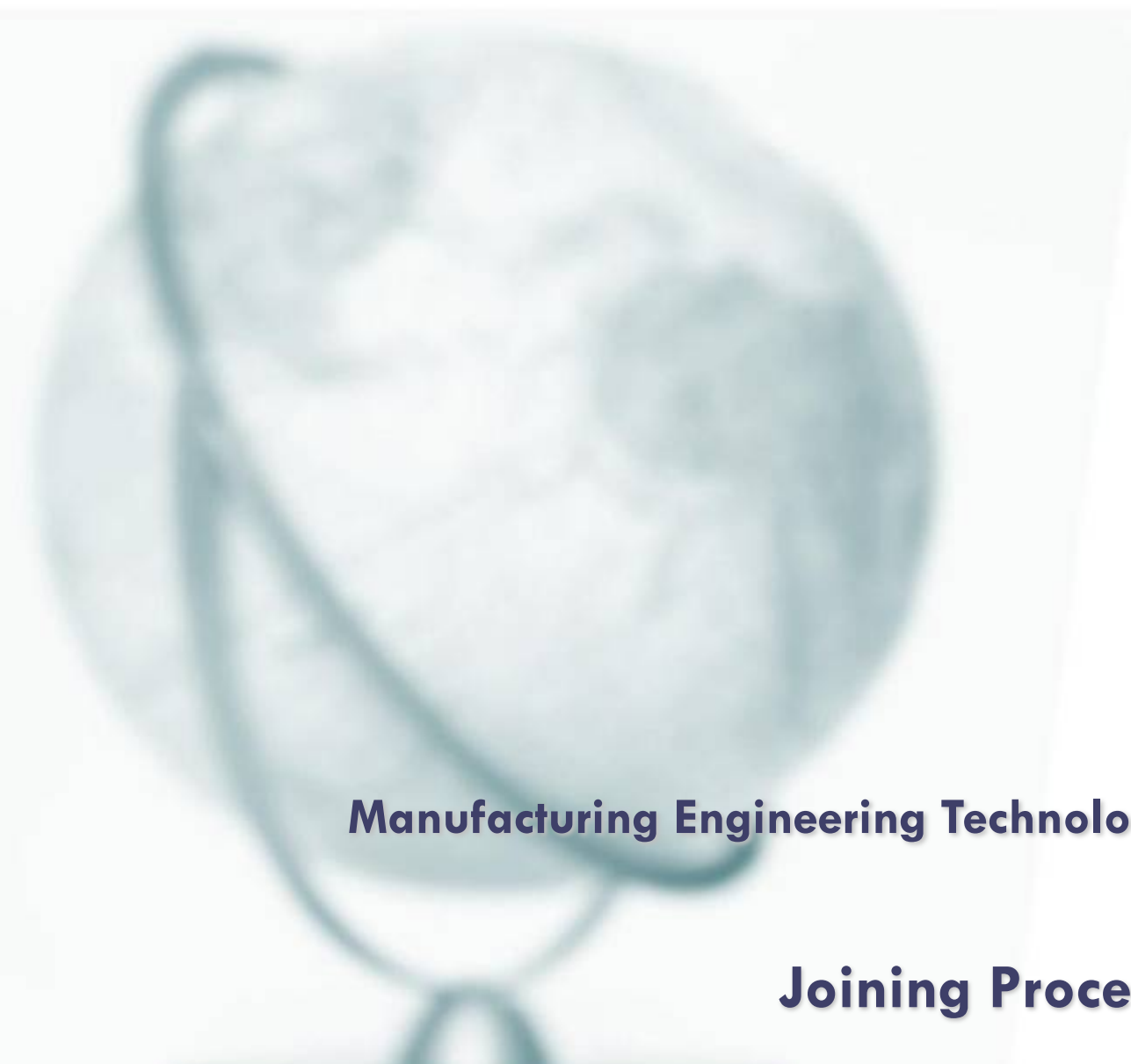


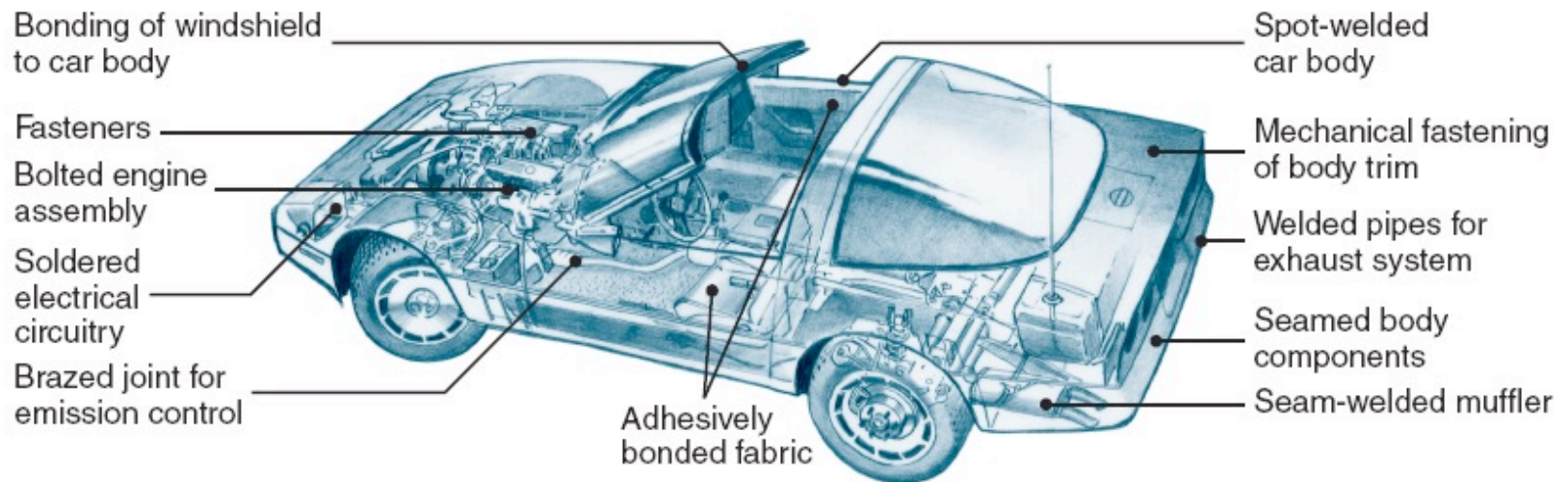


Manufacturing Engineering Technology in SI Units, 6th Edition

PART VI:
Joining Processes and Equipment

Introduction

- Numerous components are assembled and joined so that they can function reliably and economical to produce



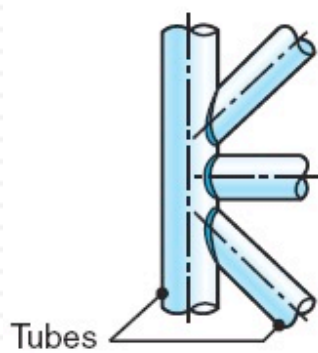
Introduction

- **Joining** is an all-inclusive term covering processes such as welding, brazing, soldering, adhesive bonding, and mechanical fastening
- Some important aspect of manufacturing and *assembly* operations:
 1. Simple product may be impossible to manufacture as a *single piece*
 2. The product is *easier and more economical* to manufacture as individual components

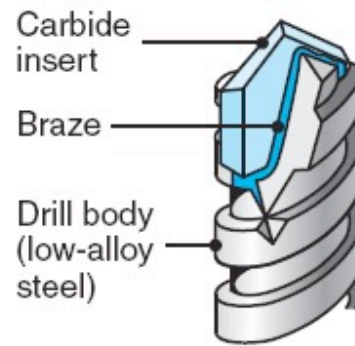
Introduction

3. Products need to be designed to be able to be *taken apart* for maintenance or replacement of their parts
4. *Different properties* may be desirable for functional purposes of the product
5. *Transporting* the product in individual components and assembling them later

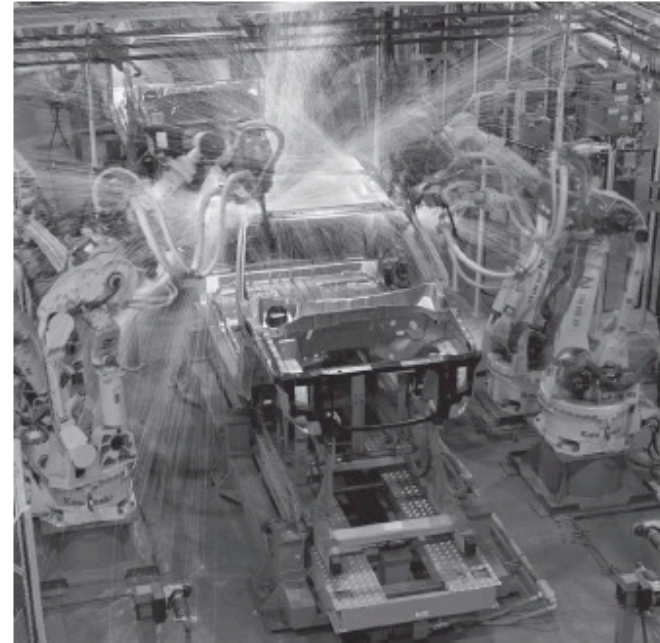
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(a)



(b)

