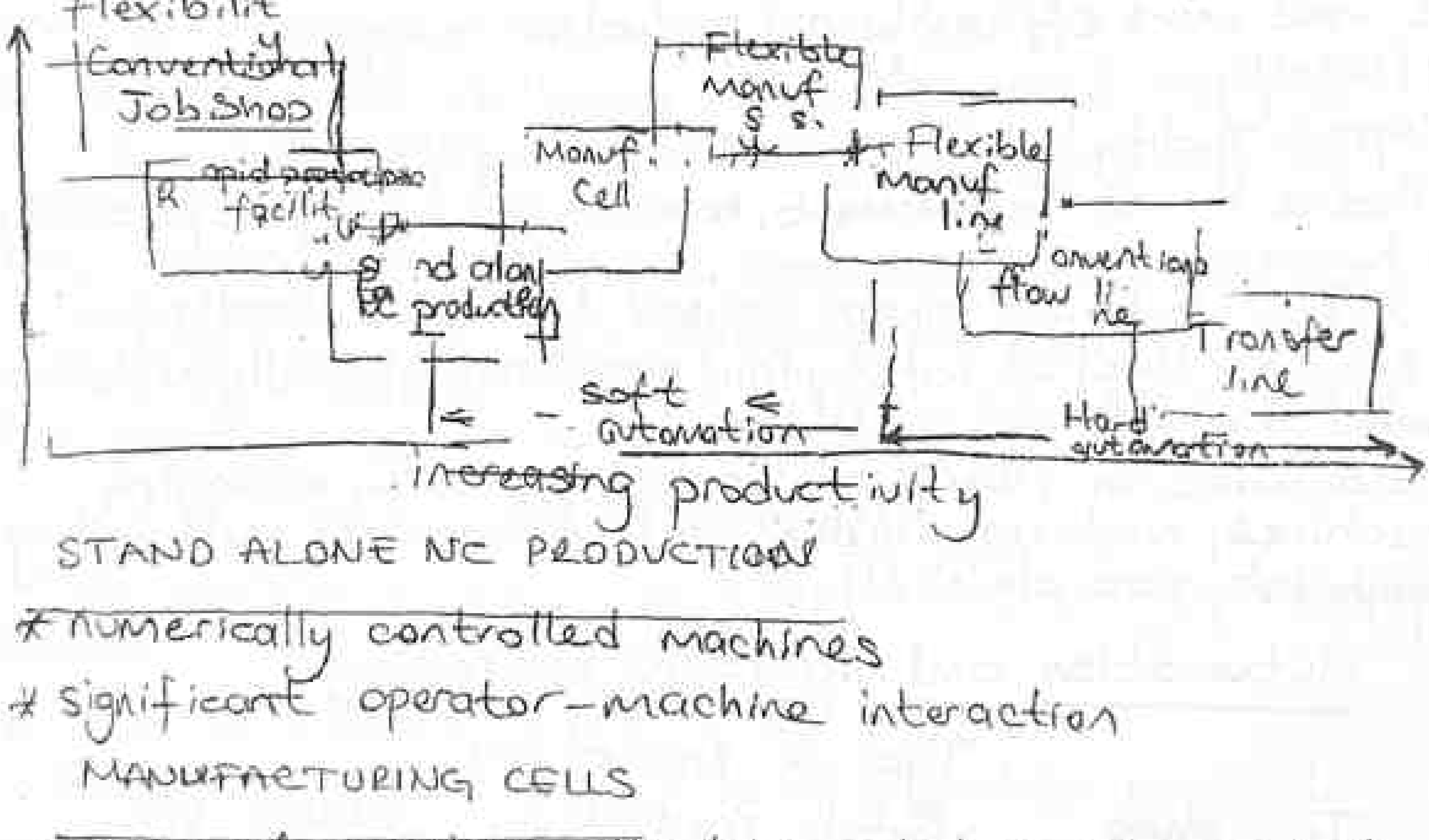
MANUFACTURING TECHNOLOGIES ME-202

CHAPTER--37 AUTOMATION of MANUFACTURING

JOB SHOP!

* ~~High levels of~~ labor involvement → in fact requires skilled labor
* General purpose
* small quantities per year
* different parts can be produced in a short time without extensive changes in tooling or in operations.
* production cost per part is high



STAND ALONE NC PRODUCTION

* numerically controlled machines
* significant operator-machine interaction

MANUFACTURING CELLS

* group of machines with integrated computer control
  * flexible material handling with industrial robots

FLEXIBLE MANUF. SYSTEM

* Use comp. cont. all aspect of manuf

FLEXIBLE MANUF LINES

* Involve computer-controlled machinery
* organized in production lines instead cells

Flow lines and transfer lines

* consist of organized groupings of machinery
* automated material handling between Machines
* goal: produce one type of part

IMPLEMENTATION of AUTOMATION

* Integrate various aspect of manufacturing operations to improve product quality and uniformity, minimize cycle times and effort, and reduce labor costs.
* Improve productivity by reducing manufacturing costs through better control of production; parts are loaded, fed, and unloaded on machines more efficiently; machines are used more efficiently; and production is organised more efficiently.
* Improve quality by using more repeatable processes.
* Reduce human involvement, boredom and thus the possibility of human error
* Reduce workpiece damage caused by manual handling
* Raise the level of safety for personnel, especially under hazardous working conditions.
* Economize on floor space in the plant by arranging machines, material handling and movement, and auxilary equipment more efficiently.

Automation and Production Quantity

Type of Production

Job Shop   Batch Production   Mass Pro.

general ←—— Equipment ——→ special

———— Production rate ——→

———— Production quantity ——→

Process ←—— Plant layout ——→ Flow line

←—— Labor skill ————

←—— Part variety ————

Piece-Part Production

* Generally involves very small quantities.
* Suitable for Job shop * 50 or less

Small-batch Production

* 10-100
* General purpose machines and machining centers

Batch Production

* involves lot sizes of 100-5000
* similar machinary to small-batch
* special designed fixtures for higher productivity

Mass Production

* over 100-000
* special purpose machinery called dedicated machines
* automated equipment for transferring materials and parts in progress.
* organised for a specific product * lack flexibility
* Although the machinery, equipment and specialized tooling are expensive, both the labor skills required and the labor costs are relatively low.

APPLICATIONS of AUTOMATION

The decision to automate a new or existing production facility includes the following

* Type of product manufactured
* Production quantity and rate of production required.
** Particular phase of the manufacturing operation
* Level of skill in the available workforce
* Reliability and maintenance problems that may be associated with automated machinery and systems
* Economics of the whole operation

** → selective automation

Hard Automation

* also called fixed-position automation
* machines are designed to produce a standart product.
* Lack of flexibility
  → Powerhead Production units
  → Transfer machines
  → Transfer lines (flow line)

Soft Automation

* greater flexibility
* also called flexible or programmable automation
* can produce parts with complex shapes ⇒ Computer Control
* extensive use of modern computers

Programmable Logic Controllers ?
Total productive maintenance?

NUMERICAL CONTROL

First prototype NC machine → M.I.T (Massachusetts Institute ...)

* a method of controlling the movements of machine components by directly inserting coded instructions

COMPUTER NUMERICAL CONTROL

Direct Numerical Control (DNC)

* controlled directly by a central mainframe computer
* the status of all machines in manufacturing facility can be monitored and assessed from a central computer
* disadvantage: if the computer shuts down for some reason, all of the machines become inoperative

Distributed Numerical Control

* central computer → inividual CNC machine
* valuable when computers lacked the memory neccessary to store all of the data for machining operations essential to produce a part.

* a recent development is to use cloud storage

Computer Numerical Control (CNC)

* small computer with large memory
* low-cost programmable controllers and microprocesso
* program editing capabilities

PRINCIPLES of NC MACHINES

* Data input * Data Processing * Data Output

Types of control circuits:

1. Open loop systems: the signals are sent to the ser omotor by the controller, but the movements and final positions of the worktable are not checked for accuracy.
2. Closed loop system: is equipped with various transducers sensors and counters that accurately measure the position of the worktable. Through feedback control, the position of the worktable is compared against the signal; the table movements terminate when the proper coordinates are reache

Position Measurement

1. Indirect Measurement
2. Direct Measurement → more accurate results

Advantages and Limitations of Numerical Control

✓ Accuracy	× initial cost
✓ Flexibility	× programming cost
✓ High precision	× maintenance
✓ Less scrap	
✓ Less skill	
✓ Complex shapes	
✓ easy to make adjustments	
✓ less requirement of skilled labor.	

37.14 ADAPTIVE CONTROL (AC)

* a dynamic feedback system
→ optimize production rate → check the parameters: cutting forces, spindle torque, temperature rise, tool wear, tool condition and surface finish produced.
→ optimize product quality
→ optimize production cost

* Systems → optimize operation → adaptive-control optimization (ACO) systems.

37.15 MATERIAL HANDLING

The factors to be considered in selecting a material-handling

* Shape, weight, and characteristics of the parts
* Distances involved and the position and orientation of the parts during their movement and at final destination.
* Conditions of the path along which the parts are to be transported.
* Level of automation, the controls needed, and any integration with other equipment and systems.
* Operator skill required
* Economic considerations.

AGV (automated guided vehicles) → used in flexible manuf. sys.

equipments used for moving materials and parts in progress may consist of:

* conveyors * rollers * carts, * forklift trucks
* self powered mono-rails * manipulators → controlled: directly by operator

37.16 INDUSTRIAL ROBOTS

Manipulator: (arm or wrist)
Most robots have six rotational joints; seven degrees of freedom also are available for special applications

End Effector: The end of the wrist.

Power Supply:

Sensors: (Feedback Devices)

Controller:

Basic types of robots:

* Cartesian, or rectilinear * Cylindirical * Spherical, or polar
* Articulated

Factors that influence the selection of robots in Manuf:

* Load carrying capacity * work envelope * speed of movement
* reliability * repeatability * arm configuration * degrees of freedom
* The control system * cost and benefit consideration.

37.7 SENSOR TECHNOLOGY

A device that produces signals in response to its detecting for measuring a specific property.

→ Mechanical → Chemical → Electrical → Magnetic
→ Thermal

Sensor Fusion: Merge all sensor outputs ⇒ 'merge = birlestirme'

37.8 ASSEMBLY SYSTEMS

Automated Assembly:

- Random assembly
- Selective assembly

Methods and Systems of Assembly

* Manual assembly
* High speed automated assembly
* Robotic assembly
  - Sychronous systems
  - Nonsychronous systems
  - Continuous systems

37.11 ECONOMIC CONSIDERATION

* Type and cost of machinery, equipment and tooling
* Cost of operation of the machinery
* Skill level and amount of labor required
* Production quantity desired.

CHAPTER-38 : COMPUTER – AIDED MANUFACTURING

38.3 COMPUTER INTEGRATED MANUF

Subsystems of CIM:

* Business planning and support
* Product design
* Manuf. process planning
* Process automation and control
* Production – monitoring systems

DATABASE

Up-to-date, detailed and accurate info abut designs, products, processes, materials, machinery ___ . This vast array of information is stored in computer

Factors in the use databases:

* accessible * easily shared
* flexible and responsive to the needs of different users
* protect data against tampering and unauthorized use
* recovered data

38.4 COMPUTER-AIDED DESIGN and ENGINEERING

CAD→design and geometric modelling of components and products

CAE → allows severall applications to share the information in the database:

a) finite-element analysis of stresses, strains, deflections, and temperature distribution in structures and load-bearing members

b) the generation, storage and retrieval of NC data

c) the design of integrated circuits and electronic devices

38.5 EXCHANGE SPECIFICATIONS

Drawing exchange format (DFX) has been superseded by the DWG file format.

STL used to export 3-D geometries

IGES → is used 2 directions and 3-D line and surface data

38.4.2. Element of CAD Systems

* Geometric modelling
* Design analysis and optimisation
* Design review and evaluation
* Database

38.5 COMPUTER-AIDED MANUFACTURING

* use of computers to assist in all phases of manuf. a product. It encompasses many technologies.
* CAD and CAM are often combined into CAD/CAM system. It allows the transfer of information from the design stage to the stage of planning for manuf.

38.6 COMPUTER-AIDED PROCESS PLANNING

* selecting methods of production
* routing sheets are the traditional means for storing manuf data.
* CAPP accomplishes the complex task of process planning by viewing the total operation as an integrated system.
* CAPP is powerful tool for efficiently planning and scheduling

38.8 GROUP TECHNOLOGY

methodology that seeks to take advantage of the design and processing similarities among the parts to be prod.
→ classifying and coding parts into families
advantages of GT
* standardization of part design and minimization of design duplication
* data that reflect the experience of the designer → new engineer
* cost can be more easily estimated
* process plans can be standardized and scheduled more efficiently
* setup times are reduced
* implementation of CAD and CAM, cellular manuf, and CIM group technology is capable of greatly improving productivity and reducing costs, with batch prod. approaching the benefits of mass prod.

CHAPTER-39 COMPUTER INTEGRATED MANUFACTURING SYSTEMS

39.2 CELLULAR MANUFACTURING

Small unit consisting of one ore more work stations.

The capabilities of cellular manuf.

* Loading and unloading raw materials and up at workstations.
* Changing tools at workstations
* Transferring workpieces and tooling between workstations
* Scheduling and controlling the total operation in the cell.

Flexible Manuf. Cells: Manuf cells can be made flexible by using CNC machines and machining centers, and by means of industrial robots.

Cell Design: U-shape, L-shape or a loop.

39.3 FLEXIBLE MANUFACTURING SYSTEMS

An FMS integrates all of the major elements of production into a highly automated system. Fir utilized late 1960s.

Consisting of

* a number of manuf cells, each containing a robot serving several CNC machines
* an automated material-handling system
* an automated guided vehicle (AGV)

An FMS capable of optimizing each step of the total operation

* one or more processes and operations
* handling of raw material and parts
* measurement and inspection
* assembly

FMS can be regarded as a system that combines the benefits of two systems

* the highly productive but inflexible transfer lines
* job-shop production → large product variety

→ time required for a changeover to a different part is very short

Charecteristic	Transfer Line	FMS
* Part variety	Few	Infinite
* Lot size	>100	1-50
* Part changing time	Long	Very-short
* Tool change	manual	automatic
* Adaptive control	difficult	available
* Inventory	high	low
* Production during breakdown	none	partial
* Justification for Capital expenditure	simple	difficult

servaye ↳ harcama

Compared with conventional manuf. system, FMS have the following major benefits

* Parts can be produced in any order, in batch sizes as small as one, and at lower unit cost
* Direct labor and inventories are reduced or eliminated
* The lead times required for product changes shorter
* Because the system is self-correcting, production is more reliable and product quality is uniform

disadvantages

* Equipment costs, and computer integration requires more highly trained operated personel
* FMS not suitable for very low or very high production rates

Elements of FMS

* Workstation and cells
* Automated handling and transport of materials and parts
* Control systems

~~***~~ When a variety of parts is to be produced, FMS is suitable for production quantities typically up to 15,000 to 35,000 aggregate parts per year.

33.5 JUST IN TIME PRODUCTION (zero inventory / stockless production / demand scheduling) 12

The goals

* Receive supplies just in time to be used.
* Produce parts just in time to be made into subassemblies
* Produce subassemblies just in time to be assembled into finished products.
* Produce and deliver finished products just in time to be sold.

=) PULL SYSTEM → parts are produced to order

JIT emphasizes

* pride and dedication in producing high-quality products
* elimination of idle resources
* teamwork among workers, engineers, and management to promptly solve any problems that arise during production or assembly.

Advantages of JIT

* Low inventory carrying costs
* Rapid detection of defects
* Reduced Inspection and reworking of parts
* High quality products

SUFACE TECHNOLOGY PART VII

Surface Roughness and Measurement; Friction, wear and Lubrication CHAPTER 33

33.2 Surface Structure and Integrity

TEKRAR OKU

CHAPTER-21 FUNDAMENTALS of MACHINING

21.1 INTRODUCTION

Cutting Processes

* Turning
* Cutting off
* Slab milling
* End milling

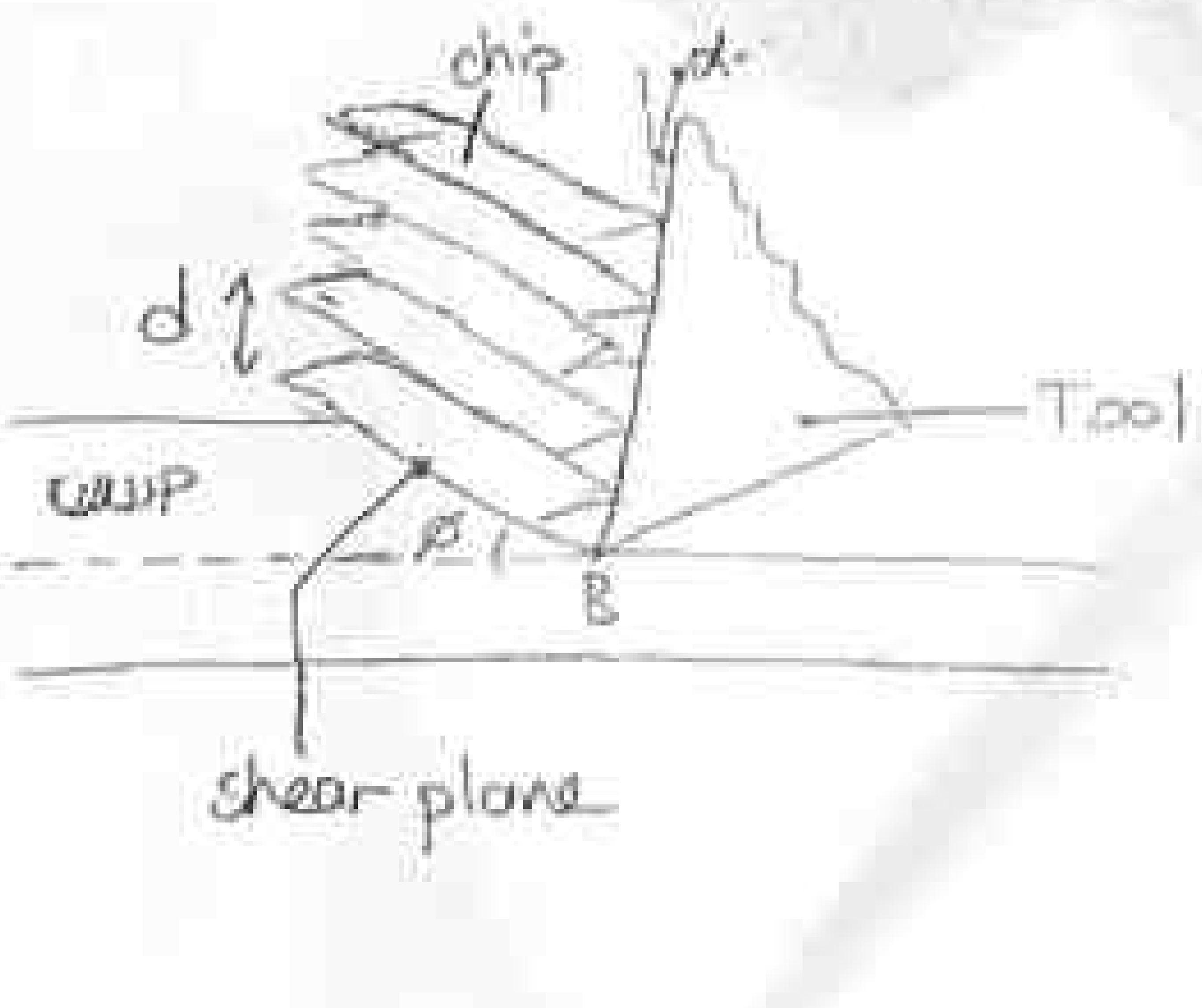
21.2 MECHANICS of CUTTING

The major independent variables in the basic cutting process

* tool material and coatings
* tool shape, surface finish, sharpness
* wp material
* cutting speed, feed and depth of cut
* cutting fluids
* characteristics of the Machine tool
* the type of workholding device

Dependent variables in cutting

* type of chip produced
* force and energy dissipated during cutting
* temperature rise in the wp, the tool and the chip.
* tool wear and failure
* surface finish and surface integrity



ϕ : shear angle

α : rake angle

Cutting Ratio:

$$r = \frac{t_o}{t_c} = \frac{\sin\phi}{\cos(\phi-\alpha)}$$

ϕ: shear angle
α: rake angle
t_o: depth of cut
t_c: chip thickness

$t_c > t_o$ always

Velocities in the cutting zone:

V_c: chip velocity
V: cutting speed

$V \cdot t_o = V_c \cdot t_c$ or $V_c = V r$

$$V_c = \frac{V \cdot \sin\phi}{\cos(\phi-\alpha)} \qquad r = \frac{V_c}{V}$$

21.2.1 Types of Chips Produced in Metal Cutting

* Continuous
* Built-up edge
* Serrated or segmented (nonhomogenous)
* Discontinuous

Continuous Chips:
- ductile materials
- high cutting speeds/high rake angles
- good surface finish
- not neccessarily desirable

Built-up edge Chips:
tendency for BUE formation can be reduced
* Increasing cutting speed
* Decrease the depth of cut
* Increase the rake angle
* use a sharp tool
* " an effective cutting fluid

Serrated Chips (Segmented, Nonhomogenous)
* semicontinuous chips with large zones of low shear strains and small zones of higher shear strain

Discontinuous chips:
Usually form under the following conditions
* Brittle wp materials
* Wp materials that contain hard inclusions and impurities
* Very low or very high cutting speed
* Large depth of cut, d
* Low rake angle α
* Lack of an effective cutting fluid
* Low stiffness of the toolholder or the machine tool, thus allowing vibration and chatter to occur.

CHIP CURL

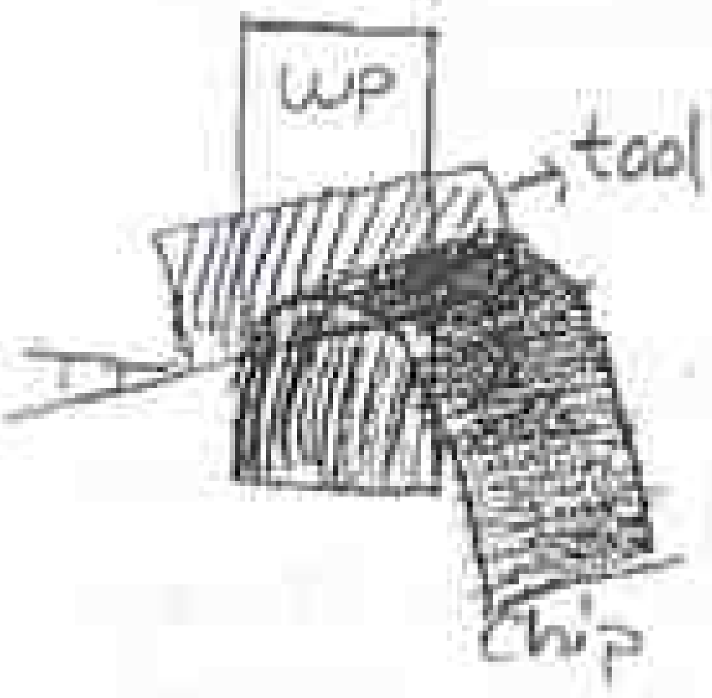
Among the factors affecting the chip curl
* The distribution of stresses in the primary and secondary shear zones
* Thermal effects in the cutting zone
* Work-hardening characteristics of the wp material
* The geometry of the cutting tool
* Processing variables
* Cutting fluids

→ depth of cut ↓ the chip becomes curlier

CHIP BREAKERS

Because cont. and long chips are not desirable, we use chip breakers.

21.2.2 OBLIQUE CUTTING



The chip becomes hellical and leaves the wp surface at angle i, called the inclination angle

SHAVING and SKIVING
* used improving surface finish
* dimensional accuracy ↑

21.3 CUTTING FORCES and POWER

* Flank surface: bottom of the tool

$P = F \cdot v$
$= F_c \cdot V$

excessive = aşırı

induce = sebep olmak

* rake surface: surface of the tool in touch with chips

21.4 TEMPERATURES in CUTTING

* Excessive temp. lowers the strenghth, hardness, stiffness and wear resistance of the cutting tool;
* Increased heat causes uneven dimensional changes in the part being machined,
* An excessive temperature rise can induce thermal damage and metallurgical changes

Main sources of heat in machining:
* the work done in shearing
* friction between tool-chip
* heat generated between tool and wp surface

21.5 TOOL LIFE: WEAR and FAILURE

The conditions induce tool wear
* high localized stresses at the tip of the tool
* high temperatures especially along rake face
* sliding of the chip at high speeds along the rake face
* sliding of the tool along the newly machined wp surface

Tool wear adversely effects
* tool life
* the quality of the machined surface
* dimensional accuracy
* the economics of cutting operations

Rate of tool wear depends on:
* wp material
* tool "
* coatings
* tool geometry
* process parameters
* cutting fluids
* characteristics of the machine tool

Types of wear and resulting changes in tool geometry
* Flank wear
* Crater wear
* nose wear
* notching
* plastic deformation
* chipping
* gross fracture

Taylor tool-life equation: $V.T^n = C$ — V: cutting speed; n: depends on the tool; T: time

To obtain a constant tool life

* feed or depth of cut ↑, the cutting speed must be ↓ and vice versa
* reduction in speed can result in an increase in the volume of the material removed, because of the increased feed or depth of cut.

⇒ Crater wear (happens on the rake face of the tool)

→ What's machinable?

* good surface quality
* tool life
* low force & power
* surface integrity

21.7.4 THERMALLY ASSISTED MACHINING

Also called hot machining. Advantages:

* reduced cutting forces
* increased tool life
* higher material-removal rates
* a reduced tendency for vibration and chatter

CHAPTER-22 CUTTING-TOOL MATERIALS and CUTTING FLUIDS

22.1 INTRODUCTION

The cutting tool material must possess the following characteristics

- Hot Hardness

Hardness, strength and wear resistance of the tool are maintained at the temperatures encountered in machining operations. This property ensures that the tool does not undergo any plastic deformation, and thus retains its shape and sharpness.

* Carbon tool steel lose their hardness rapidly
* Ceramics maintain their hardness at high temperatures

• Toughness and Impact Strength

forces in interrupted cutting operations and forces due to vibration and chatter during machining do not chip or fracture the tool.

• Thermal Shock Resistance

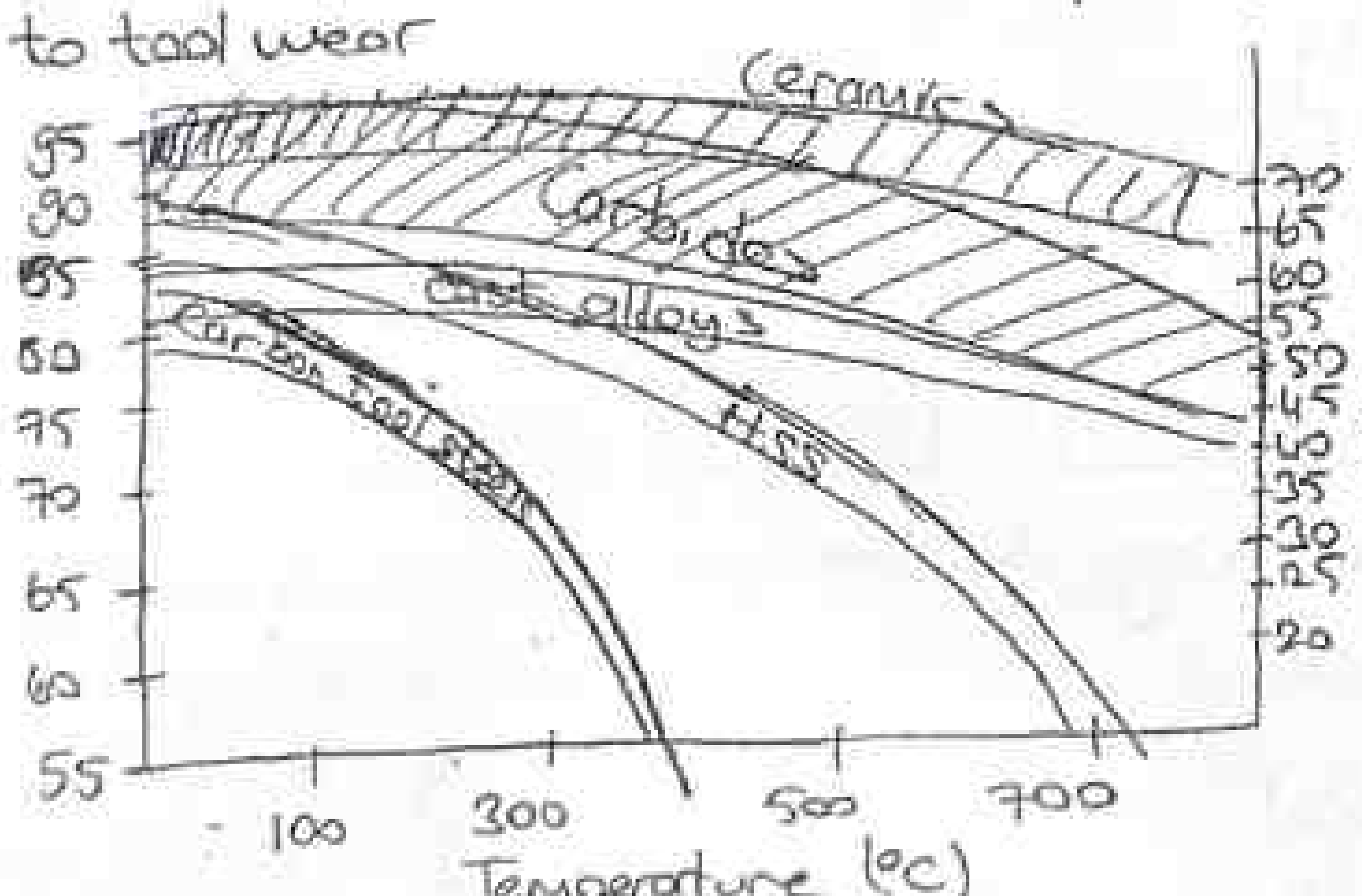
To withstand the rapid temperature cycling

• Wear Resistance

an acceptable tool life is obtained before replacement is necessary

• Chemical Stability and inertness

wrt the wp material, to avoid or minimize any adverse reactions, adhesion, and tool chip diffusion that would contribute to tool wear



* HSS are tough, but they have limited hot hardness

* Ceramics have high resistance to temperature and wear but they are brittle and can easily chip

General Characteristics of Cutting-tool Materials

HSS | Cast-Cobalt Alloys | Uncoated Carbides | Coated Carbides | Ceramics | CBN | Diamond

Hot hardness →

Toughness ←

Impact strength ←

Wear resistance →

Chipping resistance ←

Cutting speed →

Thermal shock resis ←

Tool material cost →

HIGH SPEED STEELS

General Characteristics
* High taghness
* Resistance to fracture
* Wide range of roughing and
* finishing cuts,
* Good for interrupted cuts

Modes of Tool wear or failure
→ Flank wear
→ Crater wear

Limitations: * Low hot hardness
* Limited hardenability * Limited wear resistance

→ relatively inexpensive

Suitable for:

a) high positive rake angle tools
b) interrupted cuts
c) machine tools with low stiffness
d) Complex tools such as drills, reamers, taps and gear cutters

Two basic type

a) Molybdenum (M-series)
b) Tungsten (T-series)

UNCOATED CARBIDES

General Characteristics
* High hardness over a wide range of temperatures
* taghness
* wear resistance
* versatile
* wide range of app.

Models of Tool wear and Failure
* Flank wear
* Crater wear

Limitations: Cannot use at low speeds because of coldwelding of chips and microchipping

CAST-COBALT ALLOYS

* High hardness → good wear resistance
  maintained their hardness at elevated temp.
* Not as tough as HSS
* Sensitive to Impact forces → unsuitable for interrupted cutting operations
* used only for special app
  ↳ deep, high feeds and speeds → twice the rates of HSS

COATED CARBIDES

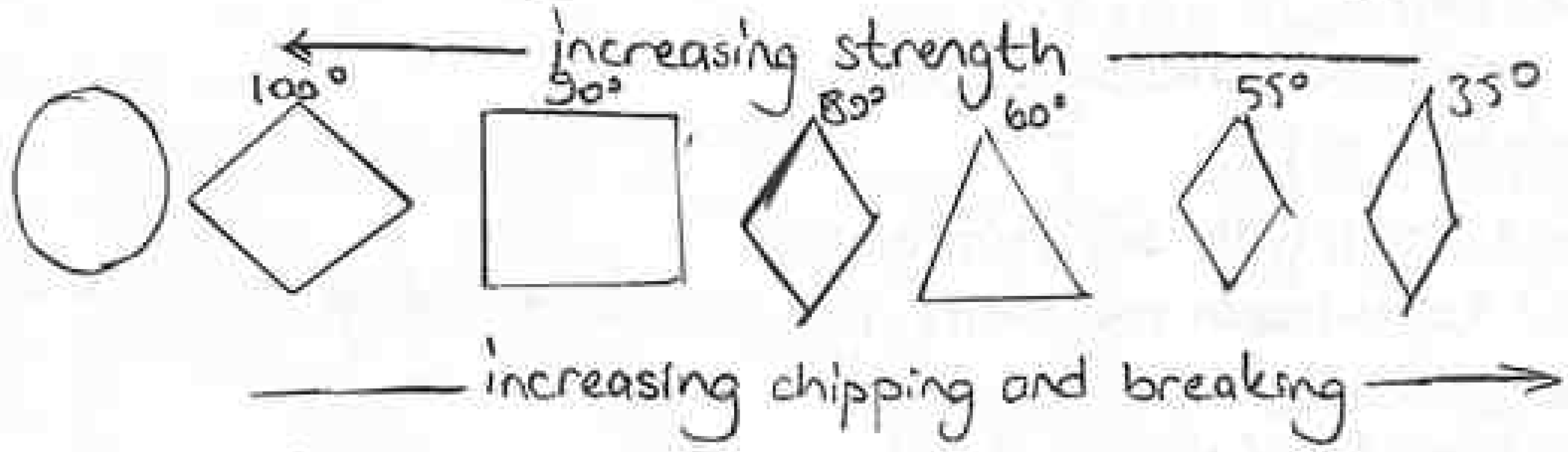
General Characteristics
* Improved wear resistance over uncoated carbides
* better frictional and thermal properties

Models of Tool wear or failure
* Flank wear
* Crater wear

Limitations: Cannot use at low speeds because of cold welding of chips and microchipping

INSERTS

* decrease the time of tool changing operations
* individual cutting tools with several cutting points



Chip breaker:

* Control chip flow during machining
* Eliminating long chips
* Reducing heat generated
* Reducing the tendency for vibration and chatter

[illegible]

✓ high strength and toughness — new metal alloys and engineering materials 1960s
✗ abrasive and chemically reactive with tool materials
→ coated tool'un özelliği değil

COATED TOOLS

* Lower Friction
* Flank wear minimized
* Al_2O_3 mostly used
* Higher resistance to wear and cracking
* Higher hot hardness and impact resistance
* Acting as a diffusion barrier between tool and the chip
* Can last 10 times more than uncoated thus allowing high cutting speeds
↳ reduces time required for machining and production costs

Applied on tool by { chemical-vapor deposition (CVD) / physical-vapor deposition (PVD) } 21

Multiphase Coating: Two or more layers of such coatings

DIAMOND COATING:

Diamond coated tools are particularly effective in machining

* Nonferrous metals
* Abrasive materials
* Fiber reinforced and metal-matrix composite materials
* Graphite

=) Material becomes between graphite and diamond in terms of hardness.

22.6 ALUMINA BASED CERAMICS

* high abrasion resistance
* hot hardness
* more stable than HSS and carbides → lower tendency to form a built up edge
* irons and steels → good surface finish by using ceramic tools

→ lack toughness
→ premature tool failure

* effective in high speed, uninterrupted cutting op.
* To reduce thermal shock, cutting should be dry or with a copious amount of cutting fluid
* negative rake angle → avoid chipping
  ↳ poor tensile strength

22.7 CUBIC BORON NITRIDE

* Next to diamond → hardest material available
* carbide provides shock resistance
* CBN layer → high wear resistance and cutting edge streng
* thermochemically stable → can be used up to 1200 °C
* brittle → the stiffness of the machine and the fixturing is important in order to avoid vibration and chatte

* machining should be dry → avoid chipping and cracking due to thermal shock

22.8 SILICON-NITRIDE-BASED CERAMICS

* High toughness
* Hot hardness
* Good thermal shock resistance

X Chemical affinity to iron at elevated temperatures
↳ are not suitable for machining steels

22.9 DIAMOND

* Hardest substance
* Low friction
* High wear resistance
* Maintain a sharp cutting edge
* Good surface finish
* Dimensional accuracy

X Brittle → tool shape and sharpness are important

* Low rake angle → to provide a strong cutting edge
* used almost all speed
* Most suitable for light, uninterrupted finishing cuts
* to minimize tool fracture → must be resharpened as soon as it becomes dull.

X chemical affinity at elevated temperatures for plain-carbon steels, titanium, nickel and cobalt-based alloys

22.10 WHISKER-REINFORCED MATERIALS and NANOMATERIALS

* High fracture toughness
* Resistance to thermal shock
* Cutting edge strength
* Creep resistance
* Hot hardness
* Suitable nanomaterials carbides and ceramics

22.12 CUTTING FLUIDS

Purposes

* Reduce friction and wear → improve tool life and surface finish
* Cool the cutting zone → Improve tool life and reducing the temp. and thermal distortion of the wp
* Reduce forces and energy consumption

* Flush away chips
* Protect the machined surface

⇒ It may need a coolant, a lubricant, or both

The effectiveness of cutting fluids depends on

* machining operation * cutting speed
* tool and wp materials * method of application

Water → excellent coolant
not an effective lubricant → does not reduce friction

Types of Cutting Fluids

1. **Oils**: used for low-speed operations, where temperature rise is not significant

2. **Emulsions**: (soluble oils)

* Mixture of oil and water and additives → generally used for high speed operations where temp. rise is significant

The presence of water makes emulsions highly effective coolants, and the presence of oil reduces or eliminates the tendency of water to cause oxidation of wp surfaces

3. **Semisynthetics**

* chemical emulsions containing little material oil, diluted in water, and with additives that reduce the size of oil particles thus making more effective

4. **Synthetics**

Chemical with additives, diluted in water, and containing no oil

Effect of Cutting Fluids

* WP material
* Machine tool components
* Biological Considerations
* The environment

CHAPTER-23 MACHINING PROCESSES: TURNING and HOLE MAKING

23.2 THE TURNING PROCESS

Tool Geometry:

Rake Angle: is important in controlling both the direction of chip flow, and the strength of the tool tip.

* Positive rake angle → improve cutting by reducing forces and temperatures.
* possibly leading premature tool chipping and failure depending on the toughness of the tool material

Side rake angle: more important than back rake angle, which usually controls the direction of the chip flow; these angles typically are in the range from -5° to +5°

Cutting edge angle: affects chip formation, tool strength, and cutting forces to various degrees, around 15°

Relief Angle: Controls interference and rubbing at the tool-wp interface. If it is too large, the tool tip may chip off; if it is too small, flank wear may be excessive. Relief angles typically are 5°.

Nose Radius:

smaller nose radius (sharp tool) → rougher surface finish
→ lower strength of tool

larger nose radii → tool chatter

· Material Removal Rate:

* volume of material removed per unit time

each revolution → ring shaped material is removed

$Volume = (f)(d)$ d: depth of cut, f: feed

Average Circumference $= \pi . D_{avg}$ $D_{avg} = \frac{D_o + D_f}{2}$

$MRR = \pi D_{avg} . d . f . N$ N: rotational speed of the wp

$MRR = d f . V$ V: cutting speed

$t = \frac{l}{f . N}$ t: cutting time l: wp of length l

FORCES in TURNING

Cutting force: F_c acts downward on the tool tip tends to deflect the tool downward and wp upward

Thrust force: F_t also called feed force because it is in the feed direction of the tool tends to push the tool toward the right and away from the chuck

Radial Force: F_r acts in the radial direction and tends to push the tool away from the wp

* F_t and F_r are difficult to calculate directly, are usually determined experimentally.

Roughing cut → High feed rates, large depths, MRR high

Finishing cut → lower MRR to produce good surface finish

23.3 LATHES and LATHE OPERATIONS

LATHE COMPONENTS

Bed: supports all major components of the lathe

Gap-bed lathe → a section of lathe is removed, s.t. our ability to reach further areas is increased

Carriage: slides along the ways and consists of cross-slide, tool post and apron. Tool is mounted on the tool post, it has tool positioning and adjustment.

Headstock: Power supply, motor, circuit board is there

Tailstock: can be clamped any position, supports the other end of the wp

*** dead center

long material isn't mounted properly. Lubrication is needed

*** live center

preferred one, material and tailstock turn at the same spee

Feed Rod and Lead Screw: Feed road rotates during lathe operation, and provides movement to carriage and the cross slide by means of gears, a friction clutch, and a keyw along the length of the road.

Closing a split nut around the lead screw engages the rod with the carriage. The split nut is also used for cutting threads accurately

Lathe Specifications:

* Its swing, the maximum diameter of the wp
* The max. distance between the headstock and tailstock centers
* The length of the bed

23.3.2 WORK-HOLDING DEVICES and ACCESSORIES

Chuck: 3 Jaws : self centering → round wp,
4 Jaws : flexible → square, rectangular wp

Collets: draw in collet: collet is pulled into the spindle
push-out collet: collet is pushed "

Face Plates: irregular wp

Mandrels: * machine both end of wp
* you can machine a lot a time
* Cone mandrels have much more flexibility as diameter of holder isn't constant.

23.3.3 LATHE OPERATIONS

If material is too long and it may be bending under the cutting forces and its weight. We use to prevent that
* Steady rest → directly clamped on the way of lathe
* Follow rest → clamped on the carriage

23.3.4 TYPES of LATHES

Bench Lathes: * placed on a table or a workbench
* for small wp's
* low power, operated by hand feed
* simplest of lathes
** toolroom bench lathes have higher precision, dimensional acc.

Special Purpose Lathes: for big workpieces, in diameter 1.7 M, length: 8M, machine capacity: 450 kW

Tracer Lathes: have special attachments that are capable of turning parts with various contours.

Automatic Lathes: * parts are fed and removed automatically
* Semi-automatic lathes (cnc turning centers) cnc+manipulator

Automatic Bar Machines: designed for high-production rate of screws and threaded parts

* Single spindle → high precision machining of small-diameter 27
  ↳ the bar stock is clamped close to the headsto
* Multiple spindle → have 4 to 8 spindles

Turret Lathes: capable of performing multiple cutting operation

* Ram Type → short wp's → ram slides along a saperete base
* Saddle Type → large wp's, Main turret on the saddle

CNC Lathes: * equipped with one or more turrets

* Wp diameter as much as 1M
* operate faster
* higher power available
* automatic tool changer (ATC's)
* desired dimensional accuracy
* require less skilled labor
* waste ↓

23.3.6 DESIGN CONSIDERATIONS and GUIDELINES for TURNING OPERATIONS

a) wp should be mountable
b) dimensional accuracy and surface finish specified should be as wide as permissable
c) sharp corners, tapers, steps, should be avoided
d) Design of your tool should'nt obscure the tool
e) standard tools (cost to be minimized)
f) Machinability

Guidelines for turning operations

h) Support wp's rigidly
i) tool overhang (tool should be inside not outside of the chuck
j) high damping capacity and high stifness machine tools
k) N, f, d should be optimized

23.3.7 CHIP COLLECTION SYSTEMS

* Gravity
* Magnets
* Vacuum
* Augers with feed screws
* Dragging

23.4 BORING and BORING MACHINES

* enlarging a hole made previously
* cutting tools similar to turning → mounted on a boring bar
* large wp machined on boring mills, small wp → lathes

→ Horizontal boring mill → wp move horizontally
→ Vertical "

Design Consideration
* Through hole instead blind
* smaller length-to-bore diameter ratios
* interupted internal surfaces, such as internal splines or radial holes that go through the thickness of the part, should be avoided.

23.5 DRILLING, DRILLS and DRILLING MACHINES

DRILLS

* have high length to diameter ratios
* leave a burr on the bottom surface of the part
* when heat produced during drilling, final hole diameter could be smaller than the drill diameter ports cool down

Twist Drill: The most common use
* Two spiral grooves (called flutes)
↳ passageways for cutting fluid

Step Drill: produces holes with two or more different dia.
↳ Flute diameter changes

Core Drill: for hard materials → make existing hole larger

Counterboring: (Bolt, nut) } produce depressions on the surface to accomodate the heads of screws and bolts below the wp surface
Countersinking: (Rivets)

Center Drill: short

Spot Drill: Spot a hole at the desired location on a surface

Spade Drills: have removable tips or bits, used to produce large-diameter and deep holes. have advantage of higher stiffness (because of the absence of flutes in the body of the drill) ease of grinding the cutting edges, and lower cost.

Gun Drilling: l/d ↑ → deep holes → special fluid passages in it
→ high cutting speed → the thrust force balanced
→ low feed → self centering ↳ wear pads

Straight Flute Drill:

Trepanning Tool: You can cover large diameter

Material-Removal Rate in Drilling

D: Diameter

A: cross sectional area

f: feed

N: rotational speed

$N = V/\pi D \quad A = \pi D^2/4$

$MRR = \left(\frac{\pi D^2}{4}\right) f N$

THRUST FORCE in drilling

depends on

* the strength of wp * feed * rotational speed * drill diameter
* drill geometry * cutting fluids

Pecking: If you don't have enough fluid for long holes, you simply move downwards at more than one steps.

DRILLING MACHINES

Vertical Drilling Press

Only moves in z axis

Bench type drills

Radial Drilling Press

moves in x, y, z axis

NC Turret Drills

Gang Drills

Manufacture more than on wp at a time → high production rate

Universal Drilling Machine

complicated processes

One met DOF to radial drilling press

DESIGN CONSIDERATION FOR DRILLS

* flat surfaces and perpendicular drills should be allowed
* hole bottom match drill point angle → flat surface avoided
* through holes ✓ blind holes ✗
* dimples should be provided → prevent drill to walk
* all drill can be performed with a minimum fixturing
* l/d ↓ "pecking"

23.6 REAMING and REAMERS

* Make existing hole dimensionally more accurate
* improve surface finish

Most accurate holes
→ Centering (start with a marking)
→ Drilling
→ Boring
→ Reaming

REAMERS

- Hand: straight or have a tapered end in the first third of their length
- Chucking: → Rose Reamer: more relief angles, more MR
  have cutting edges

  → Fluted Reamers: Small margins and relief, on light materials, light cuts.
- Shell
- Expansion
- Adjustable (more flexible than expansion reamer)

Reamers typically are made of high-speed steels

23.7 TAPPING - TAPS

* available with two, three, or four flutes
→ most common two flutes

Tapered taps → reduce the torque required for tapping of through holes

Bottoming taps → for tapping blind holes

Collapsible taps → large-diameter hole

⇒ For higher tapping productivity, drilling and tapping can be combined ⇒ DRAPPING

drilling + reaming ⇒ DREAMERS

CHAPTER-24 MILLING, BROACHING, SAWING FILING and GEAR MANUFACTURING

24.2 MILLING and MILLING MACHINES

24.2.1 PERIPHERAL MILLING

* axis of cutter parallel to wp
* cutter generally made of HSS
* when cutter longer than the width of cut, operation is called slab milling

Conventional Milling (Up milling)	Climb Milling (Down)
* Common	
* Sharp cutter	
* Maximum chip thickness: at the end	* at the beginning
* Direction of rotation push wp: upward	* downward
* tooth engagement not a function of wp surface characteristic	* wp surface charac. ↳ Gear backlash in the table feed mechanism must be eliminated
* wp scale does not affect tool life opposite to the down milling	* not suitable for machining of wp with surface scale

MILLING PARAMETERS

Cutting speed $V = \pi . D . N$

For a straight cutter tool:

Chip thickness: $t_c = 2f\sqrt{\frac{d}{D}}$

$T = F_c . \frac{D}{2}$

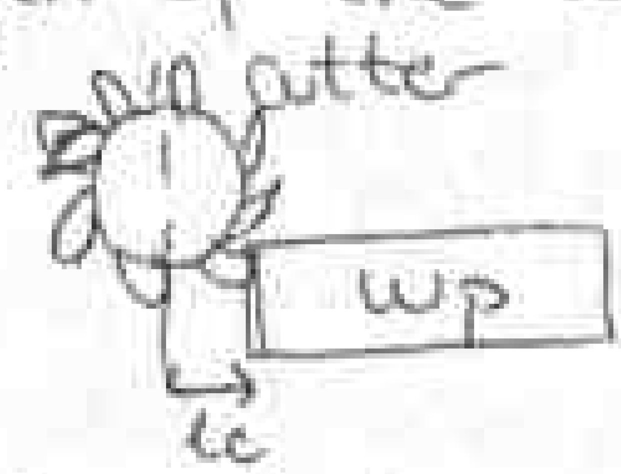
$f = \frac{v}{N . n}$

$P = T . \omega$ (angular speed)

Cutting time t: $\frac{l + l_c}{v}$

$MRR : \frac{l . w . d}{t} = wdv$

D: diameter of cutter
N: tool rotational speed
f: feed per tooth of cutter
d: depth of cut
n: number of teeth
v: linear speed (feed rate)
l: length of the wp
l_c:

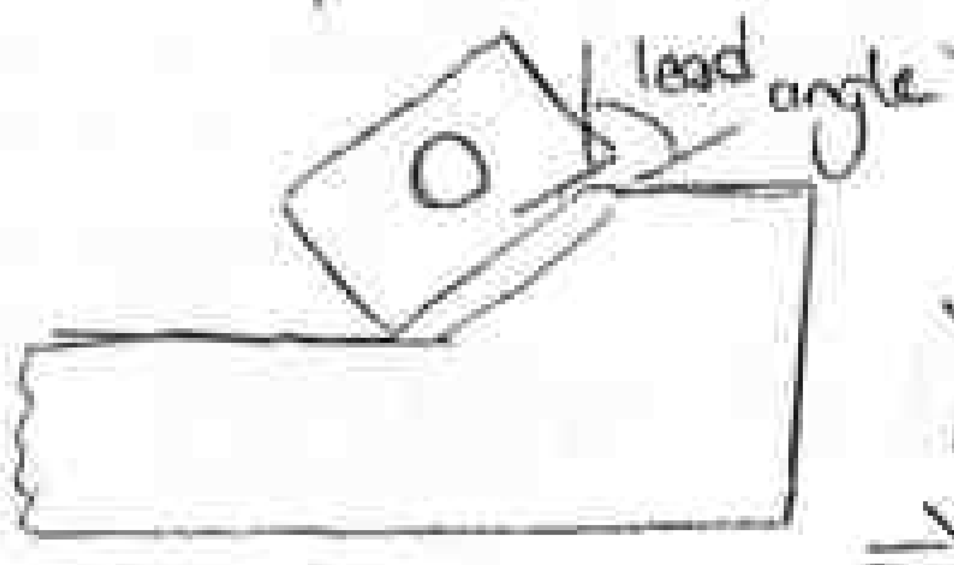


* In slab milling width of the cut is equal to width of the wp

w: width of the cut

24.2.2 FACE MILLING

* axis of rotation perpendicular to the wp surface
* Because of the relative motion beetween the cutter and wp, face milling leaves feed marks



* Lead angle should be high so that we increase the contact area, reduce vibrations. Hence, surface quality increases
Chip volume decreases
⇒ Lead angle decreases, smaller vertical force component.

0° < Lead angle < 45° (typically)

* D/w should be no less than 3/2

24.2.3 END MILLING

* Made of HSS, solid carbide, coated or uncoated carbide inserts similar to those for face milling
* axis of rot. perp. to wp but it can be tilted
* End mills with hemispherical ends called ball nose mills.
⇒ you can manufacture some artistic figures, detailed ones
* Hollow end mills have internal cutting teeth and are used to machine round wp's.
* High-speed end milling → large aluminium alloy aerospace components and honeycomb structures.
⇒ Very high spindle speeds ⇒ machine must have high stifness
⇒ Producing cavities in metalworking dies also is done by high-speed end milling.

24.2.4 OTHER MILLING OPERATIONS and CUTTER

* Stradle Milling
⇒ two or more cutter
⇒ machine two parallel surface
* Form Milling
⇒ produces curved profiles
* Slotting and Slitting
⇒ performing with circular cutters
Slitting saws are relatively thin

* T-Slot Cutting

* Fly Cutting

⇒ Milling with a single cutting tool
⇒ Simple face milling and boring operations

24.2.5 TOOLHOLDERS

* Arbor Cutters

⇒ Mounted on an arbor (shaft)
⇒ peripheral, face, straddle and for milling

* Shank-Type Cutters

⇒ cutter and shank made in one piece
⇒ end mills ⇒ small end mills have straight shanks
⇒ larger end mills have tapered shanks

24.2.6 MILLING PROCESS CAPABILITIES

Back striking involves double feed marks. (made by trailing edge of cutter)

24.2.7 DESIGN and OPERATING GUIDELINES for MILLING

* standard milling cutters (cost)
* chamfers instead radii
* internal cavities and pockets with sharp corners avoided
* corner radius should match → the milling cutter
* small milling cutters tend to chatter, tool breakage more than large
* wp should rigid

⇒ GUIDELINES

* Cutters should be mounted as close to the spindle base as possible
* Toolholders and fixturing devices rigid
* when chatter occur, parameters should be modified

24.2.8 MILLING MACHINES

* Column and knee-type machines ⇒ (3 DOF)

Worktable: moves longitudinaly relative to the saddle
Saddle: supports table and move in transverse direction
Knee: Supports the saddle and moves in vertical

* Overarm: used on horizontal machines, it is adjustable to accomodate different arbor lengths
* Head: Contains spindle and cutter holder
  Can be adjusted vertically

Bed-type Milling Machines

* worktable mounted on the bed → more rigid → more accurate products

OTHER TYPES of MILLING MACHINES

* Planer type milling machines
* Rotary table-machines
* Profile milling machines → five axis of movement

WORK HOLDING DEVICES

- Universal dividing head
  * Gears (turns it)

24.3 PLANNING and SHAPING

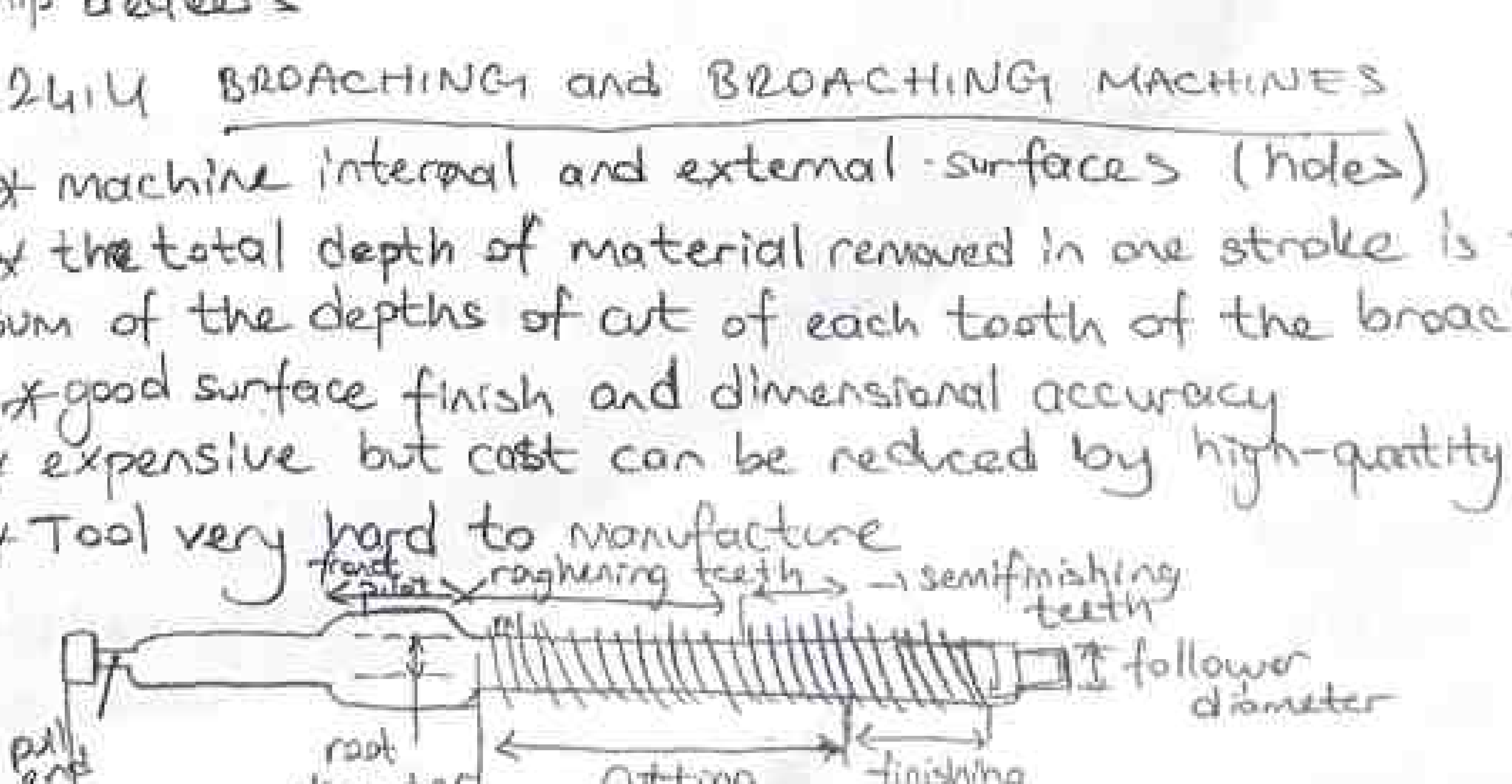
Planning
* Large wp's
* WP reciprocating motion ↓↑
* Tool stationary
* Because of the length of the wp, there should use chip breakers

Shaping
* WP stationary
* Tool reciporating

} Nowadays, since we have milling machines we don't use them that much

24.4 BROACHING and BROACHING MACHINES

* machine internal and external surfaces (holes)
* the total depth of material removed in one stroke is the sum of the depths of cut of each tooth of the broach
* good surface finish and dimensional accuracy
* expensive but cost can be reduced by high-quantity prod.
* Tool very hard to manufacture



* With a single motion you can create complicated shapes
  ↳ Flat broach
  ↳ Round broach

* The force required to pull or push the broach depends on
  a) strength of the wp material   c) cutting speed
  b) tool periphery of the cut   d) tooth profile
  e) type of cutting fluid used

DESIGN CONSIDERATIONS

* Clampable   * Keyways, splines, gear teeth in stantard sizes
* Radii difficult to broach, chamfer ✓
* Blind holes avoided
* Balanced cross-sections are preferable, to keep the broach from drifting laterally, thus maintaining close tolerances

24.5 SAWING

* all materials and various shapes
* removal material low
* width of the cut is called kerf
* Saw blades made of high-carbon and HSS

24.6 FILING

* small scale material remove
* improve surface quality

24.7 GEAR MANUFACTURING BY MACHINING

* Complicated process

FORM CUTTING

* simple
* Some type of machine required skilled labor

GEAR GENERATING

* A pinion shaped cutter
* Rack shaper
* Hob ⇒ used to machine worm gears in a shorter times

GEAR FINISHING PROCESS

Shaving :

* rapid and most commonly used
* surface finish and good dimensional accuracy
* heat treated and ground impoovend hardness

Burnishing

* improve surface finish
* induce compressive residual stress and improve fatigue life
* does not significantly improve dimensional accuracy

Grinding , Honing, Lapping

* single index form grinder most commonly used
* honing faster than grinding

further improve surface finish → lapping

DESIGN CONSIDERATIONS and ECONOMICS of GEAR MACHINING

* machining should be completed before assembly
* Clearences should be provided, No collision between cutter and WP
* Finishing allowances
* Spur gears are easier to machine than hellical gears, which in turn are easier to machine than bevel gears or worm gears.
* Correct dimensional clearences

Special operations increase the cost

CHAPTER-25 MACHINING CENTERS

Components of Machining Center

* WP placed on a pallet, that can be moved and oriented in various directions.
* Automatic pallet changer ⇒ a produced wp and unworked wp change
* Automatic tool changer
* Work envelope → the max dimensions that cutting tool can reach

* The tool exchange arm → swing around to pick up a tool and places it in the spindle 37
* tool checking and part checking stations ⇒ inform machine control system that variations in tool settings or tool wear
* Touch probes

25.2.1 TYPES of MACHINING CENTERS

* Verticle Spindle Machining Centers:
  * deep cavities (mold and die making)
  * tool magazine on the left
  * thrust directed downward ⇒ high stifness
  * less expensive than horizontal
* Horizontal Spindle Machining Centers
  * large and tall wp
  * pallet can be oriented on different axes.
  * Turning Centers: another category of horizontal spindle machines
    * two horizontal spindle and two turrets
    * variety of cutting tools
  * Universal Machining Centers
  * Both vertical and horizontal spindle

25.2.2 CHARACTERISTICS of MACHINING CENTERS

* capable of wide variety of part size and shapes with high dimensional accuracy
* versatile and quick change wp
* times required loading and unloading etc reduced
* labor requirement reduced
* can be equipped with tool condition monitoring device

CHAPTER-26 ABRASIVE MACHINING and FINISHING OPERATIONS

26.2 ABRASIVES and BONDED ABRASIVES

Conventional Abrasives
- Aliminum oxide (Al_2O_3)
- Silicon carbide (SiC)

(most commonly used)

Superabrasives
- Cubic Boron Nitride (cBN)
- Diamond

* Abrasives are much harder than conventional cutting tool
* friability → the ability of abrasive grains to fracture into smaller part. (self-sharpening)
* High friability → low strength or low fracture resistance

Abrasive grain size: the size of an abrasive grain is identified by a grit number. smaller the grain size, the larger the grit number

26.4 GRINDING OPERATION and MACHINES

Surface grinding: Grinding of flat surfaces
* Traverse grinding occurs as the table reciprocates longitudinally and is fed laterally after each stroke
* The movement of the grinding wheel may be along the surface of wp (traverse grinding), or the wheel may move radially in to the wp (plunge grinding) as is the case when grinding a groove.
* Surface grinders mostly used
* Rotary table grinding, vertical spindles → Lots of wp at a time

Cylindirical Grinding: (Center-type grinding)
* the external cylindirical surfaces and shoulders of wp's are grand
*

Internal Grinding: small wheel is used
Centerless Grinding: a high production process for grinding cylindirical surfaces; the wp supported not by centers or chucks, but by a blade.

