Weld Joints

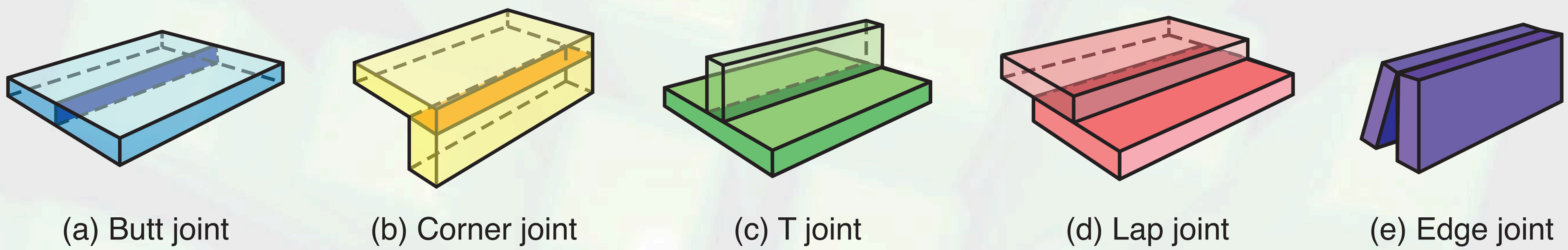

FIGURE 12.1 Examples of welded joints.

Method	Strength	Design Variability	Small Parts	Large Parts	Tolerances	Relibility	Ease of Maintenance	Visual Inspection	Cost
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, 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.

TABLE 12.1 Comparison of various joining methods.

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General Summary

Joining Process	Operation	Advantage	Skill Level Required	Welding Position	Current Type	Distortion*	Cost of Equipment
Shielded metal arc	Manual	Portable and flexible	High	All	ac, dc	1 to 2	Low
Submerged arc	Automatic	High deposition	Low to medium	Flat and horizontal	ac, dc	1 to 2	Medium
Gas metal arc	Semiautomatic or automatic	Works with most metals	Low to high	All	dc	2 to 3	Medium to high
Gas tungsten arc	Manual or automatic	Works with most metals	Low to high	All	ac, dc	2 to 3	Medium
Flux-cored arc	Semiautomatic or automatic	High deposition	Low to high	All	dc	1 to 3	Medium
Oxyfuel	Manual	Portable and flexible	High	All	–	2 to 4	Low
Electron beam, laser beam	Semiautomatic or automatic	Works with most metals	Medium to high	All	–	3 to 5	High

* 1, highest; 5, lowest

TABLE 12.2 General characteristics of joining processes.

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Oxyfuel Gas Welding

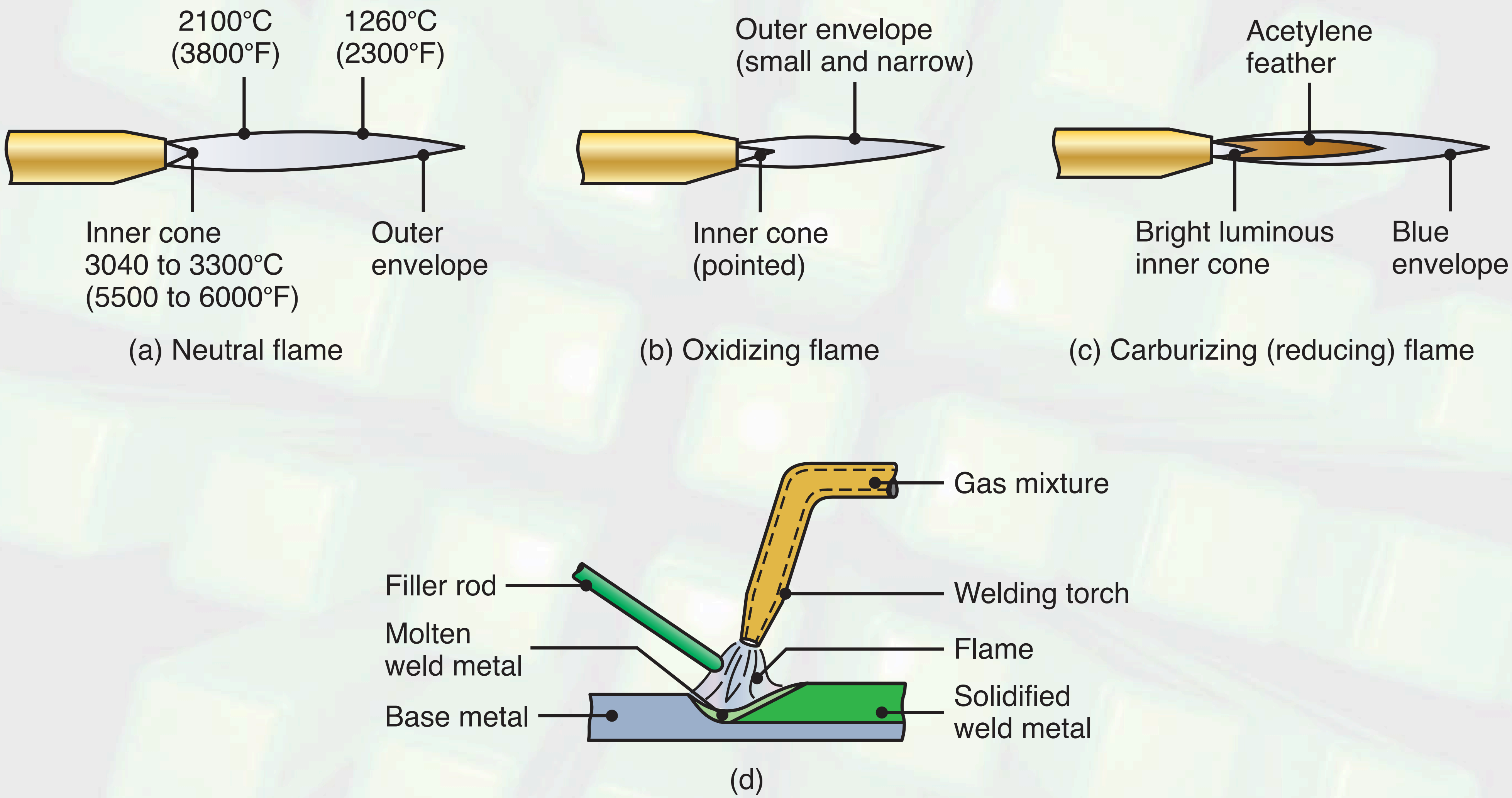

FIGURE 12.2 Three basic types of oxyacetylene flames used in oxyfuel gas welding and cutting operations: (a) neutral flame; (b) oxidizing flame; (c) carburizing, or reducing, flame. (d) The principle of the oxyfuel gas welding operation.

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Pressure Gas Welding

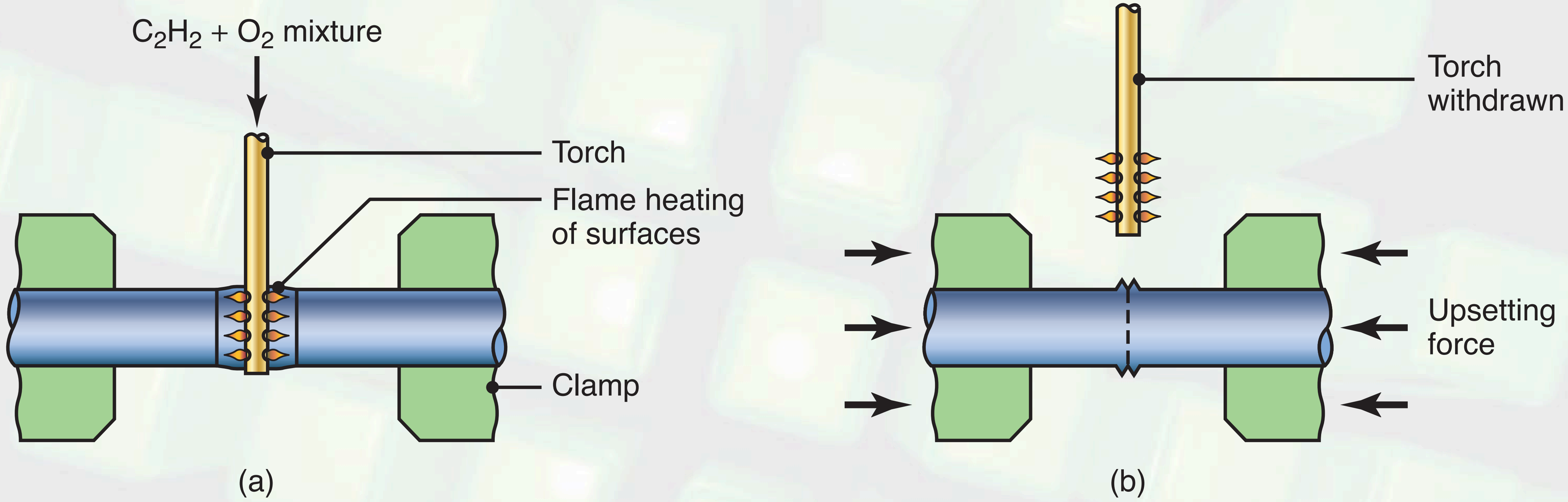

FIGURE 12.3 Schematic illustration of the pressure gas welding process; (a) before, and (b) after. Note the formation of a flash at the joint, which can later be trimmed off.

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Heat Transfer in Welding

Material	Specific Energy, u	
	J/mm^3	BTU/in^3
Aluminum and its alloys	2.9	41
Cast irons	7.8	112
Copper	6.1	87
Bronze (90Cu-10Sn)	4.2	59
Magnesium	2.9	42
Nickel	9.8	142
Steels	9.1-10.3	128-146
Stainless steels	9.3-9.6	133-137
Titanium	14.3	204

TABLE 12.3 Approximate specific energy required to melt a unit volume of commonly welded materials.

Heat input

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

Welding speed

$$v = e\frac{VI}{uA}$$

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Shielded Metal Arc Welding

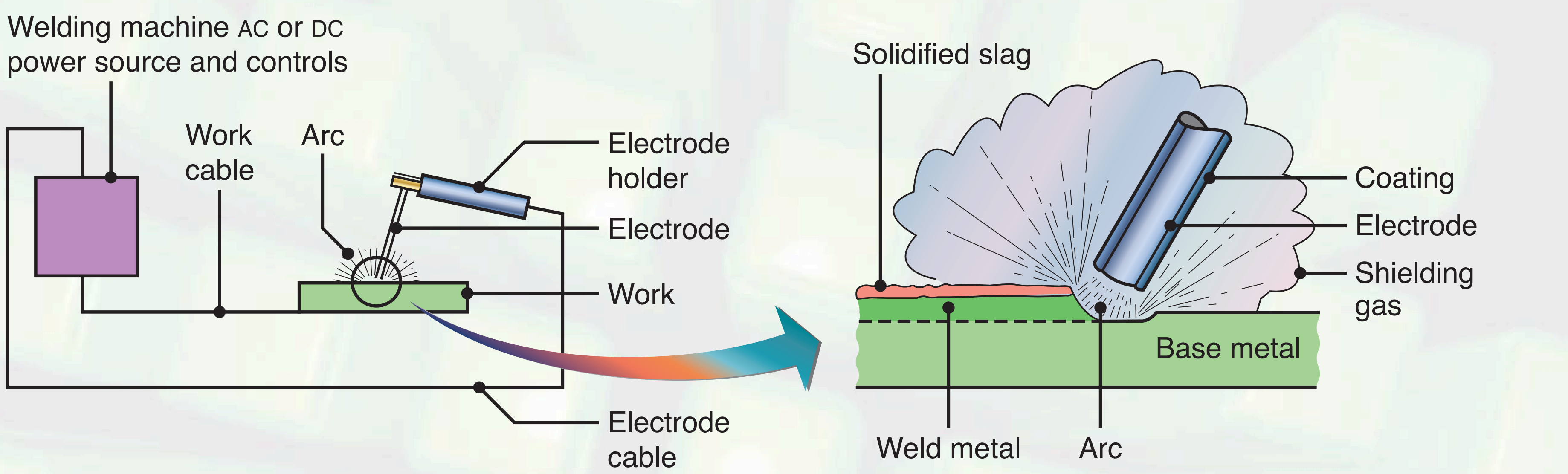

FIGURE 12.4 (a) Schematic illustration of the shielded metal arc welding process. About one-half of all large-scale industrial welding operations use this process. (b) Schematic illustration of the shielded metal arc welding operation.

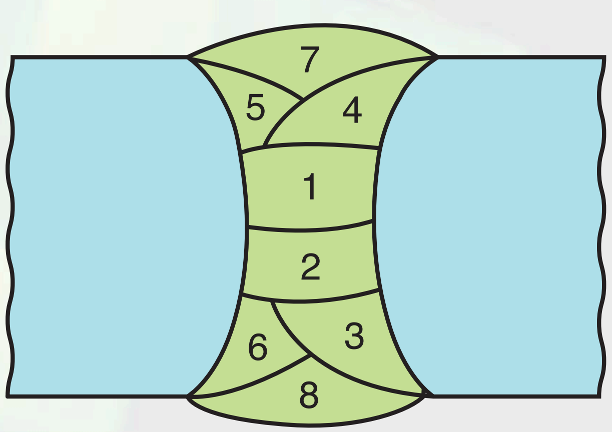

FIGURE 12.5 A weld zone showing the build-up sequence of individual weld beads in deep welds.

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Submerged Arc Welding

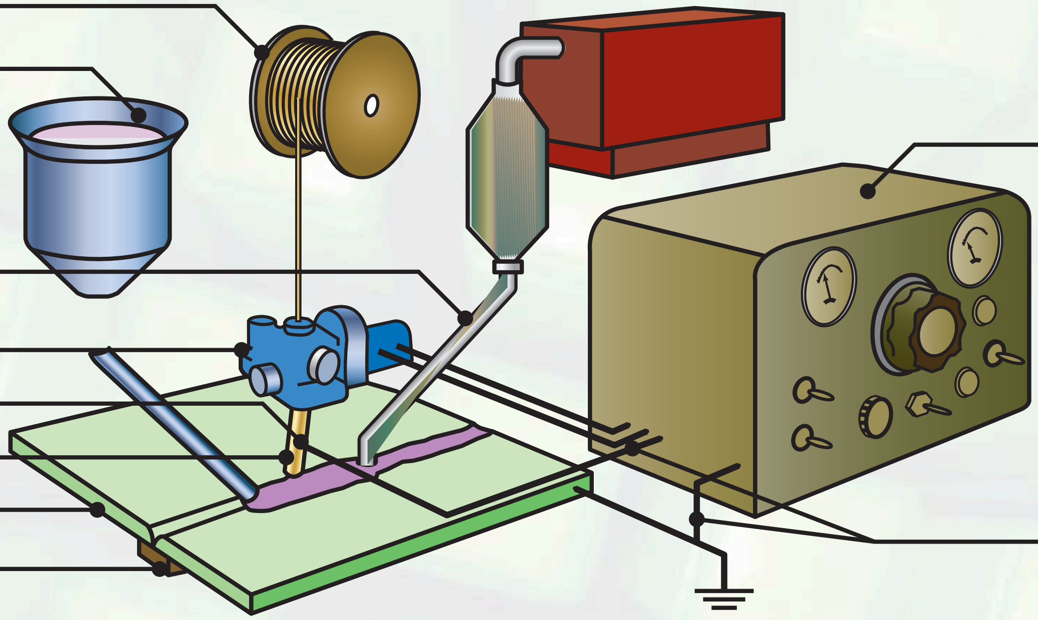

FIGURE 12.6 Schematic illustration of the submerged arc welding process and equipment. Unfused flux is recovered and reused.

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Gas Metal Arc Welding

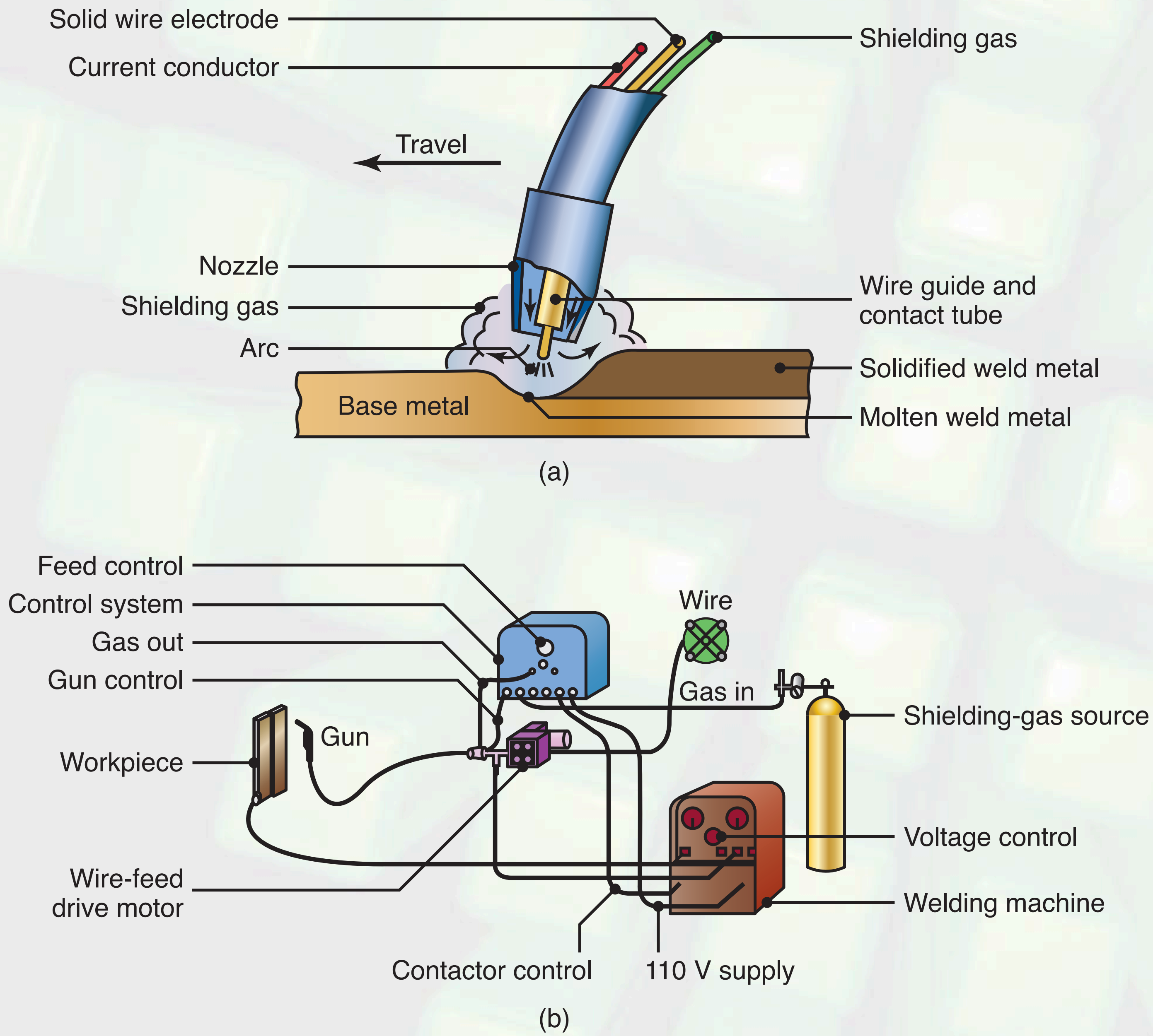

FIGURE 12.7 (a) Gas metal arc welding process, formerly known as MIG welding (for metal inert gas). (b) Basic equipment used in gas metal arc welding operations.

