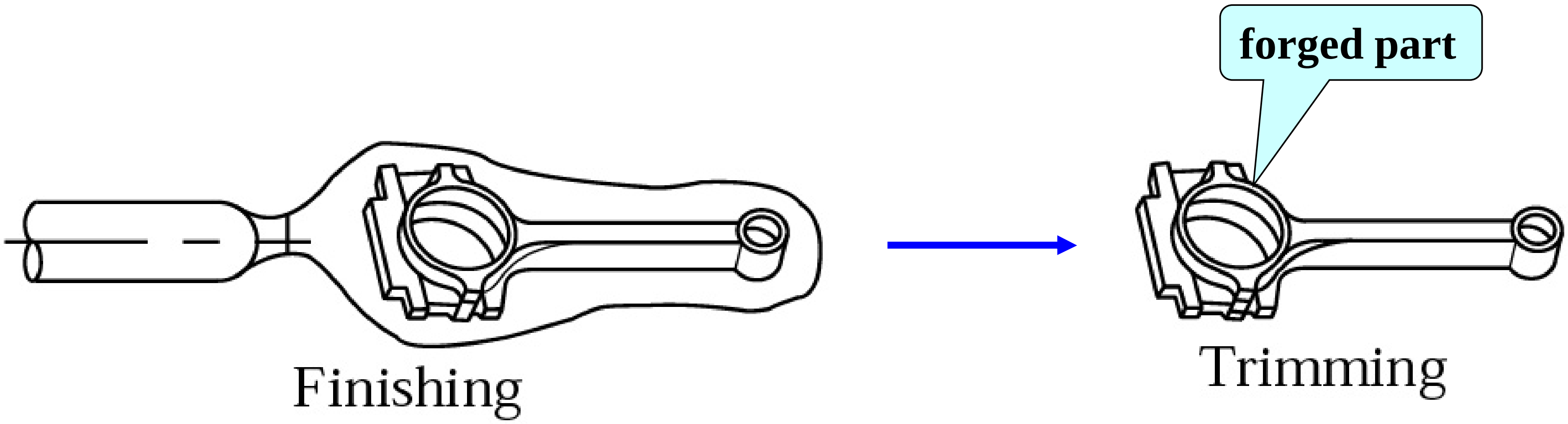
– the final operation to give the forging its final shape in impression dies（终锻模）





e. Removing Flash（去除飞边）

– by a **trimming** （切边）operation.



Trimming Flash from a Forged Part

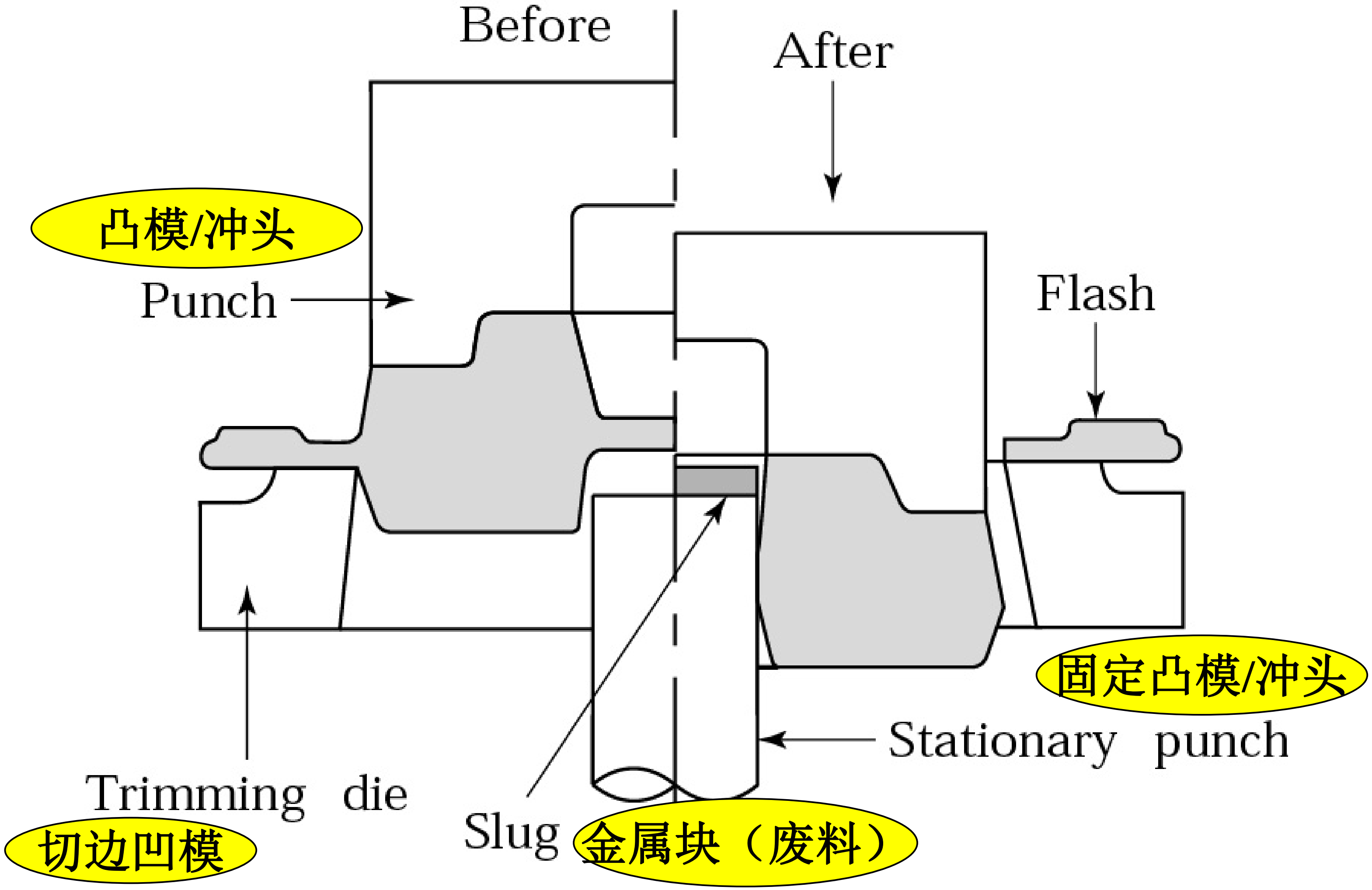
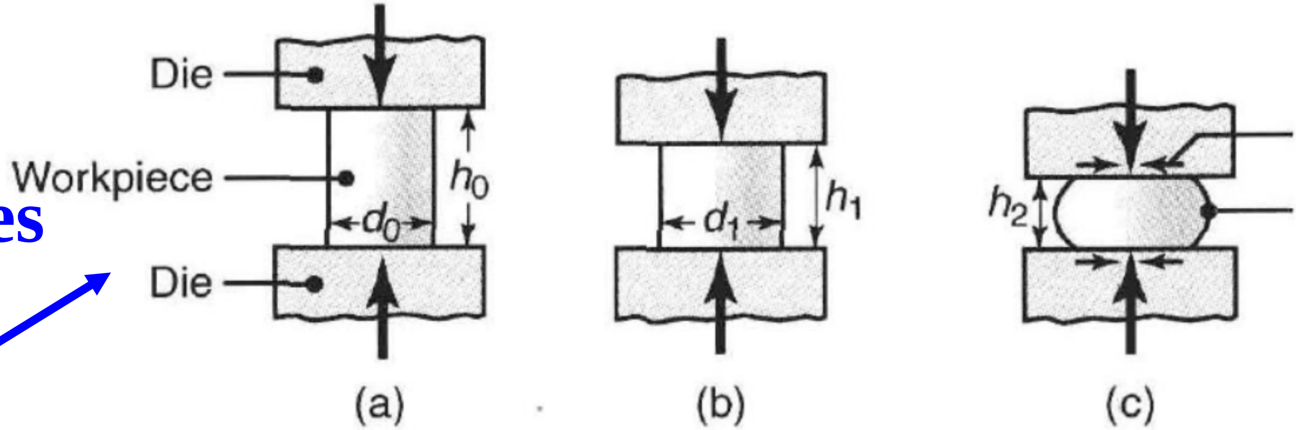


Figure 5.8 Trimming flash from a forged part. Note that the thin material at the center is removed by punching （冲孔）.

Impression-die Forging 模锻实例

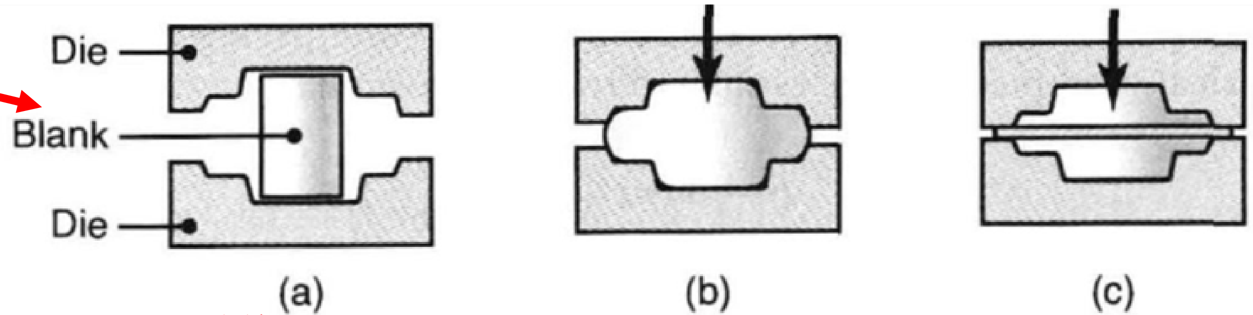
Comparison of Two Forging Processes

- **open-die forging**
  - **uses two flat dies**



开模锻造

开式模锻

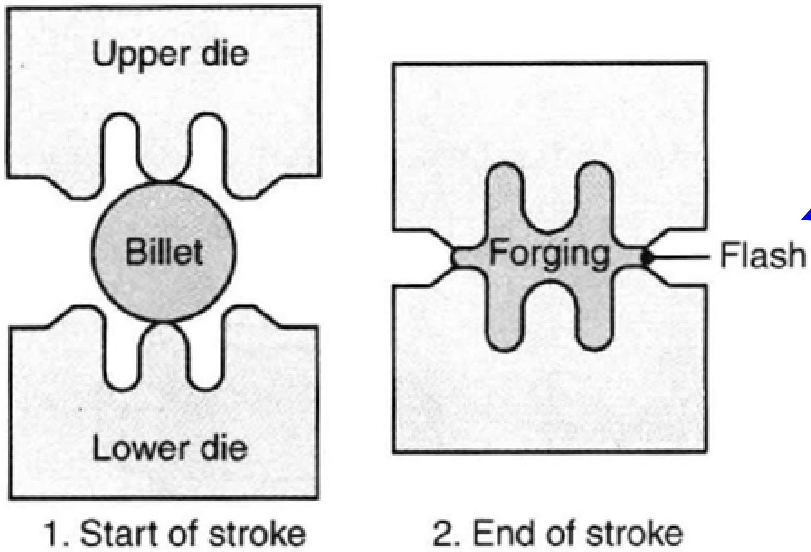


- **impression-die forging（*模锻*）**
  - **metal fills die cavity with flash**

5.3.2 Closed-die Forging and Flashless Forging
（闭式模锻和无飞边模锻）

- a typical impression die forging
- also referred to as closed-die forging（with flash）