* Through-feed grinding: the wp is supported on a work rest blade and is ground continuously between two wheels. Grinding is done by the larger wheel, while the smaller one regulates the axial movement of wp. Smaller wheel runs much smaller than grinding wheel.

* Infeed (Plunge) Grinding: Parts with variable diameters can be grand by this process, an operation similar to plunge or form grinding on cylindirical grinders.

* End-Feed Grinding: Tapered pieces are centerless ground by end-feed grinding.

* Internal Centerless Grinding: the wp supported between three rolls and is ground internally; typical applications are sleeve-shaped parts and rings.

Creep-Feed Grindling

* High power
* High damping capacity
* High stiffness
* Large scale material removal rate
* Variable spindle speed and worktable speed.
* High capacity for grinding fluids
* Embedded dressing tools

⇒ It's like face milling as material is removed but it's also grinding.

Heavy-Stock Removal Grinding

* increasing process parameters
* can be economical
* surface finish is of secondary importance

Several type of grinders are used for various operations
* Universal Tool and Cutter Grinders
⇒ are used for grind single-point or multipoint cutters
⇒ A variety of CNC available
* Tool post grinders
⇒ self-contained units and attached to the tool post of

a lathe, mounted on the headstock and is ground by moving the tool post.

⇒ Versatile, but essential for the lathe components to be protected from abrasive debris

* Swing-frame Grinders for Large casting ground. Rough grinding of casting is called snagging and usually done on floorstand grinders

* Portable Grinders
⇒ grinding of weald beads and cutting of using thin abrasive disks

* Bench and Pedestal Grinders
⇒ routine offhand grinding of tools and small parts
⇒ ↳ everyday used material

GRINDING FLUIDS

* Reduce temp ↑ in wp
* Improve surface fin. dime. acc.
* reducing wheel wear, loading of the wheel
* lowering power consump.

⇒ A common method to maintain a more uniform wp temp., is to use refrigerating systems (chillers), through which the grinding fluid is circulated continuously and maintained at a roughly constant temp.

GRINDING CHATTER

* adversely affects surface finish and wheel performance
* Chatter marks help identify the problem
* controlling chatter → stifness of the grinding machine

26.5.4 DESIGN CONSIDERATION for GRINDING

* mounted securly wp
* When dim. acc. required, interrupted surfaces such as holes and keyways should be avoided to minimize deflections
* long and slender designs should be avoided → cylindrical grinding
* In centerless grinding short pieces may be difficult to grind, because the blade may not support them. In through feed grinding, only the largest diameter on the parts can be ground.

* Deep and small holes, blind holes X → internal grinding
* Simple positioning
* Less material removal

26.6 ULTRASONIC MACHINING

* time of contact between the particle and the surface is very short
* the area of contact very small
* best suited for hard and brittle material

Design consideration for ultrasonic machining

* avoid sharp profiles, corners and radii, becauce they can be eroded by the abrasive slurry.
* remember that holes produced will have some taper
* because of the tendency of brittle materials to chip at the exit end of holes, the bottom of the parts should have a backup plate

26.7 FINISHING OPERATIONS

Coated Abrassives
Belt grinding
Wire Brushing
Honing (stones are used, wp is stationary)
Superfinishing (stone is stationary, wp is moving)
Lapping (You should apply some forces for better surface q.)
Polishing (Heat generated from friction)
Chemical-mechanical Polishing
Electropolishing

26.8 DEBURRING OPERATIONS

Disadvantages:

* interfere with mechanical assembly of parts
* sharp → safety hazard
* reduces fatique life
* decreases bendability of sheet metals

Advantages:

* Improve the holding torque of screws ←
* Additional thickness after drilling and tapping

26.9 ECONOMICS of ABRASIVE MACHINING and FINISHING OPERATIONS

* part size
* part shape
* required accuracy
* labor
* machining, fixture, tool
* production time

CHAPTER-27

CHAPTER 27 | ADVANCED MACHINING PROCESSES and EQUIPMENT

27.1 INTRODUCTION

* The strength and hardness of the wp material is very high
* The material is too brittle to be machined without damage to the part, typically the case with highly heat-treated alloys, glass ceramics, and powder metallurgy parts
* The wp is too flexible or slender withstand forces involved in machining or grinding, or the parts are difficult to clamp in fixtures and workholding devices.
* The parts has a complex shape, including such features as internal and external profiles or holes with high-length to diameter ratios in very hard materials.
* Special surface finish and dimensional tolerance requirements that cannot be obtained by other manufacturing processes or are uneconomical
* The temperature rise during processing and residual stress developed in the wp are not acceptable

⇒ A major advantage of these processes is that their efficiency is independent of wp hardness.

⇒ When selected and applied properly, advanced machining processes offer major technical and economic advantages over more traditional methods.

27.2 CHEMICAL MACHINING

* chemical attack and etch most materials
* removing small amount of material
* The CM processes is carried out by chemical dissolutn using reagents or etchants.
* oldest of advanced machining
* Chemical Milling

The procedure for chemical milling consists of following steps

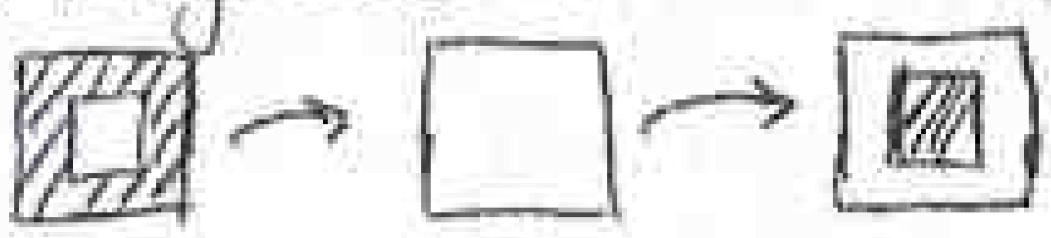
1 ⇒ Relieve residual stresses
2 ⇒ Clean surface
3 ⇒ Apply maskant
4 ⇒ Peel of maskant
5 ⇒ Etching
6 ⇒ Wash with water
7 ⇒ Remove maskant
8 ⇒ Finishing operations
9 ⇒ Repeat the steps

* Chemical milling is used in the aerospace industry to remove shallow layers of material
* The process is also used to fabricate microelectronice devices, and often is referred to as wet etching.
* Chemical milling of welded and brazed structures also may result in uneven material removal, and castings may result in uneven surfaces, caused by porosity and property nonuniformities in the material

* Photochemical Blanking (Photochemical Machining)

The procedure in photochemical blanking consists of the following steps

1 ⇒ Design part x100
2 ⇒ Blank sheet coated
3 ⇒ Negative on block → UV
4 ⇒ Blank is developed
5 ⇒ The blank is then immersed into a bath of reagent, or is sprayed with the reagent
6 ⇒ Remove mask and wash



* The disposal of chemical by-products from this process is a major drawback, although some by-products can be recycled.
* skilled labor required, tooling costs are low
* can be automated, and is economical for medium to high production volume
* Capable of making very small parts

(*) DESIGN CONSIDERATION for CHEMICAL MACHINING

* sharp corners, deep and narrow cavities X
* undercuts may develop, in the areas under the edges of maskent
* the bulk of the wp should be proccessed before
* thin material preferred
* Temp & humidity

27.3 ELECTROCHEMICAL MACHINING

* basicly the reverse of electroplating
* Electrolyte acts as the curret carrier, and the high flow rate of electrolyte in tool-wp gap washes metal ions away from the wp before they have a chance to plate onto the tool. Note that the cavity produced is the matting image of the tool shape
* We can machine complicated shapes but the tool should be special, and cost is high.

MRR for a current efficiency:

MRR: CI   c: material constant
           I: current

* negative imaged of the desired shape.

⇒ An advance in ECM is shaped-tube electrolytic machining (STEM) used for small diameter deep holes, as in turbine blades. Tool → titanium tube

⇒ Larger holes can be produced by electrolytic trepanning

Advantages

+ side is wp
− side is tool

* Burr-free
* No thermal damage
*** No tool wear
* Complicated parts
* CNC
  ↳ increase productivity
  ↳ Flexible
  ↳ Tolerances are better

DESIGN CONSIDERATION for ELECTROCHEMICAL MACHINING

* not suited for product sharp corner, flat bottoms
* controlling the electrolyte flow difficult
* Part designs should make provision for a small taper for holes and cavities to be machined.

27.4 ELECTROCHEMICAL GRINDING

* Combines ECM with conventional grinding
* wheel is rotating cathode
* Abrasives have two functions:

⇒ to serve as insulaters between the wheel and wp
⇒ to mechanically remove electrolytic products from the working area

* Material removal <%5 abrassive action thus wheel wear is very low and the wp remains cool.
* Finishing cuts usually are made by the grinding action, but only to produce a surface with good finish and dimens. accs
* have more advantage than diamond-wheel grinding of very hard-material, where wheel wear is very high.

Electrochemical hooning:

* 5 times faster than conventional one, tool last 10 times longer
* equipment is costly

DESIGN CONSIDERATION for ECMG

* sharp inside radii ✗
* surface to be flat, narrower than width of grinder ✓

27.5 ELECTRICAL DISCHARGE MACHINING

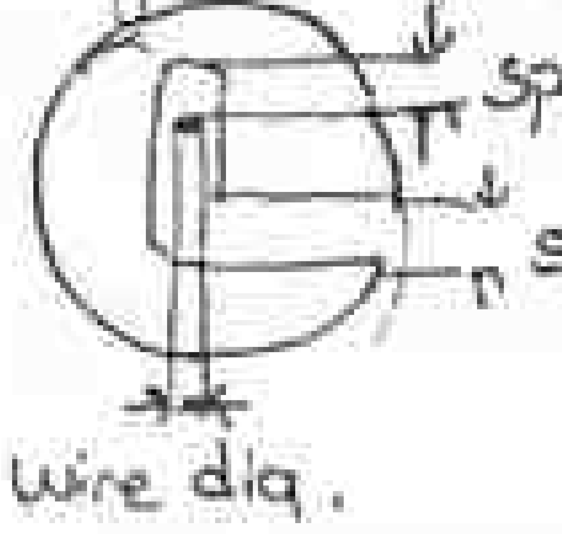
* erosion of metals by spark discharges
* consist of shaped tool and the wp, connected to a DC and placed in dielectric fluid
* the capacitor discharges repeatedly ranging between 50 and 380 V and currents from (0.1–500 A) (200–500 Hz)
* can be used on any material that is electrical conducter
* Dielectric Fluids:

⇒ Acts as an insulator until the potential is sufficiently high
⇒ Provide a cooling medium
⇒ Acts as a flushing medium and carry away the debries in the gap

* The gap between the tool and wp is critical; thus the downward feed of the tool is controlled by a servomechanism which automatically maintains a constant gap

27.5.1 WIRE EDM

* Wire is continuously supplied with rotors like sawing
* We cool and remove chips with dielectric supply
* Wire is moved constantly, as if it was stationary, due to high temperature, our tool which is wire would break deform



* there should be a gap with tool and wp
* Multiaxis EDM wire cutting machining centers are capable of producing 3-D shapes and are equipped with

⇒ Computer controls → controlling cutting path
⇒ Multiheads for cutting two parts at the same time
⇒ Features such as controls for preventing wire breakage
⇒ Automatic self-threading features, in case of "
⇒ Programmed machining strategies, to optimize the operation

Electrical Discharge Grinding: → no abrassives

27.6 LASER BEAM MACHINING

* source of energy is a laser → focuses optical energy on the surface of the wp
* Accuracy is high
* You don't have to have conductive material, any material can be machined

DESIGN

* Sharp corners should be avoided
* Deep cuts will produce tapered walls
* Dull and unpolished surfaces are preferable
* There may be adverse effects on the properties of wp, caused by high local temp. and heat affected zone

27.7 ELECTRON BEAM MACHINING

* energy source → high velocity electrons
* unlike lasers EBM requires vacuum
* much less frequently than LBM
* very accurate cutting for wide variety of metals

* surface finish is better, kerf narrower than in other thermal cutting processes
* require highly skilled labor → hazardous effects

DESIGN CONS.

* Because vacuum chambers have limited capacity, inuidual parts or batches should closely match the size of the vacuum chamber
* If small portion of wp require ebm, manuf. it as a number of component and assemble.

Plasma-arc Cutting: plasma beams are used to rapidly cut ferrous and nonferrous sheets and plates.
* very high temp ⇒ MRR very higher
* fast process
* Surface finish is good
* parts as thick as 150 mm can be cut

27.8 WATER JET MACHINING

* Momentum change of a stream water
* wide varrety of wp
* efficient and clean ⇒ food-processing industry

advantages of WJM:

* cuts can be start at any position without the need of predrilled holes
* no heat is produced.
* suitable for flexible materials
* Little wetting of wp takes place
* Burr produced minimal
* environmentally ✓

abrasive water jet machining → contains abrassive
* increase removal rate
* may not be economical → high production rates

27.9 ABRASIVE JET MACHINING

* high material removal rate
* cutting small holes, slots or intricate patterns in very hard or brittle materials
* deburring or removing small flash from parts
* trimming and beveling of edges
* removing oxides and other surface films
* cleaning of components with irregular surfaces
* holes made tend to be tapered

27.10 HYBRID MACHINING SYSTEM

* Two or more invidual machining combined
* increase efficiency, production speed
* able to handle variety of materials

IMPORTANT CONSIDERATION

* wp and its manuf characteristics
* compatibility of parameters among the two or more proc.
* cycle time each invidual process
* safety consideration
* consequence of a failure

27.11 ECONOMICS of ADVANCED MACHINING PROCESSES

* cost of tooling and equipment
* operating costs
* mrr required
* level of operator skill required
* secondary and finishing operations that subsequently neccessary

Chemical machining ⇒ cost of reagents, maskent and disposal and cleaning

EDM → cost of electrolyde

CHAPTER 10

FUNDAMENTALS OF METAL CASTING

- First used about 6000 years ago, casting continues to be an important manufacturing process for producing very small, as well as very large and complex, parts.

10.1 Introduction

The casting process basically involves (a) pouring molten moral into a mold, patterned after the part to be cast, (b) allowing it to solidify, and (c) removing the part from the mold. As with all other manufacturing processes, an understanding of the underlying science is essential for the production of good quality and economical parts, and for establishing proper techniques for mold design and casting practice.

Important considerations in casting operations arc:

- How of the molten metal inro the mold cavity, and design of gating systems or pathways for molten literal to fill the cavity
- Solidification and cooling of the metal in the mold
- Influence of the mold material

10.2 Solidification of Metals

After molten metal is poured into a mold, a sequence of events takes place during solidification and cooling of the metal to ambient temperature. These events greatly influence the size, shape, uniformity, and chemical composition of the grains formed throughout the casting, which, in turn, influence the overall properties of the casting. The significant factors affecting these events are :

- The type of metal cast,
- The thermal properties of both the metal and the mold,
- The geometric relationship between volume and surface area of the casting,
- The shape of the mold.

10.2.1 Pure Metals

Because a pure metal has a clearly defined melting, or freezing, point, it solidifies at a constant temperature. After the temperature of the molten metal drops to its freezing point, its temperature remains constant while the *latent heat of fusion* is given off. The solidification front (the solid-liquid interface) moves through the molten metal from the mold walls in toward the center. The solidified metal, called the *casting*, is then removed from the mold and allowed to cool to ambient temperature.

Metals shrink while cooling and, generally, also shrink when they solidify. This is an important consideration, because shrinkage can lead to microcracking and the associated porosity, which can adversely affect the mechanical properties of the casting. The grains generally grow in a direction opposite to that of the heat transfer out through the mold.

Those grains that have favorable orientation grow preferentially, and are called columnar grains. Those grains that have substantially different orientations are blocked from further growth. As the driving force of the heat transfer decreases away from the mold walls, the grains become equiaxed and coarse. This sequence of grain development is known as homogenous nucleation, meaning that the grains (crystals) grow upon themselves, starring at the mold wall.

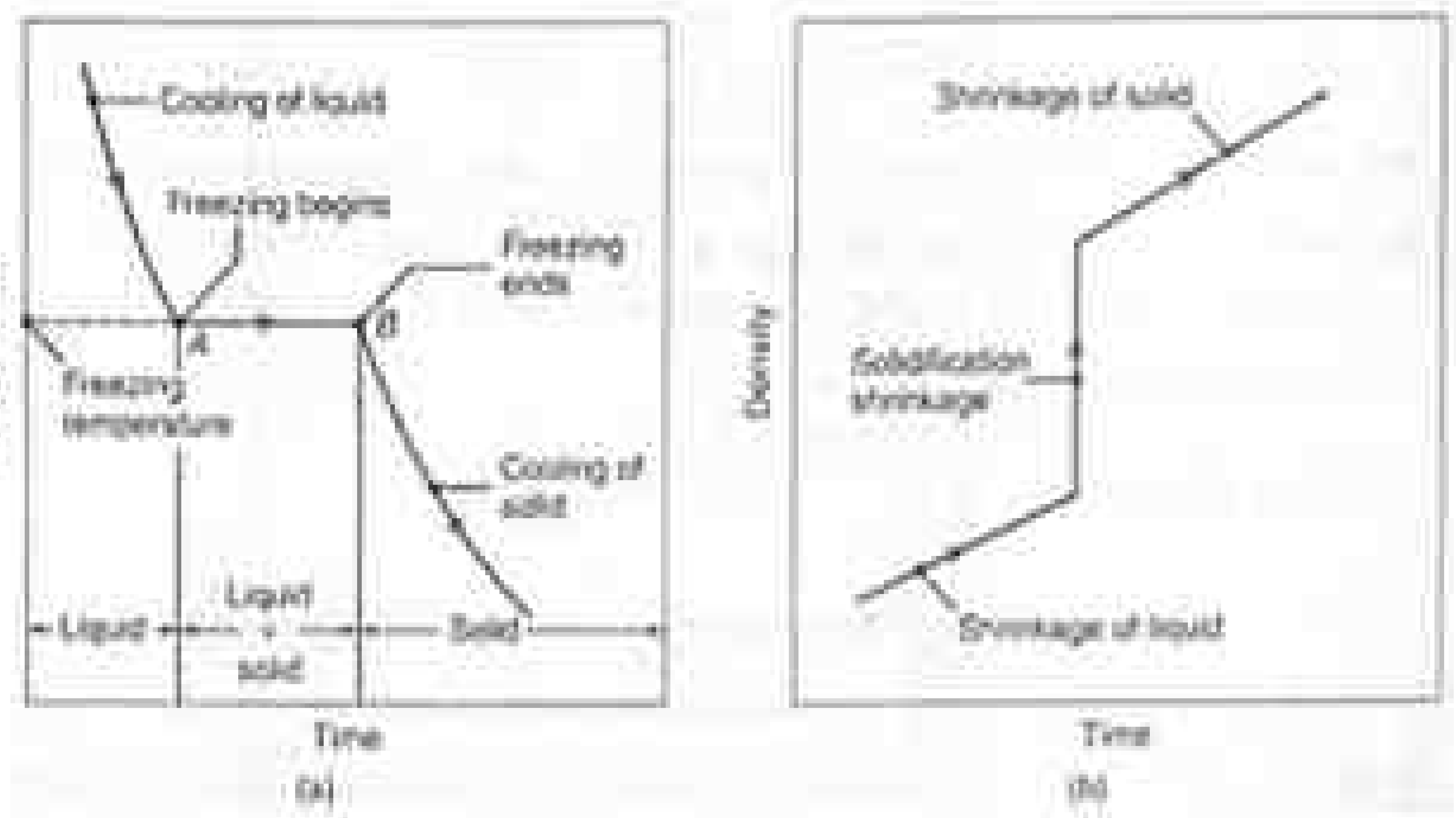


FIGURE 10.1 (a) Temperature as a function of time for the solidification of pure metals; note that freezing takes place at a constant temperature. (b) Density as a function of time.

10.5 Heat Transfer

The heat transfer during rhe complete cycle (from pouring, to solidification, and to cooling to room temperature) is another important consideration in metal casting. Heat flow at different locations in the system is a complex phenomenon and depends on several factors relating to the material cast, the mold, and process parameters.

10.5.1 Solidification Time

During rhe early stages of solidification, a thin skin begins to form at the relatively cool mold walls, and as time passes, the thickness of the skin increases. With flat mold walls, the thickness is proportional to the square root of time; thus, doubling the time will make the skin $\sqrt{2} = 1.41$ times or 41% thicker.

The **solidification time** is a function of the volume of a casting and its surface area (Chvorinov's rule):

$$\text{Solidification time} = C\left(\frac{\text{Volume}}{\text{Surface area}}\right)^n,$$

where C is a constant that reflects (a) the mold material, (b) the metal properties (including latent heat), and (c) the temperature. The parameter n has a value between 1.5 and 2, but usually is taken as 2. Thus, a large solid sphere will solidify and cool to ambient temperature at a much slower rate than will a smaller solid sphere. The reason for this is that the volume of a sphere is proportional to the cube of its diameter, whereas the surface area is proportional to the square of its diameter.

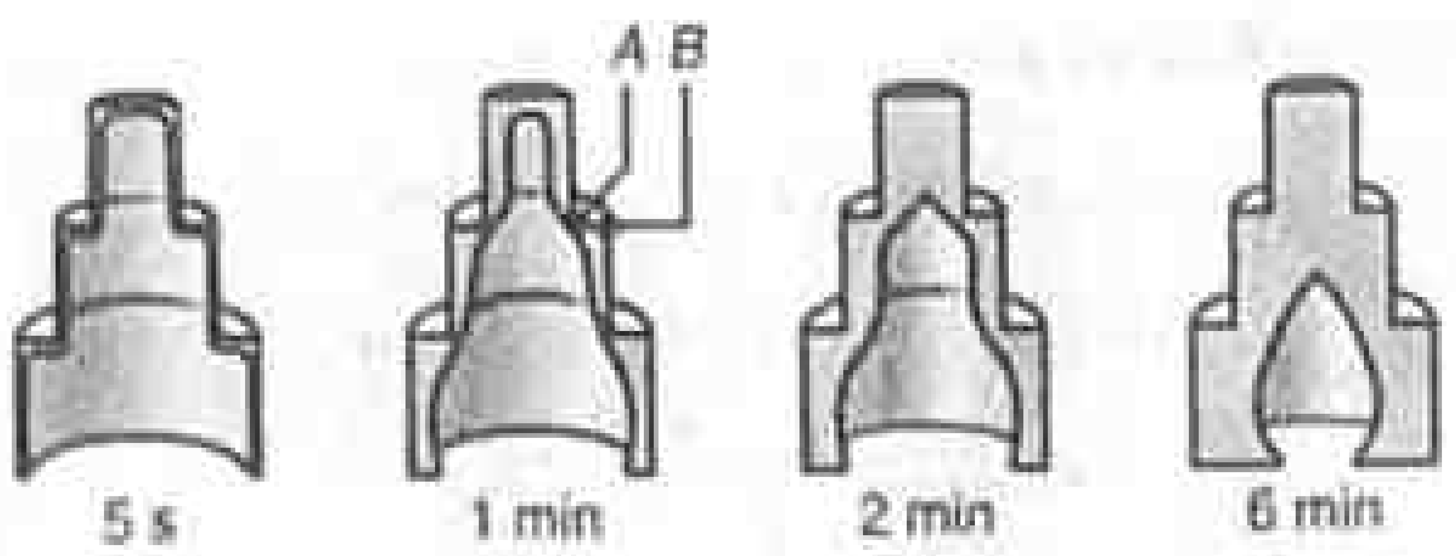


FIGURE 10.11 Solidified skin on a steel casting. The remaining molten metal is poured out at the times indicated in the figure. Hollow ornamental and decorative objects are made by a process called flush casting, which is based on this principle.

10.5.2 Shrinkage

Because of their thermal expansion characteristics, metals usually shrink (contract) during solidification and while cooling to room temperature. *Shrinkage*, which causes dimensional changes and sometimes warping and cracking, is the result of the following three sequential events:

1. Contraction of the molten metal as it cools prior to its solidification
2. Contraction of the metal during phase change from liquid to solid
3. Contraction of the solidified metal (the casting) as its temperature drops to ambient temperature

The largest shrinkage occurs during the phase change of the material from liquid ro solid, but this can be reduced or eliminated through the UK or tints or pressure feeding of molten metal.

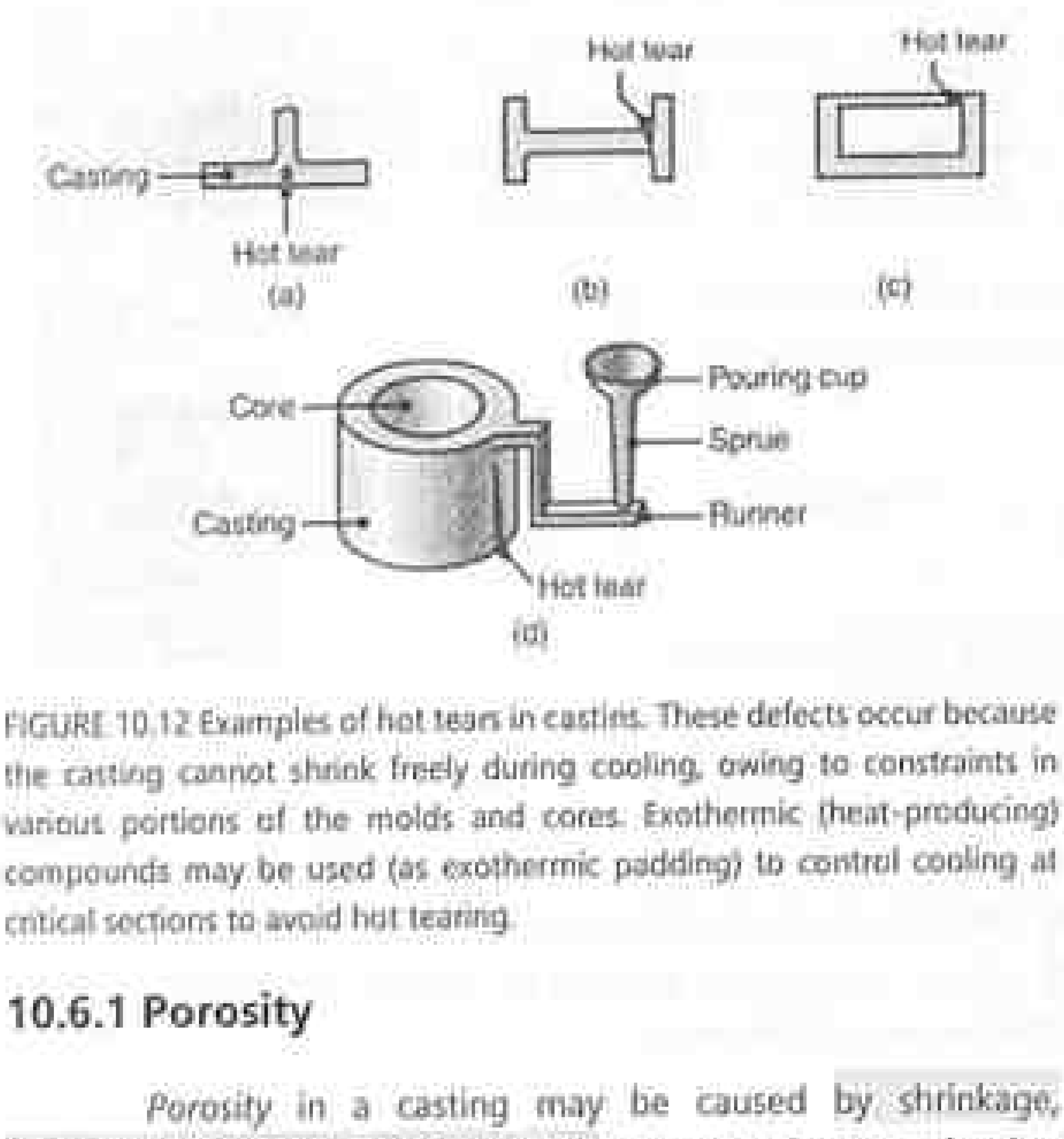


FIGURE 10.12 Examples of hot tears in castins. These defects occur because the casting cannot shrink freely during cooling, owing to constraints in various portions of the molds and cores. Exothermic (heat-producing) compounds may be used (as exothermic padding) to control cooling at critical sections to avoid hot tearing.

10.6.1 Porosity

Porosity in a casting may be caused by shrinkage, entrained or dissolved gases, or both. Porous regions can develop in castings because of shrinkage of the solidified metal. Thin sections in a casting solidify sooner than thicker regions; as a result, molten metal flows into the thicker regions that have not yet solidified. Porous regions may develop at their centers because of contraction as the surfaces of the thicker region begin to solidify first. Microporosity also can develop when the liquid metal solidifies and shrinks between dendrites and between dendrite branches.

Porosity is detrimental to the strength and ductility of a casting and its surface finish, potentially making the casting permeable, thus affecting the pressure tightness of a cast pressure vessel.

Porosity caused by shrinkage can be reduced or eliminated by various means, including the following:

- Adequate liquid metal should be provided to prevent cavities caused by shrinkage.
- Internal or external chills, also are an effective means of reducing shrinkage porosity. The function of chills is to increase the rate of solidification in critical regions. Internal chills are usually made from the same material as the casting itself, and are left in the casting. However, problems may arise that involve proper fusion of the internal chills with the casting; thus, foundries generally avoid the use of internal chills. External chills may be made from the same material as the casting or may be made of iron, copper, or graphite.
- With alloys, porosity can be reduced or eliminated by high temperature gradients, that is, by increasing the cooling rate; for example, mold materials with higher thermal conductivity may be used.
- Subjecting the casting to hot isostatic pressing is another method of reducing porosity.

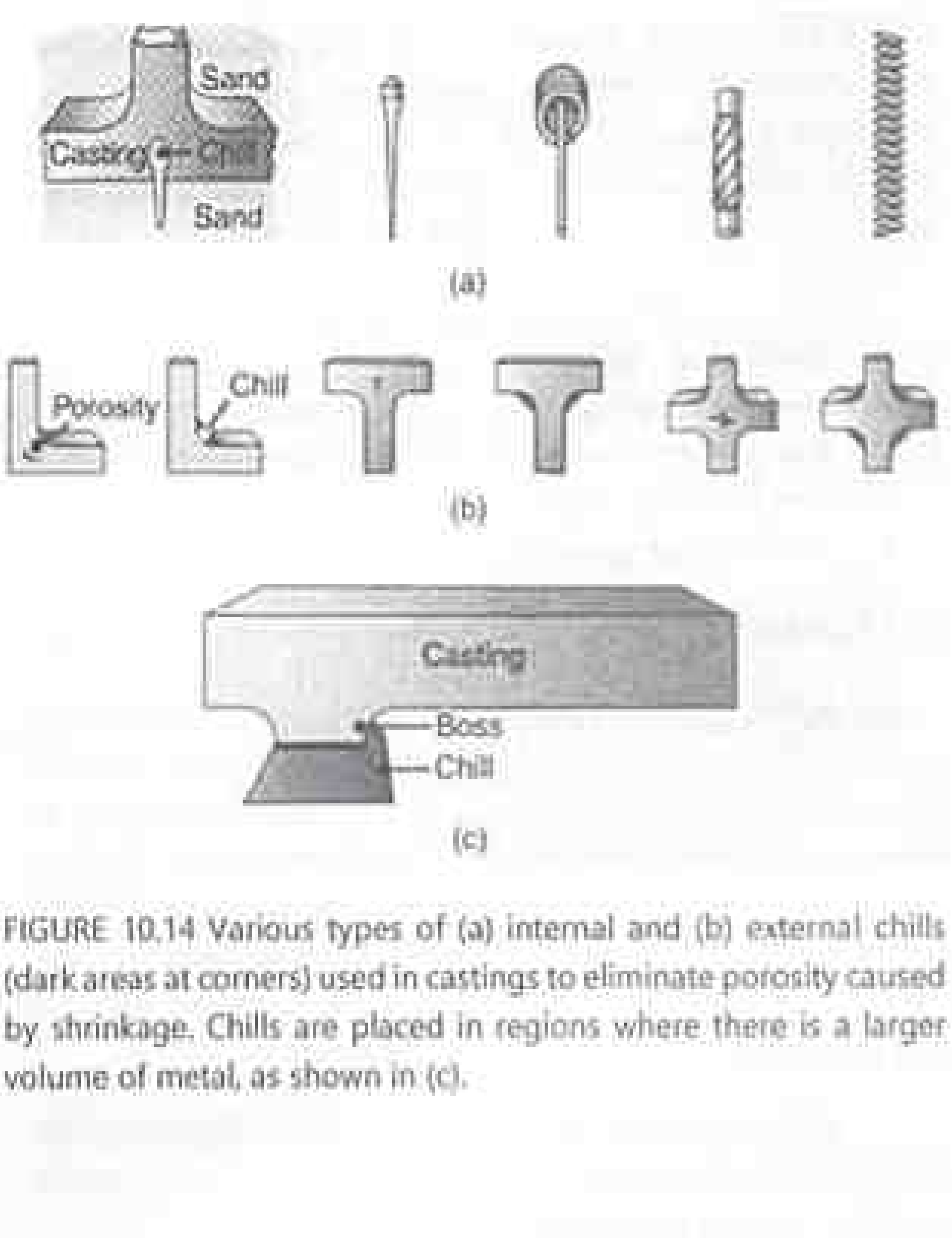


FIGURE 10.14 Various types of (a) internal and (b) external chills (dark areas at corners) used in castings to eliminate porosity caused by shrinkage. Chills are placed in regions where there is a larger volume of metal, as shown in (c).

SUMMARY

- Casting is a solidification process in which molten metal is poured into a mold and allowed to cool. The metal may flow through a variety of passages (pouring basins, sprues, runners, risers, and gating systems) before reaching the mold cavity. Bernoulli's theorem, the continuity law, and the Reynolds number are the analytical tools used in designing castings, with the goals of achieving an appropriate flow rate and eliminating defects associated with fluid flow.

- Solidification of pure metals takes place at a constant temperature, whereas solidification of alloys occurs over a range of temperatures. Phase diagrams are important tools for identifying the solidification point or points for technologically important metals.

- The composition and cooling rates of the molten metal both affect the size and shape of the grains and the dendrites in the solidifying alloy; in turn, the size and structure of grains and dendrites influence properties of the solidified casting. Solidification time is a function of the volume and surface area of a casting (Chvorinov's rule).

- The grain structure of castings can be controlled by various means to obtain desired properties. Because most metals contract during solidification and cooling, cavities can form in the casting. Porosity caused by gases evolved during solidification can be a significant problem, particularly because of its adverse effect on the properties of castings. Various defects also can develop in castings from lack of control of material and process variables.

- Dimensional changes and cracking (hot tearing) are difficulties that can arise during solidification and cooling. Several basic categories of casting defects have been identified.

CHAPTER 11

METAL-CASTING PROCESSES AND EQUIPMENT

These classifications are related to mold materials, pattern production, molding processes, and methods of feeding the mold with molten metal. The major categories are:

1. **Expendable molds**, typically made of sand, plaster, ceramics, and similar materials, and generally mixed with various *binders* (bonding agents) for improved properties. A typical sand mold consists of 90% sand, 7% clay, and 3% water. These materials are *refractories* (i.e., they are capable of withstanding the high temperatures of molten metals). After the casting has solidified, the mold is broken up to remove the casting, hence the word *expendable*.

The mold is produced from a pattern; in some processes, and although the mold is expendable, the pattern is reused to produce several molds. Such processes are referred to as *expendable-mold, permanent-pattern casting processes*. On the other hand, investment casting requires a partem for each mold produced, and is an example of an *expendable-mold, expendable-pattern process*.

2. **Permanent molds**, made of metals that maintain their strength at high temperatures: The molds are used repeatedly, and are designed in such a way that the casting can be removed easily and the mold used for the next casting. Metal molds are better heat conductors than expendable nonmetallic molds, hence the solidifying casting is subjected to a higher rate of cooling, which in turn affects the microstructure and grain size within the casting.

3. **Composite molds**, made of two or more different materials (such as sand, graphite, and metal), combining the advantages of each material. These molds have a permanent and an expendable portion, and are used in various casting processes to improve mold strength, control the cooling rate, and optimize the overall economics of the casting operation.

Summary of Casting Processes

Process	Advantages	Limitations
Sand	Almost any metal can be cast; no limit to part size, shape, or weight; low tooling cost	Some finishing required; relatively coarse surface finish; wide tolerances
Shell mold	Good dimensional accuracy and surface finish; high production rate	Part size limited; expensive patterns and equipment
Evaporative pattern	Most metals can be cast, with no limit to size; complex part shapes	Patterns have low strength and can be costly for low quantities
Plaster mold	Intricate part shapes; good dimensional accuracy and surface finish; low porosity	Limited to nonferrous metals; limited part size and volume of production; mold-making time relatively long
Ceramic mold	Intricate part shapes; close-tolerance parts; good surface finish; low cooling rate	Limited part size
Investment	Intricate part shapes; excellent surface finish and accuracy; almost any metal can be cast	Part size limited; expensive patterns, molds, and labor
Permanent mold	Good surface finish and dimensional accuracy; low porosity; high production rate	High mold cost; limited part shape and complexity; not suitable for high-melting-point metals
Die	Excellent dimensional accuracy and surface finish; high production rate	High die cost; limited part size; generally limited to nonferrous metals; long lead time
Centrifugal	Large cylindrical or tubular parts with good quality; high production rate	Expensive equipment; limited part shape

11.2 Expendable-mold, Permanent-pattern Casting Processes

The major categories of expendable-mold, permanent-pattern casting processes are sand, shell mold, plaster mold, ceramic mold, and vacuum casting.

11.2.1 Sand Casting

Sand casting basically consists of;

(a) placing a pattern, having the shape of the part to be cast, in sand to make an imprint,

(b) incorporating a gating system,

(c) removing the pattern and filling the mold cavity with molten metal,

(d) allowing the metal to cool until it solidifies,

(e) breaking away the sand mold, and

(f) removing the casting

Sands. Most sand-casting operations use silica sand (SiO2) as the mold material. Sand is inexpensive and is suitable as a mold material because of its high-temperature characteristics and high melting point. There are two general types of sand: **naturally bonded** *(bank sand)* and synthetic *(lake sand)*. Because its composition can be controlled more accurately, synthetic sand is preferred by most foundries.

Several factors are important in the selection of sand for molds, and certain tradeoffs with respect to properties have to be considered. Sand having fine, round grains can be packed closely and thus forms a smooth mold surface. Although fine-grained sand enhances mold strength, the fine grains also lower mold *permeability* (where fluids and gases can pass through pores). Good permeability of molds and cores allows gases and steam evolved during the casting process to escape easily. The mold also should have good *collapsibility,* in order to allow the casting to shrink while it is cooling, and thus prevent detects in the casting, such as hot tearing and cracking.

Types of Sand Molds. Sand molds are characterized by the types of sand that comprise them and by the methods used to produce them. There are three basic types of sand molds:

(a) green-sand,

(b) cold-box, and

(c) no-bake molds.

The most common mold material is green molding sand, a mixture of sand, clay, and water. The term "green" refers to the fact that the sand in the mold is moist or damp while the metal is poured into it.

Sand Properties:

- Refactoriness
- Cohesiveness
- Permeability
- Collapsibility

In the **cold-box** mold process, various organic and inorganic binders are blended into the sand to bond the grains chemically for greater strength. These molds are more dimensionally accurate than green-sand molds but are more expensive to make. In the no-bake mold process, a synthetic liquid resin is mixed with the sand, and the mixture hardens at room temperature. Because the bonding of the mold in this and in the cold-box process takes place without heat, they are called **cold-setting processes**.

Sand molds can be oven dried *(baked)* prior to pouring the molten metal; they then become stronger than green-sand molds and impart better dimensional accuracy and surface finish to the casting. However, this method has drawbacks in that:

(a) distortion of the mold is greater;

(b) the castings are more susceptible to hot tearing, because of the lower collapsibility of the mold; and

(c) the production rate is lower, because of the considerable drying time required.

The major features of molds in sand casting are:

1. The **flask**, which supports the mold itself. Two-piece molds consist of a cope on top and a **drag** on the bottom; the seam between them is the parting line. When more than two pieces are used in a sand mold, the additional parts are called *cheeks*.

2. A **pouring basin** or **pouring cup**, into which the molten metal is poured.

3. A **sprue**, through which the molten metal flows downward.

4. The **runner system**, which has channels that carry the molten metal from the sprue to the mold cavity. **Gates** are the inlets into the mold cavity.

5. **Risers**, which supply additional molten metal to the casting as it shrinks during solidification. Two types of risers : *a blind riser* and *an open riser*

6. **Cores**, which are inserts made from sand; they are placed in the mold to form hollow regions or otherwise define the interior surface of the casting. Cores also are used on the outside of the casting to form features, such as lettering or numbering.

7. **Vents**, which are placed in molds to carry off gases produced when the molten metal comes into contact with the sand in the mold and the core. Vents also exhaust air from the mold cavity as the molten metal flows into the mold.

Patterns. Patterns are used to mold the sand mixture into the shape of the casting, and may be made of wood, plastic, or metal. Patterns may also made of a combination of materials to reduce wear in critical regions; they usually are coated with a **parting agent** to facilitate the removal of the pattern from the molds.

Patterns can be designed with a variety of features for specific applications and economic requirements. One-piece patterns, also called *loose or solid patterns*, are generally used for simpler shapes and low-quantity production; they generally are made of wood and are inexpensive. Split patterns are two-piece patterns, made such that each part forms a portion of the cavity for the casting; in this way, castings with complicated shapes can be produced. Match-plate patterns are a common type of mounted pattern in which two-piece patterns are constructed by securing each half of one or more split patterns to the opposite sides of a single plate. In such constructions, the gating system can be mounted on the drag side of the pattern. This type of pattern is used most often in conjunction with molding machines and for large production runs to produce smaller castings.

An important development in mold and pattern making is the application of **rapid prototyping**. In sand casting, for example, a pattern can be fabricated in a rapid-prototyping machine, and fastened to a backing plate at a fraction of the time and the cost of machining a pattern. There are several rapid-prototyping techniques with which these tools can be produced quickly. These technologies are best suited for small production runs.

Pattern design is a critical aspect of the total casting operation. The design should provide for **metal shrinkage**, permit proper metal flow in the mold cavity, and allow the pattern to be easily removed from the sand mold, by means of a taper or draft or some other geometric feature.

Cores. For castings with internal cavities or passages, such as those found in automotive engine blocks or valve bodies, cores are utilized. Cores are placed in the mold cavity to form the interior surfaces of the casting, and are removed from the finished part during shakeout and further processing. Like molds, cores must possess strength, permeability, collapsibility, and the ability to withstand heat; hence cores are made of sand aggregates.

The core is anchored by **core prints**, which are geometric features added to the pattern to locate and support the core and to provide vents for the escape of gases. A common problem with cores is that, for some casting requirements, as in the case where a recess is required, they may lack sufficient structural support in the cavity. To keep the core from shifting, metal supports (**chaplets**) may be used to anchor the core in place.

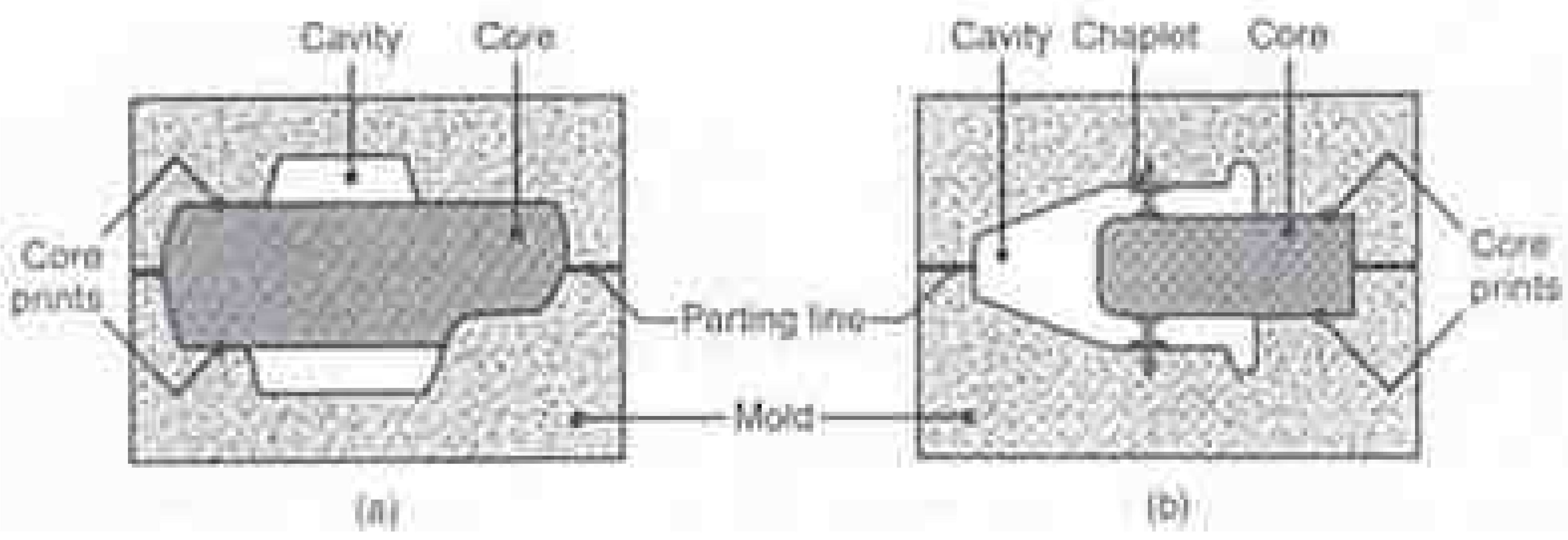


FIGURE 11.6 Examples of sand cores, showing core prints and chaplets to support the cores.

Sand-molding Machines. The oldest known method of molding, which is still used for simple castings and for small production runs, is to compact the sand by hand hammering (tamping) or ramming it around the pattern. For most operations, however, the sand mixture is compacted around the pattern by *molding machines*. These machines eliminate arduous labor, manipulate the mold in a controlled manner, offer high-quality casting by improving the application and distribution of forces, and increase production rate.

In **vertical flaskless molding**, the pattern halves form a vertical chamber will against which sand is blown and compacted. Then, the mold halves are packed horizontally with the parting line oriented vertically, and moved along a pouring conveyor. This is a simple operation and eliminates the need to handle flasks, allowing for very high production rates, particularly when other aspects of the operation (such as coring and pouring) are automated.

Sandslingers fill the flask uniformly with sand under a high-pressure stream; they are used to fill large flasks and are often automated. An impeller in the machine throws sand from its blades or cups at such high speeds that the machine not only places the sand but also rams it appropriately.

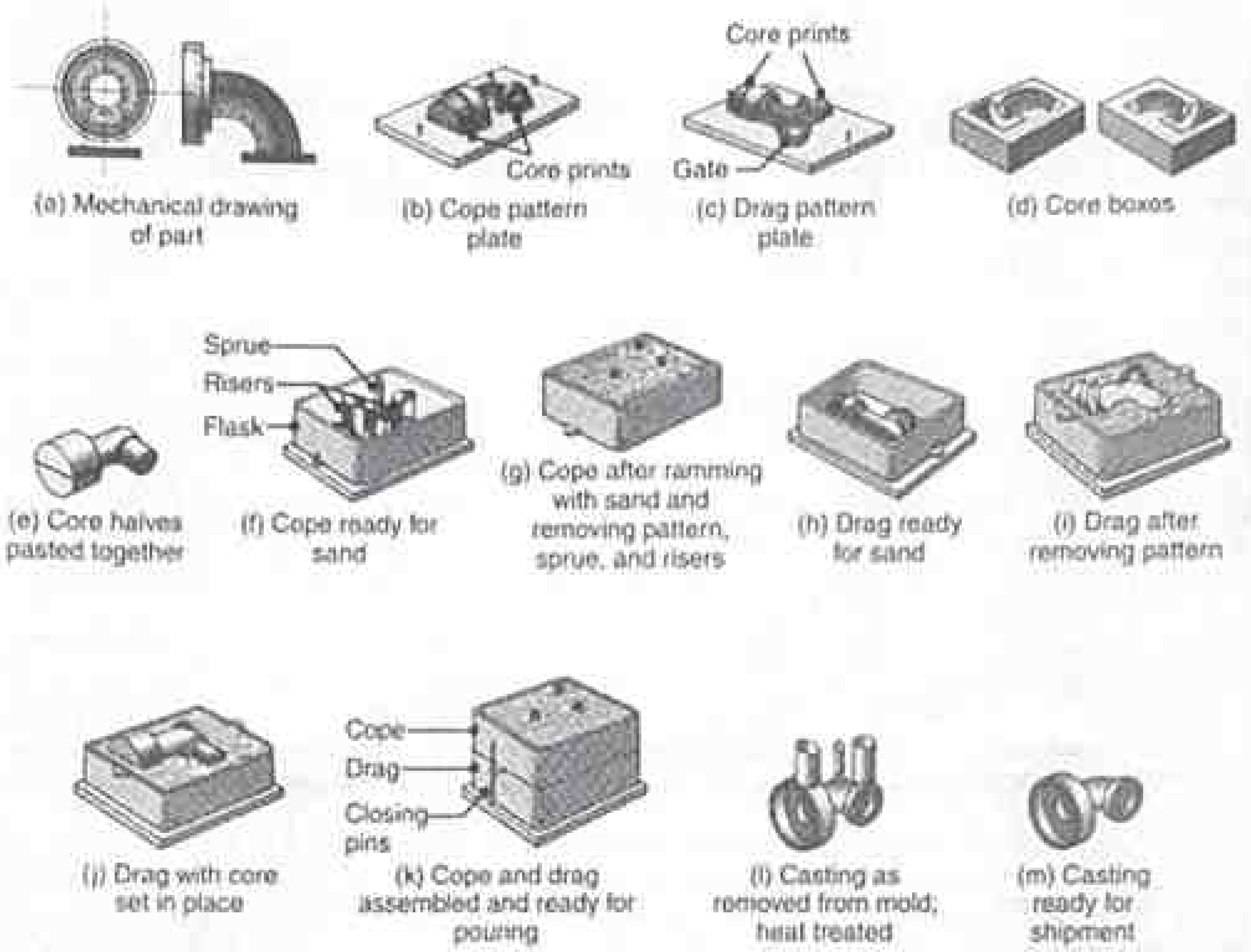


FIGURE 11.9 Schematic illustration of thesequence of operations for sand casting. (a) A mechanical drawing of the part is used to generate a design for the pattern. Considerations such as part shrinkage and draft must be built into the drawing. (b) and (c) Patterns have been mounted on plates equipped with pins for alignment; note the presence of core prints designed to hold the core in place. (d) and (e) Core boxes produce core halves, which are pasted togither; the cores will be used to produce the hollow area of the part shown in (a). (f) The cope half of the mold is assembled by securing the cope pattern plate to the flask with aligning pins and attaching inserts to form the sprue and risers. (g) The flask is rammed with sand, and the plate and inserts are removed. (h) The drag half is produced in a similar manner with the pattern inserted; a bottom board is placed below the drag and aligned with pins. (i) The pattern, flask, and bottom board are inverted, and the pattern is withdrawn, leaving the appropriate imprint. (j) The core is set in place within the drag cavity. (k) The mold is closed by placing the cope on top of the drag and securing the assembly with pins; the flasks are then subjected to pressure to counteract buoyant forces in the liquid, which might lift the cope. (l) After the metal solidifies, the casting is removed from the mold. (m) The sprue and risers are cut off and recycled, and the casting is cleaned, inspected, and heat treated (when necessary).

11.2.2 Shell Molding

Shell molding has grown significantly because it can produce many types of castings, with close dimensional tolerances and good surface finish, and at low cost. Shell-molding applications include small mechanical parts requiring high precision, such as gear housings, cylinder heads, and connecting rods. The process is also used widely in producing high-precision molding cores.

In this process, a mounted pattern, made of a ferrous metal or aluminum, is

(a) heated to a range of 175°-370°C,

(b) coated with a parting agent (such as silicone), and

(c) damped toa box or chamber.

The box contains fine sand, mixed with 2.5-4% of a thermosetting resin binder (such as phenol-formaldehyde), which coats thesand particles. Either the box is rotated upside down (Fig. 11.10) or the sand mixture is blown over the pattern, allowing it to form a coating.

Shell sand has a much smaller grain size, and therefore a lower permeability than the sand used for green-sand molding. The decomposition of the shell-sand binder also produces a high volume of gas. Thus, unless the molds are vented properly, trapped air and gas can result in defects in the shell molding of ferrous castings. The high quality of the finished casting can reduce cleaning, machining, and other finishing costs significantly. Complex shapes can be produced with less labor, and the process can be automated fairly easily.

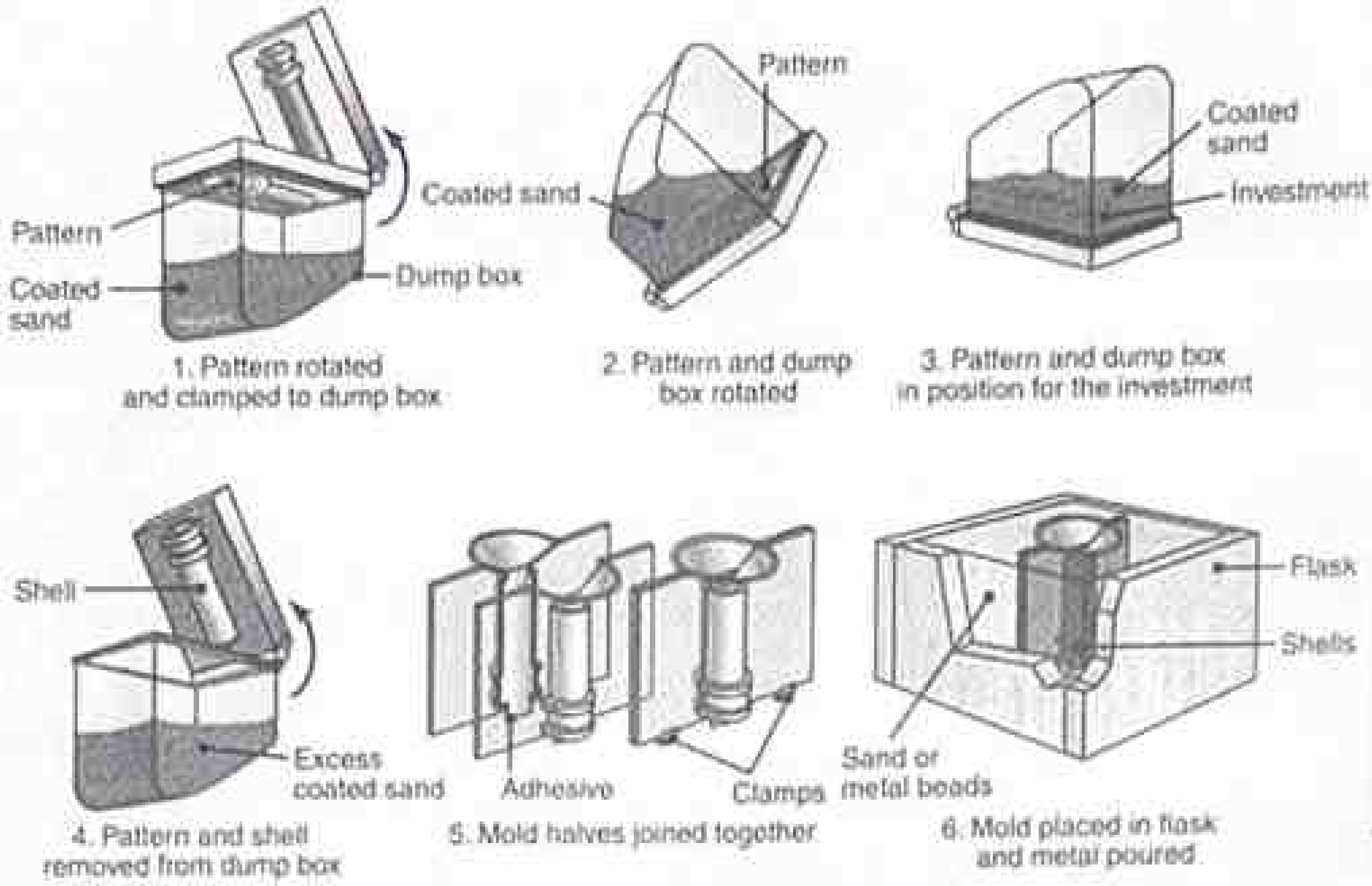


FIGURE 11.10 The shell-molding process, also called the dump-box technique

11.2.3 Plaster-mold Casting

This process are known as precision casting, because of the high dimensional accuracy and good surface finish obtained. Typical parts made are lock components, gears, valves, fittings, tooling, and ornaments.

Because plaster molds have very low permeability, gases evolved during solidification of the metal cannot escape; consequently, the molten metal is poured either in a vacuum or under pressure. Mold permeability can be increased substantially by the *Antioch process*, in which the molds are dehydrated in an autoclave (pressurized oven) for 6-12 h, and then rehydrated in air for 14 h. Another method of increasing the permeability of the mold is to use foamed plaster, containing trapped air bubbles.

11.2.4 Ceramic-mold Casting

The ceramic-mold casting process (also called *cope-and-drag investment casting*) is similar to the plaster-mold process, except that it uses refractory mold materials suitable for high-temperature exposure. Typical parts made are impellers, cutters for machining operations, dies for metalworking, and molds for making plastic and rubber components.

The pattern may be made of wood or metal. After setting, the molds (ceramic facings) are removed, dried, ignited to burn off volatile matter, and baked. The molds are clamped firmly and used as all ceramic molds. In the *Shaw process*, the ceramic facings are backed by fireclay (which resists high temperatures) to give strength to the mold. The facings are then assembled into a complete mold, ready to be poured.

The high-temperuture resistance of the refractory molding materials allows these molds to be used for casting ferrous and other high-temperature alloys, stainless steels and tool steels. Although the process is somewhat expensive, the castings have good dimensional accuracy and surface finish over a wide range of sizes and intricate shapes.

11.3 Expendable-mold. Expendable-pattern Casting Processes

Evaporative-pattern and investment casting also are referred to as *expendable-pattern* casting processes or *expendable mold-expendable pattern* processes. They are unique in that a mold and a pattern must be produced for each casting. Typical applications are cylinder heads, engine blocks, crankshafts, brake components, manifolds, and machine bases.

11.3.1 Evaporative-pattern Casting (Lost-foam Process)

The *evaporative-pattern casting* (EPC) process uses a polystyrene pattern, which evaporates upon contact with molten metal to form a cavity for the casting; this process is also known as *lost-foam casting*, or *full-mold casting* (FMC) process. It has become one of the more important casting processes for ferrous and nonferrous metals, particularly for the automotive industry.