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Flux-Cored Arc Welding

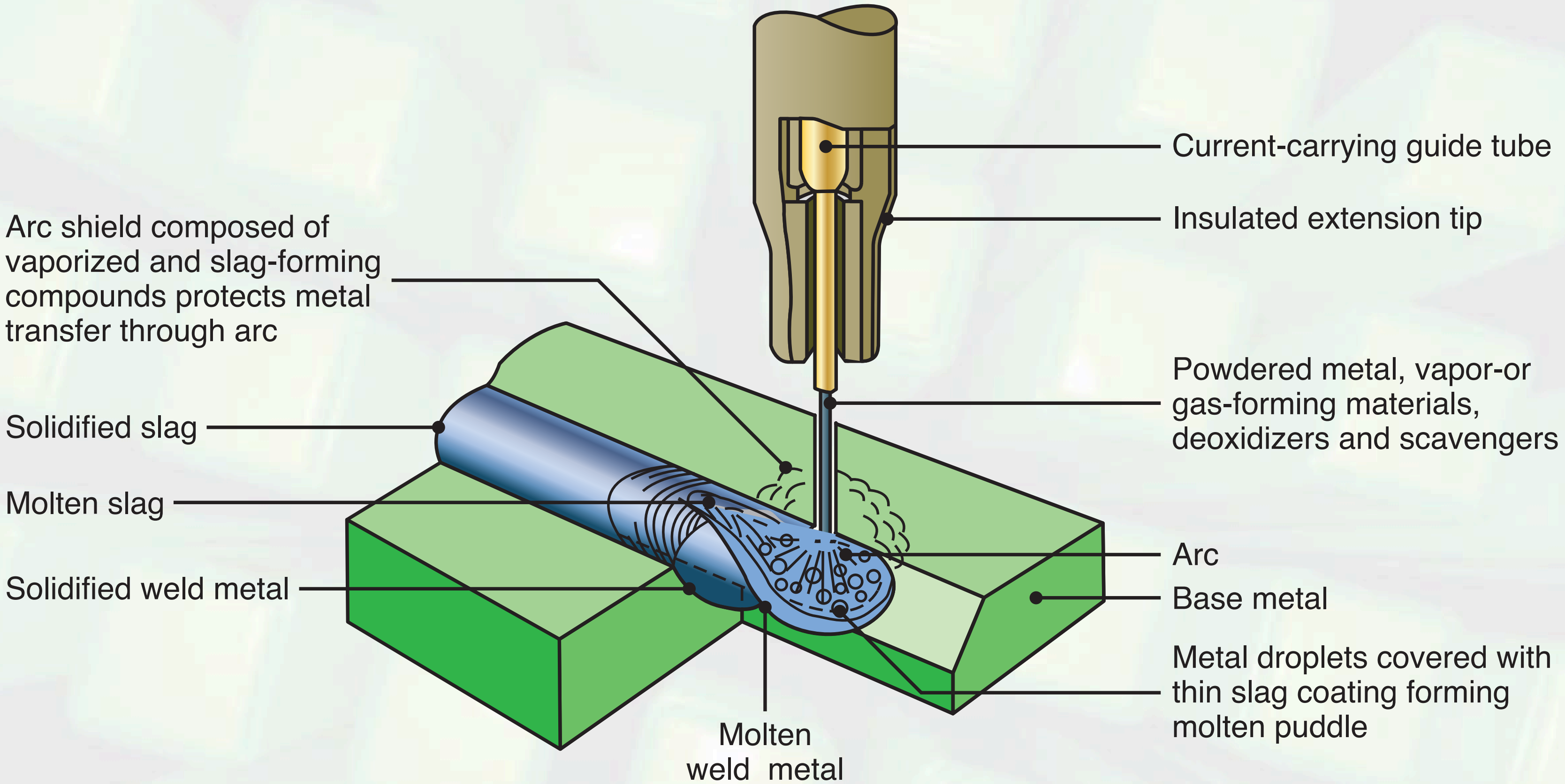

FIGURE 12.8 Schematic illustration of the flux-cored arc welding process. This operation is similar to gas metal arc welding.

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Electrogas & Electroslag Welding

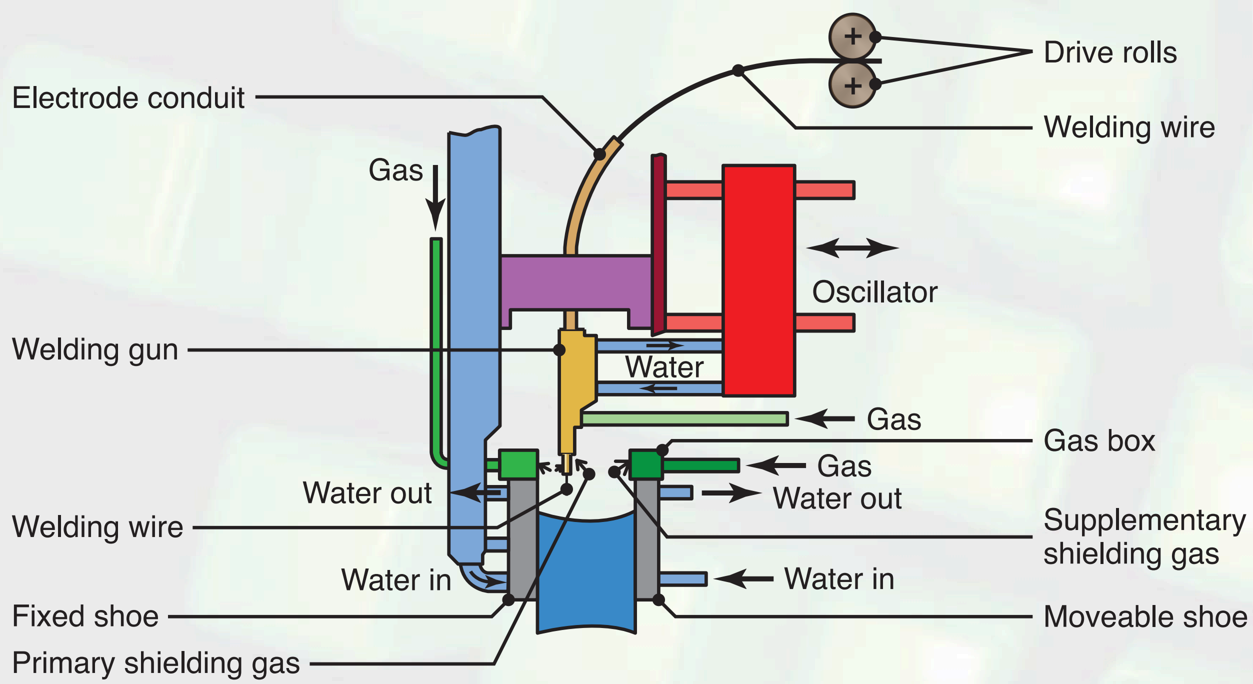

FIGURE 12.9 Schematic illustration of the electrogas welding process.

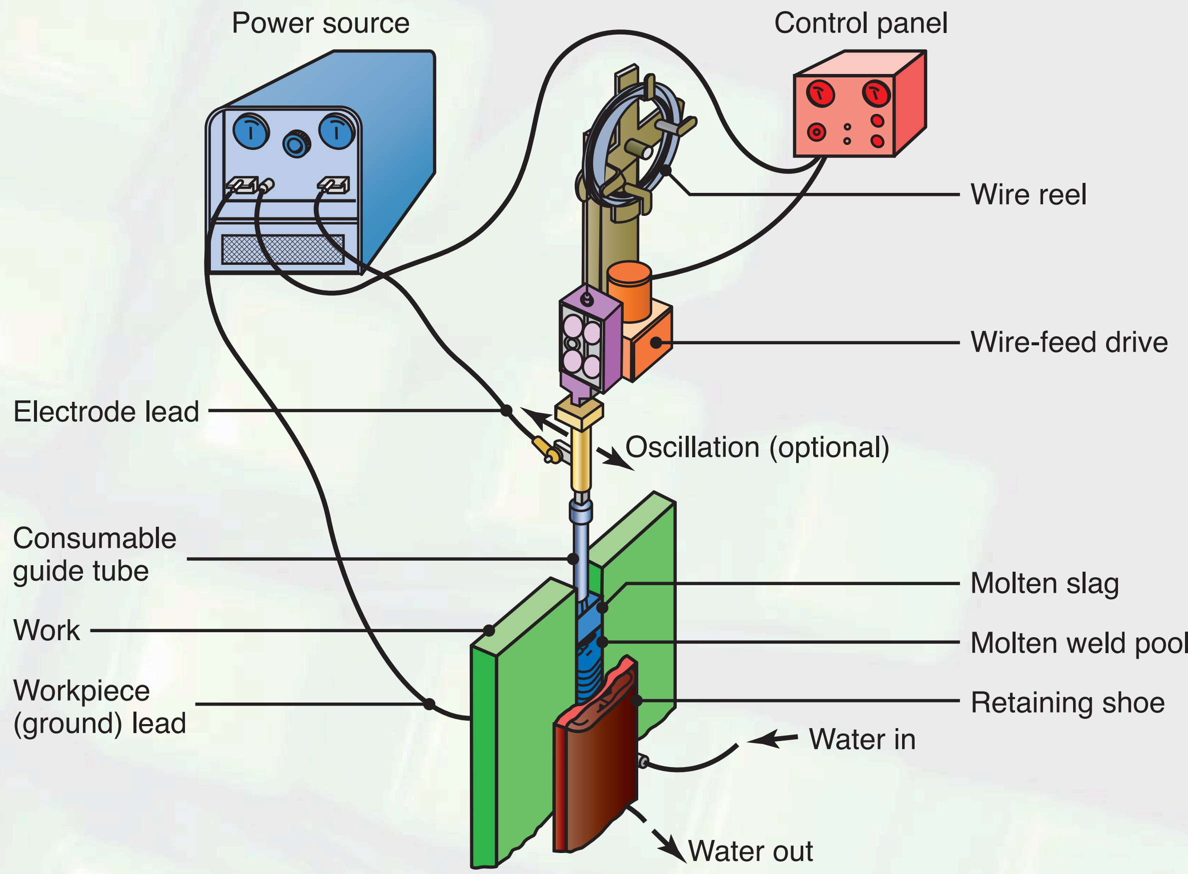

FIGURE 12.10 Equipment used for electroslag welding operations.

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Gas Tungsten Arc Welding

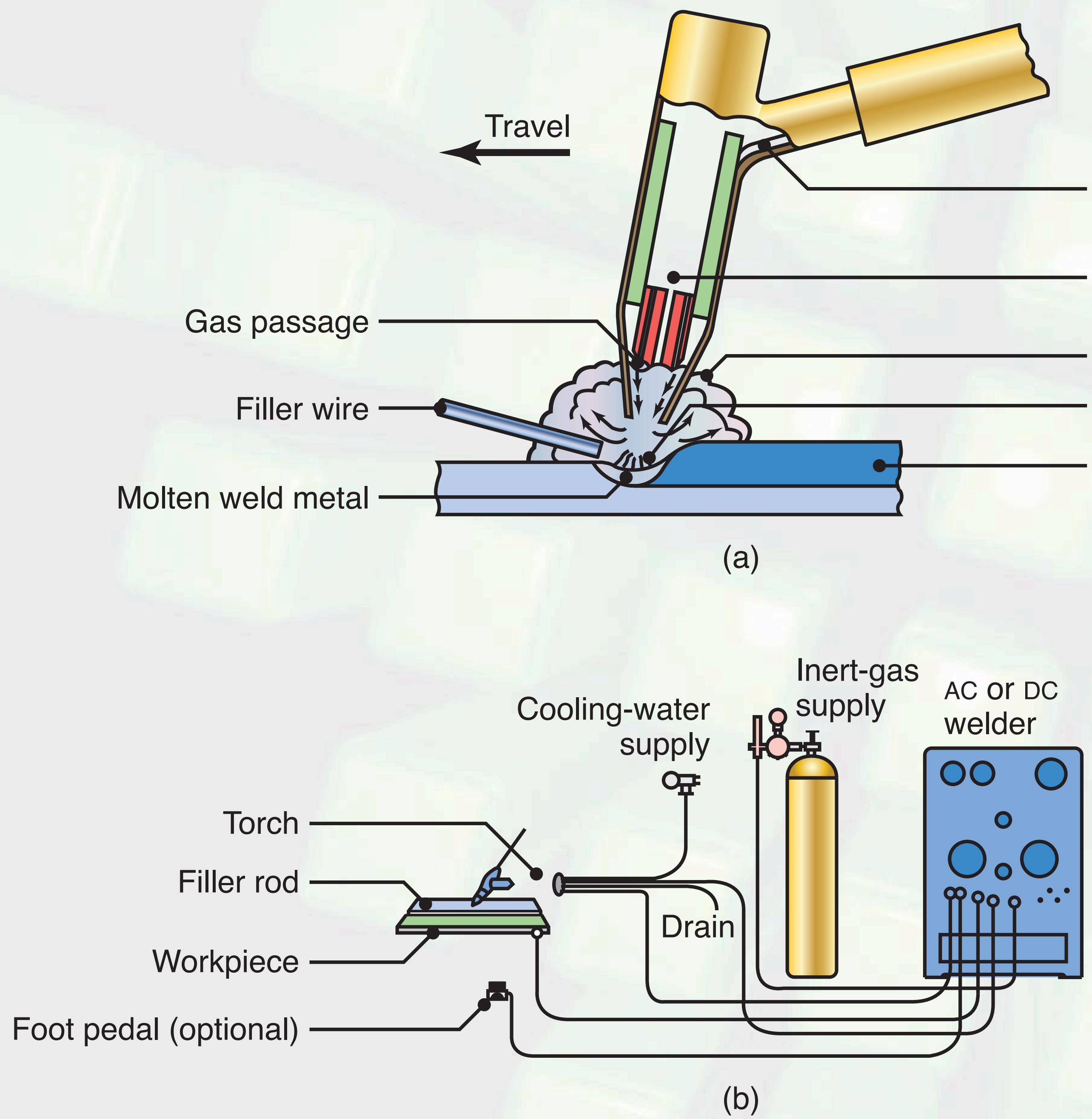

FIGURE 12.11 (a) Gas tungsten arc welding process, formerly known as TIG welding (for tungsten inert gas). (b) Equipment for gas tungsten arc welding operations.

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Plasma Arc Welding

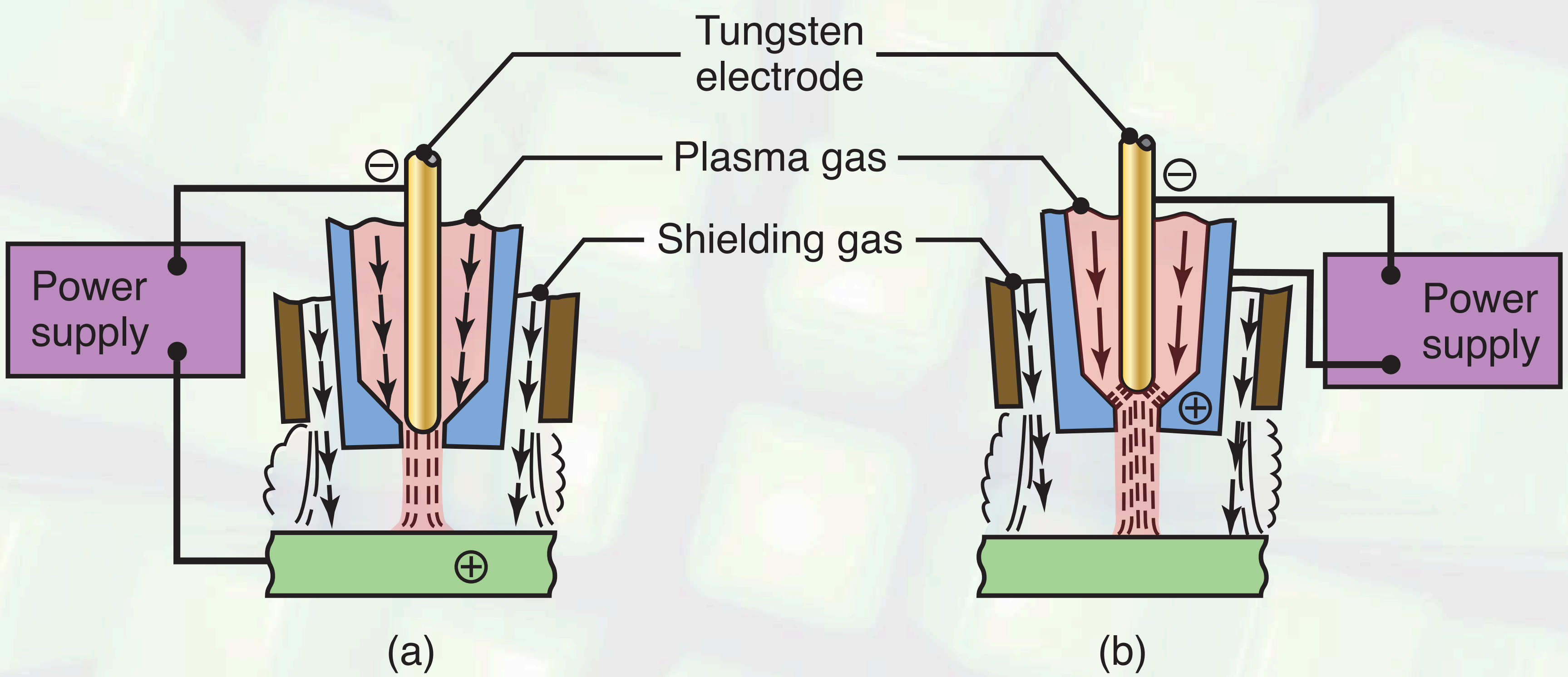

FIGURE 12.12 Two types of plasma arc welding processes: (a) transferred and (b) nontransferred. Deep and narrow welds are made by this process at high welding speeds.

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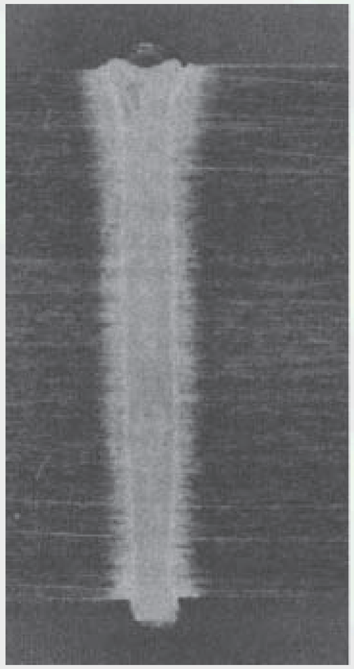
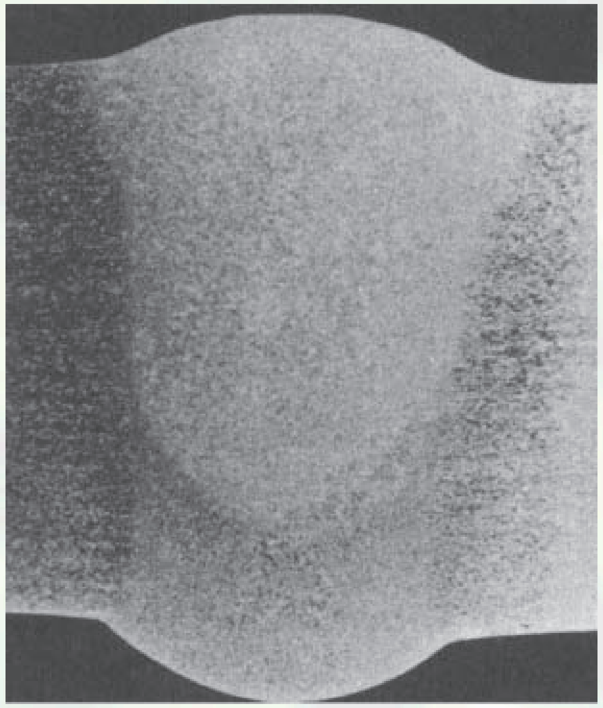
Weld Bead Comparisons



(a)



(b)

FIGURE 12.13 Comparison of the size of weld beads in (a) electron-beam or laser-beam welding with that in (b) conventional (tungsten arc) welding. *Source:* American Welding Society, *Welding Handbook*, 8th ed., 1991.

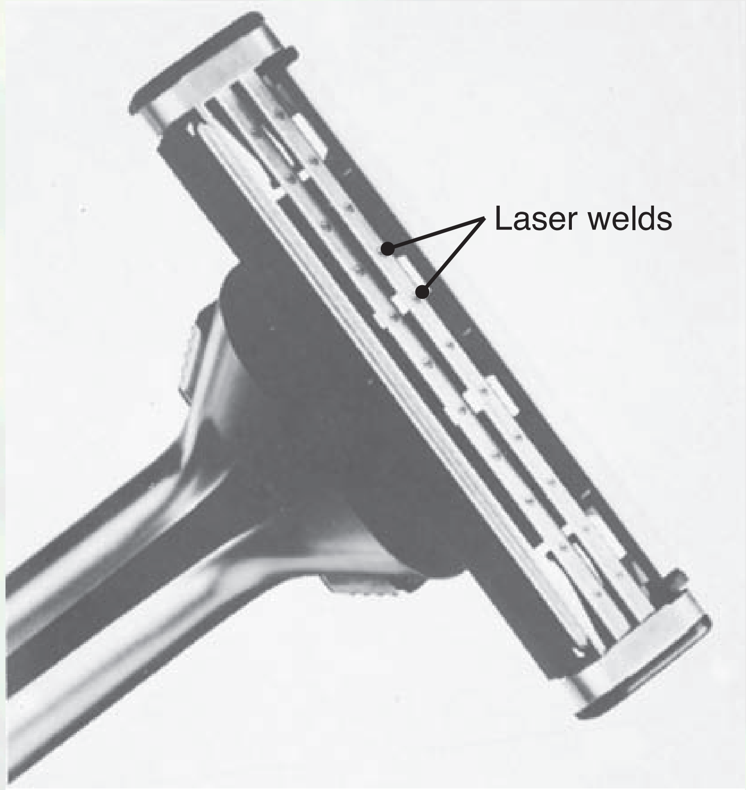


FIGURE 12.14 Gillette Sensor razor cartridge, with laser-beam welds.