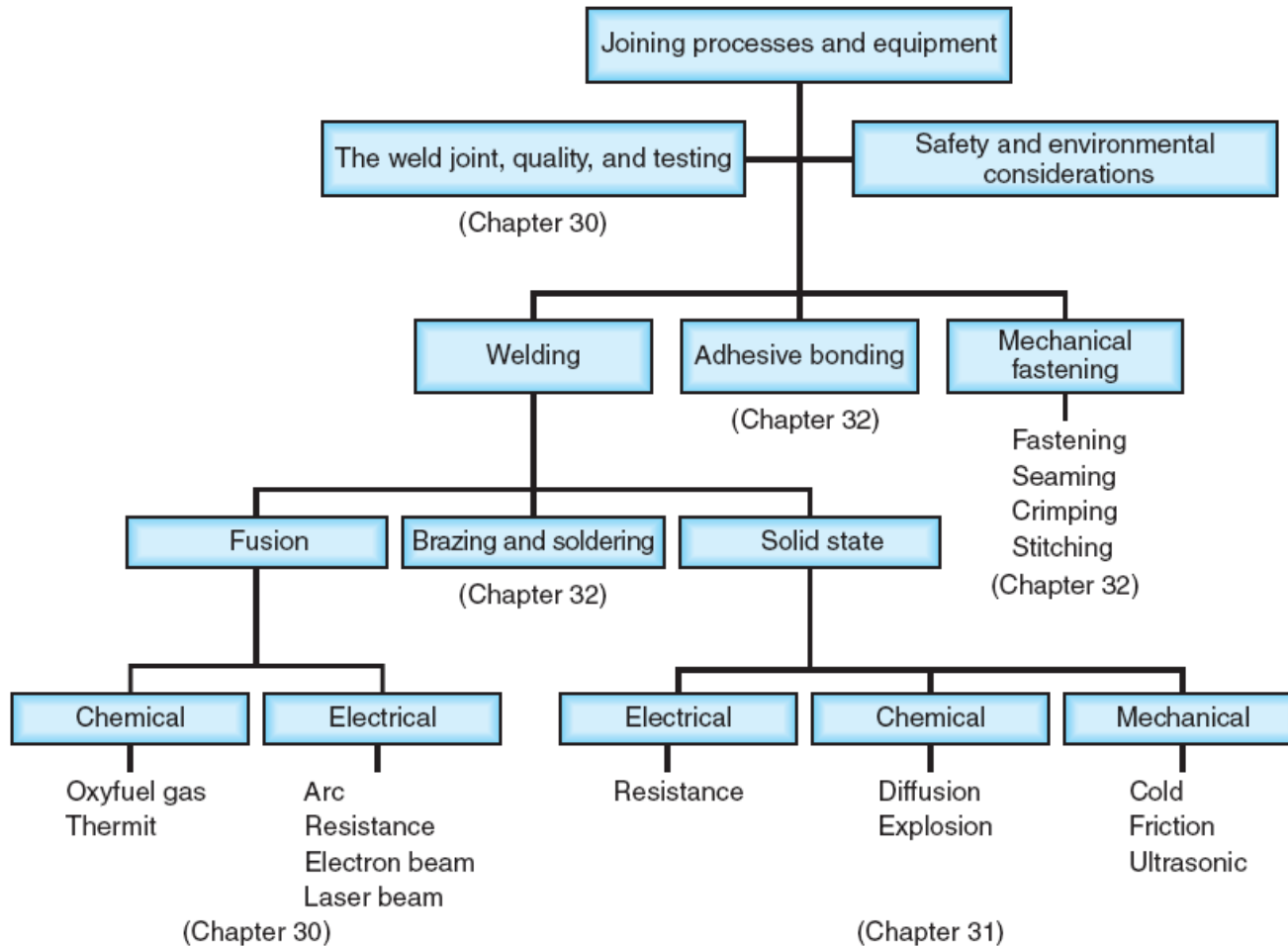


(c)

Introduction

- Joining processes fall into three major categories:
 1. **Welding**
 2. **Adhesive bonding**
 3. **Mechanical fastening**
- Welding processes are classified into 3 categories:
 1. **Fusion welding**
 2. **Solid-state welding**
 3. **Brazing and soldering**

Introduction

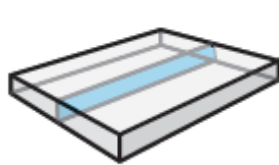


Introduction

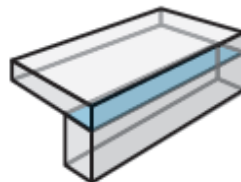
Comparison of Various Joining Methods

Method	Characteristics								Cost
	Strength	Design	Small parts	Large parts	Tolerances	Reliability	Ease of manufacture	Ease of inspection	
Arc welding	1	2	3	1	3	1	2	2	2
Resistance welding	1	2	1	1	3	3	3	3	1
Brazing	1	1	1	1	3	1	3	2	3
Bolts and nuts	1	2	3	1	2	1	1	1	3
Riveting	1	2	3	1	1	1	3	1	2
Fasteners	2	3	3	1	2	2	2	1	3
Seaming and crimping	2	2	1	3	3	1	3	1	1
Adhesive bonding	3	1	1	2	3	2	3	3	2

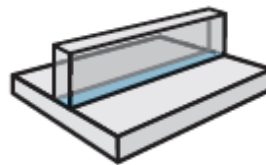
Note: 1 = very good; 2 = good; 3 = poor. For cost, 1 is the lowest.



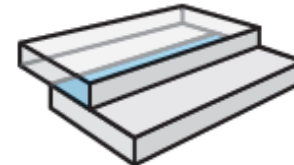
(a) Butt joint



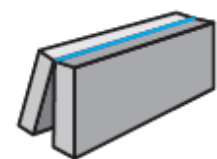
(b) Corner joint



(c) T joint



(d) Lap joint



(e) Edge joint

Manufacturing Engineering Technology in SI Units, 6th Edition
Chapter 30: Fusion-Welding Processes

Chapter Outline

1. Introduction
2. Oxyfuel – gas Welding
3. Arc-welding Processes: Nonconsumable Electrode
4. Arc-welding Processes: Consumable Electrode
5. Electrodes for Arc Welding
6. Electron-beam Welding
7. Laser-beam Welding
8. Cutting
9. The Weld Joint, Quality, and Testing
10. Joint Design and Process Selection

Introduction

- ❑ Welding processes involve the partial melting and fusion between two members to be joined
- ❑ **Fusion welding** is defined as *melting together and coalescing* materials by means of heat
- ❑ *Filler metals* are metals added to the weld area during welding
- ❑ Fusion welds made without the use of filler metals are known as *autogenous welds*



Introduction

General Characteristics of Fusion-welding Processes

Joining process	Operation	Advantage	Skill level required	Welding position	Current type	Distortion*	Typical cost of equipment (\$)
Shielded metal arc	Manual	Portable and flexible	High	All	AC, DC	1 to 2	Low (1500+)
Submerged arc	Automatic	High deposition	Low to medium	Flat and horizontal	AC, DC	1 to 2	Medium (5000+)
Gas metal arc	Semiautomatic or automatic	Most metals	Low to high	All	DC	2 to 3	Medium (3000+)
Gas tungsten arc	Manual or automatic	Most metals	Low to high	All	AC, DC	2 to 3	Medium (5000+)
Flux-cored arc	Semiautomatic or automatic	High deposition	Low to high	All	DC	1 to 3	Medium (2000+)
Oxyfuel	Manual	Portable and flexible	High	All	—	2 to 4	Low (500+)
Electron beam, laser beam	Semiautomatic or automatic	Most metals	Medium to high	All	—	3 to 5	High (100,000–1 million)

*1 = highest; 5 = lowest.

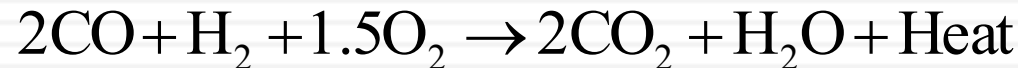
Oxyfuel–gas Welding

- *Oxyfuel–gas welding* (OFW) is a general term used to describe any welding process that uses a **fuel gas** combined with *oxygen* to produce a flame

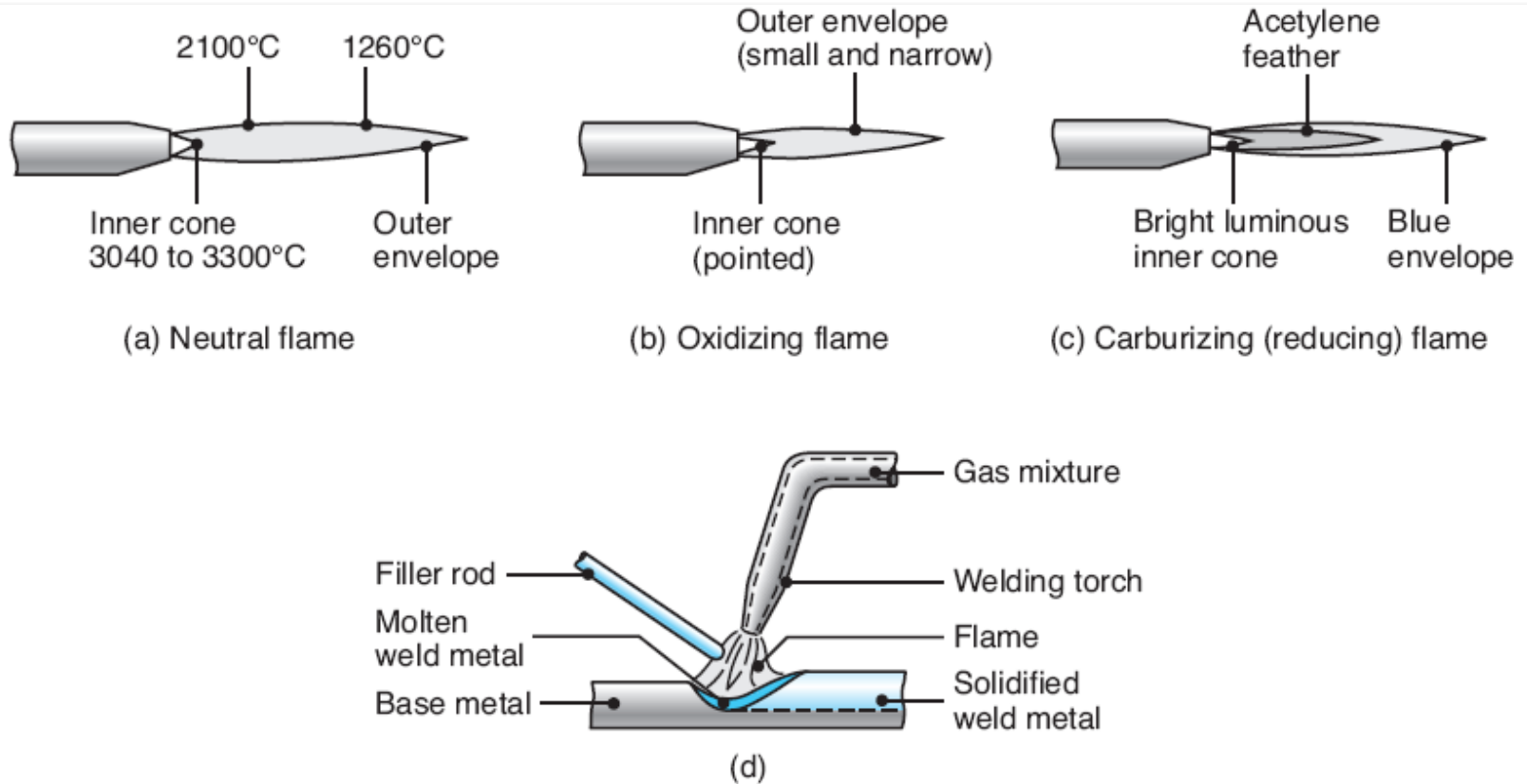
- The primary combustion process involves



- The secondary combustion process is



Oxyfuel-gas Welding



Oxyfuel–gas Welding

Flame Types

- The proportion of acetylene and oxygen in the gas mixture is an important factor
- At a ratio of 1:1, the flame is *neutral*
- For greater oxygen supply, it is known as an **oxidizing flame**
- For insufficient oxygen, the flame is a **reducing**, or **carburizing flame**

Oxyfuel–gas Welding

Filler Metals

- Used to supply additional metal to the weld zone during welding
- Available as **filler rods** or *wire* and may be bare or coated with **flux**
- Purpose of the flux is to retard oxidation of the surfaces of the parts being welded by generating a *gaseous shield* around the weld zone