In this process, polystyrene beads, containing 5-8% pentane (a volatile hydrocarbon), are placed in a preheated die, usually made of aluminum. Complex patterns may be made by bonding various individual pattern sections using hot-melt adhesive. Polymethylmethacrylate (PMMA) and polyalkylene carbonate also may be used as pattern materials for ferrous castings.

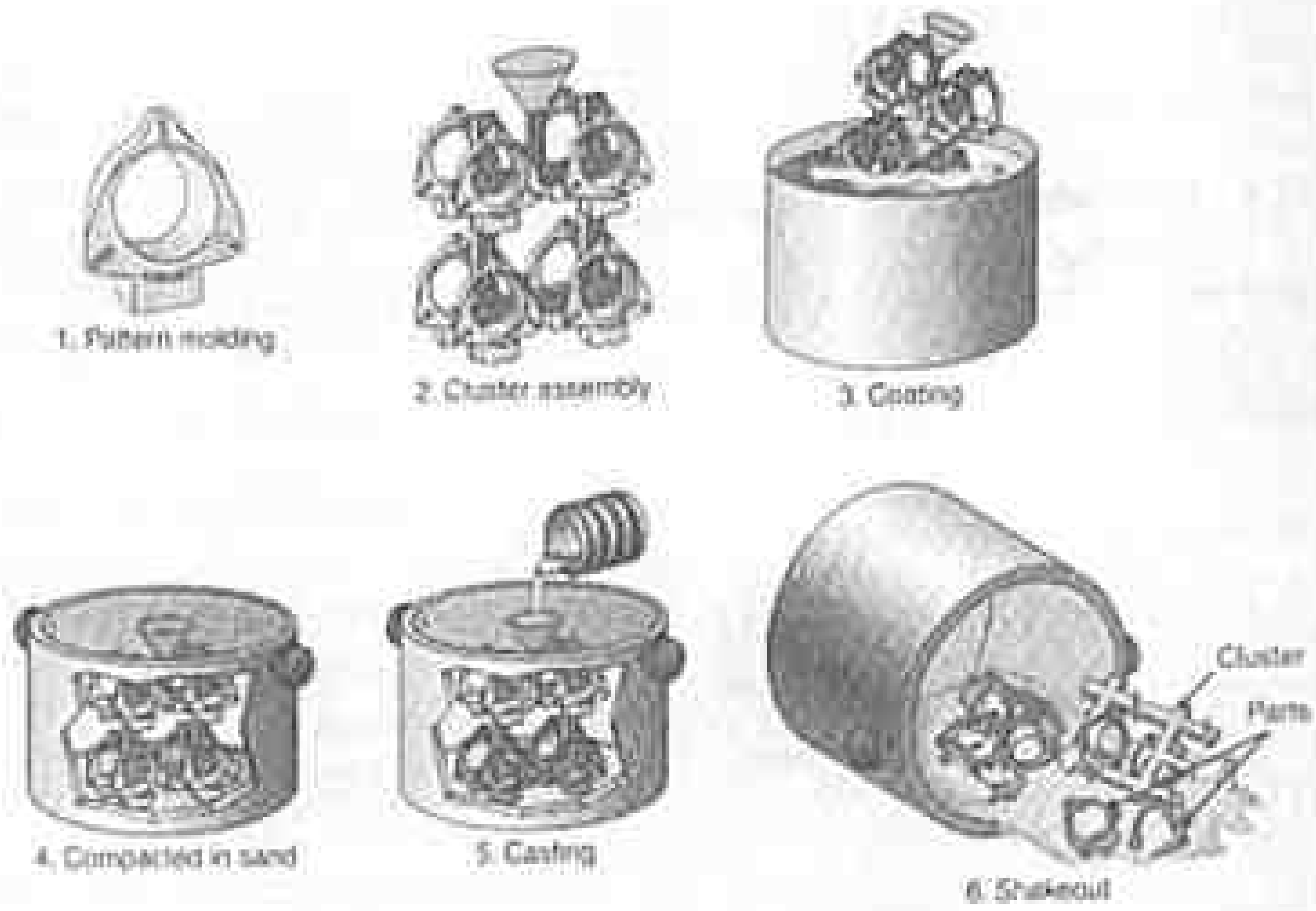


FIGURE 11.12 Schematic illustration of the expendable-pattern casting process, also known as lost-foam or evaporative-pattern casting.

11.3.2 Investment Casting

The investment-casting process, also called **the lost-wax process**, was first used during the period from 4000 to 3000 b.c.

The pattern is made of wax, or of a plastic such as polystyrene, by molding or rapid-prototyping techniques. It is then dipped into a slurry of refractory material such as very fine silica and binders, including water, ethyl silicate, and acids. After this initial coating has dried, the pattern is coated repeatedly to increase its thickness, for higher strength. Note that smaller particles can be used for the initial coating to develop a better surface finish in the casting; subsequent layers use larger particles and are intended to increase the coating thickness quickly.

The term investment derives from the fact that the pattern is invested (surrounded) with the refractory material. Wax patterns require careful handling, because they are not strong enough to withstand the force s encountered during mold making; unlike plastic patterns, however, wax can be recovered and reused.

Ceramic-shell Investment Casting. A variation of the investment-casting process is ceramic-shell casting. It uses the same type of wax or plastic pattern, which is dipped first in ethyl silicate gel and subsequently into a fluidized bed of fine grained fused silica or zircon powder. The pattern is then dipped into coarser grained silica, to build up additional coatings and develop a proper thickness so that the pattern can withstand the thermal shock during pouring. The rest of the procedure is similar to investment casting. The process is economical and is used extensively for the precision casting of steels and high-temperature alloys.

<u>**SUMMARY**</u>

- Expendable-mold, permanent-pattern processes include sand, shell-mold, plaster-mold, and ceramic-mold casting. These processes require the destruction of the mold for each casting produced, but mold production is facilitated by reusable patterns.

- Expendable-mold, expendable-pattern processes include lost-foam and investment casting. In these processes, a pattern is consumed for each mold produced, and the mold is destroyed after each casting.

- Permanent-mold processes have molds or dies that can be used to produce castings at high production rates. Common permanent-mold processes include slush casting, pressure casting, die casting, and centrifugal casting.

- The molds used in permanent-mold casting are made of metal or graphite, and are used repeatedly to produce a large number of parts. Because metals are good heat conductors but do not allow gases to escape, permanent molds have fundamentally different effects on castings than sand or other aggregate mold materials.

- In permanent-mold casting, die and equipment costs are relatively high, but the processes are economical for large production runs. Scrap loss is low, dimensional accuracy is relatively high, and good surface detail can be achieved.

- Other casting processes include squeeze casting (a combination of casting and forging), semisolid-metal forming, rapid solidification (for the production of amorphous alloys), and casting of single-crystal components (such as turbine blades and silicon ingots for making wafers in integrated-circuit manufacture).

- Melting processes and their control also are important factors in casting operations. They include proper melting of the metals, preparation for alloying and removal of slag and dross, and pouring the molten metal into the molds. Inspection of castings for possible internal or external defects also is essential.

13.1 Introduction

Rolling is the process of reducing the thickness or changing the cross-section of a long workpiece by compressive forces applied through a set of **rolls** (Fig. 13.1), a process that is similar to rolling dough with a rolling pin. Rolling, which accounts for about 90% of all metals produced by metalworking processes, was first developed in the late 1500s. Modern steelmaking practices and the production of various ferrous and nonferrous metals and alloys now generally integrate *continuous casting* with rolling processes; this method greatly improves productivity and lowers production costs, as described in Section 5.4. Nonmetallic materials also are rolled to reduce their thickness and enhance their properties.

Rolling is first carried out at elevated temperatures (*hot rolling*). During this phase, the coarse-grained, brittle, and porous structure of the ingot or the continuously cast metal is broken down into a *wrought structure*, having a finer grain size and enhanced properties, such as increased strength and hardness. Subsequently, rolling can be performed at room temperature (cold rolling), whereby the rolled sheet has higher strength and hardness, and better surface finish. Cold rolling will, however, result in a product with anisotropic properties, due to preferred orientation or mechanical fibering.

Plates generally have a thickness of more than 6mm, and are used for structural applications, such as ship hulls, boilers, bridges, and heavy machinery.

Sheets are generally less than 6 mm thick, and are typically provided to manufacturing facilities as coils, weighing as much as 30,000 kg, or as flat sheets for further processing into a wide variety of sheet-metal products. Sheets are used for trucks and aircraft bodies, appliances, food and beverage containers, and kitchen and office equipment. Commercial aircraft fuselages and trailer bodies usually are made of aluminum-alloy sheets, with a minimum thickness of 1-mm.

13.2 The Flat-rolling Process

The metal accelerates in the roll gap, in the same manner as an incompressible fluid flows through a converging channel.

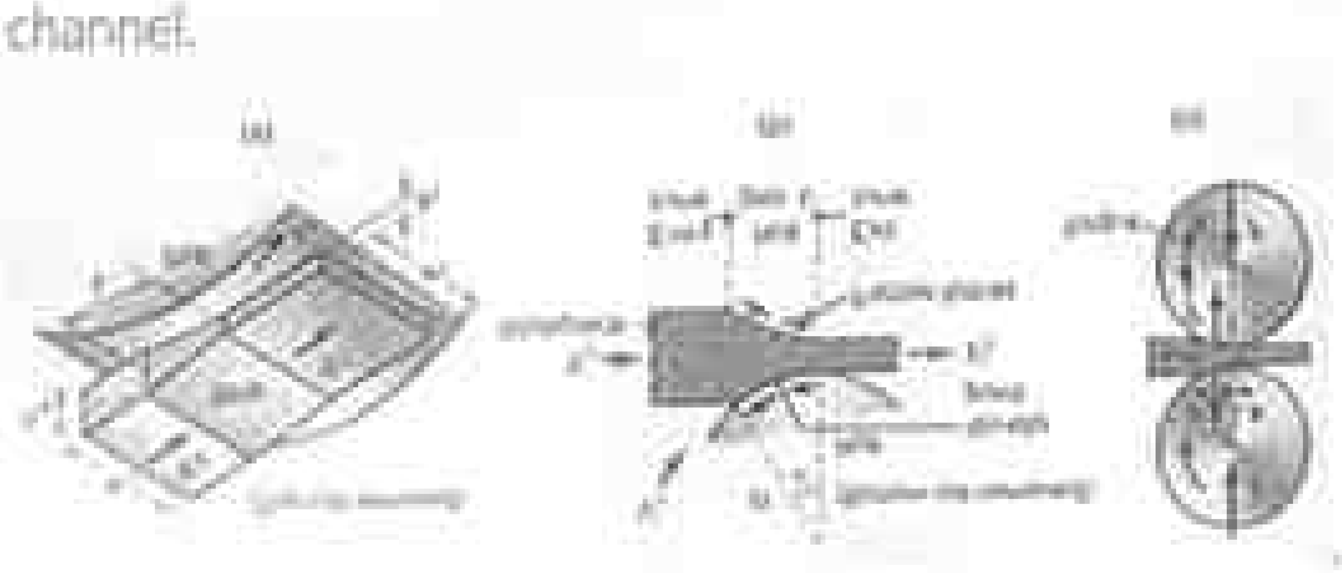


FIGURE 13.2 (a) Schematic illustration of the flat-rolling process. (b) Friction forces acting on strip surfaces. (c) Roll force, F, and torque, T, acting on the rolls. The width of the strip, w, usually increases during rolling.

Reducing Roll Force. Roll force can cause significant deflection and flattening of the rolls, as it does in a rubber tire. Such changes will, in turn, affect the rolling process, its efficiency, and its ability to produce a uniform thickness in the rolled sheet (known as gage control). Also, the columns of the **roll stand** would deflect under high roll forces to such an extent that the roll gap may open up significantly. Consequently, the rolls have to be set closer than originally calculated in order to compensate for this deflection and to obtain the desired final thickness.

Roll forces can be reduced by the following means:

- Using smaller diameter rolls, to reduce the contact area
- Taking smaller reductions per pass, to reduce the contact area
- Rolling at elevated temperatures, to lower the strength of the material
- Applying back and/or front tensions to the strip, to reduce the roll pressure
- Reducing friction at the roll-workpiece interface

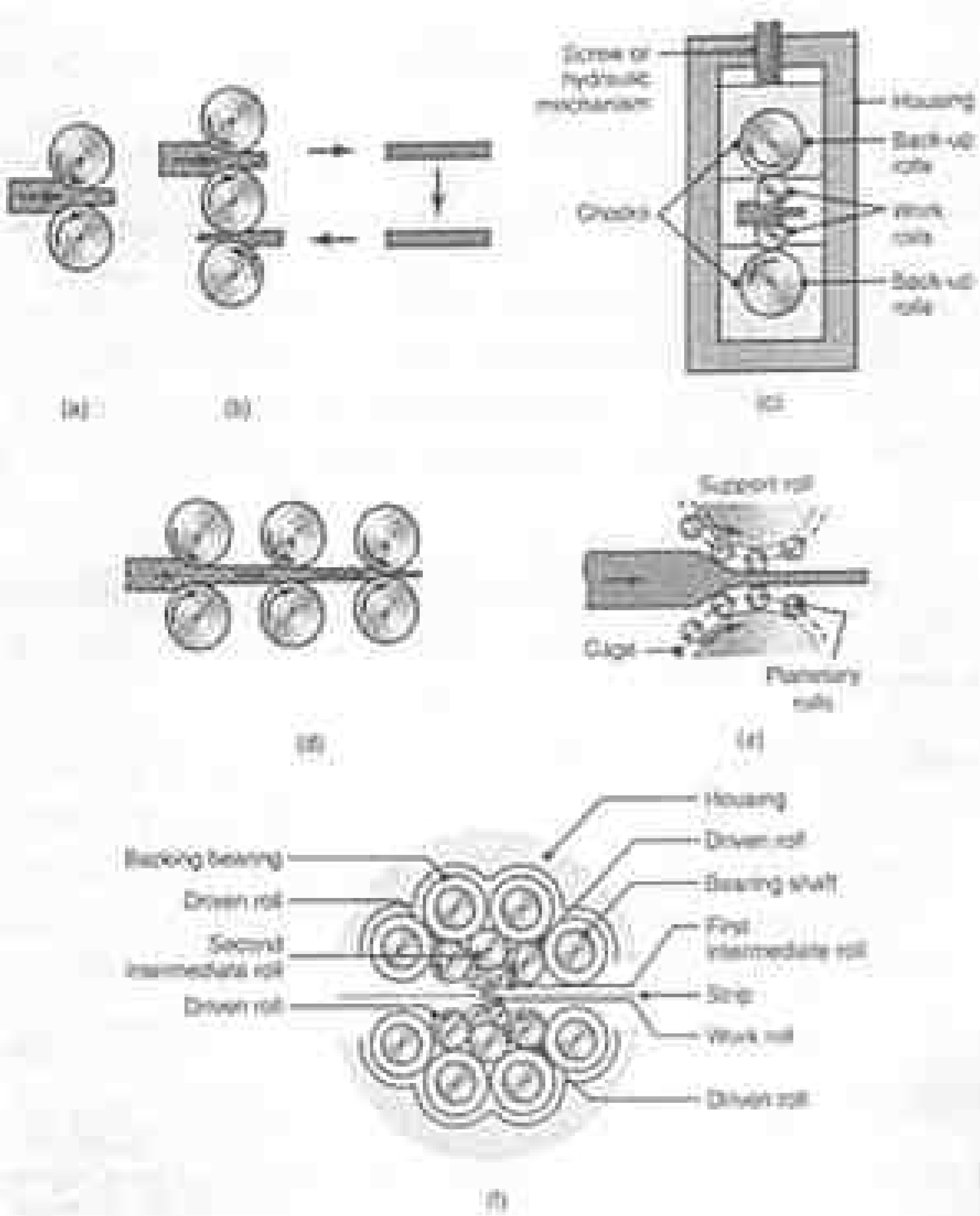


FIGURE 13.3 Schematic illustration of various roll arrangements: (a) Two-high mill; if a two-high mill is used for thick but short workpieces, it will commonly roll a billet back and forth in multiple passes, known as a reversing mill. (b) Three-high mill with elevator for multiple passes. (c) Four-high rolling mill showing various features; the stiffness of the housing, the rolls, and the roll bearings are all important in controlling and maintaining the thickness of the rolled strip. (d) Tandem rolling, with three stands. (e) Planetary mill, and (f) Cluster mill, also known as a *Sendzimir* or Z-mill.

13.2.2 Geometric Considerations

Because of the forces acting on the rolls, they undergo shape changes during rolling. Just as a straight beam deflects under a transverse load, roll forces tend to *elastically* bend the rolls during rolling; as a result, the rolled strip will be thicker at its center than at its edges, known as **crown**. A common method of avoiding this problem is to grind the rolls in such a way that their diameter at the center is slightly larger than that at their edges (called **camber**). Thus, when the rolls bend, the strip being rolled will have a constant thickness along its width.

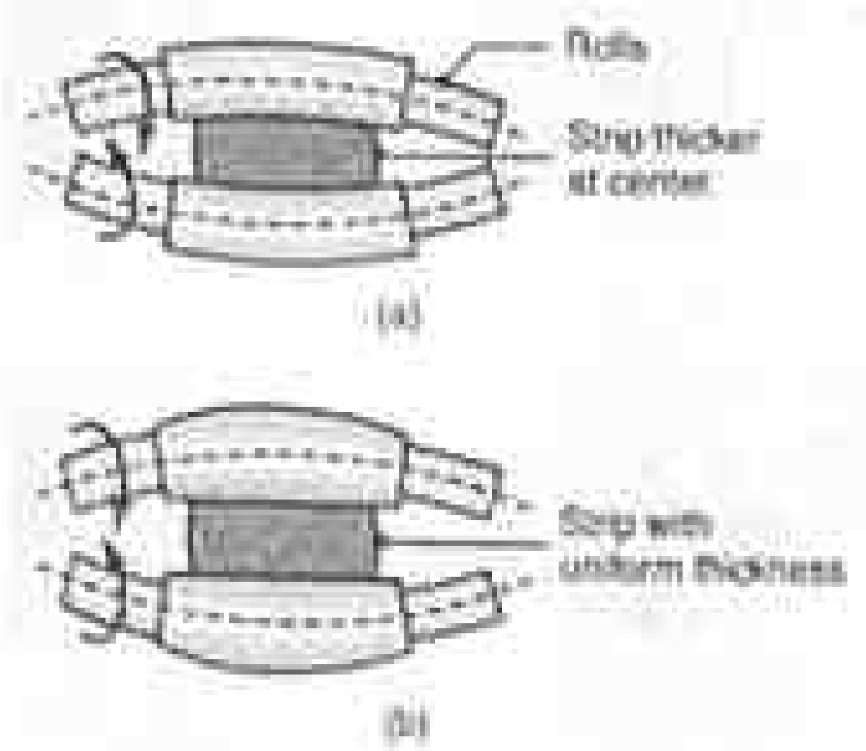


FIGURE 13.4 (a) Bending of straight cylindrical rolls caused by roll forces. (b) Bending of rolls ground with camber, producing a strip with uniform thickness through the strip width. (Roll deflections have been exaggerated for clarity.)

Spreading. In rolling places and sheets, with high width-to-thickness ratios, the width of the strip remains effectively constant during rolling. However, with smaller ratios (such as a bar with a square cross-section), its width increases significantly as it passes through the rolls, an effect that can easily be observed in the rolling of dough with a rolling pin. The increase in width is called spreading.

It can be shown that spreading increases with (a) decreasing width-to-thickness ratio of the entering strip, because of reduction in the width constraint, (b) increasing friction, and (c) decreasing ratio of roll radius to strip thickness. Spreading can also be prevented by using vertical rolls, in contact with the strip edges; known as edger mills, the vertical rolls provide a physical constraint to spreading.

3.2.3 Vibration and Chatter

Vibration and chatter can have significant adverse effects on product quality and productivity in manufacturing operations. Generally defined as *self-excited* vibration, chatter in rolling leads to periodic variations in the rolled sheet thickness and surface finish, and may lead to excessive scrap. Chatter in rolling is found predominantly in tandem mills. Chatter is very detrimental to productivity.

Although not always practical to implement, it also has been suggested that chatter can be reduced by (a) increasing the distance between the stands of the rolling mill, (b)increasing the strip width, (c)decreasing the reduction per pass (draft), (d) increasing the roll radius, (e)increasing the strip-roll friction, and (f)incorporating external dampers in the roll supports.

FIGURE 13.5 Spreading in flat rolling; note that similar spreading can he observed when dough is rolled with a rolling pin.

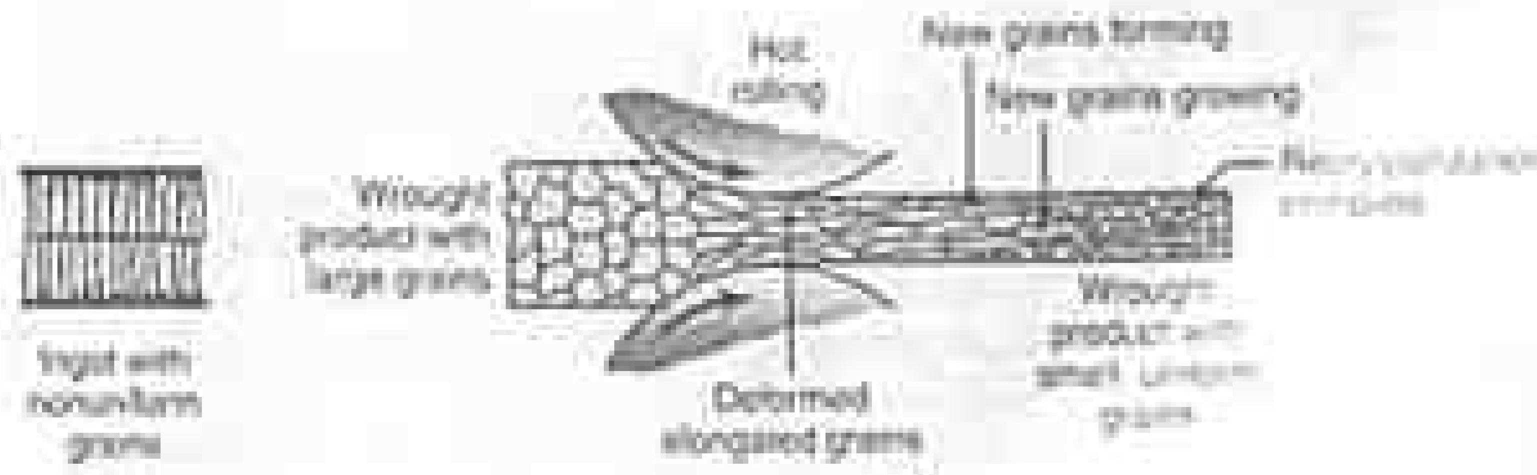


FIGURE 13.6 : Changes in the grain structure of cast or of large-grain wrought metals during hot rolling. Hot rolling is an effective way to reduce grain size in metals for improved strength and ductility; cast structures of ingots or continuous casting are converted to a wrought structure by hot working.

3.3.2 Other Characteristics of Rolled Metals

Residual Stresses. Because of nonuniform deformation of the material in the roll gap, residual stresses can develop in rolled plates and sheets, especially in cold rolling. Small-diameter rolls or small thickness reductions per pass tend to plastically deform the metal to a higher degree at its surfaces than in its bulk. This situation results in compressive residual stresses on the surfaces and tensile stresses in the bulk. Conversely, large-diameter rolls or high reductions per pass tend to deform the bulk more than its surfaces. This is due to the higher frictional constraint at the surfaces along the arc of contact, a situation that produces residual stress distributions that arc the opposite of those with small-diameter rolls.

Dimensional Tolerances. Thickness tolerances for cold-rolled sheets usually range from ±0.01 to 0.05 mm; tolerances are much greater for hot-rolled plates. *Flatness* tolerances arc usually within ±15 mm/m for cold rolling and ±55 mm/m for hot rolling.

13.4 Rolling Mills

Although the designs of equipment for hot and cold rolling are essentially the same, there are important differences in the roll materials, process parameters, lubricants, and cooling systems. The design, construction, and operation of rolling mills require major investments. Highly automated mills now produce close-tolerance, high-quality plates and sheets, at high production rates and at low cost per unit weight, particularly when integrated with continuous casting. The width of rolled products may range up to 5 m, and rolling speeds arc up to 40 m/s.

Roll Material. The basic requirements for roll materials are strength and resistance to wear.

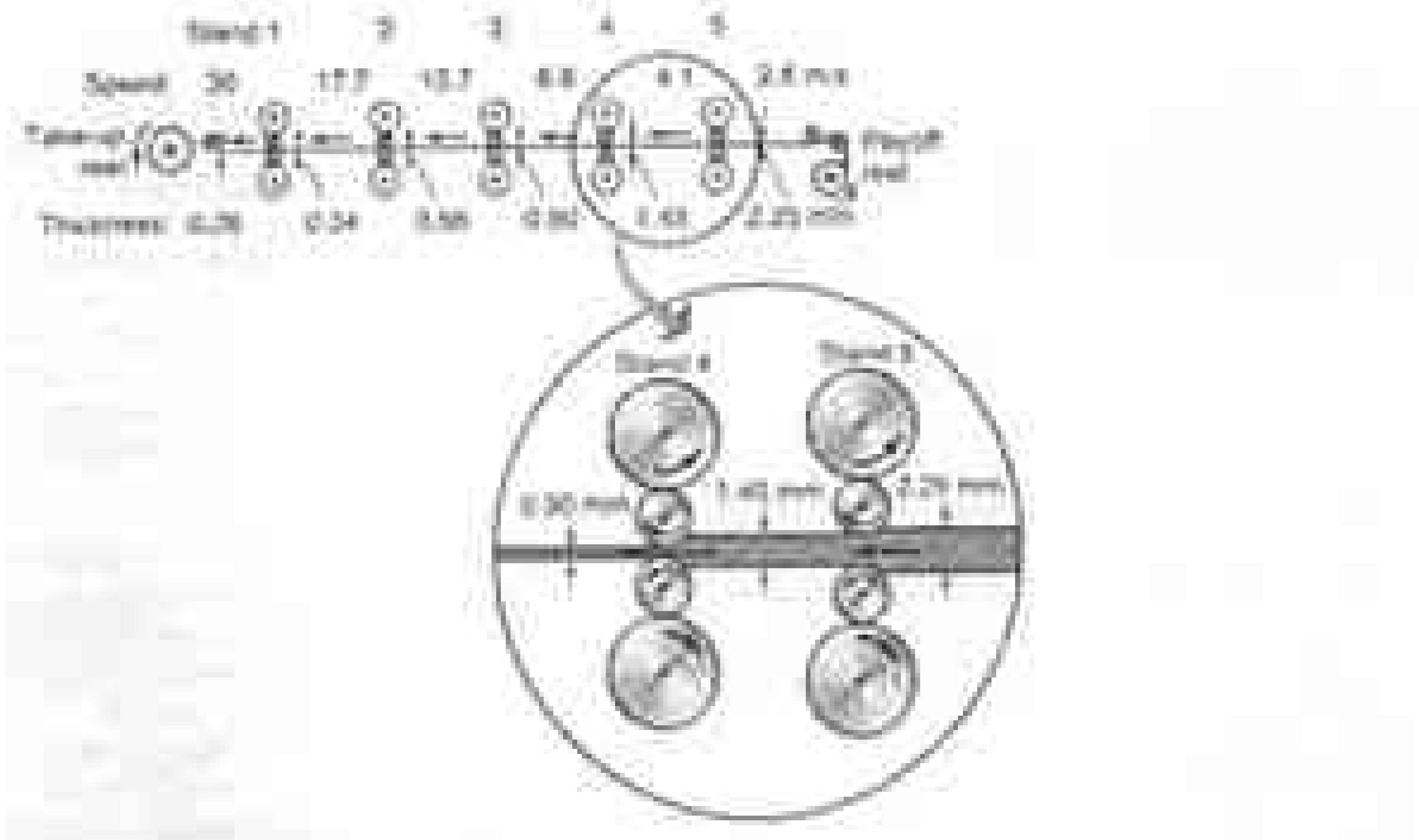


FIGURE 13.11 An example of a tandem-rolling operation.

13.5 Various Rolling Processes and Mills

Shape Rolling. Straight and long structural shapes (such as channels, I-beams, railroad rails, and solid bars) are formed by *shape rolling (profile rolling)*, in which the heated stock passes through pairs of specially designed rolls. *Cold shape rolling* also can be done, with the starting materials in the shape of rod, with various cross-sections. Because the entering material's cross-section is reduced nonuniformly, the proper design of a roll sequence, called roll-pass design, is critical in order to prevent the formation of external and internal defects, hold dimensional tolerances, and to reduce roll wear.

Roll Forging. In this operation, also called cross rolling, the cross-section of a round bar is shaped by passing it through a pair of rolls with specially profiled grooves. This process is typically used to produce tapered shafts and leaf springs, table knives, and hand tools. Roll forging also may be used as a preliminary forming operation, to be followed by other forging processes.

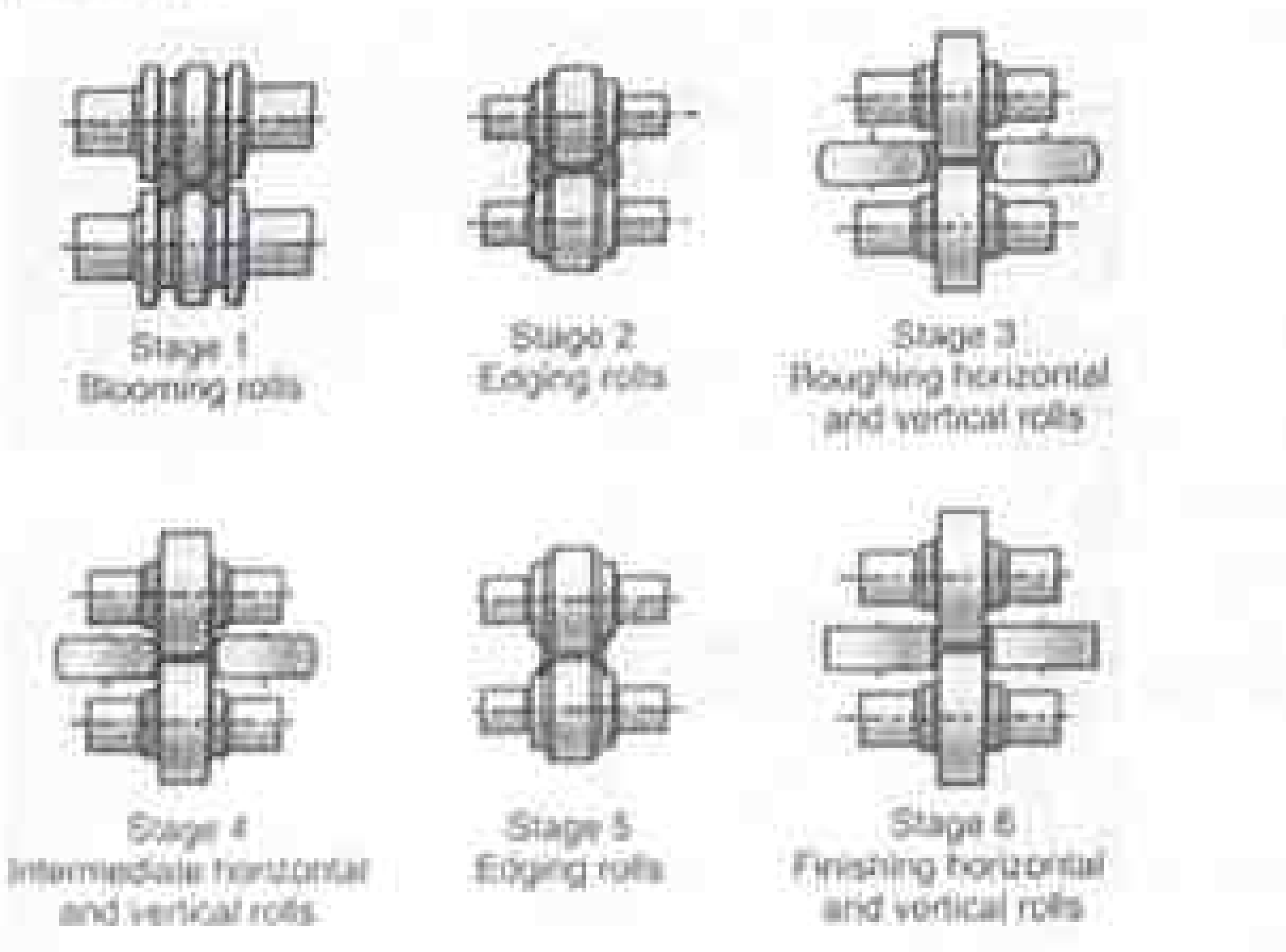


FIGURE 13.12 Steps in the shape rolling of an I-beam. Various other structural sections, such as channels and rails, also are rolled by this process.

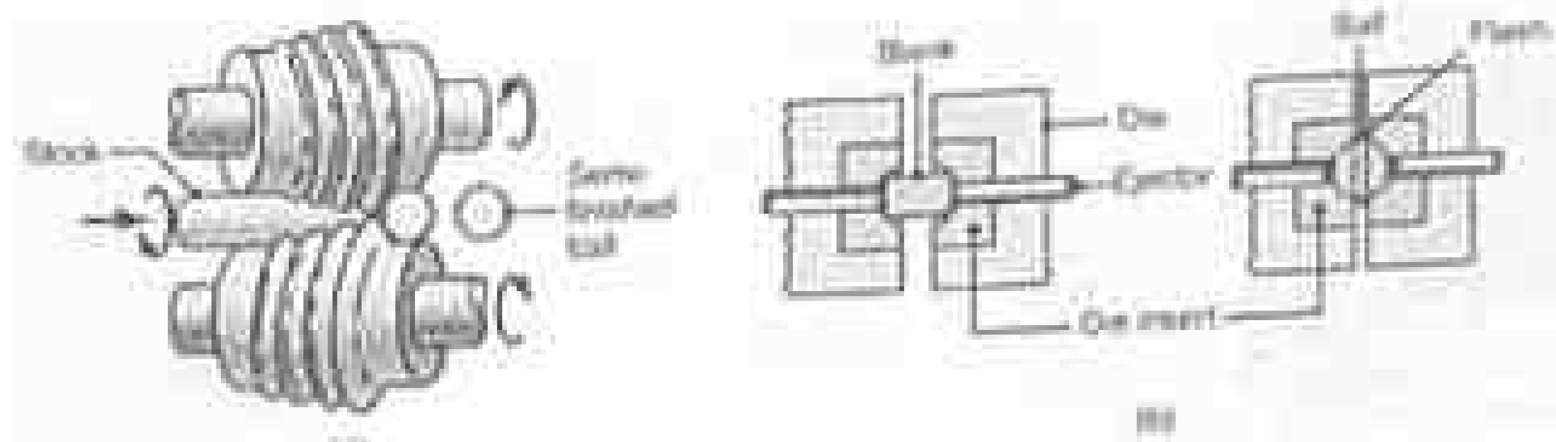


FIGURE 13.14 (a) Production of steel kills by the skew-rolling process. (b) Production of steel balls by upsetting a cylindrical blank; note the formation of flash. The balls made by these processes are subsequently ground and polished for use in ball bearings.

Skew Rolling. A process similar to roll forging is *skew rolling*, typically used for making ball bearings.(Fig. 13.14a) Round wire or rod is fed into the roll gap, and spherical blanks are formed continuously by the action of the rotating rolls. (Another method of forming ball bearings is illustrated in Fig. 13.14b, which is basically a forging operation.) The balls, which require further finishing, are subsequently ground and polished in special machinery.

Ring Rolling. In ring rolling, a ring-shaped blank is placed between two rolls, one of which is driven while the other idles (Fig. 13.15a). The thickness of the ring is reduced by bringing the rolls closer together as they rotate. Since the volume of the ring remains constant during deformation (volume constancy), the reduction in ring thickness results in its increase in diameter. The process can be carried out at room temperature or at an elevated temperature, depending on the, and strength and ductility of the material.

Depending on its size, the blank may be produced by such means as cutting from a plate, piercing, or sawing or shearing a thick-walled pipe. Various shapes can be ring rolled using shaped rolls (Figs. 13.15b-d). The thickness of rings also can be reduced by an open-die forging process; however, dimensional control and surface finish will not be as good as in ring rolling. Compared with other manufacturing processes that are capable of producing the same part, the advantages of ring rolling are short production times, low scrap, close dimensional tolerances, and favorable grain flow in the product, thus enhancing its strength in the desired direction.

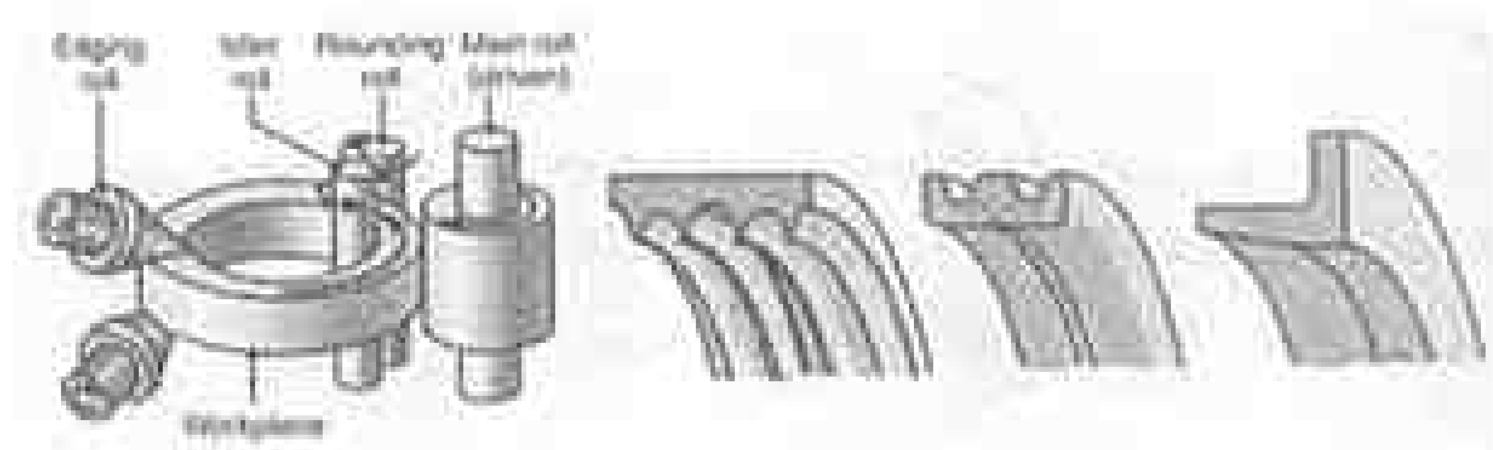


FIGURE 13.15 (a) Schematic illustration of a ring-rolling operation: thickness reduction results in an increase in the part diameter. (b) through (d) Examples of cross-sections that can be formed by ring rolling.

Thread Rolling. *Thread rolling* is a cold-forming process by which straight or tapered threads arc formed on round rods or wire. The threads are formed on the rod or wire with each stroke of a pair of flat reciprocating dies (Fig. 13.16a). In another method, threads arc formed using two rolls (Fig. 13.16b) or rotary or planetary dies (Fig. 11.16c), at production rates as high as 80 pieces per second. Typical parts made arc screws, bolts, and similar threaded parts. Depending on die design, the major diameter of a rolled thread may or may not be larger than a machined thread (Fig. 13.17a), thar is, the same as the blank diameter.

The thread-rolling process has the advantages of generating threads at high production rates and without any scrap. The surface finish produced is very smooth, and the process induces compressive residual stresses on the surfaces, thus improving fatigue life. Thread rolling is superior to other methods of thread manufacture, because machining the threads cuts through the grain-flow lines of the material, whereas rolling the threads results in a grain-flow pattern that improves thread strength (Figs. 13.17b-c). **Internal thread rolling** can be carried out with a fluteless **forming tap**. This is an operation that is similar to external thread rolling, and it produces accurate internal threads and with good strength.

Spur and helical gears can be produced by a cold-rolling process similar to thread rolling; the operation may be carried out on solid cylindrical blanks or on precut gears. Cold rolling of gears has extensive applications in automatic transmissions and in power tools.

Lubrication is important in thread-rolling operations in order to obtain good surface finish and surface integrity and to minimize defects. Lubrication affects the manner in which the material deforms during deformation, an important consideration because of the possibility of internal defects being developed. Typically made of hardened steel, rolling dies are expensive because of their complex shape. The dies usually cannot be reground after they are worn. With proper die materials and preparation, however, die life may range up to millions of pieces.

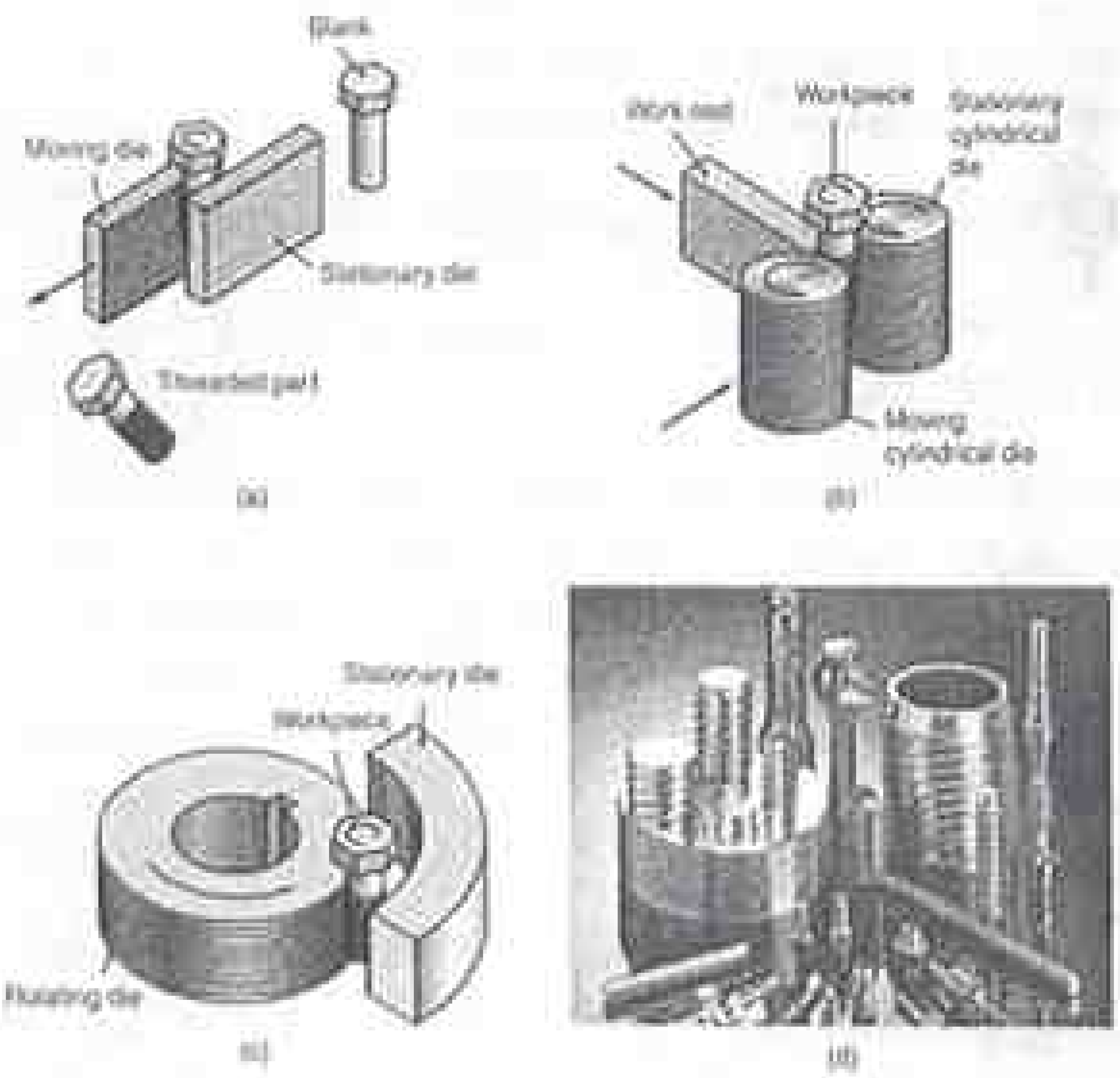


FIGURE 13.14 Thread-rolling processes: (a) reciprocating flat dies used to produce a threaded fastener; (b) two-roll dies; (c) rotary or planetary die set; and (d) a collection of thread-rolled pans made economically at high production rates.

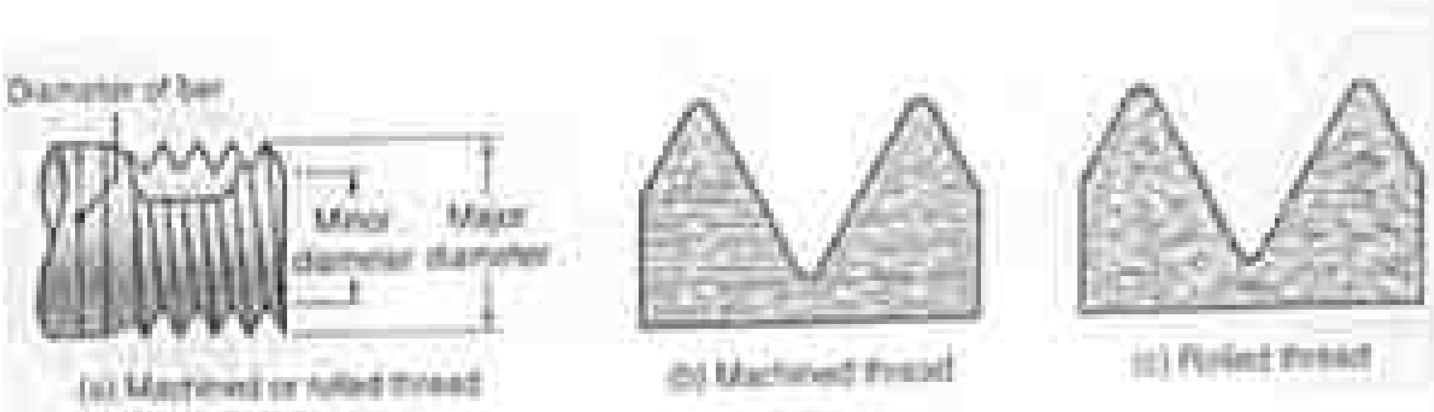


FIGURE 13.17 (a) Features of a machined or rolled thread. Grain flow in (b) machined and (c) rolled threads. Unlike machining, which cuts through the grains of the metal, the rolling of threads imparts improved strength because of cold working and favorable grain flow.

Rotary Tube Piercing. Also known as the Mannesmann process, this is a hot-working operation for making long, thick-walled *seamless pipe and tubing*. Rotary tube piercing is carried out using an arrangement of rotating rolls (Fig. 13.18c). The axes of the rolls are skewed in order to pulp the round bar through the rolls, by the axial component of the rotary motion.

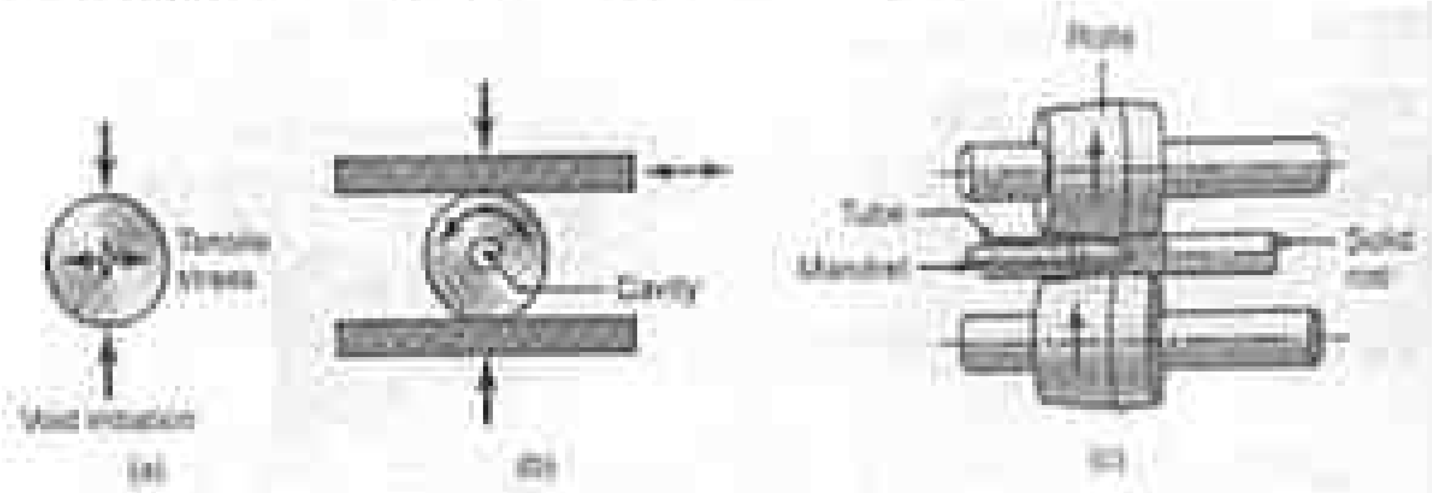


FIGURE 13.18 Cavity formation in a solid, round bar and its utilization in the rotary tube piercing process for making seamless pipe and tubing.

Tube Rolling. The diameter and thickness of pipes and tubing can be reduced by lube rolling, which utilizes shaped rolls, arranged in various configurations (Fig. 13.19).

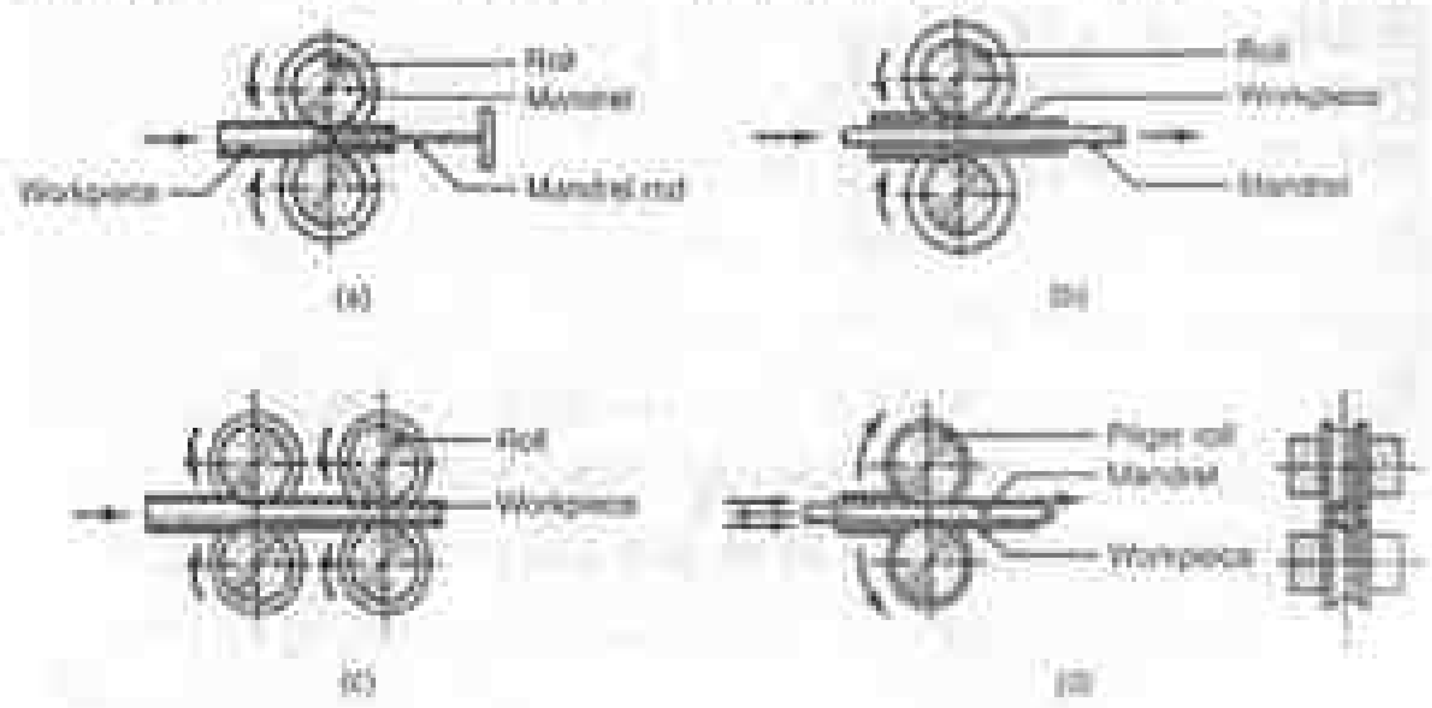


FIGURE 13.19 Schematic illustration of various tube-rolling processes: (a) with a fixed mandrel; (b) with a floating mandrel; (c) without a mandrel; and (d) pilger rolling over a mandrel and a pair of shaped rolls. Tube diameters and thicknesses also can be changed by other processes, such as drawing, extrusion, and spinning.

14.1 Introduction

Forging is a basic process in which the workpiece is shaped by compressive forces applied through various dies and tooling. One of the oldest and most important metalworking operations, dating back at least to 4000 B.C. Unlike rolling operations, that generally produce continuous plates, sheets, strips, and various structural cross-sections, forging operations produce discrete parts. Because the metal flow in a die and the material's grain structure can be controlled, forged parts have good strength and toughness, and are very reliable for highly stressed and critical applications.

Forging may be carried out at room temperature (*cold forging*) or at elevated temperatures (*warm or hot forging*), depending on the homologous temperature. Cold forging requires higher forces, because of the higher strength of the workpiece material, which also must possess sufficient ductility at room temperature to be able to undergo the required deformation without cracking. Cold-forged parts have good surface finish and dimensional accuracy. Hot forging requires lower forces, but the dimensional accuracy and surface finish of the parts are not as good as those in cold forging.

Forgings generally are subjected to additional finishing operations, such as heat treating to modify properties and machining for accuracy in final dimensions and good surface finish. The finishing operations can be minimized by precision forging, which is an important example of *net-shape or near-net-shape* forming processes.

14.2 Open-die Forging

Open-die forging is the simplest forging operation. Although most opendie forgings generally weigh 15 to 500 kg. Part sizes may range from very small (such as pins, nails, and bolts) to very large (up to 23 m long shafts for ship propellers). Open-die forging can be simply described by a metal workpiece (blank), placed between two flat dies, and reduced in height by compressing it, a process called **upsetting** or **flat-die forging.**

Limitations

Open Die: 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: High die cost, not economical for small quantities; machining often necessary

Blocker: Machining to final shape necessary; pans with thick webs and large fillets

Conventional: Higher die cost than blocker type

Precision: High forging forces, intricate dies, and provision for removing forging from dies

Advantages

Open die: Simple and inexpensive dies; wide range of part sizes; good strength characteristics; generally for small quantities

Closed die: Relatively good utilization of material; generally better properties than open-die forgings; good dimensional accuracy; high production rates; good reproducibility

Blocker: Low die costs; high production rates

Conventional: Requires much less machining than blocker type; high production rates; good utilization of material

Precision: Close dimensional tolerances; very thin webs and flanges possible; machining generally not necessary; very good material utilization

14.3 Impression-die and Closed-die Forging

In *impression-die forging*, the workpiece takes the shape of the die cavity while being forged between two shaped dies.

Closed-die Forging. The process shown in Fig. 14. is also referred to as closed-die forging. In true dosed-die forging, however, a flash does not form (hence the term flashless forging), and the workpiece completely fills the die cavity.

Precision Forging. In order to reduce the number of additional finishing operations (hence cost), the trend continues toward greater precision in forged products (net-shape forming). Typical precision-forged products are gears, connecting rods, and turbine blades. Precision forging requires (a) special and more complex dies, (b) precise control of the blank's volume and shape, and (c) accurate positioning of the blank in the die cavity.

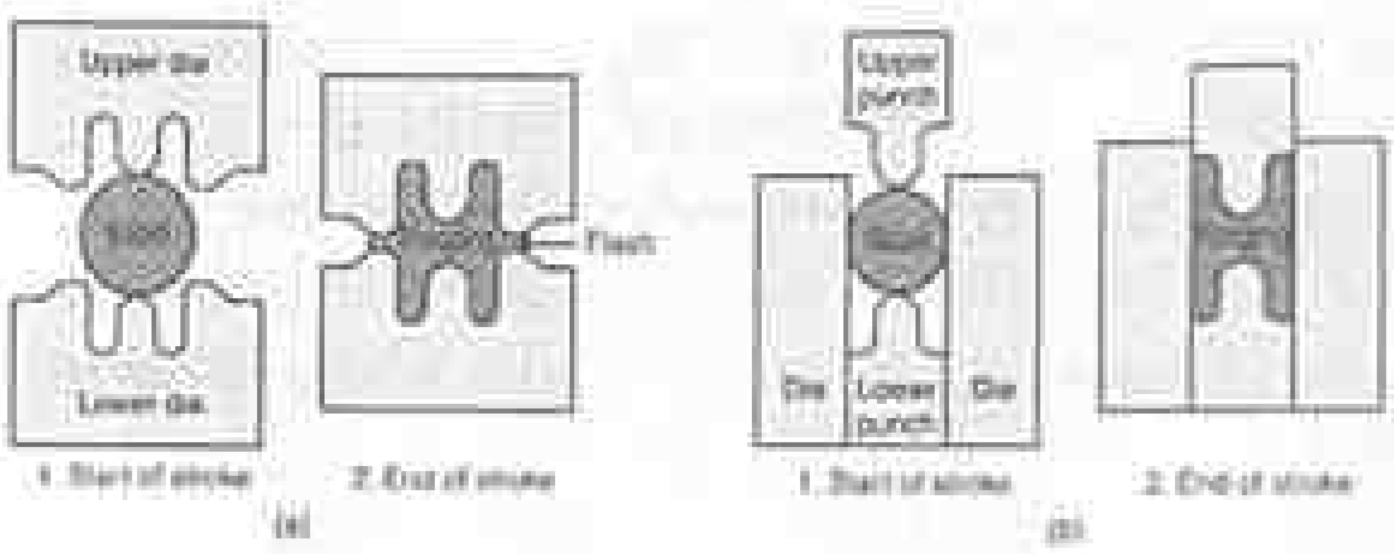


FIGURE 14.10 Comparison of (a) closed-die forging with flash and (b) precision or flashless forging of a round billet.

14.4 Various Forging Operations

Several other operations related to the basic forging process are described below.

Coining. A closed-die forging process, coining was originally used in the minting of coins, medallions, and jewelry, but currently is used to produce a wide range of parts with high accuracy, such as gears, industrial seals, and medical devices. Lubricants should not be applied in coining, because they can become entrapped in the die cavities and, being incompressible, prevent the full reproduction of die-surface details and surface finish.

Marking pans with letters and numbers also can be done rapidly through coining. Sizing is a process used in forging, and other processes, to improve surface finish and to impart the desired dimensional accuracy with little or no change in pan size.

Heading. Also called upset forging, heading is essentially an upsetting operation, performed on the end of a rod or wire in order to increase the cross-section.

Heading operations are performed on machines called headers. Hot heading on larger parts typically are performed on horizontal upsetters.

Piercing. This is a process of indenting (but not breaking through) the surface of a workpiece with a punch, in order to produce a cavity or an impression.

The piercing force depends on (a) the cross-sectional area and the tip geometry of the punch, (b) the strength of the workpiece, and (c) friction at the punch-workpiece interfaces.

Hubbing. This process consists of pressing a hardened punch, with a particular tip geometry, into the surface of a block of metal. The cavity produced is subsequently used as a die for forming operations, such as those employed in making tableware. The die cavity usually is shallow, but for deeper cavities, some material may first be removed from the surface of the block by machining prior to hubbing.

Isothermal Forging. Also known as hot-die forging, the dies in this process are heated to the same temperature as that of the hot workpiece. The process is expensive and the production rate is low.

Rotary Swaging. In this process, also known as *radial forging, rotary forging,* or simply *swaging,* a solid rod or tube is subjected to radial impact forces using a set of reciprocating dies.

Tube Swaging. In this process, the internal diameter and/or the thickness of the tube is reduced, with or without the use of internal mandrels.