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Fusion Weld Characteristics

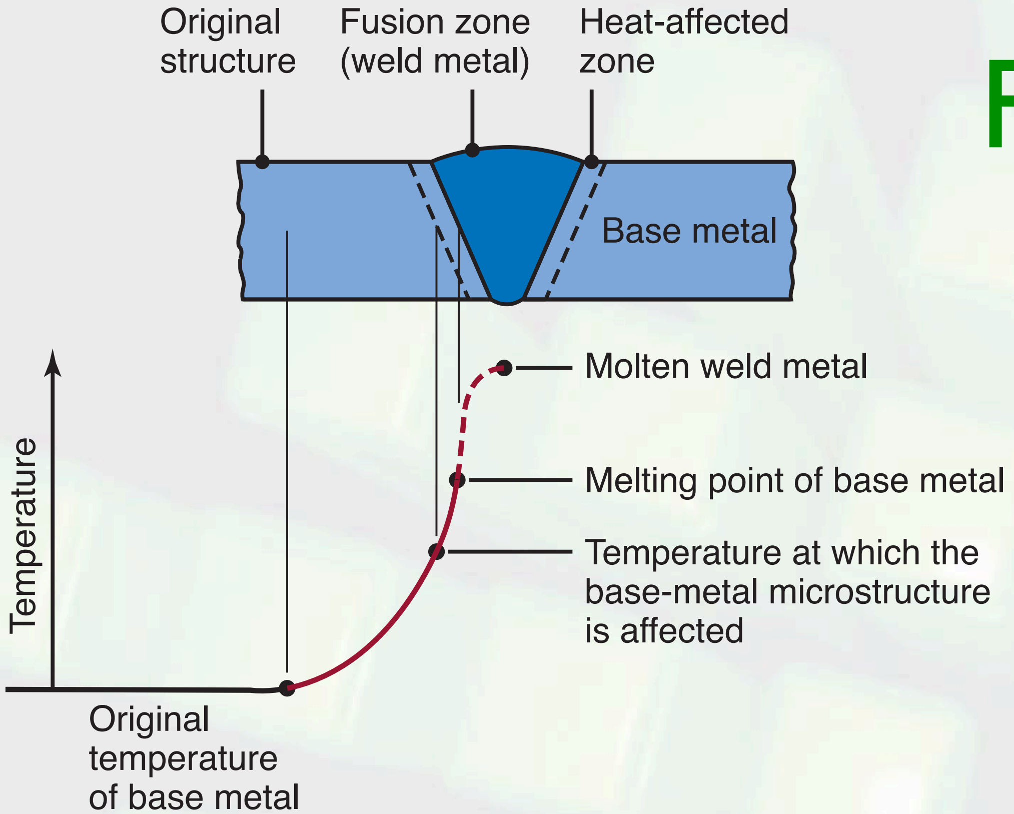

FIGURE 12.15 Characteristics of a typical fusion weld zone in oxyfuel gas welding and arc welding processes.

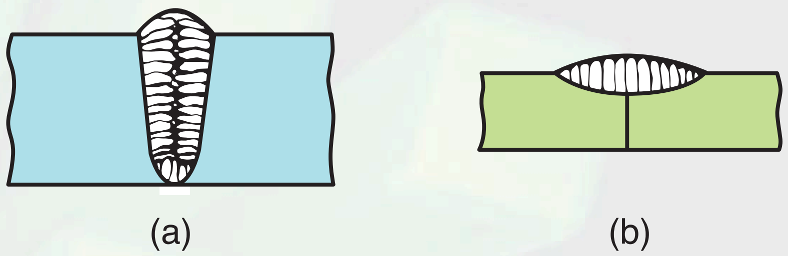

FIGURE 12.16 Grain structure in (a) a deep weld and (b) a shallow weld. Note that the grains in the solidified weld metal are perpendicular to their interface with the base metal.

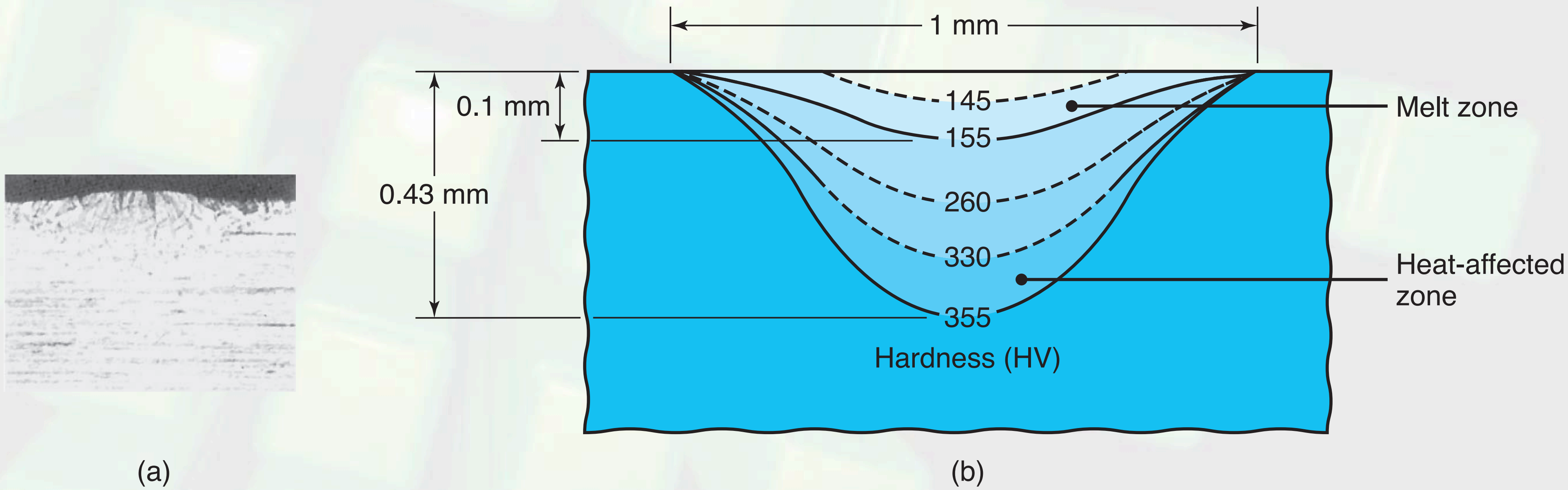

FIGURE 12.17 (a) Weld bead on a cold-rolled nickel strip produced by a laser beam. (b) Microhardness profile across the weld bead. Note the lower hardness of the weld bead as compared with the base metal. *Source:* IIT Research Institute.

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Fusion Defects

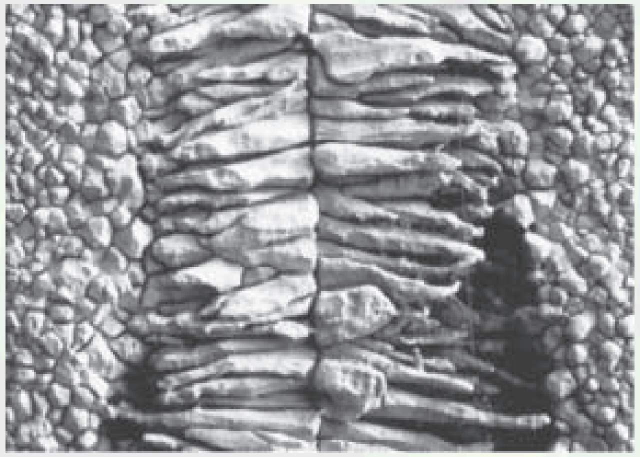

FIGURE 12.18 Intergranular corrosion of a weld joint in ferritic stainless-steel welded tube, after exposure to a caustic solution. The weld line is at the center of the photograph. *Source:* Courtesy of Allegheny Ludlum Corp.

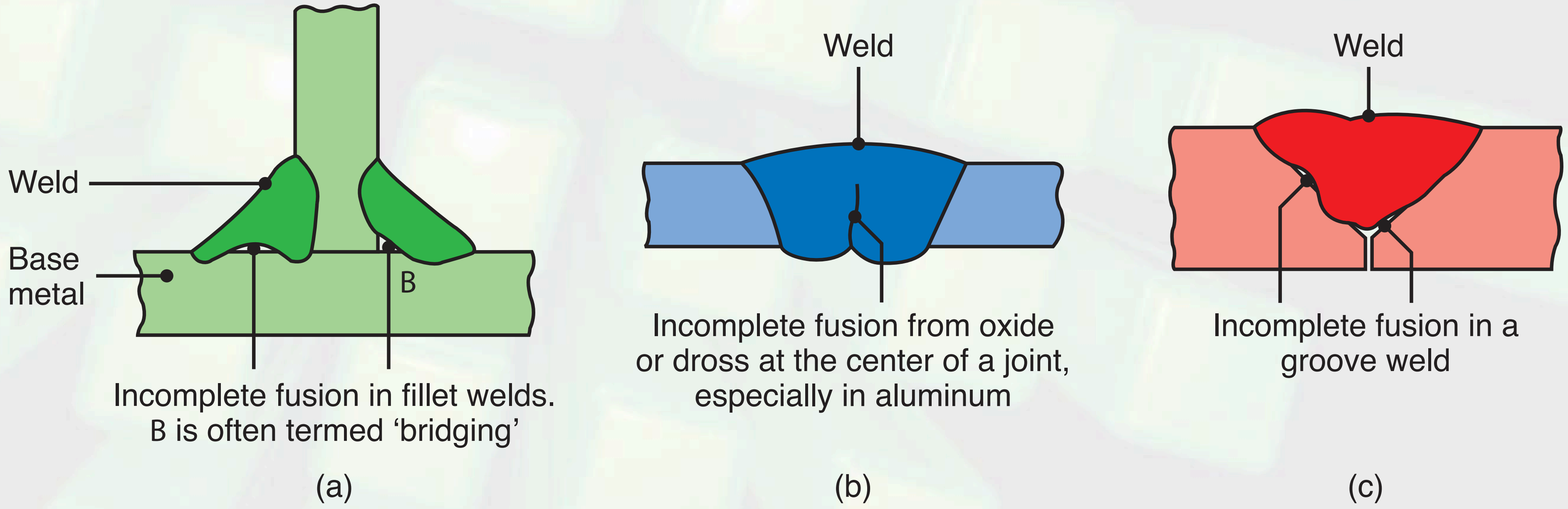

FIGURE 12.19 Examples of various incomplete fusion in welds.

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Defects in Welded Joints

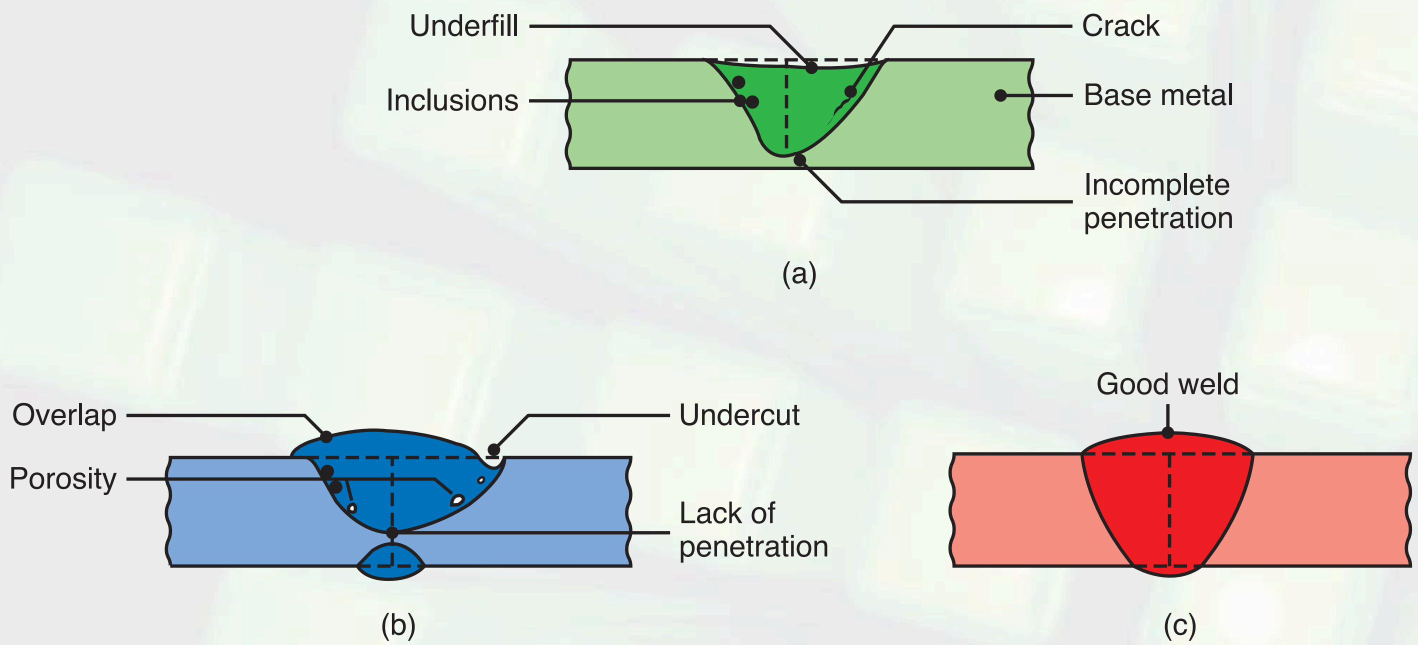

FIGURE 12.19 Examples of various incomplete fusion in welds.

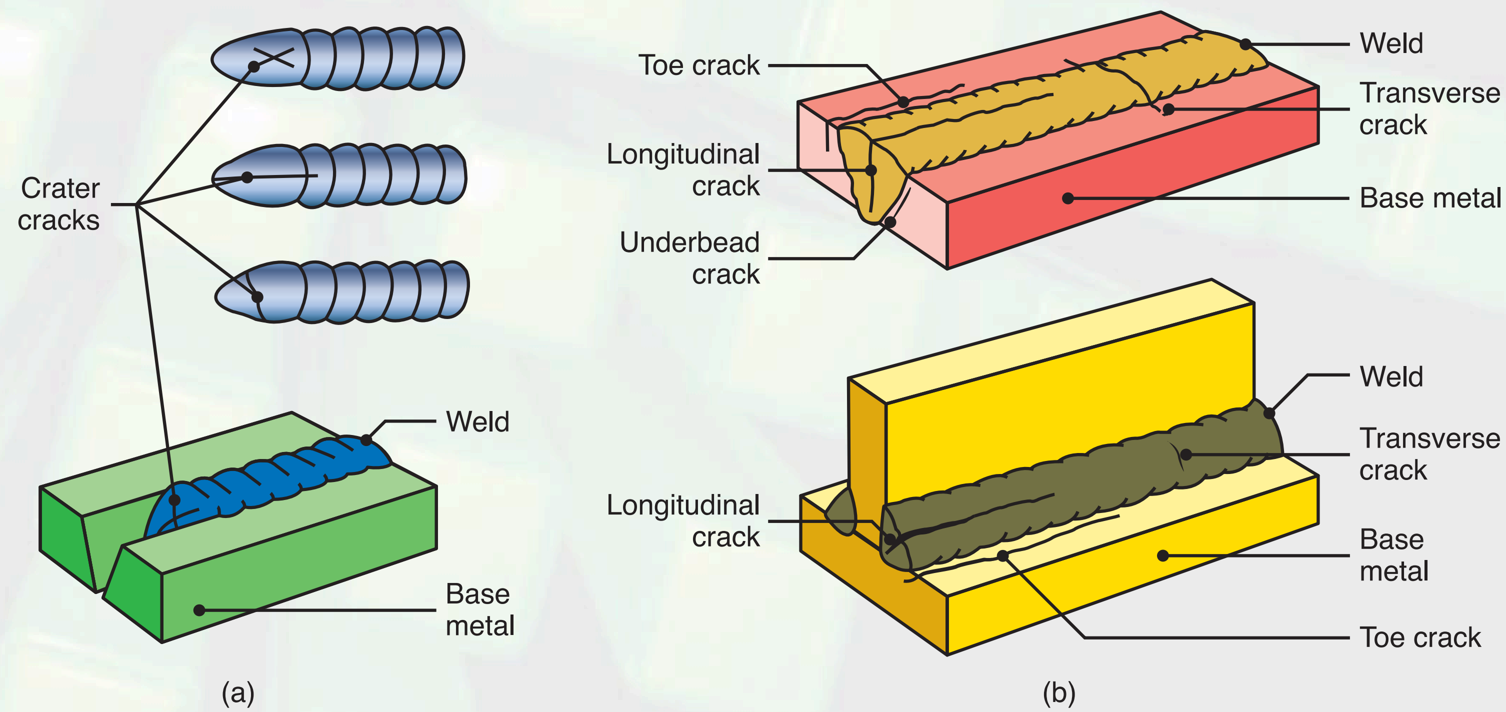

FIGURE 12.20 Examples of various defects in fusion welds.

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Weld Crack

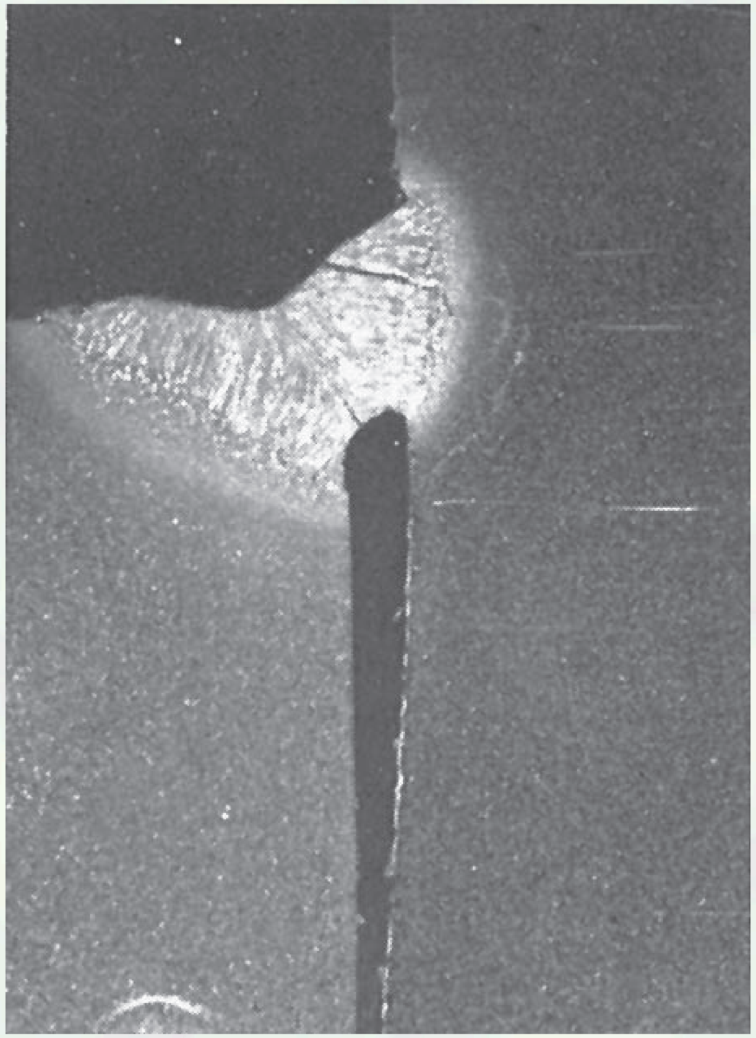

FIGURE 12.22 Crack in a weld bead, due to the fact that the two components were not allowed to contract after the weld was completed. *Source:* Courtesy of Packer Engineering.

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Distortion in Welds

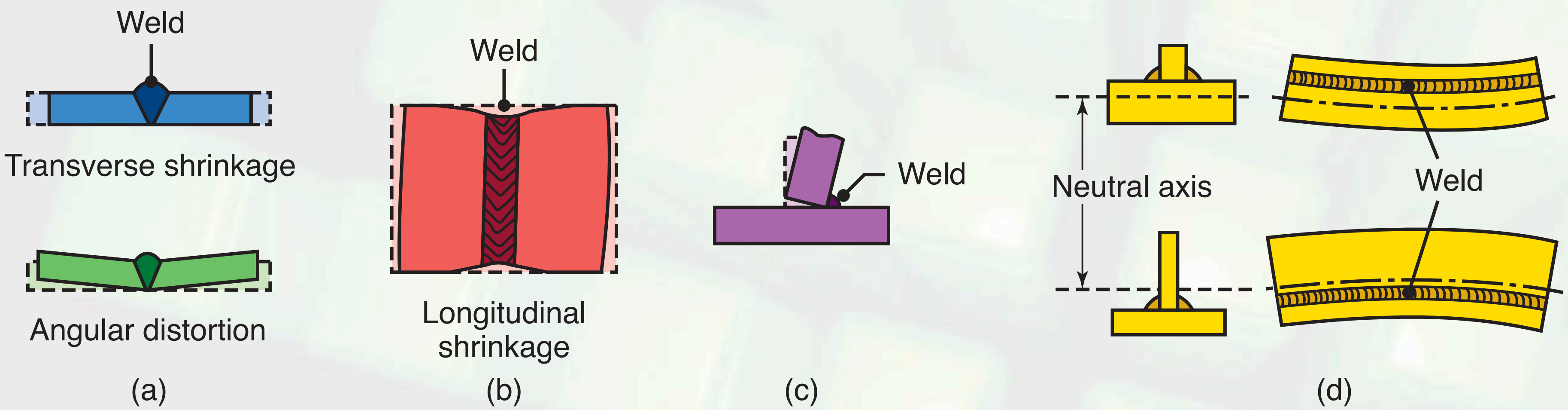

FIGURE 12.23 Distortion and warping of parts after welding, caused by differential thermal expansion and contraction of different regions of the welded assembly. Warping can be reduced or eliminated by proper weld design and fixturing prior to welding.