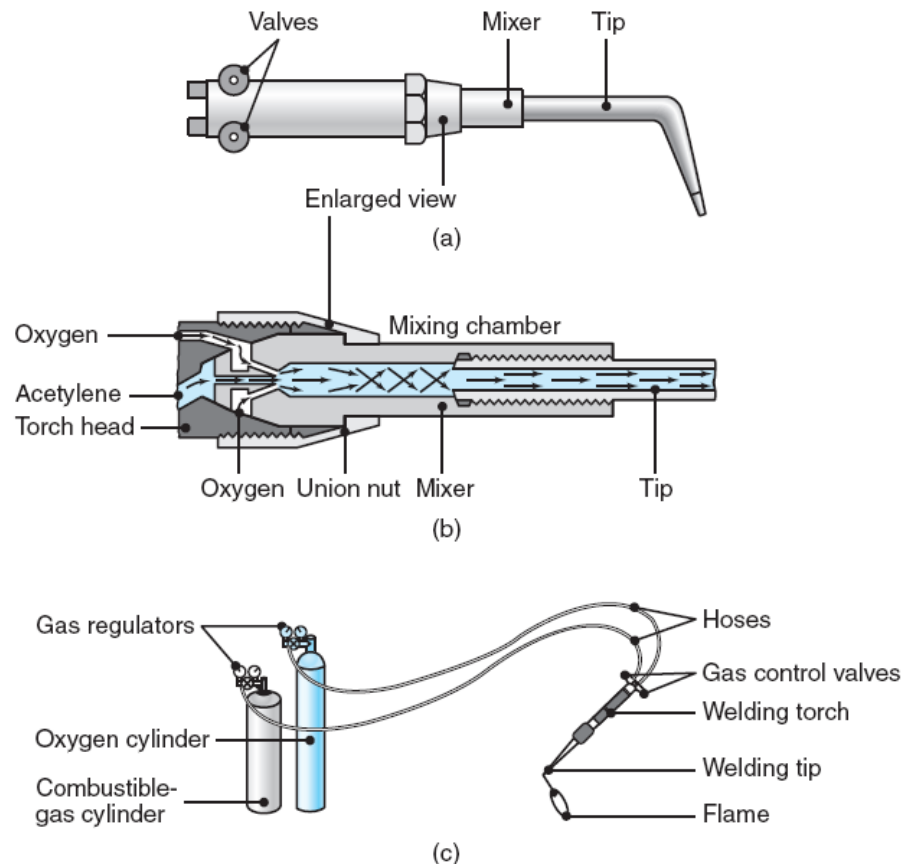
Oxyfuel–gas Welding

Welding Practice and Equipment

- Can be used with most ferrous and nonferrous metals for almost any workpiece thickness
- The equipment consists of a **welding torch** connected by hoses to high-pressure gas cylinders and equipped with pressure gages and regulators
- The low equipment cost is an attractive feature

Oxyfuel-gas Welding

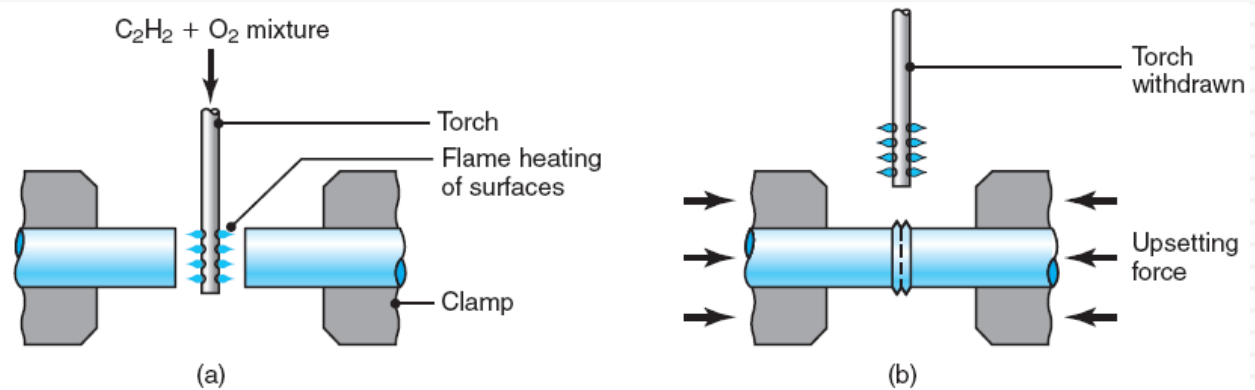
Welding Practice and Equipment



Oxyfuel-gas Welding

Pressure-gas Welding

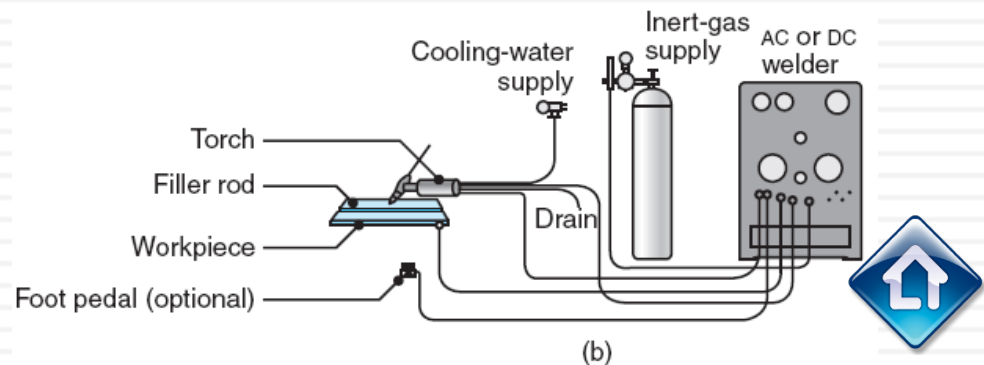
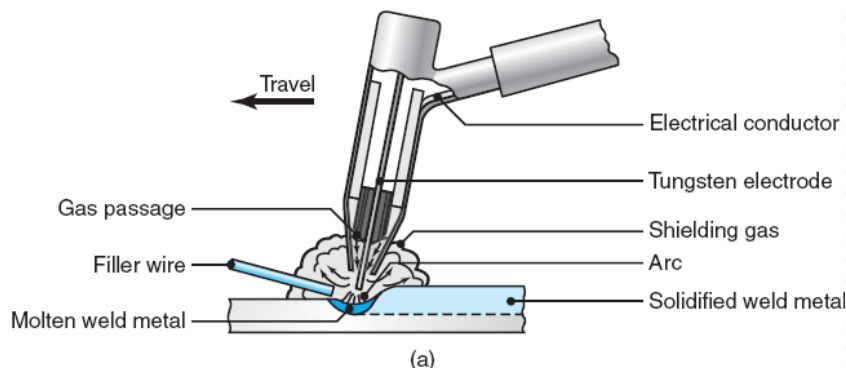
- Welding of two components starts with the heating of the interface by means of a torch using an oxyacetylene-gas mixture
- A force is applied to press the two components together and maintained until the interface solidifies



Arc-welding Processes:

Nonconsumable Electrode

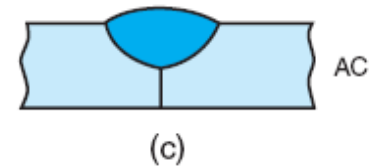
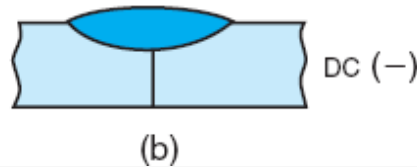
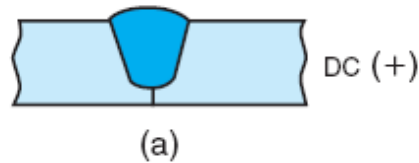
- In *arc welding*, the heat required is obtained from electrical energy
- Process involves a *consumable* or a *nonconsumable electrode*
- In *nonconsumable-electrode* welding processes, the electrode is a **tungsten electrode**



Arc-welding Processes:

Nonconsumable Electrode

- In **straight polarity**, the workpiece is positive (anode) and the electrode is negative (cathode)
- It produces welds that are narrow and deep
- In **reverse polarity**, the workpiece is negative and the electrode is positive
- The weld zone is shallower and wider



Arc-welding Processes:

Nonconsumable Electrode

Heat Transfer in Arc Welding

- The heat input in arc welding is given by

$$\frac{H}{l} = e \frac{VI}{v}$$

H = heat input (J or BTU)

l = weld length

V = voltage applied

I = current (amperes)

v = welding speed

- The heat input that melts a certain volume of material is

$$H = uV_m = uAl$$

u = specific energy required for melting

V_m = volume of material melted

A = cross section of the weld

Arc-welding Processes:

Nonconsumable Electrode

Heat Transfer in Arc Welding

- Expression for the welding speed is $v = e \frac{VI}{uA}$

Approximate Specific Energies Required to Melt a Unit Volume of Commonly Welded Metals

Material	Specific energy, u J/mm ³
Aluminum and its alloys	2.9
Cast irons	7.8
Copper	6.1
Bronze (90Cu–10Sn)	4.2
Magnesium	2.9
Nickel	9.8
Steels	9.1–10.3
Stainless steels	9.3–9.6
Titanium	14.3

Arc-welding Processes:

Nonconsumable Electrode

EXAMPLE 30.1

Welding Speed for Different Materials

Consider a situation in which a welding operation is being performed with 20 volts, 200 A, and the cross-sectional area of the weld bead is 30 mm^2 . Estimate the welding speed if the workpiece and electrode are made of (a) aluminum, (b) carbon steel, and (c) titanium. Use an efficiency of 75%.

Arc-welding Processes:

Nonconsumable Electrode

Solution

Welding Speed for Different Materials

From Table, we have for aluminum

$$v = e \frac{VI}{uA} = (0.75) \frac{(20)(200)}{(2.9)(30)} = 34.5 \text{ mm/s}$$

For carbon steel, $v = 10.3 \text{ mm/s}$

For titanium, $v = 7.0 \text{ mm/s}$

Arc-welding Processes:

Nonconsumable Electrode

Gas Tungsten-arc Welding

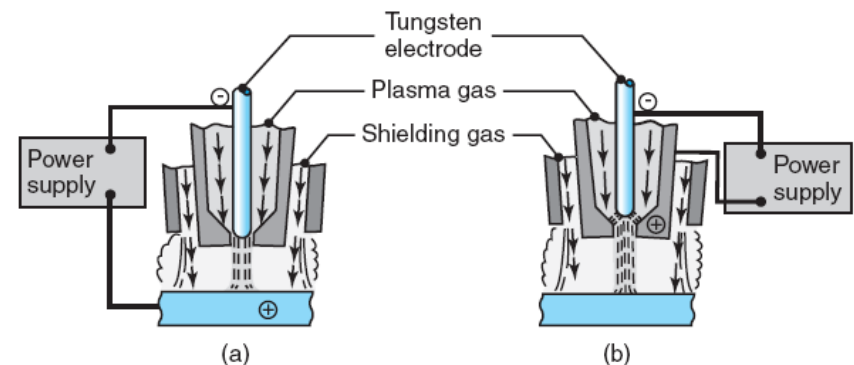
- The filler metal is supplied from a **filler wire**
- As the tungsten electrode is not consumed, a constant and stable *arc gap* is maintained at a constant current level
- GTAW process is used for applications with aluminum, magnesium, titanium and the refractory metals
- Cost of the inert gas is more expensive but provides high quality welds and surface finish

Arc-welding Processes:

Nonconsumable Electrode

Plasma-arc Welding

- A concentrated plasma arc is produced and directed towards the weld area
- A **plasma** is an ionized hot gas composed of nearly equal numbers of electrons and ions
- 2 methods of plasma-arc welding:
 1. **Transferred-arc**
 2. **Non-transferred arc**



Arc-welding Processes:

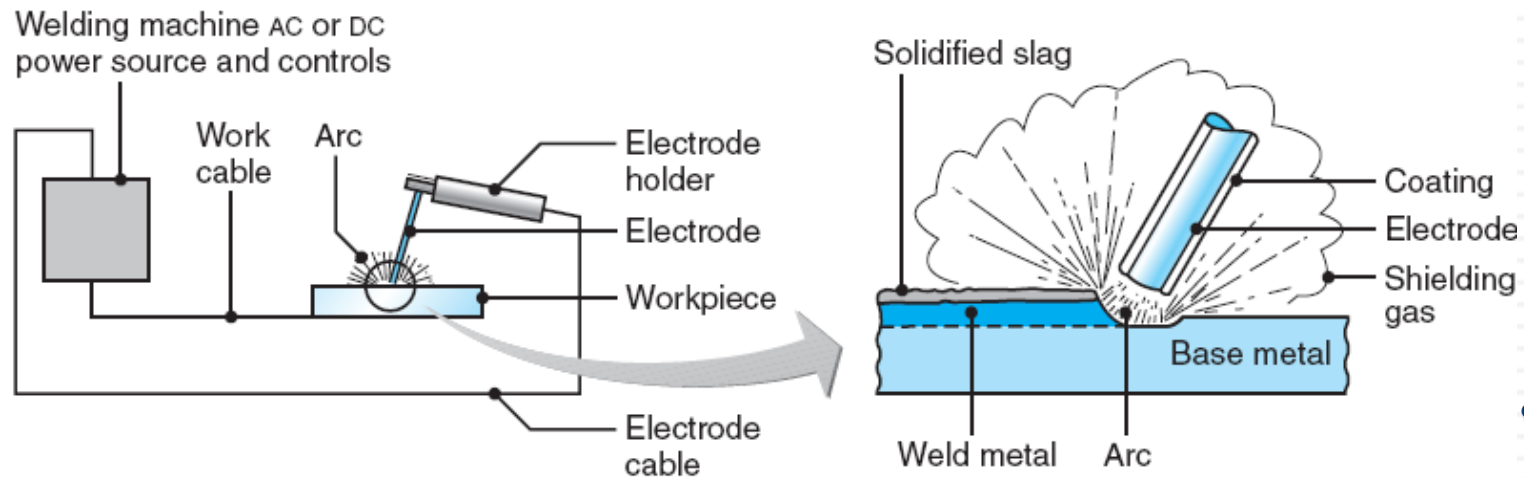
Nonconsumable Electrode

Atomic-hydrogen Welding

- An arc is generated between two tungsten electrodes in a shielding atmosphere of hydrogen gas
- The arc is maintained independently of the workpiece or parts being welded
- When hydrogen strikes the cold surface, it recombines into its diatomic form and releases the stored heat

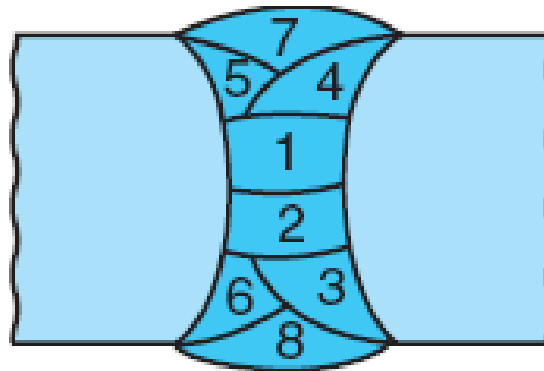
Arc-welding Processes: Consumable Electrode-Shielded Metal-arc Welding

- *Shielded metal-arc welding* (SMAW) is one of the oldest, simplest, and most versatile joining processes
- Electric arc is generated by tip of a *coated electrode* against the workpiece



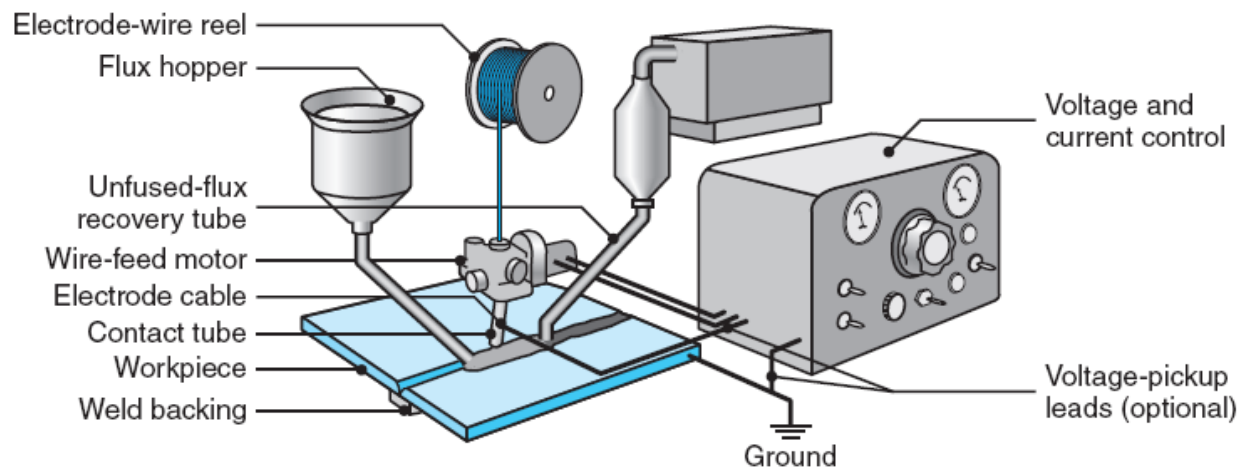
Arc-welding Processes: Consumable Electrode - Shielded Metal-arc Welding

- It is simple, versatile and requiring a smaller variety of electrodes
- The multiple-pass approach requires that the slag be removed after each weld bead



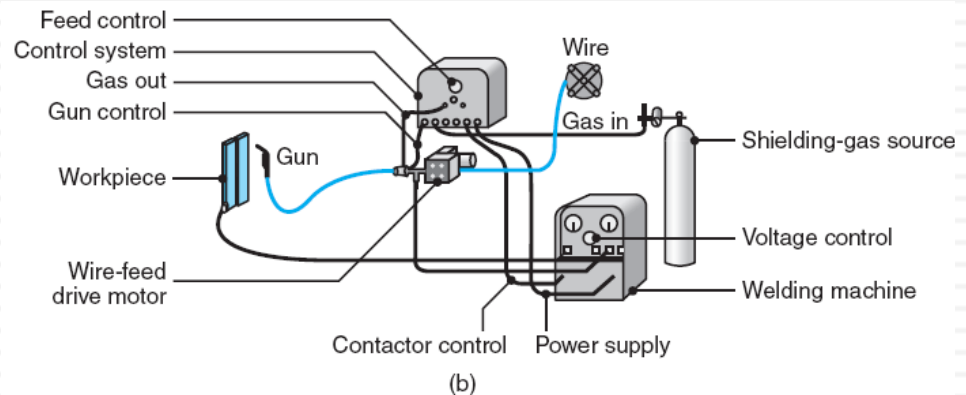
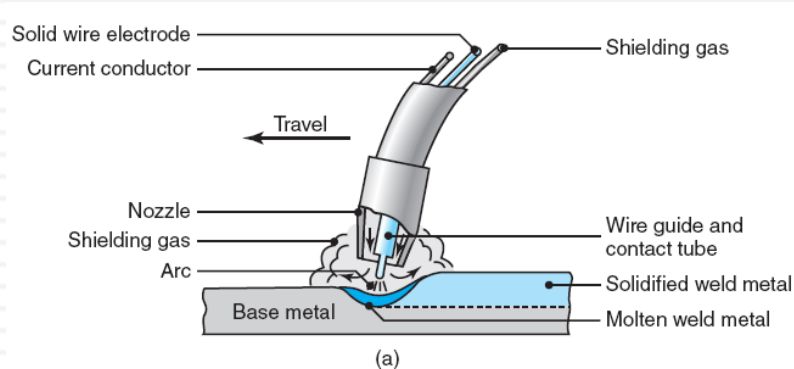
Arc-welding Processes: Consumable Electrode - Submerged-arc Welding

- The weld arc is shielded by a *granular flux*
- The flux is fed into the weld zone from a hopper by gravity flow through a nozzle
- SAW process is limited to welds in a flat or horizontal position having a backup piece



Arc-welding Processes: Consumable Electrode-Gas Metal-arc Welding

- The weld area is shielded by an effectively inert atmosphere of gases
- The consumable bare wire is fed automatically through a nozzle into the weld arc by a wire-feed drive motor

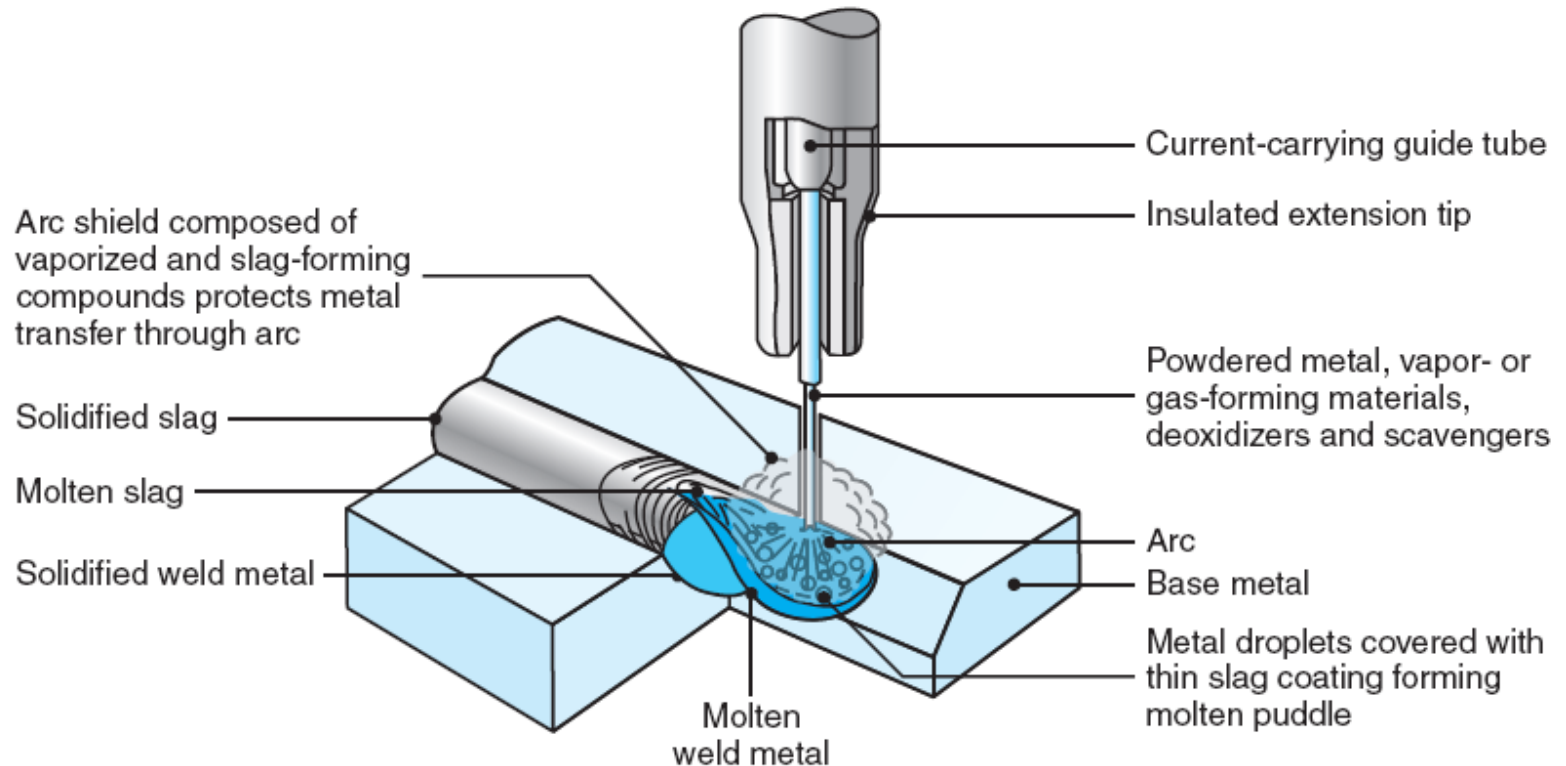


Arc-welding Processes: Consumable Electrode-Gas Metal-arc Welding

- Metal can be transferred by 3 methods in the GMAW process:
 1. **Spray transfer**
 2. **Globular transfer**
 3. **Short circuiting**
- The temperatures generated in GMAW are relatively low
- Suitable for welding most ferrous and nonferrous metals