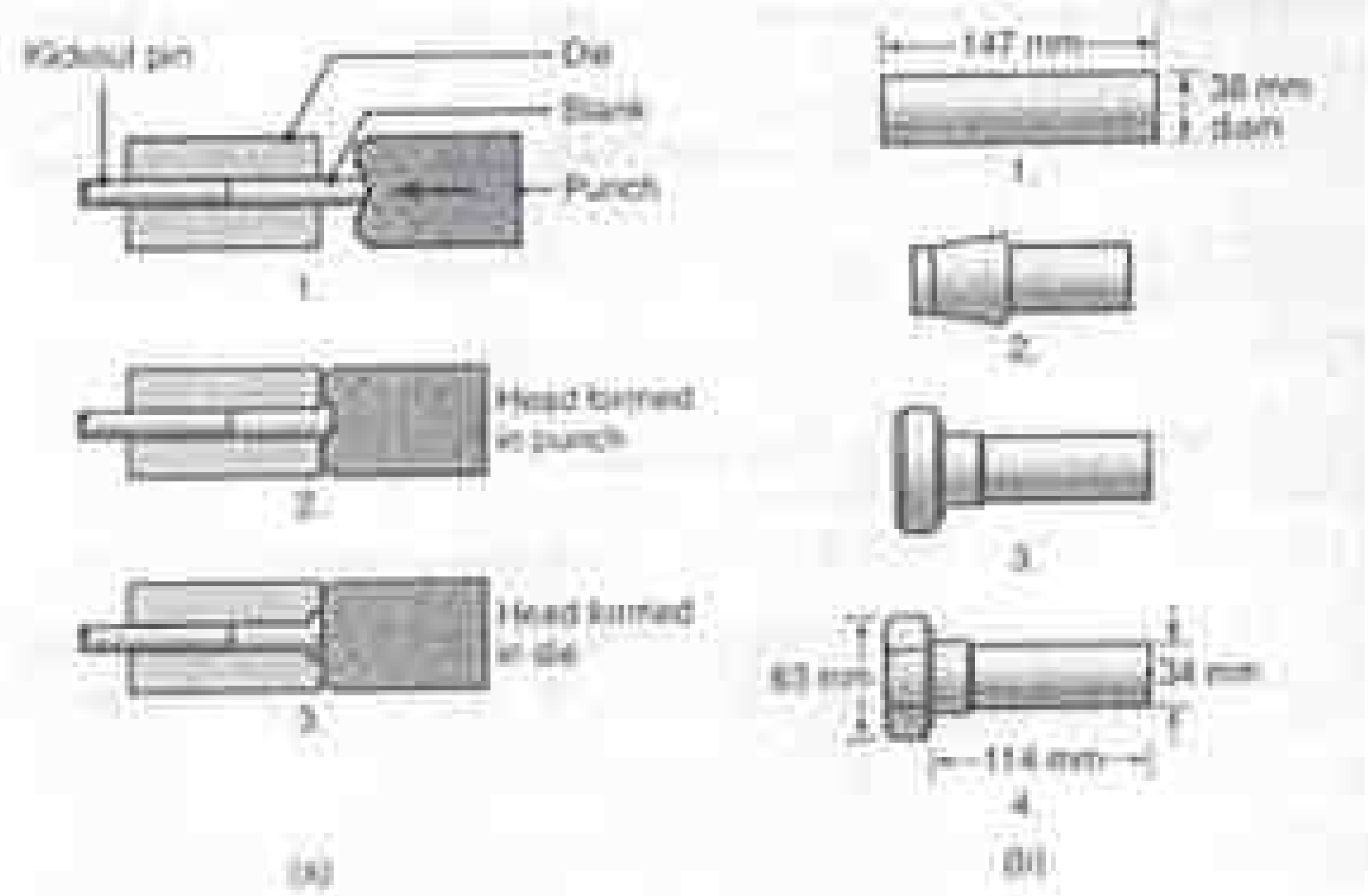
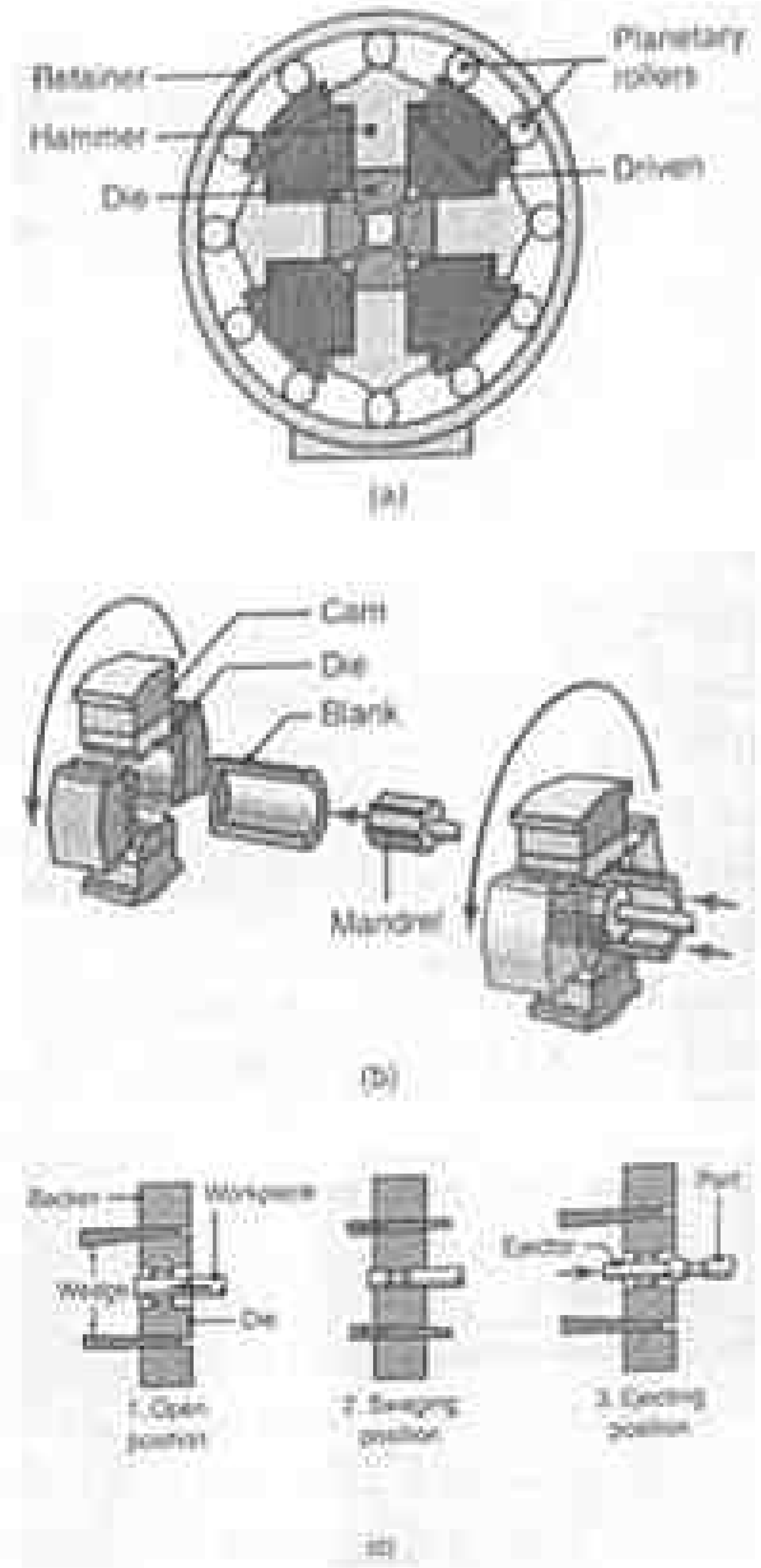


FIGURE 14.12 (a) Heading operation to form heads on fasteners, such as nails and rivets. (b) Sequence of operations in producing a typical bolt head by heading.

14.5 Forgeability of Metals; Forging Defects

Forgeability is generally defined as the capability of a material to undergo deformation in forging without cracking.



(d)

FIGURE 14. 15 (a) Schematic illustration of the rotary-swaging process. (b) Forming internal profiles on a tubular workpiece by swaging. (c) A die-closing swaging machine, showing forming of a stepped shaft. (d) Typical parts made by swaging.

14.8 Forging Machines

Various types of forging machines are available, with a wide range of capacities (tonnage), speeds, and speed-stroke characteristics.

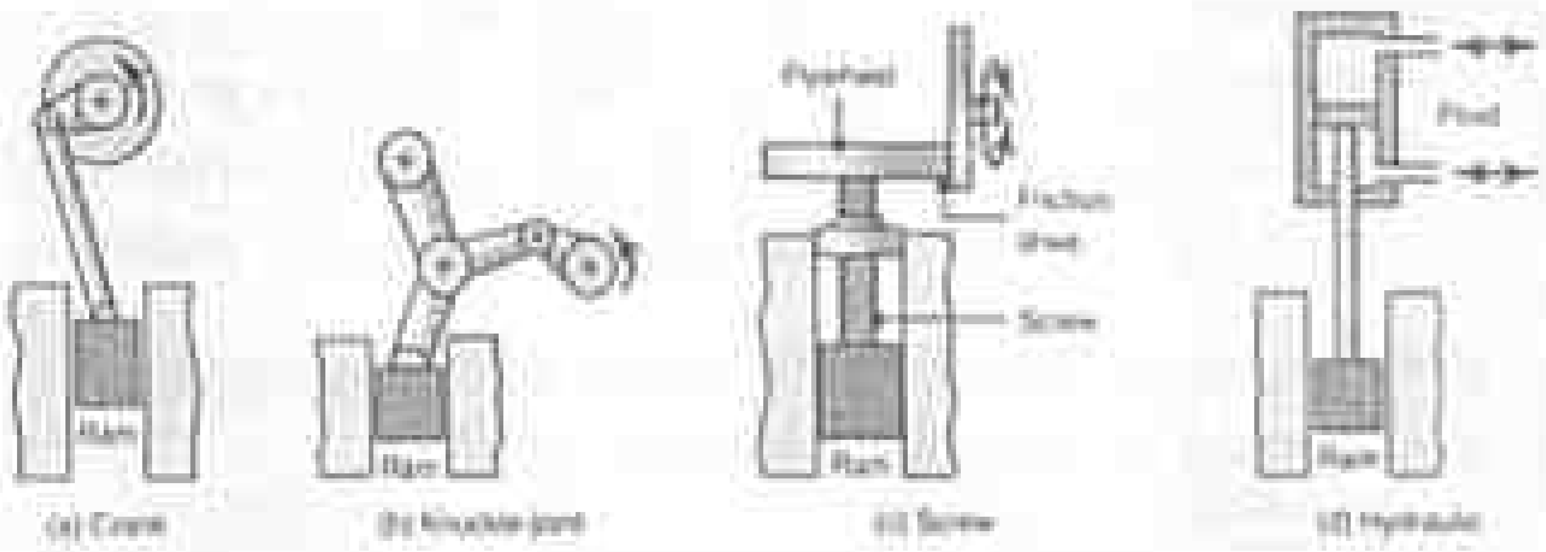


FIGURE 14.19 Schematic illustration of the principles of various forging machines. (a) Crank press with an eccentric drive; the eccentric shaft can be replaced by a crankshaft to give up-and-down motion to the ram. (b) Knuckle-joint press. (c) Screw press. (d) Hydraulic press.

TABLE 14.4

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

Mechanical Presses. These presses are basically of either the crank or the eccentric type. The speed varies from a maximum at the center of the stroke to zero at the bottom of the stroke, thus mechanical presses are stroke limited. The energy in a mechanical press is generated by a large flywheel powered by an electric motor. A clutch engages the flywheel to an eccentric shaft; a connecting rod then translates the rotary motion into a reciprocating linear motion. A *knuckle-joint* mechanical press is shown in Fig. 14.19b; because of the linkage design, very high forces can be applied in this type of press.

The force available in a mechanical press depends on the stroke position, and becomes extremely high at the end of the stroke; thus, proper setup is essential to avoid breaking the dies or equipment components. Mechanical presses have high production rates, are easier to automate, and require less operator skill than do other types of machines.

Screw Presses. These presses (Fig. 14.19c) derive their energy from a flywheel, hence they are *energy limited*. They are particularly suitable for small production quantities and for thin parts with high precision, such as turbine blades.

Hydraulic Presses. These presses (Fig. 14. 19d) operate at constant speeds and are load limited (load restricted), whereby the press stops if the load required exceeds its capacity. Large amounts of energy can be transmitted from the press to the work-piece by a constant load throughout the stroke, the speed of which can be controlled. Because forging in a hydraulic press lakes longer than in the other types of forging machines, the workpiece may cool rapidly unless the dies are heated. Compared with mechanical presses, hydraulic presses are slower and involve higher initial costs, but they require less maintenance.

Hammers. Hammers derive their energy from the potential energy of the ram, which is converted into kinetic energy; thus they are *energy limited*. Unlike hydraulic presses, hammers operate at high speeds, minimizing the cooling of a hot forging.

Drop Hammers. In *power drop hammers*, the ram's downstroke is accelerated by steam, air, or hydraulic pressure.

Counterblow Hammers. These hammers have two rams that simultaneously approach each other horizontally or vertically to forge the part. Counterblow hammers operate at high speeds and transmit less vibration to their bases.

High-energy-rate Forging Machines. In these machines, the ram is accelerated rapidly by inert gas at high pressure, and the part is forged in one blow at a very high speed.

Servo Presses. A recent development is the use of servo presses for forging and stamping applications.

SUMMARY

- Forging denotes a family of metalworking processes in which deformation of the workpiece is carried out by compressive forces applied through a set of dies. Forging is capable of producing a wide variety of structural parts, with favorable characteristics such as higher strength, improved toughness, dimensional accuracy, and reliability in service.

- The forging process can be carried out at room, warm, or high temperatures. Workpiece material behaviour during deformation, friction, heat transfer, and material-flow characteristics in the die cavity are important considerations, as are the proper selection of die materials, lubricants, workpiece and die temperatures, forging speeds, and equipment.

- Various defects can develop if the process is nor designed or controlled properly. Computer-aided design and manufacturing techniques are now used extensively in die design and manufacturing, preform design, predicting material flow, and avoiding the possibility of internal and external defects during forging.

- A variety of forging machines is available, each with its own capabilities and characteristics. Forging operations are now highly automated, using industrial robots and computer controls.

- Swaging is a type of rotary forging in which a solid rod or a tube is reduced in diameter by the reciprocating radial movement of a set of two or four dies. The process is suitable for producing short or long lengths of bar or tubing, with various internal or external profiles.

- Because die failure has a major economic impact, die design, material selection, and production method are of great importance. A variety of die materials and manufacturing methods is available, including advanced material-removal and finishing processes.

CHAPTER 15

Metal Extrusion and Drawing Processes and Equipment

15.1 Introduction

In extrusion, a usually cylindrical billet is forced through a die (Fig. 15.1), in a manner similar to squeezing toothpaste from a tube.

A characteristic of extrusion is that large deformations can take place without fracture, because the material is under high triaxial compressive stresses. Since the die geometry remains unchanged throughout the process, extruded products typically have a constant cross-section.

Each billet is extruded individually, thus extrusion is a batch or semicontinuous operation. Tool costs generally are low, particularly for producing simple, solid cross-sections. Extrusion at room temperature is often combined with forging operations, in which case it is generally called cold extrusion.

In drawing, the cross-section of a solid rod, wire, or tubing is reduced or changed in shape by pulling it through a die. In addition to round rods, various profiles also can be drawn.

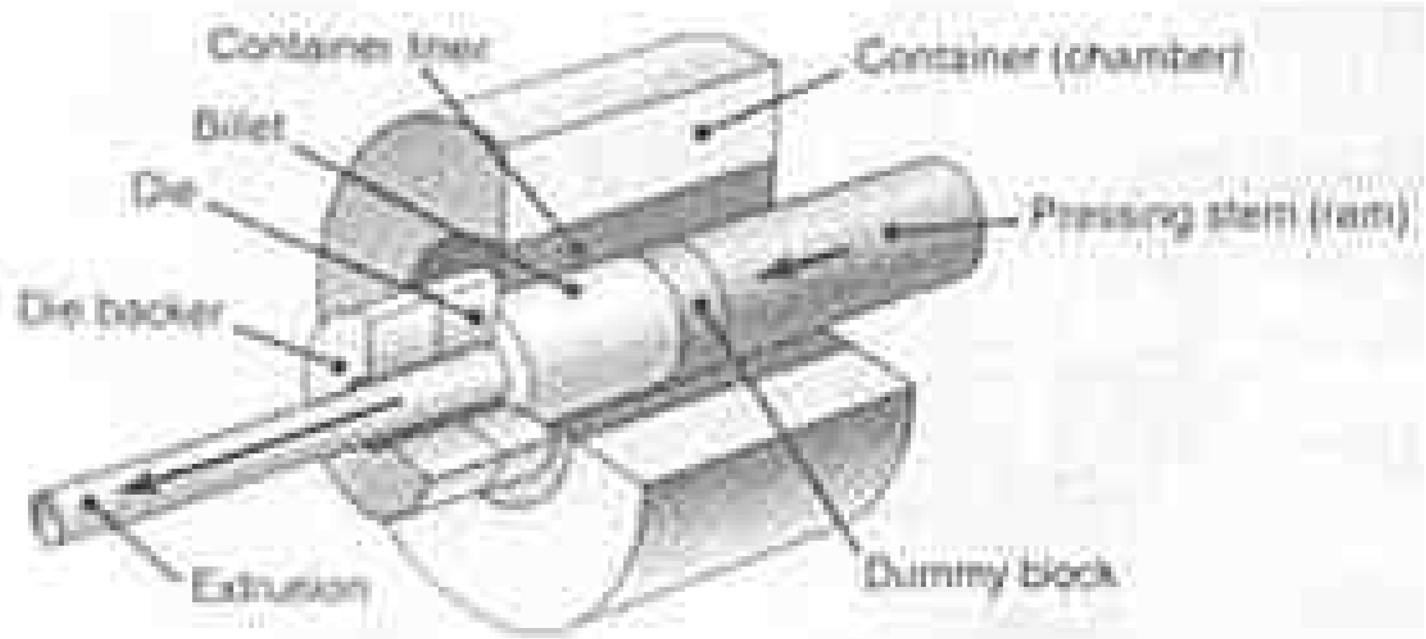


FIGURE 15.1 Schematic illustration of the direct-extrusion process.

15.2 The Extrusion Process

There are three basic types of extrusion. In direct or forward extrusion, a billet is placed in a container (*chamber*) and forced through a die.

In indirect extrusion, also called *reverse, inverted, or backward extrusion*, the die moves toward the unextruded billet. Indirect extrusion has the advantage of having no billet-container friction, since there is no relative motion; thus, it is used on materials with very' high friction, such as hot extrusion of high strength and stainless steels.

In hydrostatic extrusion, the billet is smaller in diameter than the container (which is filled with a fluid), and the pressure is transmitted to the fluid by a ram. The fluid pressure imparts triaxial compressive stresses acting on the workpiece and thus has improved formability. Furthermore, there is much less workpiece-container friction than in direct extrusion. A less common type of extrusion is *lateral* or *side extrusion*.

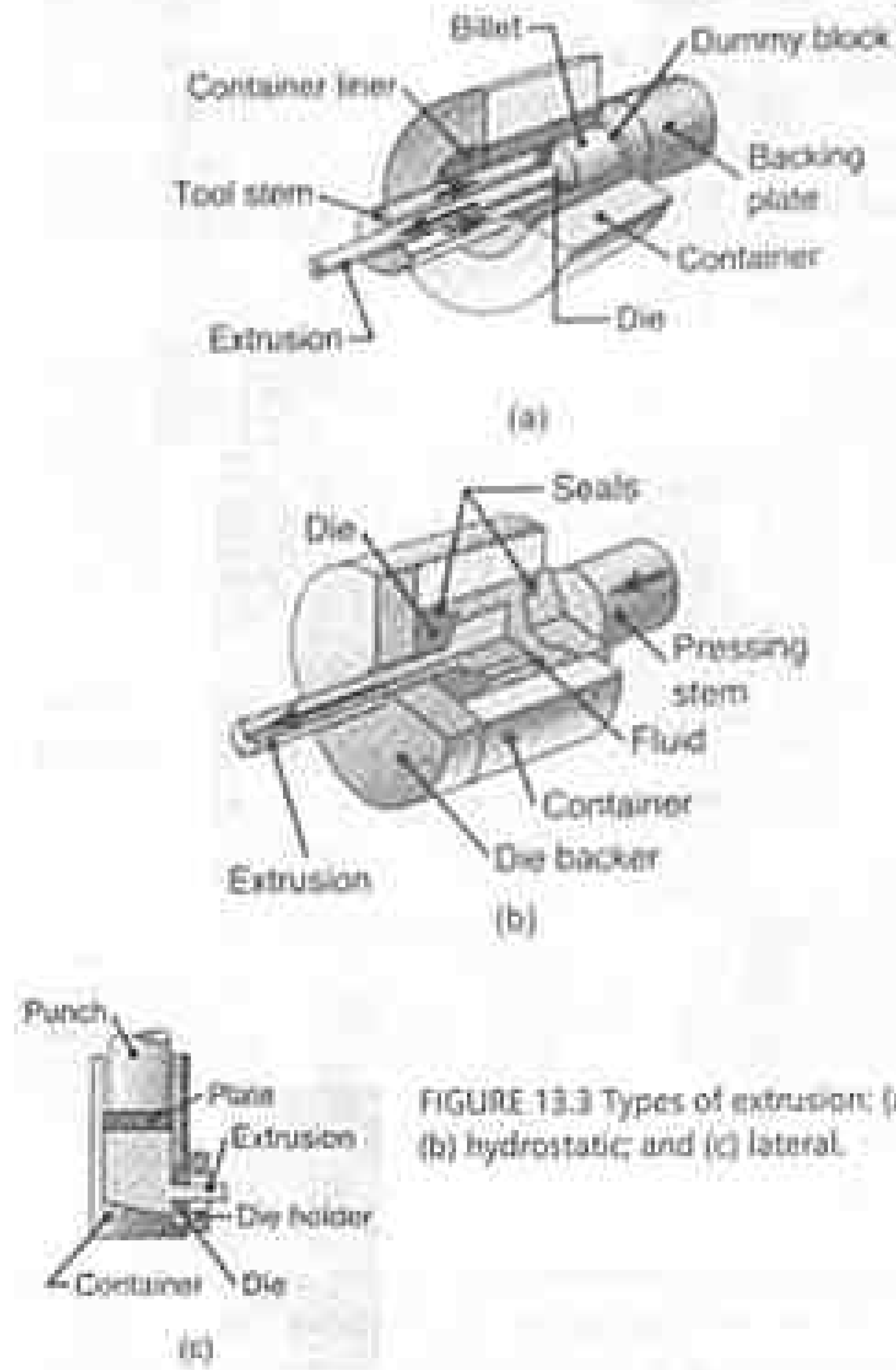


FIGURE 15.3 Types of extrusion: (a) indirect (b) hydrostatic; and (c) lateral.

The geometric variables in extrusion are the die angle, α, and the ratio of the cross-sectional area of the billet to that of the extruded part, A_0/A_f, called the extrusion ratio, R.

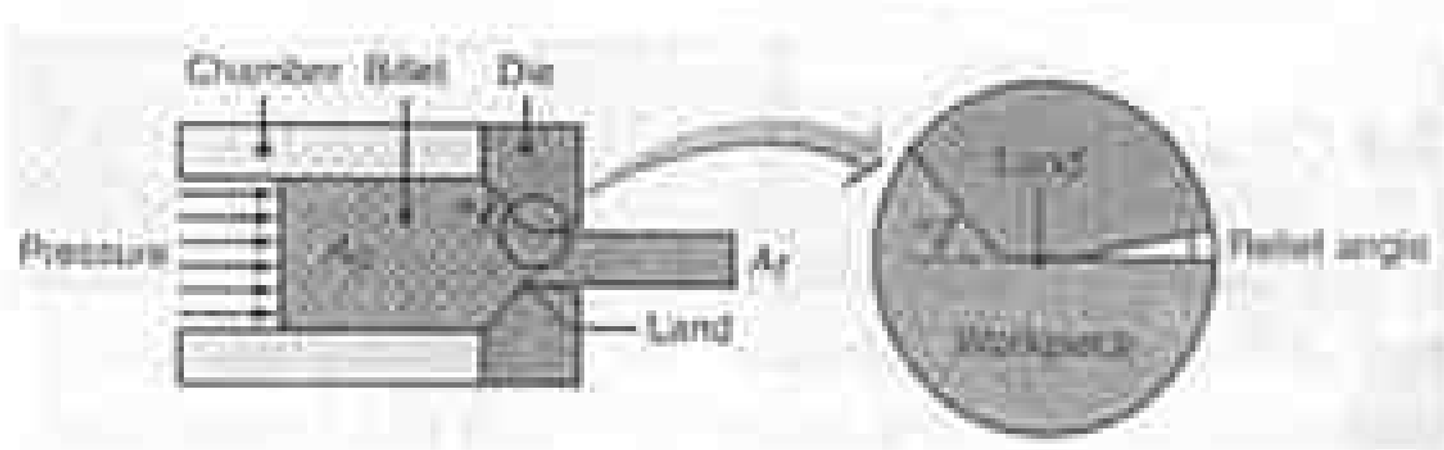


FIGURE 15.4 Process variables in direct extrusion: the die angle, reduction in cross-section, extrusion speed, billet temperature, and lubrication all affect the extrusion pressure.

The presence of a die angle causes a small portion of the end of the billet to remain in the chamber after the stroke of the ram. This portion, called *scrap or the butt end*, is later removed by cutting it off.

In coaxial extrusion, or cladding, coaxial billets are extruded together, provided that the strength and ductility of the two metals are compatible.

15.3 Hot Extrusion

In order to reduce the forces required, extrusion can be carried out at elevated temperatures. As in all other elevated-temperature operations, hot extrusion has special requirements, because of the high operating temperatures involved. For example, die wear can be excessive, and cooling of the hot-billet surfaces (in the cooler container) and the die can result in highly nonuniform deformation of the billet. Thus, extrusion dies may be preheated, as is done in hot-forging operations. Because the billet is hot, it develops an oxide film, unless it is heated in an inert atmosphere.

Die Design. Die design requires considerable experience. *Square dies*, also called *shear dies* are used in extruding nonferrous metals, especially aluminum. These dies develop *dead-metal zones*, which in turn form a "die angle" along which the material flows. Tubing can be extruded from a solid or hollow billet.

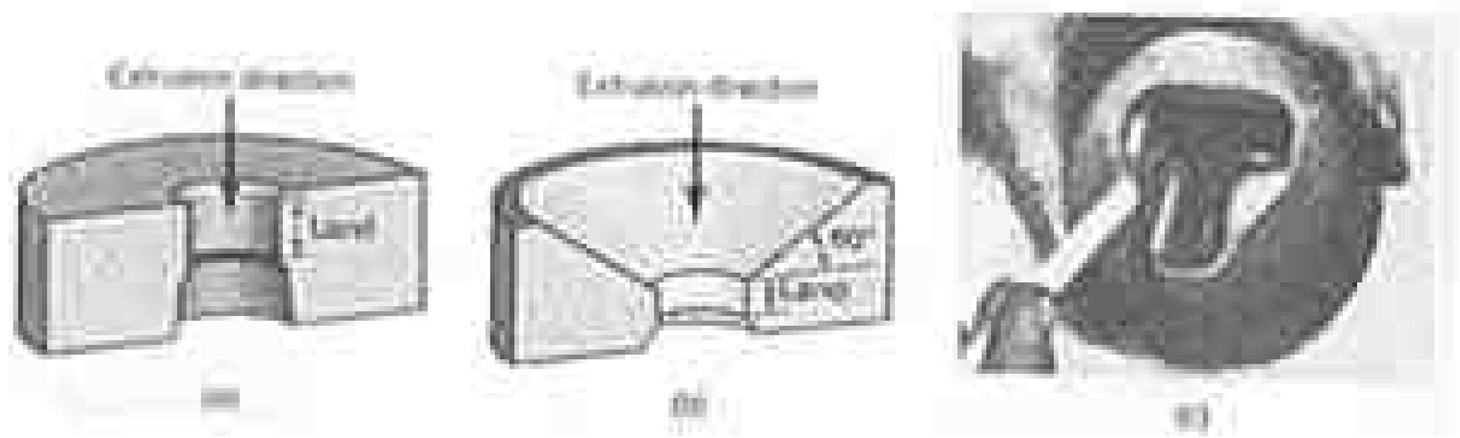


FIGURE 15.7 Typical extrusion die shapes: (a) die for nonferrous metals; (b) die for ferrous metals; and (c) die for a T-shaped extrusion made of hot-work die steel and used with molten glass as a lubricant.

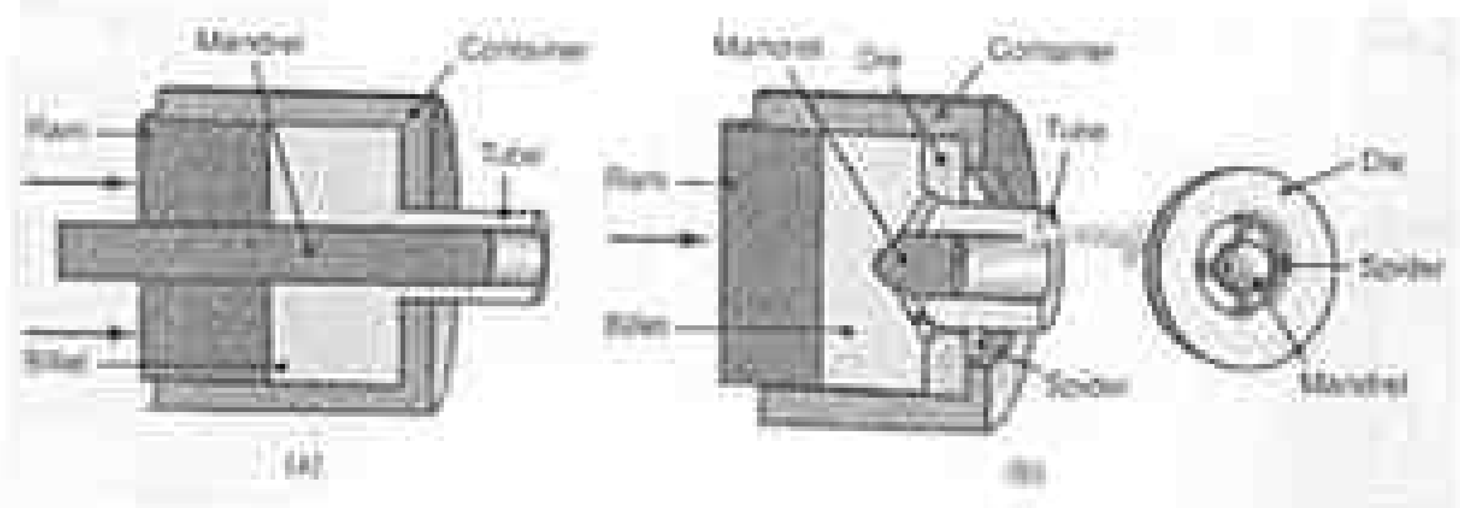


FIGURE 15.8 Extrusion of a seamless tube (a) using an internal mandrel that moves independently of the ram: an alternative arrangement has the mandrel integral with the ram and (b) using a spider to produce seamless tubing.

Lubrication. Lubrication is important in hot extrusion, because of its effects on (a) material flow during extrusion, (b) surface finish and integrity, (c) product quality, and (d) extrusion forces.

15.4 Cold Extrusion

Developed in the 1940s, *cold extrusion* is a general term often denoting a *combination* of operations, such as a combination of direct and indirect *extrusion* and *forging*. Cold extrusion is used widely for components in automobiles, motorcycles, bicycles, appliances, and in transportation and farm equipment.

Cold extrusion has the following advantages over hot extrusion:

- Improved mechanical properties, resulting from work hardening, provided that the heat generated by plastic deformation and friction does not recrystallize the extruded metal.
- Good control of dimensional tolerances, thus reducing the need for subsequent machining or finishing operations.
- Improved surface finish, due partly to the absence of an oxide film and provided that lubrication is effective.
- Production rates and costs are competitive with those of other methods of producing the same part. Some machines are capable of producing more than 2000 parts per hour.

15.4.1 Impact Extrusion

Impact extrusion is similar to indirect extrusion, and the process often is included in the cold-extrusion category. The punch descends rapidly on the blank (slug), which is extruded backward. Because of volume constancy, the thickness of the tubular extruded region is a function of the clearance between the punch and the die cavity.

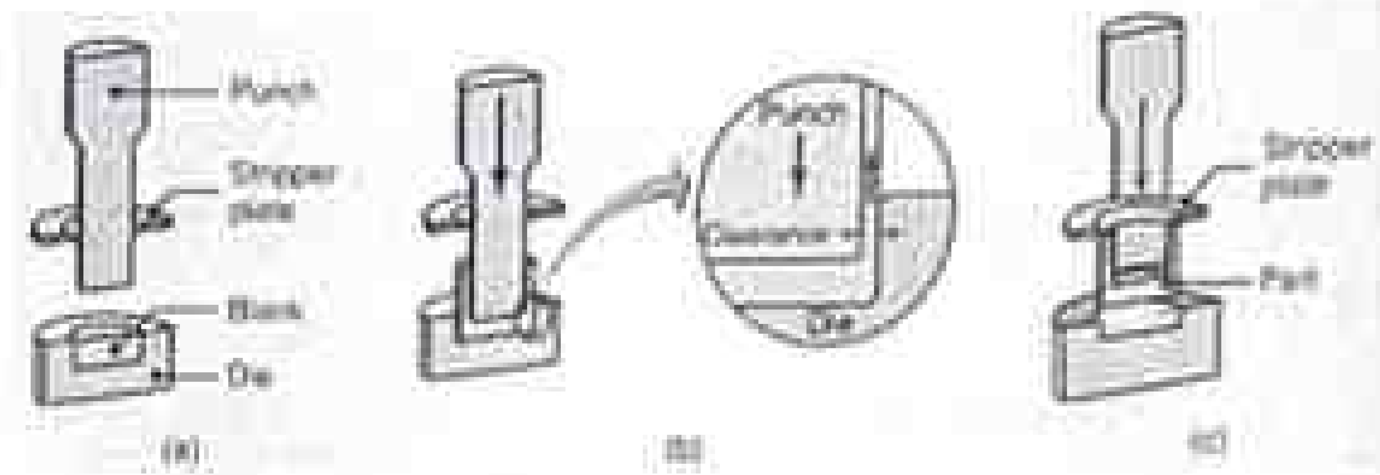


FIGURE 15.14 Schematic illustration of the impact-extrusion process; the extruded parts are stripped by using a stripper plate.

15.4.2 Hydrostatic Extrusion

In *hydrostatic extrusion*, the pressure required in the chamber is supplied via a piston and through an incompressible fluid medium surrounding the billet. Pressures are typically on the order of 1400 MPa. The high pressure in the chamber transmits some of the fluid to the die surfaces, where it significantly reduces friction. Hydrostatic extrusion is usually carried out at room temperature, typically using vegetable oils as the fluid.

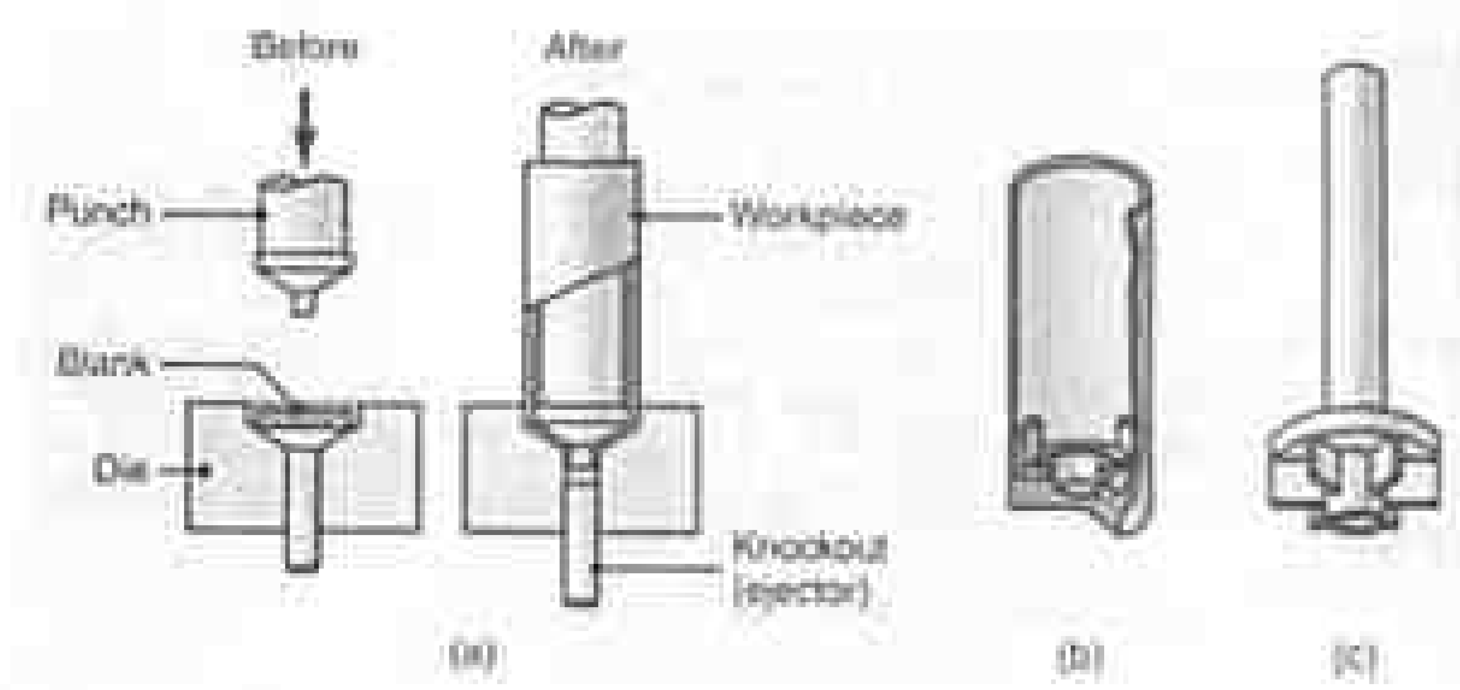


FIGURE 15.15 (a) Impact extrusion of a collapsible tube by the Hooker process. (b) and (c) Two examples of products made by impact extrusion. These parts also may be made by casting, forging, or machining; the choice depends on the materials part dimensions and wall thickness, and the properties desired. Economic considerations also are important in final process selection.

15.9 Drawing Practice

Lubrication. Lubrication is essential in drawing operations in order to improve die life and product surface finish, and to reduce drawing forces and temperature rise. Lubrication is critical, particularly in tube drawing, because of the difficulty of maintaining a sufficiently thick lubricant film at the mandrel-tube interface. In the drawing of rods, a common method of lubrication uses phosphate conversion coatings.

The following are the basic methods of lubrication used in wire drawing:

- Wet drawing: the dies and the rod are immersed completely in the lubricant.
- Dry drawing: the surface of the rod to be drawn is coated with a lubricant, by passing it through a box filled with the lubricant (*stuffing box*).
- Metal coating: the rod or wire is coated with a soft metal, such as copper or tin, that acts as a solid lubricant.

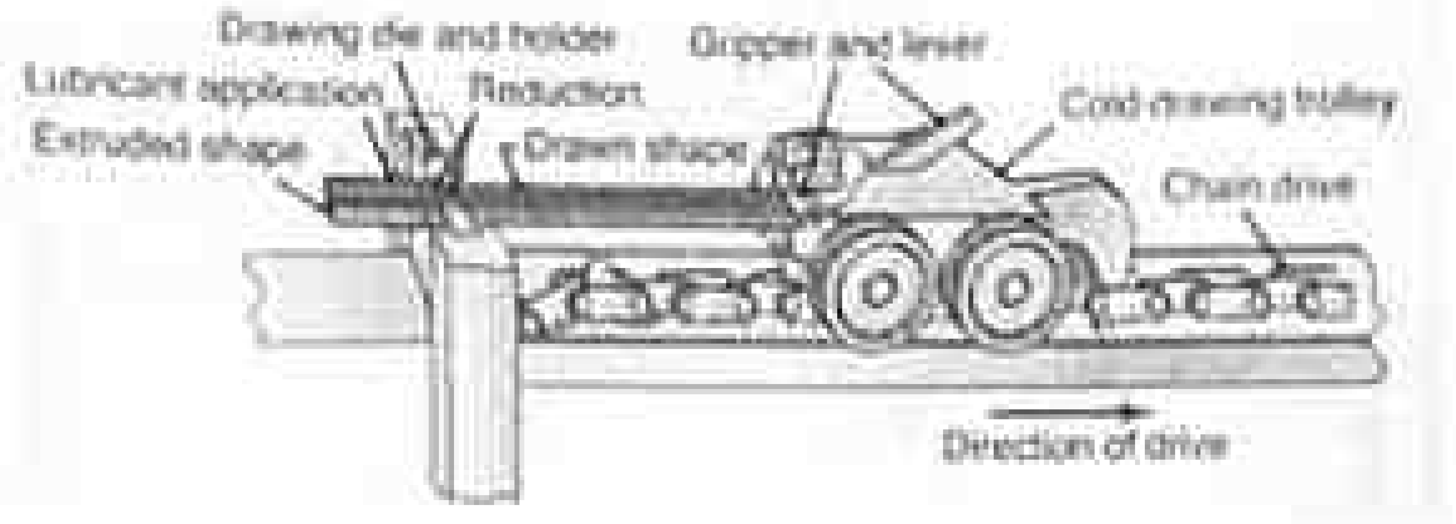


FIGURE 15.24 Cold drawing of an extruded channel on a draw bench to reduce its cross-section; individual lengths of straight rods or of cross-sections are drawn by this method.

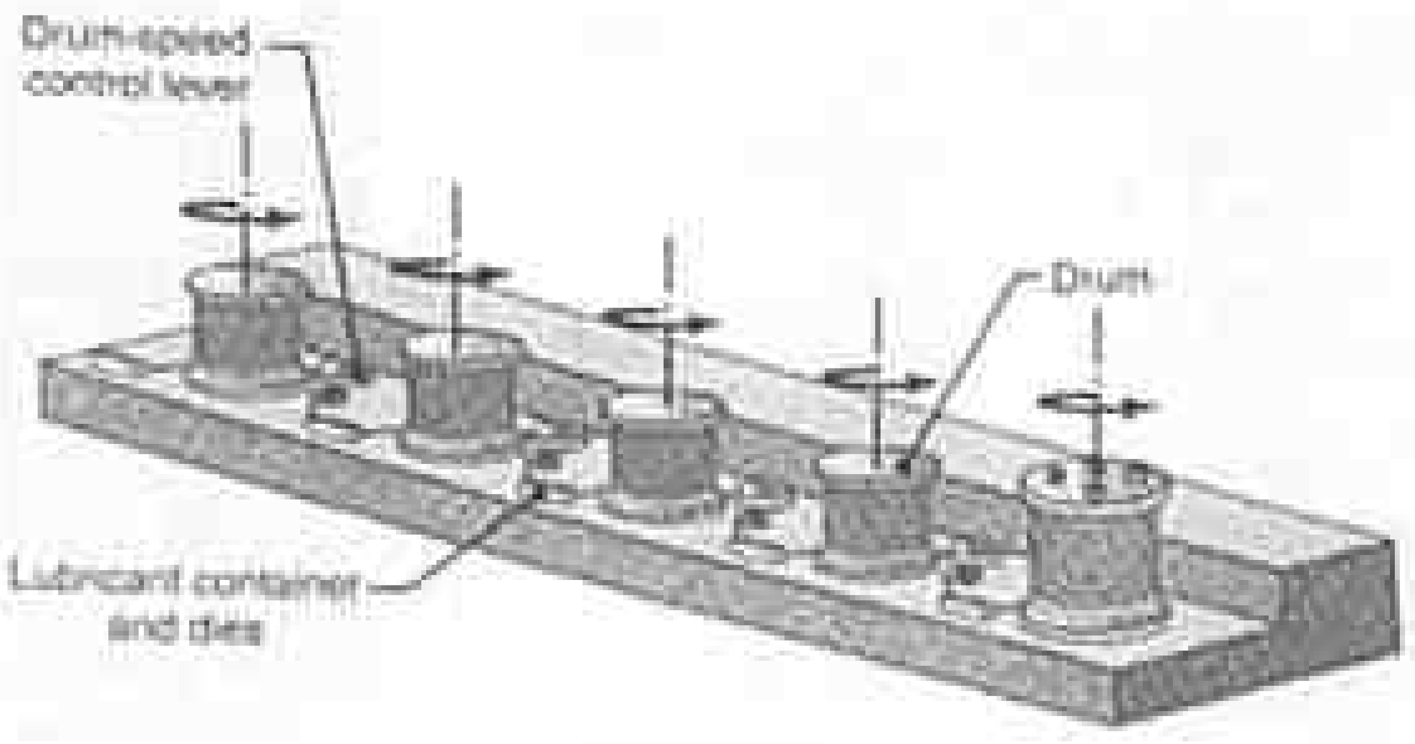


FIGURE 15.25 An illustration of multistage wire drawing typically used to produce copper wire for electrical wiring. Shown is a five bull block configuration; wire drawing machines can incorporate 15 or more of these drums, depending on the material and wire size.

SUMMARY

- Extrusion is the process of pushing a billet through a die, to reduce its cross-section or to produce various solid or hollow cross-sections. This process is generally carried out at elevated temperatures, in order to reduce the extrusion force and improve the ductility of the material.

- Important factors in extrusion are die design, extrusion ratio, billet temperature, lubrication, and extrusion speed. Although the term "cold extrusion" applies to extrusion at room temperature, it is also the name for a combination of extrusion and forging operations. Cold extrusion is capable of economically producing discrete parts in various shapes and with good mechanical properties and dimensional tolerances.

- Rod, wire, and tube drawing operations basically involve pulling the material through a die or a set of dies in tandem. The cross-sections of most drawn products are round, but other shapes also can be drawn. Drawing tubular products, to reduce either their diameter or their thickness, usually requires the use of internal mandrels.

- Die design, reduction in cross-sectional area per pass, and selection of die materials and lubricants are all important parameters in making drawn products of high quality and with a good surface finish. External and internal defects can develop both in extrusion and in drawing. The significant factors are the die angle, reduction per pass, and quality of the workpiece material.

CHAPTER 16

Sheet-Metal Forming Processes and Equipment

16.2 Shearing

All sheet-metal forming operations begin with a **blank** of suitable dimensions and removed from a large sheet (usually from a *coil*) by **shearing**. Shearing subjects the sheet to shear stresses, generally using a punch and a die.

General Characteristics of Sheet-Metal Forming Processes

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

The clearance is a major factor in determining the shape and the quality of the sheared edge. As clearance increases, the deformation zone becomes larger and the sheared-edge surface becomes rougher.

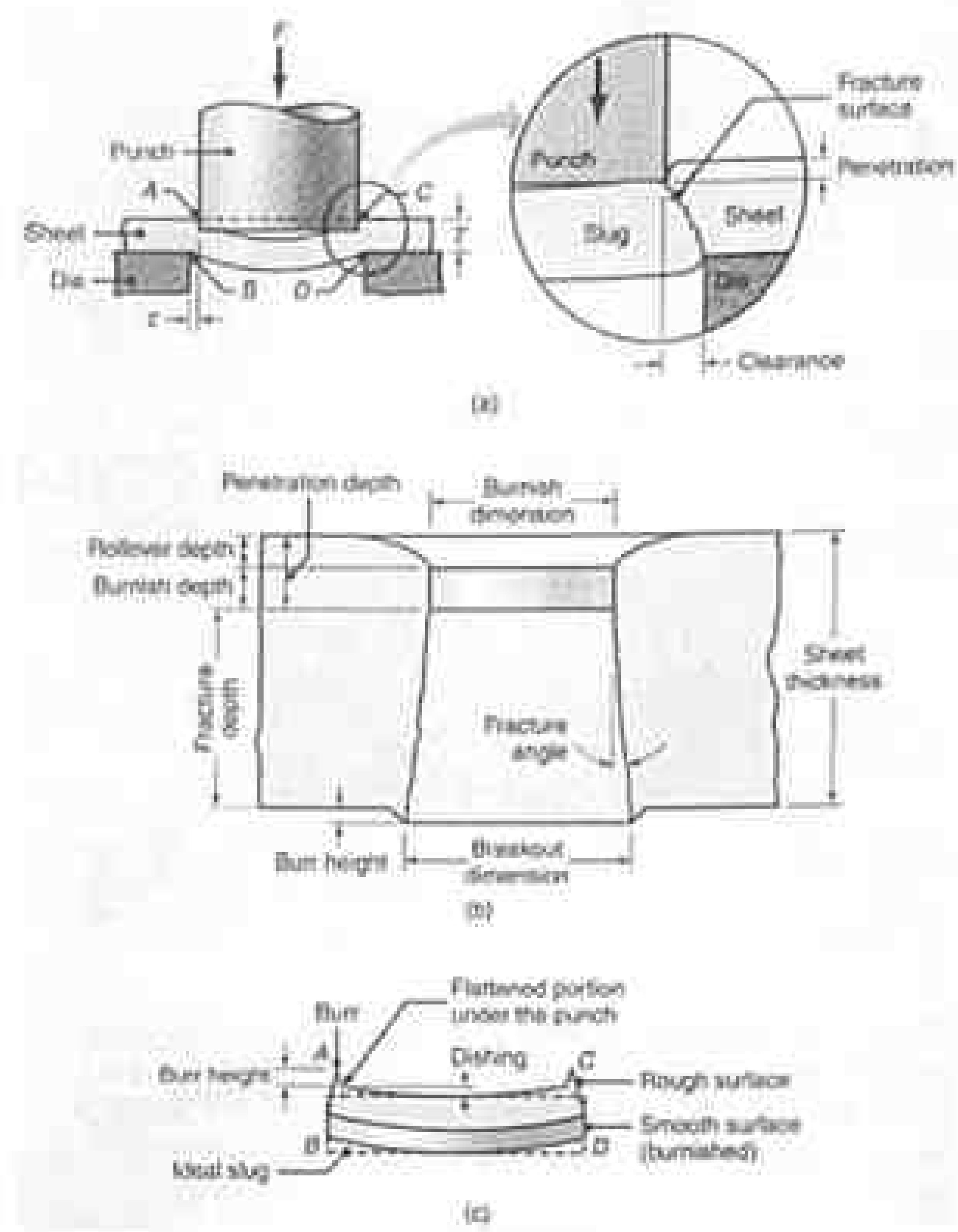


FIGURE 16.2 (a) Schematic illustration of shearing with a punch and die, indicating some of the process variables. Characteristic features of (b) a punched hole and (c) the slug; note that the scales of (b) and (c) are different.

16.2.1 Shearing Operations

The most common shearing operations are punching (where the sheared slug is scrap or may be used for some other purpose) and blanking (where the slug is the part to be used and the rest is scrap).

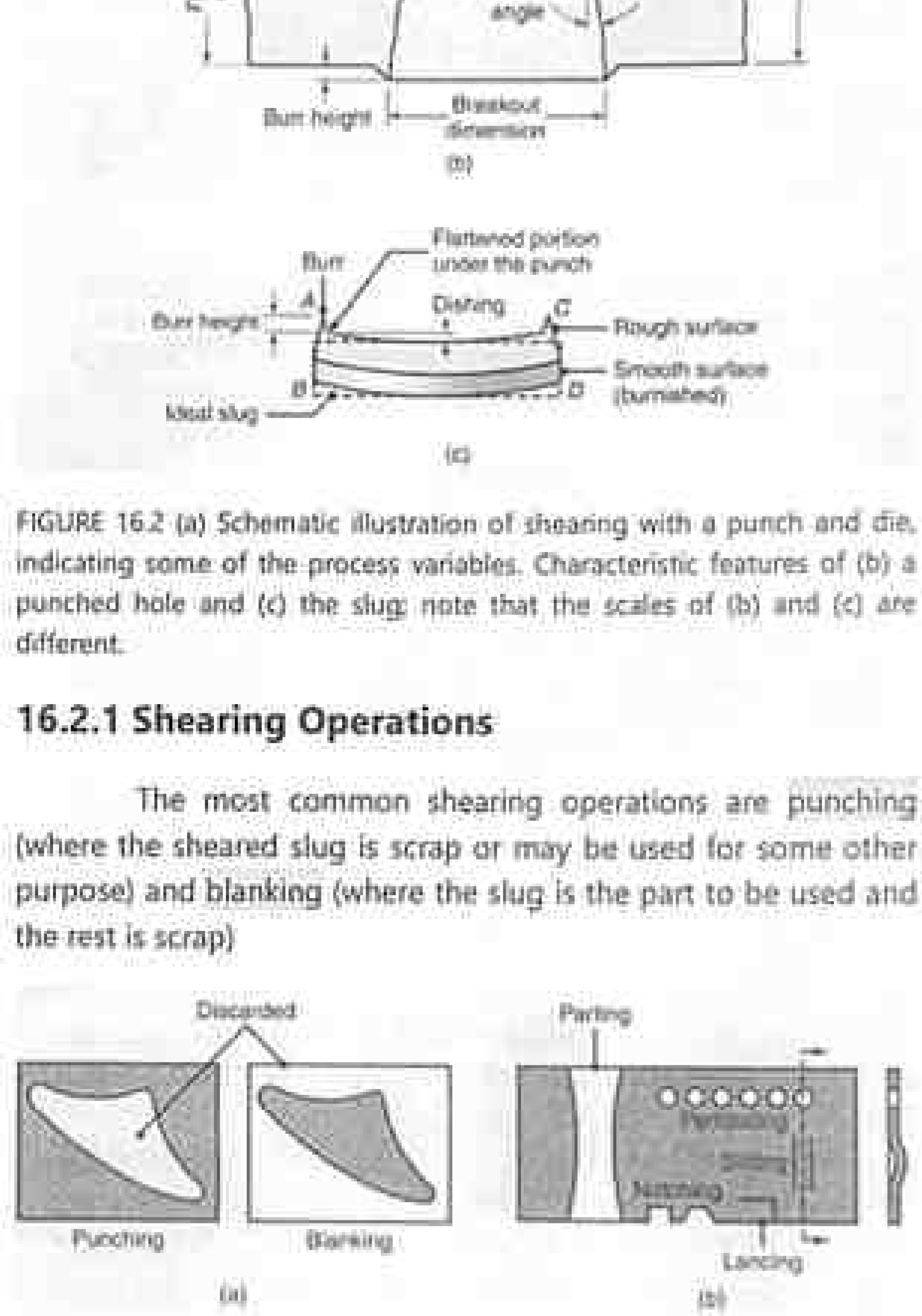


FIGURE 16.4 (a) Punching (piercing) and blanking, (b) Examples of various die-cutting operations on sheet metal; lancing involves slitting the sheet to form a tab.

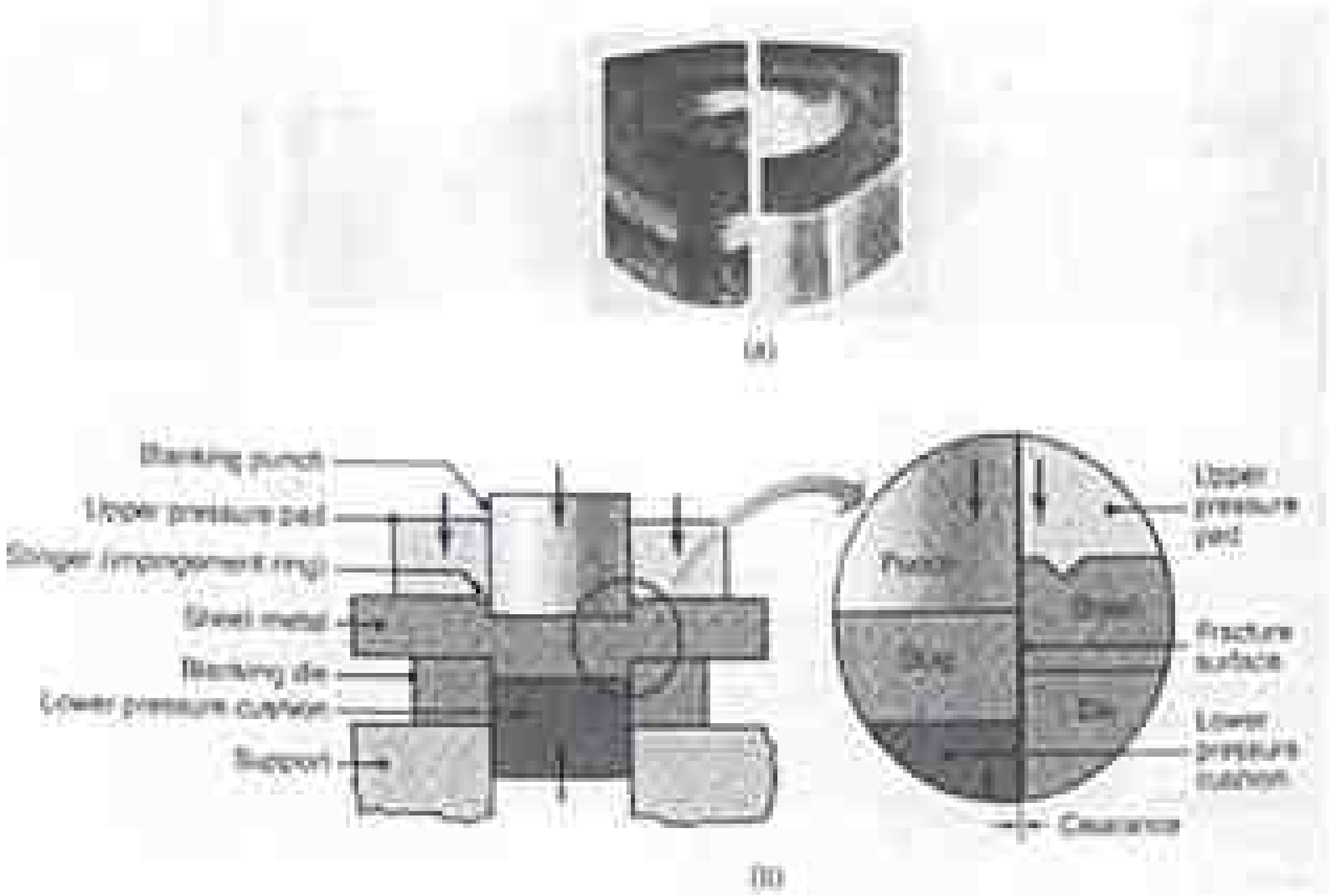


FIGURE 16.5 (a) Comparison of sheared edges produced by conventional (left) and by fine-blanking (right) techniques. (b) Schematic illustration of one setup for fine blanking.

16.2.3 Characteristics and Types of Shearing Dies

Clearance. Because the formability of the sheared part can be influenced by the quality of its sheared edges, clearance control is important. The appropriate clearance depends on

- Type of material and its temper
- Thickness and size of the blank
- Proximity to the edges of other sheared edges or the edges of the original blank

Clearances generally range between 2 and 8% of the sheet thickness, although they may be as small as 1% (as in *fine blanking*) or as large as 30%. The smaller the clearance, the better is the quality of the edge. If the sheared edge is rough and not acceptable, it can be subjected to a process called shaving whereby the extra material from the edge is trimmed by cutting, as also depicted in.

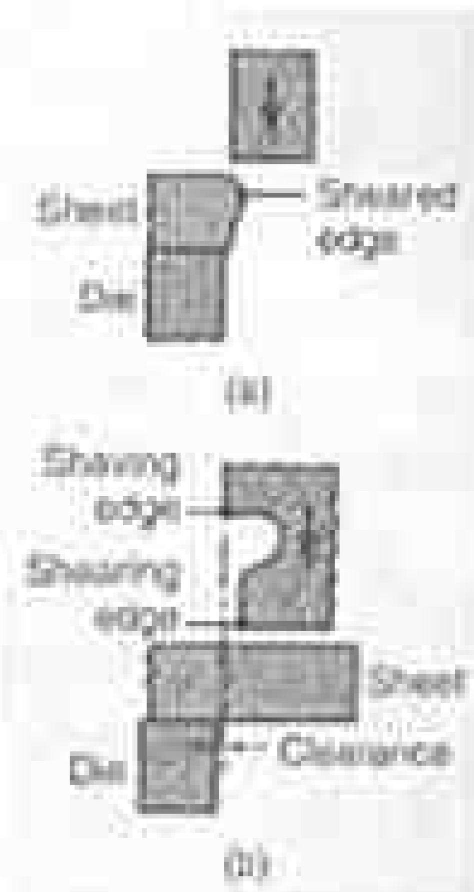


FIGURE 16.9 Schematic illustrations of the shaving process. (a) Shaving a sheared edge. (b) Shearing and shaving combined in one stroke.