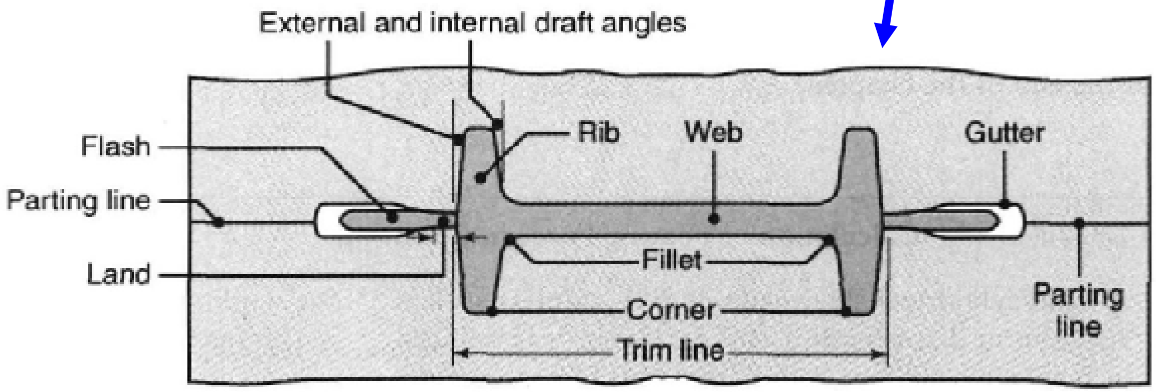
闭模锻造



冲程起始

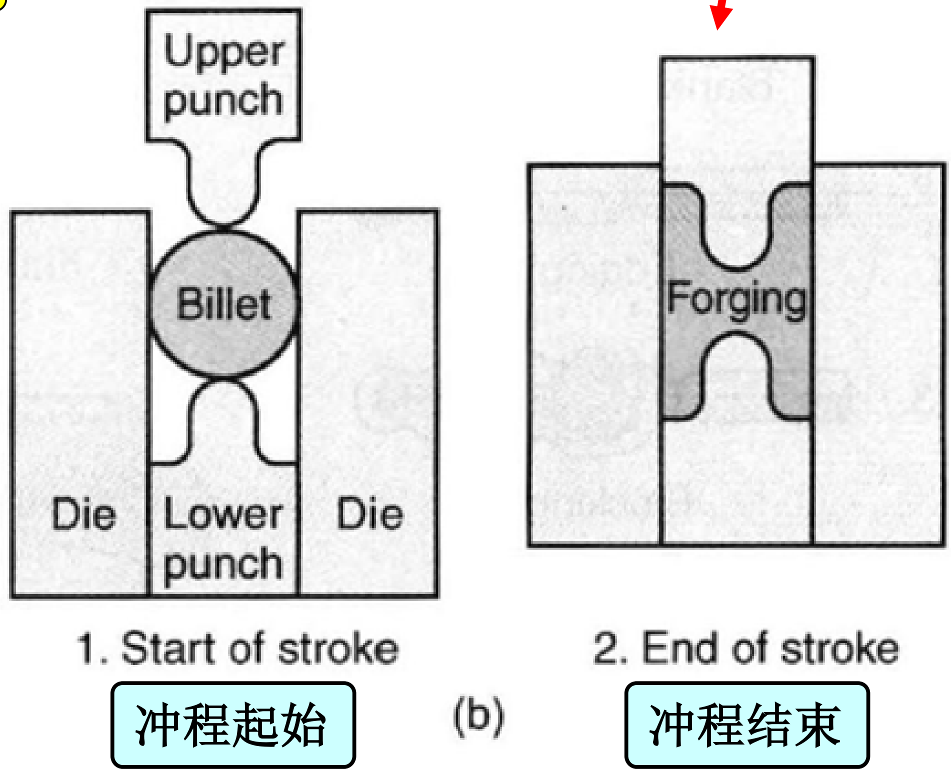
冲程结束

模锻/开式模锻



- For true closed-die forging（without flash）闭式模锻
  - Ø flash does not form;
  - Ø workpiece completely fills the die cavity.

flashless forging（无飞边模锻）



Essential Conditions in Closed-die Forging

① **accurate control of the volume of material**

- **undersize**（*尺寸不足*）**blanks prevent the complete filling of the die cavity;**
- **oversize**（*尺寸过大*）**blanks generate excessive pressures and may cause dies to fail prematurely**（*过早失效*）**or to jam**（*压裂*）**.**

② **proper die design**

③ **high forging pressure**

P144 in Textbook

闭模锻造（带飞边）

- **Regardless, the term *closed-die forging* is often applied to *impression-die forging* with flash generation**
- **whereas *open-die forging* generally applies to operations with simple dies and tooling and with large deformations.**

开模锻造/自由锻

Summary: 中英文专业术语对照

- 开模锻造 /平模锻造/ 自由锻 → **open-die forging/flat-die forging /free forging (uses flat dies)**
- 模锻/开式模锻
- 闭模锻造

→ **impression-die forging**
closed-die forging
(metal fills die cavity with flash)

- 闭式模锻 → **flashless forging/closed-die forging (metal fills die cavity without flash)**

- **closed-die forging**
  - 闭式模锻 $\xrightarrow{\text{theoretically/literally}}$ **without flash**
  - 闭模锻造 $\xrightarrow{\text{practically/often}}$ **with flash**

5.3.3 Precision Forging （*精密锻造*）

- In order to reduce the number of additional finishing operations required-hence the cost- the trend has been toward greater precision in forged products.
- The part formed is at or close to the final dimensions of the desired component
- known as net-shape or near-net-shape forming（*净成形/近净成形*）.

Production Process Sequence of Bevel Gear（伞齿轮）

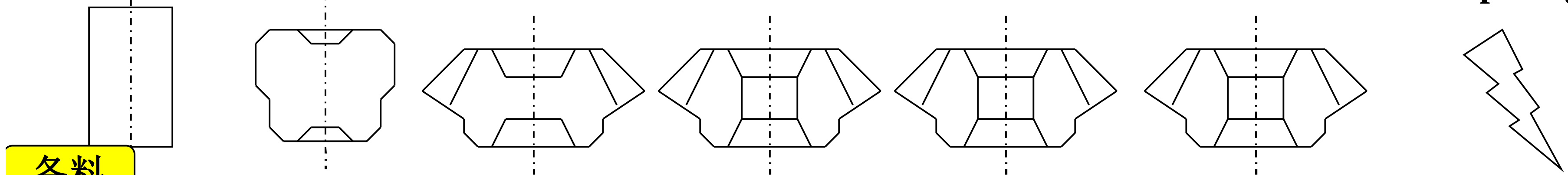
退火
淬火
回火

Soft annealing（*软化退火*）
Cutting
Lubrication
(Bonderite)（*磷化*）

Forming performed on a mechanical press

Straight the distortion

Annealing,
Quenching
Tempering



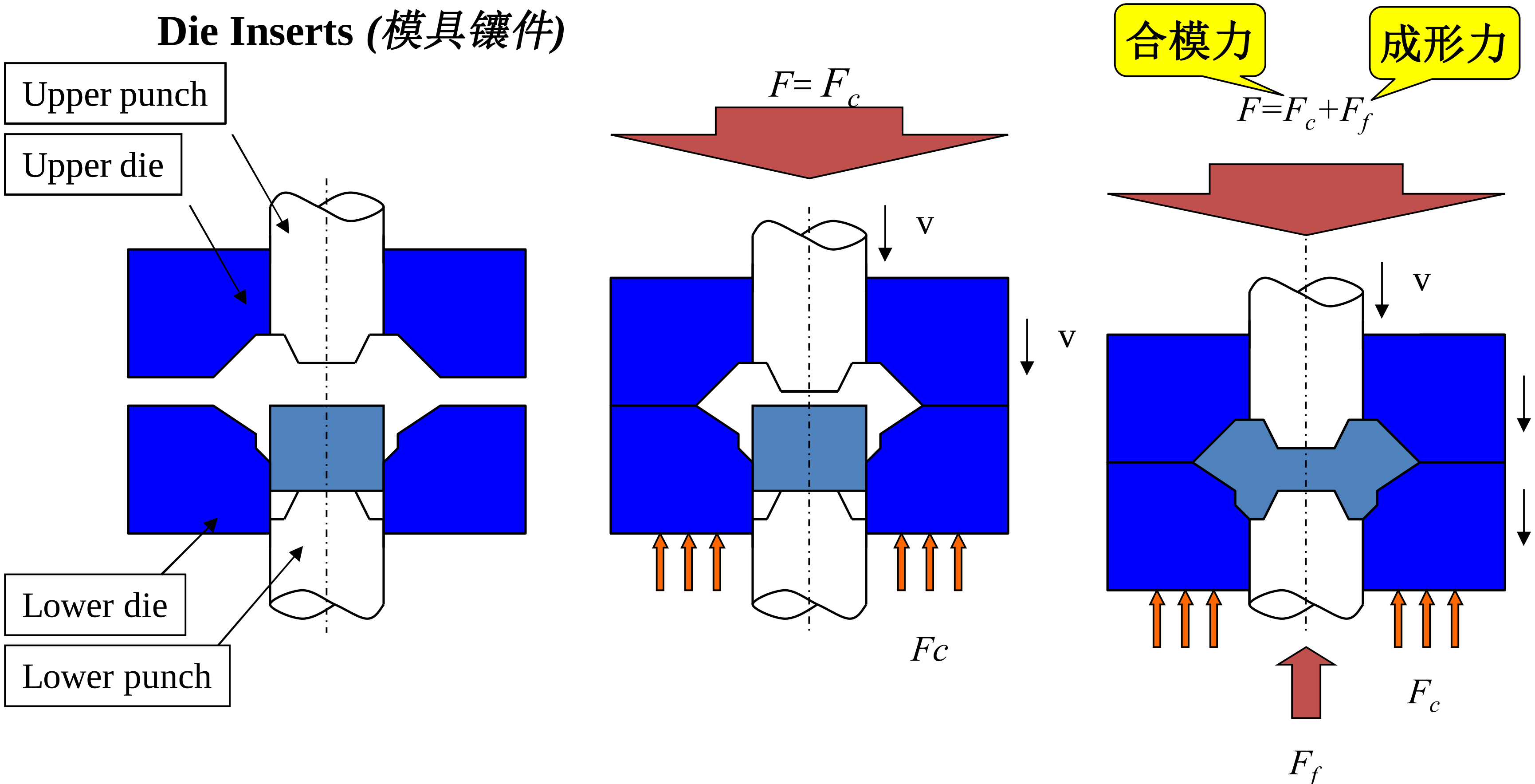
备料						
Billet production	Preforming + annealing + lubrication	Forming	Punching	Deburring	Sizing	Heat treatment + shot blasting
		成形	冲孔	去毛刺	校正/精压	喷丸处理

预成形
+
退火
+
润滑

Precision forging

Usually for big gears

Tool Set（模架）for Bevel Gear Production



lay in the billet → **close the dies** → **formed by the punches**

F = total production process force

F_c = closing force (force between upper and lower die) - provided by hydraulic unit

F_f = forming force (force acting on the punches) - provided by press

Requirements of Precision Forging

- special and more complex dies
- precise control of the billet’s volume and shape
- accurate positioning（定位） of the billet in the die cavity
- higher capacity equipment, because of the greater forces required to obtain fine details on the part

investment
（投资）

Advantages of Precision Forging

- **parts having greater accuracies, which can significantly reduce the number of subsequent finishing operations**
- **no or less material is wasted**

manufacturing cost

- **Thus, the choice between conventional forging and precision forging requires an economic analysis, particularly in regard to the production volume （产量/生产批量）.**

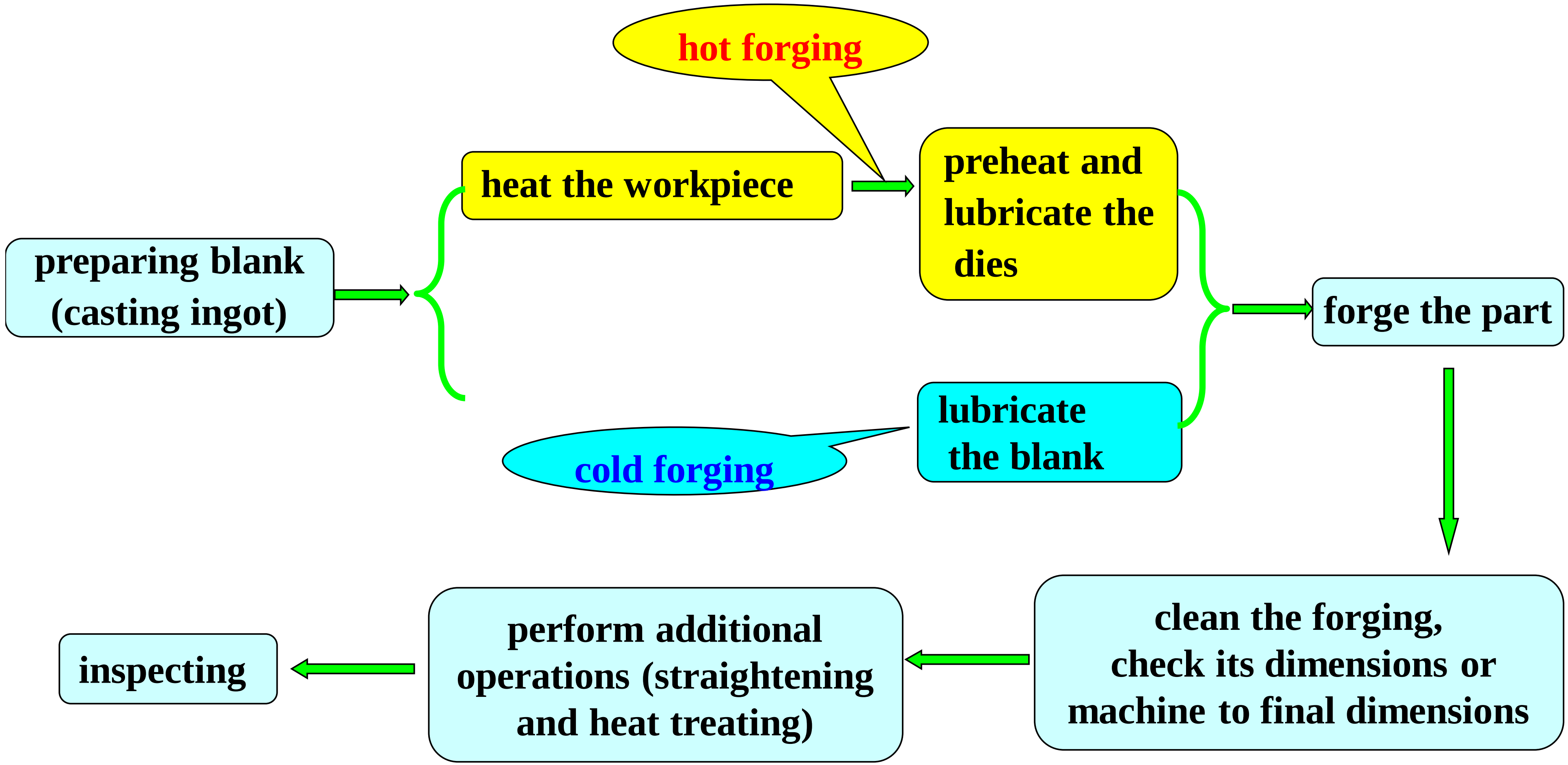
* Application of Precision Forging

- **Aluminum（*Al*） and Magnesium（*Mg*） alloys:**
  - **are particularly suitable, because of the relatively low forging loads and temperatures that they require;**
- **Steel and Titanium （*Ti*）；**
- **Typical precision-forged products：**
  - **gears**
  - **connecting rods**
  - **housings（*机架/罩盖*）**
  - **turbine blades（*涡轮叶片*）**