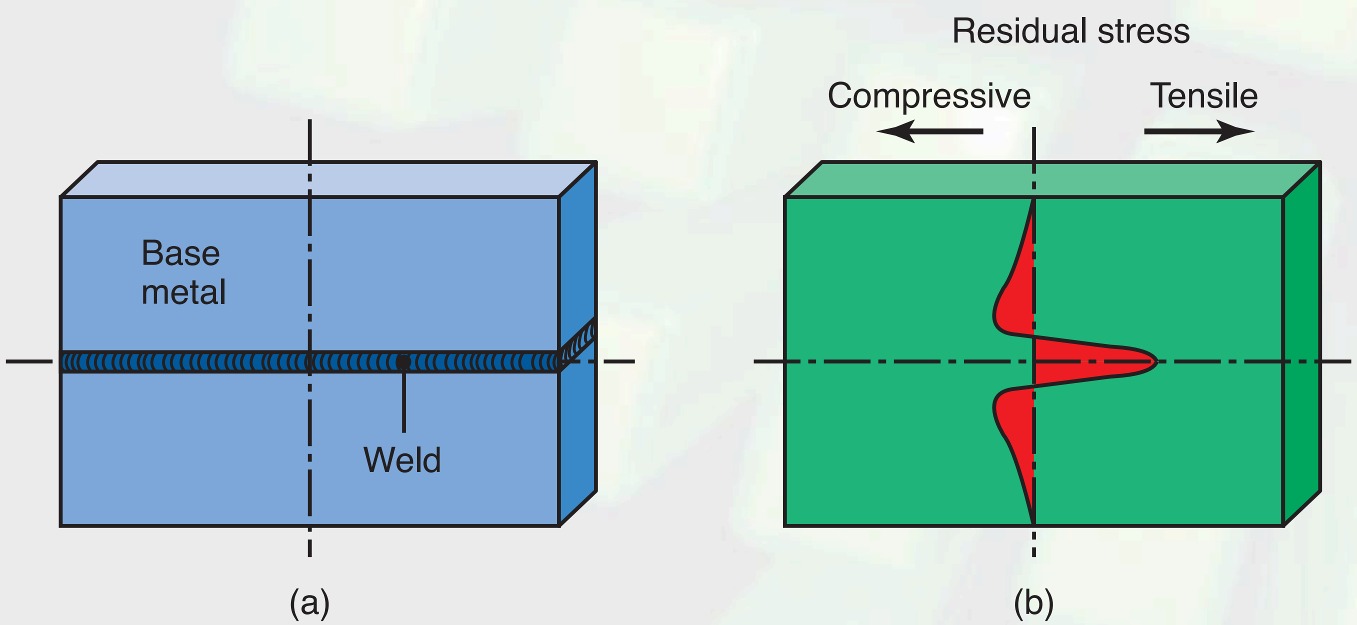

FIGURE 12.24 Residual stresses developed in a straight butt joint. *Source:* Courtesy of the American Welding Society.

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Distortion of Welded Structures

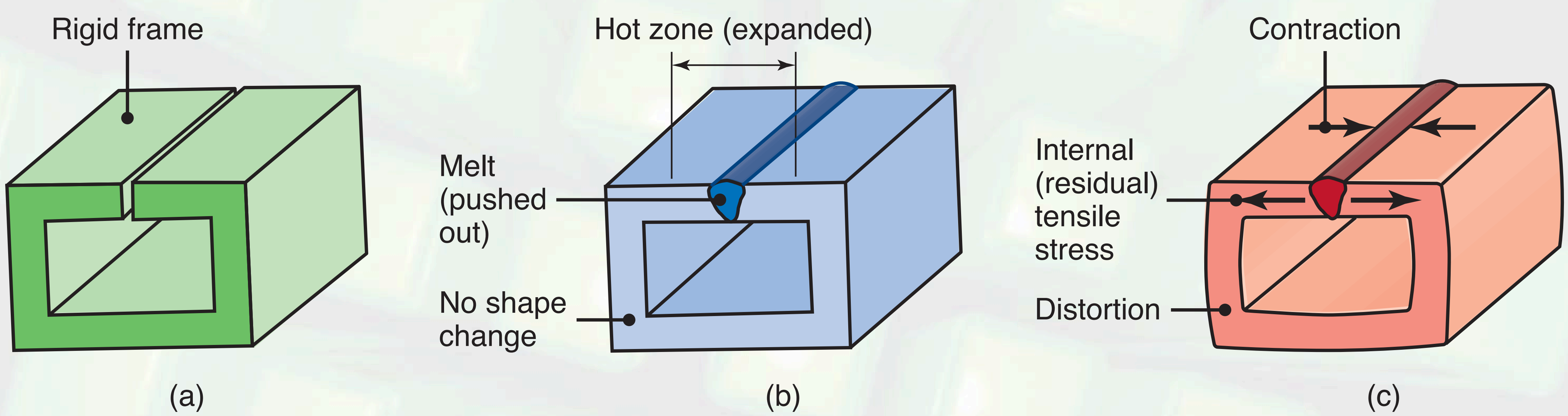

FIGURE 12.25 Distortion of a welded structure. (a) Before welding; (b) during welding, with weld bead placed in joint; (c) after welding, showing distortion in the structure. *Source:* After J.A. Schey.

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Tension-Shear Testing

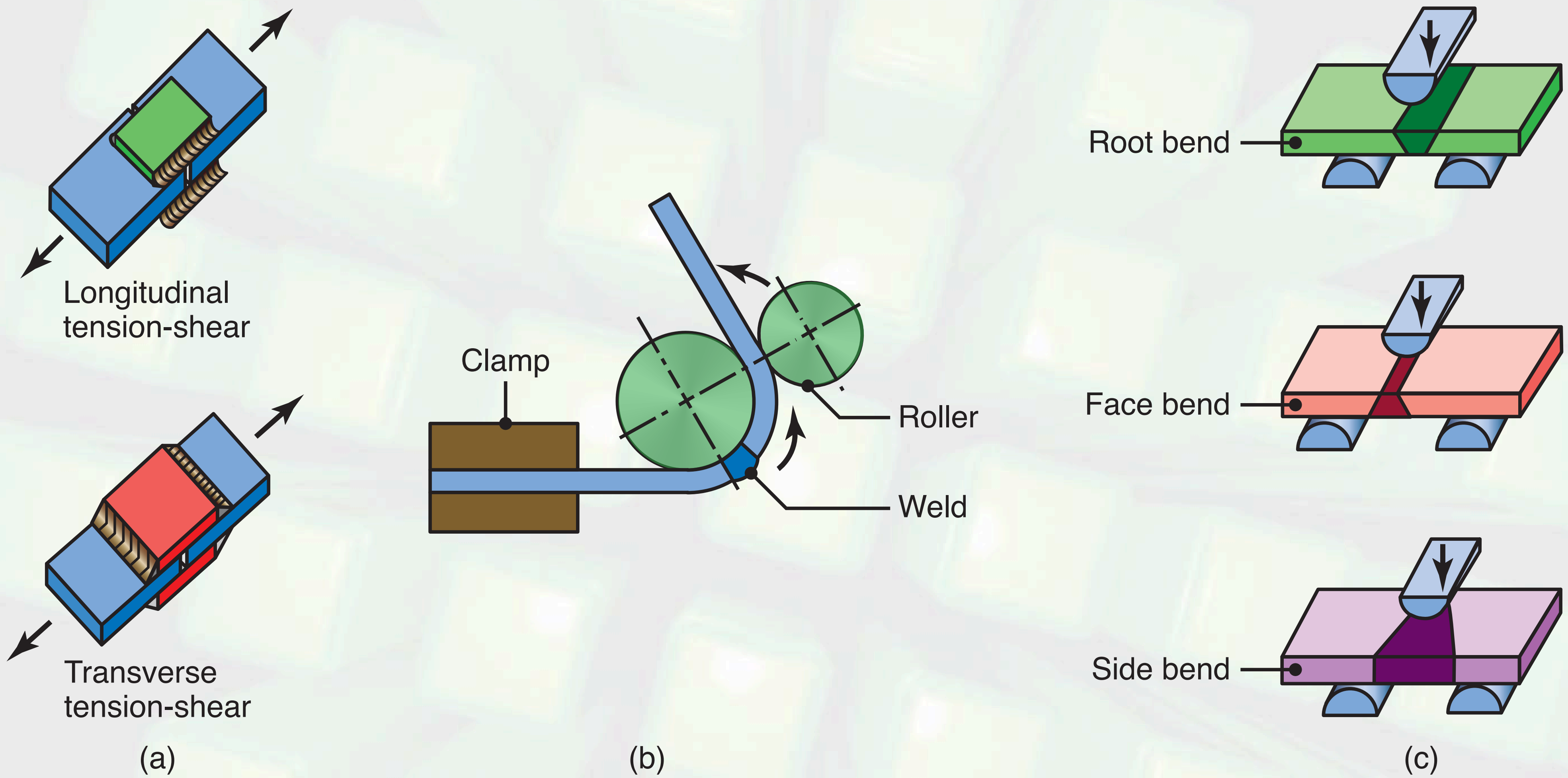

FIGURE 12.26 (a) Types of specimens for tension-shear testing of welds. (b) Wraparound bend test method. (c) Three-point bending of welded specimens. (See also Fig. 2.21.)

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Tension-Shear Test of Spot Welds

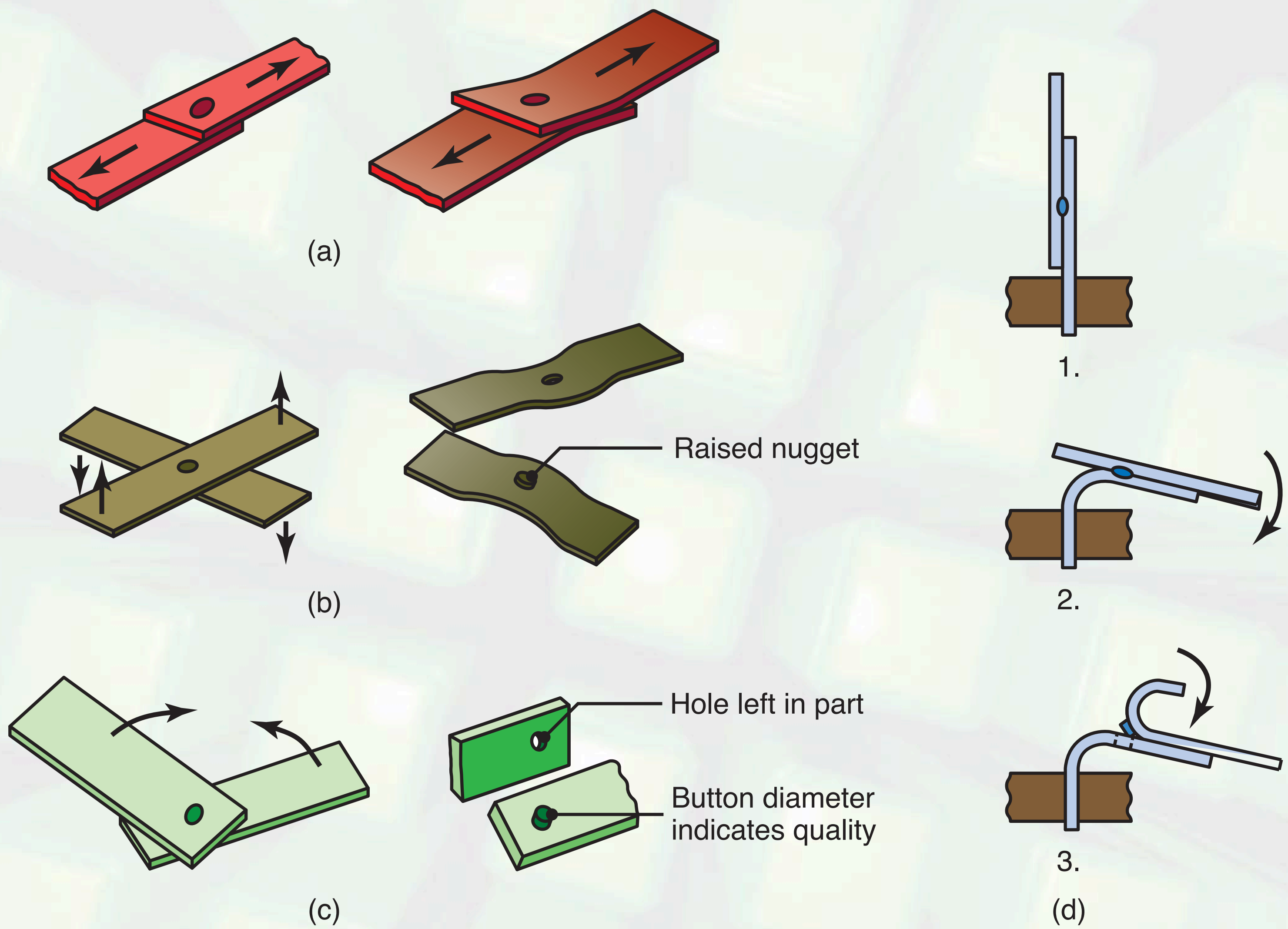

FIGURE 12.27 (a) Tension-shear test for spot welds; (b) cross-tension test; (c) twist test; (d) peel test.

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Roll Bonding & Ultrasonic Welding

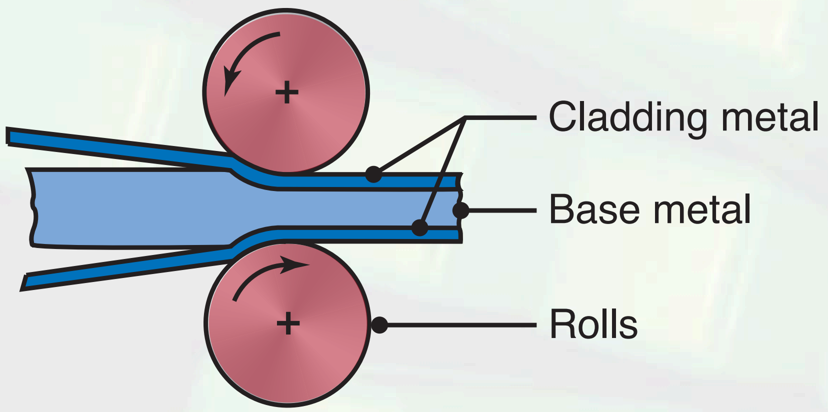

FIGURE 12.28 Schematic illustration of the roll-bonding, or cladding, process.

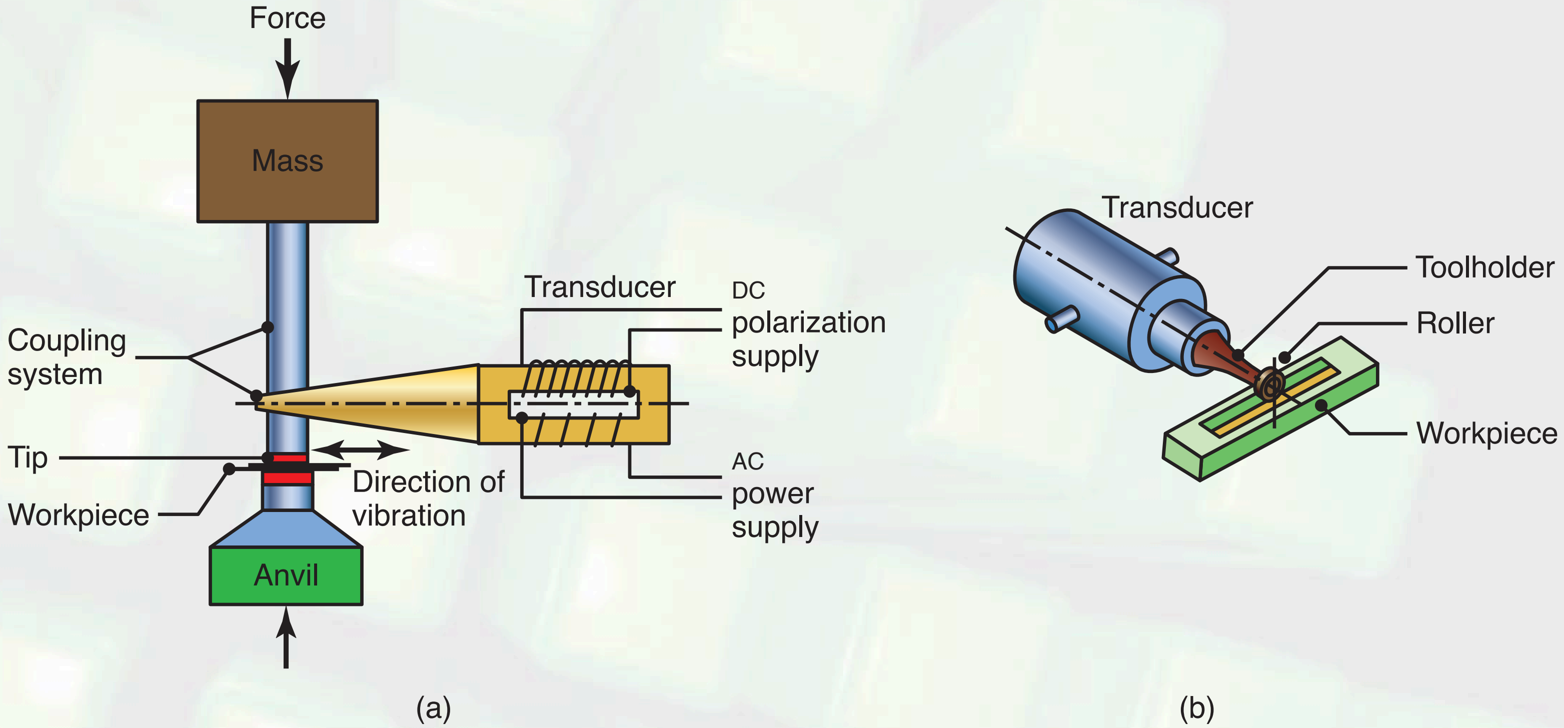

FIGURE 12.29 (a) Components of an ultrasonic welding machine for lap welds. (b) Ultrasonic seam welding using a roller.

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Friction Welding

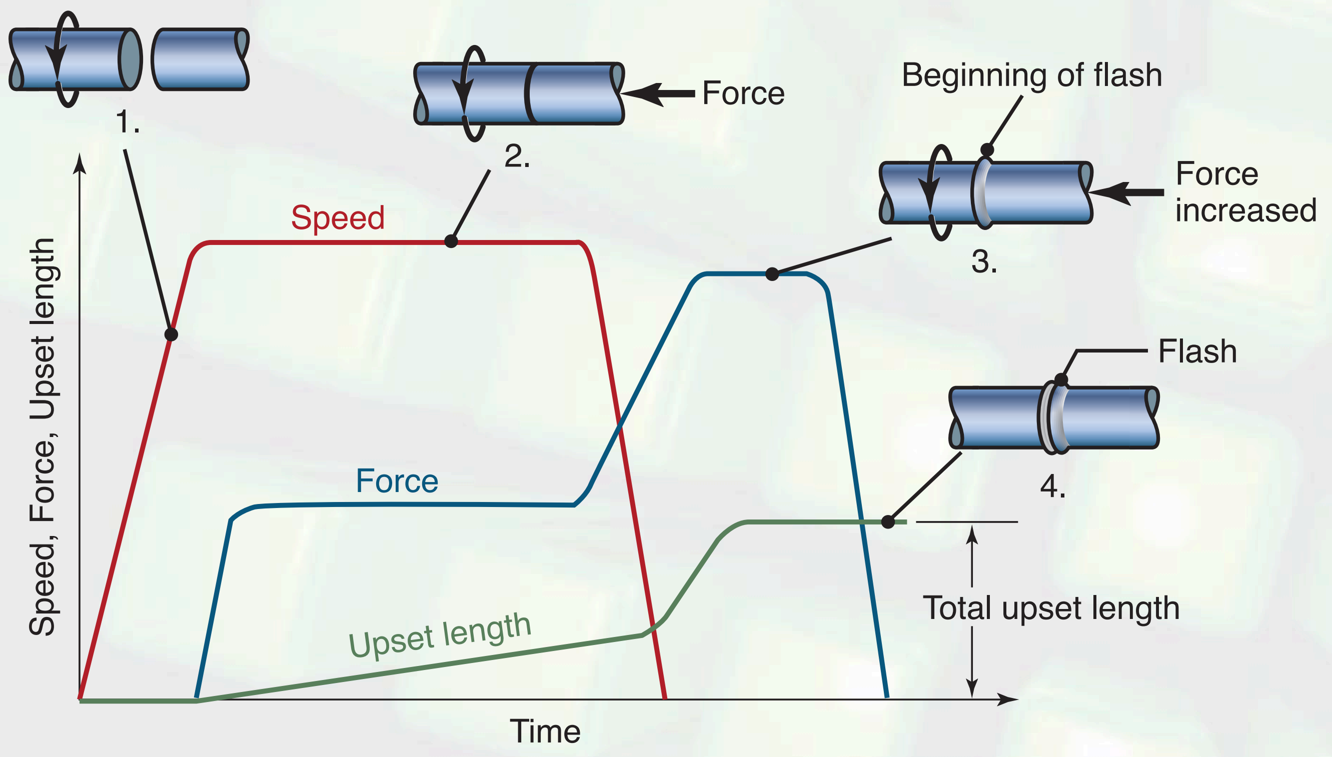

FIGURE 12.30 Sequence of operations in the friction welding process. (1) The part on the left is rotated at high speed. (2) The part on the right is brought into contact under an axial force. (3) The axial force is increased, and the part on the left stops rotating; flash begins to form. (4) After a specified upset length or distance is achieved, the weld is completed. The upset length is the distance the two pieces move inward during welding after their initial contact; thus, the total length after welding is less than the sum of the lengths of the two pieces. If necessary, the flash can be removed by secondary operations, such as machining or grinding.