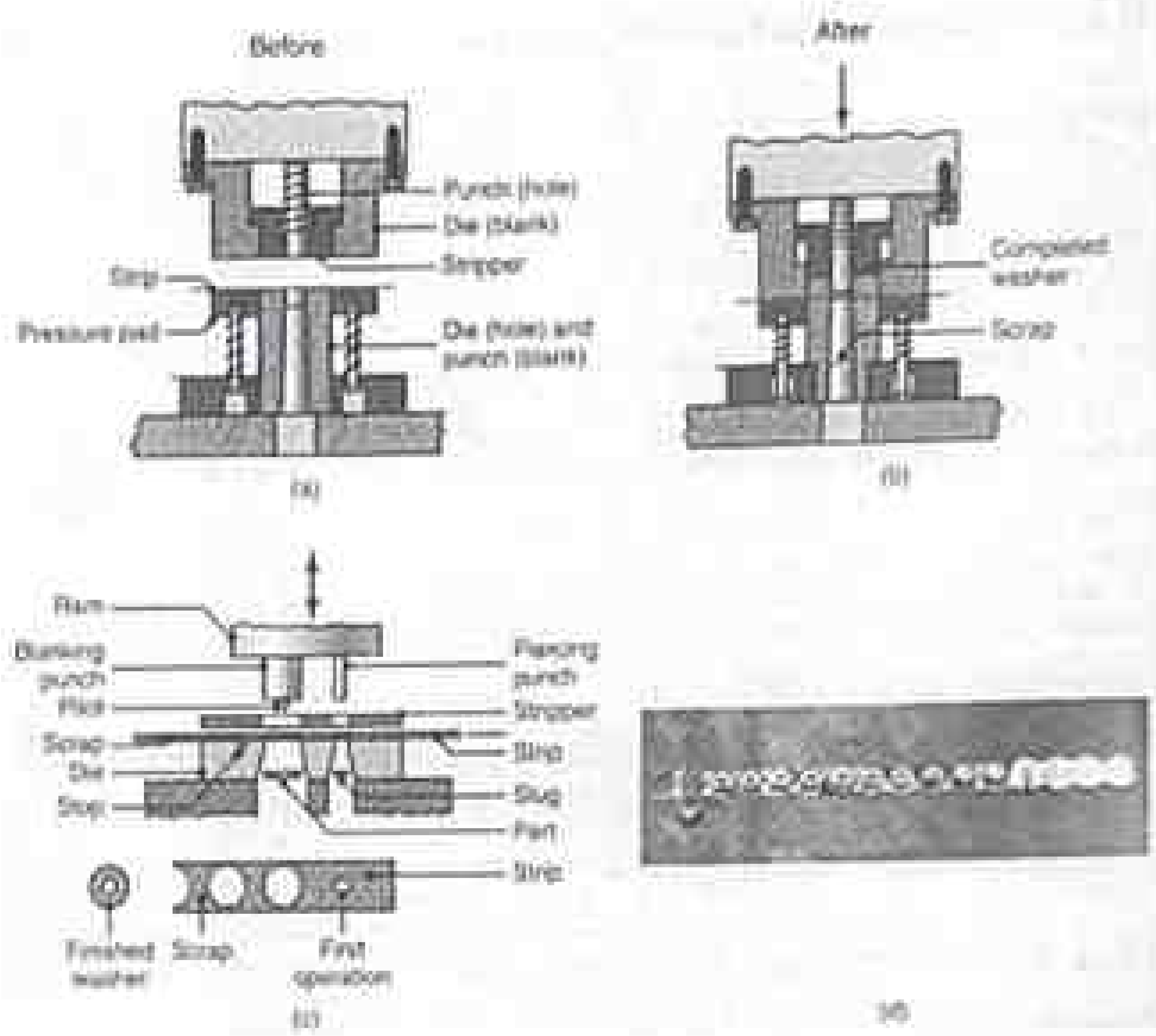


FIGURE 16.11 Schematic illustrations (a) before and (b) after blanking a common washer in a compound die; note the separate movements of the die (for blanking) and the punch (for punching the hole in the washer). (c) Schematic illustration of making a washer in a progressive die. (d) Forming of the top piece of an aerosol spray can in a progressive die; the part is attached to the strip until the last operation is completed.

Progressive Dies. Parts requiring multiple forming operations can be made, at high production rates, using *progressive dies*. The sheet metal is fed through as a coil strip, and a different operation (such as punching, blanking, and notching) is performed at the same station of the machine, with each stroke using a series of punches.
Transfer Dies. In a *transfer die* setup, the sheet metal undergoes different operations at different stations of the machine, arranged along a straight line or a circular path. After each step in a station, the part is transferred to the next station for further operations.

16.2.4 Miscellaneous Methods of Cutting Sheet Metal

There are several other methods of cutting metal sheets and plates:

- Laser-beam cutting is an important process, and typically used with computer-controlled equipment to cut a variety of shapes consistently, in various thicknesses, and without the use of dies. The process can also be combined with punching and shearing operations. Some parts with certain features, may be produced best by one process, while others, with various features, may best be produced by the other process. Combination machines, incorporating both capabilities, have been designed and built for this reason.
- Water-jet cutting is effective on metallic as well as nonmetallic materials.
- Cutting with a band saw; this is a chip-removal process.
- Friction sawing involves a disk or blade that rubs against the sheet or plate at high surface speeds, thus raising the temperature and separating it into two pieces.
- Flame cutting is another common method, particularly for thick plates; it is used widely in shipbuilding and on heavy structural components.

16.5 Bending Sheets, Plates, and Tubes

Springback. Because all materials have a finite modulus of elasticity, plastic deformation is always followed by some elastic recovery when the load is removed. In bending, this recovery is called *springback*, which can easily be observed by bending and then releasing a piece of sheet metal or wire.

Compensation for Springback. Springback in forming operations usually is compensated by overbending the part, although several trials may be necessary to obtain the desired results. Another method is to coin the bend area by subjecting it to highly localized compressive stresses between the tip of the punch and the die surface, a technique called *bottoming the punch*. In another method, the part is subjected to *stretch bending*, in which it is under external tension while being bent.

16.6 Miscellaneous Bending and Related Forming Operations

Press-brake Forming. Sheet metal or plate can easily be bent with simple fixtures using a press. The machine utilizes long dies, in a mechanical or hydraulic press, and is particularly suitable for small production runs.

Bending in a Four-slide Machine. Bending relatively short pieces can be done on a machine.

Roll Bending. In this process, plates are bent using a set of rolls. By adjusting the distance between the three rolls, various curvatures can be obtained. The process is flexible, and is used widely for bending plates for applications such as boilers, cylindrical pressure vessels, and various curved structural members.

Beading. In beading, the periphery of the sheet metal is bent in the cavity of a die. The bead imparts stiffness to the part by increasing the moment of inertia of that section. Also, beads improve the appearance of the part and eliminate exposed sharp edges that may be hazardous.

Flanging. This is a process of bending the edges of sheet metals, usually to 90°. In shrink flanging, the flange is subjected to compressive hoop stresses which, if excessive, can cause the flange periphery to wrinkle. The wrinkling tendency increases with decreasing radius of curvature of the flange. In *stretch flanging*, the flange periphery is subjected to tensile stresses which, if excessive, can lead to cracking along the periphery.

Roll Forming. Also called contour-roll forming or cold-roll forming, this process is used for forming continuous lengths of sheet metal and for large production runs. As it passes through a set of driven rolls, the metal strip is bent in consecutive stages. The formed strip is then sheared into specific lengths and stacked.

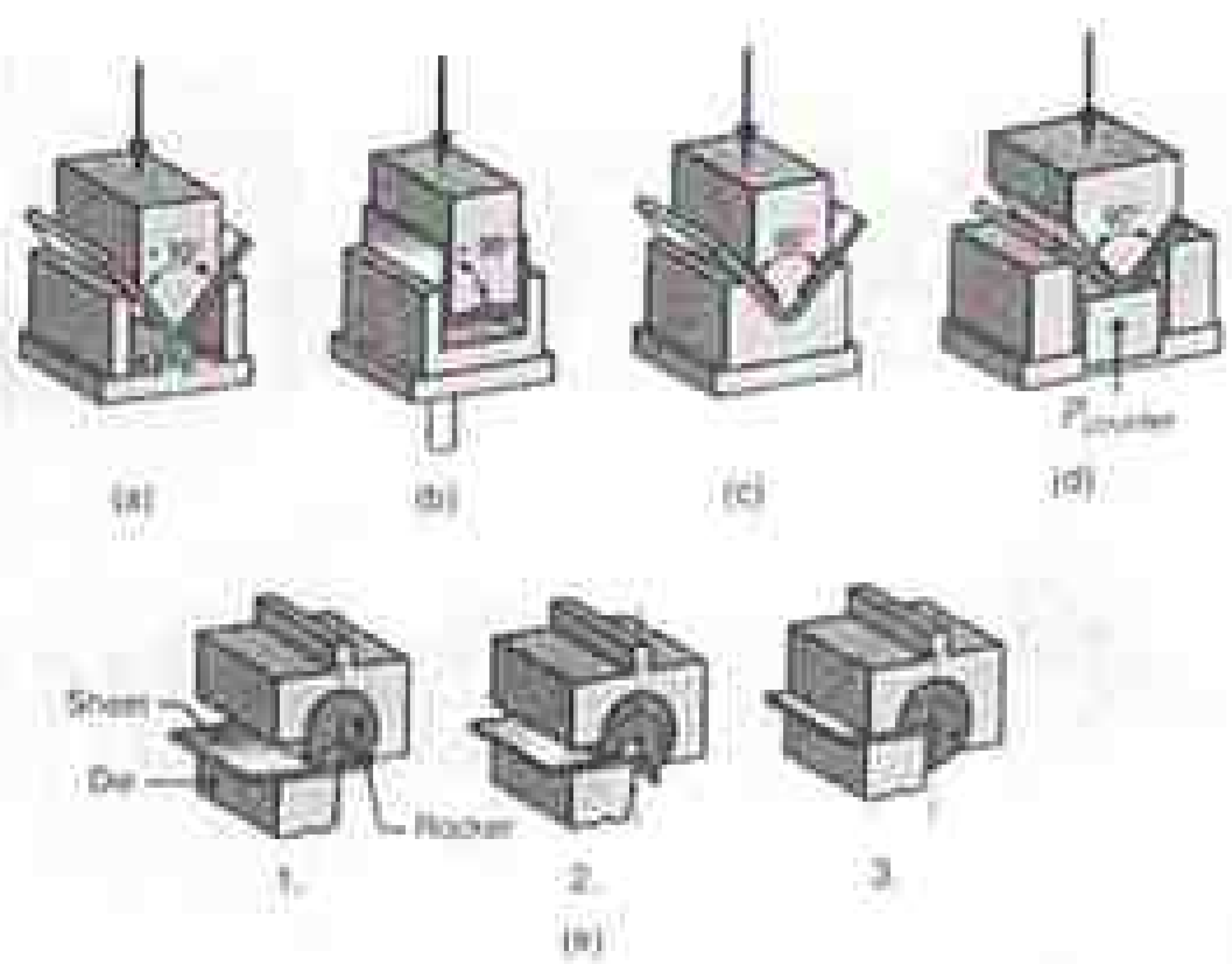


FIGURE 16.20 Methods of reducing or eliminating springback in bending operations.

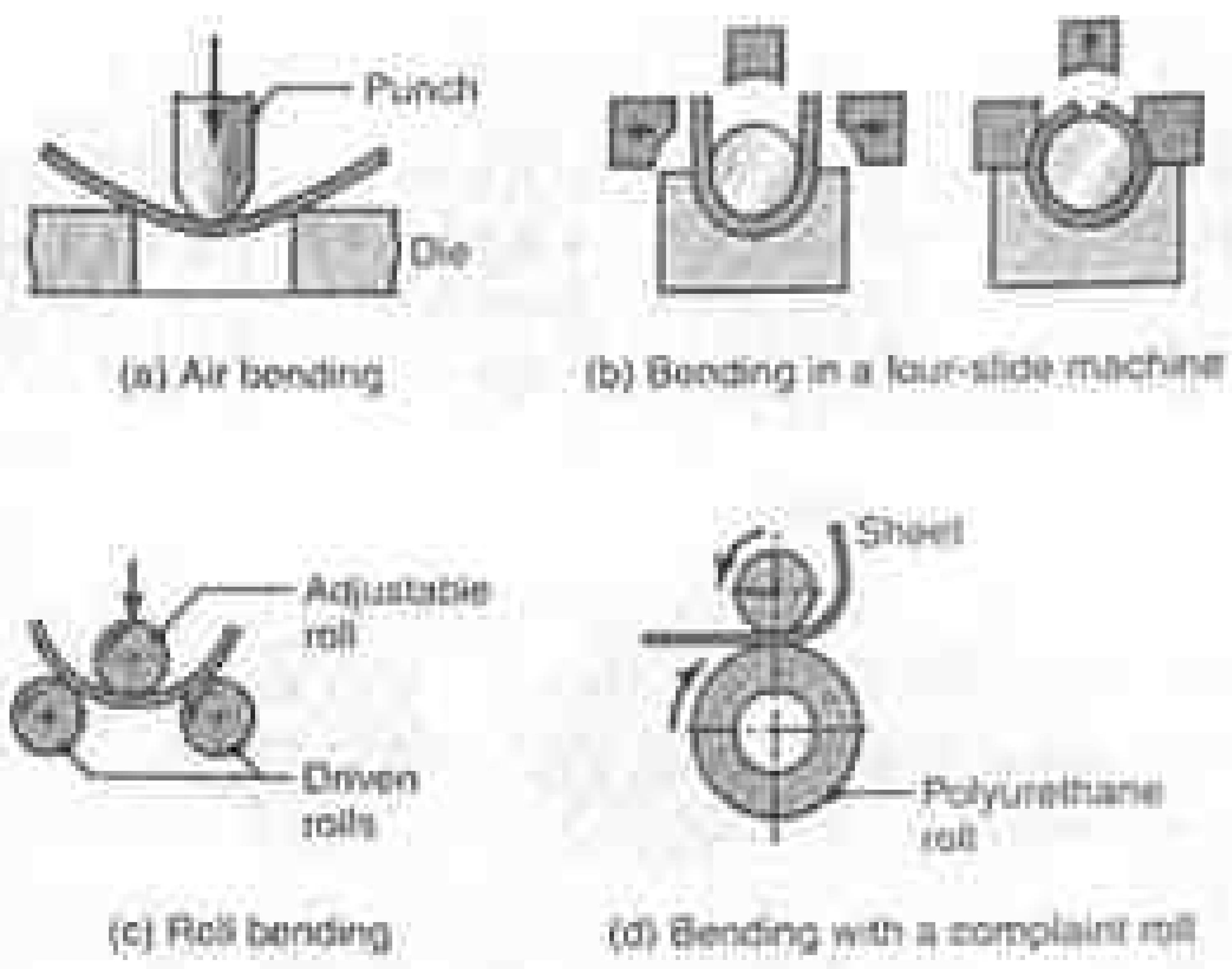


FIGURE 16.22 Examples of various bending operations.

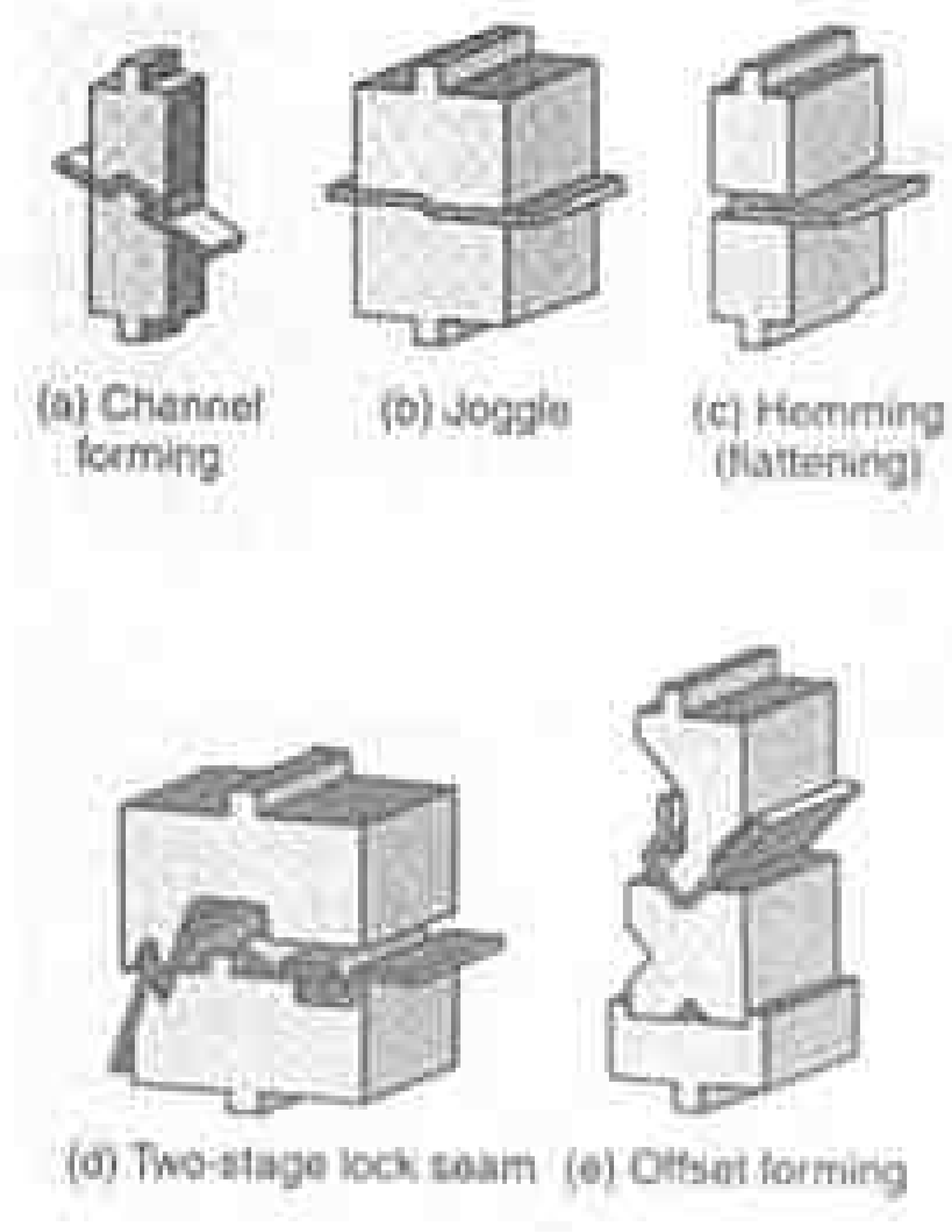


FIGURE 14.23 (a) through (e) Schematic illustrations of various bending operations in a press brake.

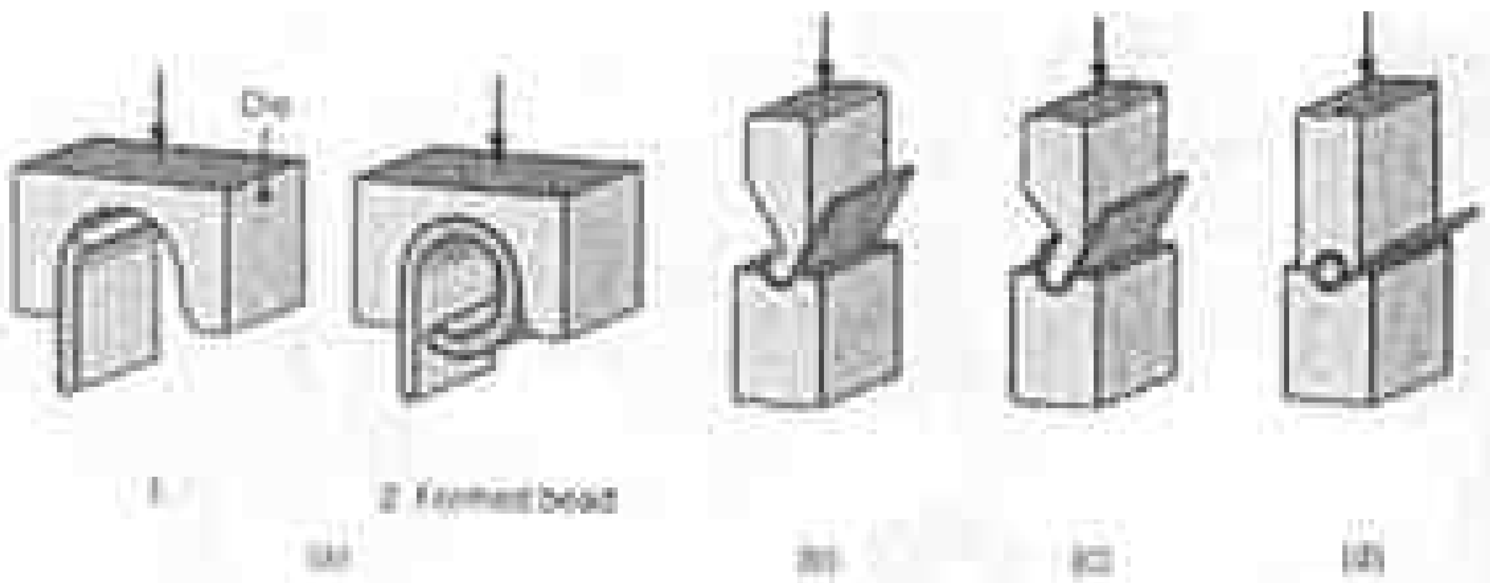


FIGURE 16.24 (a) Bead forming with a single die. (b) through (d) Bead forming with two dies in a press brake.

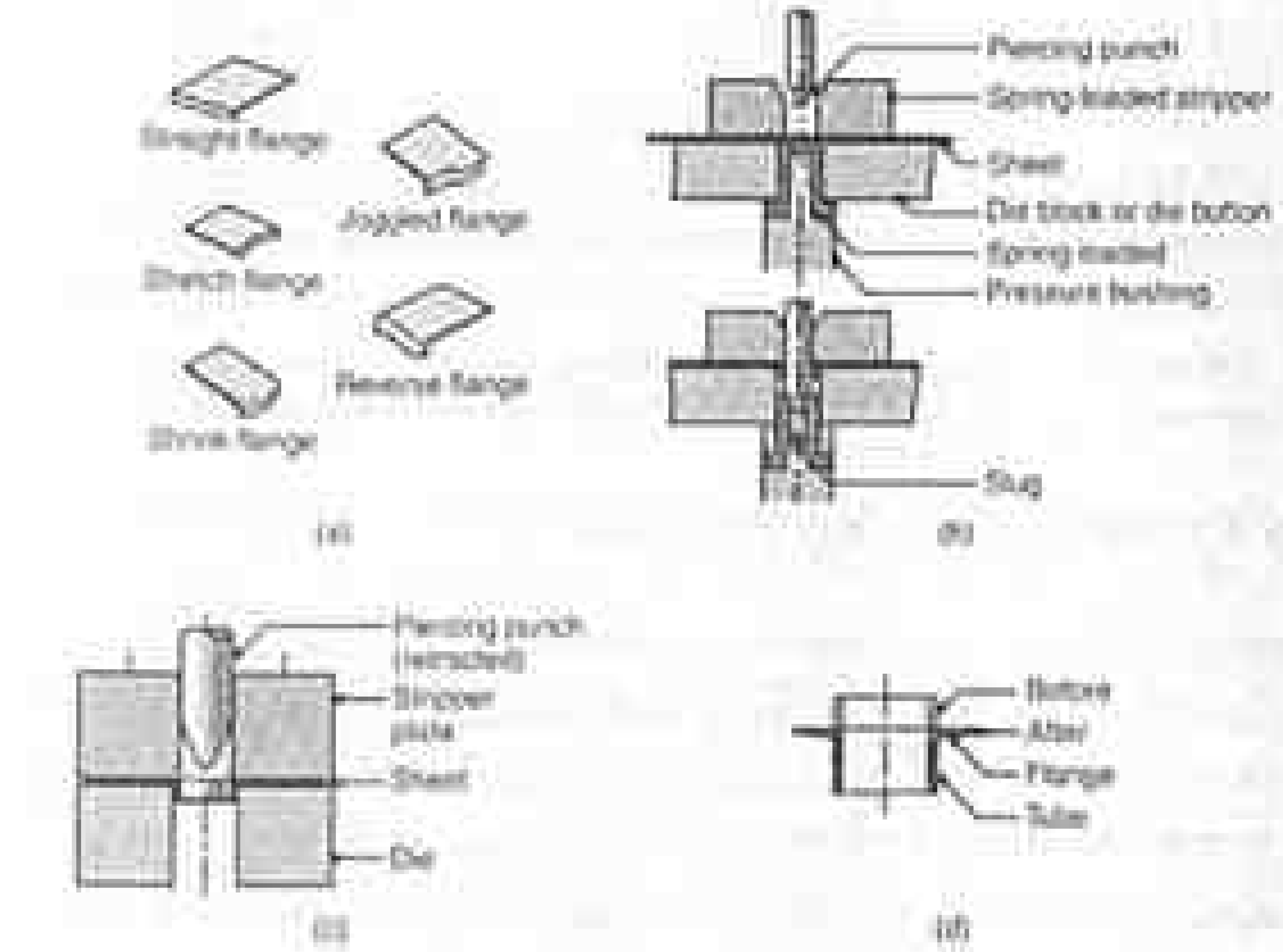


FIGURE 16.25 Various flanging operations. (a) Flanges on flat sheet. (b) Dimpling. (c) The piercing of sheet metal to form a flange. In this operation, a hole does not have to be prepunched before the punch descends; note the rough edges along the circumference of the flange. (d) The flanging of a tube; note the thinning of the edges of the flange.

Tube Bending and Forming. Bending and forming tubes and other hollow sections requires special tooling because of the tendency for buckling and folding, as one can note while trying to bend a piece of copper tubing or even a plastic soda straw. The oldest method of bending a tube or pipe is to first fill it with loose particles (commonly sand), and then bend it in a suitable fixture. The function of the filler is to prevent the tube from buckling inward; after the tube has been bent, the sand is shaken out. Tubes also can be plugged with various flexible internal mandrels, for the same purpose as sand. Note that, because of its lower tendency for buckling, a relatively thick tube can be bent safely without using fillers or plugs.

Dimpling, Piercing, and Flaring. In *dimpling*, a hole is first punched and then expanded into a flange. Flanges also may be produced by piercing with a shaped punch, and tube ends can be flanged by a similar process. When the bend angle is less than 90°, as in fittings with conical ends, the process is called *flaring*.

Hemming and Seaming. In the hemming process, also called *flattening*, the edge of the sheer is folded over itself. Hemming increases the stiffness of the part, improves its appearance, and eliminates sharp edges. *Seaming* involves joining two edges of sheet metal by hemming. Double seams are made by a similar process, using specially shaped rolls for watertight and airtight joints, such as those in food and beverage containers.

Bulging. This process involves placing a tubular, conical, or curvilinear part into a split-female die, and then expanding the part, usually with a polyurethane plug. The punch is then retracted, the plug returns to its original shape (by total elastic recovery), and the formed part is removed by opening the split dies. For parts with complex shapes, the plug, instead of being cylindrical, may be shaped, in order to be able to apply higher pressures at critical regions of the part. The major advantages of using polyurethane plugs are that they are highly resistant to abrasion and wear, and do not damage the surface finish of the part being formed.

Segmented Dies. These dies consist of individual segments that are placed inside the part to be formed and expanded mechanically in a generally radial direction. The segments are then retracted to remove the formed part. These dies are relatively inexpensive, and they can be used for large production runs.

Stretch Forming. In *stretch forming*, the sheet metal is clamped along its edges and then stretched over a male die, called form block or form punch. The die can move upward, downward, or sideways, depending on the particular design of the machine.

In most operations, the blank is a rectangular sheet, clamped along its narrower edges and stretched lengthwise, thus allowing the material to shrink in its width. Controlling the amount of stretching is important in order to prevent tearing. Stretch forming cannot produce parts with sharp contours or with reentrant corners. Various accessory equipment can be used in conjunction with stretch forming, including further forming with both male and female dies while the part is under tension.

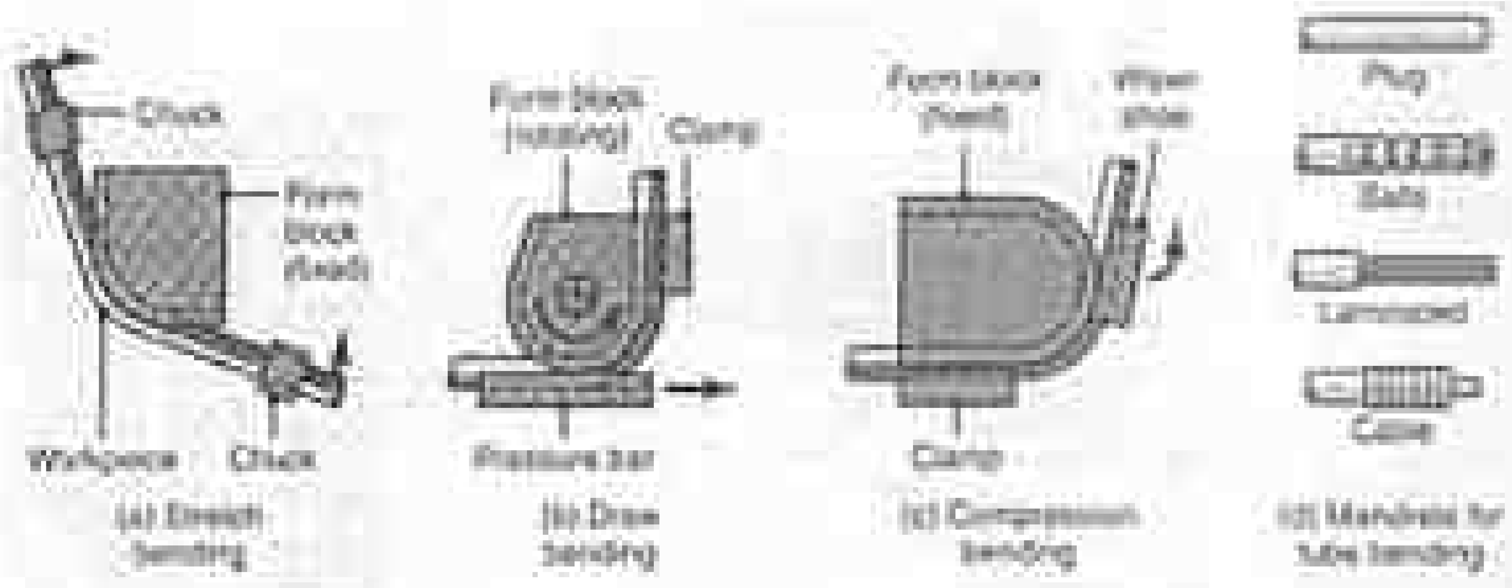


FIGURE 16.27 Methods of bending tubes. Internal mandrels or filling of tubes with particulate materials such as sand are often necessary to prevent collapse of the tubes during bending. Tubes also can be bent by a technique in which a stiff, helical tension spring is slipped over the tube. The clearance between the outer diameter of the tube and the inner diameter of the spring is small; thus, the tube cannot kink and the bend is uniform.

16.7 Deep Drawing

It can be noted that numerous sheet metal parts are *cylindrical or box shaped*. Deep drawing is one of the most important metalworking processes because of its widespread use.

Consider the case of a round sheet-metal blank placed over a circular die opening, and held in place with a blankholder, or *hold-down ring*. The punch travels downward, forcing the blank into the die cavity, thus forming a cup. The major variables in this process are (a) properties of the sheet metal, (b) ratio of blank diameter, D_o, (c) punch diameter, D_p, (d) clearance, c, between punch and die; (e) punch radius, R_p, (f) die-corner radius, R_d, (g) blankholder force; and (h) friction and lubrication between all contacting interfaces.

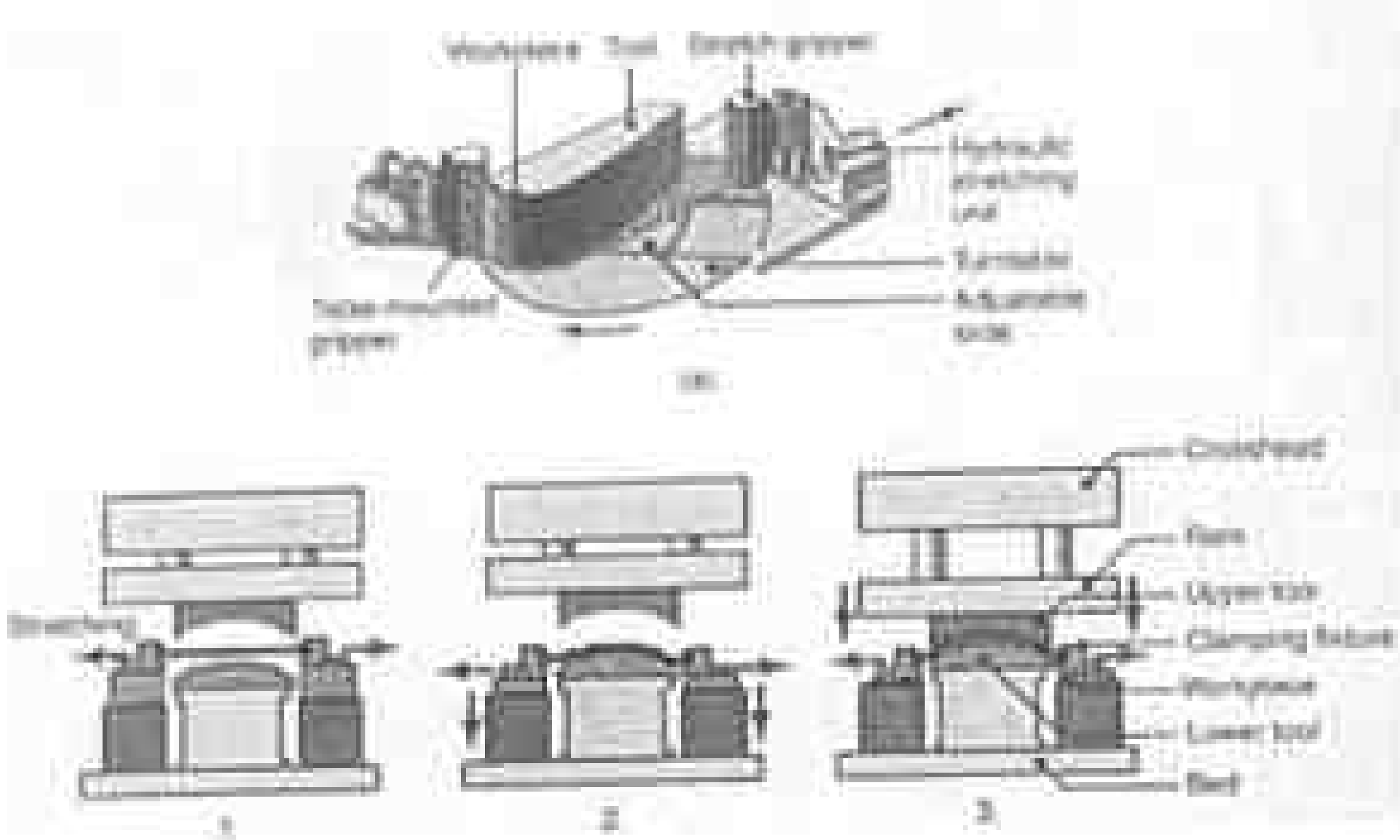


FIGURE 14.30 Schematic illustration of a stretch-forming process; aluminum skins for aircraft can be made by this method.

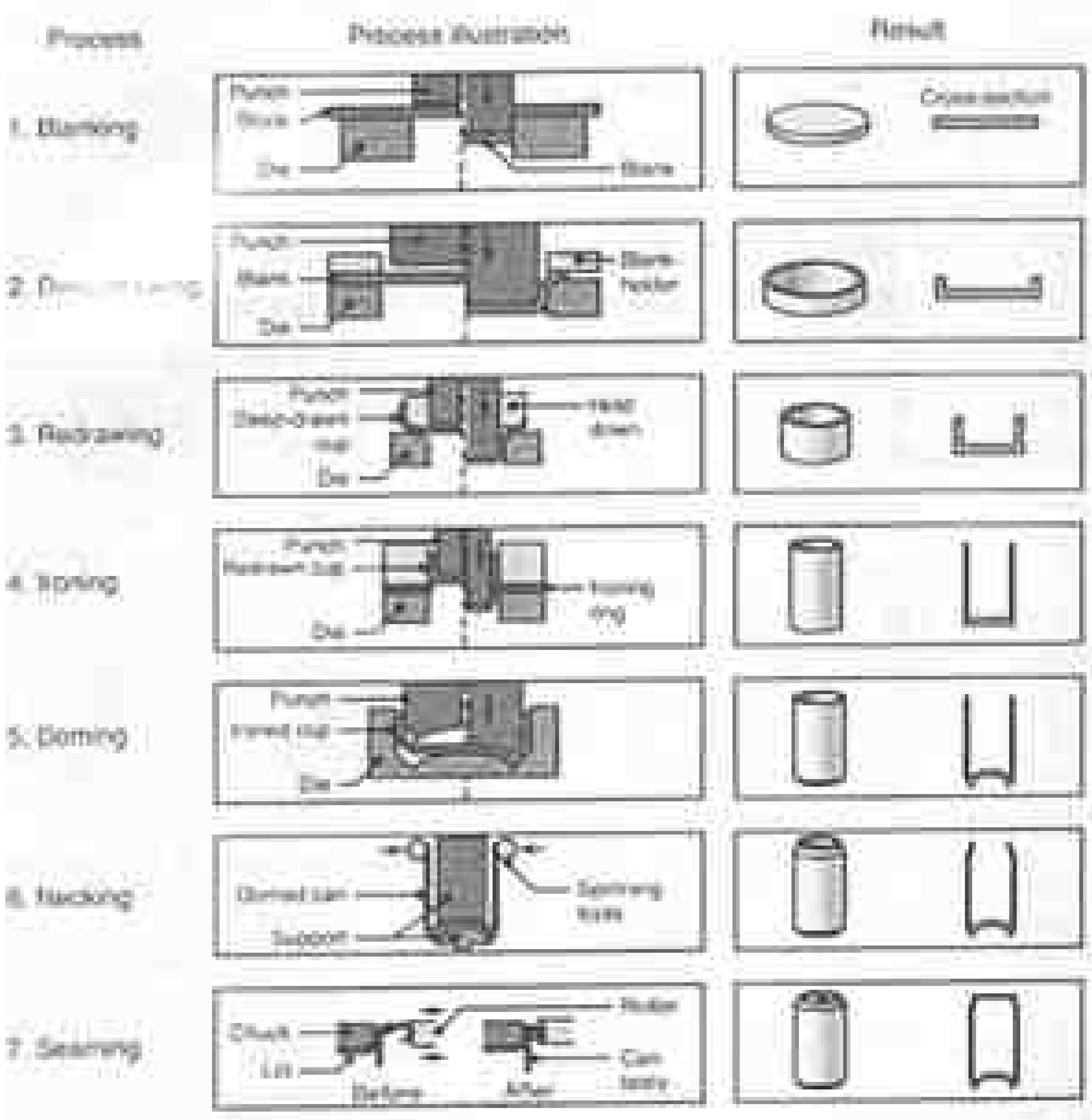
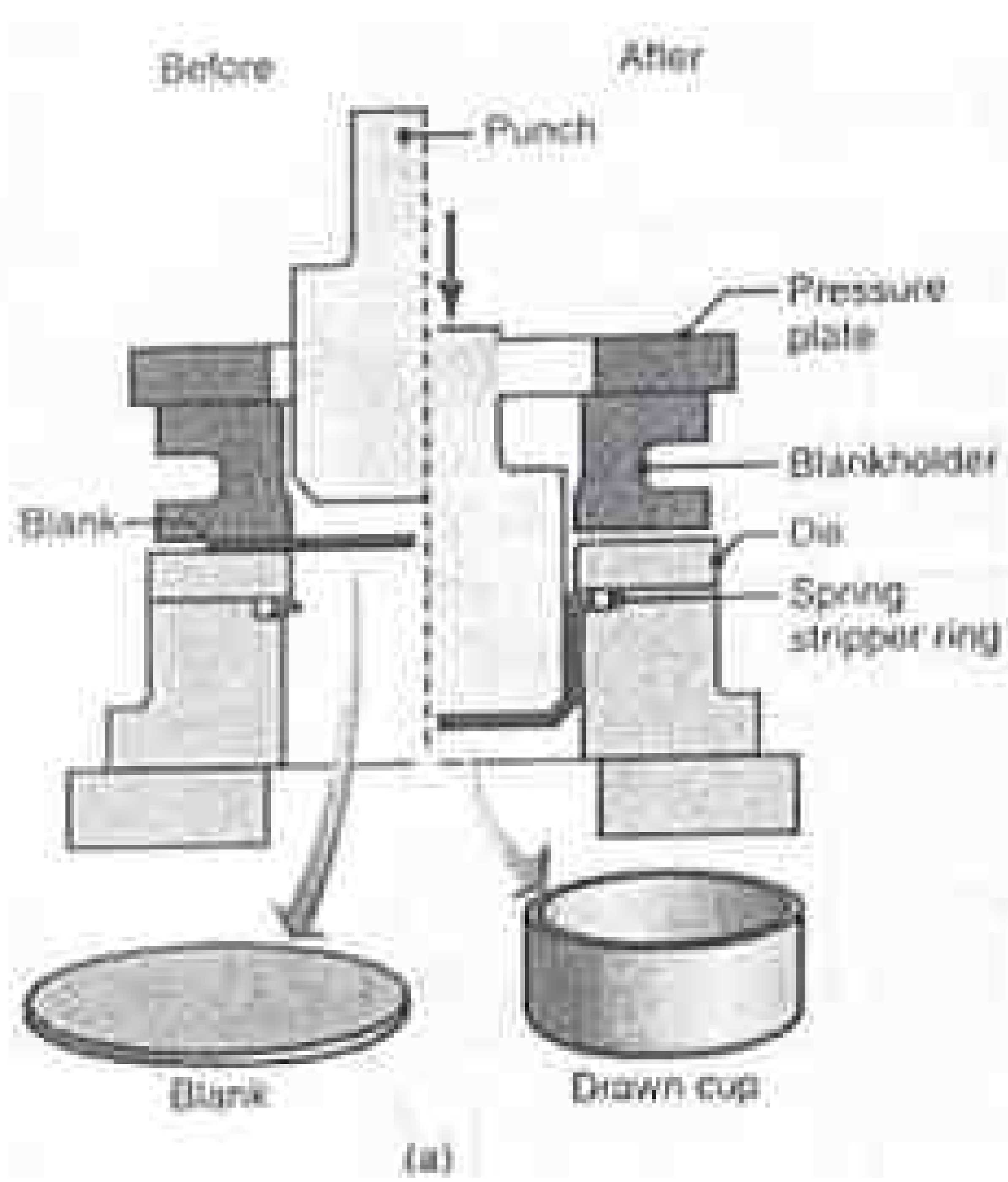


FIGURE 14.31 The metal-forming processes employed in manufacturing two-piece aluminum beverage cans.



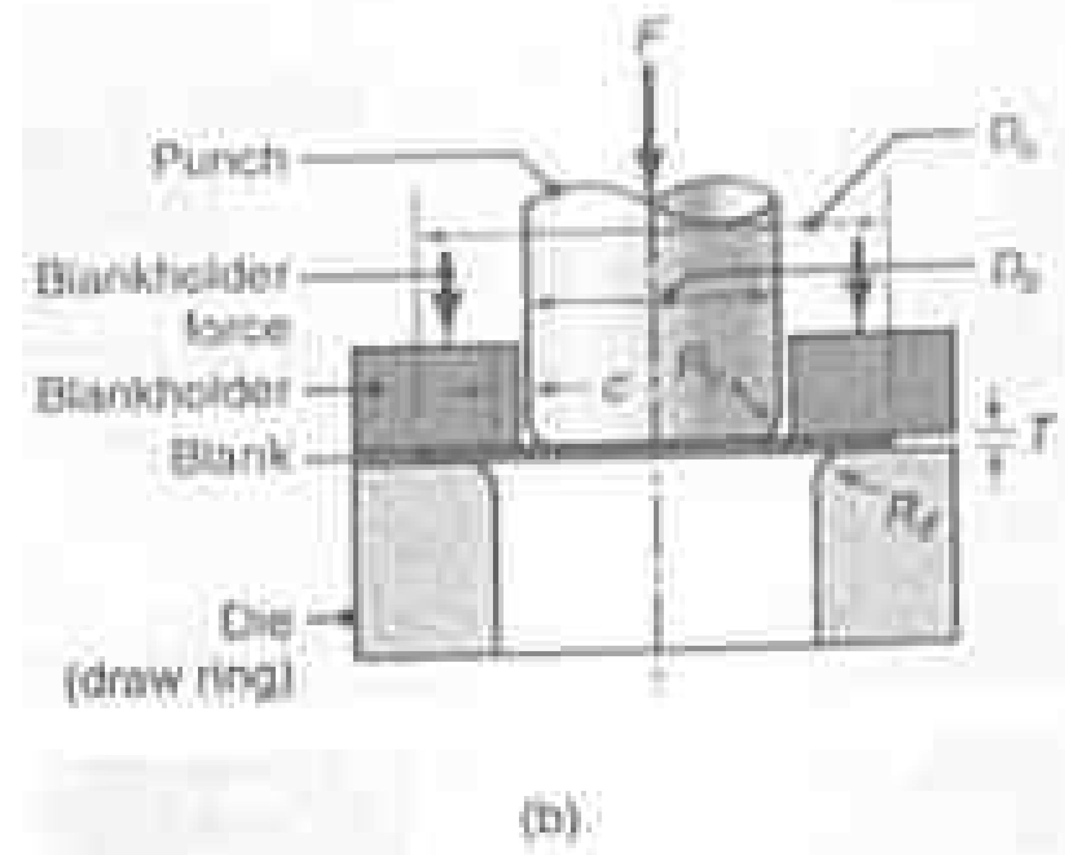


FIGURE 14.32 (a) Schematic illustration of the deep-drawing process on a circular sheet-metal blank; the stripper ring facilitates the removal of the formed cup from the punch. (b) Process variables in deep drawing. Except for the punch force, F, all the parameters indicated in the figure are independent variables.

16.7.2 Deep-drawing Practice

Ironing. If the clearance between the punch and the die is sufficiently large, the drawn cup will have thicker walls at its rim than at its base (see Fig. 16.32). The reason for this is that the cup rim consists of material from the outer diameter of the blank hence, it has been reduced in diameter more, and thus becomes thicker, than the material constituting the rest of the cup wall. As a result, the cup will develop a nonuniform wall thickness.

The thickness of the wall can be controlled by ironing, a process in which a drawn cup is pushed through one or more ironing rings. The clearance between the punch and ironing rings is less than the cup wall thickness, thus the drawn cup essentially has a constant wall thickness.

Redrawing. Containers that are too difficult to draw in one operation generally undergo *redrawing*. Because of the volume constancy of the metal, the cup becomes longer as it is redrawn to smaller diameters. In *reverse redrawing*, the cup is placed upside down in the die, and thus undergoes bending in the direction opposite to its original configuration.

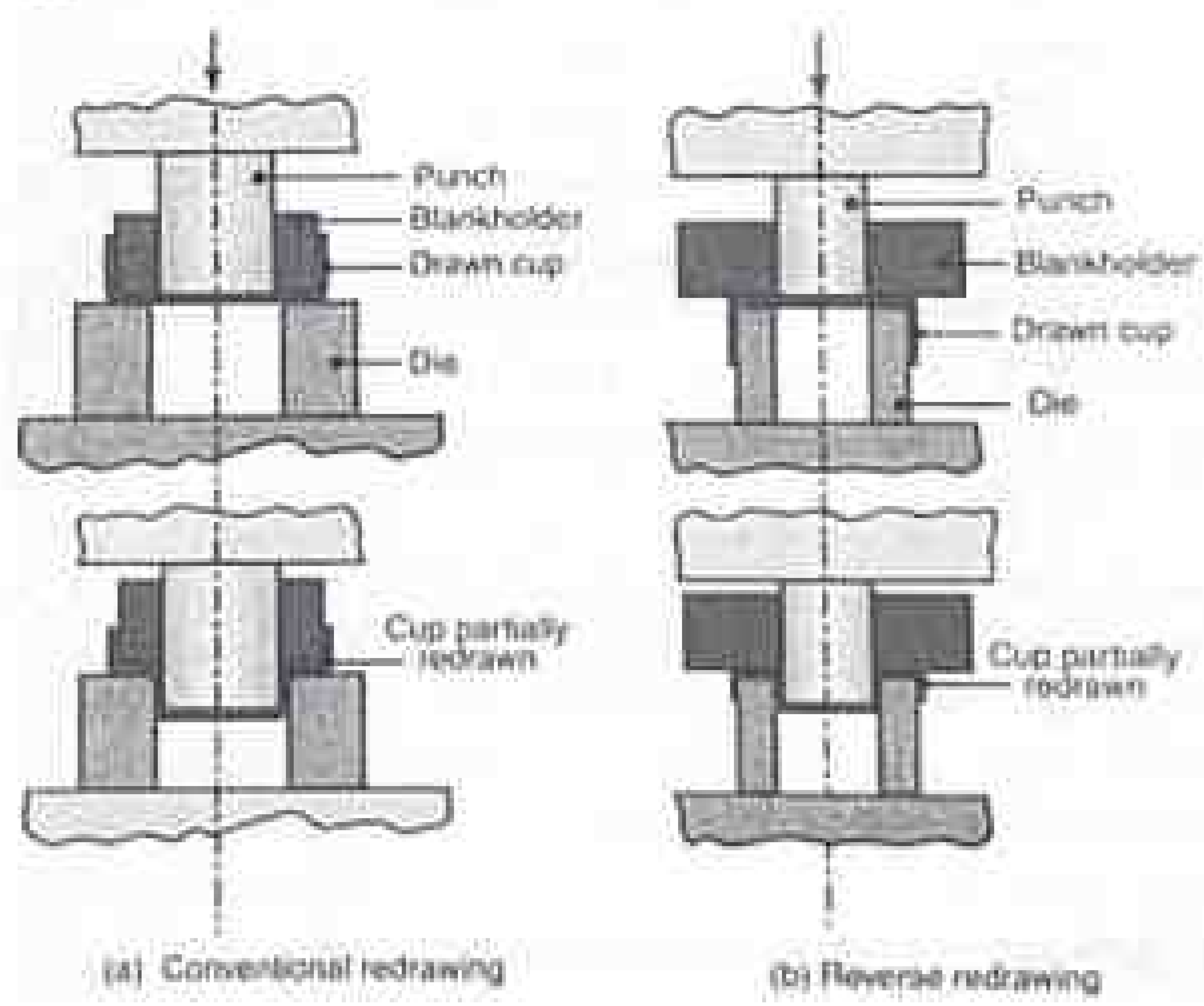


FIGURE 16.37 Reducing the diameter of drawn cups by redrawing operations: (a) conventional redrawing and (b) reverse redrawing. Small-diameter deep containers may undergo several redrawing operations.

Embossing. This is an operation consisting of shallow or moderate drawing, made with male and female matching shallow dies.

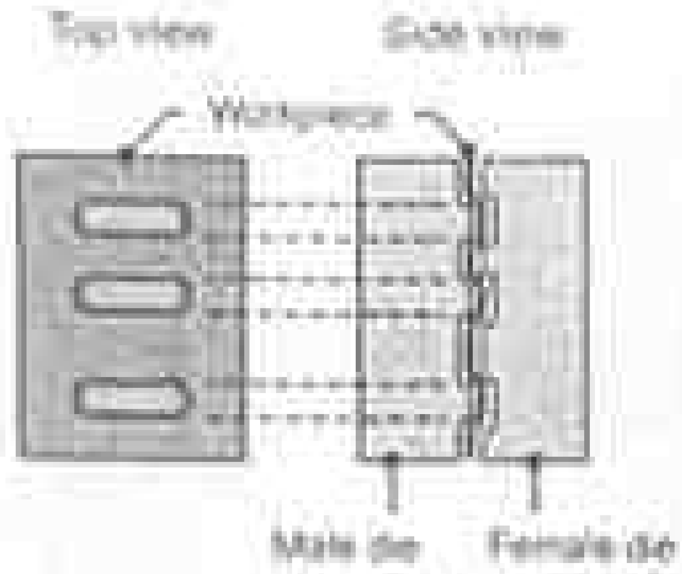


FIGURE 16.39 An embossing operation with two dies; letters, numbers, and designs on sheet-metal parts can be produced by this process.

16.8 Rubber Forming and Hydroforming

In the processes described in the preceding sections, it has been noted that the dies generally are made of solid materials, such as steels and carbides. In *rubber*, one of the dies in a set is made of a flexible material, typically a polyurethane membrane. Polyurethanes are used widely because of their abrasion resistance, fatigue life, and resistance to cutting or tearing.

In the *hydroform* or *fluid-forming process*, the pressure over the rubber membrane is controlled throughout the forming cycle, with a maximum pressure of up to 100 MPa. This procedure allows close control of the part during forming, and prevents wrinkling or tearing.

In tube hydroforming, metal tubing is formed in a die and pressurized internally by a fluid, usually water. This process, which now is being applied more widely, can form either simple tubes or various intricate hollow shapes. Parts made include automotive-exhaust and tubular structural components.

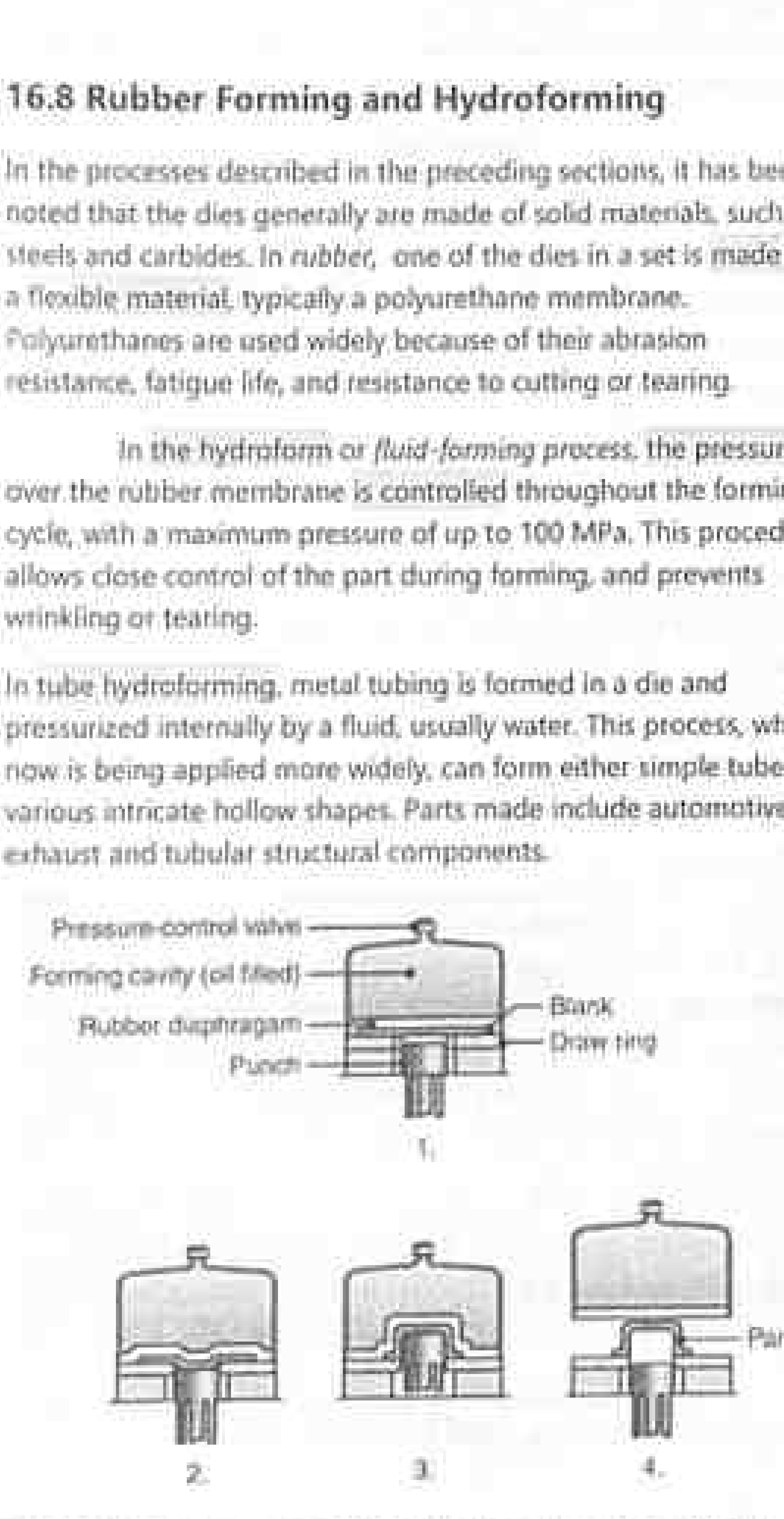


FIGURE 16.42 The hydroform (or fluid-forming) process; note that, in contrast to the ordinary deep-drawing process, the pressure in the dome forces the cup walls against the punch. The cup travels with the punch; in this way, deep drawability is improved.

16.9 Spinning

Spinning is a process that involves forming of axisymmetric parts over a mandrel, using various tools and rollers; a process similar to that of shaping clay on a potter's wheel.

Conventional Spinning. In *conventional spinning*, a circular blank of flat or preformed sheet metal is placed and held against a mandrel, and rotated while a rigid tool shapes the material over the mandrel.

Shear Spinning. Also known as *power spinning, flow turning, hydrospinning,* and *spin forging*, this operation produces an axisymmetric conical or curvilinear shape, reducing the sheet's thickness while maintaining its blank diameter.

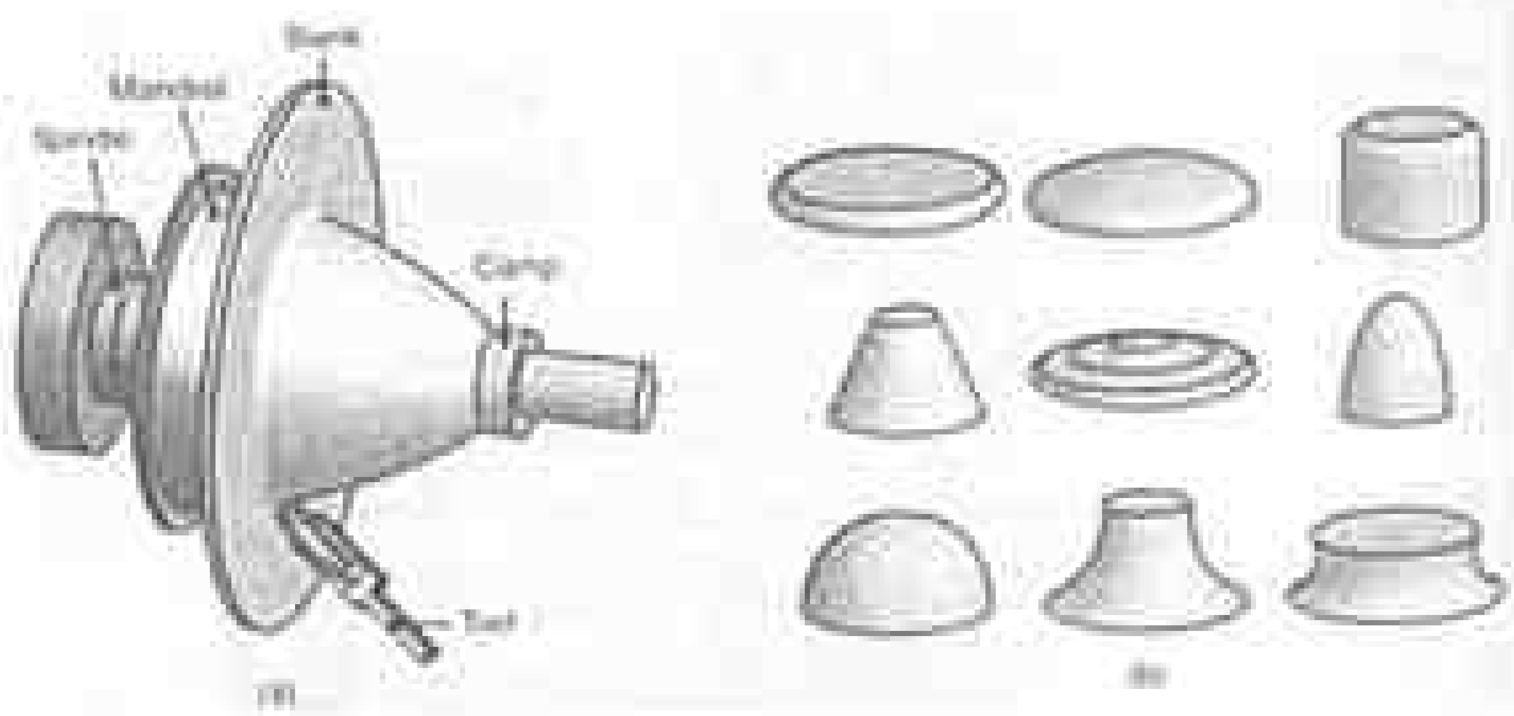


FIGURE 16.48 (a) Schematic illustration of the conventional spinning process. (b) Types of parts conventionally spun. All parts are axisymmetric.