Precision Forging Dies

* 5.3.4 Forging Practice and Product Quality

- **A forging operation typically involves the following sequence of steps:**



- **A forging operation typically involves the following sequence of steps:**

1. **Prepare a slug, billet, or preform by processes such as shearing (cropping), sawing, or cutting off. If necessary, clean surfaces by such means as shot blasting.**
2. **For hot forging, heat the workpiece in a suitable furnace** *（加热炉）* **and then, if necessary, descale** *（去除氧化皮）* **it with brush, water jet, or by scraping. Some descaling also may occur during the initial stages of forging, when the scale (which is brittle) falls off during deformation.**
3. **For hot forging, preheat and lubricate the dies; for cold forging, lubricate the blank.**

- **A forging operation typically involves the following sequence of steps:**

4. **Forge the billet in appropriate dies and in the proper sequence. If necessary, remove any excess material (such as flash) by trimming, machining, or grinding.**
5. **Clean the forging, check its dimensions, and (if necessary) machine it to final dimension and specified tolerances.**
6. **Perform additional operations, such as straightening***（整形/校正）*** and heat treating (for improved mechanical properties). Also, perform any finishing operations that may be required, such as machining and grinding.**
7. **Inspect***（检测）*** the forging for any external and internal defects.**

* Product Quality

- The quality, dimensional tolerances, and surface finish of a forging depend on how well these operations are performed and controlled.
- Generally, dimensional tolerances:
  - for hot forging: ranges between ±0.5～ ± 1% of the dimensions of the forging ;
  - in good practice: less than ±6mm
  - in precision forging: can be as low as ±0.25mm

* Product Quality

- Other factors that contribute to dimensional inaccuracies（*尺寸误差/尺寸偏差*）:
  - draft angles（*拔模角/脱模斜度*）
  - radii
  - fillets
    （*模具内外圆角*）
  - die wear（*模具磨损*）
  - die closure (whether the dies have closed properly) （*模具闭合*）
  - mismatching of the dies（*模具装配误差*）
- The surface finish of the forging depends on:
  - blank preparation
  - die surface finish
  - die wear
  - the effectiveness of the lubricant

5.4 Various Forging Operations

- **A number of other forging operations are carried out in order to impart（*给予*） the desired shape and features to forged products.**
- **Common used forging operations:**
  - **coining** （*压印*）
  - **heading**（*顶镦*）
  - **piercing**（*冲缺*）
- **Other forging operations:**
  - **hubbing**（*压制阴模*）
  - **orbital forging** （*摆碾锻造*）
  - **incremental forging**（*增量锻造*）
  - **isothermal forging** （*恒温锻造/等温锻造*）
  - **rotary swaging**（*回转模锻/旋锻*）
  - **tube swaging** （*管件挤锻*）

1. Coining （压印）

flashless forging （无飞边模锻/闭式模锻）

- **Closed-die forging process：the blank or slug（金属块） is coined in a completely closed die cavity.**
- **Used for minting coins（造币）, medallions（奖章）, and jewelry with fine details**
- **Pressures required can be as high as five or six times the strength of the material**
- **Lubricants can NOT be used in coining**

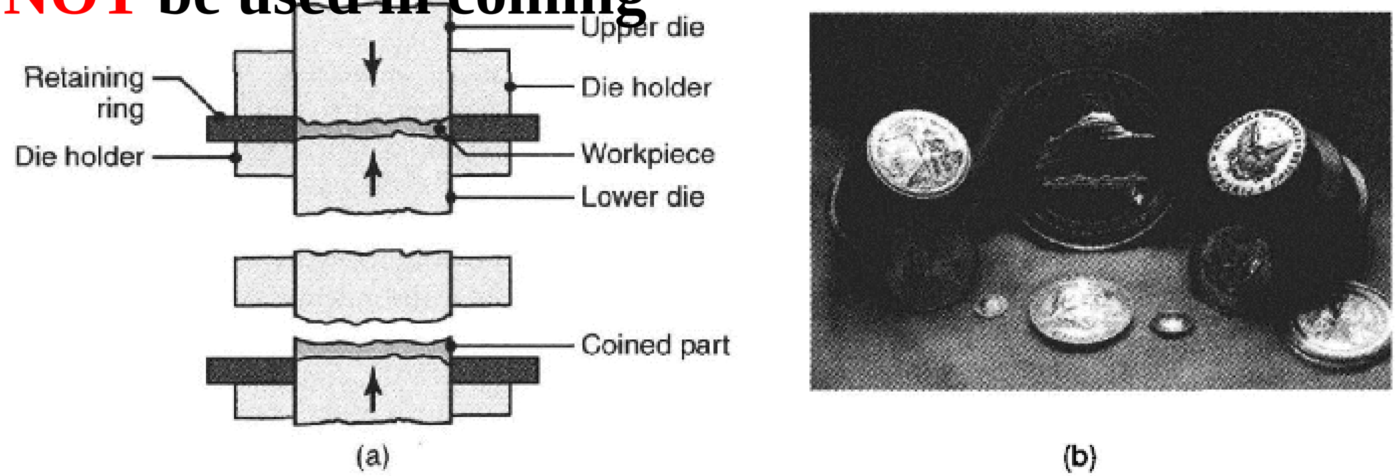
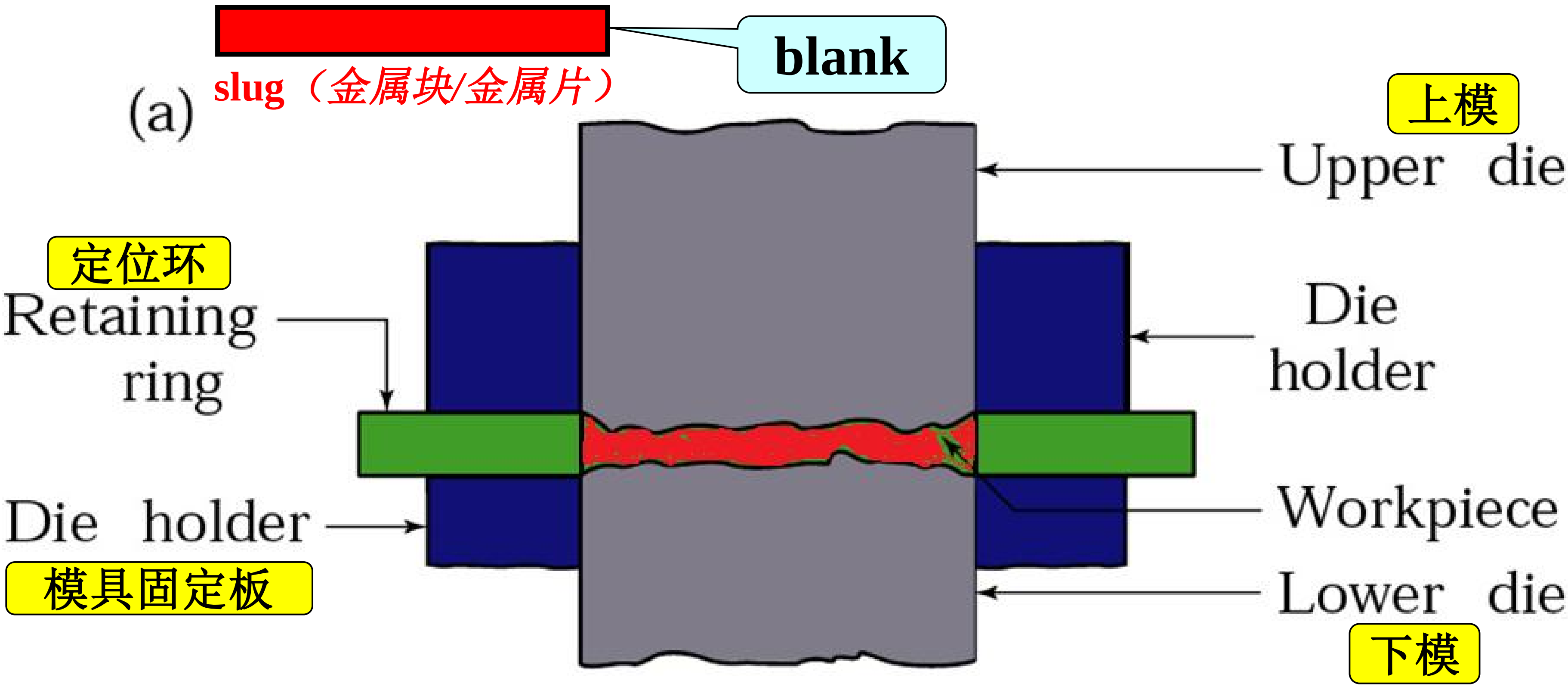


FIGURE 5.10 (a) Schematic illustration of the coining process. The earliest coins were made by open-die forging and lacked precision and sharp details. (b) An example of a modern coining operation, showing the coins and tooling. Note the detail and superior surface finish that can be achieved in this process. *Source*: Courtesy of C & W Steel Stamp Co., Inc.



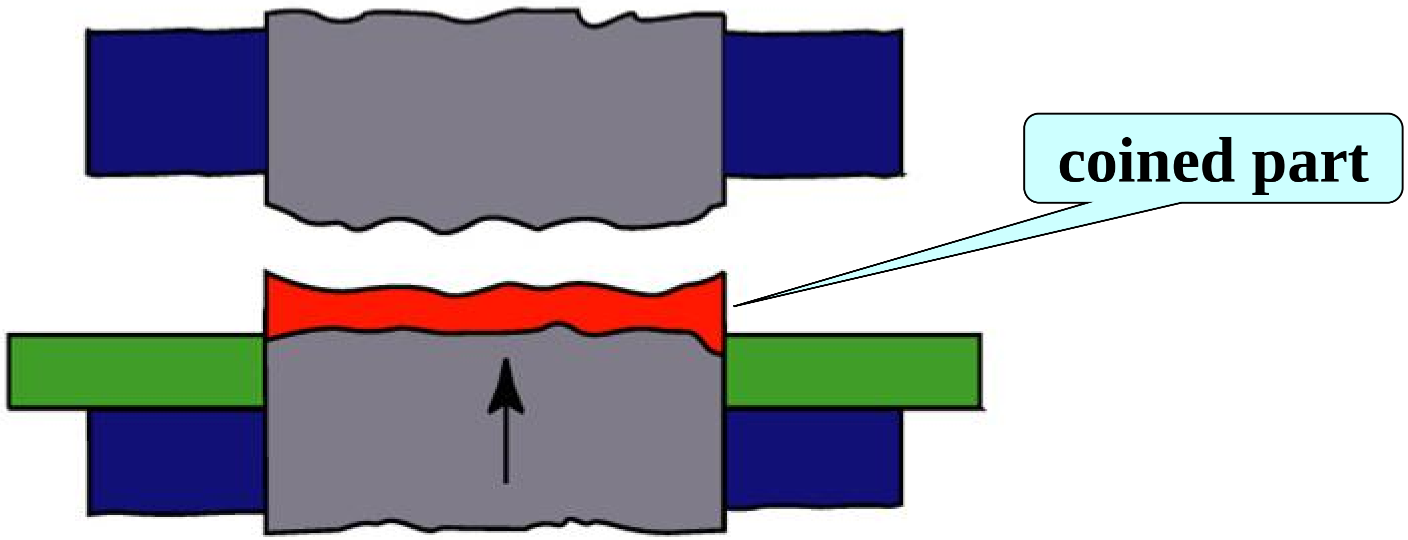


Figure 5.10 (a) Schematic illustration of the coining process. the earliest coins were made by open-die forging and lacked sharp details.

- **Coining can be used to improve surface finish to impart the desired dimensional accuracy, called sizing（*精压/精整*）**
  - **requires high pressures**
  - **with little or no change in part size**
- **Marking（*标记/做记号*） of parts with letters（*字母*） and numbers can be done rapidly by a process similar to coining.**

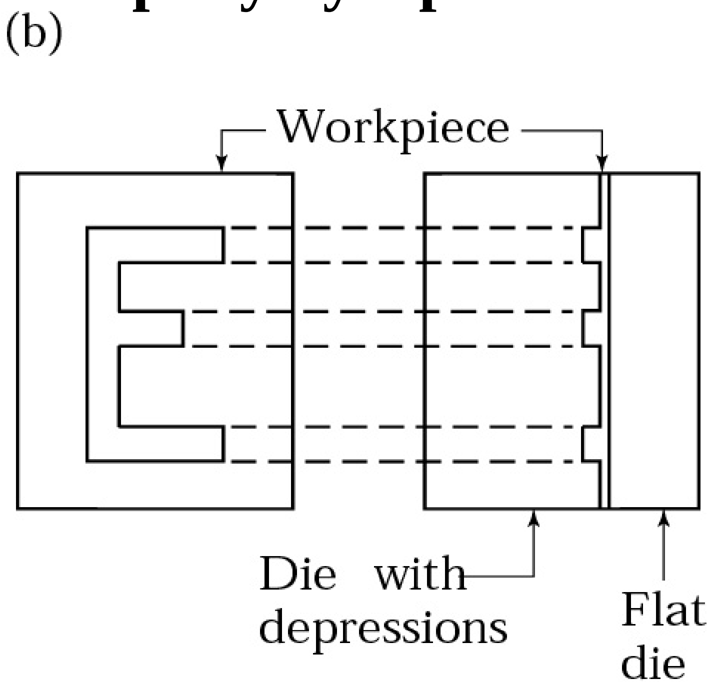


Figure 5.10 (b) An example of a coining operation to produce an impression of the letter E on a block of metal.