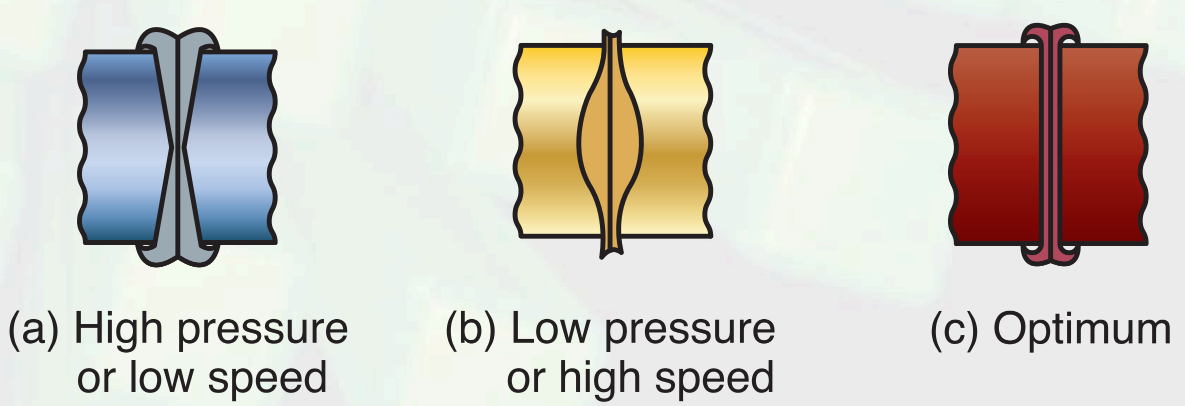

FIGURE 12.31 Shapes of the fusion zone in friction welding as a function of the force applied and the rotational speed.

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Friction Stir Welding

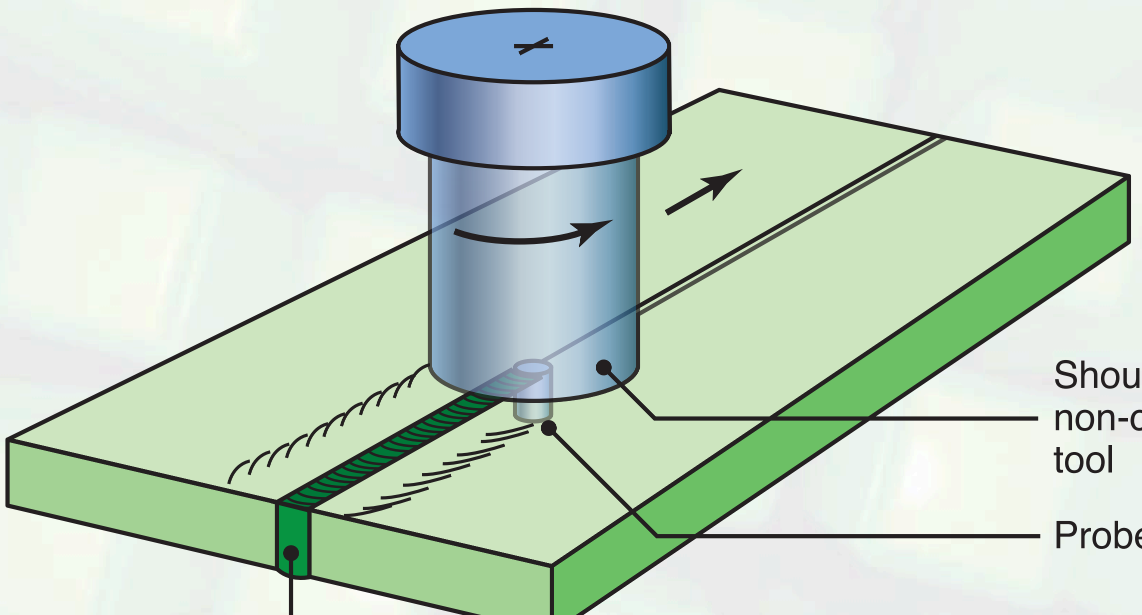

FIGURE 12.32 The principle of the friction stir welding process. Aluminum-alloy plates up to 75 mm (3 in.) thick have been welded by this process. *Source:* TWI, Cambridge, United Kingdom.

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Resistance Spot Welding

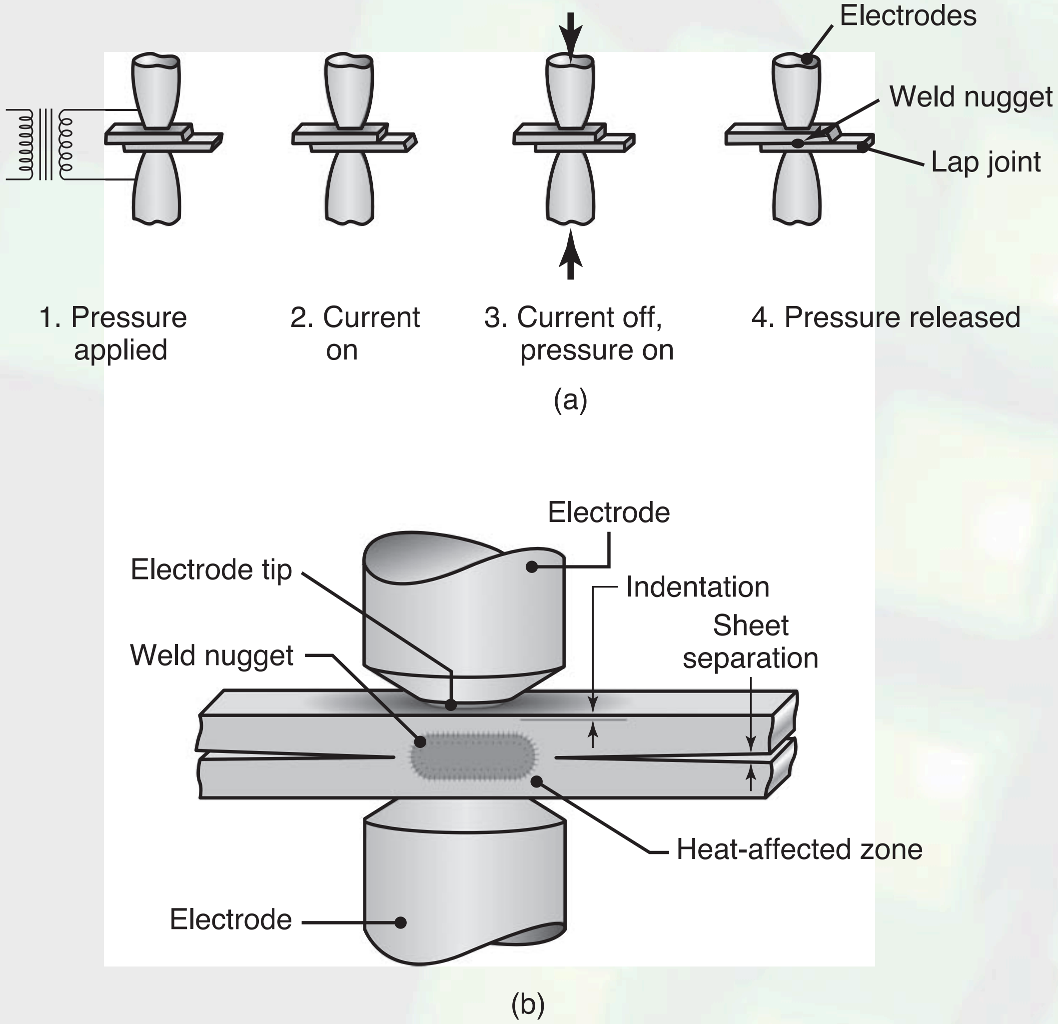

FIGURE 12.33 (a) Sequence in the resistance spot welding operation. (b) Cross-section of a spot weld, showing weld nugget and light indentation by the electrode on sheet surfaces.

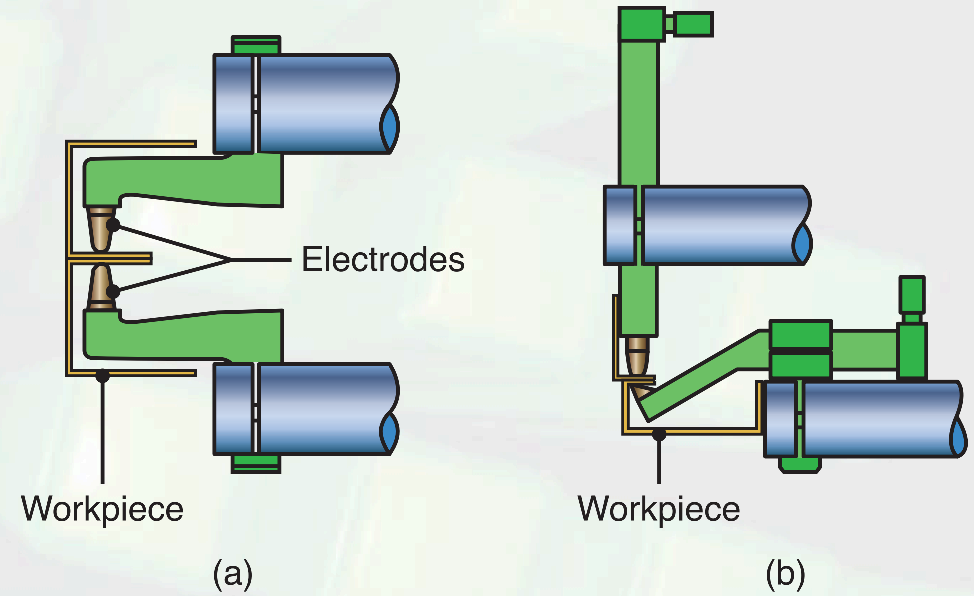

FIGURE 12.34 Two types of electrode designs for easy access in spot welding operations for complex shapes.

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Seam & Resistance Projection Welding

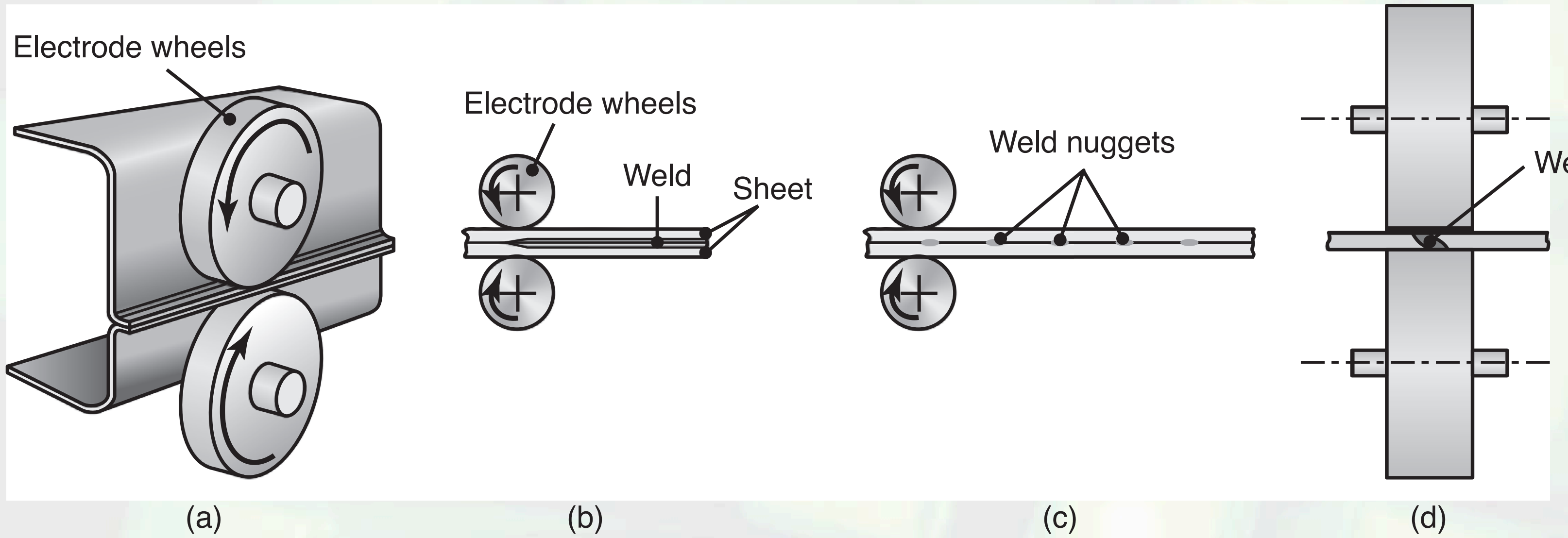

FIGURE 12.35 (a) Illustration of the seam welding process, with rolls acting as electrodes. (b) Overlapping spots in a seam weld. (c) Cross-section of a roll spot weld. (d) Mash seam welding.

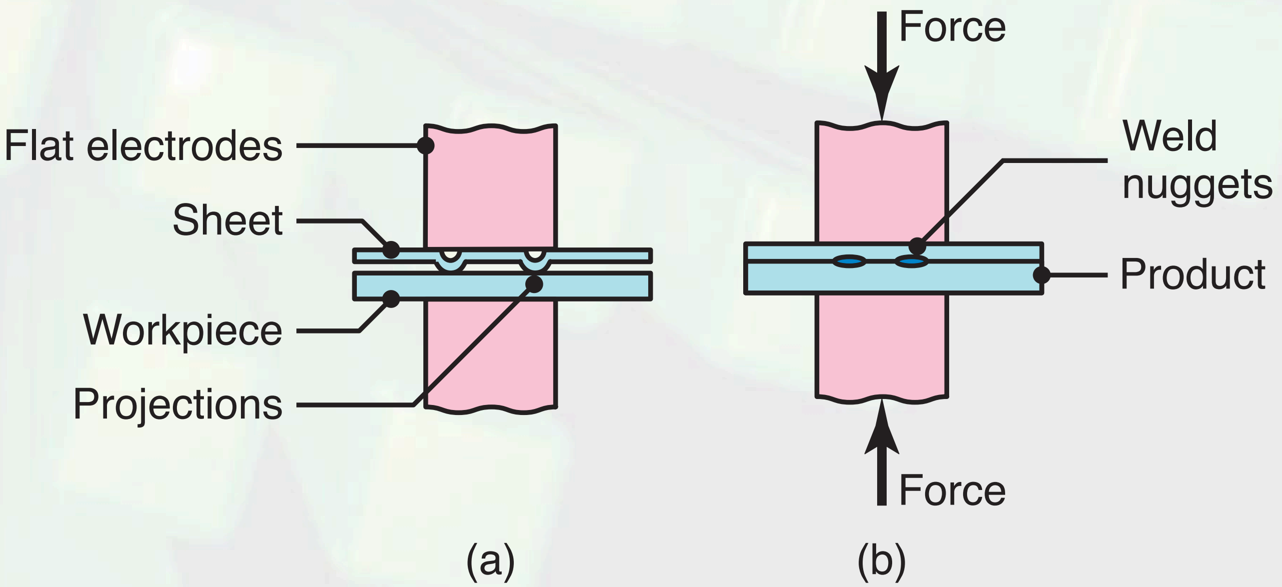

FIGURE 12.36 Schematic illustration of resistance projection welding: (a) before and (b) after. The projections on sheet metal are produced by embossing operations, as described in Section 7.5.2.

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Flash & Stud Welding

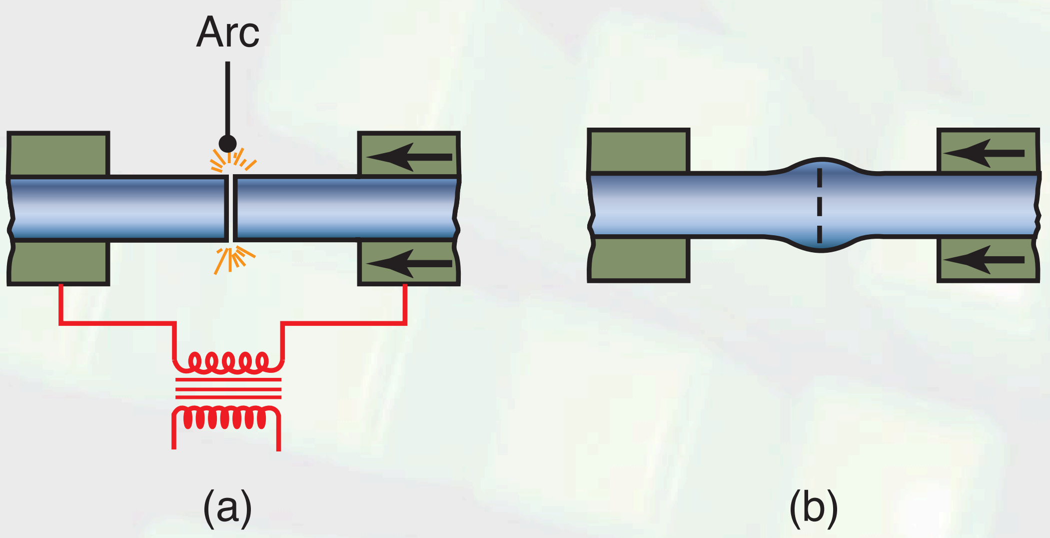
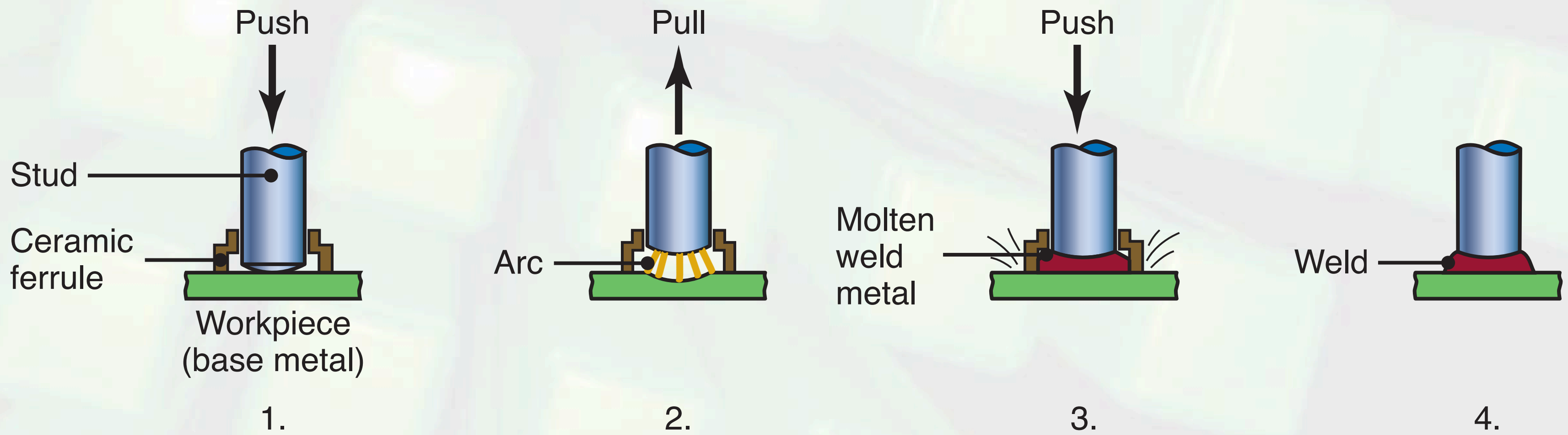


FIGURE 12.37 Flash welding process for end-to-end welding of solid rods or tubular parts. (a) Before and (b) after.

FIGURE 12.38 Sequence of operations in stud arc welding, used for welding bars, threaded rods, and various fasteners on metal plates.



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Explosion Welding

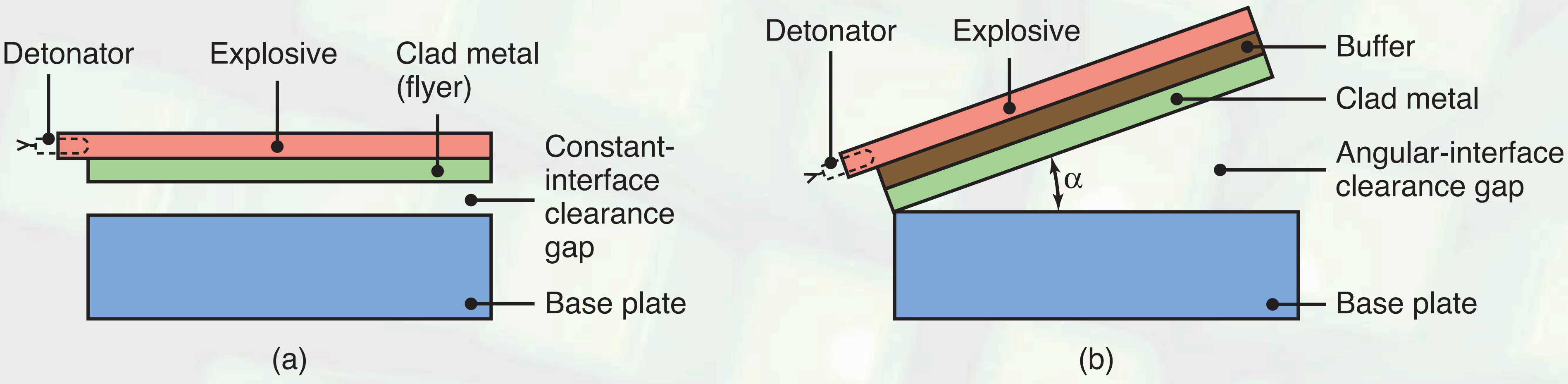

FIGURE 12.39 Schematic illustration of the explosion welding process: (a) constant interface clearance gap and (b) angular interface clearance gap.