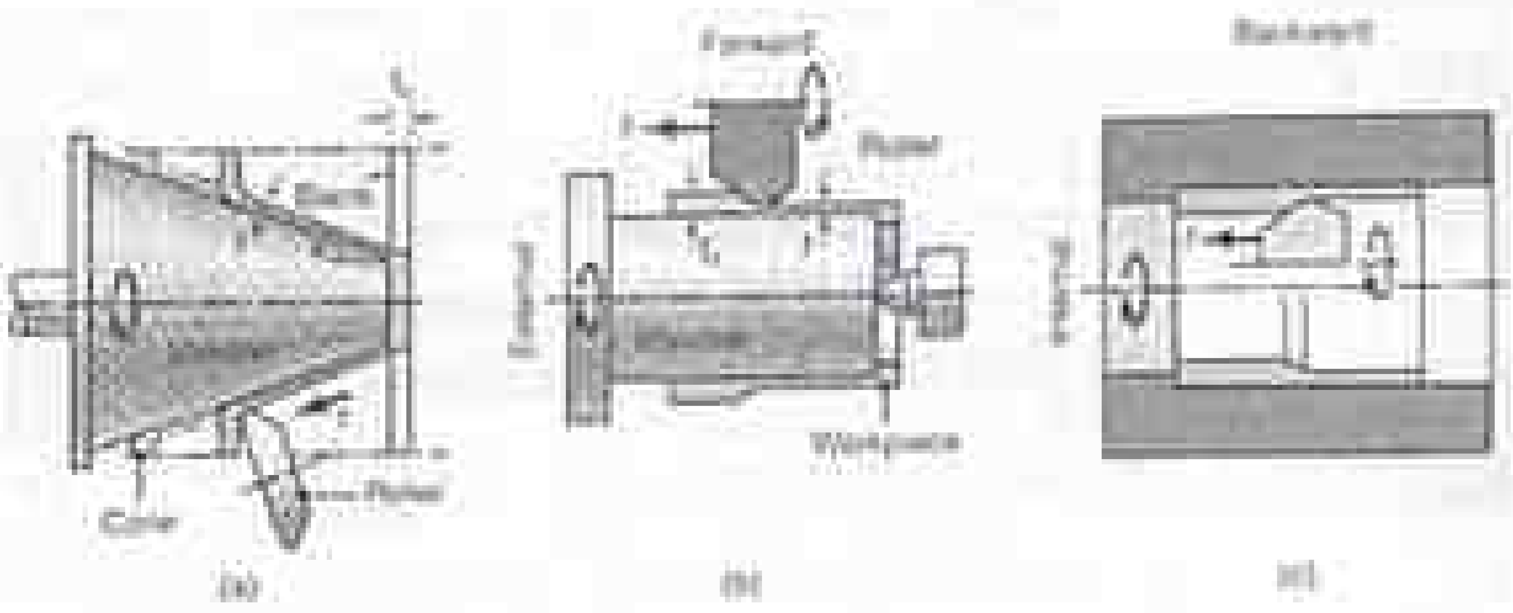


FIGURE 16.49 (a) Schematic illustration of the shear-spinning process for making conical parts; the mandrel can be shaped so that curvilinear parts can be spun. (b) and (c) Schematic illustrations of the tube-spinning process.

16.12 Specialized Forming Processes

Explosive Forming. Explosives generally are used for demolition in construction, in road building, and for destructive purposes. However, controlling their quantity and shape makes it possible to use explosives as a source of energy for sheet-metal forming.

In *explosive forming* first utilized to form metals in the early 1900s, the sheet-metal blank is clamped over a die, and the entire assembly is lowered into a tank, filled with water. The air in the die cavity is then evacuated, an explosive charge is placed at a certain height, and the charge is detonated.

Electromagnetically Assisted Forming. In *electromagnetically assisted forming*, also called *magnetic-pulse forming*, the energy stored in a capacitor bank is discharged rapidly through a magnetic coil.

Peen Forming. Peen forming is used to produce curvatures on thin sheet metals by *shot peening* one surface of the sheet. As a result, the surface of the sheet is subjected to compressive stresses, which tend to expand the surface layer. Because the material below the peened surface remains rigid, the surface expansion causes the sheet to develop a curvature. The process also induces compressive surface residual stresses, which improve the fatigue strength of the sheet metal.

Laser Beam Forming. This process involves the application of laser beams as a localized heat source over specific regions of the sheet metal. The steep thermal gradients developed through the thickness of the sheet produce thermal stresses, which are sufficiently high to cause localized plastic deformation of the sheet. With this method, a sheet, for example, can be bent permanently without using dies. In laser-assisted forming, the laser acts as a localized heat source, thus reducing the strength of the sheet metal at specific locations, improving formability and increasing process flexibility. Applications include straightening, bending, embossing, and forming of complex tubular or flat components.

Microforming. This is a more recent development and includes a family of processes that are used to produce very small metallic parts and components. Typical components made by microforming include small shafts for micromotors, springs, screws, and a variety of cold-headed, extruded, bent, embossed, coined, punched, or deep-drawn parts.

Electrohydraulic Forming. Also called *underwater spark* or *electric-discharge forming*, the source of energy in this process is a spark between two electrodes, connected with a short, thin wire. The rapid discharge of the energy, from a capacitor bank, through the wire generates a shock wave in the water, similar to those created by explosives. The pressure developed in the water medium is sufficiently high to form the part. The energy levels are lower than those in explosive forming. Electrohydraulic forming is a batch process and can be used in making various small parts.

16.15 Equipment for Sheet-metal Forming

For most general pressworking operations, the basic equipment consists of mechanical, hydraulic, pneumatic, or pneumatic-hydraulic presses, with a wide variety of designs, features, capacities, and computer controls. Recently, servo presses are being used for sheet-metal forming, because of their ability to vary speed and forces in a controlled manner during forming.

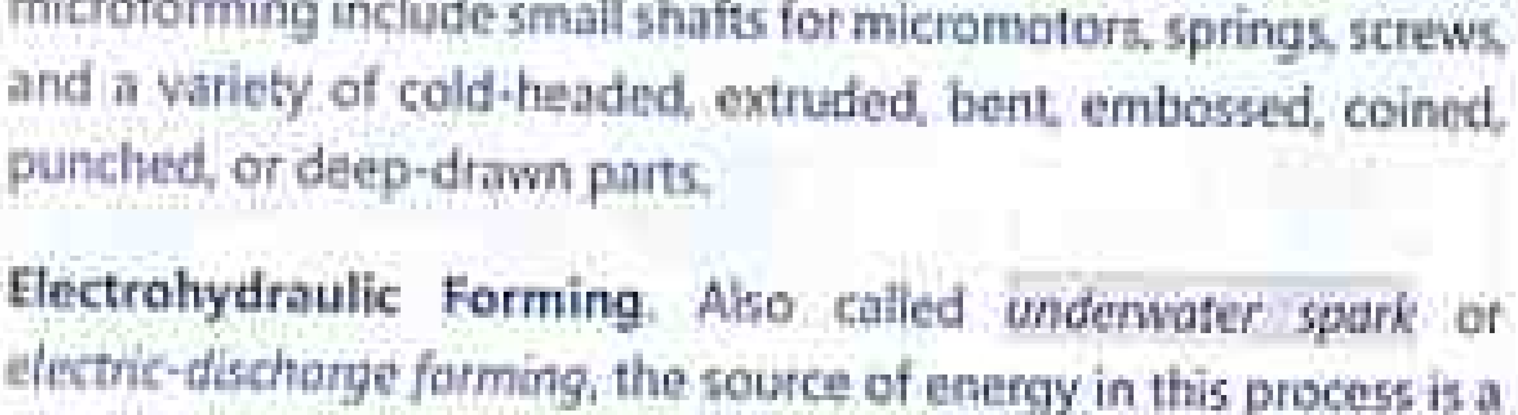


FIGURE 16.64 (a) through (f) schematic illustrations of types of press frames sheet-forming operations; each type has its own characteristics of stiffness, capacity, and accessibility.

16.16 Economics of Sheet-forming Operations

Deep drawing requires expensive dies and tooling, but a very high number of parts, such as containers, cans, and similar household products, can be produced with the same setup. These costs for other processes, such as punching, blanking, bending, and spinning, vary considerably.

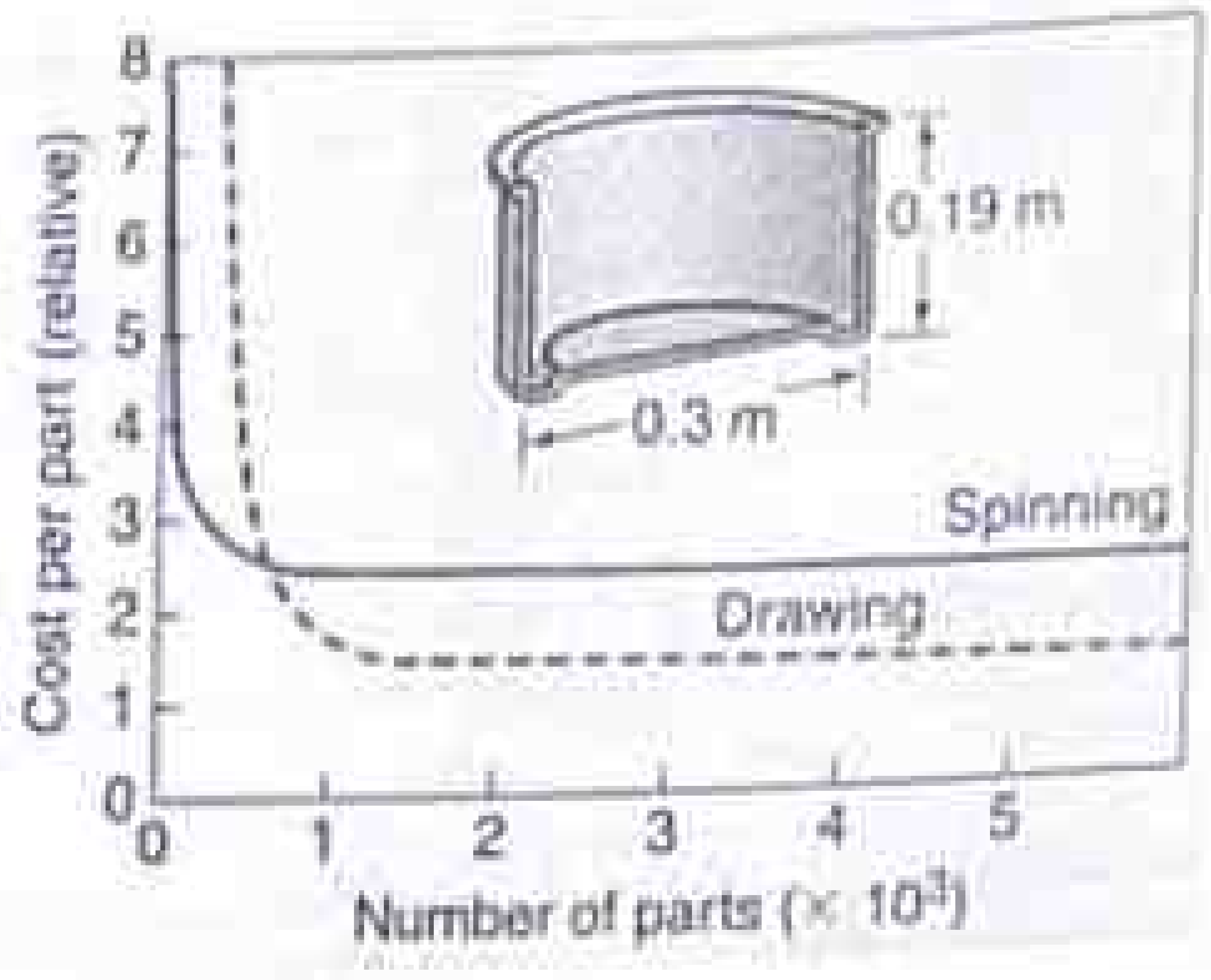


FIGURE 16.65 Cost comparison for manufacturing a round sheet-metal container either by conventional spinning or by deep drawing; note that for small quantities, spinning is more economical.

SUMMARY

- Sheet-metal forming processes are among the most versatile of all metalworking operations. They generally are used on workpieces having high ratios of surface area to thickness. Unlike bulk deformation processes, such as forging and extrusion, sheet-metal forming operations often prevent the sheet thickness from being reduced.
- Important material parameters are the quality of the sheared edge of the blank, the capability of the sheet to stretch uniformly, the material's resistance to thinning, its normal and planar anisotropy, grain size, and for low-carbon steels, yield-point elongation.
- The forces and energy required in forming processes are transmitted to the sheet through solid tools and dies, by flexible rubber or polyurethane members, or by electrical, chemical, magnetic, and gaseous means.
- Because of the relatively thin materials used, springback, buckling, and wrinkling are significant factors in sheet forming. These difficulties can be eliminated or reduced by proper tool and die design, minimizing the unsupported length of the sheet during processing, and controlling the thickness and surface finish of the incoming sheet and its mechanical properties.
- Superplastic forming of diffusion-bonded sheets is an important process for making complex sheer-metal structures, particularly for aerospace applications in which high stiffness-to-weight ratios arc important.
- Several test methods have been developed for predicting the formability of sheet metals.
- For general stamping operations, forming-limit diagrams are very useful, because they establish quantitative relationships among the major and minor principal strains that limit safe forming.

CHAPTER 17

Powder Metal Processes and Equipment

This chapter describes powder metallurgy (PM), in which metal powders are compacted into desired and often complex shapes and sintered (heated without melting) to form a solid piece. This process first was used in Egypt in about 3000 B.C. to make iron tools. One of its first modern uses was in the early 1900s to make the tungsten filaments for incandescent light bulbs.

17.2 Production of Metal Powders

The powder metallurgy process basically consists of the following operations, in sequence:

1. Powder production
2. Blending
3. Compaction
4. Sintering
5. Finishing operations

17.2.1 Methods of Powder Production

There are several methods of producing metal powders, and most powders can be produced by more than one method; the choice depends on the requirements of the end product. The microstrucrure, bulk and surface properties, chemical purity, porosity, shape, and size distribution of the particles depend on the particular process used. These characteristics are important because they significantly affect the flow and permeability during compaction.

Atomization. Atomization involves a liquid-metal stream produced by injecting molten metal through a small orifice. The stream is broken up by jets of inert gas or air or water

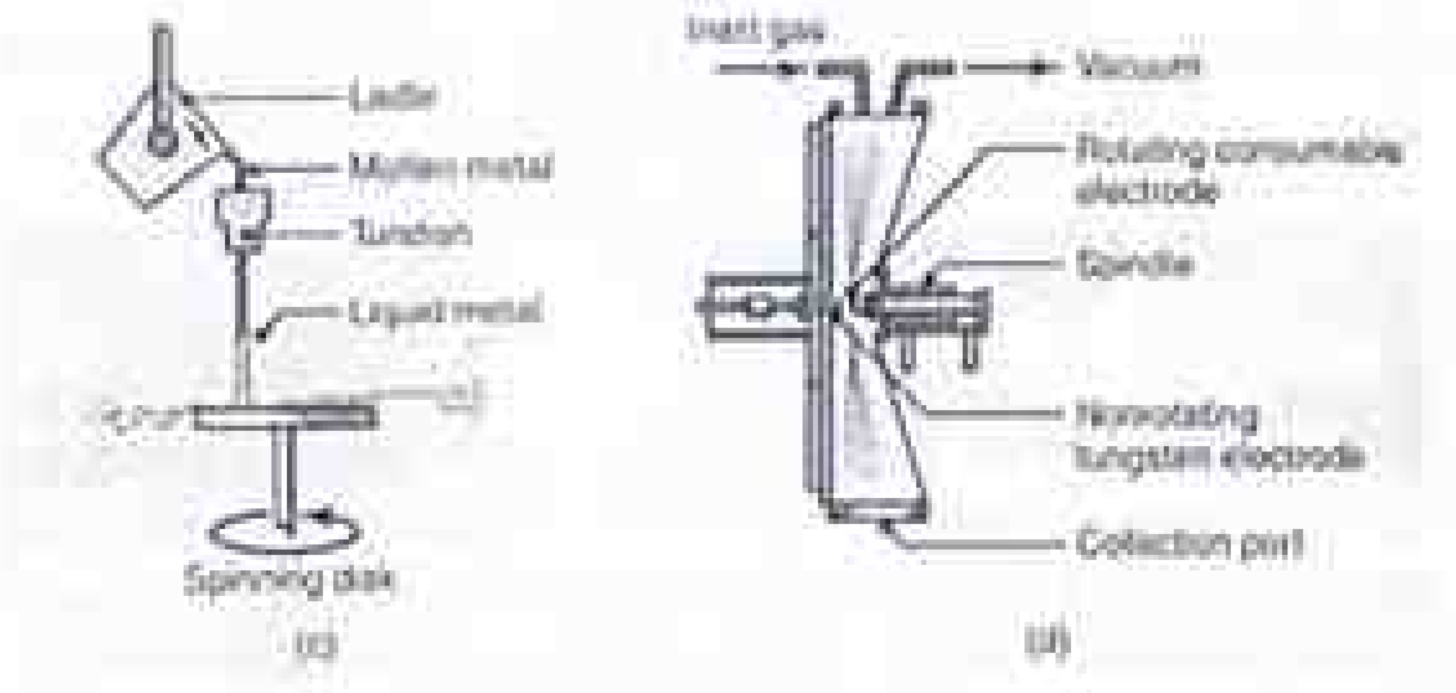


FIGURE 17.5 Methods of metal powder production by atomization: (a) gas atomization; (b) water atomization; (c) centrifugal atomization with a spinning disk or cup; and (d) atomization with a rotating consumable electrode.

17.2.3 Blending Metal Powders

Blending (mixing) powders is the next step in powder metallurgy processing, and is carried out for the following purposes:

- Powders of different metals and other materials can be blended or mixed in order to impart special physical and mechanical properties and characteristics to the PM product. Proper mixing is essential to ensure the uniformity of mechanical properties throughout the part.
- Even when a single metal is used, the powders may vary significantly in size and shape, hence they must be blended to ensure uniformity from part to part. An ideal mix is one in which all of the particles of each material, and of each size and morphology, are distributed uniformly.
- *Lubricants* can be mixed with the powders to improve their flow characteristics. They reduce friction between the metal particles, improve flow of the powder metals into the dies, and improve die life. Lubricants typically are stearic acid or zinc stearate, in a proportion of 0.25-5% by weight.
- Other additives, such as *binders* are used to impart sufficient *green strength;* additives also can be used to facilitate sintering.

17.3 Compaction of Metal Powders

Compaction is the step in which the blended powders are pressed into dies. The purposes of compaction are:

(a) to obtain the required shape, density, and particle-to-particle contact (b) to make the part sufficiently strong for further processing.

The presses used are actuated either hydraulically or mechanically, and the process generally is carried out at room temperature, although it can also be done at elevated temperatures for high melting point metals.

The pressed powder is known as green compact, because it has low strength. The green parts are very fragile, and can easily crumble or become damaged; a situation that is exacerbated by poor pressing practices, such as rough handling or insufficient compaction. For higher green strengths, the powder must be fed properly into the die cavity, and sufficient pressure must be developed throughout the part.

The *density* of the green compact depends on the compacting pressure. As the pressure is increased, the compact density approaches that of the metal in its bulk form. An important factor in density is the size distribution of the particles. If all of the particles are of the same size, there will always be some porosity when packed together. Theoretically, the porosity is at least 24% by volume. Introducing smaller particles into the powder mix will fill the spaces between the larger powder particles, and thus result in a higher density of the compact.

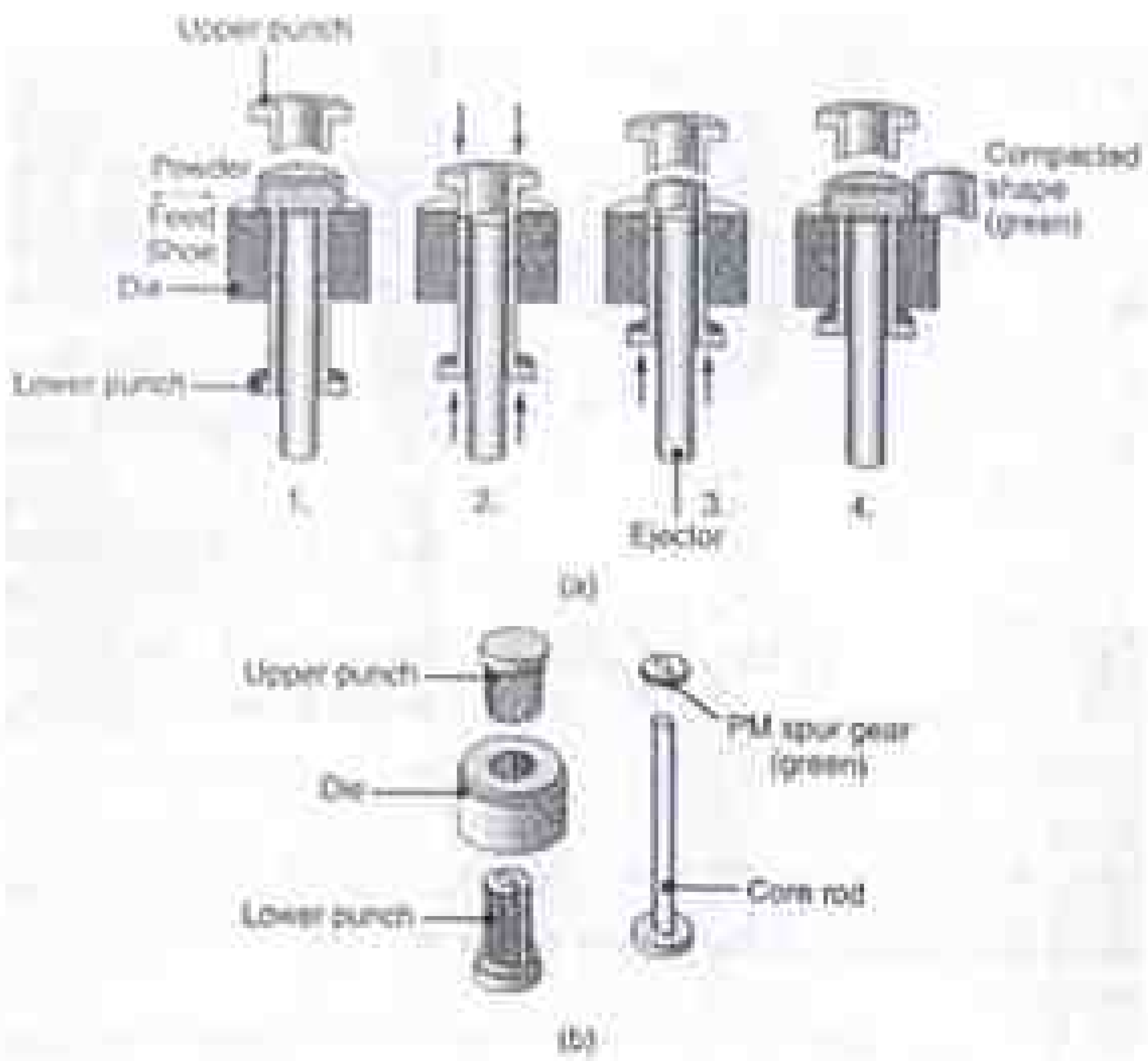


FIGURE 17.9 (a) Compaction of metal powder to form a bushing; the pressed powder part is called green compact, (b) A typical tool and die set for compacting a spur gear.

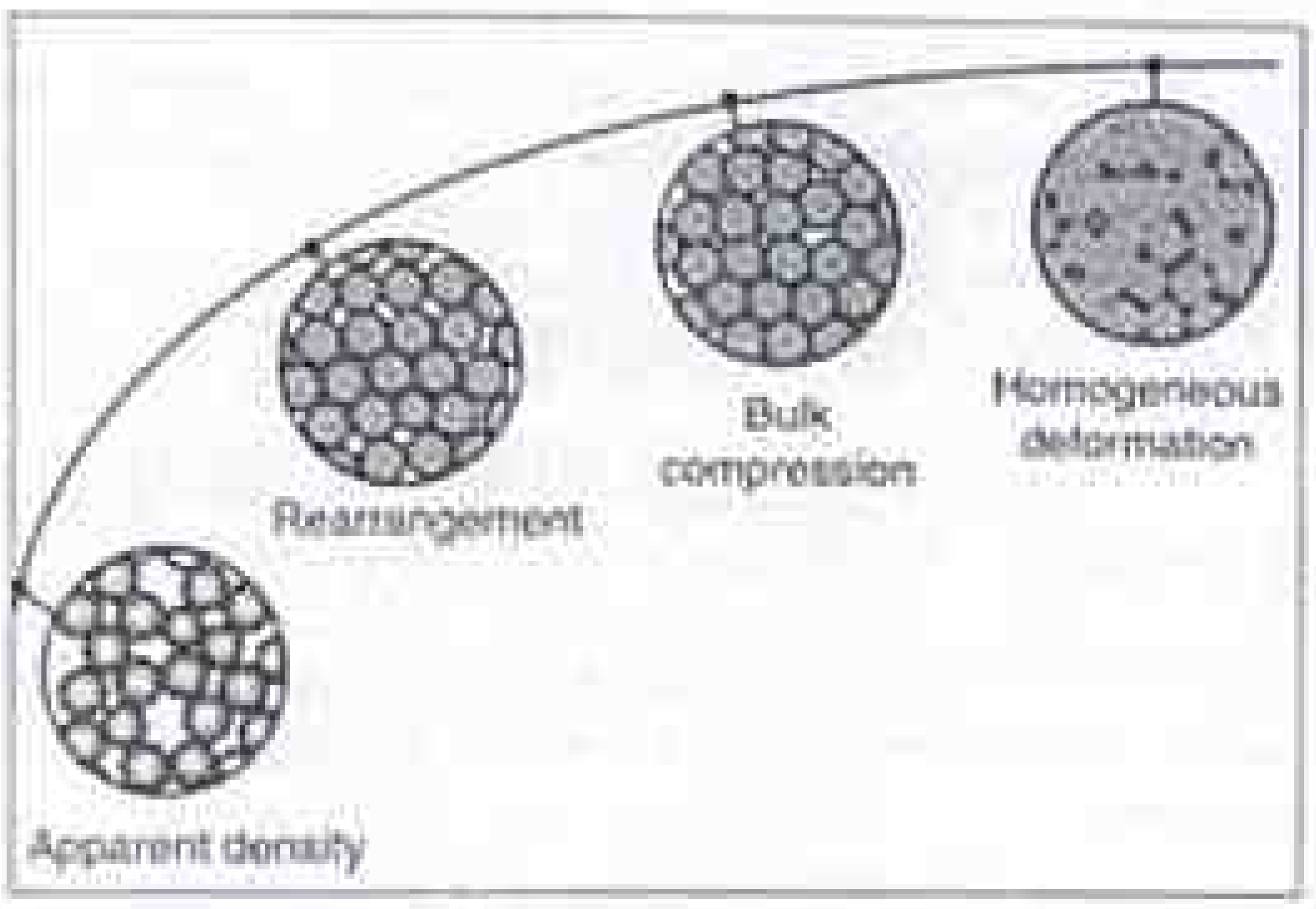


FIGURE 17.10 Compaction of metal powders; at low compaction pressures, the powder rearranges without deforming, leading to a high rate of density increase. Once the powders are more closely packed, plastic deformation occurs at their interfaces, leading to further density increases but at lower rates. At very high densities, the powder behaves like a bulk solid.

The higher the density of the compacted part, the higher are its strength and elastic modulus. The reason is that the higher the density, the higher the amount of solid metal in the same volume, and hence the higher its strength. Because of friction between (a) the metal particles in the powder and (b) the punch surfaces and die walls, the density within the part can vary considerably. This variation can be minimized by proper punch and die design and by control of friction. Thus, it may be necessary to use multiple punches, each with separate movements, in order to ensure that the density is more uniform throughout the part.

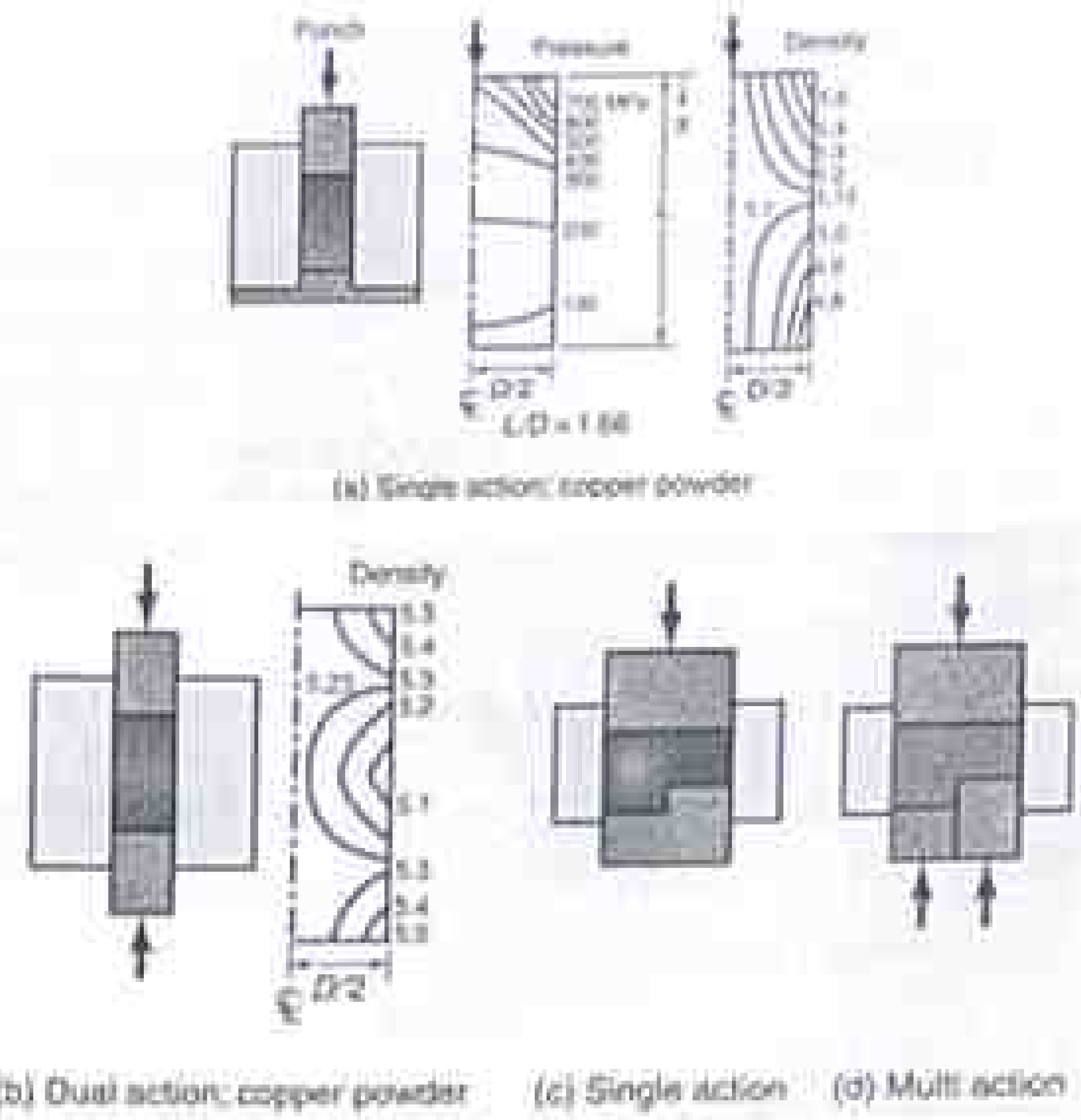


FIGURE 17.12 Density variation in compacting metal powders in various dies

17.3.2 Isostatic Pressing

Green compacts may be subjected to *hydrostatic pressure* in order to achieve more uniform compaction and, hence, density. In cold isostatic pressing (CIP), the metal powder is placed in a flexible rubber mold, typically made of neoprene rubber, urethane, polyvinyl chloride, or another elastomer. The assembly then is pressurized hydrostatically in a chamber, usually using water.

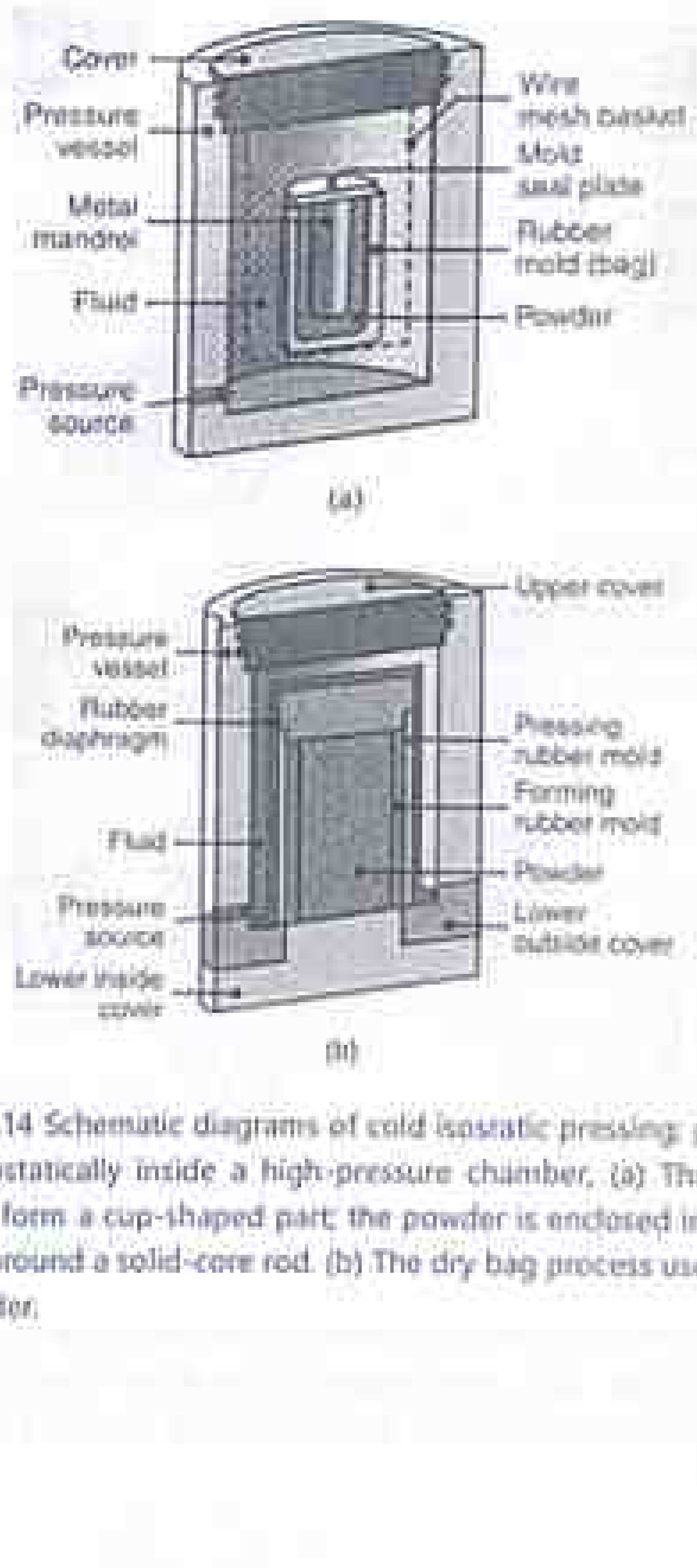


FIGURE 17.14 Schematic diagrams of cold isostatic pressing; pressure is applied isostatically inside a high-pressure chamber, (a) The wet bag process to form a cup-shaped part; the powder is enclosed in a flexible container around a solid-core rod. (b) The dry bag process used to form a PM cylinder.

In hot isostatic pressing (HIP), the container is generally made of a high-melting-point sheer metal, generally of mild or stainless steel, and the pressurizing medium is high-temperature inert gas or a vitreous (glasslike) fluid. The main advantage of HIP is its ability to produce compacts having almost 100% density, good metallurgical bonding of the particles, and good mechanical properties.

The HIP process is used mainly to produce superalloy components for the aircraft and aerospace industries and in military, medical, and chemical applications. It also is used (a) to close internal porosity, (b) to improve properties in superalloy and titanium-alloy castings for the aerospace industry, and (c) as a final densification step for tungsten-carbide cutting tools and PM tool steels.

The main advantages of HIP over conventional PM are:

- Because of the uniformity of pressure from all directions and the absence of die-wall friction, it produces fully dense compacts of practically uniform grain structure and density, irrespective of part shape (thus the properties are isotropic). Parts with high length-to-diameter ratios have been produced, with very uniform density, strength, toughness, and good surface detail.
- HIP is capable of handling much larger parts than those in other compacting processes; on the other hand, if has some limitations, such as:

Dimensional tolerances are higher than those in other compacting methods.

Equipment costs are higher and production time is longer than those in other processes.

- HIP is applicable only to relatively small production quantities, typically less than 10,000 parts per year.

17.4 Sintering

The green compact is brittle and its green strength is low. Sintering is the process whereby green compacts are heated, in a controlled-atmosphere furnace, to a temperature below the melting point of the metal, but sufficiently high to allow bonding (fusion) of the individual particles to impart strength to the part. The nature and strength of the bond between the particles, and thus that of the sintered compact, involve the complex mechanisms of diffusion, plastic flow, evaporation of volatile materials in the compact, recrystallization, grain growth, and extent of pore shrinkage.

The principal variables in sintering are temperature, time, and the furnace atmosphere. Sintering temperatures are generally within 70-90% of the melting point of the metal or alloy.

Continuous-sintering furnaces, which arc used for most production, have three chambers:

1. *Burn-off chamber*, for volatilizing the lubricants in the green compact, in order to improve bond strength and prevent cracking
2. High-temperature chamber, for sintering
3. Cooling chamber

Sintering Temperature and Time for Various Metals

Material	Temperature (°C)	Time (min)
Copper, brass, and bronze	760–900	10–45
Iron and iron graphite	1000–1150	8–45
Nickel	1000–1150	30–45
Stainless steels	1100–1290	30–60
Alnico alloys (for permanent magnets)	1200–1300	120–150
Ferrites	1200–1500	10–600
Tungsten carbide	1430–1500	20–30
Molybdenum	2050	120
Tungsten	2350	480
Tantalum	2400	480

Sintering mechanisms depend on the composition of the metal particles, as well as on the processing parameters. The mechanisms are *diffusion*, *vapor-phase transport*, and *liquid-phase sintering*. As the temperature increases, two adjacent powder particles begin to form a bond by a diffusion mechanism. As a result, the strength, density, ductility, and thermal and electrical conductivities of the compact increase. At the same time, however, the compact shrinks, thus allowances must be made for shrinkage, as are done in casting.

A second sintering mechanism is vapor-phase transport. Because the material is heated to close to its melting temperature, metal atoms will be released to the vapor phase from the particles. At convergent geometries (the interface of two particles), the melting temperature is locally higher and the vapor phase resolidifies. Thus, the interface grows and strengthens while each particle shrinks as a whole.

It two adjacent particles are of different metals, alloying can take place at the interface of the two particles. If one of the particles has a lower melting point than the other, the particle will melt and, because of surface tension, surround the particle that has not melted. An example of this mechanism, known as liquid-phase sintering, is cobalt in tungsten-carbide tools and dies, and stronger and denser parts can be obtained in this way. In spark sintering, loose metal powders are placed in a graphite mold, heated by electric current, subjected to a high-energy discharge, and compacted, all in one step.

17.5 Secondary and Finishing Operations

In order to further improve the properties of sintered PM products or to impart special characteristics, several additional operations may be carried out following sintering:

1. Coining and sizing are compacting operations, performed under high pressure in presses. The purposes of these operations are to impart dimensional accuracy to the sintered part and to improve its strength and surface finish by further densification.
2. Preformed and sintered alloy-powder compacts subsequently may be cold or hot forged to the desired final shapes, and sometimes by *impact forging*. These products have good surface finish and dimensional tolerances, and uniform and fine grain size. The superior properties obtained make this technology particularly suitable for such applications as highly stressed automotive and jet-engine components.

3. Powder metal parts may be subjected to other finishing operations, such as

- Machining, for producing various geometric features by milling, drilling, and tapping
- Grinding, for improving dimensional accuracy and surface finish
- Plating, for improving appearance and resistance to wear and corrosion
- Heat treating, for increasing hardness and strength

4. The inherent porosity of PM components can be utilized by impregnating them with a fluid. Bearings and bushings that are lubricated internally, with up to 30% oil by volume, are made by immersing the sintered bearing in heated oil. The bearings have a continuous supply of lubricant during their service lives, due to capillary action (also referred to as permanently lubricated).

5. Infiltration is a process whereby a slug of a lower-melting-point metal is placed in contact with the sintered part. The assembly is then heated to a temperature sufficiently high to melt the slug. The molten metal infiltrates the pores by capillary action, producing a relatively pore-free part having good density and strength. The advantages of infiltration are that the hardness and tensile strength of the part are improved and the pores are filled, thus preventing moisture penetration, which could cause corrosion. Moreover, because some porosity is essential w hen an infiltrant is used, the part may be sintered only partially, thus resulting in lower thermal warpage.

6. Electroplating can be applied on PM parts, but special care is required to thoroughly remove the electrolytic fluid, since it presents health hazards. Under some conditions, electroplating can seal a part and eliminate its permeability.

7. Densification, or roll densification, is similar to roller burnishing, where a small-diameter hard roll is pressed against a PM part, resulting in sufficiently high contact pressures to cause plastic deformation of its surface layers. Thus, instead of cold working the part, the effect is to cause an increase in density, or densification, of the surface layers. Powder metallurgy gears and bearing races are generally treated by roll densification, since the surface layer is more fatigue resistant and better able to support higher contact stresses than untreated components.

17.7 Economics of Powder Metallurgy

Because PM can produce parts at net or near-net shape, and thus eliminate many secondary manufacturing and assembly operations, it increasingly has become competitive with casting, forging, and machining. On the other hand, the high initial cost of punches, dies, and equipment for PM processing means that production volume must be sufficiently high to warrant this expenditure. Although there are exceptions, the process generally is economical for quantities over 10,000 pieces.

SUMMARY

- Powder metallurgy is a net-shape forming process consisting of metal powder production, blending, compaction in dies, and sintering in order to impart strength, hardness, and toughness. Although the size and the weight of PM products are limited, the process is capable of producing relatively complex parts economically, in net-shape form, to dose dimensional tolerances, and from a wide variety' of metal and alloy powders.
- Secondary and finishing operations may be performed on PM parts, to improve their dimensional accuracy, surface finish, mechanical and physical properties, and appearance. These operations include forging, heat treating, machining, grinding, plaring, impregnation (as with oil), and infiltration (as with low-melting-point metals).
- Control of powder shape and quality, process variables, and sintering atmospheres are important considerations in product quality. Density and mechanical and physical properties can be controlled by tooling design and by adjusting the compacting pressure.
- An important PM process is powder-injection molding, which involves mixing the very fine metal powders with a polymer, to make them flow more easily into molds of complex shape.
- Design considerations for PM include the shape of the part, the ability ro eject the green compact from the die, and the dimensional tolerances that are acceptable for the particular application.
- The PM process is suitable for medium- to high-volume production runs and for relatively small parts. It has some competitive advantages over other methods of production, such as casting, forging, and machining.

CHAPTER 19

PLASTICS AND COMPOSITE MATERIALS: FORMING AND SHAPING

19.2 Extrusion

In extrusion, which produces the largest volume of plastics, raw materials in the form of thermoplastic pellets, granules, or powder are placed into a *hopper* and fed into the barrel of a *screw extruder*. The barrel is equipped with a helical screw, which builds up pressure in the barrel, blends the pellets, and conveys them down the barrel toward the die. The barrel heaters and the internal friction from the mechanical action ol the screw heat the pellets and liquify them.

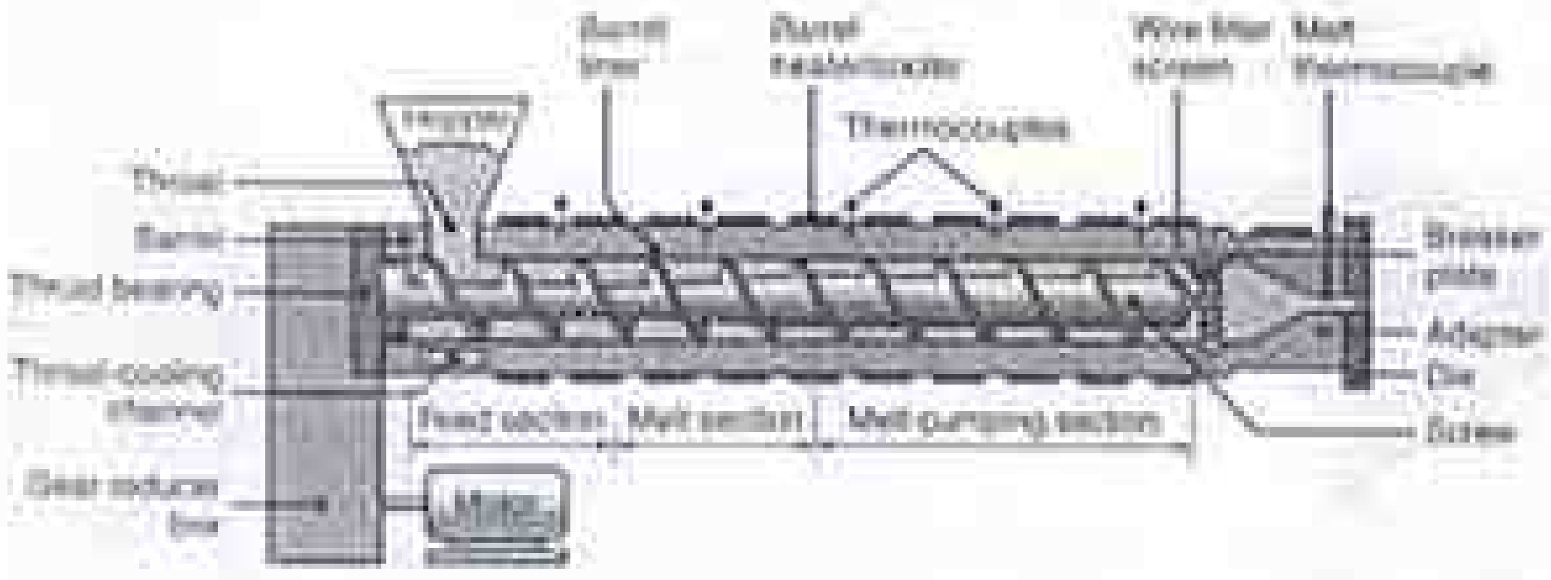


FIGURE 19.2 (a) Schematic illustration of a typical screw extruder.

19.2.1 Miscellaneous Extrusion Processes

There are several variations of the basic extrusion process for producing a number of different polymer products.

Plastic Tubes and Pipes. These are produced in an extruder with a spider die. Woven fiber or wire reinforcements also may be fed through specially designed dies in this operation, for the production of reinforced products to withstand higher pressures. The extrusion of tubes is also a first step for related processes, such as extrusion blow molding and blown film.

Rigid Plastic Tubing. Extruded by a process in which the die is rotated, rigid plastic tubing causes the polymer to be sheared and biaxially oriented during extrusion. As a result, the rube has a higher crushing strength and a higher strength-to-weight ratio than conventionally extruded tubing.

Coextrusion. Coextrusion involves simultaneous extrusion of two or more polymers through a single die; the product cross-section thus contains different polymers, each with its own characteristics and function. Coextrusion is commonly performed in shapes such as flat sheets, films, and tubes, and used especially in food packaging where different layers of polymers have different functions. These are: **(a)** providing inertness for food, **(b)** serving as barriers to fluids, such as water or oil, and **(c)** labeling of the product.

Plastic-coated Electrical Wire. Electrical wire, cable, and strips are simultaneously extruded and coated with plastic. The wire is fed into the die opening, at a controlled rate with the extruded plastic, in order to have a uniform coating on the wire. To ensure proper insulation, extruded electrical wires are checked continuously for their electrical resistance as they exit the die; the wire is also marked with ink using a roller to identify the specific type of wire. Plastic coated wire *paper clips* also are made by this coating process.

Polymer Sheets and Films. Sheet and film can be produced by using a specially designed flat extrusion die, such as that shown in Fig. 19.3a. Also known as a coat-hanger die, it is designed to distribute the polymer melt evenly throughout the width of the die opening. The polymer is extruded by forcing it through the die, after which the extruded sheet is taken up by rolls, first on water-cooled rolls (to cool the sheets), and then by a pair of rubber-covered pull-off rolls.

Thin Polymer Films. Common plastic bags and other thin polymer film products are made from blown film, which itself is made from a thin-walled rube produced by an extruder. In this process, a tube is extruded vertically, continuously pulled upward and expanded into a balloon shape, by blowing air through the center of the extrusion die until the desired film thickness is reached. Because of the molecular orientation of thermoplastics, a frost line develops on the balloon, which reduces its transparency.

The ratio of the blown diameter to the extruded tube diameter is called the blow ratio, which is about 3:1. Note that the polymer must have a high strain-rate sensitivity exponent, *m*, to successfully be blowm by this process without tearing.

Plastic Films. Plastic films, especially polytetrafluoroethylene (PTFE; trade name: Teflon), can be produced by shaving the circumference of a solid round plastic billet, with specially designed knives and in a manner similar to producing veneer from a large piece of round wood, in a process called **skiving**.

Pellets. Used as raw material lor other plastic-processing methods, pellets also are made by extrusion. A small-diameter, solid rod is extruded continuously, and then chopped into short lengths (pellets). With some modifications, extruders also can be used as simple melters for other shaping processes, such as injection molding and blow molding.

19.3 Injection Molding

Injection moldig is similar to hot-chamber die casting. Because the material is molten when injected into the mold, complex shapes with good dimensional accuracy can be obtained.

19.4 Blow Molding

In injection blow molding, a short tubular piece (**parison**) is injection molded in cool dies. The dies are then opened, and the parison is transferred to a blow-molding die using an indexing mechanism. Hot air is injected into the parison, expanding it to contact the walls of the mold cavity. Typical products made are plastic beverage bottles (generally made of polyethylene or polvetherther-ketone, PEEK) and small, hollow containers. A related process is **stretch blow molding**, in which the parison is expanded and elongated simultaneously, subjecting the polymer to biaxial stretching, and thus enhancing its properties.

Multilayer blow molding involves the use of coextruded tubes or parisons, and thus permits the production of a multilayer structure. A typical example of such a product is plastic packaging for food and beverages, having such characteristics as odor and permeation barrier, taste and aroma protection, scuff resistance, the capability of being printed, and the ability to be filled with hot fluids. Other applications of this process are for containers in the cosmetics and the pharmaceutical industries.

19.16 Economics of Processing Plastics and Composite Materials

The most expensive machines are for injection molding, followed by compression molding and transfer molding; tool and die costs also are high for these operations. Thus, in an operation like injection molding, the size of the die, and the optimum number of cavities in the die for producing more and more parts in one cycle are important considerations as they are in an operation like die casting. Larger dies may be considered in order to accommodate several cavities (with runners to each cavity), but at the expense of increasing die cost even further. On the other hand, more parts will be produced per machine cycle, thus the production rate will increase.

A detailed analyis is thus required in order to determine the overall die size, the number of cavities in the die, and the machine capacity required to optimize the total operation, and to produce parts at minimum cost. Similar considerations also apply to all other processing methods described throughout this chapter.

SUMMARY

- Thermoplastics can be shaped by a variety of processes, including extrusion, molding, casting, and thermoforming, as well as by some of the processes used in metalworking. The raw material usually is in the form of pellets, granules, and powders.

- The high strain-rate sensitivity of thermoplastics allows extensive stretching in forming operations; thus, complex and deep parts can be produced easily. Thermosetting plastics generally are molded or cast, and they have better dimensional accuracy than forming thermoplastics.

- Fiber-reinforced plastics are processed into structural components using liquid plastics, prepregs, and bulk- and sheet-molding compounds. Fabricating techniques include various molding methods, filament winding, pulrrusion, and pulforming. The type and orientation of the fibers and the strength of the bond between fibers and matrix and between layers of materials are important considerations.

- The design of plastic parts must take into account their low strength and stiffness, and such physical properties as high thermal expansion and generally low resistance to temperature. Inspection techniques arc available to determine the integrity of these products.

- Processing of metal-matrix and ceramic-matrix composites continues to undergo significant developments, to ensure product integrity, reliability, and reduced costs. Metal-matrix composites are processed by liquid-phase, solid-phase, and two-phase processes. Ceramic-matrix composites can be processed by slurry infiltration, chemical synthesis, or chemical-vapor infiltration.

- The relevant factors in the economics of the operations described include the costs of the machinery, the level of controls, tooling, cycle times, and production rate and volume.

CHAPTER 20

RAPID-PROTOTYPING PROCESSES AND OPERATIONS

20.1 Introduction

In the development of a new product, there is invariably a need to produce a sample, or prototype, of a designed part or system before allocating large amounts of capital to new production facilities or assembly lines. The main reasons for this need are that the capital is very high and production tooling takes considerable time to prepare. Consequently, a working prototype is needed for design evaluation and troubleshooting before a complex product or system is ready to be produced and marketed.

- Rapid prototyping serves as an important tool for visualisation and for product concept verification.
- With suitable materials, the prototype itself can be used in subsequent manufacturing operations, to produce the final parts. Also called direct prototyping this approach can serve as an important manufacturing technology.
- Rapid-prototyping operations can be used in some applications to produce actual tooling for manufacturing: thus, one can make tooling in a matter of a few days.

Rapid-prototyping processes can be classified into three major groups:

1. Subtractive, removing material from a workpiece that is larger than the final part
2. Additive, building up a part by adding material incrementally
3. Virtual, using advanced computer-based visualization technologies

Characteristics of Additive Rapid-prototyping Technologies

Process	Supply phase	Layer creation technique	Type of phase change	Materials
Stereolithography	Liquid	Liquid layer curing	Photopolymerization	Photopolymers (acrylates, epoxies, colorable resins, and filled resins)
Multi Jet/PolyJet modeling	Liquid	Liquid layer curing	Photopolymerization	Photopolymers
Fused-deposition modeling	Solid	Extrusion of melted polymer	Solidification by cooling	Polymers (such as ABS, polycarbonate, and polysulfone)
Ballistic-particle manufacturing	Liquid	Droplet deposition	Solidification by cooling	Polymers and wax
Three-dimensional printing	Powder	Binder-droplet deposition onto powder layer	No phase change	Ceramic, polymer, metal powder, and sand
Selective laser sintering	Powder	Layer of powder	Sintering or melting	Polymers, metals with binder, metals, ceramics and sand with binder
Electron-beam melting	Powder	Layer of powder	Melting	Titanium and titanium alloys, cobalt chrome
Laminated-object manufacturing	Solid	Deposition of sheet material	No phase change	Paper and polymers
Laser-engineered net shaping	Powder	Injection of powder stream	No phase change	Titanium, stainless steel, aluminum

20.3 Additive Processes

Additive rapid-prototyping operations all build parts *in layers*. These processes consist of *stereolithography, Multi Jet/PolyJet modeling, fused-deposition modeling, ballistic-particle manufacturing, three-dimensional printing, selective laser sintering, electron-beam melting,* and *laminated-object manufacturing*. In order to visualize the methodology employed, it is beneficial to think of the construction of a loaf of bread, by stacking and bonding individual slices of bread on top of each other (hence the term additive). The main difference between the various additive processes lies in the method of producing the individual slices although they can be thicker in some systems.

20.3.1 Fused-deposition Modeling

In the *fused-deposition-modeling* (FDM) process, a gantry-robot controlled extruder head moves in two principal directions over a table, which can be raised and lowered as required. The extruder head is heated, and extrudes polymer filament at a constant rate through a small orifice. The head follows a predetermined path; the extruded polymer bonds to the previously deposited layer. (The initial layer is placed on a foam foundation.) When the first layer is completed, the table is lowered so that subsequent layers can be superimposed over the first layer. When the part is finished, it can be easily removed from the loam base.

Complex parts may be difficult to build up directly, because once the part has been constructed up to height, the next slice would require the filament to be placed at a location where no material exists underneath to support it. The solution is to extrude a support material separately from the modeling material. Note that the use of such support structures allows all of the layers to be supported by the material directly beneath them. The support material is produced with a less dense filament spacing on a layer, so that it is weaker than the model material and can thus be broken off easily after the part is completed.

A variety of polymers are available for different applications. *Flat wire metal deposition* uses a metal wire, instead of a polymer filament, but also requires a laser to heat and bond the deposited wire to build parts.

Close examination of an FDM-produced part will indicate that a stepped surface exists on oblique exterior planes. If this surface roughness is objectionable, a heated tool can be used to smoothen the surface, or it can be hand sanded, or a coating can be applied, often in the form of a polishing wax. However, the overall tolerances may then be compromised unless care is taken in these finishing operations.

Although some commercial FDM machines can be obtained for around $20,000, others can cost as much as $300,000. Some self-replicating machines are based on FDM and can cost around $1000. The main differences among them are the maximum size of the parts that can be produced and the numbers and types of materials that can be used.

20.3.2 Stereolithography

A common rapid-prototyping process one that actually was developed prior to FDM, is *stereolithography (STL)*. This process is based on the principle of curing (hardening) of a liquid photopolymer into a specific shape. A vat, containing a mechanism whereby a platform can be lowered and raised, is filled with a photocurable liquid-acrylate polymer. The liquid is a mixture of acrylic monomers, oligomers (polymer intermediates), and a photoinitiator (a compound that undergoes a reaction upon absorbing light).

At the highest position of the platform, a shallow layer of liquid exists above the platform. A laser, generating an ultraviolet (UV) beam, is focused upon a selected surface area of the photopolymer, and then moved around in the x-y plane. The beam cures that portion of the photo-polymer (say, a ring-shaped portion), and thereby produces a layer of the solid body. The platform is then lowered sufficiently to cover the cured polymer with another layer of liquid polymer, and the sequence is repeated. The process is repeated until level ***b*** in Fig. 20.6 is reached. Thus far, a cylindrical part with a constant wall thickness has been generated. Note that the platform is now lowered by a vertical distance ***ab***.