2. Heading（顶镦）

- essentially（实质上） an upsetting operation
- usually performed at the end of round rod or wire in order to produce a larger cross-section.
- can be carried out cold, warm, or hot.

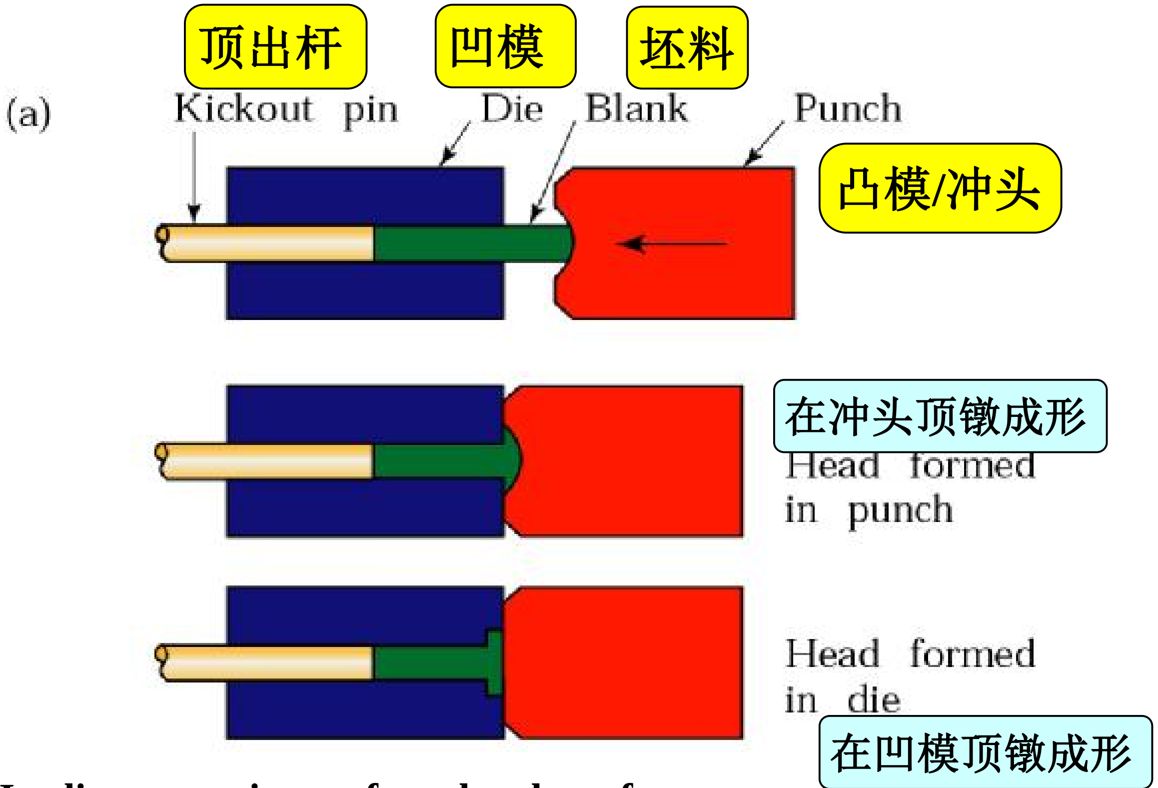


Figure 5.11 (a) Heading operation, to form heads on fasteners such as nails and rivets.

Typical products

- screws （螺杆）
- rivets （铆钉）
- nails（钉子）
- other fasteners（紧固件）
- bolts（螺栓）

thread rolling

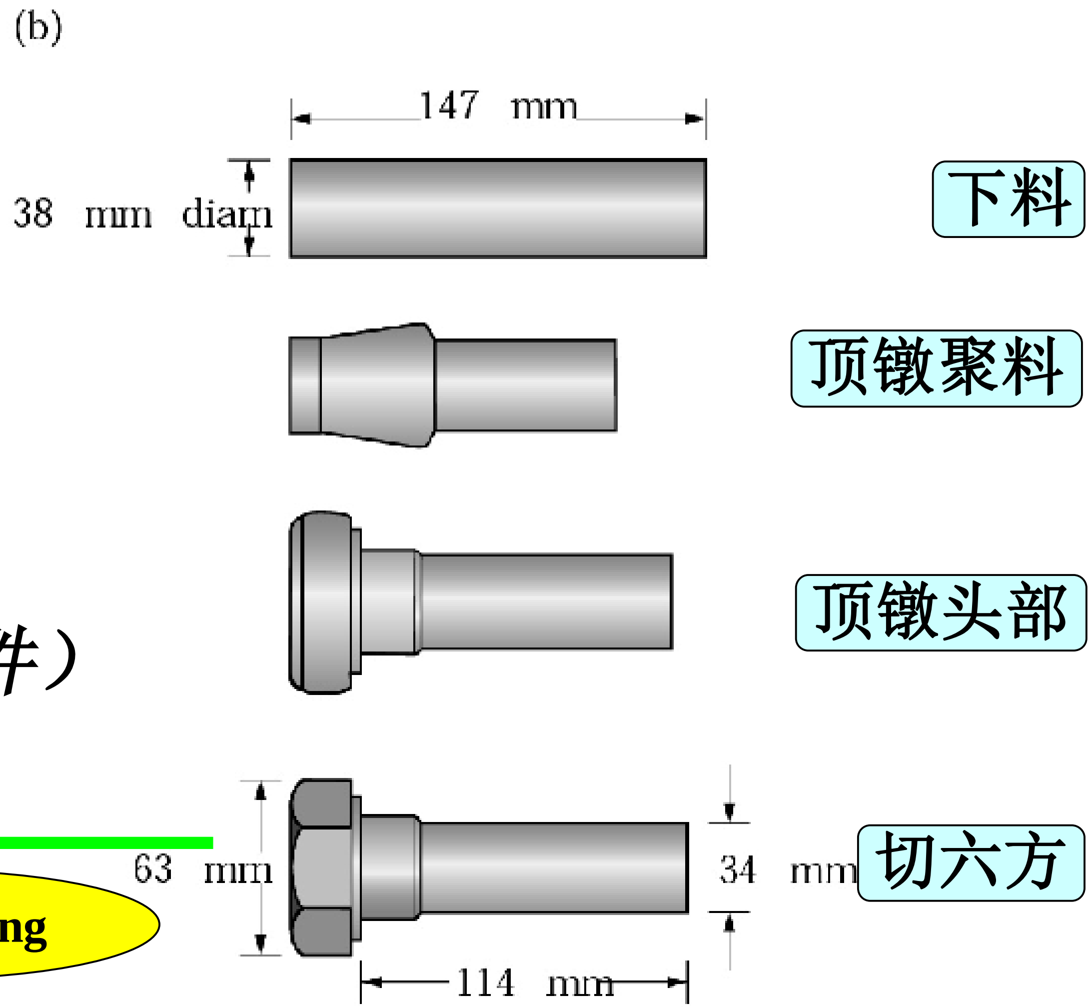


Figure 5.11 (b) Sequence of operations to produce a bolt head by heading.

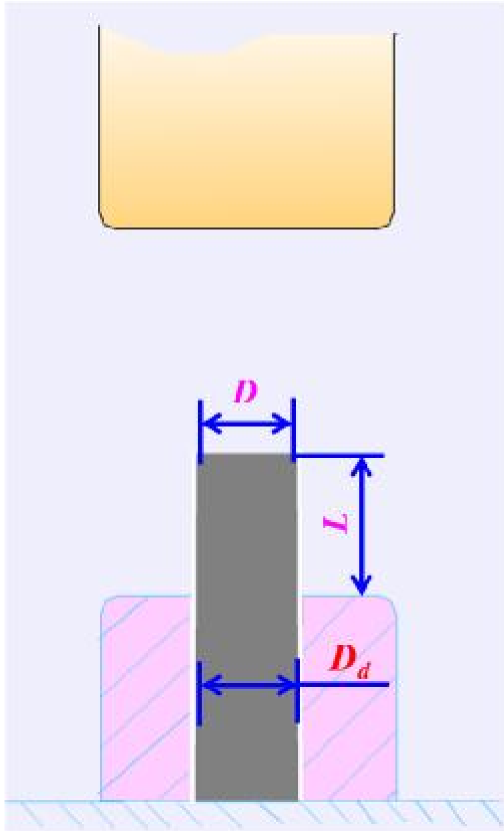
Important Consideration in Heading

L: the unsupported length of the bar
D: the diameter of the bar

- **Usually:** $\frac{L}{D} \leq 3$
- **Too high** $\frac{L}{D}$ **may cause the bar to buckle（*歪曲/变形*）**
- **With appropriate dies, it can be higher**

$D_d \leq 1.5D \longrightarrow \frac{L}{D} \uparrow$

D_d: the diameter of the die cavity



* Headers（*顶镦机*）

- **Usually are highly automated with production rates of hundreds of pieces per minutes for small parts.**
- **Hot heading operations on larger parts typically are performed on horizontal upsetters（*平镦机/平锻机*）.**
  - **these machines tend to be noisy**
  - **require *soundproof enclosure*（*隔音罩*） or the use of ear protectors（*护耳器*）**
- **Heading operations can be combined with cold-extrusion processes to make various parts**

§ 6.4

Forming Near-spherical Blanks for Ball Bearings
（滚珠轴承近球状毛坯的成形）

- to shear pieces from a round bar and then upset（镦粗） them in headers（顶镦机） between two dies with semispherical cavities
- The balls made by these processes are subsequently ground and polished for use in ball bearings

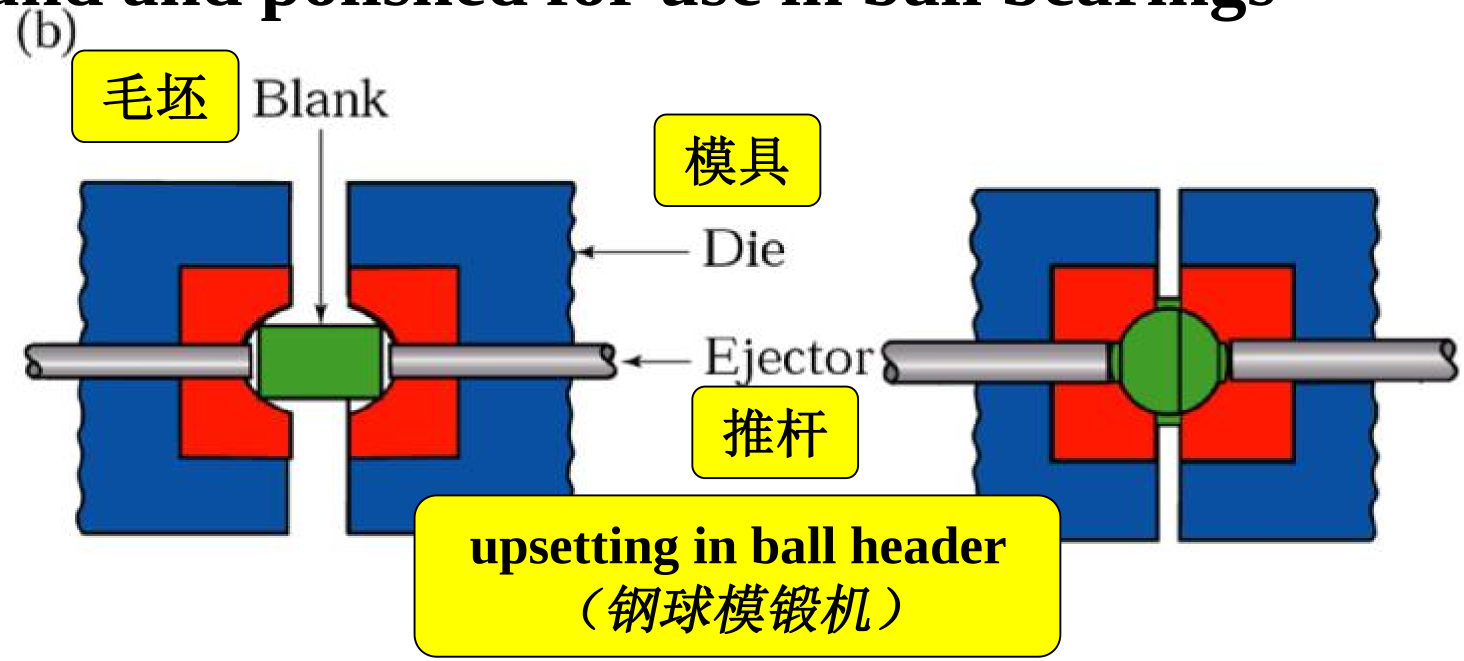


Figure 4.14 (b) Production of steel balls by upsetting a cylindrical blank. Note the formation of flash. The balls made by these processes are subsequently ground and polished for use in ball.