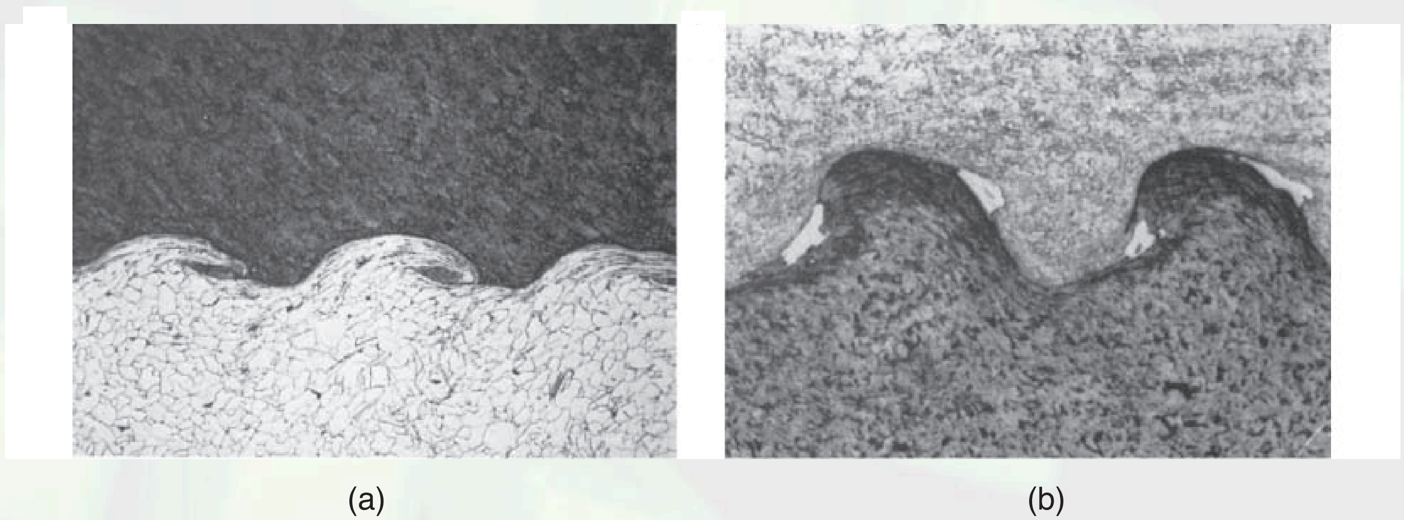

FIGURE 12.40 Cross-sections of explosion welded joints: (a) titanium (top) on low-carbon steel (bottom) and (b) Incoloy 800 (iron-nickel-base alloy) on low-carbon steel. The wavy interfaces shown improve the shear strength of the joint. Some combinations of metals, such as tantalum and vanadium, produce a much less wavy interface. If the two metals have little metallurgical compatibility, an interlayer may be added that has compatibility with both metals. {\it Source:} Courtesy of DuPont Company.

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Diffusion Bonding

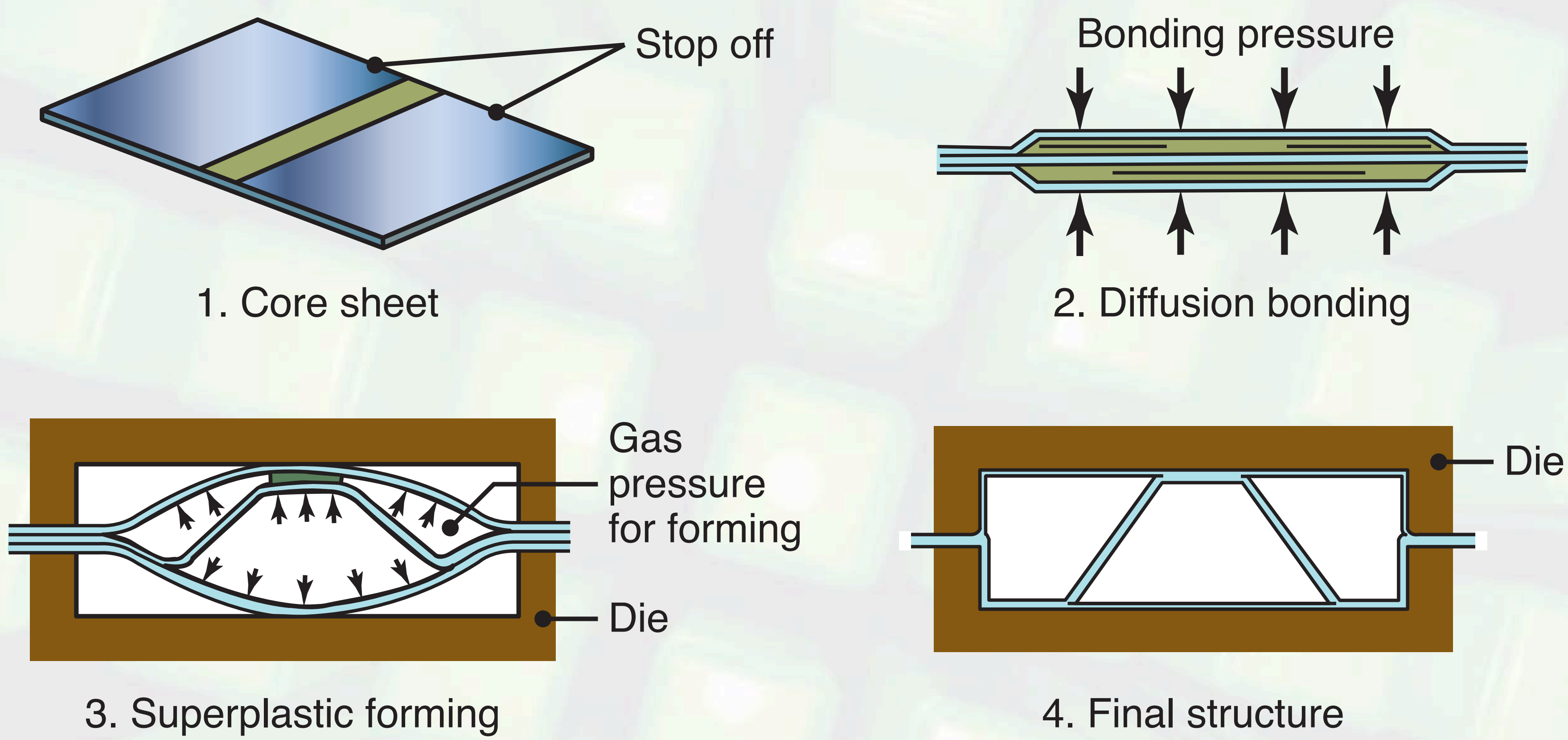

FIGURE 12.41 Sequence of operations in diffusion bonding and superplastic forming of a structure with three flat sheets. See also Fig. 7.46. *Source:* After D. Stephen and S.J. Swadling.

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Brazing & Braze Welding

FIGURE 12.42 (a) Brazing and (b) braze welding operations.

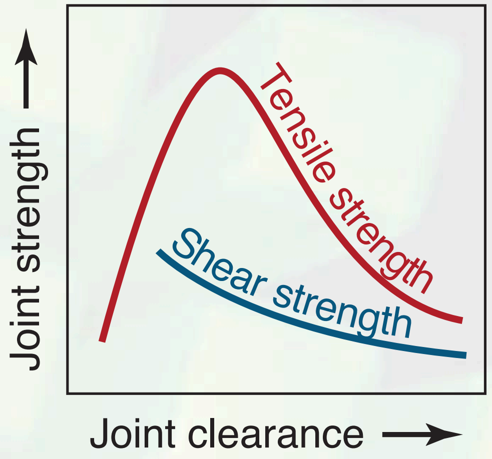

FIGURE 12.43 The effect of joint clearance on tensile and shear strength of brazed joints. Note that unlike tensile strength, shear strength continually decreases as clearance increases.

TABLE 12.4 Typical filler metals for brazing various metals and alloys.

Base Metal	Filler Metal	Brazing Temperature (°C)
Aluminum and its alloys	Aluminum-silicon	570-620
Magnesium alloys	Magnesium-aluminum	580-625
Copper and its alloys	Copper-phosphorus	700-925
Ferrous and nonferrous alloys (except aluminum and magnesium)	Silver and copper alloys, copper-phosphorus	620-1150
Iron-, nickel-, and cobalt-base alloys	Gold	900-1100
Stainless steels, nickel- and cobalt-base alloys	Nickel-silver	925-1200

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Furnace Brazing & Brazed Joints

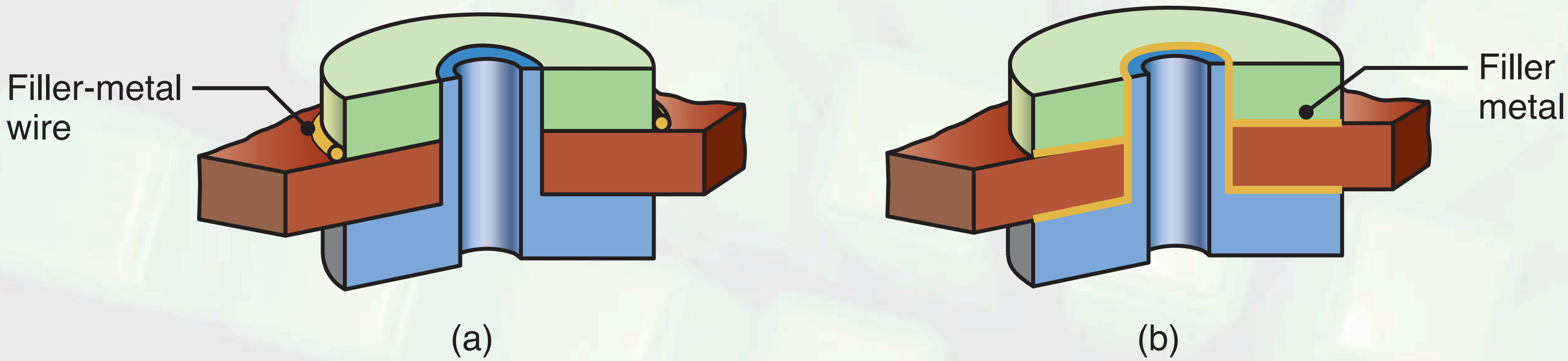

FIGURE 12.44 An application of furnace brazing: (a) before and (b) after. Note that the filler metal is a shaped wire.

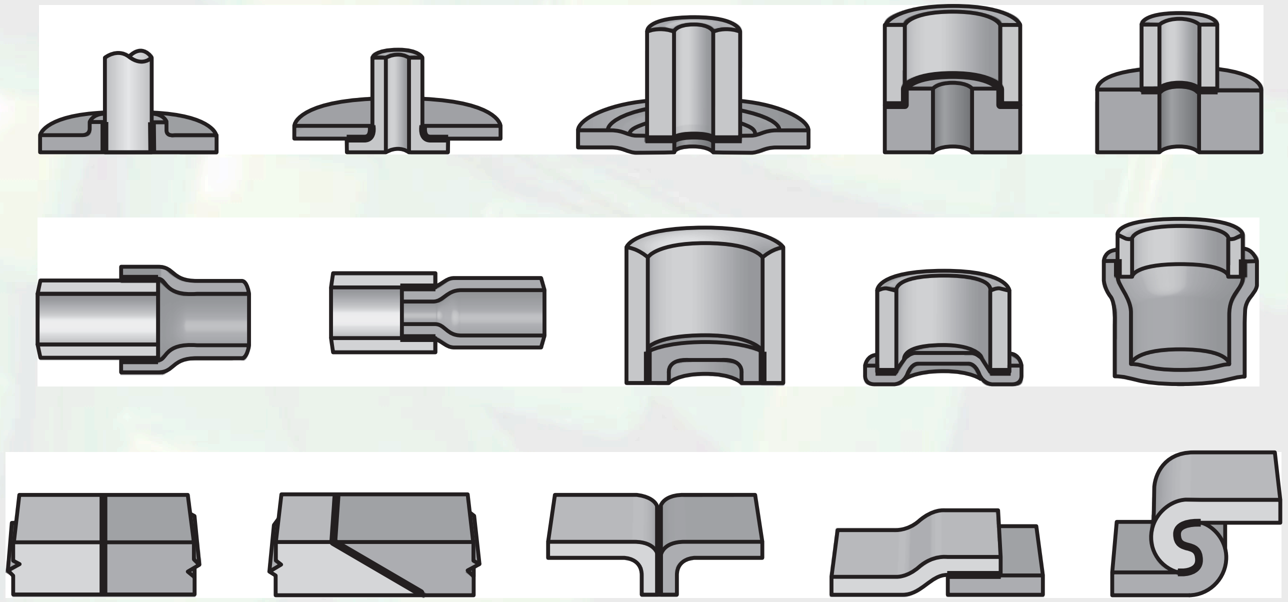

FIGURE 12.45 Joint designs commonly used in brazing operations.

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Solder Joints

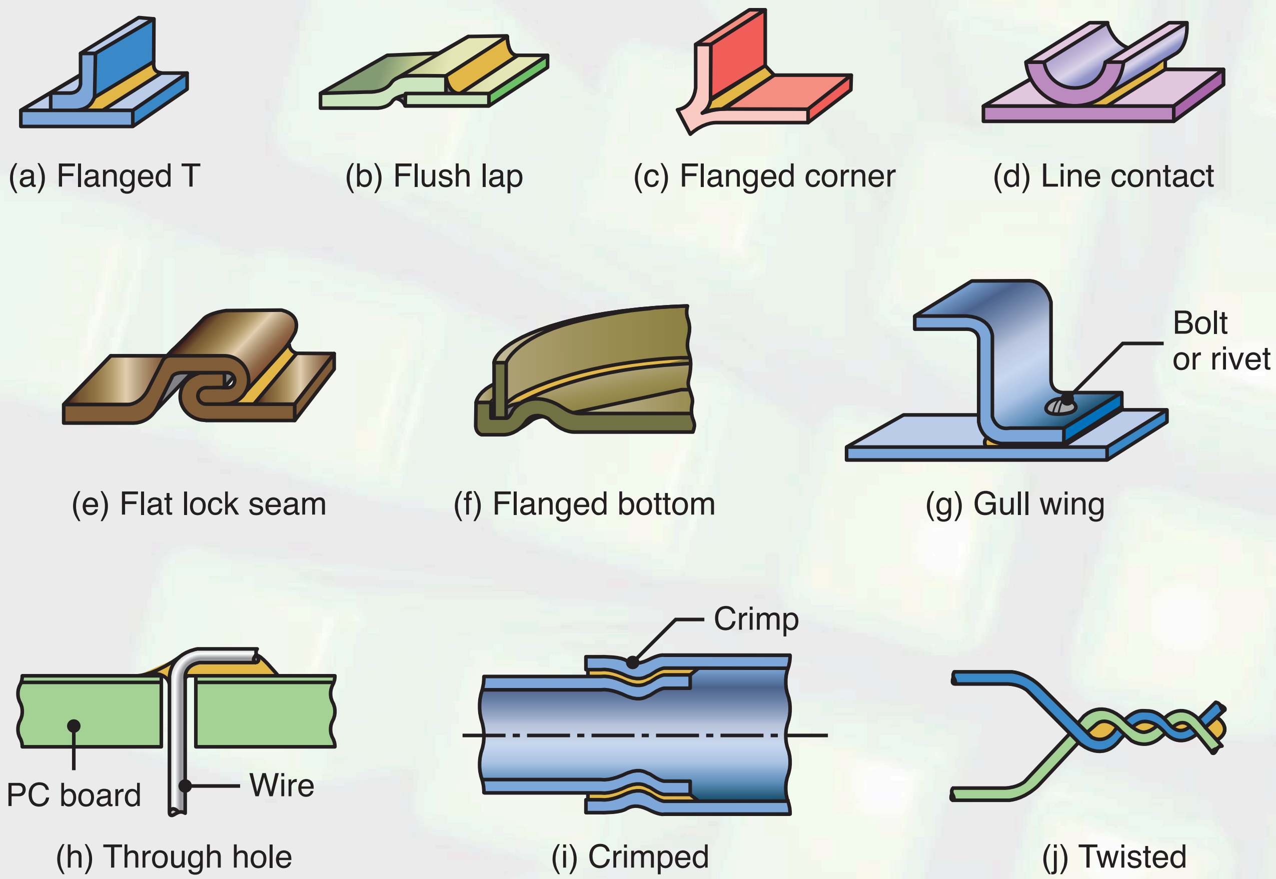

FIGURE 12.46 Joint designs commonly used for soldering.

TABLE 12.5 Types of solders and their applications.

Solder	Typical Application
Tin-lead	General purpose
Tin-zinc	Aluminum
Lead-silver	Strength at higher than room temperature
Cadmium-silver	Strength at high temperatures
Zinc-aluminum	Aluminum; corrosion resistance
Tin-silver	Electronics
Tin-bismuth	Electronics

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Soldering for Circuit Boards

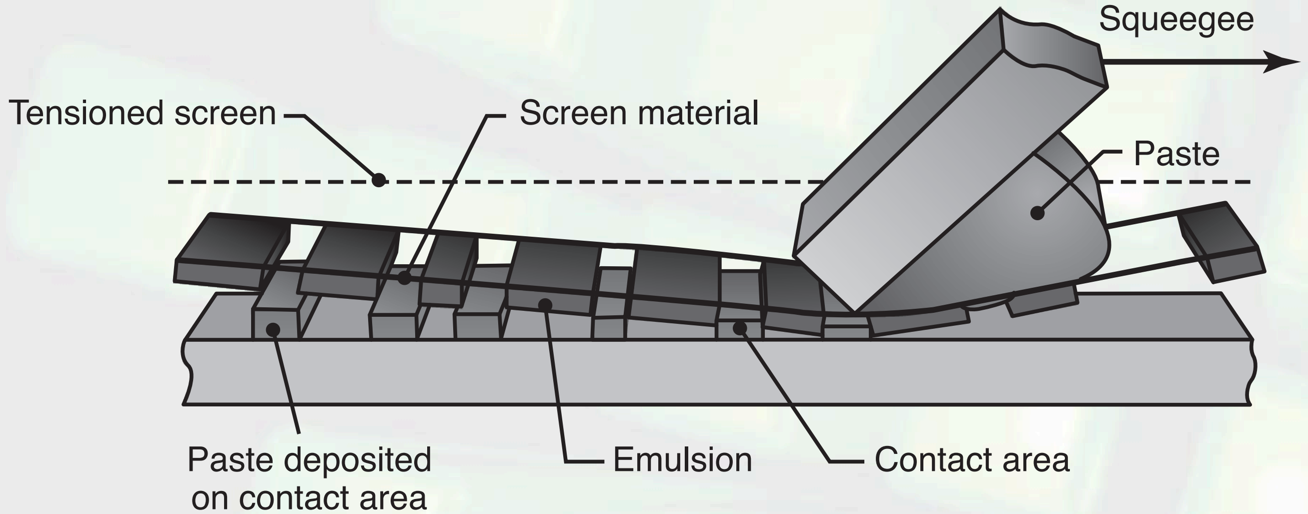

FIGURE 12.47 Screening solder paste onto a printed circuit board in reflow soldering. *Source:* After V. Solberg.

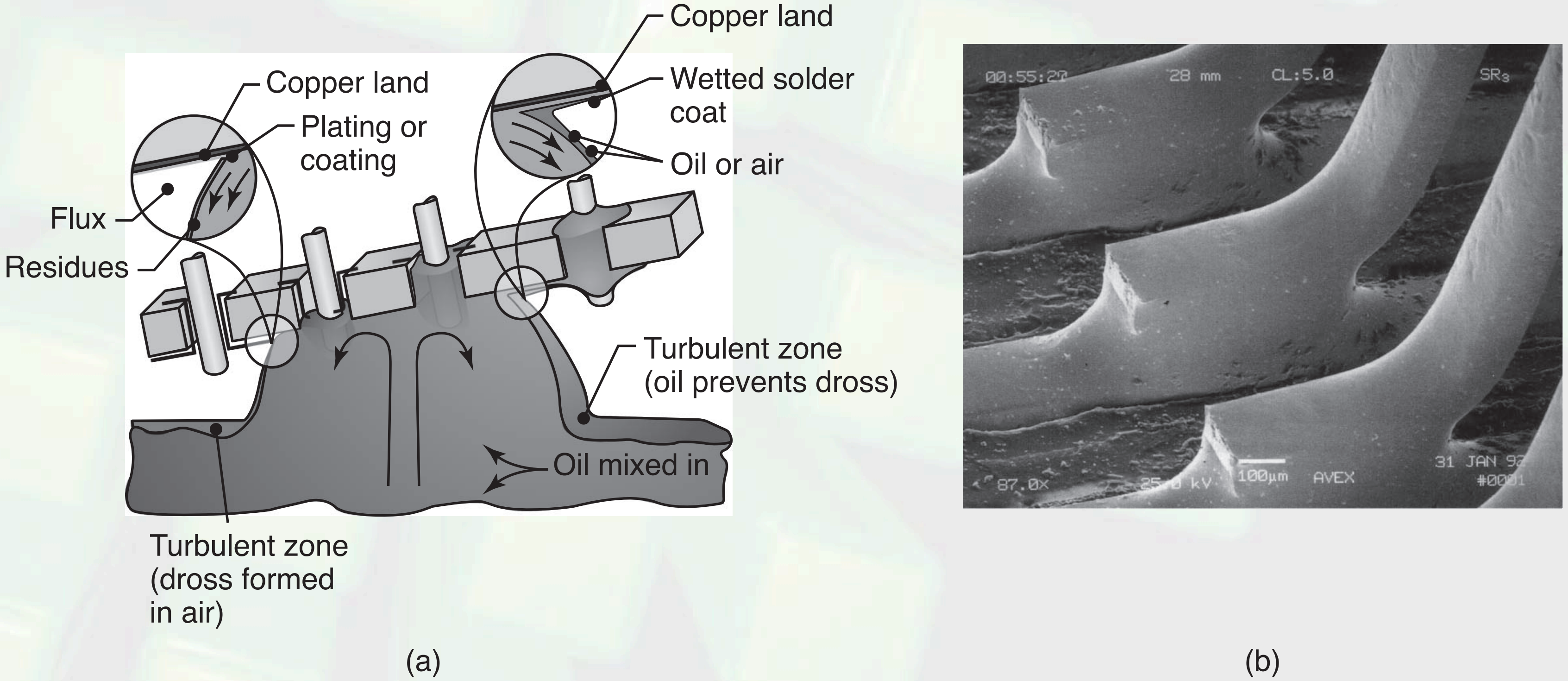

FIGURE 12.48 (a) Schematic illustration of the wave soldering process. (b) SEM image of a wave soldered joint on a surface-mount device. See also Section 13.13.