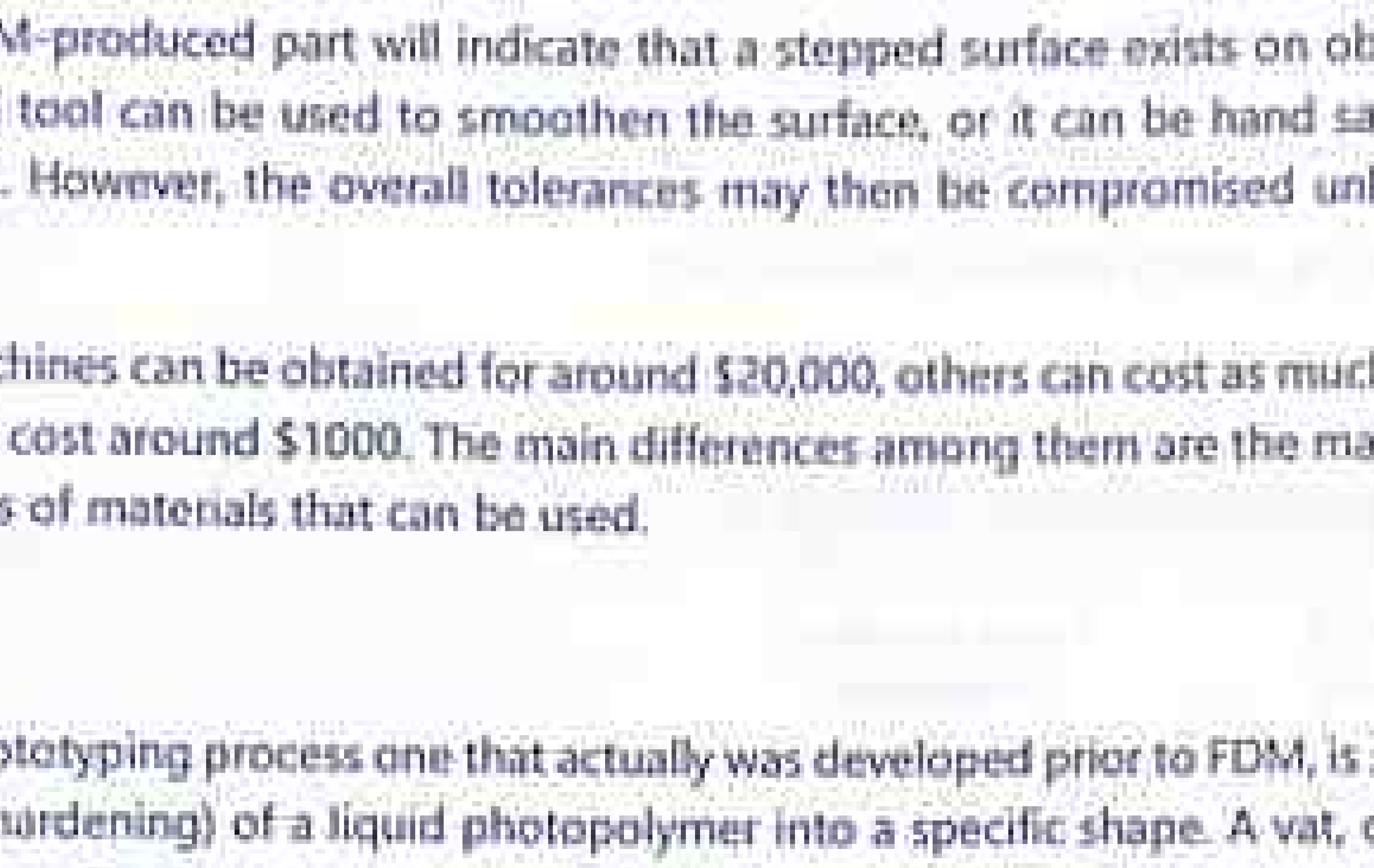


FIGURE 20.6

At level ***b***, the x-y movements of the beam define a wider geometry, thus a flange-shaped portion is being produced over the previously formed segment. After the proper thickness of the liquid has been cured, the process is repeated, producing another cylindrical section between levels ***b*** and ***c***. Note that the surrounding liquid polymer is still fluid (because it has not been exposed to the UV beam), and that the part has been produced from the bottom up in individual "slices." The unused portion of the liquid polymer can be used again to make another part or another prototype.

Note that the term "stereolithography," as used to describe this process, comes from the facts that the movements a three dimensional (hence the word stereo) and the process is similar to lithography, in which the image to be printed on a flat surface is ink receptive and the blank areas are ink repellent. Note also that, as in FDM, stereolithography can require a weaker support material. In stereolithography, this support takes the form of perforated structures.

After its completion, the part is removed from the platform, blotted, and cleaned ultrasonically and with an alcohol bath. Then the support structure is removed, and the part is subjected to a final curing cycle in an autoclave. The smallest tolerance that can be achieved in stereolithography depends on the sharpness of the focus of the laser. Oblique surfaces also can be produced with high quality.

Stereolithography has been used with highly focused lasers to produce parts with micrometer-sized features. The use of the optics required to produce such features necessitates thinner layers and lower volumetric cure rates. When stereolithography is used to fabricate micromechanical systems, it is called microstereolithography.

20.3.3 MultiJet/PolyJet Modeling

The Multi jet modeling (MJM) or *PolyJet process* is similar to ink-jet printing, where print heads deposit the photopolymer on the build tray. Ultraviolet bulbs, alongside the jets, instantly cure and harden each layer, thus eliminating the need for any postmodeling curing (that is needed in stereolithography). The result is a smooth surface of layers as thin as 16 μm that can be handled immediately after the process is completed.

20.3.4 Selective Laser Sintering

Selective laser sintering (SLS) is a process based on the sintering of non-metallic or, less commonly, metallic powders selectively into an individual object. The bottom of the processing chamber is equipped with two cylinders:

1. A powder-feed cylinder, which is raised incrementally to supply powder to the part-build cylinder, through a roll mechanism
2. A part-build cylinder, which is lowered incrementally as the part is being formed

A thin layer of powder is first deposited in the part-build cylinder. Then a laser beam, guided by a process-control computer using instructions generated by the three-dimensional CAD program of the desired part, is focused on that layer, tracing and sintering a particular cross-section into a solid mass. The powder in other areas remains loose, but it supports the sintered portion. Another layer of powder is then deposited; this cycle is repeated again and again until the entire three-dimensional part has been produced.

A variety of materials can be used in this process, including polymers (such as ABS, PVC, nylon, polyester, polystyrene, and epoxy), wax, metals, and ceramics, with appropriate binders. It is most common to use polymers because of the smaller, less expensive, and less complicated lasers required for sintering. With ceramics and metals, it is a common practice to sinter only a polymer binder that has been blended with the ceramic or metal powders. If desired, the part can be sintered again in a furnace and infiltrated with another metal.

20.3.5 Electron-beam Melting

A process similar to selective laser sintering and electron-beam welding, electron-beam, or E-beam, melting uses the energy source associated with an electron beam to melt titanium or cobalt-chrome powder to make metal prototypes. The workpiece is produced in a vacuum, thus part size is limited to around 200 mm x 200 mm x 180 mm. Although applied mainly to titanium and cobalt-chrome to date, the process is being developed for stainless steels, aluminum, and copper alloys.

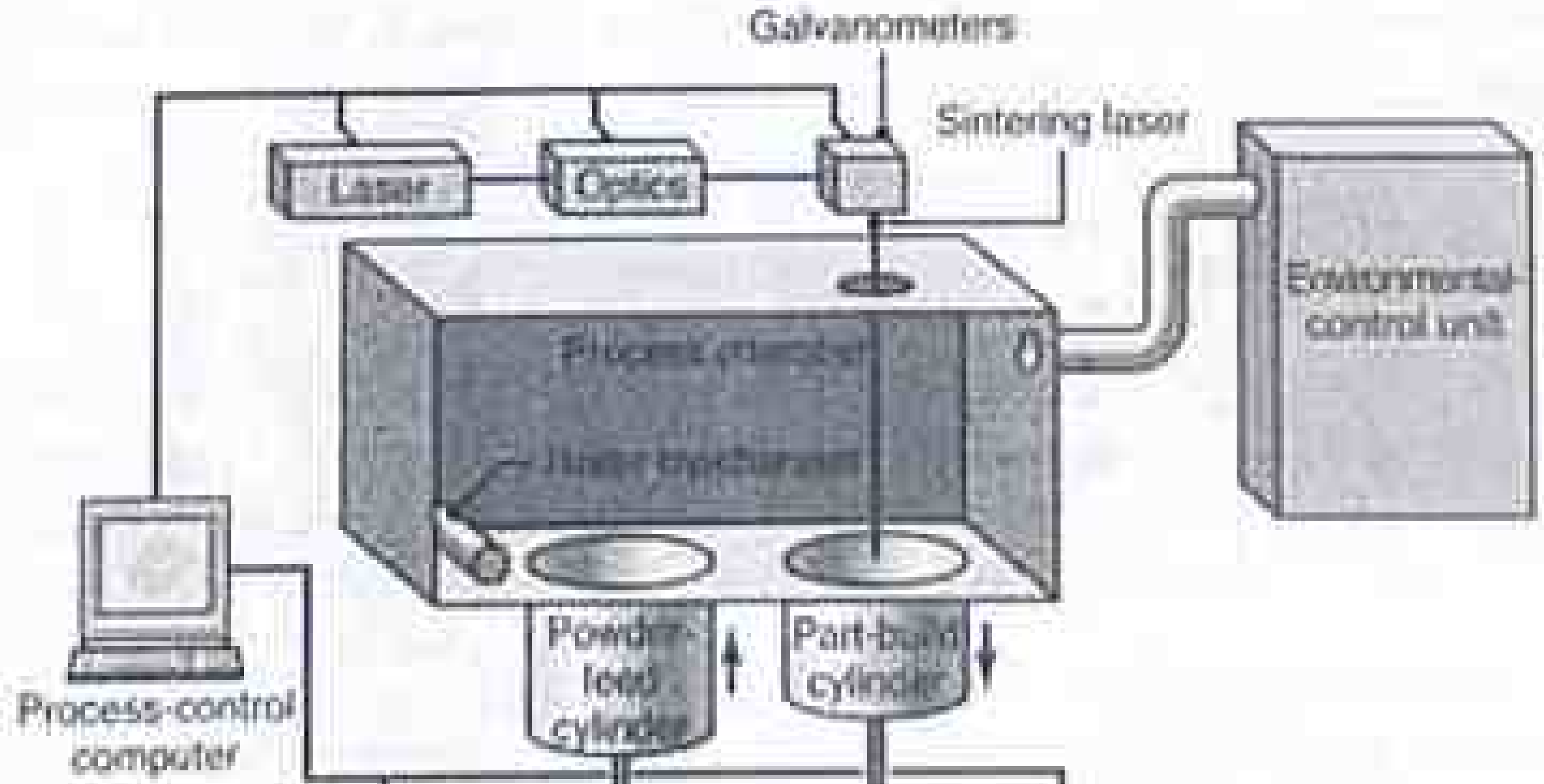


FIGURE 20.8 Schematic illustration of the selective-laser sintering process.

20.3.6 Three-dimensional Printing

In the three-dimensional-printing (3DP) process, a print head deposits an inorganic binder material onto a layer of polymer, ceramic, or metallic powder. A piston, supporting the powder bed, is lowered incrementally, and with each step, a layer is deposited and then fused by the binder.

Multi Jet modeling and PolyJet processes are sometimes referred to as three-dimensional printing technologies, because they operate similarly to inkjet printers, but incorporate a third (thickness) direction. In fact, 3DP has been used interchangeably with rapid prototyping or digital manufacturing to include all rapid prototyping operations; however, 3DP is most commonly associated with printing a binder onto powder.

Three-dimensional printing allows considerable flexibility in the materials and binders used. Commonly used powder materials are blends of polymers and fillers, foundry sand, and metals. Furthermore, since multiple binder print heads can be incorporated into one machine, it is possible to produce full-color prototypes by having different-color binders. The effect is a three-dimensional analog to printing photographs, using three ink colors (red, cyan, and blue) on an ink-jet printer.

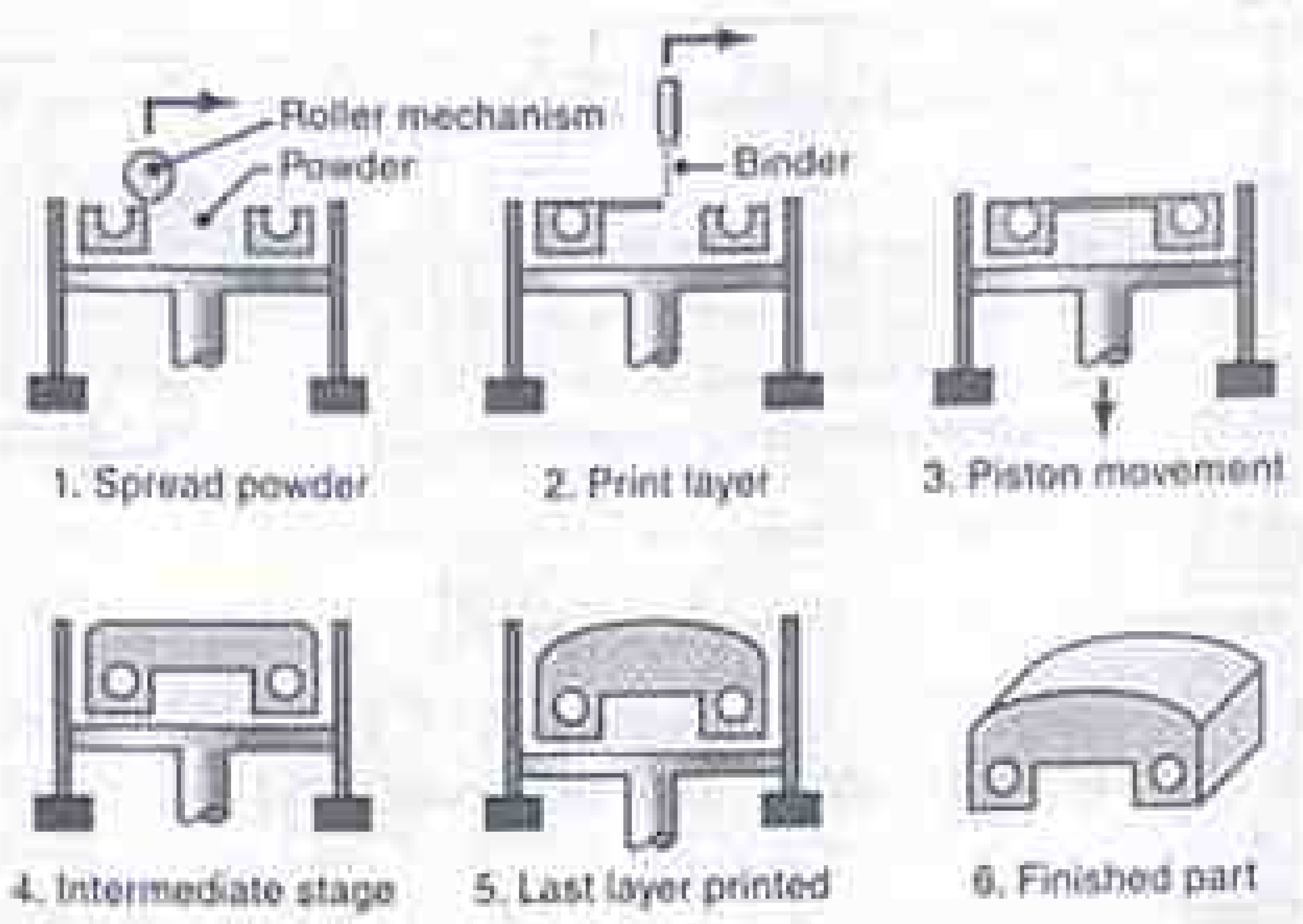


FIGURE 20.9 Schematic illustration of the three-dimensional-printing process.

20.3.7 Laminated-object Manufacturing

Lamination involves laying down layers that are bonded adhesively to one another. Several variations of laminated-object manufacturing (LOM) are available. The simplest and least expensive versions of LOM involve using control software and vinyl cutters to produce the prototype. Vinyl cutters are simple CNC machines that cut shapes from vinyl or paper sheets. Each sheet has a number of registration holes, which allow proper alignment and placement onto a build fixture. LOM systems are highly economical and are popular in schools and universities, because of the hands-on demonstration of additive manufacturing and production of parts by layers.

LOM systems can also be elaborate, where the more advanced systems use layers of paper or plastic, with a heat-activated glue on one side to produce parts. The shapes are burned into the sheet with a laser, and the parts are built layer by layer. On some systems, the excess material must be removed manually once the part is completed. Removal is simplified by programming the laser to burn perforations in crisscrossed patterns. The resulting grid lines make the part appear as if it had been constructed from gridded paper, with squares printed on it, similar to graph paper.

20.3.8 Laser-engineered Net Shaping

More recent developments in additive manufacturing processes involve the principle of using a laser beam to melt and deposit metal powder or wire, again layer by layer, over a previously molten layer. The patterns of deposited layers are controlled by a CAD file. This near-net-shaping process is called *laser-engineered net shaping* (LENS, a trade name), and is based on the technologies of laser-beam welding and cladding. The heat input and cooling are controlled precisely to develop a favorable microstructure.

The deposition process is carried out inside a closed area and in an argon environment, to avoid the adverse effects of oxidation, particularly on aluminum. It is suitable for a wide variety of metals and specialty alloys, for the direct manufacturing of parts, including fully dense tools and molds. It can also be used for repairing thin and delicate components. There are other, similar processing methods using lasers, including *controlled-metal buildup* (CMB) and *precision-metal deposition* (PMD).

20.6 Direct Manufacturing and Rapid Tooling

While extremely beneficial as a demonstration and visualization tool, rapid-prototyping processes also have been used as a manufacturing step in actual production. There are two basic methodologies used:

1. Direct production of engineering metal, ceramic, and polymer components or parts, by rapid prototyping
2. Production of tooling or patterns by rapid prototyping, for use in various manufacturing operations

The main limitations to the widespread use of rapid prototyping for direct manufacturing, or rapid manufacturing, are:

- Raw-material costs are high, and the time required to produce each part is too long to be viable for large production runs; however, there are many applications in which production runs are sufficiently small to justify direct manufacturing.
- The long-term and consistent performance of rapidly manufactured parts (as compared with the more traditional methods of manufacturing them) may be suspect, especially with respect to fatigue, wear, and life cycle of the parts made.

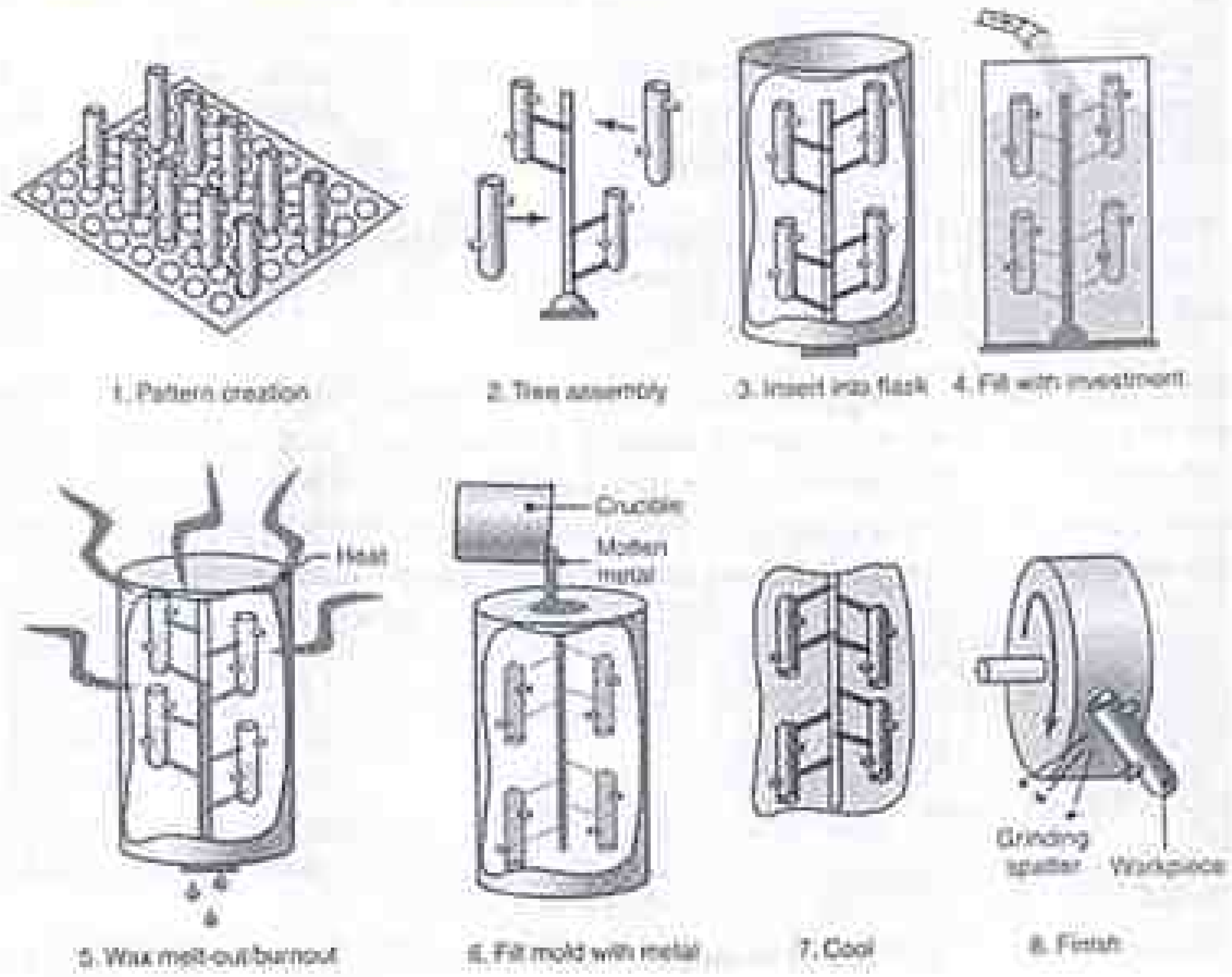


FIGURE 20.18 Manufacturing steps for investment casting with rapid-prototyped wax parts as blanks; this method uses a flask for the investment, but a shell method also can be used.

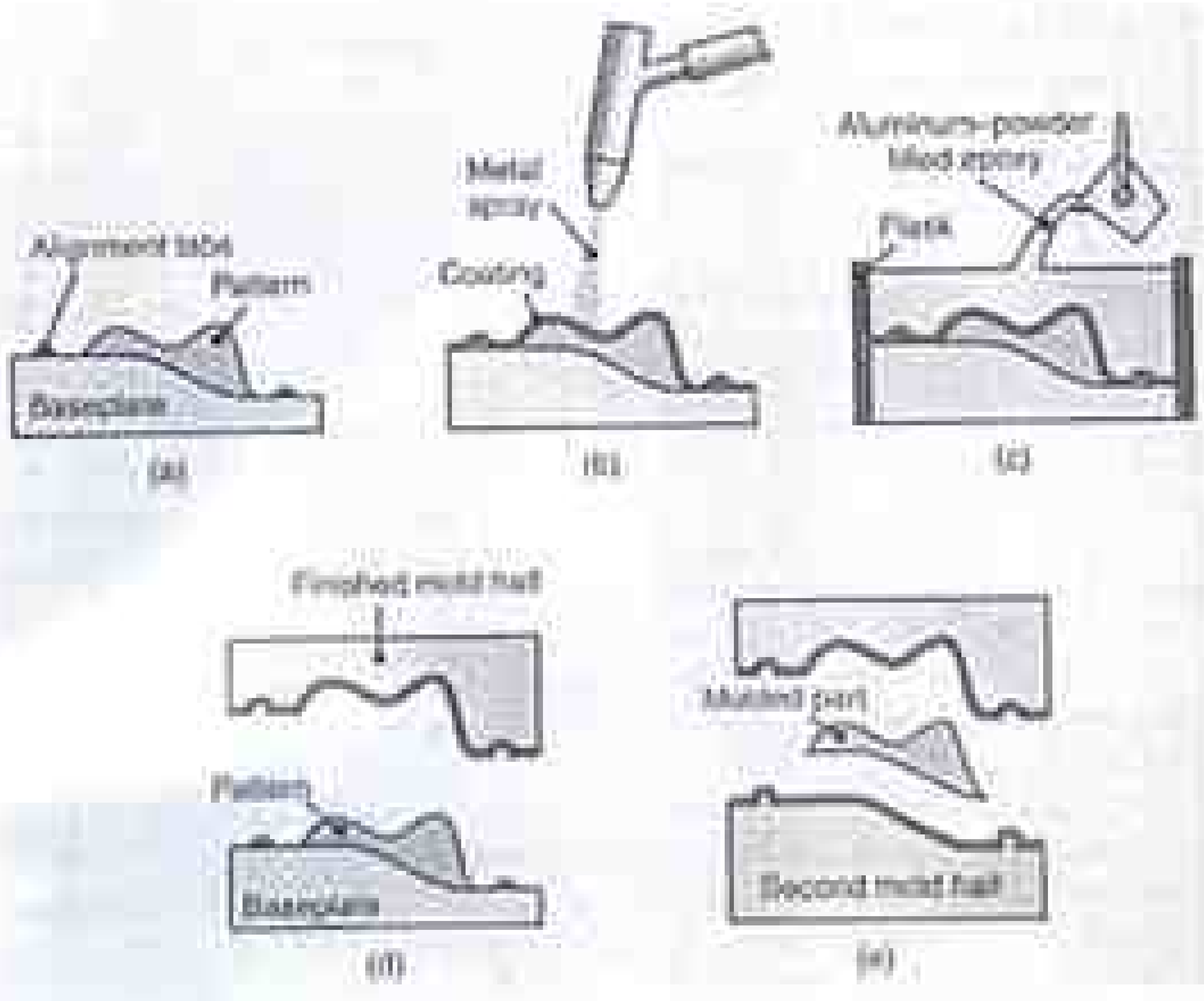


FIGURE 20.19 Production of tooling for injection molding by the sprayed-metal tooling process. (a) A pattern and baseplate are prepared through a rapid-prototyping operation; (b) a zinc-aluminum alloy is sprayed onto the pattern; (c) the coated baseplate and pattern assembly are placed together in a flask and backfilled with aluminum-impregnated epoxy; (d) after curing, the baseplate is removed from the brushed mold; and (e) a second mold half suitable for injection molding is prepared.

SUMMARY

- Rapid prototyping continues to grow into a unique manufacturing discipline. As a physical-model producing technology, it is a useful technique for identifying and correcting design errors. Several techniques have been developed for producing parts through rapid prototyping.

- Fused-deposition modeling consists of a computer-controlled extruder, through which a polymer filament is deposited to produce a part slice by slice.

- Stereolithography involves a computer-controlled laser-focusing system that cures a liquid thermosetting polymer containing a photosensitive curing agent.

- Multijet and PolyJet modeling use mechanisms similar to ink-jet printer heads to eject photopolymers to directly build prototypes.

- Laminated-object manufacturing uses a laser beam or vinyl cutter to first cut the slices on paper or plastic sheets (laminations); then it applies an adhesive layer, if necessary, and finally stacks the sheets to produce the part.

- Three-dimensional printing uses an ink-jet mechanism to deposit liquid droplets of the liquid binder onto polymer, metal, or ceramic powders. The related process of ballistic particle manufacturing directly deposits the build material. Using multiple printheads, three-dimensional printing can also produce full-color prototypes.

- Selective laser sintering uses a high-powered laser beam to sinter powders or coatings on the powders in a desired pattern. Selective laser sintering has been applied to polymers, sand, ceramics, and metals. Electron-beam melting uses the power of an electron beam to melt powders and form fully-dense functional parts.

- Rapid-prototyping techniques have made possible much faster product development times, and they are having a major effect on other manufacturing processes. When appropriate materials are used, rapid-prototyping machinery can produce blanks for investment casting or similar processes, so that metallic parts can now be obtained quickly and inexpensively, even for lot sizes as small as one part. Such technologies also can he applied to producing molds for operations (such as injection molding, sand and shell mold casting, and even forging), thereby significantly reducing the lead time between design and manufacture.

CHAPTER 21

Fundamentals of Machining

2.1: Introduction:

Cutting processes remove material from the various surfaces of a workpiece by producing chips.

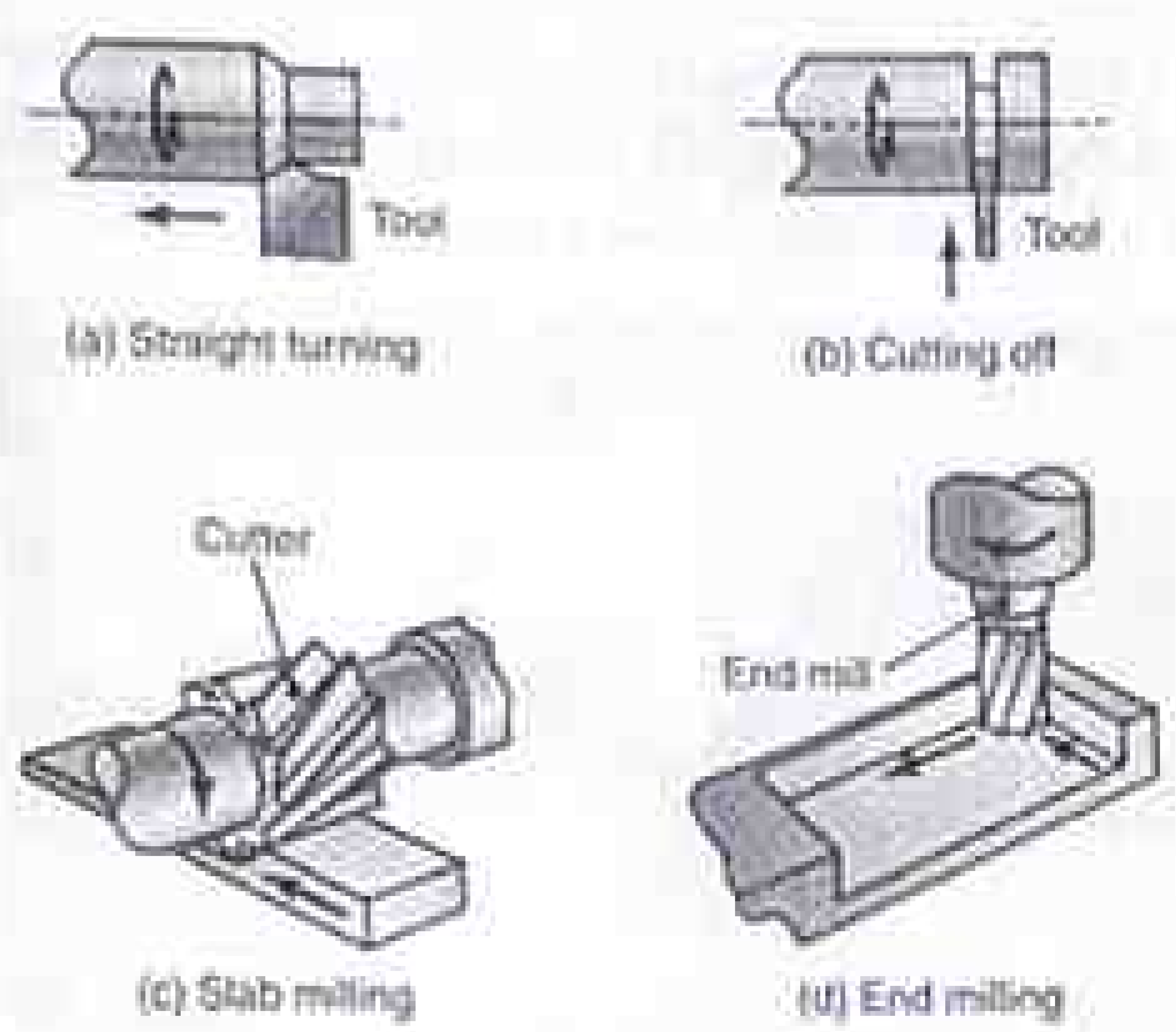


FIGURE 21.1 Some examples of common machining operations.

21.2: Mechanics of Cutting

The major independent variables in the basic cutting process are:

a) Tool material and coatings. (kaplama)
b) Tool shape, surface finish and sharpness
c) Workpiece material and its processing history
d) Cutting speed, feed and depth of cut
e) Cutting fluid
f) Characteristics of the machine tool
g) The type of work-holding device and fixturing.

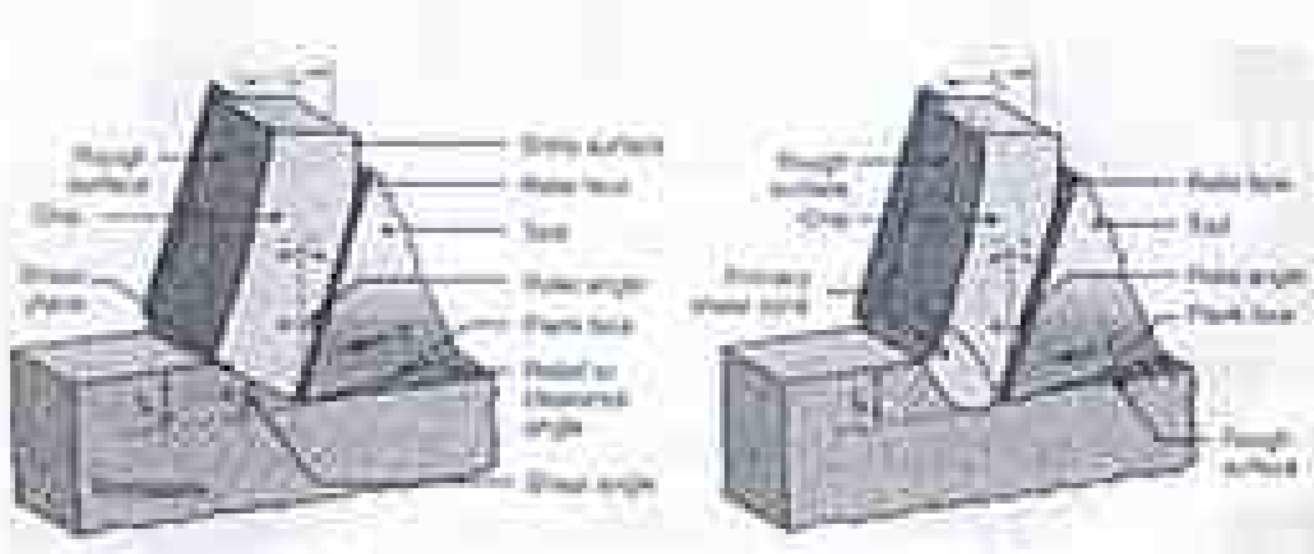


FIGURE 21.3 Schematic illustration of a two-dimensional cutting process, also called orthogonal cutting. (a) Orthogonal cutting with a well-defined shear plane, also known as the M.E. Merchant model. Note that the tool shape, the depth of cut, t_o and the cutting speed, V, are all independent variables. (b) Orthogonal cutting without a well-defined shear plane.

Dependent variables in cutting which are influenced by changes made in the independent variables.

Dependent variables:

a) Type of chip produced
b) Force and energy dissipated during cutting
c) Temperature rise in the workpiece, the tool and the chips
d) Tool wear and failure
e) Surface finish and surface integrity of the workpiece

Cutting Ratio: The chip thickness, t_c can be determined from the depth of cut, t_o, the rate angle α, the shear angle Φ.

Cutting Ratio (Chip Thickness Ratio) $= \frac{t_o}{t_c}$

$$\tan\phi = \frac{r\cos\alpha}{1 - r\sin\alpha}$$

$$r = \frac{t_o}{t_c} = \frac{\sin\phi}{\cos(\phi - \alpha)}.$$

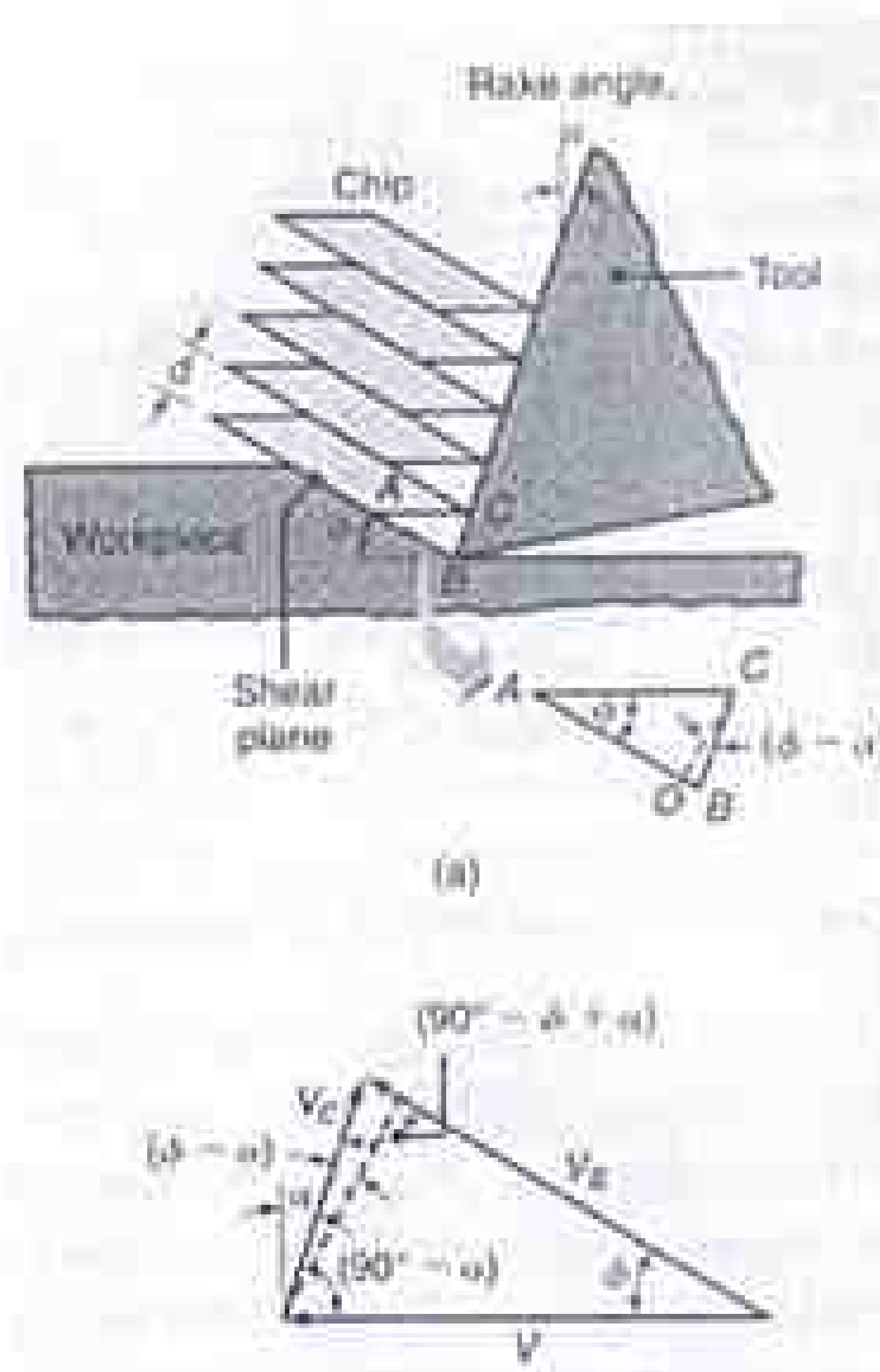


FIGURE 21.4 (a) Schematic illustration of the basic mechanism of chip formation by shearing. b) Velocity diagram showing angular relationships among the three speeds in the cutting zone.

$$\emptyset = 45 + \frac{\alpha}{2} - \frac{\beta}{2}$$

$$\mu(Coefficient\ of\ Friction) = \tan\beta$$

Types of Chips:

1. **Continuous**
2. **Built-Up Edge**
3. **Serrated or Segmented**
4. **Discontinuous**

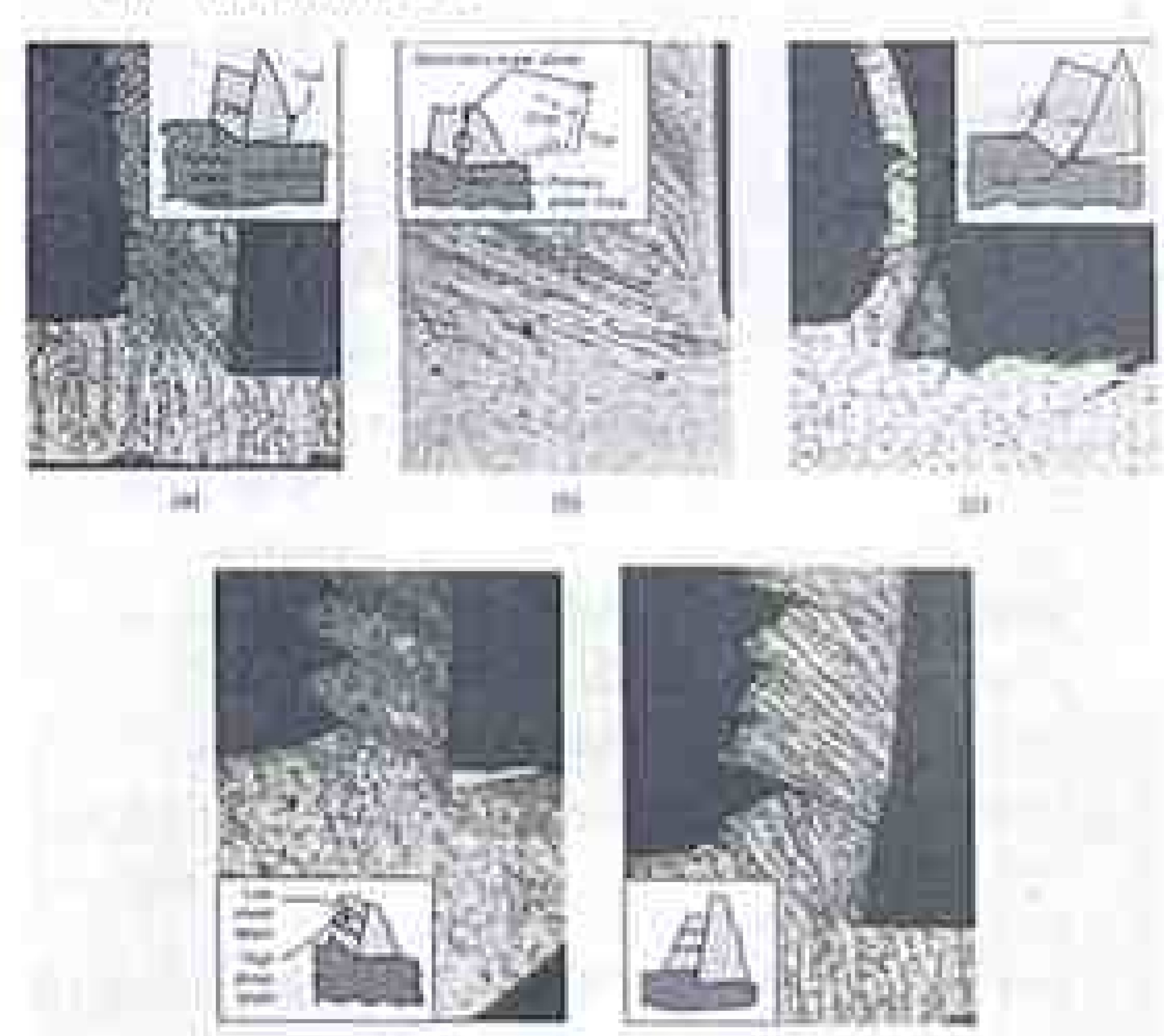


FIGURE 21.5 (a) continuous chip, with narrow, straight, and primary shear zone; (b) continuous chip, with secondary shear zone at the chip-tool interface; (c) built-up edge; (d) segmented or nonhomogeneous chip; and (e) discontinuous chip.

Continuous Chip:

- Formed with ductile materials
- Machined at high cutting speeds and high rake angle

Primary Shear Zone = Deformation of the material takes place along a narrow shear zone.

Secondary Shear Zone = Due to high friction at tool-chip interface.

By friction increase, this zone become thicker

- Although they produce good surface finish, they tend to become tangled (karmakarışık) around the tooldholder, the fixturing and the workpiece.

Built-Up Edge Chips:

- Consisting of layers of material from workpiece that gradually are deposited on the tool tip.
- As BUE grows larger, BUE becomes unstable, and eventually breaks apart.

The tendency for BUE formation can be reduced by one or more of following means.

1. Increase the cutting speed
2. Decrease the depth of cut
3. Increase the rake angle
4. Use a cutting tool that has lower chemical affinity for the workpiece material or use a sharp tool
5. Use an effective cutting tool

Serrated Chips:

- Also called segmented/nonhomogeneous chips.
- They are semicontinuous chips with large zones of low shear strain and small zones of high shear strain, hence the latter zone is called shear localization.
- The chips have a sawtooth-like apperance

Discontinuous Chips:

Discontnuous chips consist of segments, attached either firmly or loosely to each other. Discontinuous chips usually form under the following conditions:

1. Brittle workpiece materials, because they do not have the capacity to undergo the high shear strains encountered in machining
2. Workpiece materials that contain hard inclusions and impurities, or have structures
3. Very low or very high cutting speed, V
4. Large depth of cut, d
5. Low rake angle, ∝
6. Lack of an effective cutting fluid
7. Low stiffness of the toolholder or the machine tool, thus allowing vibration and chatter to occur.

Chip Breakers. Continuous and long chips are undesirable in machining operations, as they tend to become entangled, severely interfere with machining operations, and can also become a potential safety hazard. If all of the processing variables are under control, the usual procedure employed to avoid such a situation is to break the chip intermittently, with shapes of cutting tools that have chip-breaker features, as shown in Fig. 21.7.

The basic principle of a chip breaker on a tools rake face is to bend and break the chip periodically. Chips also can be broken by changing the tool geometry to control chip flow, as in the turning operations show n in Fig. 21.8.

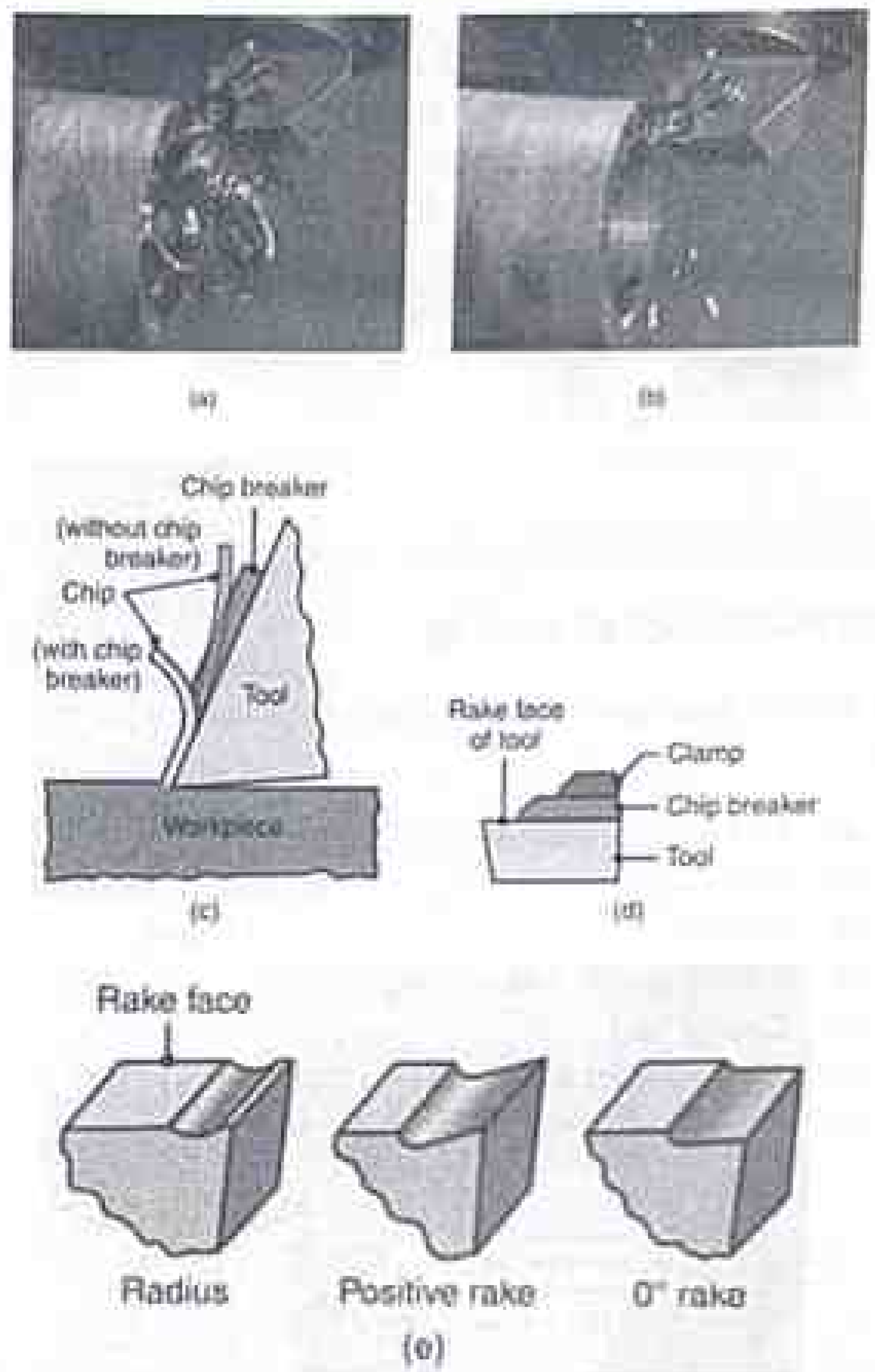


FIGURE 21.7 (a) Machining of aluminum using an insert without a chip breaker; note the long chips that can interfere with the tool and present a safety hazard. (b) Machining of aluminum with a chip breaker. (c) Schematic illustration of the action of a chip breaker; note that the chip breaker decreases the radius of curvature of the chip and eventually breaks it. (d) Chip breaker clamped on the rake face of a cutting tool. (e) Grooves in cutting tools acting as chip breakers. Most cutting tools now used are inserts with built-in chip-breaker features.

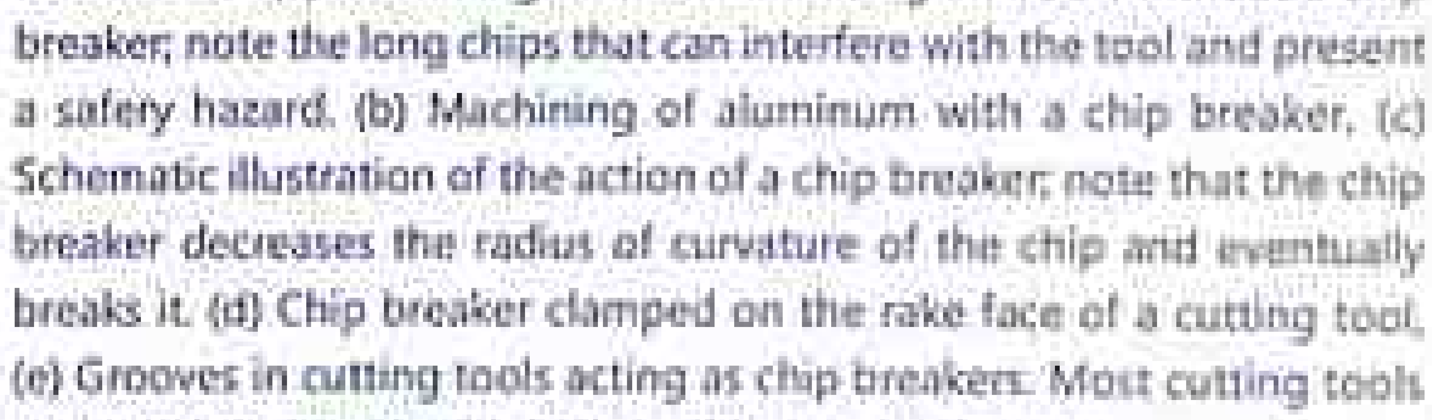


FIGURE 21.8 Chips produced in turning: (a) tightly curled chip; (b) chip hits workpiece and breaks off; (c) continuous chip moving radially away from workpiece; and (d) chip hits tool shank and breaks off.

21.2.2 Oblique Cutting

Shaving and Skiving. Thin layers of material can be removed from straight or curved surfaces by a process similar to the use of a plane to shave wood. Sharing is particularly useful in improving the surface finish and dimensional accuracy of sheared sheet metals and punched slugs. Another common application of shaving is in finishing gears, using a cutter that has the shape of the gear tooth. Parts that are long or have complex shapes are shaved by *skiving*, using a specially shaped cutting tool that moves tangentially across the length of the workpiece.

Shaving = Amaç pürüzsüz yüzey elde etmek. (Gear shaving with gear)

Skiving = Shaving'in diğer hali for complex workpieces.

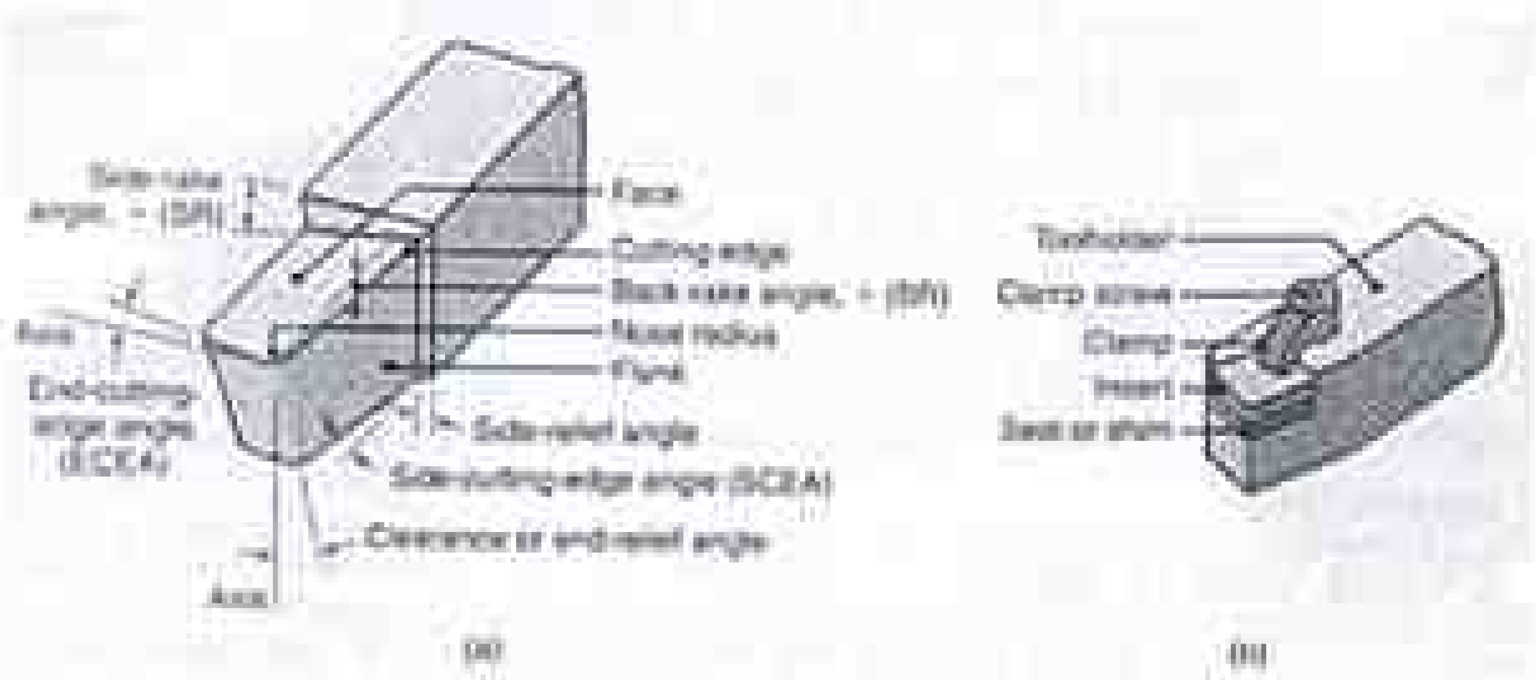


FIGURE 21.10 (a) Schematic illustration of a right-hand cutting tool. The various angles on these tools and their effects on machinin. Although these tools traditionally have been produced from solid tool-steel bars, they have been replaced largely with (b) inserts made of carbides and other materials of various shapes and sizes.

21.3 Cutting Forces and Power

The forces acting in orthogonal cutting are shown in Fig. 21.11a. The cutting force, F_c, acts in the direction of the cutting speed, V, and supplies the energy required for cutting. The ratio of the cutting force to the cross-sectional area being cut (i.e., the product of width of cut and depth of cut) is referred to as the *specific cutting force*.

The **thrust force**, F_t, acts in a direction normal to the cutting force. These two forces produce the **resultant force**, R, as can be seen from the force circle diagram shown in Fig. 21.11b. Note that the resultant force can be resolved into two components on the tool face: a **friction force**, F, along the tool-chip interface, and a **normal force**, N, perpendicular to it. It can also be shown that

$$F = R \sin\beta$$

$$N = R \cos\beta.$$

Note that the resultant force is balanced by an equal and opposite force along the shear plane, and is resolved into a **shear force**, F_s, and a **normal force**, F_n. These forces can be expressed, respectively, as

$$F_s = F_c \cos\phi - F_t \sin\phi$$

$$F_n = F_c \sin\phi + F_t \cos\phi.$$

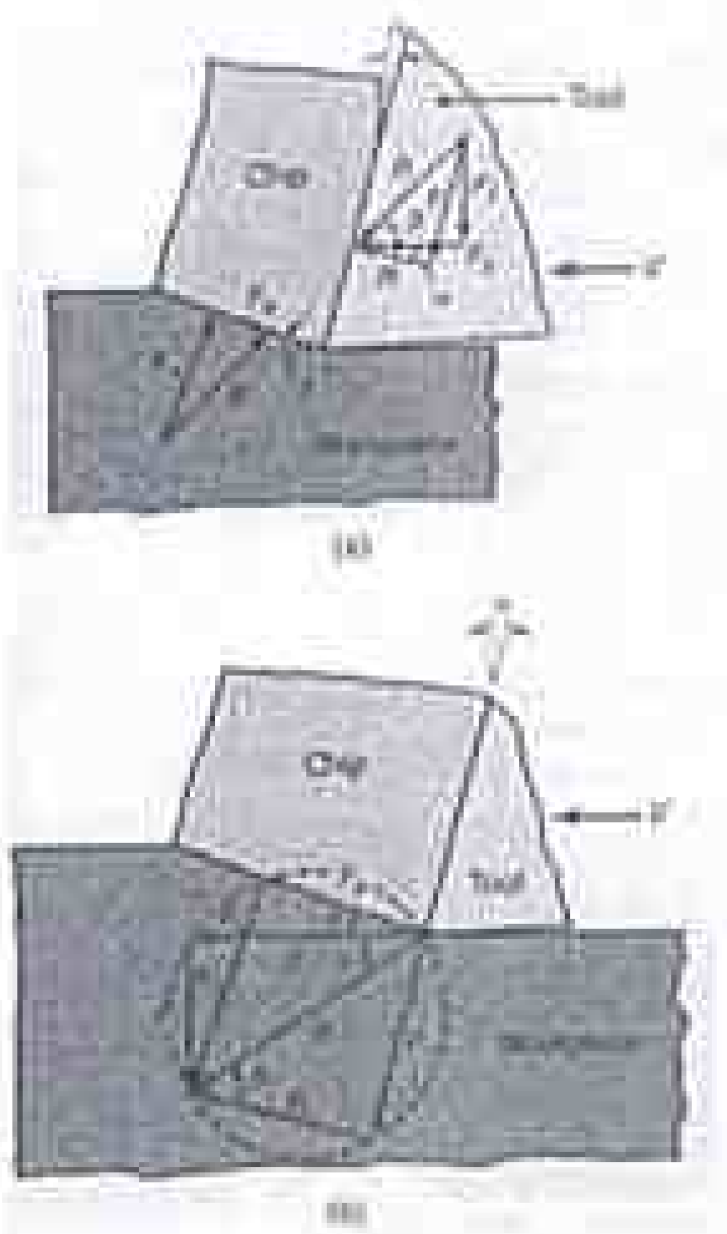


FIGURE 21.11 (a) Forces acting in the cutting zone during two-dimensional cutting; note that the resultant force, R, must be colinear to balance the forces. (b) Force circle to determine various forces acting in the cutting zone.

Thrust Force. The *thrust force* in cutting is important because the toolholder, the work-holding devices, and the machine tool itself must be sufficiently stiff to support that force, with minimal deflections. For example, if the thrust force is too high or if the machine tool is not sufficiently stiff, the tool will be pushed away from the workpiece surface being machined. This movement will, in turn, reduce the depth of cut, resulting in poor dimensional accuracy of the machined part.

Measuring Cutting Forces and Power. Cutting forces can be measured using a force transducer (typically with quartz piezoelectric sensors), a dynamometer, or a load cell (with resistance-wire strain gages placed on octagonal rings) mounted on the cutting-tool holder. It is also possible to calculate the cutting force from the power consumption during cutting.

21.4 Temperatures in Cutting

As in all metalworking processes where plastic deformation is involved, the energy dissipated in cutting is converted into *heat* which, in turn, raises the temperature in the cutting zone and the workpiece surface. *Temperature rise* is a very important factor in machining because of its major adverse effects:

- Excessive temperature lowers the strength, hardness, stiffness, and wear resistance of the cutting tool; tools also may soften and undergo plastic deformation, thus altering the tool shape.
- Increased heat causes uneven dimensional changes in the part being machined, depending on the physical properties of the material, thus making it difficult to control its dimensional accuracy and tolerances.
- An excessive temperature rise can induce thermal damage and metallurgical changes in the machined surface, adversely affecting its properties.

21.5 Tool Life: Wear and Failure

The previous sections have shown that cutting tools are subjected to (a) high localized stresses at the tip of the tool; (b) high temperatures, especially along the rake face; (c) sliding of the chip at high speeds along the rake face; and (d) sliding of the tool along the newly machined workpiece surface. These conditions induce tool wear, a major consideration in all machining operations, as are mold and die wear in casting and metalworking processes. Tool wear adversely affects tool life, the quality of the machined surface and its dimensional accuracy, and, consequently, the economics of cutting operations.