3. Piercing（冲缺/冲孔）

- is a process of indenting （压槽/压痕） the surface of a workpiece with a punch（冲头/凸模）(but not breaking through) in order to produce a cavity or an impression .
- workpiece my be confined in a container (such as a die cavity) or my be unconstrained
- may be followed by punching （冲孔）, to produce a hole in the part;
- also performed to produce hollow （中空的） regions in forgings using side-acting auxiliary equipment（横向运动的辅助设备）

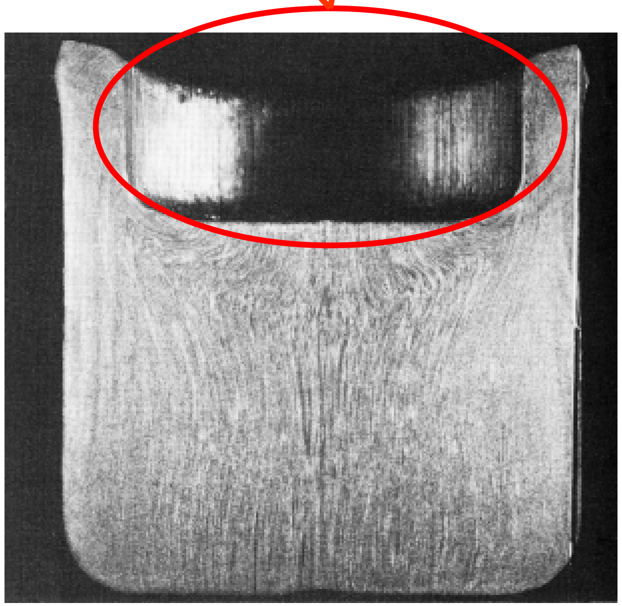


Figure 5.12 A pierced round billet, showing grain flow pattern. *Source*: Courtesy of Ladish Co., Inc.

* Piercing Force

- **The piercing force depends on:**

  a) the cross-sectional area and the tip geometry of the punch

  b) the strength of the material

  c) the magnitude of friction at the sliding interfaces

- **The pressure may range from three to five times the strength of the material, which is approximately the same level of stress required to make an indenting in hardness testing.**

Stepped Pin（阶梯杆）by Heading and Piercing Operations

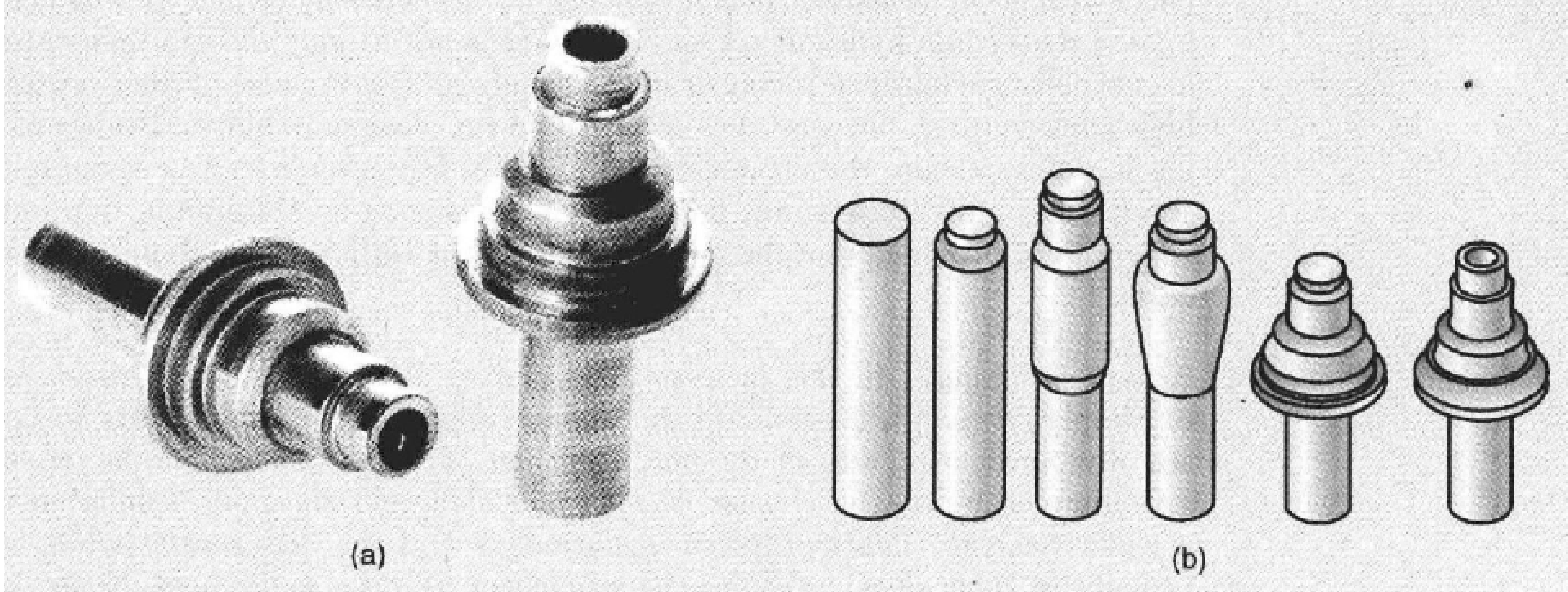


FIGURE 5.13 (a) The stepped pin used in Case Study 5.1. (b) Illustration of the manufacturing steps used to produce the stepped pin. *Source*: Courtesy of National Machinery, LLC.

5.5 Forgeability of Metals; Forging Defects

（金属可锻性；锻造缺陷）

- Forgeability
  - is generally defined as the capability of a material to undergo deformation without cracking.
  - Various tests have been developed to quantify（量化）forgeability
  - However, because of their complex nature, only two simple tests have had general acceptance
    - upsetting（镦粗）
    - hot twist（热扭转）

Test Method

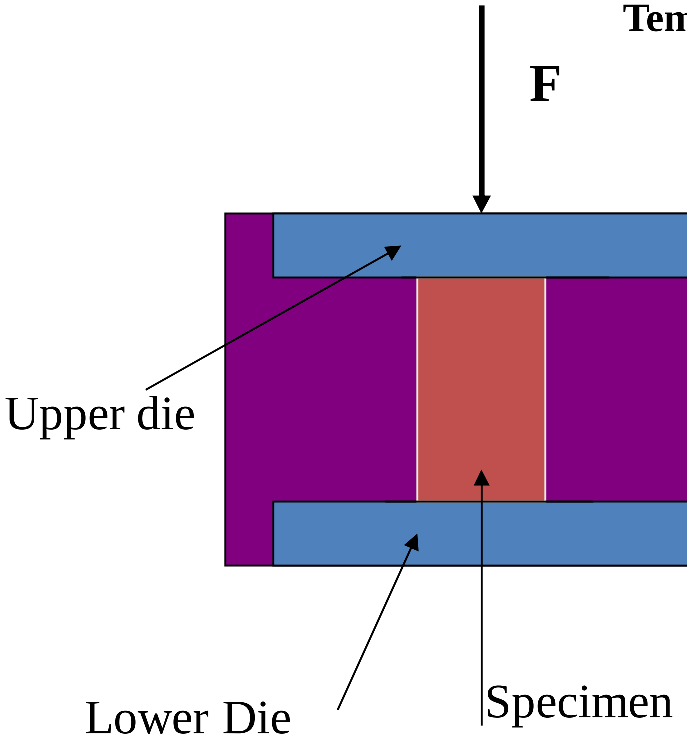
1. upsetting test（镦粗试验）

- to upset a solid cylindrical specimen （试样） between two flat dies and note（记录） the reduction in height at which cracking on the barreled surfaces begins
- the greater the deformation prior to cracking, the greater the forgeability of the metal.
- can be performed at various temperatures and deformation rates（变形速率/应变速率）

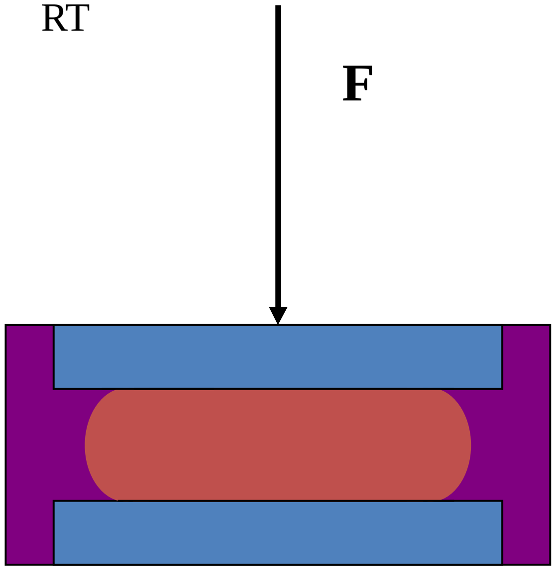
Upsettabilty Test

Billet:

Diameter:	11.97mm
Hight:	18.00mm
Material:	2025 (Al25/JIS) and S45C (JIS)
Lubrication:	without lubrication
Temperature:	RT

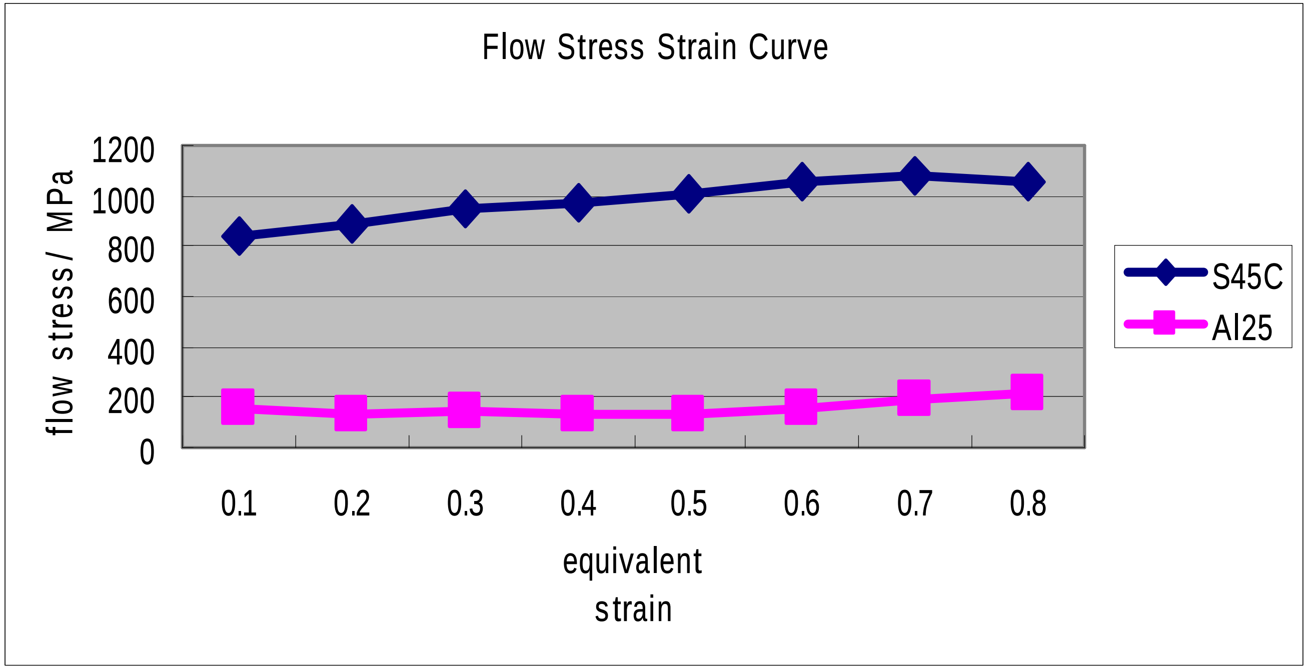


A, before compression



B, after compression

Results



The flow stress of steel is much more higher than those of the aluminum alloy.

The steel needs a higher forming force than the aluminum alloy.

2. hot-twist test（*热扭转试验*）

- **a round specimen is twisted continuously in the same direction until it fails.**
- **the test is performed on a number of specimens at different temperatures**
- **the number of turns（*扭转圈数*） that each specimen undergoes before failure is plotted（*标记*）.**
- **the temperature at which the maximum number of turns occurs then becomes the forging temperature for maximum forgeability.**
- **the hot-twist test is particularly useful for steels**

Table 5.3 Forgeability of Metals, in Decreasing Order

	Metal or alloy	Approximate range of hot forging temperature (°C)
铝合金	Aluminum alloys	400–550
镁合金	Magnesium alloys	250–350
铜合金	Copper alloys	600–900
碳钢和低合金钢	Carbon and low–alloy steels	850–1150
马氏体不锈钢	Martensitic stainless steels	1100–1250
奥氏体不锈钢	Austenitic stainless steels	1100–1250
钛合金	Titanium alloys	700–950
铁基超合金	Iron-base superalloys	1050–1180
钴基超合金	Cobalt-base superalloys	1180–1250
钽合金	Tantalum alloys	1050–1350
钼合金	Molybdenum alloys	1150–1350
镍基超合金	Nickel-base superalloys	1050–1200
钨合金	Tungsten alloys	1200–1300

可锻性

* Influence Factors of Forgeability

- ductility and strength of the material
- forging temperature
- frictional behavior
- quality of the forgings produced
- metallographic phase（金相） of the material
  - for Ti: two-phase alloys are more difficult to forge than single-phase alloys
  - requires careful selection and control of forging temperature.