Arc-welding Processes: Consumable Electrode - Flux-cored Arc Welding

- Similar to gas metal-arc welding, except that the electrode is tubular in shape and is filled with flux

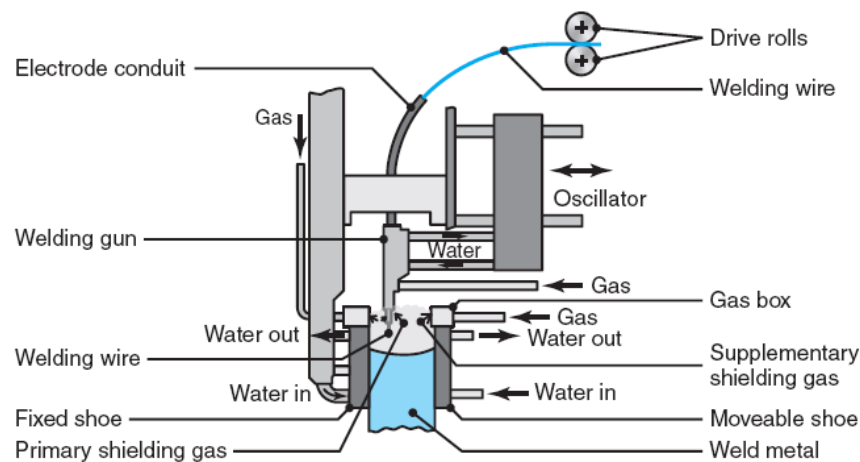


Arc-welding Processes: Consumable Electrode - Flux-cored Arc Welding

- FCAW process combines the versatility of SMAW with the continuous and automatic electrode-feeding feature of GMAW
- Major advantage of FCAW is the ease with which specific weld-metal chemistries can be developed

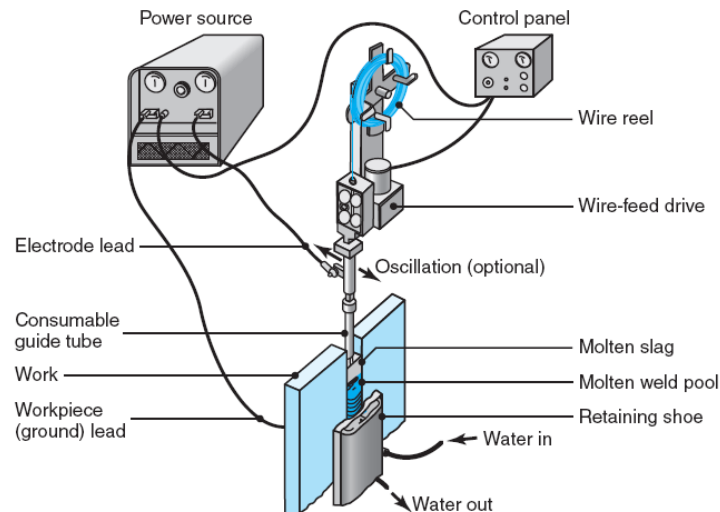
Arc-welding Processes: Consumable Electrode - Electrogas Welding

- Used for welding the edges of sections vertically and in one pass with the pieces placed edge to edge
- The weld metal is deposited into a weld cavity between the two pieces to be joined



Arc-welding Processes: Consumable Electrode - Electroslag Welding

- Main difference is that the arc is started between the electrode tip and the bottom of the part to be welded
- Flux is added and melts by the heat of the arc
- Weld quality is good and used for large structural-steel sections



Electrodes for Arc Welding

- *Electrodes* for consumable arc-welding processes are classified by:
 1. Strength of the deposited weld metal
 2. Current (AC or DC)
 3. Type of coating

Designations for Mild-steel Coated Electrodes

The prefix “E” designates arc welding electrode.

The first two digits of four-digit numbers and the first three digits of five-digit numbers indicate *minimum tensile strength*:

E60XX	60,000 psi
E70XX	70,000
E110XX	110,000

The next-to-last digit indicates position:

EXX1X	All positions
EXX2X	Flat position and horizontal fillets

The last two digits together indicate the type of covering and the current to be used.

The suffix (Example: EXXXX-A1) indicates the approximate alloy in the weld deposit:

—A1	0.5% Mo
—B1	0.5% Cr, 0.5% Mo
—B2	1.25% Cr, 0.5% Mo
—B3	2.25% Cr, 1% Mo
—B4	2% Cr, 0.5% Mo
—B5	0.5% Cr, 1% Mo
—C1	2.5% Ni
—C2	3.25% Ni
—C3	1% Ni, 0.35% Mo, 0.15% Cr
—D1 and D2	0.25–0.45% Mo, 1.75% Mn
—G	0.5% min. Ni, 0.3% min. Cr, 0.2% min. Mo, 0.1% min. V, 1% min. Mn (only one element required)

Note: Multiply pounds per square in. (psi) by 6.9×10^{-3} to obtain megapascals (MPa).



Electrodes for Arc Welding

Electrode Coatings

- The coating is brittle and takes part in complex interactions during welding
- Basic functions:
 1. Stabilize the arc.
 2. Generate gases to act as a shield
 3. Control the rate at which the electrode melts
 4. Act as a flux to protect the weld
 5. Add alloying elements to the weld zone to enhance the properties of the joint

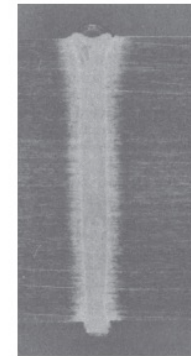
Electron-beam Welding

- Heat is generated by high velocity narrow-beam electrons
- The kinetic energy of the electrons is converted into heat as they strike the workpiece
- Process requires special equipment to focus the beam on the workpiece, typically in a vacuum
- Almost any metal can be welded by EBW
- The weld quality is good and of very high purity

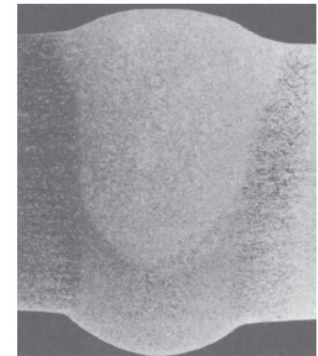


Laser-beam Welding

- Utilizes a high-power laser beam as the source of heat to produce a fusion weld
- The beam can be focused onto a very small area
- Process is suitable particularly for welding deep and narrow joints
- Produces welds of good quality with minimum shrinkage or distortion



(a)



(b)

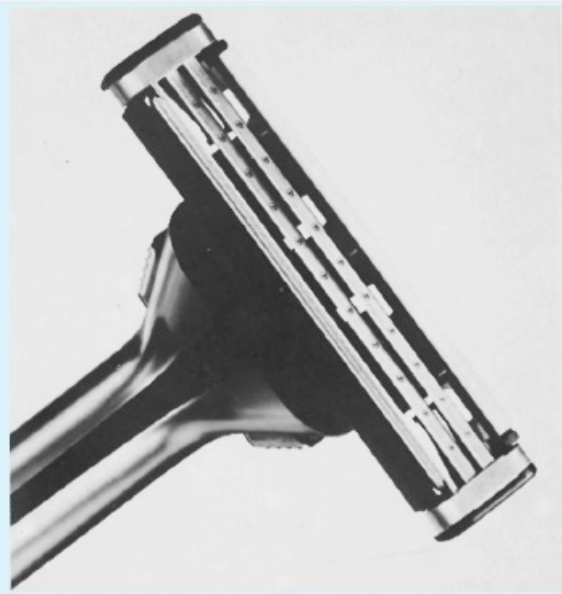


Laser-beam Welding

EXAMPLE 30.2

Laser Welding of Razor Blades

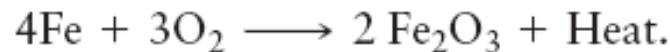
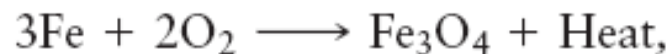
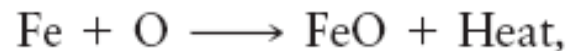
- Detail of Gillette Sensor™ razor cartridge, showing laser spot welds



Cutting

Oxyfuel–gas Cutting

- The heat source is now used to remove a narrow zone from a metal plate or sheet
- Suitable for steels, basic reactions with steel are



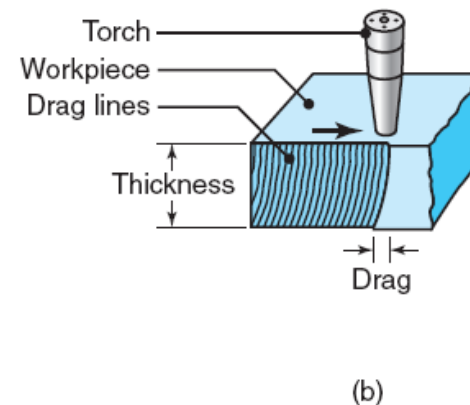
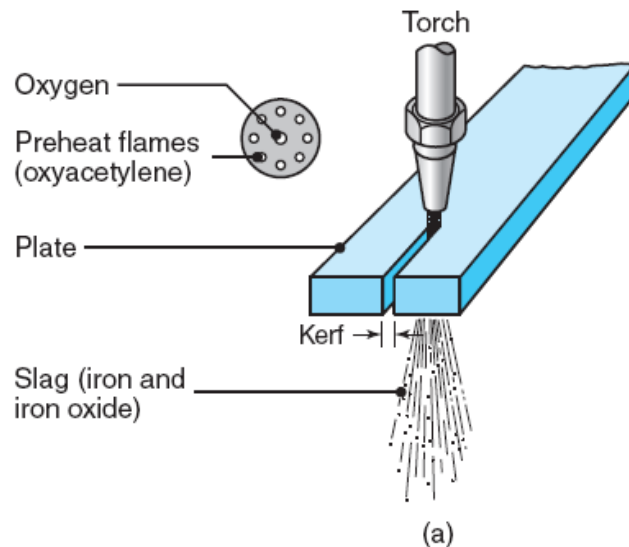
- Greatest heat is generated by the second reaction
- Temperature is not high to cut steels and the workpiece need to *preheat* with fuel gas



Cutting

Oxyfuel–gas Cutting

- The process generates a **kerf**
- Maximum thickness that can be cut by OFC depends mainly on the gases used