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Adhesive Bonding

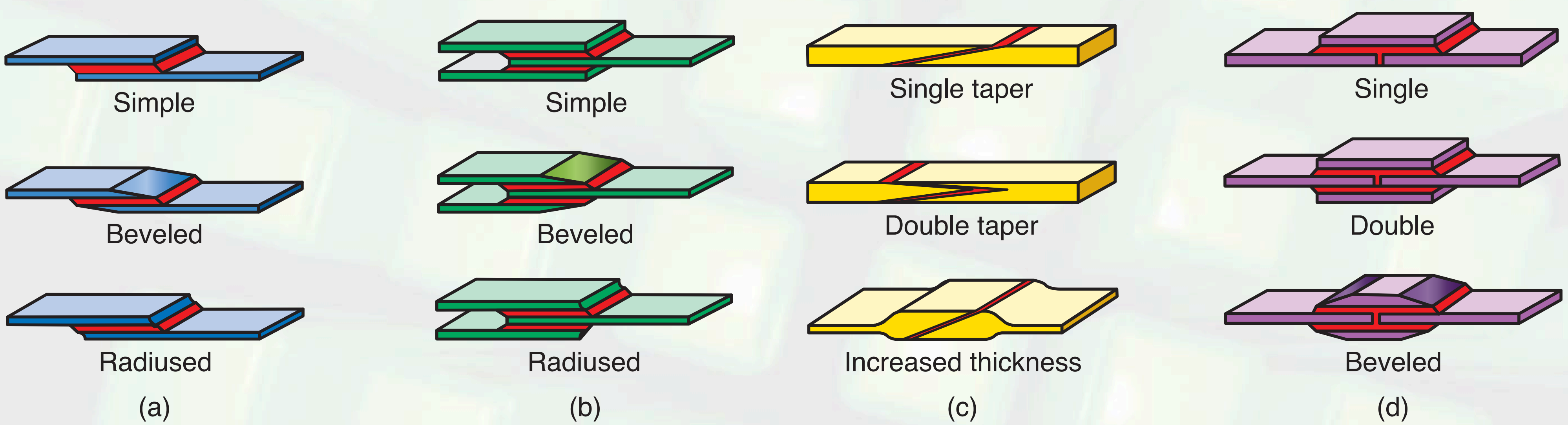
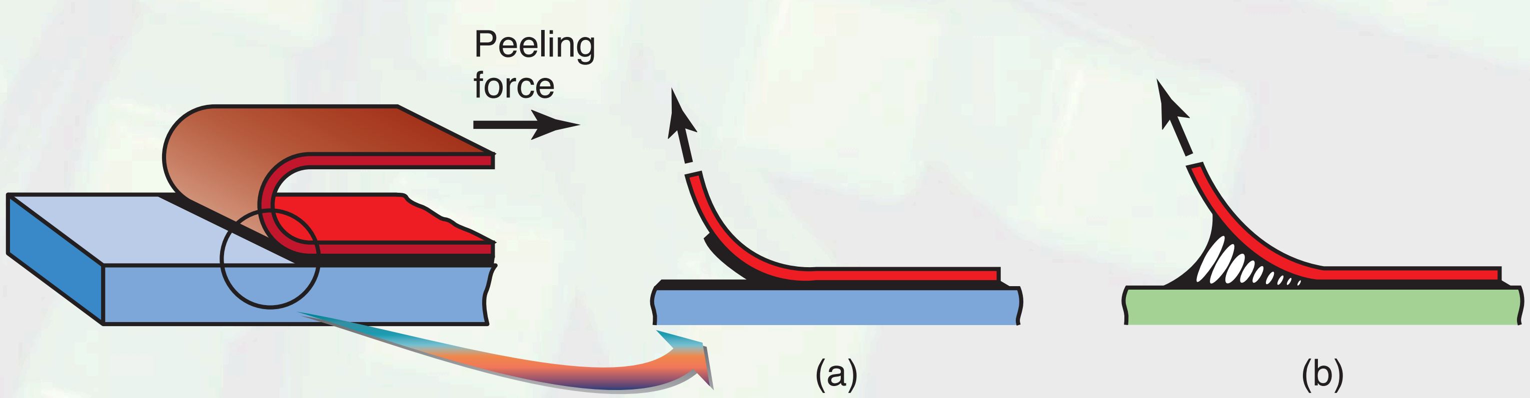


FIGURE 12.49 Various configurations for adhesively bonded joints: (a) single lap, (b) double lap, (c) scarf, and (d) strap.

FIGURE 12.50 Characteristic behavior of (a) brittle and (b) tough and ductile adhesives in a peeling test. This test is similar to peeling adhesive tape from a solid surface.



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Properties of Adhesives

	Epoxy	Polyurethane	Modified Acrylic	Cyanocrylate	Anaerobic
Impact resistance	Poor	Excellent	Good	Poor	Fair
Tension-shear strength, MPa (10^3 psi)	15-22 (2.2-3.2)	12-20 (1.7-2.9)	20-30 (2.9-4.3)	18.9 (2.7)	17.5 (2.5)
Peel strength*, N/m (lb/in.)	$<$ 523 (3)	14,000 (80)	5250 (30)	$<$ 525 (3)	1750 (10)
Substrates bonded	Most	Most smooth, nonporous	Most smooth, nonporous	Most non-porous metals or plastics	Metals, glass, thermosets
Service temperature range, °C (°F)	-55 to 120 (-70 to 250)	-40 to 90 (-250 to 175)	-70 to 120 (-100 to 250)	-55 to 80 (-70 to 175)	-55 to 150 (-70 to 300)
Heat cure or mixing required	Yes	Yes	No	No	No
Solvent resistance	Excellent	Good	Good	Good	Excellent
Moisture resistance	Good-Excellent	Fair	Good	Poor	Good
Gap limitation, mm (in.)	None	None	0.5 (0.02)	0.25 (0.01)	0.60 (0.025)
Odor	Mild	Mild	Strong	Moderate	Mild
Toxicity	Moderate	Moderate	Moderate	Low	Low
Flammability	Low	Low	High	Low	Low

Note: Peel strength varies widely depending on surface preparation and quality.

TABLE 12.6 Typical properties and characteristics of chemically reactive structural adhesives.

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Rivets and Stapling

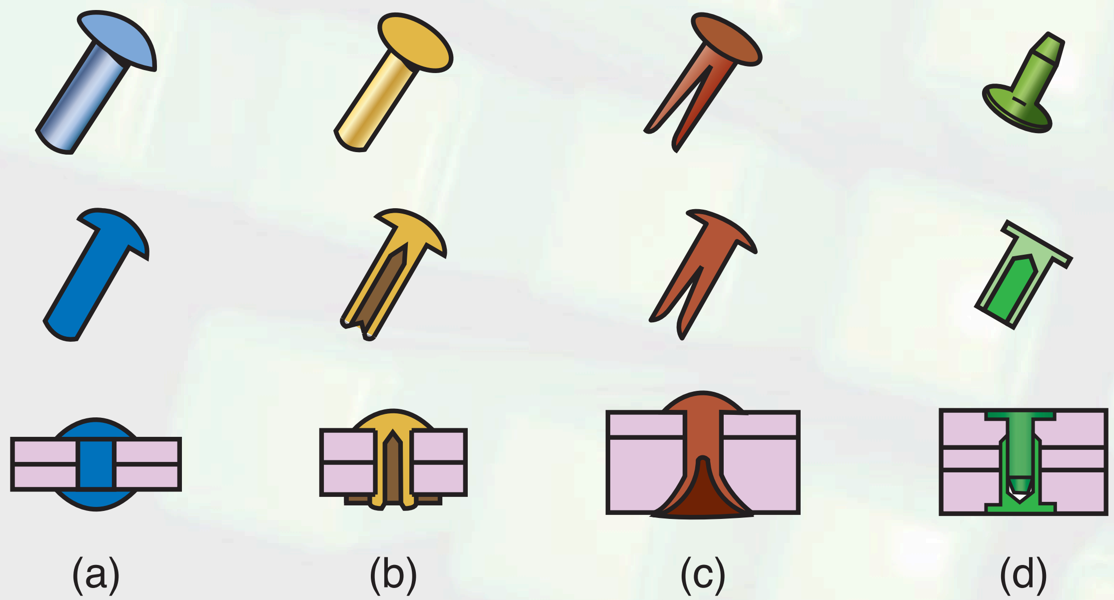

FIGURE 12.51 Examples of rivets: (a) solid, (b) tubular, (c) split, or bifurcated, and (d) compression.

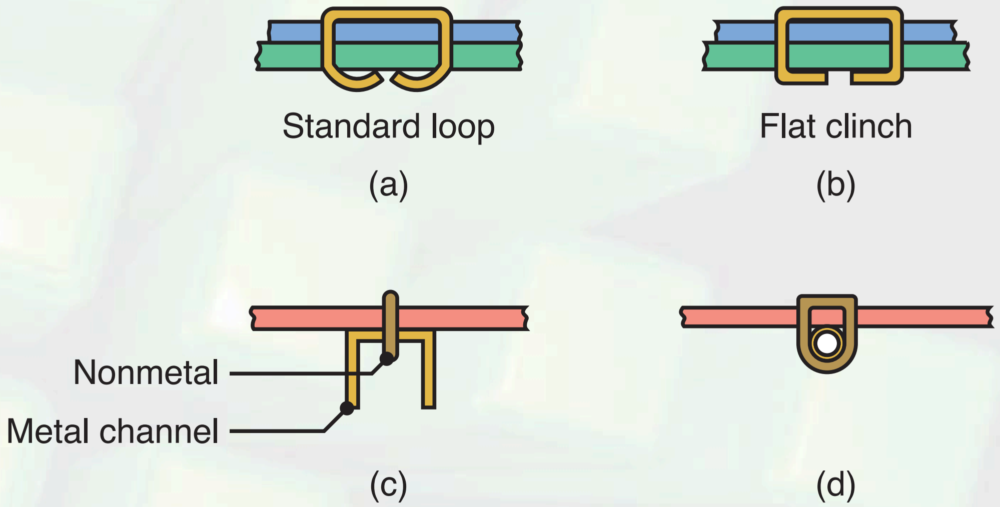

FIGURE 12.52 Examples of various fastening methods. (a) Standard loop staple; (b) flat clinch staple; (c) channel strap; (d) pin strap.

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Seams & Crimping

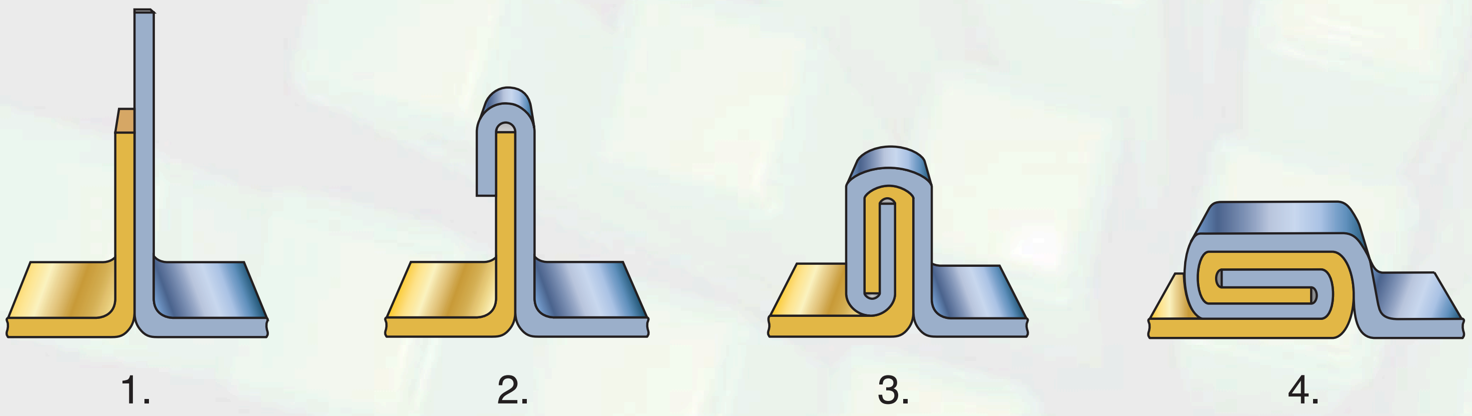
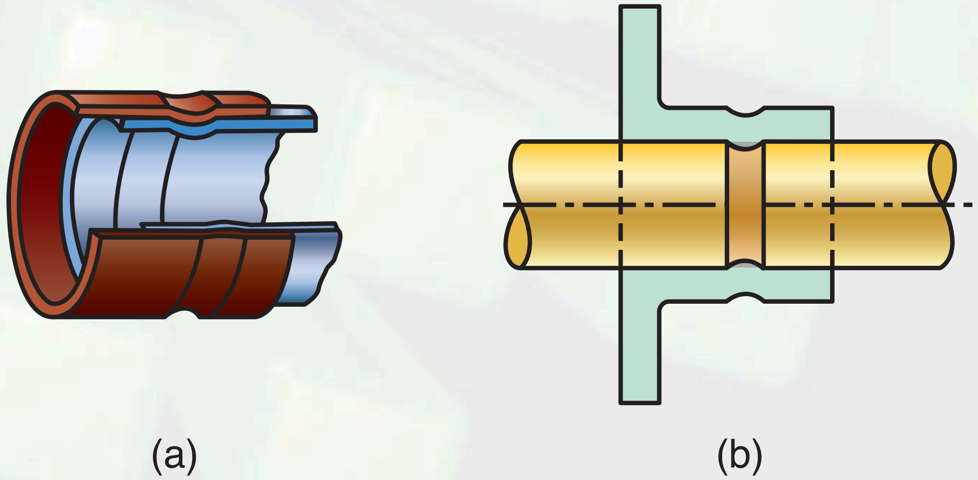


FIGURE 12.53 Stages in forming a double-lock seam. See also Fig. 7.23.

FIGURE 12.54 Two examples of mechanical joining by crimping.



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Snap Fasteners

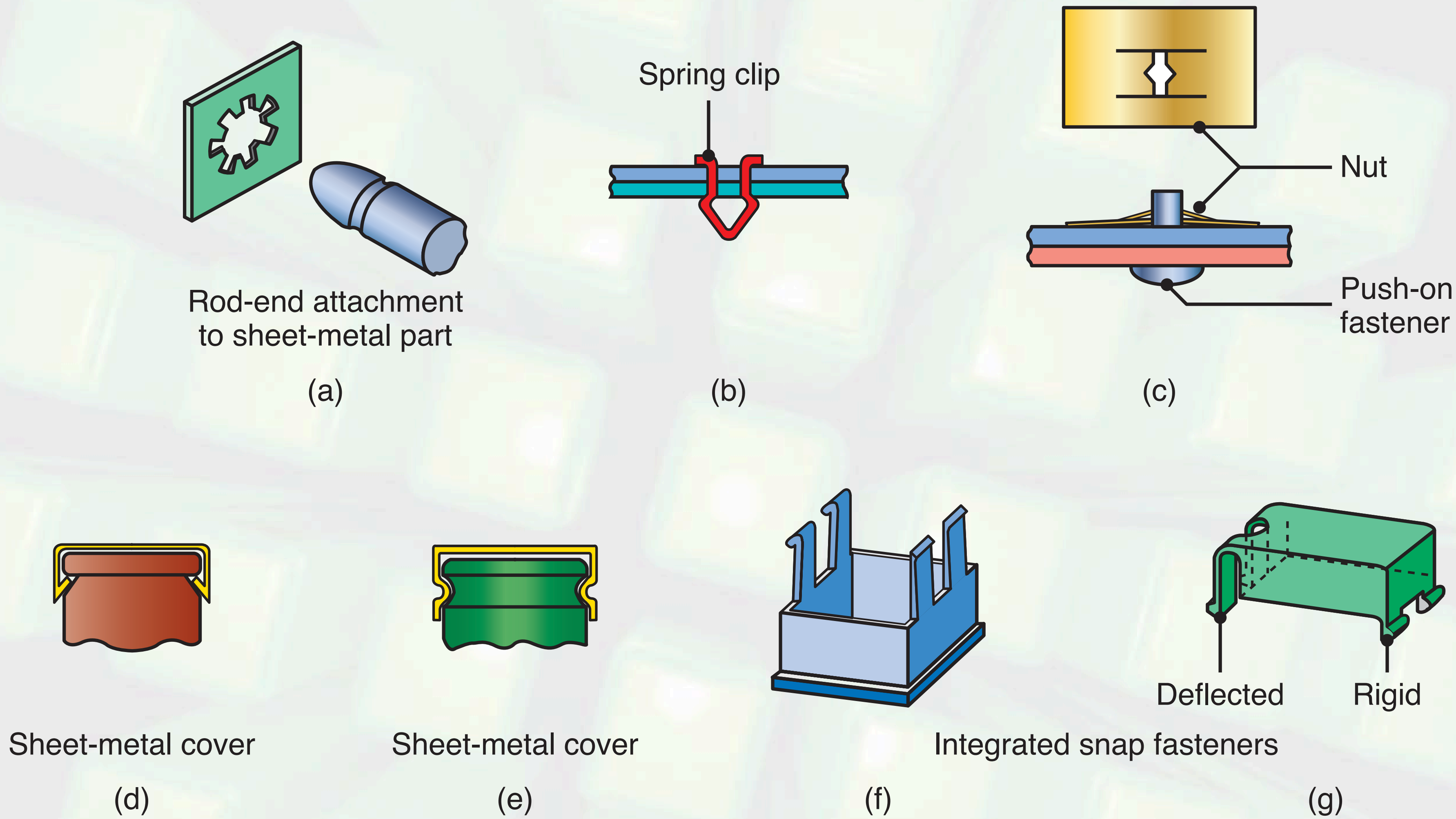

FIGURE 12.55 Examples of spring and snap-in fasteners to facilitate assembly.

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Design Guidelines for Welding

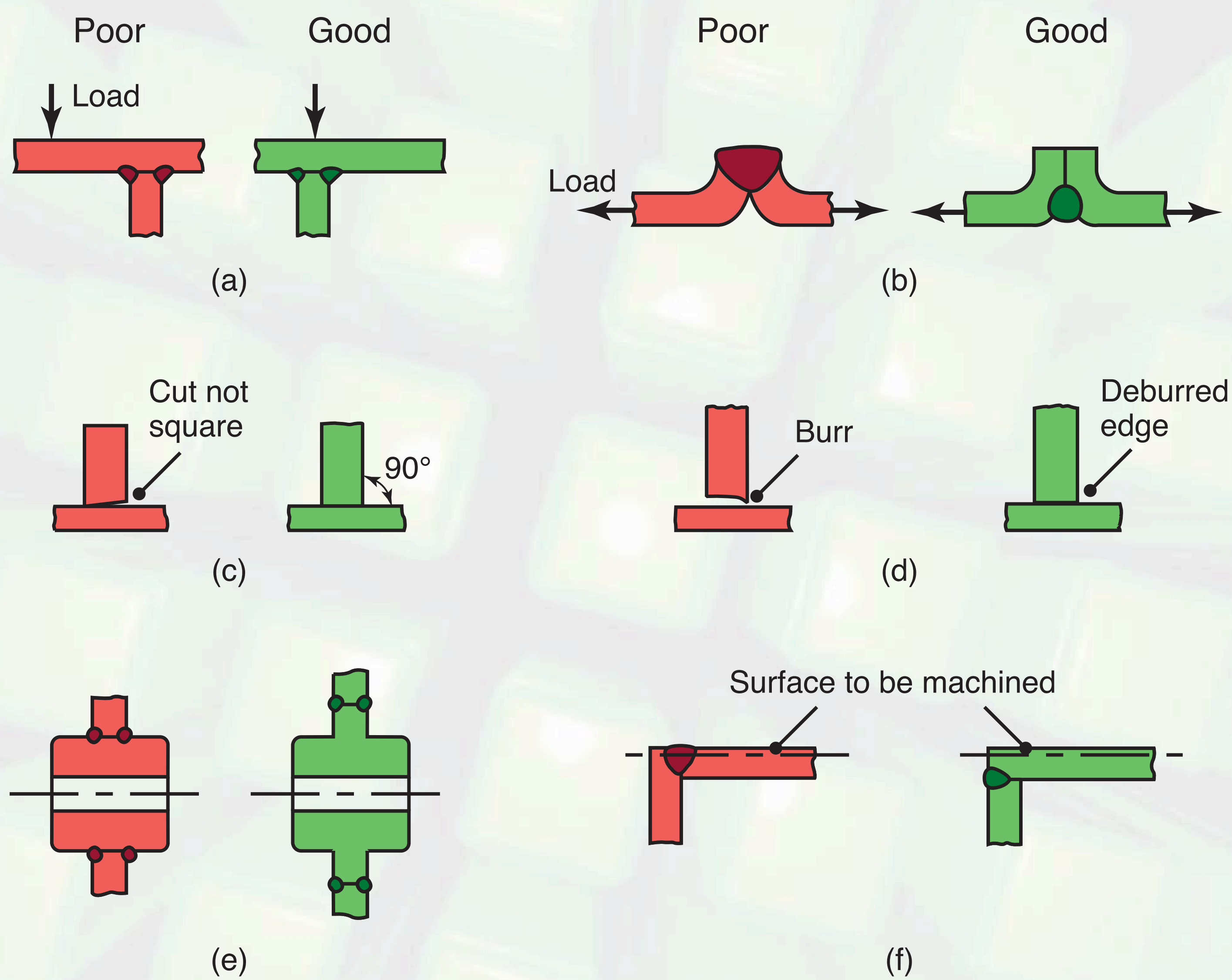

FIGURE 12.56 Design guidelines for welding. *Source:* Bralla, J.G. (ed.) *Handbook of Product Design for Manufacturing*, 2d ed. McGraw-Hill, 1999.