* Forging Temperature

- differences in ductility at different temperatures
- For hot forging:
  - above recrystallization temperature of a material
  - higher temperature does not necessarily indicated（指示）greater difficulty in forging that material
- For warm forging:
  - aluminum alloys: 200℃ ～ 300℃ ;
  - steels: 550℃ ～ 750℃

Austenitic stainless steels	1100–1250
Titanium alloys	700–950

5.6 Die Design, Die Materials, and Lubrication

（模具设计、模具材料与润滑）

Die Design Features

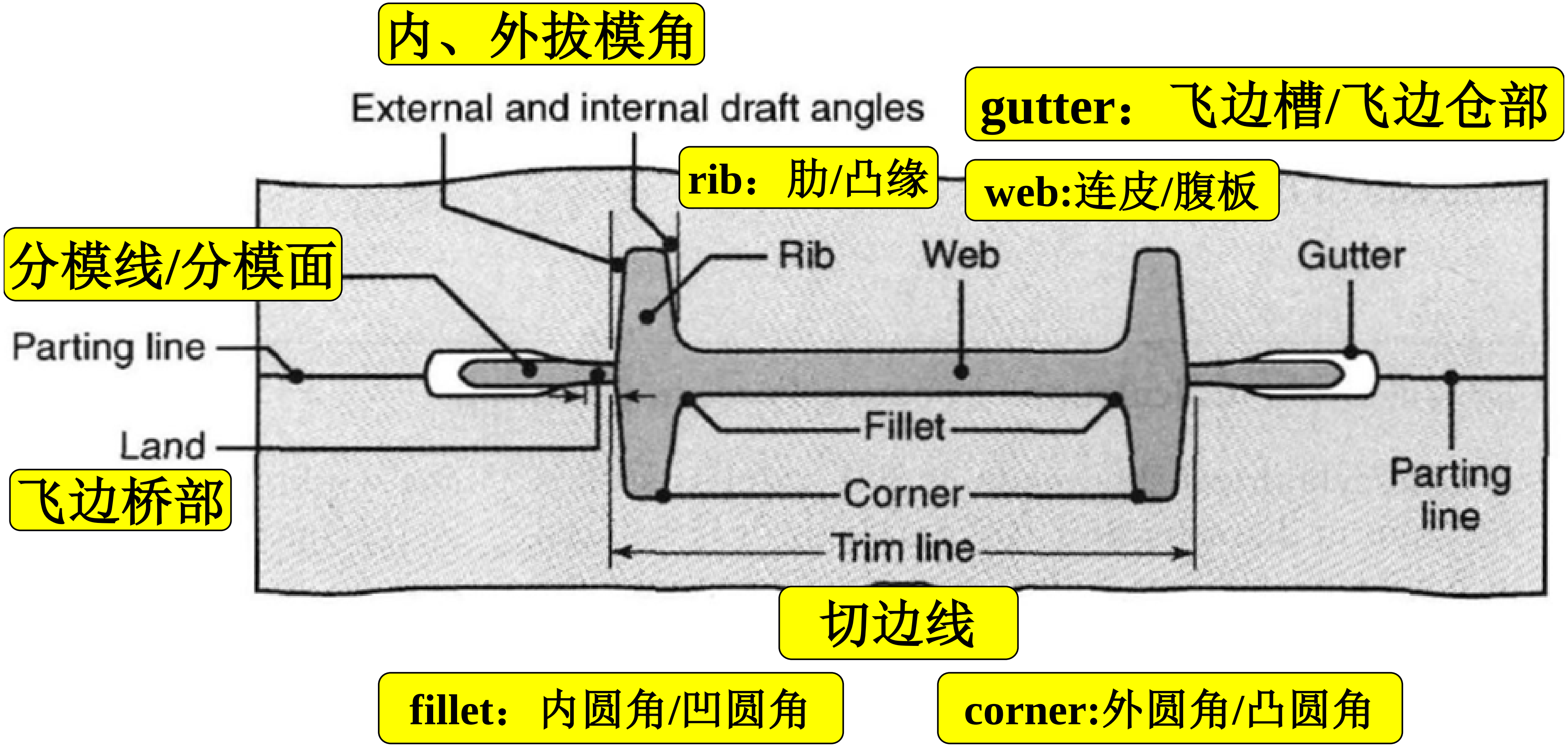


Figure 5.5 Standard terminology（*标准术语*）for various features of a typical impression-forging die.

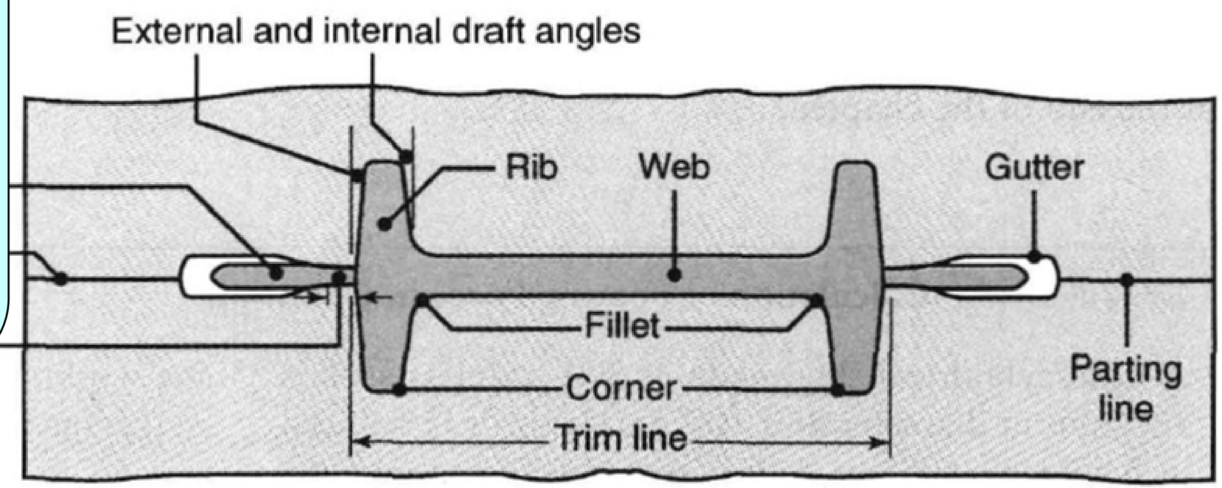
- **Parting line （分模线/分模面/分型面）**
  - usually at the **largest cross-section** of the part
  - mostly linear（直线的）
  - may be folding line（折线） to ensure the metal fill the die properly for the complex shape
  - The dies **lock（锁紧）** during engagement
    - to avoid side thrust（侧推力）
    - to balance forces
    - to maintain die alignment（对齐） during forging

closing force（合模力）

- **Draft angles（拔模角/脱模斜度）**
  - are **necessary** in almost all forging dies
  - in order to facilitate（便于） the removal of the part from the die（脱模）
  - involve **external angle** and **internal angle**

external draft angles:3° ～5 ° < internal draft angles:7° ～10 °

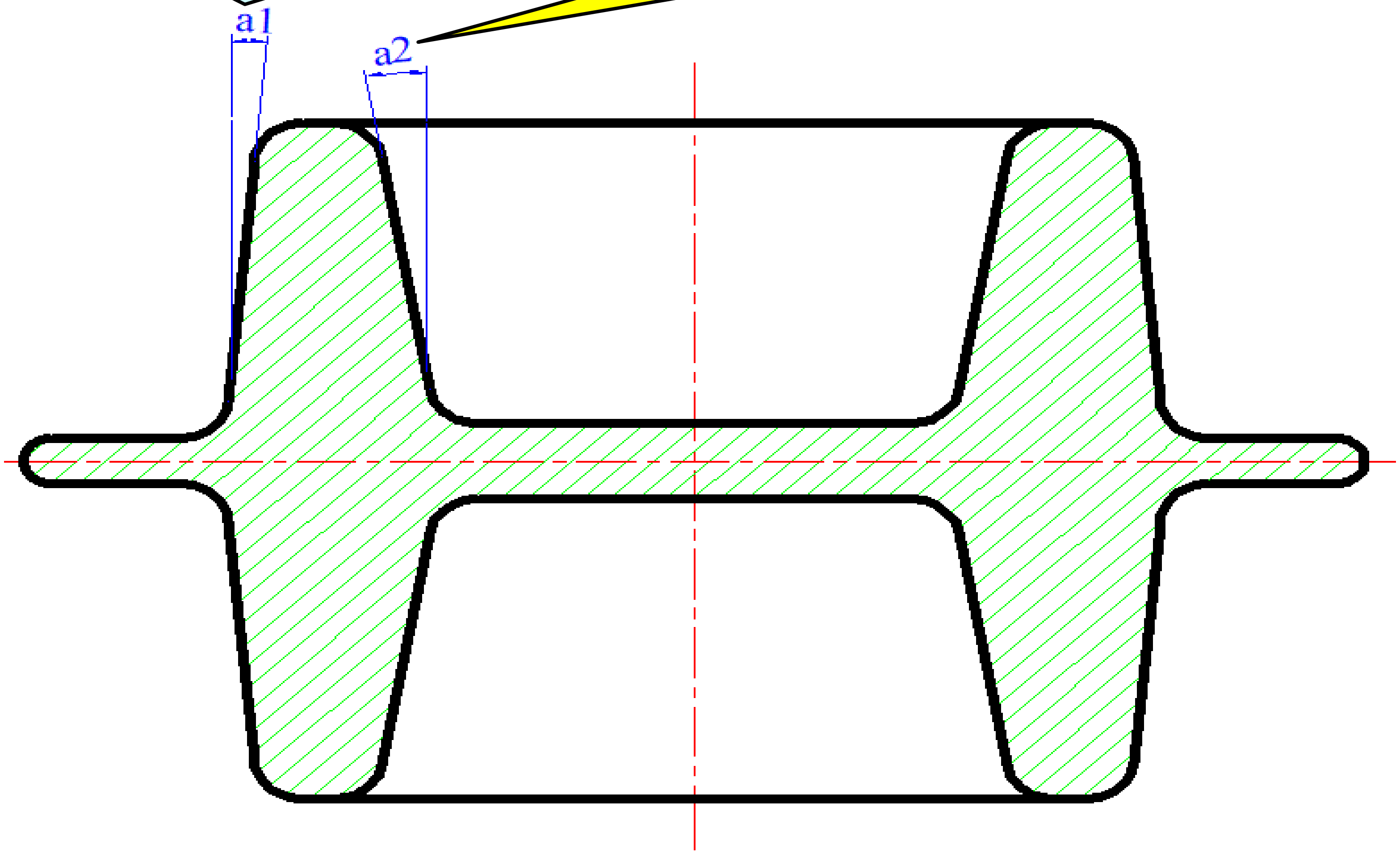
Reasons:
Upon cooling, the forging **shrinks**（收缩） both radially（径向地） and longitudinally（纵向地）



Reasons:

Upon cooling, the forging（锻件） shrinks（收缩） both radially（径向地） and longitudinally（纵向地）

external draft angles:3° ～5 °（锻件外拔模角） < **internal draft angles:7° ～10 °（锻件内拔模角）**



- **Radii for corners and fillets**（外圆角半径与内圆角半径）
  - **in order to ensure smooth flow of the metal into the die cavity**
  - **to improve die life**
  - **disadvantages of small radii:**
    - **can adversely effect the metal flow and tend to wear**（磨损）**rapidly (as a result of stress concentration**（应力集中）**and thermal cycling**（热循环）**)**
    - **can cause fatigue cracking**（疲劳裂纹）**of the dies.**
  - **as a general rule, these radii should be as large as can be permitted by the design of the forging, usually ≥3mm**

- **Machining allowances** （*切削余量/加工余量*）
  - **are provided in forging-die design because machining** （*切削加工*） **the forging**（*锻件*） **may be necessary to obtain final desired dimensions and surface finish.**
  - **allowance should be provided at flanges**（*法兰/凸缘*）**, at holes, and mating surfaces**（*配合面*）**.**

* Die material

- **General Requirements:**

  a. **strength** **and** **toughness** **at elevated temperature;**

  b. **hardenability** ***(淬硬性/淬透性）*** **and ability to** **harden uniformly** ***（均匀淬硬）*****；**

  c. **resistance** **to mechanical and thermal shock** ***（耐机械冲击与热冲击）***

  d. **wear resistance** ***（耐磨性）*****, particularly resistance to** **abrasive wear** ***（磨粒磨损/磨耗）*****, because of the presence of** **scale** **in hot forging.**