Cutting

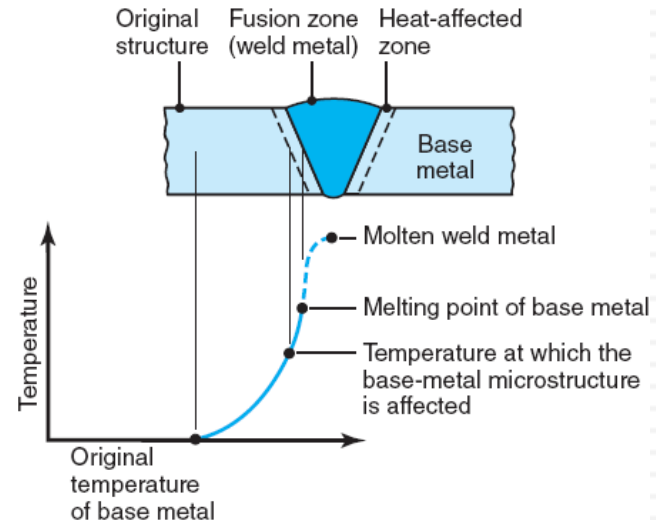
Arc Cutting

- Based on the same principles as arc-welding processes
- A variety of materials can be cut, leave a heat-affected zone that needs to be taken into account
- In **air carbon-arc cutting (CAC-A)**, a carbon electrode is used and the molten metal is blown away by a high-velocity air jet
- **Plasma-arc cutting (PAC)** used for rapid cutting of nonferrous and stainless-steel plates

The Weld Joint, Quality, and Testing

- 3 distinct zones can be identified in a typical weld joint:

1. **Base metal**
2. **Heat-affected zone**
3. **Weld metal**



- Metallurgy and properties of the second and third zones depend strongly on the type of metals joined



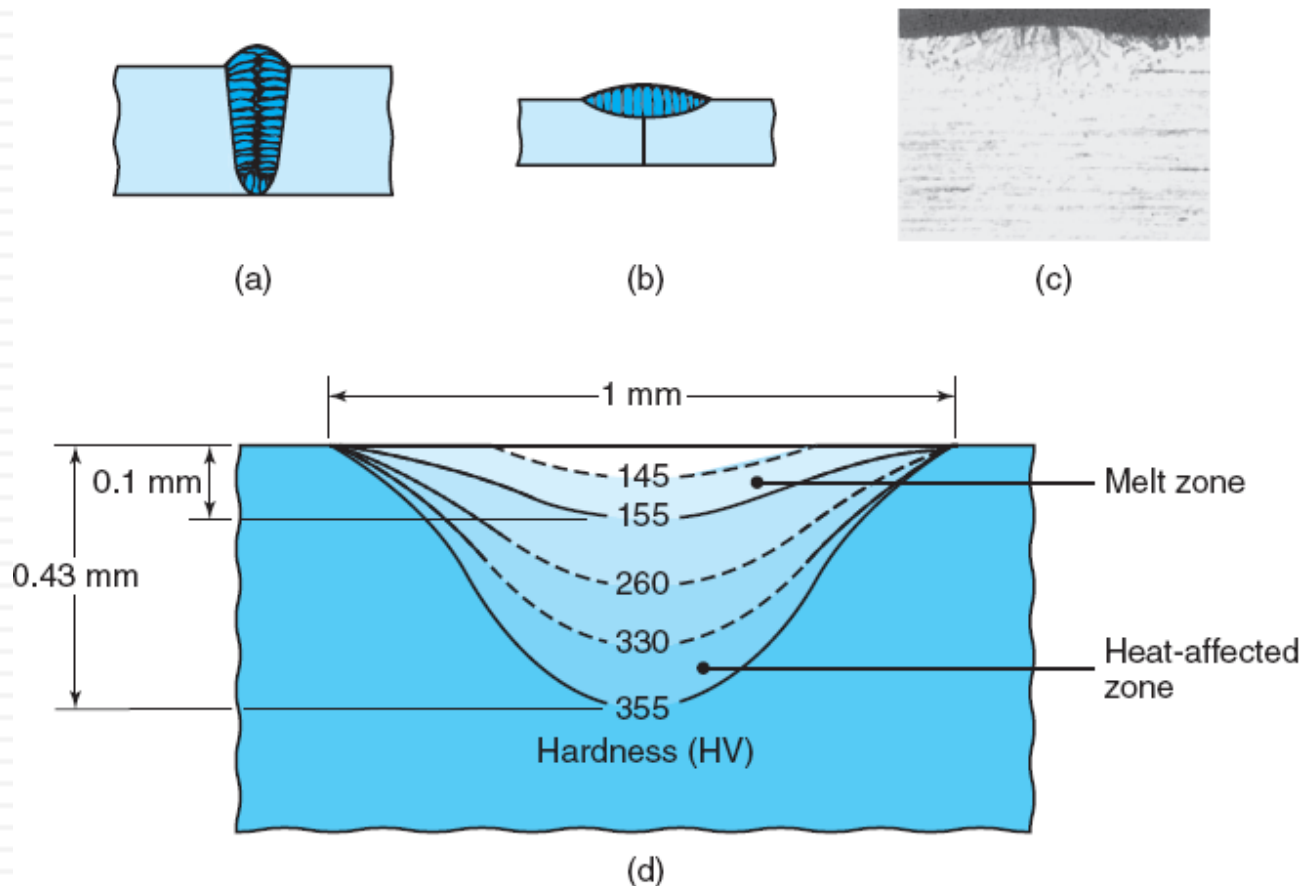
The Weld Joint, Quality, and Testing

Solidification of the Weld Metal

- *Solidification* process is similar to that in casting and begins with the formation of columnar (dendritic) grains
- Grain structure and grain size depend on the specific metal alloy, the welding process employed and the type of filler metal

The Weld Joint, Quality, and Testing

Solidification of the Weld Metal



The Weld Joint, Quality, and Testing

Heat-affected Zone

- The strength and hardness depend on the original strength and hardness of the base metal
- The heat applied during welding *recrystallizes* the elongated grains of the coldworked base metal
- The effects of heat on the HAZ for joints are too complex

The Weld Joint, Quality, and Testing:

Weld Quality

- A welded joint may develop various **discontinuities**
- Can be caused by an inadequate or careless application of proper welding technologies or by poor operator training

Porosity

- Caused by gases released during melting of the weld area, chemical reactions and contaminants

The Weld Joint, Quality, and Testing:

Weld Quality

Porosity

- Can be reduced by:
 1. Proper selection of electrodes and filler metals
 2. Improved welding techniques
 3. Proper cleaning and the prevention of contaminants
 4. Reduced welding speeds

The Weld Joint, Quality, and Testing:

Weld Quality

Slag Inclusions

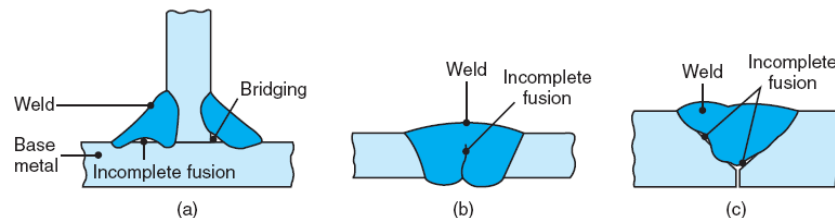
- *Slag inclusions* are compounds and electrode coating materials that are trapped in the weld zone
- Can be prevented by:
 1. Cleaning the weld-bead surface
 2. Providing sufficient shielding gas
 3. Redesigning the joint

The Weld Joint, Quality, and Testing:

Weld Quality

Incomplete Fusion and Penetration

- Produces poor weld beads
- Better weld can be obtained by:
 1. Raising the temperature of the base metal
 2. Cleaning the weld area before welding
 3. Modifying the joint design
 4. Providing sufficient shielding gas

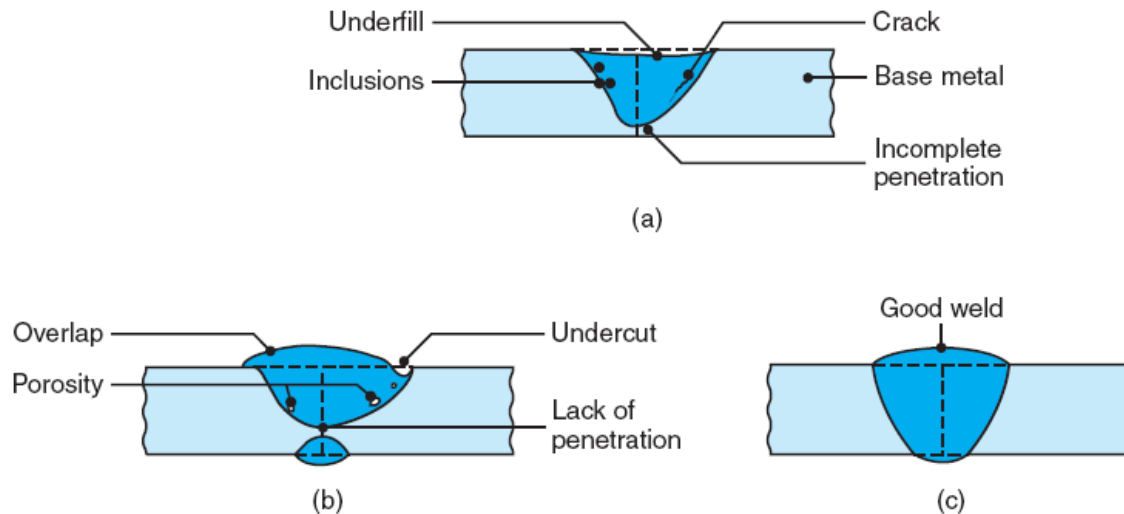


The Weld Joint, Quality, and Testing:

Weld Quality

Weld Profile

- It is important because its effects on the strength and appearance of the weld, indicate incomplete fusion or the presence of slag inclusions in multiple-layer welds



The Weld Joint, Quality, and Testing:

Weld Quality

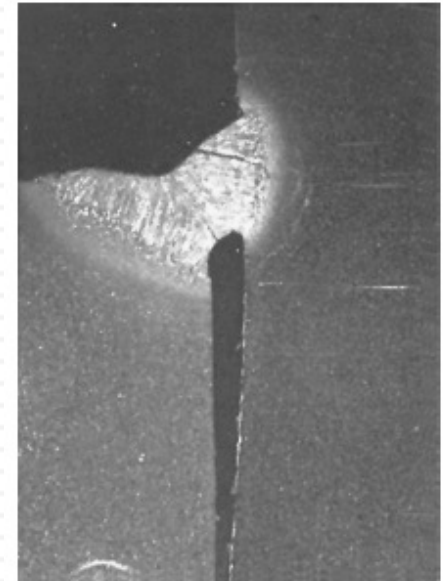
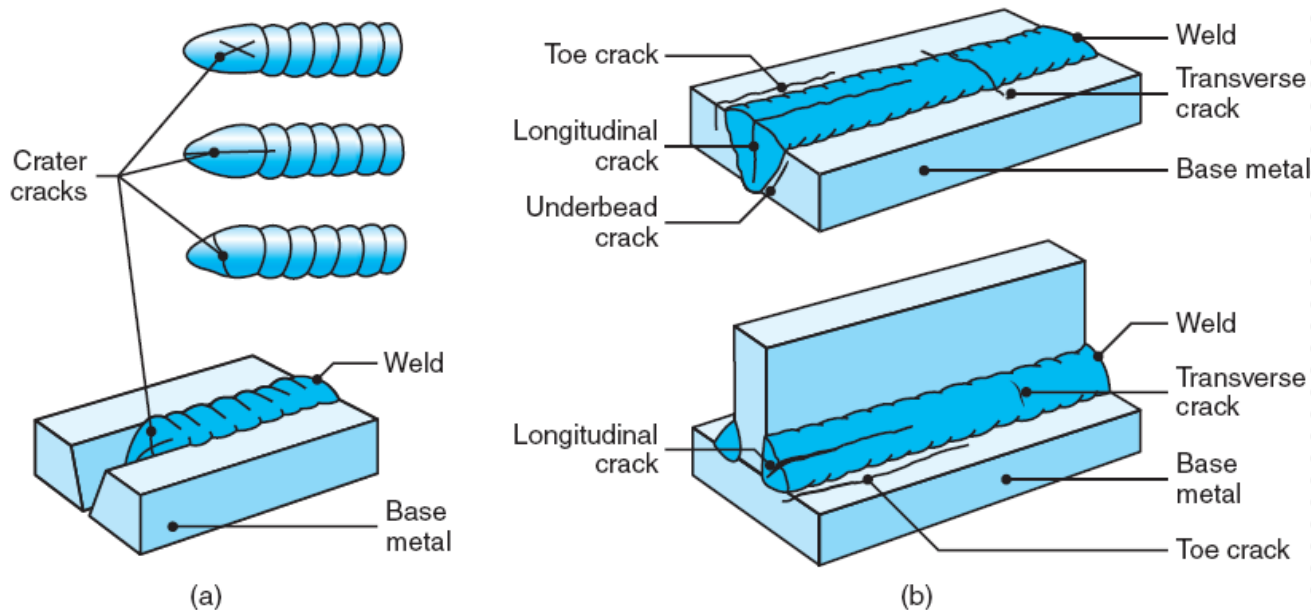
Cracks

- Occur in various locations and directions in the weld area
- Result from a combination of:
 1. Temperature gradients
 2. Variations in the composition of the weld zone
 3. Embrittlement of grain boundaries
 4. Hydrogen embrittlement
 5. Inability of the weld metal to contract during cooling

The Weld Joint, Quality, and Testing:

Weld Quality

Cracks



The Weld Joint, Quality, and Testing:

Weld Quality

Cracks

- Basic crack-prevention measures:
 1. Modify the joint design to minimize stresses
 2. Change the parameters, procedures, and sequence of the welding operation
 3. Preheat the components to be welded
 4. Avoid rapid cooling of the welded components

The Weld Joint, Quality, and Testing:

Weld Quality

Lamellar Tears

- Workpiece is weaker when tested in its thickness direction because of the alignment of nonmetallic impurities and inclusions
- *Lamellar tears* may develop because of shrinkage of the restrained components of the structure during cooling

The Weld Joint, Quality, and Testing:

Weld Quality

Surface Damage

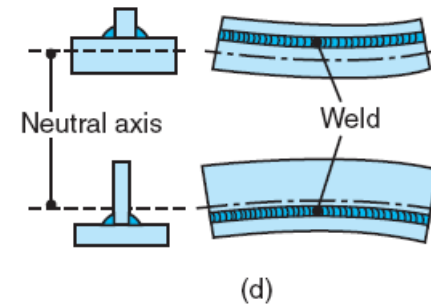
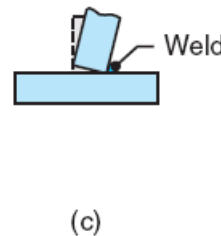
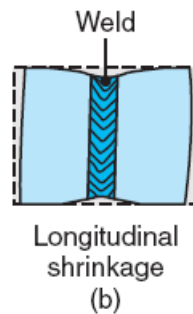
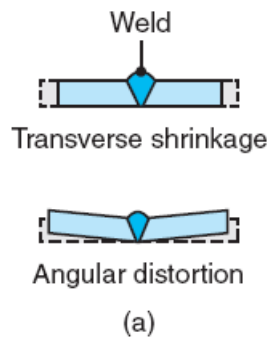
- ❑ Metal will spatter during welding and be deposited as small droplets on adjacent surfaces
- ❑ Surface discontinuities will cause appearance or subsequent use of the welded part disapproval
- ❑ Discontinuities will also affect the properties of the welded structure

The Weld Joint, Quality, and Testing:

Weld Quality

Residual Stresses

- Residual stresses can cause:
 1. Distortion, warping and buckling
 2. Stress-corrosion cracking
 3. Further distortion
 4. Reduced fatigue life

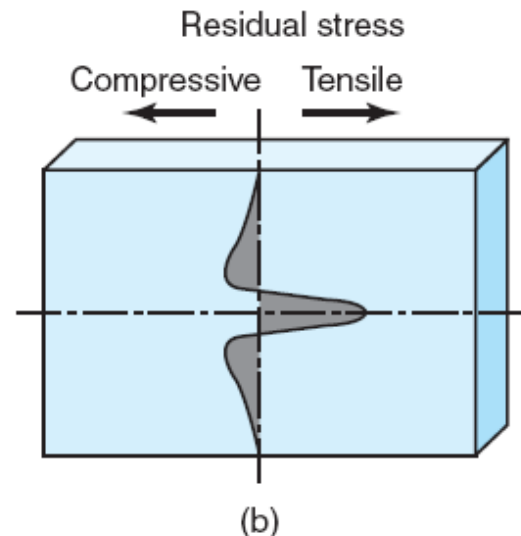
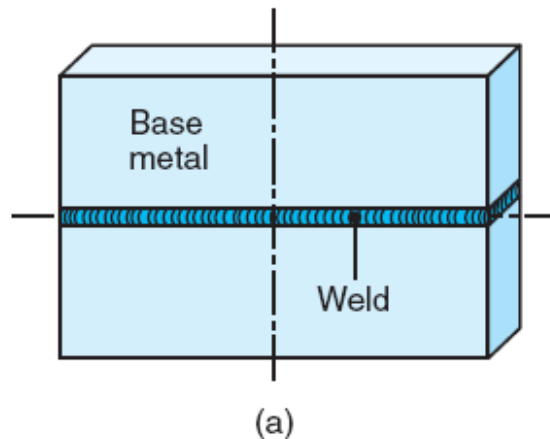


The Weld Joint, Quality, and Testing:

Weld Quality

Residual Stresses

- When two plates are being welded, the plates are at ambient temperature
- If the plate is not free to warp, it will develop residual stresses

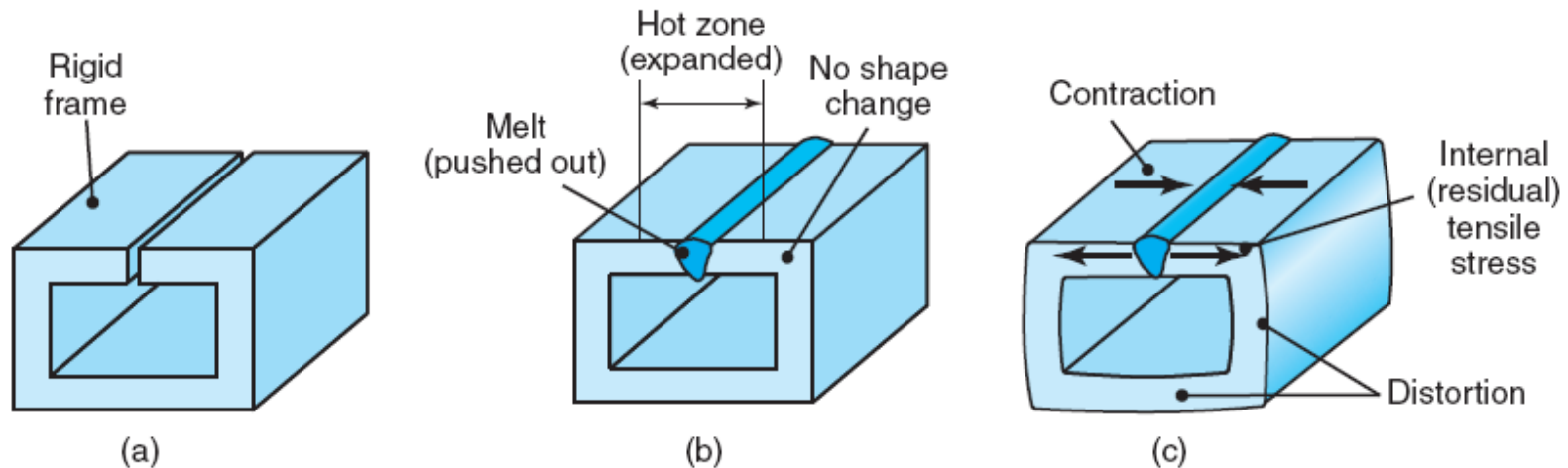


The Weld Joint, Quality, and Testing:

Weld Quality

Residual Stresses

- Distortion of a welded structure is shown
- The residual-stress distribution places the weld and the HAZ in a state of residual tension



The Weld Joint, Quality, and Testing:

Weld Quality

Stress Relieving of Welds

- Problems caused by residual stresses is reduced by **preheating** the base metal or the parts to be welded
- Preheating will reduce the cooling rate and level of thermal stresses developed
- Workpieces may be heated in a furnace, electrically or by radiant lamps for thin sections
- Residual stresses can be relieved by plastically deforming the structure by a small amount

The Weld Joint, Quality, and Testing:

Weldability

- *Weldability* is defined as its capacity to be welded into a specific structure
- Influencing factors include:
 1. Strength, toughness, ductility
 2. Notch sensitivity, elastic modulus, specific heat, melting point, thermal expansion,
 3. Surface-tension characteristics, corrosion resistance

The Weld Joint, Quality, and Testing: Weldability

Weldability of Ferrous Materials

- *Plain-carbon steels*: excellent for low-carbon steels, fair to good for medium-carbon steels, poor for high-carbon steels
- *Low-alloy steels*: similar to medium-carbon steels
- *High-alloy steels*: good under well-controlled conditions
- *Stainless steels*: weldable by various processes
- *Cast irons*: weldable

The Weld Joint, Quality, and Testing: Weldability

Weldability of Nonferrous Materials

- *Aluminium alloys*: weldable at a high heat input rate
- *Copper alloys*: weldable at a high heat input rate
- *Magnesium alloys*: weldable with the use gas and fluxes
- *Nickel alloys*: similar to stainless steels
- *Titanium alloys*: proper use of shielding gases
- *Tantalum*: similar to titanium

The Weld Joint, Quality, and Testing: Weldability

Weldability of Nonferrous Materials

- *Tungsten*: under well-controlled conditions
- *Molybdenum*: similar to tungsten
- *Niobium (columbium)*: good weldability

The Weld Joint, Quality, and Testing:

Testing of Welds

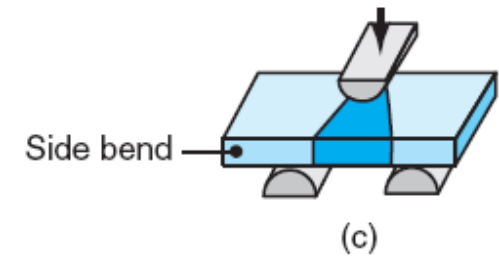
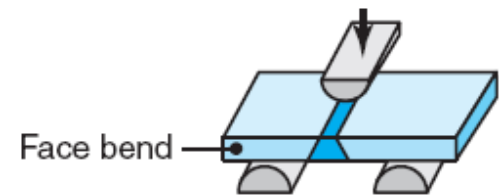
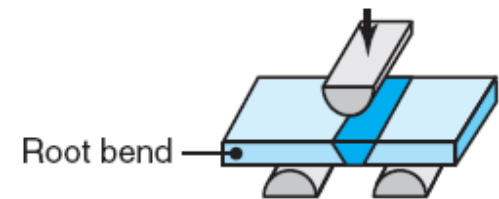
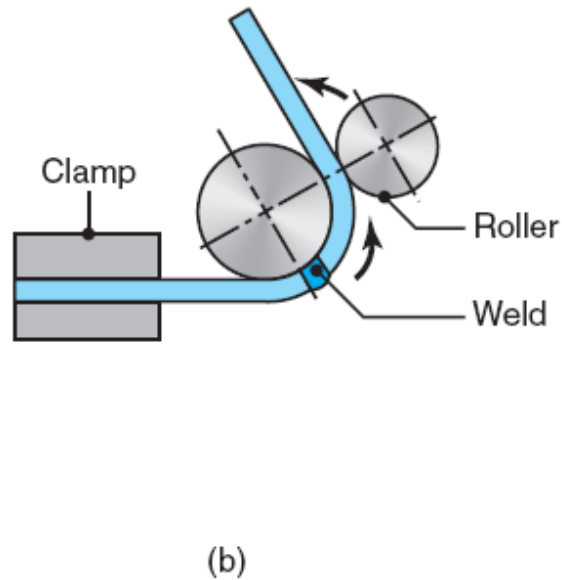
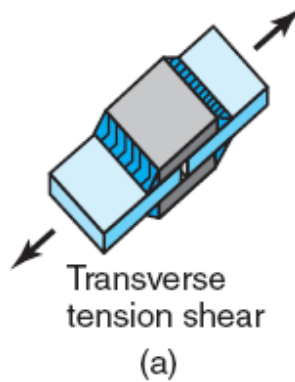
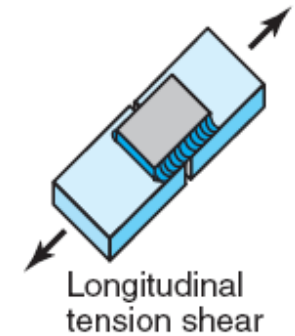
- Quality of a welded joint is established by testing
- Welded joints may be tested *destructively* or *non-destructively*

Destructive Testing Techniques

- 1) Tension test
- 2) Tension-shear test
- 3) Bend test
- 4) Fracture toughness test
- 5) Corrosion and creep tests

The Weld Joint, Quality, and Testing:

Testing of Welds



The Weld Joint, Quality, and Testing:

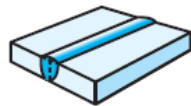
Testing of Welds

Nondestructive Testing Techniques

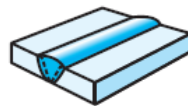
- Test for critical applications in which weld failure can be catastrophic
- Consist of the following methods:
 1. **Visual**
 2. **Radiographic (X-rays)**
 3. **Magnetic-particle**
 4. **Liquid-penetrant**
 5. **Ultrasonic**

Joint Design and Process Selection

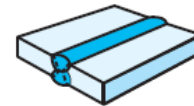
□ Examples of welded joints and their terminology



(a) Single square-groove weld



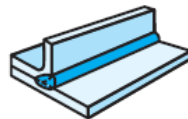
(b) Single V-groove weld



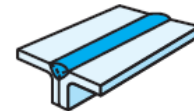
(c) Double V-groove weld



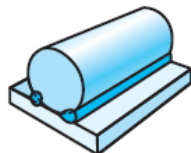
(d) Single V-groove weld
(with backing)



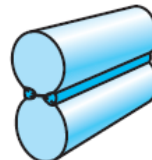
(e) Single-flare
bevel-groove weld



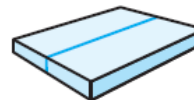
(f) Single-flare
V-groove weld



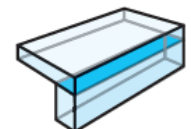
(g) Double-flare
bevel-groove weld



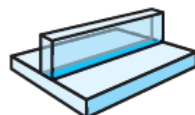
(h) Double-flare
V-groove weld



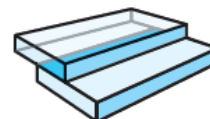
(i) Butt joint



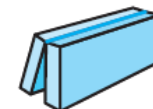
(j) Corner joint



(k) T joint



(l) Lap joint



(m) Edge joint

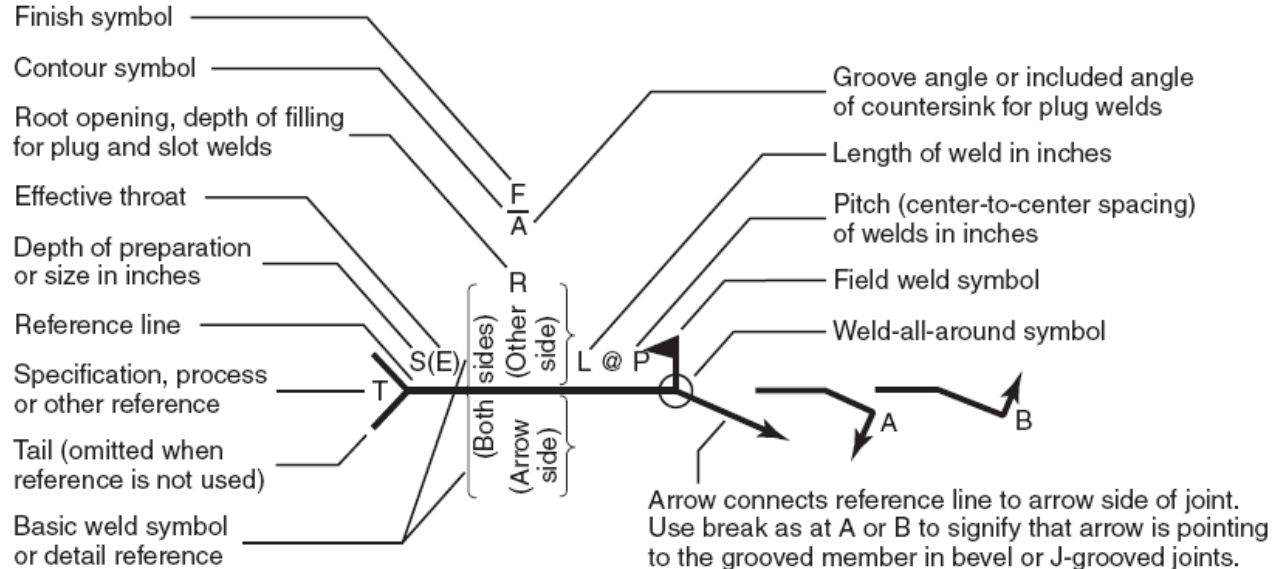


Joint Design and Process Selection

□ Standard identification and symbols for welds

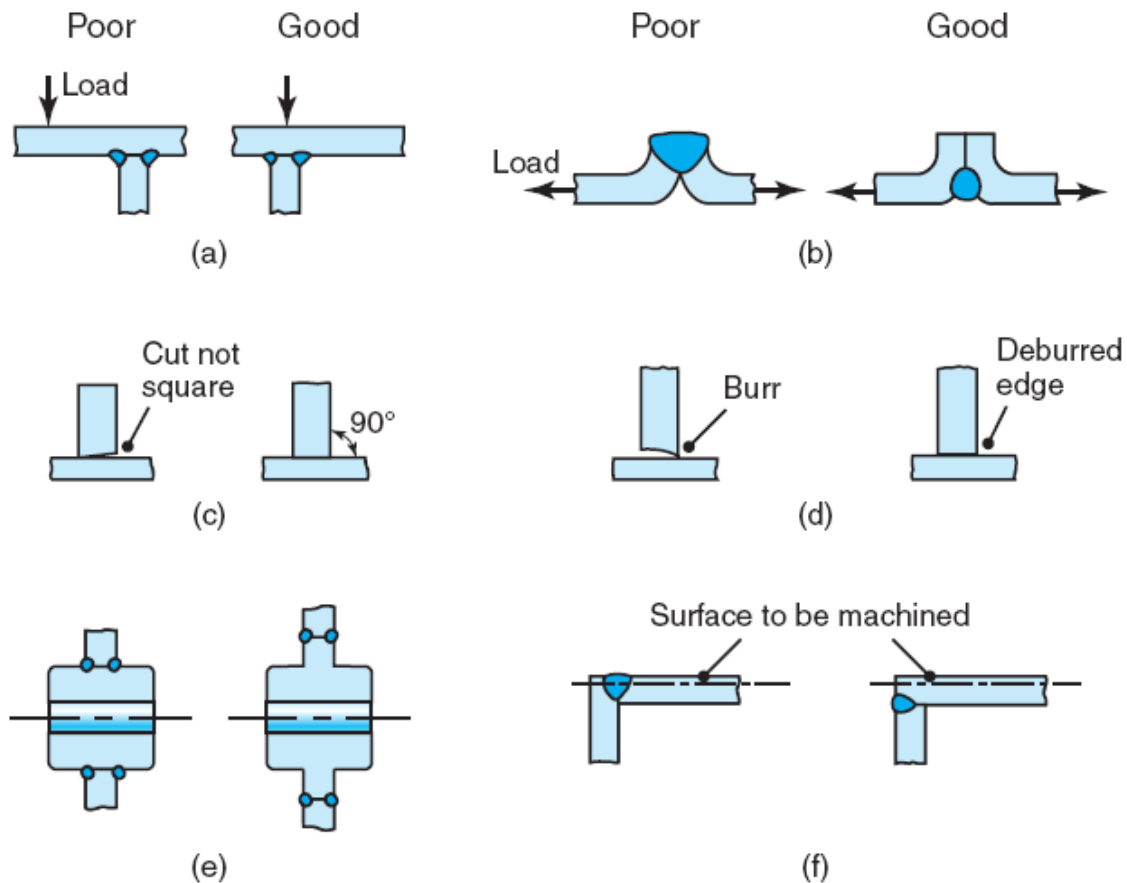
Basic arc- and gas-weld symbols							
Bead	Fillet	Plug or slot	Groove				
			Square	V	Bevel	U	J

Basic resistance-weld symbols			
Spot	Projection	Seam	Flash or upset



Joint Design and Process Selection

□ Some design guidelines for welds



Joint Design and Process Selection

- General design guidelines for welding:
 1. Minimize the number of welds
 2. Weld located to avoid excessive stresses
 3. Weld located not to interfere with other joined components
 4. Components should fit properly prior to welding
 5. Need for edge preparation should be avoided
 6. Weld-bead size should be small

Joint Design and Process Selection

Welding Process Selection

- Selection of a weld joint and an appropriate welding process involve:
 1. Configuration of the parts or structure to be joined
 2. Manufacturing methods
 3. Types of materials
 4. Location, accessibility, and ease of joining
 5. Application and service requirements
 6. Effects of distortion

Joint Design and Process Selection

Welding Process Selection

7. Costs involved in edge preparation
8. Costs of equipment

Joint Design and Process Selection

EXAMPLE 30.3

Weld Design Selection

- Examples of weld designs used