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Weld Designs

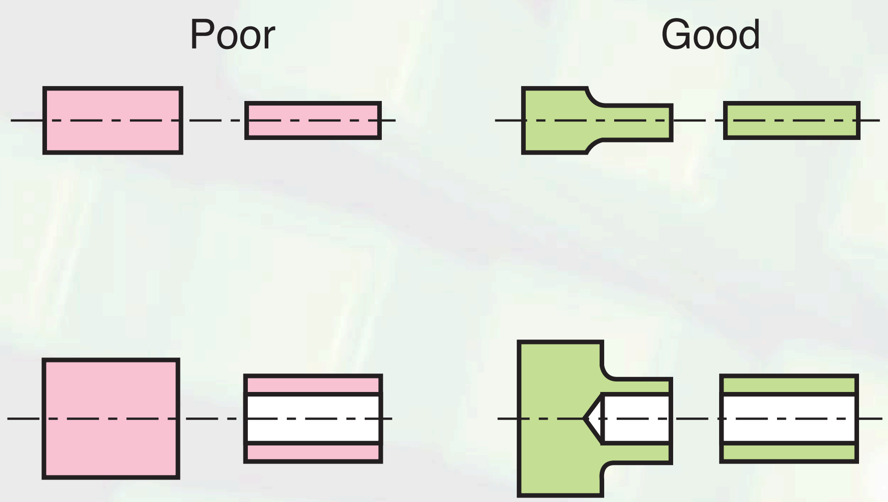

FIGURE 12.57 Design guidelines for flash welding.

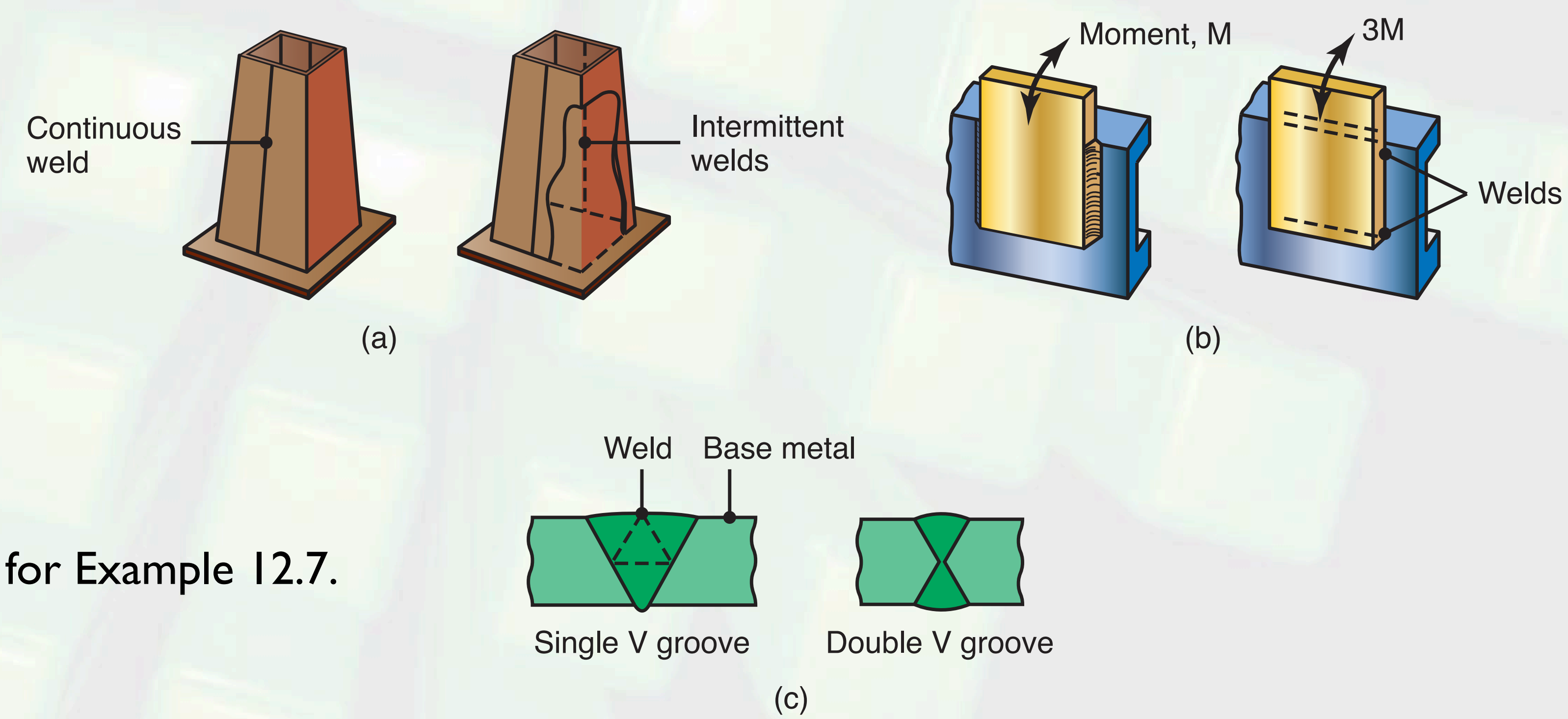

FIGURE 12.58 Weld designs for Example 12.7.

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Brazing Designs

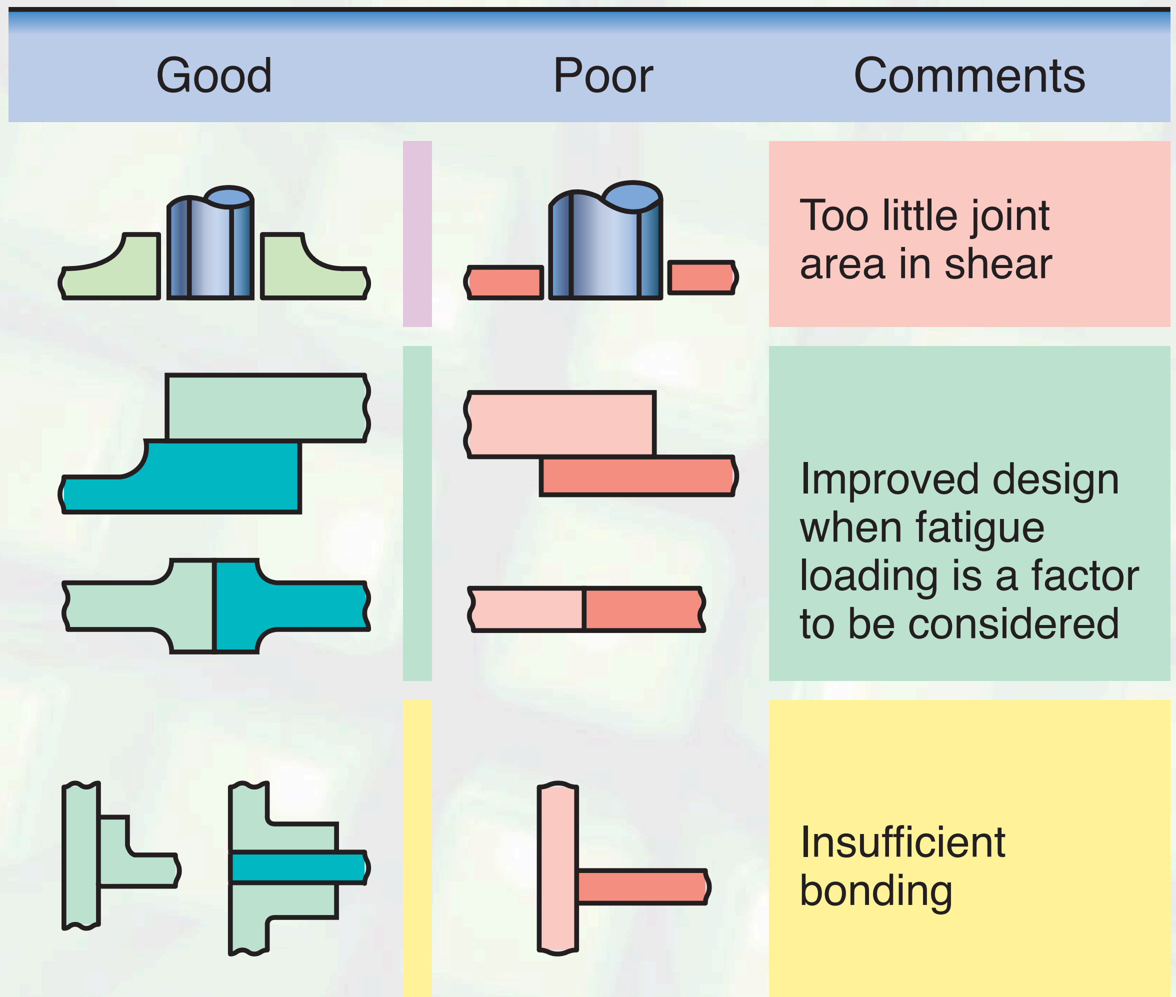

FIGURE 12.59 Examples of good and poor designs for brazing.

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Design for Adhesive Bonding

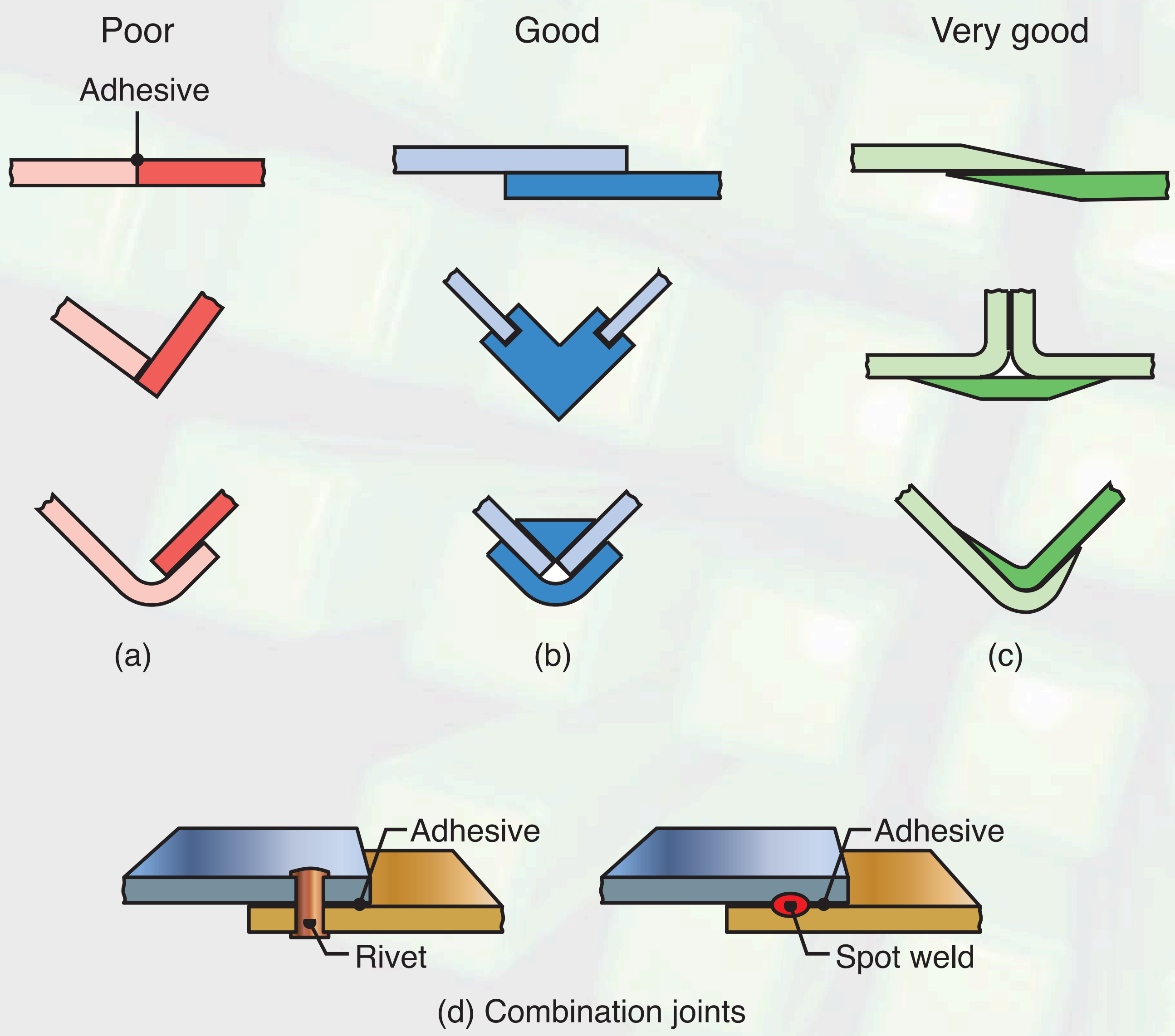

FIGURE 12.60 Various joint designs in adhesive bonding. Note that good designs require large contact areas for better joint strength.

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Design for Riveting

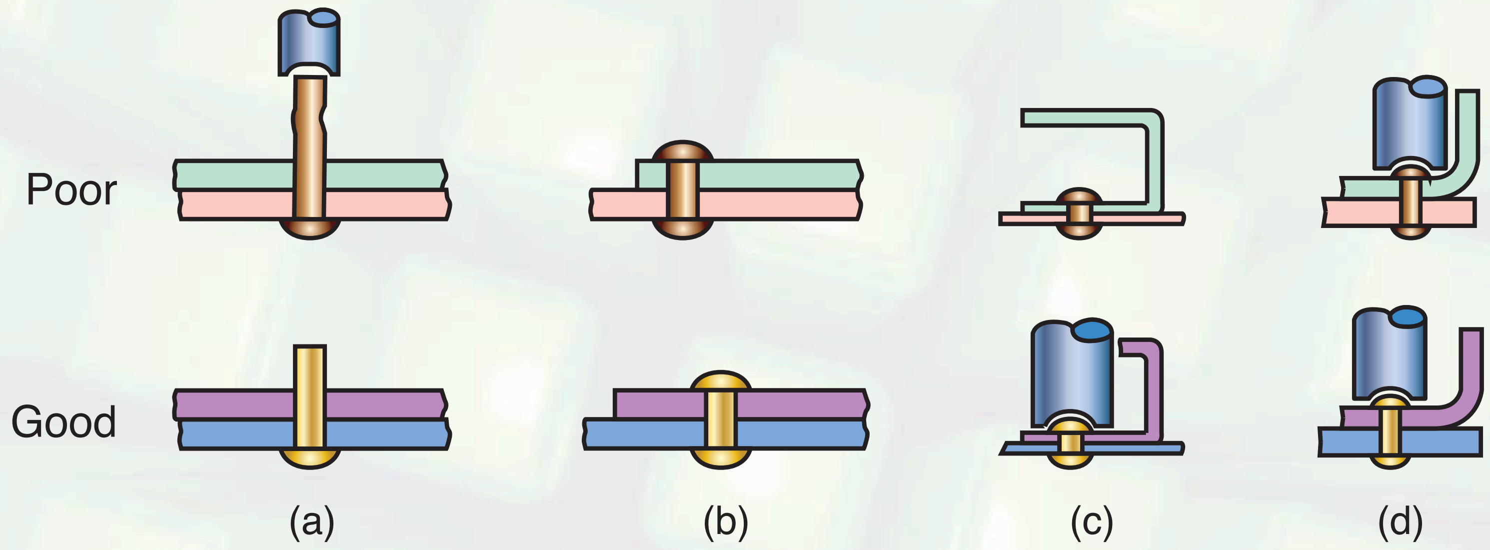

FIGURE 12.61 Design guidelines for riveting. *Source:* Bralla, J.G. (ed.) *Handbook of Product Design for Manufacturing*, 2nd ed. McGraw-Hill, 1999.

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Case Study: Monosteel® Pistons

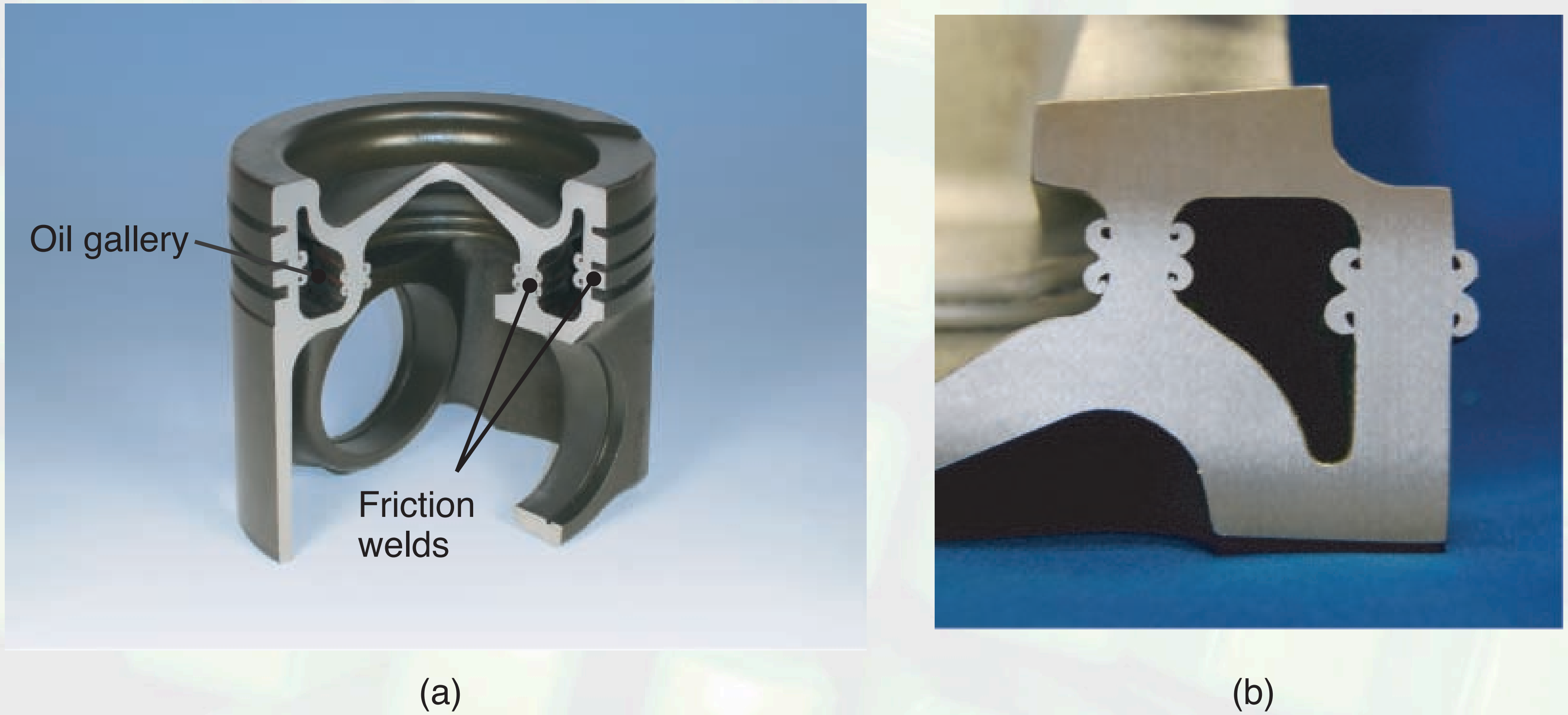

FIGURE 12.62 The Monosteel® piston. (a) Cutaway view of the piston, showing the oil gallery and friction welded sections; (b) detail of the friction welds before the external flash is removed by machining; note that this photo is a reverse of the one on the left.

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