- **Selection of proper die materials depends on:**

  a) **die size**

  b) **composition and properties of the workpiece**

  c) **complexity of the shape**

  d) **forging temperature**

  e) **type of forging operation**

  f) **cost of the die materials;**

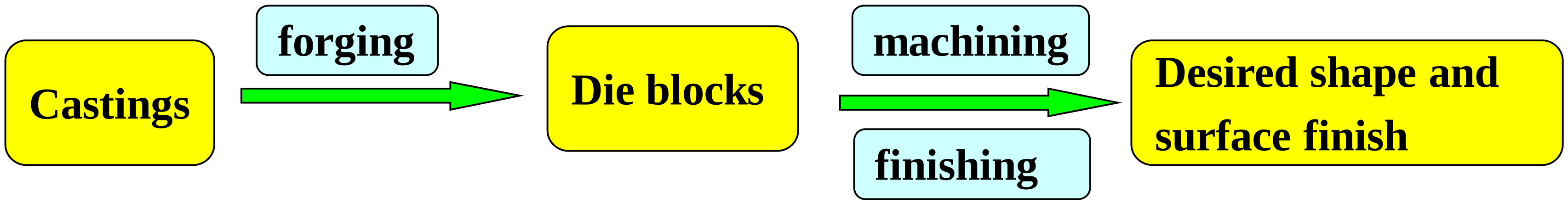
  g) **number of forgings required**

  h) **heat transfer** *（热传递）*

* Common Used Die Materials

- **tool and die steels** *（工具钢与模具钢）*
  - containing chromium (Cr), nickel (Ni), molybdenum (Mo), and vanadium (V）
- **cemented carbide***（硬质合金）* **is being used as forging die material widely.**

The procedures of producing dies



* Significance of Lubricants

- greatly influence friction and wear
- affect the forces required and the flow of the metal in die cavities
- act as a thermal barrier（*隔热层*）
  - slowing the rate of cooling of the workpiece and improving metal flow
- serve as a parting agent（*脱膜剂*）
  - inhibits（*防止*）the forging from sticking to the dies（*粘模*）and helps in its release from the die

* Application of Lubricants

- **For hot forging**
  - **graphite, molybdenum disulfide *(二硫化钼）*, and glass**
  - **applied directly to the dies**
- **For cold forging**
  - **mineral oils and soap**
  - **applied after conversion coating *（转化涂层/化学覆层）* of the blanks**
  - **applied to the workpiece**
- **The method and the uniformity of the lubricant's thickness on the blank are important to product quality.**

5.8 Forging Machines（锻造设备）

- **A variety of forging machines are in use, with a range of capacities（能力）, speeds and speed-stroke（冲程） characteristics.**
- **These machines are generally classified as：**

Ø presses（压力机）
- hydraulic presses（液压机）
- mechanical presses（机械式压力机）
- screw presses（摩擦压力机/螺旋压力机）

Ø hammers（锤锻机/锻锤）
- gravity drop hammer（重力锤）
- power drop hammer（动力锤）
- counterblow hammer（对击锤）
- high-energy-rate forging machines（高能高速压力锤）

1. Presses（压力机）

– Hydraulic Presses（液压机）

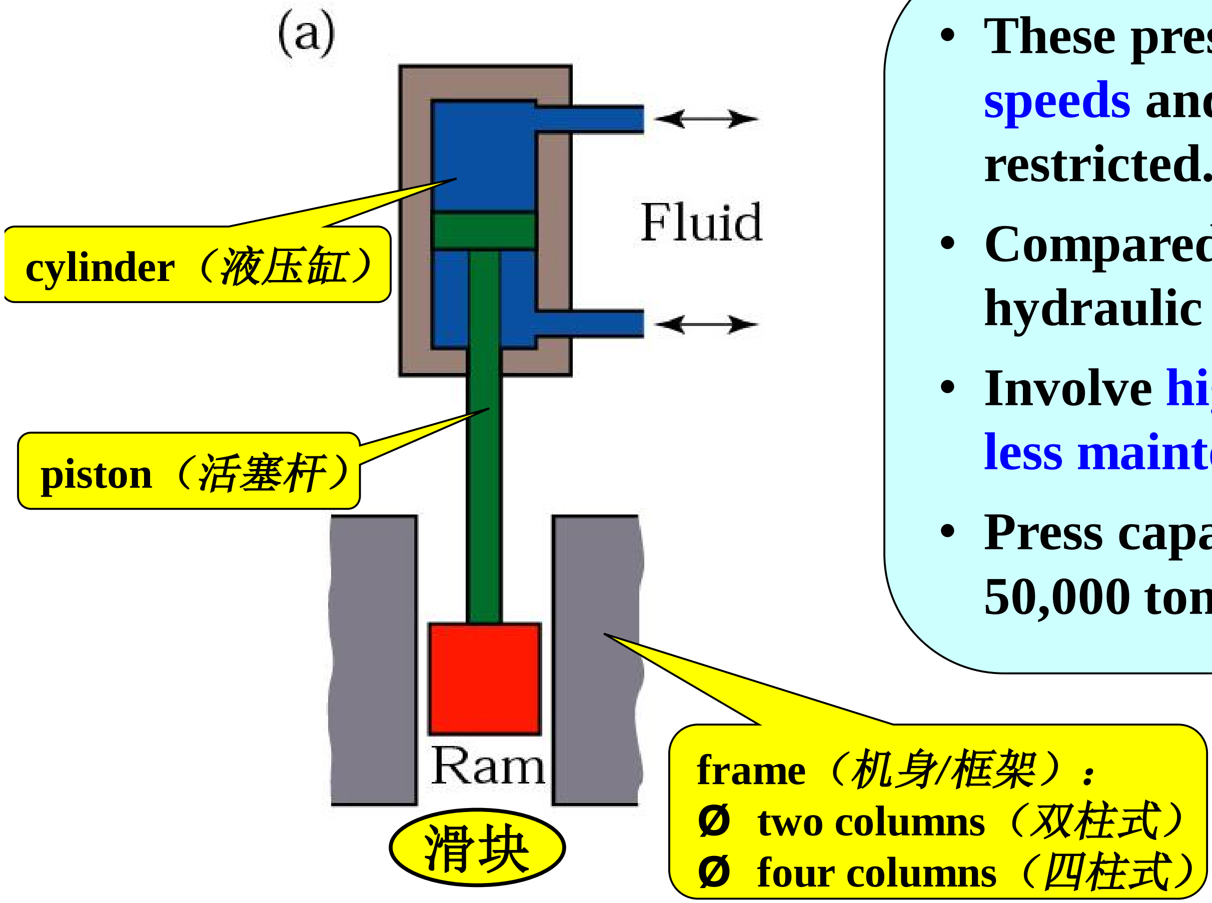


Figure 5.21 Schematic illustration of the principles of various forging machines. (a) Hydraulic press

- These presses operate at constant speeds and are load limited, or load restricted.
- Compared to mechanical presses, hydraulic presses are slower
- Involve higher initial cost, but require less maintenance.
- Press capacities can range up to 50,000 tons（≈500MN）

Hydraulic Press（液压机）

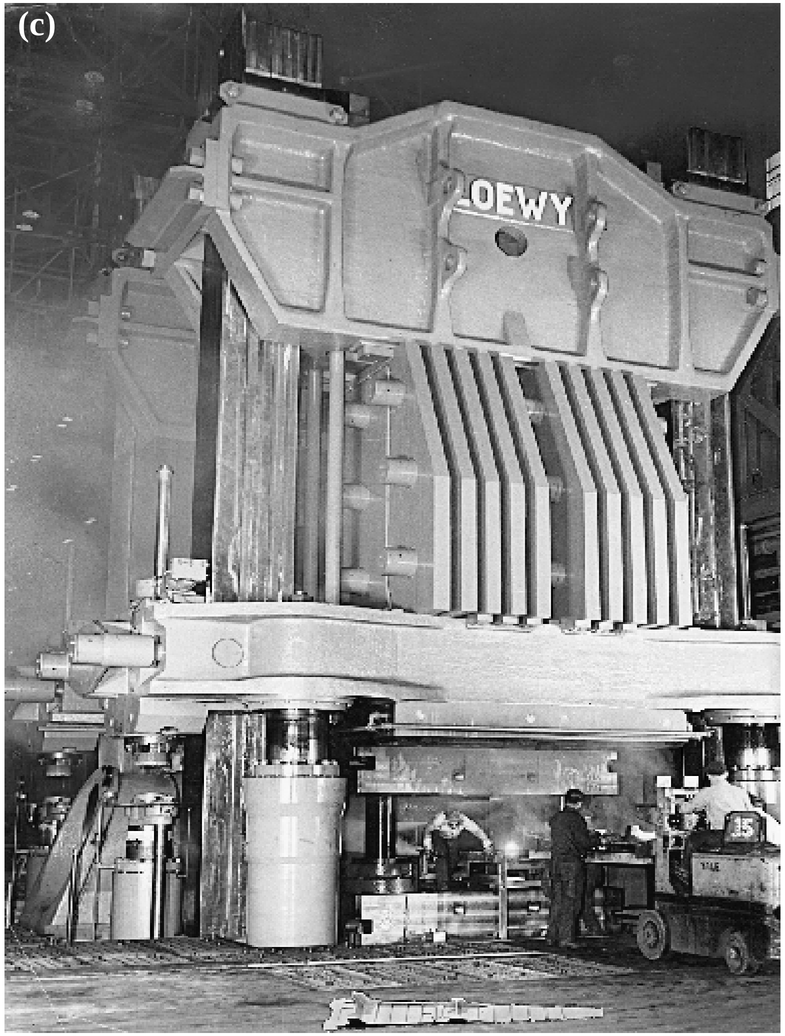
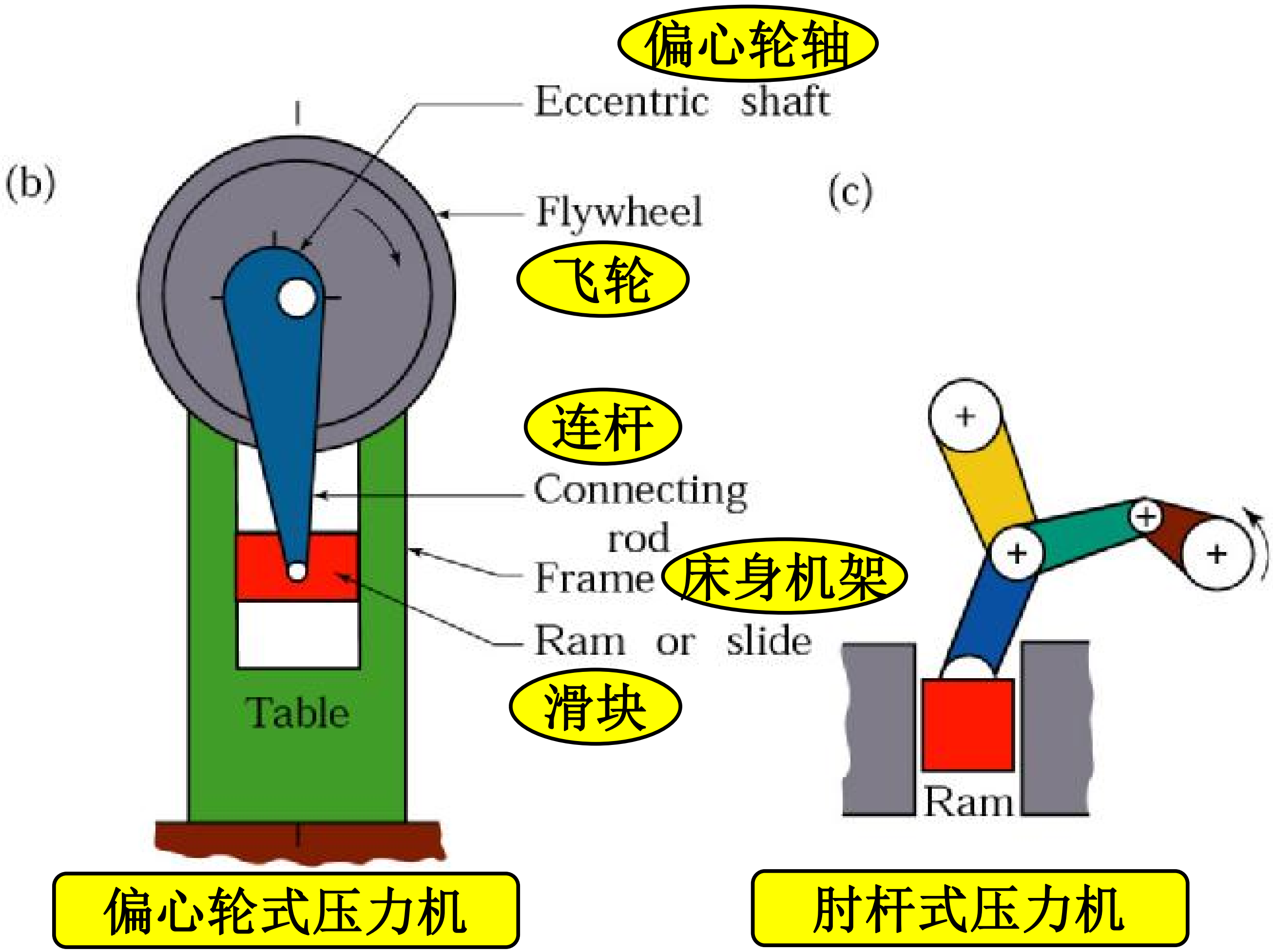


Figure 5.1 (c) general view of a 445 MN (50,000 ton) hydraulic press. *Source*: Wyman-Gordon Company.