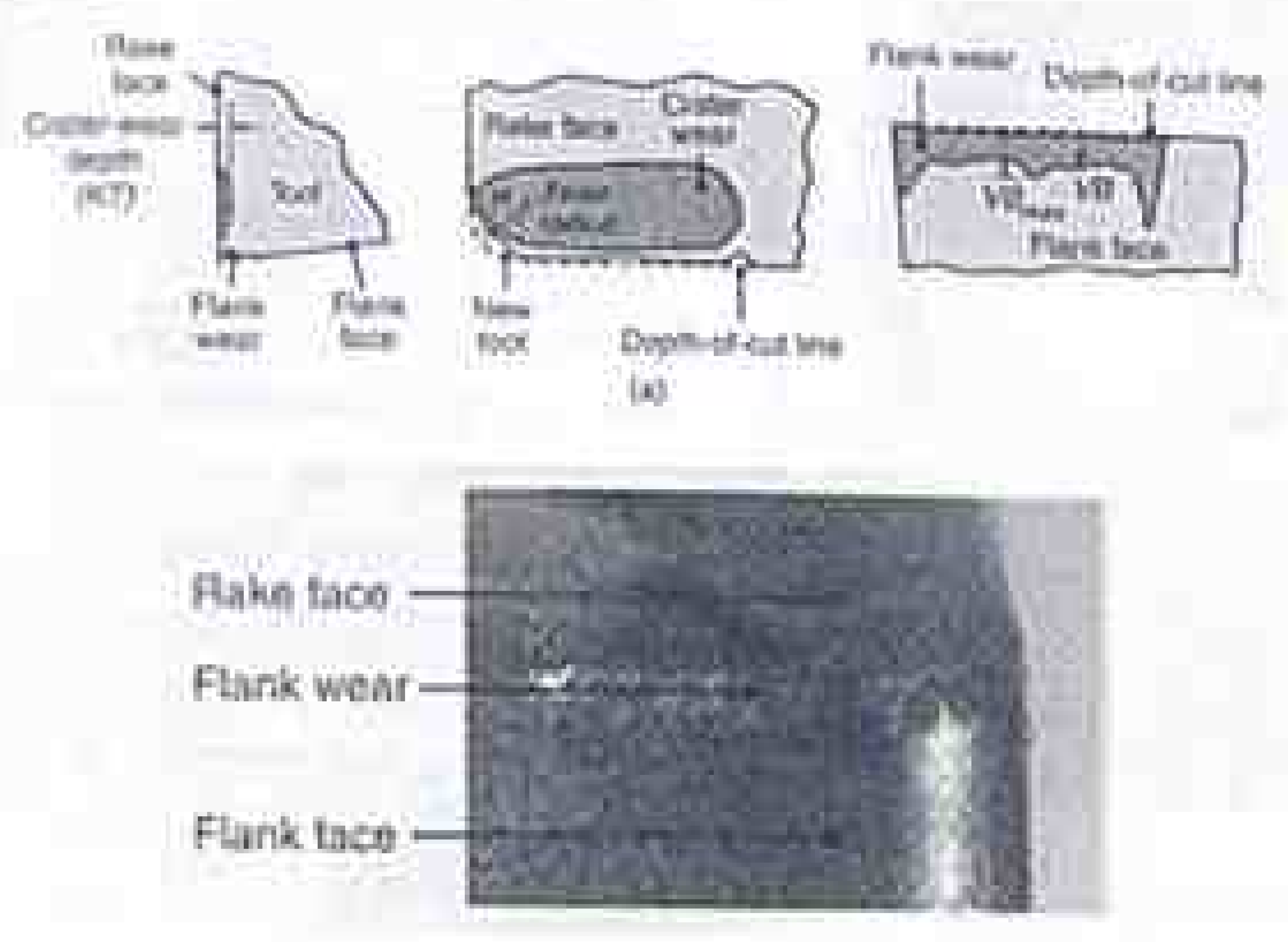


FIGURE 21.15 (a) Features of tool wear in a turning operations; the VB indicates average flank wear. (b) flank wear

21.5.1 Flank Wear

Flank wear occurs on the relief (flank) face of the tool, as shown in Figs. 21.15a and b. It generally is attributed to (a) rubbing of the tool along the machined surface, thereby causing adhesive or abrasive wear and (b) high temperatures, which adversely affect tool-material properties.

In a classic study by F.W. Taylor (1856-1915) on the machining of steels conducted in the early 1890s, the following approximate relationship for tool life, known as the *Taylor tool-life equation*, was established:

$$VT^n = C$$
$$T = (C/V)^{1/n}$$

V: Cutting Speed
T:Tool Life(min)
n: Depends on Tool Material
C: Depends on Workpiece Material

The most important variable associated with tool life is cutting speed, followed by depth of cut and feed, *f*. For turning;

$$VT^n d^x f^y = C$$

d: Depth of Cut
f: The feed in mm/rev
x,y: Must be determined experimentally

Tool-life Curves. *Tool-life curves* are plots of experimental data obtained from cutting tests on various materials and under different cutting conditions, such as cutting speed, feed, depth of cut, tool material and geometry, and cutting fluids.

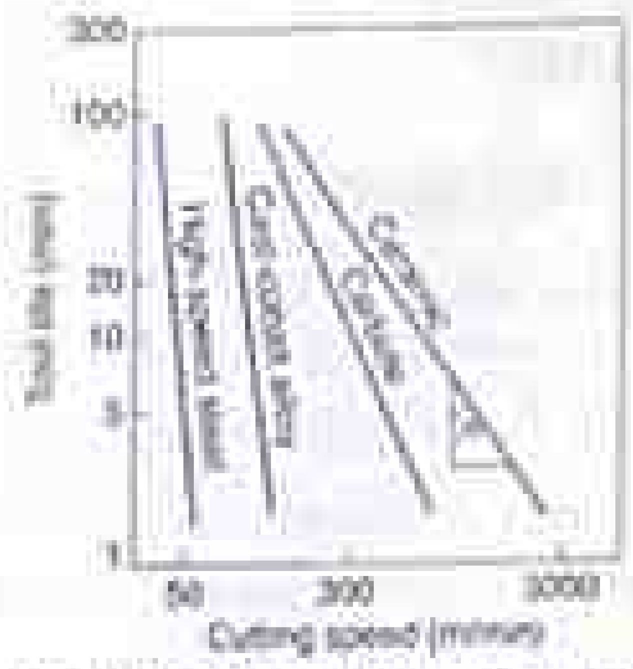


FIGURE21.17 Tool-life curves for a variety of cutting-tool materials. The negative reciprocal of the slope of these curves is the exponent *n* in the Taylor tool-life equation, and C is the cutting speed at T = 1 min, ranging from about 60 to 3,000 m/min in this figure.

The exponent *n* can be determined from tool-life curves. Note that the smaller the value of *n*, the faster the tool life decreases with increasing cutting speed.

Optimum Cutting Speed. Recall that as cutting speed increases, tool life is reduced rapidly. On the other hand, if the cutting speed is low, tool life is long, but the rate at which material is removed is also low. Thus, there is an *optimum cutting speed*, based on economic or production considerations, where the tool life is long and production speeds are reasonably high. Because it involves several other parameters.

21.5.2 Crater Wear

Crater wear occurs on the rake face of the tool. It readily can be seen that crater wear changes the tool-chip interface contact geometry. The most significant factors that influence crater wear are (a) the temperature at the tool-chip interface and (b) the chemical affinity of the tool and workpiece materials. Additionally, the same factors influencing flank wear also may affect crater wear.

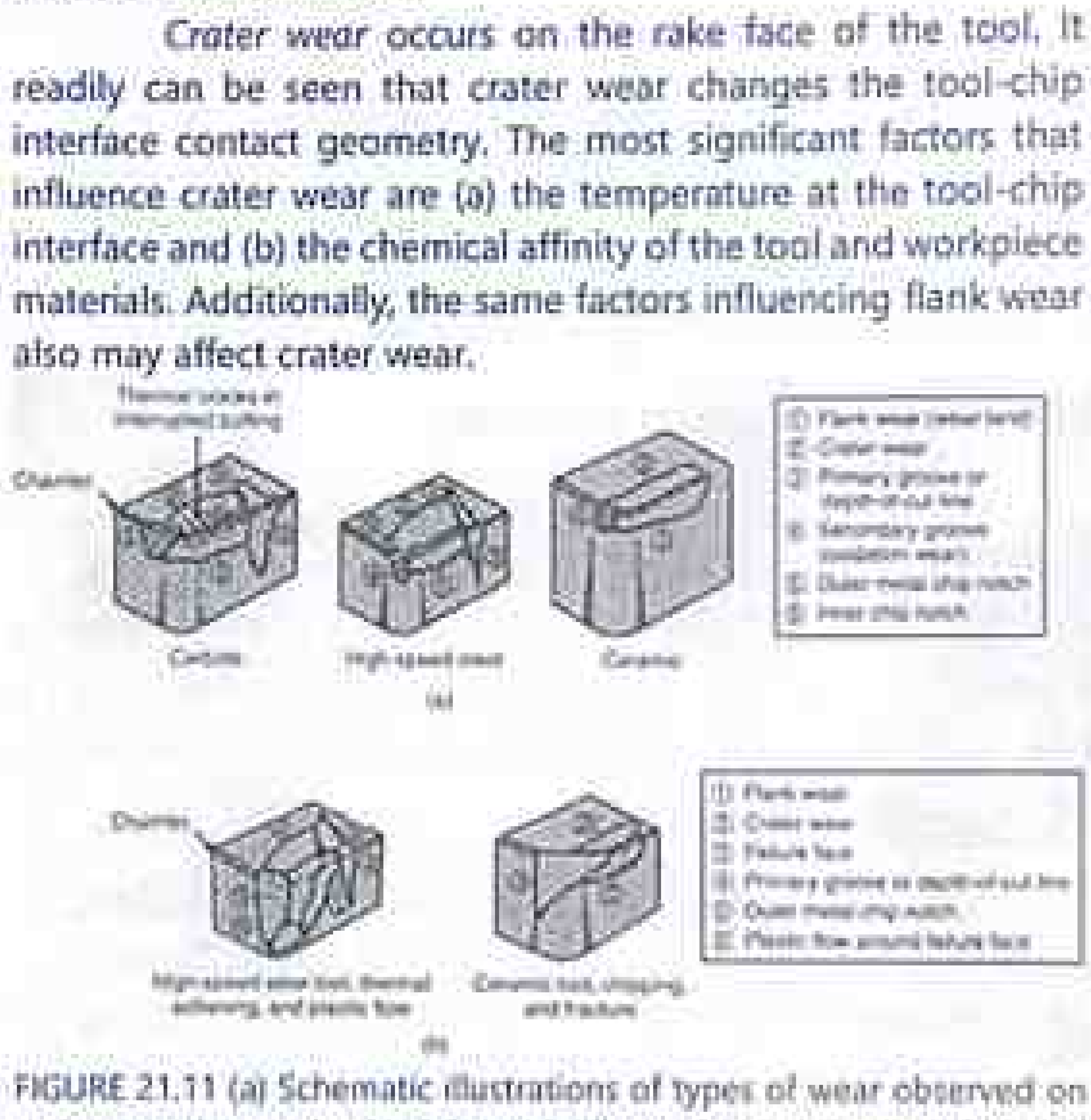


FIGURE 21.11 (a) Schematic illustrations of types of wear observed on various cutting tools, (b) Schematic illustrations of catastrophic tool failures. A wide range of parameters influence these wear and failure modes.

21.5.3 Other Types of Wear, Chipping, and Fracture

Nose wear is the rounding of a sharp tool due to mechanical and thermal effects. It dulls the tool, affects chip formation, and causes rubbing of the tool over the workpiece, raising its temperature and inducing residual stresses on the machined surface. A related phenomenon is edge rounding.

An increase in temperature is particularly detrimental to highspeed steel tools. Tools also may undergo plastic deformation because of temperature rises in the cutting zone, where temperatures can easily reach 1000 ℃ in machining steels, and can be higher depending on the strength of the material machined.

Notches or grooves observed on cutting tools have been attributed to the fact that the region where they occur is the boundary where the chip is no longer in contact with the tool.

CHAPTER 22:

Cutting-Tool Materials and Cutting Fluids

22.1 Introduction

As noted in the preceding chapter, the cutting tool is subjected to (a) high temperatures, (b) high contact stresses, and (c) rubbing along the tool-chip interface and along the machined surface. Consequently, the cutting-tool material must possess the following characteristics:

- Hot hardness, so that the hardness, strength, and wear resistance of the tool are maintained at the high temperatures encountered in machining operations. This property ensures that the tool does not undergo any plastic deformation, and thus retains its shape and sharpness
- Toughness and impact strength, so that impact forces on the tool encountered repeatedly in interrupted cutting operations (such as milling and turning a splined shaft on a lathe) or forces due to vibration and chatter during machining do not chip or fracture the tool.
- Thermal shock resistance, to withstand the rapid temperature cycling, as encountered in interrupted cutting.
- Wear resistance, so that an acceptable tool life is obtained before replacement is necessary.
- Chemical stability and inertness with respect to the workpiece material, to avoid or minimize any adverse reactions, adhesion, and tool-chip diffusion that would contribute to tool wear.

Note that many of these materials also are used for dies and molds in casting, forming, and shaping metallic and nonmetallic materials.

1. High-speed steels
2. Cast-cobalt alloys
3. Carbides
4. Coated tools
5. Alumina-based ceramics
6. Cubic boron nitride
7. Silicon-nitride-based ceramics
8. Diamond
9. Whisker-reinforced materials and nanomaterials

Carbon steels are the oldest tool materials, and have been used widely for drills, taps, broaches, and reamers since the 1880s. Low-alloy and medium-alloy steels were developed later for similar applications, but with longer tool life. Although inexpensive and easily shaped and sharpened, these steels do not have sufficient hot hardness and wear resistance for machining at high speeds, where the temperature rises significantly. Their use is limited to very low speed cutting operations, particularly in woodworking, hence they are not of any particular significance in modern machining operations.

22.2 High-Speed Steels (HSS)

High speed steel (HSS) tools are so named because they were developed to machine at higher speeds than was previously possible, first produced in the early 1900s, high-speed steels are the most highly alloyed of the tool steels. They can be hardened to various depths, have good wear resistance, and are relatively inexpensive. Because of their toughness, and associated high resistance to fracture, high-speed steels are suitable especially for (a) high positive rake-angle tools , (b) interrupted cuts, (c) machine tools with low stiffness that are subject to vibration and chatter, and (d) complex tools, such as drills, reamers, taps, and gear cutters. Their most important limitation, due to their lower hot hardness, is that the cutting speeds are low compared with those of carbide tools.

The major alloying elements in HSS are chromium, vanadium, tungsten, cobalt, and molybdenum.

- Chromium improves toughness, wear resistance, and high-temperature strength
- Vanadium improves toughness, abrasion resistance, and hot hardness
- Tungsten and cobalt have similar effects, namely, improved strength and hot hardness
- Molybdenum improves wear resistance, toughness, and high-temperature strength and hardness

22.3 Cast-cobalt Alloys

Cast-cobalt alloys have the following composition ranges: 38%-53% Co, 30%-33% Cr, and 10%-20% W. Because of their high hardness, they have good wear resistance and can maintain their hardness at elevated temperatures. They are not as tough as high-speed steels and are sensitive to impact forces; consequently, they are less suitable than high-speed steels for interrupted cutting operations. Commonly known as *Stellite* tools, these alloys are cast and ground into relatively simple shapes. They are now used only for special applications that involve deep, continuous roughing cuts at relatively high feeds and speeds, by as much as twice the rates possible with high-speed steels.

22.4 Carbides

The two groups of tool possess the required toughness, impact strength, and thermal shock resistance, but they also have important limitations, particularly with respect to strength and hot hardness. Consequently, they cannot be used as effectively where high cutting speeds, hence high temperatures, are involved; such speeds often are necessary to improve plant productivity.

To meet the challenge for increasingly higher cutting speeds, carbides, also known as *cemented or sintered carbides*, were introduced in the 1930s. Because of their high hardness over a wide range of temperatures, high elastic modulus, high thermal conductivity, and low thermal expansion, carbides ae among the most important, versatile, and cost-effective tool and die materials for a wide range of applications.

22.4.1 Tungsten Carbide

Tungsten carbide (WC) typically consists of tungsten-carbide particles bonded together in a cobalt matrix. These tools are manufactured using powder metallurgy techniques, hence the term *sintered carbides* or *cemented carbides*. Tungsten-carbide particles are first combined typically with cobalt, resulting in a composite material with a cobalt matrix surrounding the carbide particles. These particles, which are 1-5 µm in size, are then pressed and sintered into the desired *insert* shapes. Tungsten carbides frequently are also compounded with *titanium carbide* and *niobium carbide*, to impart special properties to the material.

22.4.2 Titanium Carbide

Titanium carbide (TiC) has higher wear resistance than tungsten carbide but is not as tough. Titanium carbide is suitable for machining hard materials, mainly steels and cast irons, and for machining at speeds higher than those appropriate for tungsten carbide.

22.4.3 Inserts

The need for a more effective method has led to the development of *inserts*, which are individual cutting tools with several cutting points (Fig. 22.2) Inserts usually are clamped on the *toolholder*, with various locking mechanisms (Fig. 22.3); when one point of the insert is worn, it is **indexed** (rotated in its holder) to make another cutting point available.

Carbide inserts are available in a variety of shapes, such as square, triangle, diamond, and round. The strength of the cutting edge of an insert depends on its shape; the smaller the included angle, the lower is the strength of the edge. In order to further improve edge strength and prevent chipping, insert edges usually are honed, chamfered, or produced with a negative land.

Chip-breaker features on inserts are for the purposes of **(a)** controlling chip flow during machining, **(b)** eliminating long chips, **(c)** reducing heat generated, and **(d)** reducing the tendency for vibration and chatter.

FIGURE 22.3 Methods of mounting inserts on toolholders: (a) clamping and (b) wing lock-pins. (c) Examples of inserts mounted with threadless lockpins, which are secured with side screws.

22.5 Coated Tools

New metal alloys and engineered materials are being developed continuously, particularly since the 1960s. These materials have high strength and toughness, but generally are abrasive and chemically reactive with tool materials. The difficulty of machining these materials efficiently and the need for improving their performance have led to important developments in coated tools. Compared with the tool materials themselves, coatings have advantageous properties, such as:

- Lower friction
- Higher resistance to wear and cracking
- Higher hot hardness and impact resistance
- Acting as a diffusion barrier between the tool and the chip

Coated tools can last 10 times more than those of uncoated tools, thus allowing for high cutting speeds and reducing both the time required for machining operations and production costs.

22.5.1 Coating Materials and Coating Methods

Commonly used coating materials are *titanium nitride* (TiN), *titanium carbide* (TiC), *titanium carbonitride* (TiCN), and aluminum oxide (Al_2O_3). These coatings are applied on cutting tools and inserts by two principal techniques.

1. Chemical-vapor deposition (CVD), including plasma-assisted chemical-vapor deposition
2. Physical-vapor deposition (PVD)

Titanium-nitride Coatings. Titanium-nitride coatings have low friction coefficients, high hardness, resistance to high temperature, and good adhesion to the substrate. Consequently, they greatly improve the life of high-speed steel tools, as well as the lives of carbide tools, drill bits, and cutters. Titanium-nitride-coated tools perform well at higher cutting speeds and feeds. Flank wear is significantly lower than that of uncoated tools and flank surfaces can be reground after use, since regrinding the flank face does not remove the coating on the rake face of the tool. However, these coated tools do not perform as well at low cutting speeds, because the coating can be worn off by chip adhesion, thus the use of appropriate cutting fluids to minimize adhesion is important.

Titanium-carbide Coatings. Titanium-carbide coatings on tungsten-carbide inserts have high flank-wear resistance in machining abrasive materials.

Ceramic Coatings. Because of their chemical inertness, low thermal conductivity, resistance to high temperature, and resistance to flank and crater wear, ceramics are suitable coating materials for cutting tools. The most commonly used ceramic coating is *aluminum oxide* (Al_2O_3).

Multiphase Coatings. The desirable properties of the coatings just described can be combined and optimized using multiphase coatings. Carbide tools are available with two or more layers of such coatings, and are particularly effective in machining cast irons and steels.

A typical multiphase-coated carbide tool may consist of the following layers, starting from the top, along with their primary functions:

1. TiN: low friction
2. Al_2O_3: high thermal stability

3. TiCN: fiber reinforced, with a good balance of resistance to flank wear and crater wear, effective particularly for interrupted cutting
4. A thin-carbide substrate: high fracture toughness
5. A thick-carbide substrate: hard and resistant to plastic deformation at high temperatures

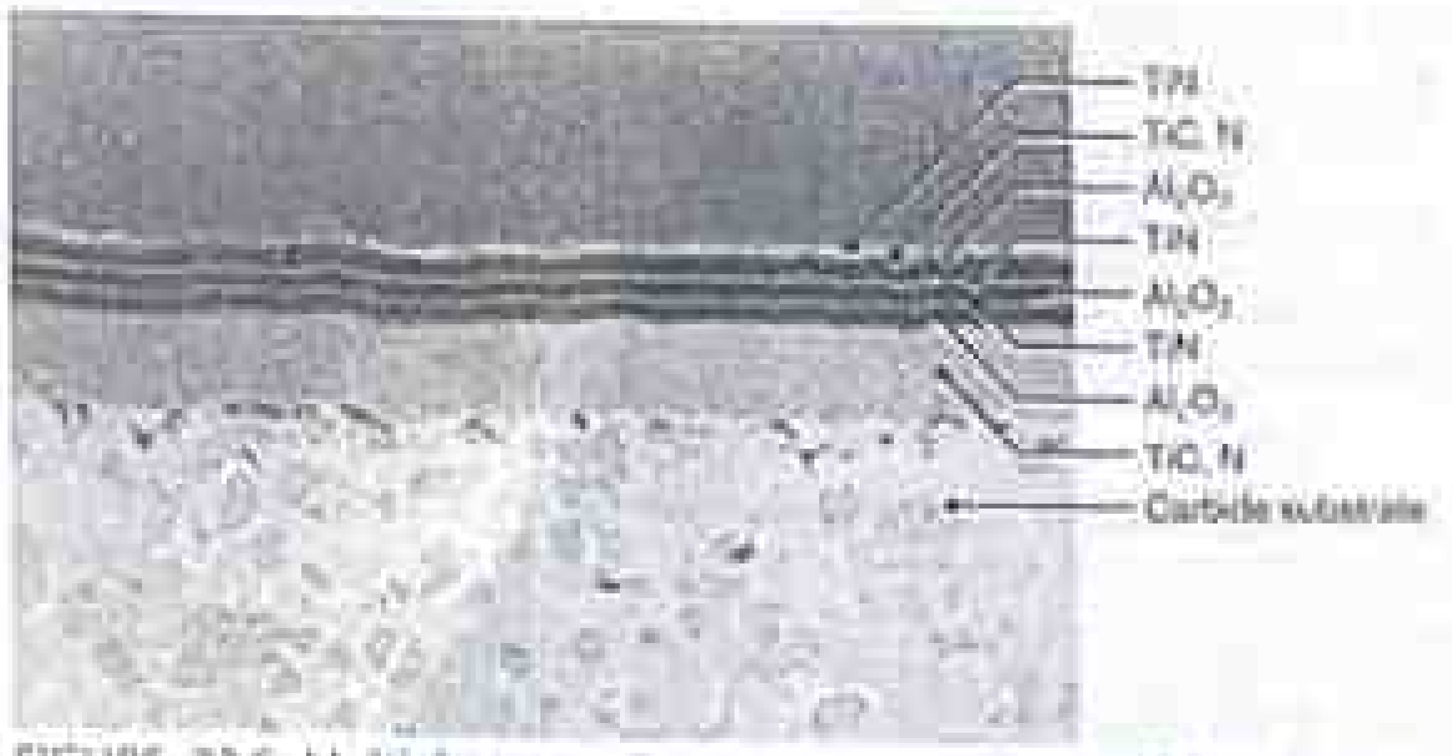


FIGURE 22.6 Multiphase coatings on a tungsten-carbide substrate; three alternating layers of aluminum nude are separated by very thin layers of titanium nitride. Inserts with as many as 13 layers of coatings have been made.

*The structure of diamondlike carbon is between that of graphite & diamond.

Diamond Coatings. The properties and applications of diamond, diamond coatings, and *diamondlike*. *Polycrystalline diamond* is used widely as a coating for cutting tools, particularly on tungsten-carbide and silicon-nitride inserts. Diamond-coated tools are particularly effective in machining (a) nonferrous metals, (b) abrasive materials, such as aluminum alloys containing silicon, (c) fiber-reinforced and metal-matrix composite materials, and (d) graphite.

Diamond-coated inserts, available commercially, have thin films deposited on substrates through PVD or CVD Techniques.

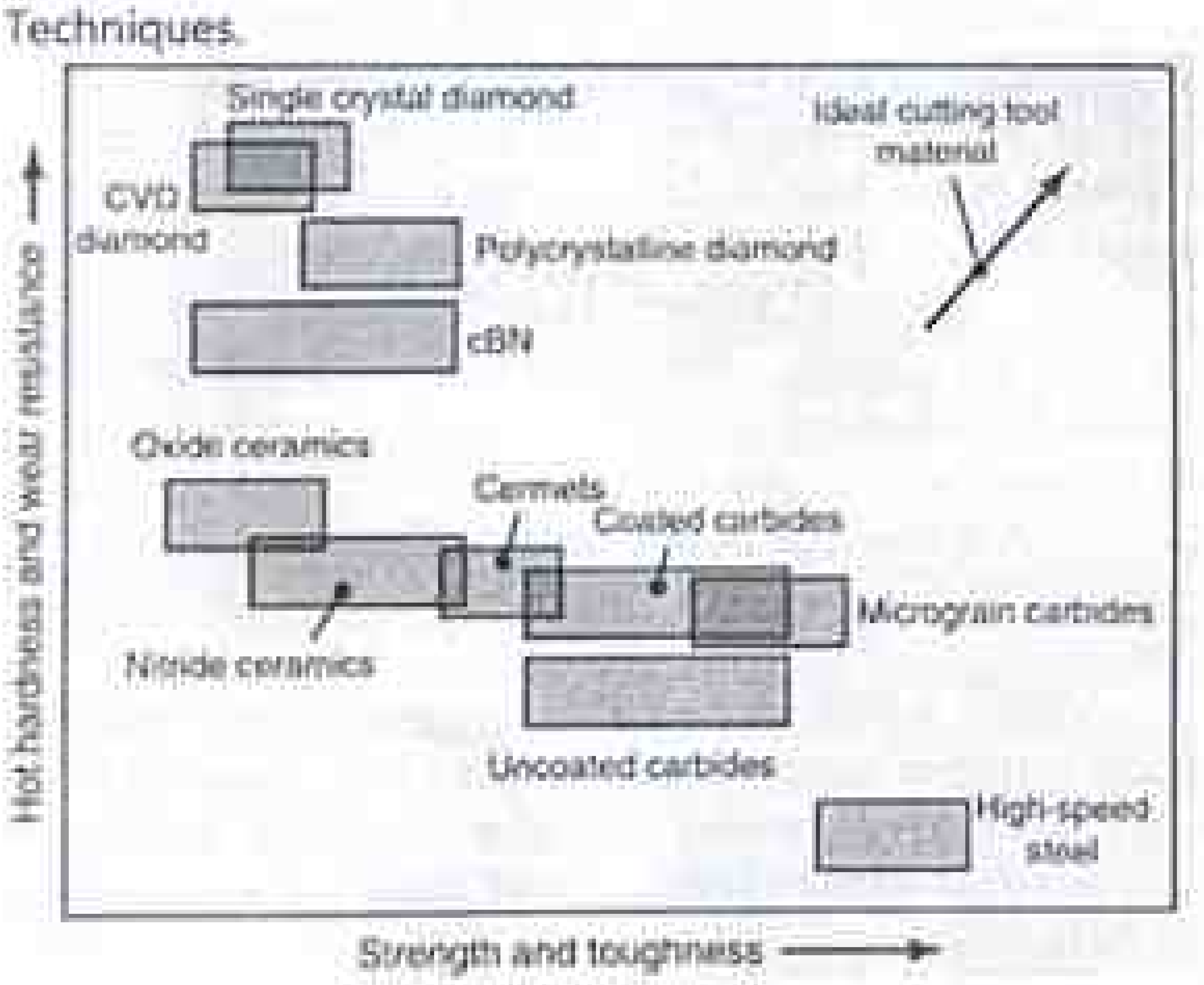


FIGURE 22.9 Ranges of mechanical properties for various groups of tool materials. HIP = hot isostatically pressed.

Cermets. *Cermets* consist of ceramic particles in a metallic matrix. They were introduced in the 1960s and are referred to as *black or hot pressed ceramics* (carboxides). Although they have chemical stability and resistance to built-up edge formation, the brittleness and high cost of cermets have been a limitation to their wider use.

22.7 Cubic Boron Nitride

Cubic boron nitride (cBN) is the hardest material available. Introduced in 1962 under the trade name Borazon. While the carbide provides shock resistance, the cBN layer provides very high wear resistance and cutting-edge strength.

The thermochemical stability of cBN is a significant advantage. Its resistance to oxidation is high, making it particularly suitable for machining hardened ferrous and high-temperature alloys and for high-speed machining operations.

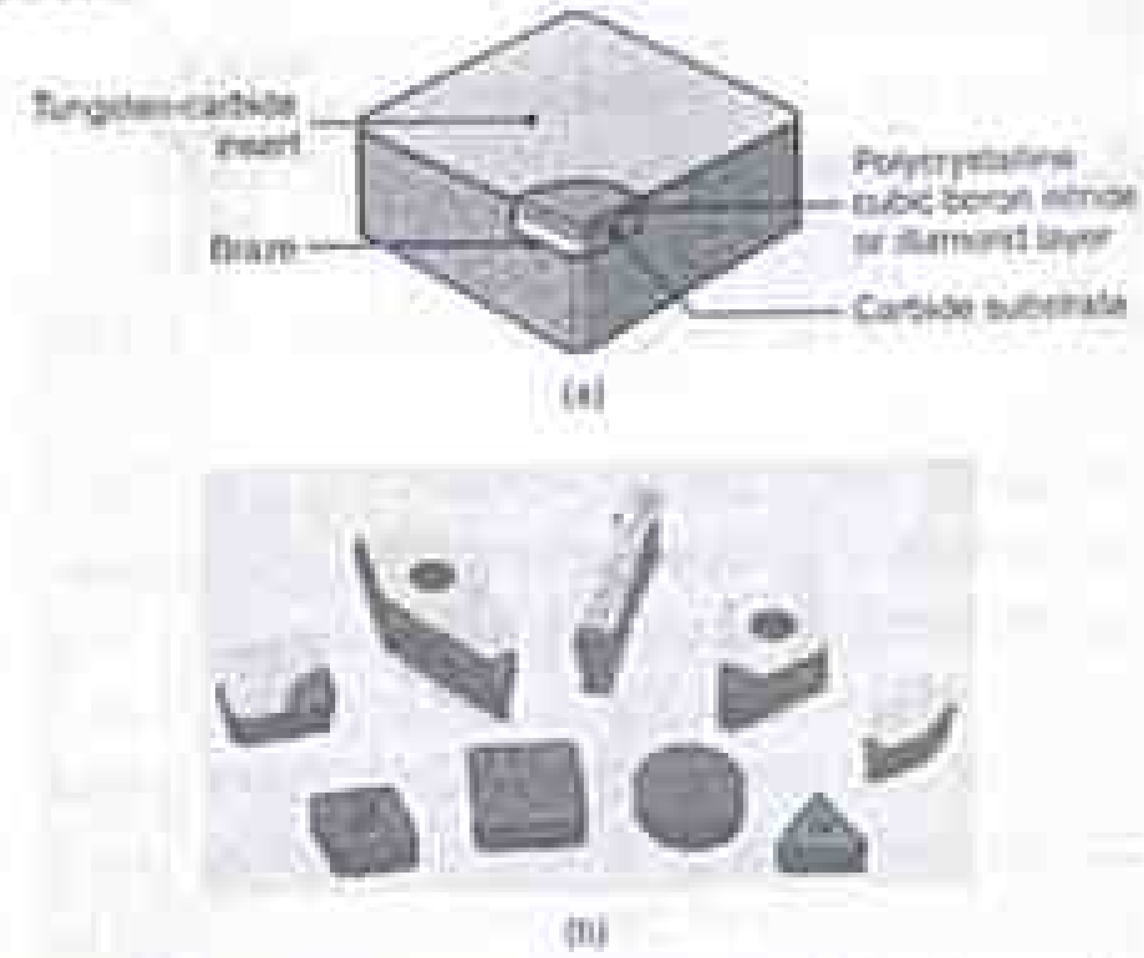


FIGURE 22.10 Cubic boron nitride inserts. (a) An insert of a polycrystalline cubic boron nitride or a diamond layer on tungsten carbide. (b) Inserts with poly crystalline cubic boron nitride tips (top row), and solid-polycrystalline cBN inserts (bottom row).

22.8 Silicon-nitride-based Ceramics (Sadece ismi lazım)

22.9 Diamond

The hardest substance is diamond. As a cutting tool, it has highly desirable properties such as low friction, high wear resistance, and the ability to maintain a sharp cutting edge. Diamond is used when good surface finish and dimensional accuracy are required, particularly when machining soft nonferrous alloys and abrasive nonmetallic and metallic materials, especially some aluminum-silicon alloys. Synthetic or industrial diamond is widely used because natural diamond has flaws, and thus its performance can be unpredictable. The random orientation of the diamond crystals prevents the propagation of tracks through die structure, thus significantly improving its toughness.

Because diamond is brittle, tool shape and sharpness are important. Low rake angles generally are used to provide a strong cutting edge, because of the larger included angles. Special attention should he given to proper mounting and crystal orientation in order to obtain optimum tool life. Wear may occur through microchipping (caused by thermal stresses and oxidation) and through transformation to carbon (caused by the heat generated during machining). Diamond tools can be used satisfactorily at almost any speed, but are most suitable for light, uninterrupted finishing cuts. In order to minimize tool fracture, the single-crystal diamond must he resharpened as soon as it becomes dull. Because of its strong chemical affinity at elevated temperatures (resulting in diffusion), diamond is not recommended for machining plain-carbon steels or for titanium, nickel, and cobalt-based alloys.

22.10 Whisker-reinforced Materials and Nanomaterials

In order to further improve the performance and wear resistance of cutting tools, particularly in machining new materials and composites, continued progress is being made in developing new tool materials with enhanced properties, such as:

- High fracture toughness
- Resistance to thermal shock
- Cutting-edge strength
- Creep resistance
- Hot hardness

Advances include the use of **whiskers** as reinforcing fibers in composite cutting-tool materials.

22.11 Tool Costs and Reconditioning of Tools

Tool costs vary widely, depending on the tool material, size, shape, chip-breaker features, and quality.

Tooling costs in machining have been estimated to be on the order of 2-4% of the manufacturing costs. This small amount is due to the fact that a single cutting tool, for example, can perform a large amount of material removal before it is indexed to use all the cutting edges of an insert, and eventually recycled. The expected tool life can be in the range of 30-60 min; thus, considering that a square insert has eight cutting edges, a tool can last many hours before it is removed from the machine tool and replaced.

Cutting tools can be **reconditioned** by resharpening them, using tool and cutter grinders with special fixtures. This operation may be carried out by hand or on computer-controlled tool and cutter grinders. Advanced methods of shaping cutting tools also are available. Reconditioning of coated tools also is done by recoating them, usually in special facilities available for these purposes; it is important that reconditioned tools have the same geometric features as the original tools. Often, a decision has to be made whether further reconditioning of tools is economical, especially when the costs of typical small inserts are not a major contribution to total costs. Recycling of tools is always a significant consideration, especially if they contain expensive and strategically important materials, such as tungsten and cobalt.

22.12 Cutting Fluids

Cutting fluids are used *extensively* in machining operations for the following purposes:

- Reduce friction and wear, thus improving the tool life and surface finish of the workpiece
- Cool the cutting zone, thus improving tool life and reducing the temperature and thermal distortion of the workpiece
- Reduce forces and energy consumption
- Flush away the chips from the cutting zone, thus preventing the chips from interfering with the cutting operation, particularly in drilling and tapping
- Protect the machined surface from environmental corrosion

Depending on the type of machining operation, the cutting fluid needed may be a **coolant**, **a lubricant**, or both. The effectiveness of cutting fluids depends on a number of factors, such as the type of machining operation, tool and workpiece materials, cutting speed, and the method of application. Water is an excellent coolant, and can effectively reduce the high temperatures developed in the cutting zone; however, water is not an effective lubricant and hence, it does not reduce friction and can cause corrosion of workpieces and machine-tool components.

Types of Cutting Fluids. Briefly, four general types of cutting fluids are commonly used in machining operations:

1. Oils, also called *straight oils*, include mineral, animal, vegetable, compounded, and synthetic oils; typically are used for low-speed operations where temperature rise is not significant.
2. Emulsions, also called *soluble oils*, are a mixture of oil and water and additives; they generally are used for high-speed operations where the temperature rise is significant. The presence of water makes emulsions highly effective coolants, and the presence of oil reduces or eliminates the tendency of water to cause oxidation of workpiece surfaces.
3. Semisynthetics are chemical emulsions containing little mineral oil, diluted in water, and with additives that reduce the size of oil particles, thus making them more effective.
4. Synthetics are chemicals with additives, diluted in water, and containing no oil.

Method of Cutting-fluid Application

1. Flooding
2. Mist
3. High-pressure systems
4. Through the cutting-tool system

Effects of Cutting Fluids. The selection of a cutting fluid should also include considerations such as its effects on

- Workpiece material
- Machine tool components
- Biological considerations
- The environment

22.12.1 Near-dry and Dry Machining

The significance of this approach becomes apparent when one notes that, in the United States alone, millions of gallons of metalworking fluids are consumed each year. Furthermore, it has been estimated that metalworking fluids constitute about 7-17% of the total machining cost.

The principle behind near-dry cutting is the application of a fine mist of an air-fluid mixture, containing a very small amount of cutting fluid, which may be reformulated to contain vegetable oil. The mixture is delivered to the cutting zone through the spindle of the machine tool. Consequently, the process is also known as *minimum-quantity lubrication (MQL).*

Dry machining also is a viable alternative. With major advances in cutting tools, dry machining has been shown to be effective in various machining operations, especially turning, milling, and gear cutting, on steels, steel alloys, and cast irons, although generally not for aluminum alloys.

Cryogenic Machining. More recent developments in machining include the use of cryogenic gases, such as nitrogen or carbon dioxide, as a coolant. Because of the reduced temperature, tool hardness is maintained and hence tool life is improved, thus allowing for higher cutting speeds. The chips also are less ductile, thus machinability is increased. There is no adverse environmental impact, and the nitrogen simply evaporates.

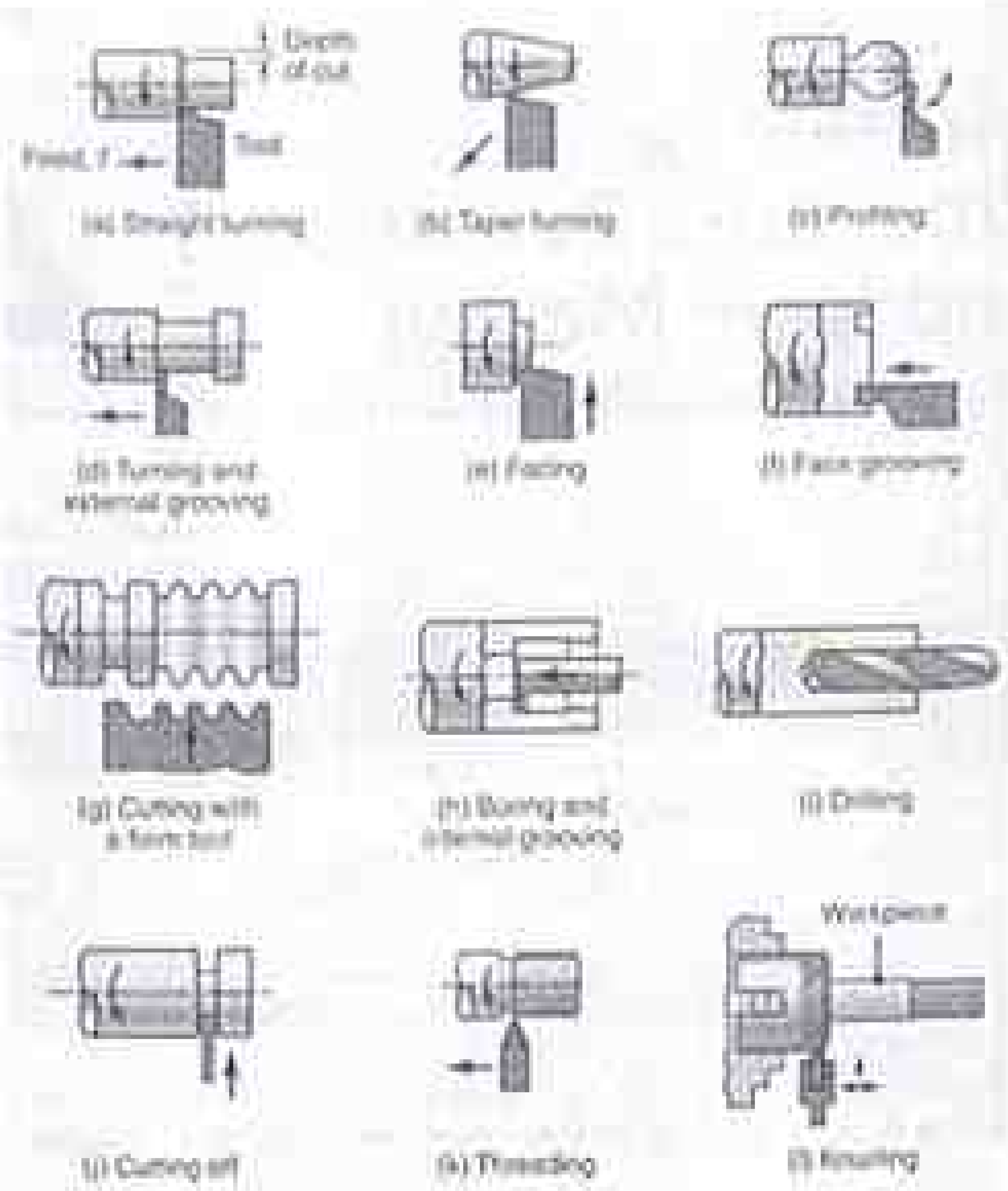


FIGURE 23.1 Miscellaneous operations that can be performed on a lathe; note that all parts are circular. The tools used, their shape, and the processing parameters are described throughout this chapter.

- **Cutting with form tools:** (Fig. 23.1g) to produce various axisymmetric shapes for functional or for aesthetic purposes
- **Boring:** to enlarge a hole or cylindrical cavity made by a previous process or to produce circular internal grooves (Fig. 23.1h)
- **Drilling:** to produce a hole (Fig. 23.1i), which then may be followed by boring it to improve its dimensional accuracy and surface finish
- **Parting:** also called cutting off, to remove a piece from the end of a part, as is done in the production of slugs or blanks for additional processing into discrete products (Fig. 23.1j)
- **Threading:** to produce external or internal threads (Fig. 23.1k)
- **Knurling:** to produce a regularly shaped roughness on cylindrical surfaces, as in making knobs and handles (Fig. 23.1l)

General Characteristics of Machining Processes and Typical Dimensional Tolerances

Turning	Turning and facing operations on all types of materials, uses single-point or form tools; engine lathes require skilled labor; low production rate (but medium-to-high rate with turret lathes and automatic machines) requiring less-skilled labor
Boring	Internal surfaces or profiles with characteristics similar to turning; stiffness of boring bar important to avoid chatter
Drilling	Round holes of various size* and depths; high production rate; labor skill required depends on hole location and accuracy specified; requires boring and reaming for improved accuracy
Milling	Wide variety of shapes involving contours, flat surfaces, and slots; versatile; low-to-medium production rate; requires skilled labor
Planing	Large flat surfaces and straight contour profiles on long workpieces, low-quantity production, labor skill required depends on part shape
Shaping	Flat surfaces and straight contour profiles on relatively small workpieces; low-quantity production; labor skill required depends on part shape
Broaching	External and internal surfaces, slots, and contours; good surface finish; costly tooling; high production rate; labor skill required depends on part shape
Sawing	Straight and contour cuts on flat or structural shapes; not suitable for hard materials unless saw has carbide teeth or is coated with diamond; low production rate; generally low labor skill

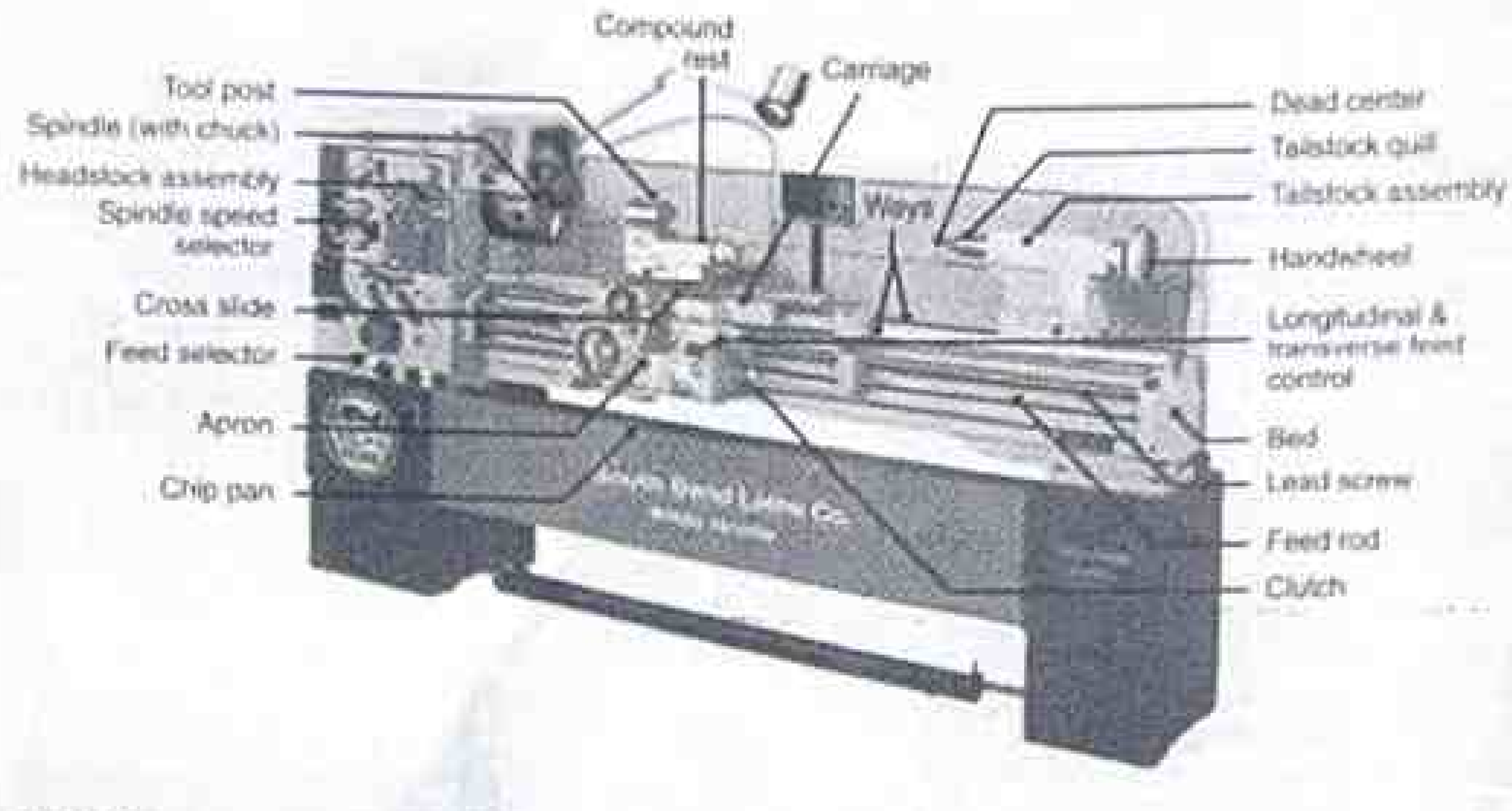


FIGURE 23.2 General view of a typical lathe, showing various components. *Source:* Courtesy of South Bend Lathe Co.

23.2 The Turning Process

The majority of turning operations involve the use of simple single-point cutting tools, with the geometry of a typical right-hand cutting tool shown in ach group of workpiece materials has an optimum set of tool angles, which have been developed largely through experience over many years.

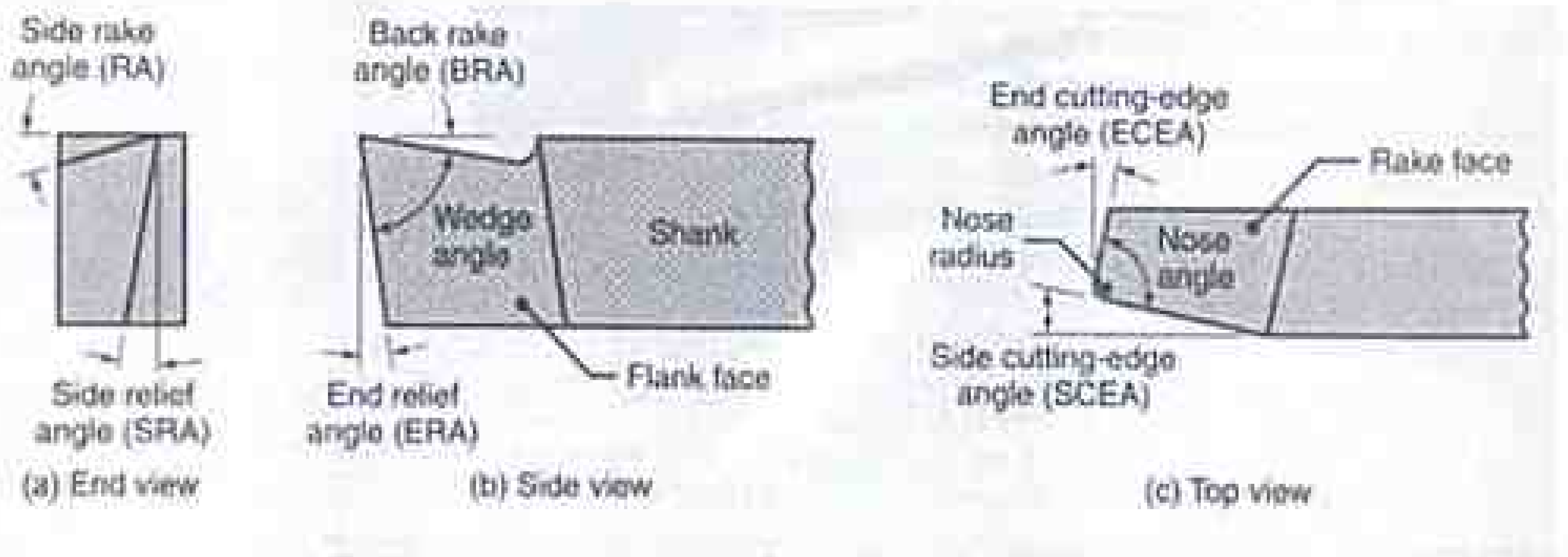


FIGURE 23.4 Designations for a right-hand cutting tool, meaning that the tool travels from right to left, as shown in Fig. 23.3b.

Tool Geometry. The various angles in a single-point cutting tool have important functions in machining operations.

- Rake angle is important in controlling both the direction of chip flow and the strength of the tool tip. Positive rake angles improve the cutting operation by reducing forces and temperatures, but they also result in a small included angle of the tool tip possibly leading to premature tool chipping and failure, depending on the toughness of the tool material.
- Side rake angle is more important than the **back rake angle**, which usually controls the direction of chip flow; these angles typically are in the range from -5° to 5°.

- Cutting-edge angle affects chip formation, tool strength, and cutting forces to various degrees; typically, the cutting-edge angle is around 15°.
- Relief angle controls interference and rubbing at the tool-workpiece interface. If it is too large, the tool tip may chip off; if it is too small, flank wear may be excessive. Relief angles typically are 5°.
- Nose radius affects surface finish and tool-tip strength. The smaller the nose radius (meaning a sharp tool), the rougher the surface finish of the workpiece and the lower the strength of the tool; a large nose radii can, however, lead to tool chatter.

f: The feed

d: Depth of cut

(f)(d): The volume of this ring is the product of the cross-sectional area

πD_{avg}: The average circumference of the ring

$$D_{avg} = \frac{D_o + D_f}{2}.$$

The rotational speed of the workpiece is N, and the material removal rate per revolution is $(\pi)(D_{avg})(d)(f)$. Since there are N revolutions per minute, the removal rate is

$$MRR = \pi D_{avg} d f N.$$

$$MRR = d f V.$$

$$t = \frac{l}{f N}.$$

The cutting time does not include the time required for tool approach and retraction.

23.3.1 Lathe Components

- Bed
- Carriage
- Headstock
- Tailstock
- Feed Rod and Lead Screw

23.3.2 Work-holding Devices and Accessories

Work-holding devices are important, as they must hold the workpiece securely in place.

A chuck usually is equipped with three or four *jaws*. *Three-jaw* chucks generally have a geared-scroll design that makes the jaws self-centering. They are used for round workpieces, such as bar stock, pipes, and tubing. Four-jaw chucks have jaws that can be moved and adjusted independently of each other; thus for example, they can be used for square, rectangular, or odd-shaped workpieces. The jaws in some types of chucks can be reversed to permit clamping of hollow workpieces, such as pipes and tubing, either on their outside or inside surfaces. Also available are jaws made of low-carbon steel (called soft laws) that can be machined into desired shapes. Because of their low strength and hardness, soft jaws conform to small irregularities on workpieces, thus resulting in better clamping. Chucks can be power or manually actuated using a chuck wrench.

Power chucks, actuated either pneumatically or hydraulically, are used in automated equipment for high production rates, including the loading of parts using industrial robots. Also available are several types of power chucks with lever- or wedge-type mechanisms used to actuate the jaws. Chucks are available in various designs and sizes. Their selection depends on the type and speed of operation, workpiece size, production and dimensional accuracy requirements, and the jaw clamping forces required. By controlling the magnitude of the jaw forces, an operator can ensure that the part does not slip in the chuck during machining. High spindle speeds can significantly reduce jaw forces due to the effect of centrifugal forces.

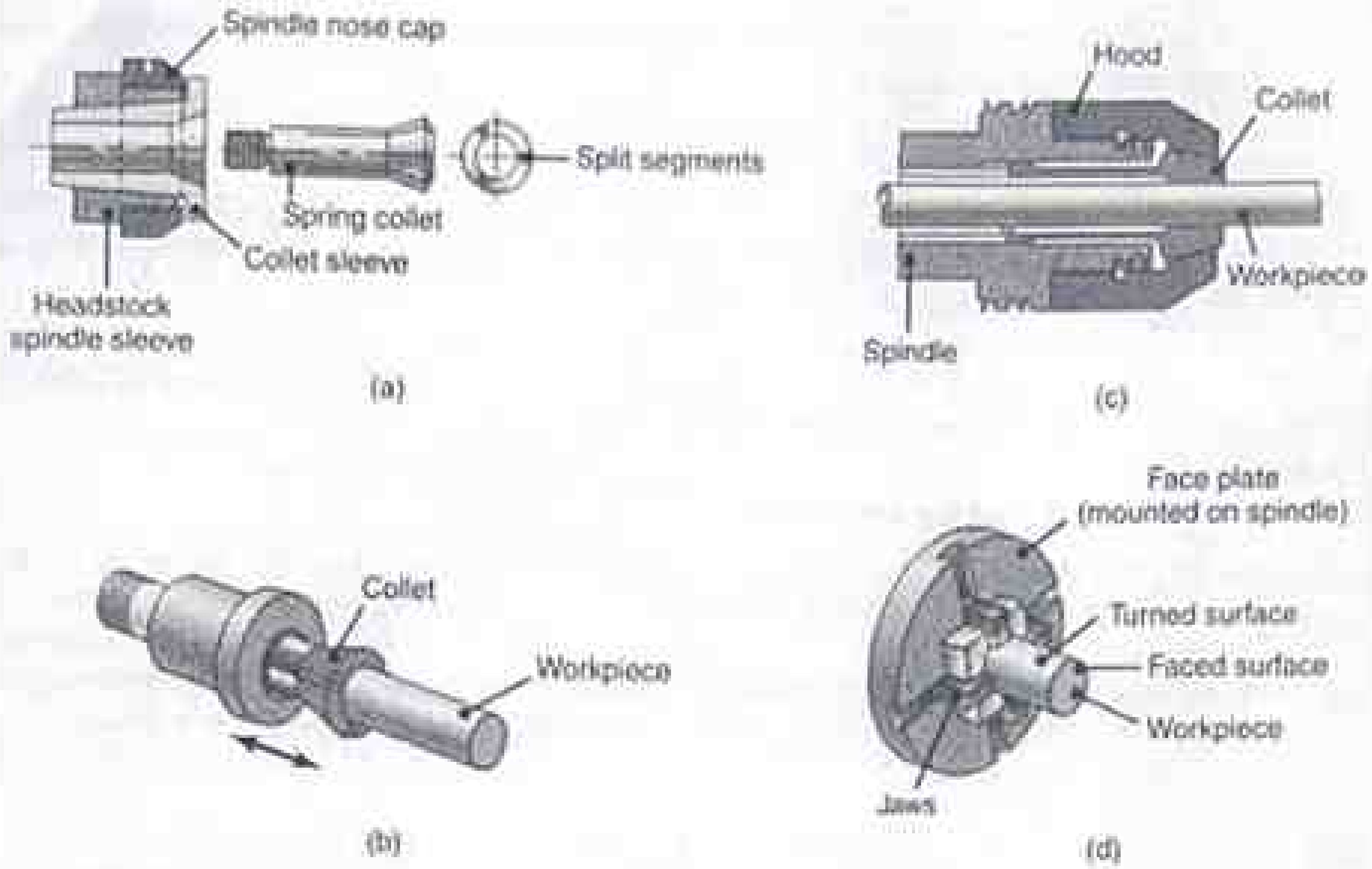


FIGURE 23.8 (a) and (b) Schematic illustrations of a draw-in type of collet. The workpiece is placed in the collet hole, and the conical surfaces of the collet are forced inward by pulling it with a draw bar into the sleeve. (c) A push-out type of collet. (d) Work holding of a workpiece on a face plate.

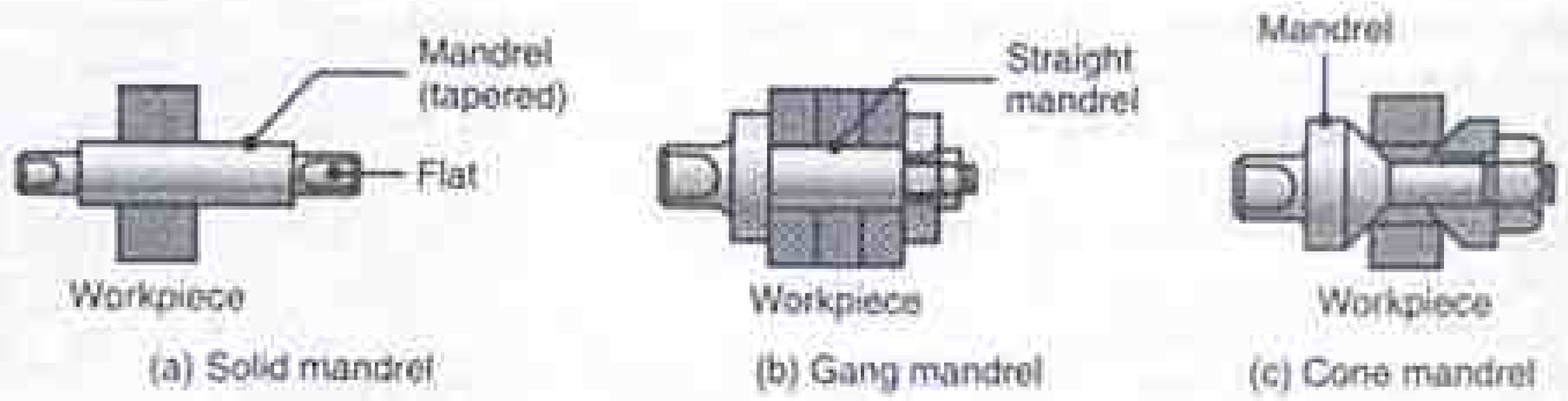


FIGURE 23.9 Various types of mandrels to hold workpieces for turning; these mandrels usually are mounted between centers on a lathe. Note that in (a) both the cylindrical and the end faces of the workpiece can be machined, whereas in (b) and (c) only the cylindrical surfaces can be machined.