– Mechanical Presses（*机械式压力机*）



- **Proper setup is essential to avoid breaking the dies or equipment components.**
- **Stroke limited.**
- **Having high production rates;**
- **Be easier to automate and require less operator skill;**
- **Capacities: 300 ～ 12,000 tons.**

Figure 5.21 Schematic illustration of the principles of various forging machines. (b) Mechanical press with an eccentric drive; the eccentric shaft can be replaced by a crankshaft（*曲轴/曲柄*）to give the up-and-down motion to the ram. (c) Knuckle-joint press.

– Screw Presses（摩擦压力机/螺旋压力机）

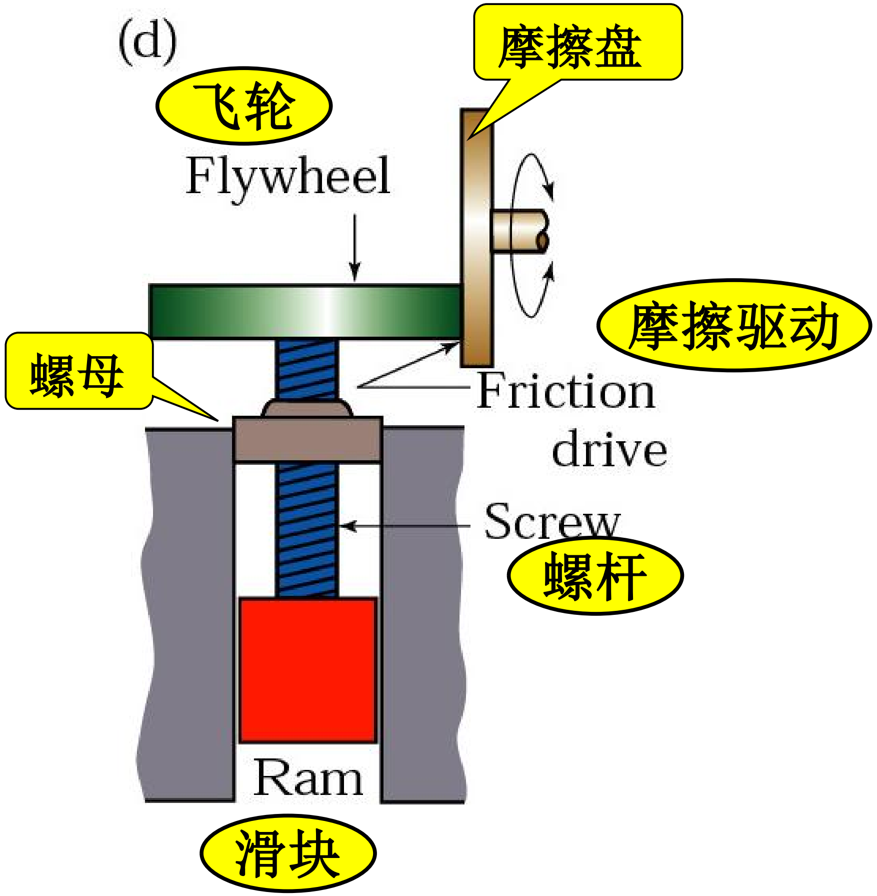
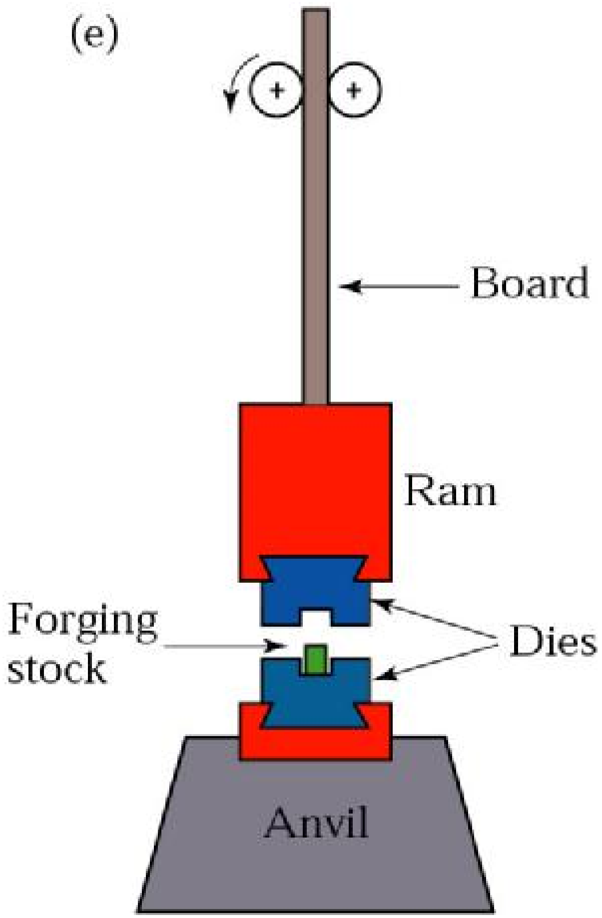


Figure 5.21 Schematic illustration of the principles of various forging machines. (d) Screw press.

- **Energy limited;**
- **Suitable for small production quantities and precision parts.**
- **Capacities: 160 ～31,500 tons.**

2. Hammers（锻锤/压力锤）



Gravity drop hammer（重力锤）

- **From the potential energy（势能） to kinetic energy（动能）, so energy limited.**
- **At high speeds, so low forming time.**
- **Suitable to forge complex shapes with thin and deep recesses（凹槽）.**

Figure 5.21 Schematic illustration of the principles of various forging machines. (e) Gravity drop hammer.

* Types of Hammers

– Gravity Drop Hammers（*重力锤*）

- **In the operation of gravity drop hammers, a process called drop forging（*落锤锻造/锤锻*）, the energy is derived form the free-falling ram.**
- **The available energy of a drop hammer is the product（*乘积*） of the ram's weight and the height of its drop.**
- **Ram wights range from 180 to 4500kg, with energy capacities ranging up to 120kJ.**

– Power Drop Hammers （*动力锤*）

- **In power drop hammers, the ram's downstroke is accelerated（*加速*） by steam, air, or hydraulic pressure at about 750kPa.**
- **Ram weights range from 225 to 22,500kg, with energy capacities 1150kJ.**

* Types of Hammers

– Counterblow Hammers （*对击锤*）

- **These hammers has two rams that simultaneously（*同时*） approach each other horizontally or vertically to forge the part.**
- **As in open-die forging operations, the part may be rotated between blows for proper shaping of the workpiece during forging.**
- **Counterblow hammers operate at high speed and transmit less vibration （*震动*） to their bases.**
- **Capacities range up to 1200kJ.**

– High-energy-rate Forging Machines （*高能高速压力锤*）

- **In these machines, the ram is accelerated rapidly by inert gas（*惰性气体*） at high pressure and the part is forged in one blow at a very high speed.**
- **Although there are several types of these machines, various problem associated with their operation and maintenance, as well as die breakage and safety considerations, have greatly limited their use in industry.**

Typical Speed Ranges of Forging Equipment

Equipment	m/s
Hydraulic press	0.06–0.30
Mechanical press	0.06–1.5
Screw press	0.6–1.2
Gravity drop hammer	3.6–4.8
Power drop hammer	3.0–9.0
Counterblow hammer	4.5–9.0

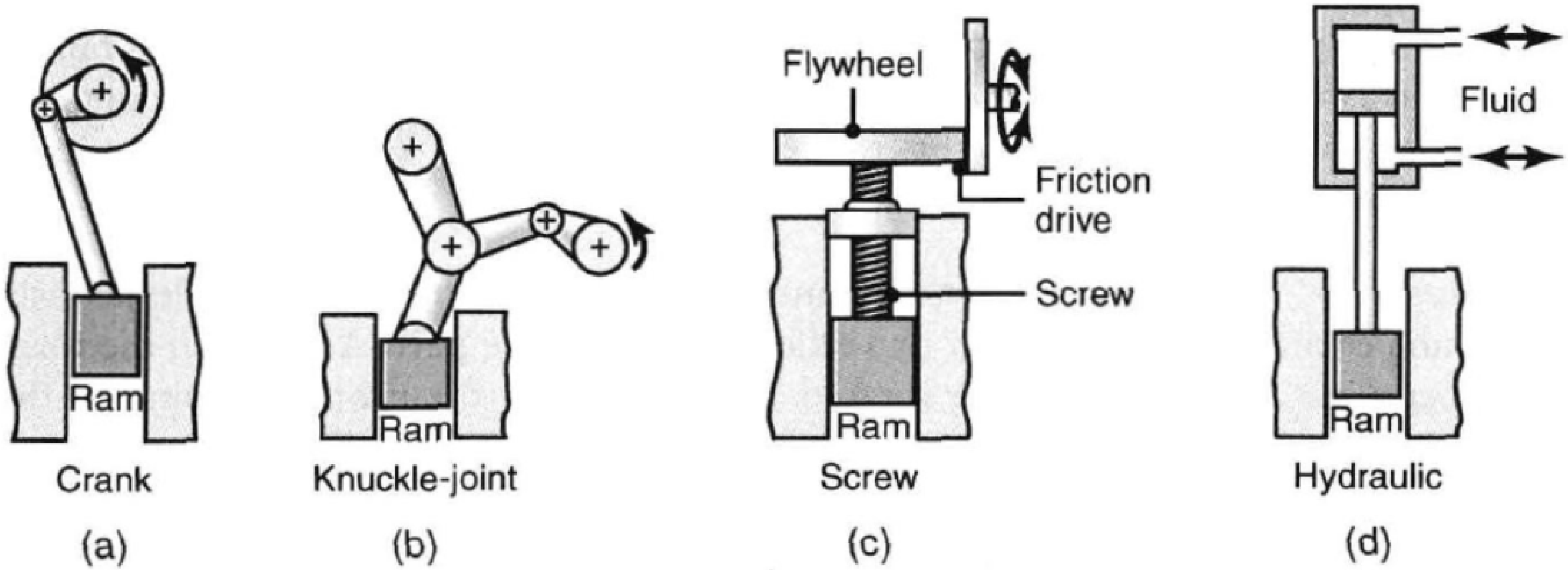


FIGURE 5.17 Schematic illustration of the principles of various forging machines. (a) Mechanical press with an eccentric drive; the eccentric shaft can be replaced by a crankshaft to give up-and-down motion to the ram. (b) Knuckle-joint press. (c) Screw press. (d) Hydraulic press.

Forging Equipment

1. **Mechanical 800 ton press** is used with hydraulic unit which provides closing pressure（*合模力/锁模力*）.

2. **Automation transfer mechanism** (mechanically or servo motor（*伺服电机*）driven)

Forces (Ø40mm pinion gear):	**Total production process force F = 2500～2800 kN**
	Die closing force F_c =1700～1800 kN (p=200 kg/cm²)
Productivity:	**Mechanical KOMATSU press - 800 ton**
	20-22 parts / minute (top speed of hydraulic system)
	8000 pieces / 8 work hours (>80 % efficiency)

KEY TERMS

forging	锻造
compressive forces	压力
press	压力机
forging hammer	锻锤
anvil	平帖
metal flow	金属流动
grain structure	晶粒结构
strength	强度
toughness	韧性
cold forging	冷锻
warm forging	温锻
hot forging	热 锻
room temperature	室温
recrystallization	再结晶
ductility	韧性
surface finish	表面精度
dimensional accuracy	尺寸精度
heat treating	热处理
machining	切削
precision forging	精密锻造
net-shape forming	净成形
near-net shape forming	近净成形
open-die forging	自由锻
impression-die	胎模锻
closed-die forging	闭式模锻
upsetting	镦粗

flat-die forging	自由锻
barrel shape	桶形，鼓形
pancaking forging	扁平锻造
frictional force	摩擦力
lubricant	润滑
resistance	阻力
deformation	变形
thermal effects	温度影响
cogging	镦粗拔长
draw out	拔长
thickness	厚度
successive forging	连续锻造

die cavities	模腔
flash	飞边
frictional resistance	摩擦阻力
pressure	压力
performing forging	预成形锻造
fullering	压槽
edging	切边
blocking	粗锻/初锻
finishing	精整
removing flash	去飞边
flashness forging	无飞边锻造

Review Questions

1. What is forging?
2. Compared to cast and machined parts, what are the advantages of forged parts ?
3. How to distinguish cold/warm/hot forging ?
4. What is the open-die forging ?
5. Describe the process of upsetting and cogging.

6. **What is the difference between forging being done under ideal condition and actual condition?**
7. **Why does barrel shape appear in forging ?**
8. **How to minimize barreling?**
9. **What is the difference between open-die forging and impression-die forging ?**
10. **What is flash ? What is the significance of flash?**

11. What are the stages involved in impression-die forging?

12. What is the closed-die forging?

13. What is the precision forging ?

5. Understand the basic process of coining, hubbing, heading, rolling forging, skew forging, orbital forging?

15. Understand the terms used in forging dies: parting line, draft angle, fillet or corner, flash gutter and land.

16. Understand the principles of two types of forging machines: press and hammer.