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Brazing, Soldering, and Adhesive Bonding

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This chapter covers three joining processes that are similar to welding in certain respects: brazing, soldering, and adhesive bonding. Brazing and soldering both use filler metals to join and bond two (or more) metal parts to provide a permanent joint. It is difficult, although not impossible, to disassemble the parts after a brazed or soldered joint has been made. In the spectrum of joining processes, brazing and soldering lie between fusion welding and solid-state welding. A filler metal is added in brazing and soldering as in most fusion-welding operations; however, no melting of the base metals occurs, which is similar to solid-state welding. Despite these anomalies, brazing and soldering are generally considered to be distinct from welding. Brazing and soldering are attractive compared to welding under circumstances where (1) the metals have poor weldability, (2) dissimilar metals are to be joined, (3) the intense heat of welding may damage the components being joined, (4) the geometry of the joint does not lend itself to any of the welding methods, and/or (5) high strength is not a requirement.

Adhesive bonding shares certain features in common with brazing and soldering. It utilizes the forces of attachment between a filler material and two closely spaced surfaces to bond the parts. The differences are that the filler material in adhesive bonding is not metallic, and the joining process is carried out at room temperature or only modestly above.

30.1 Brazing

Brazing is a joining process in which a filler metal is melted and distributed by capillary action between the faying surfaces of the metal parts being joined. No melting of the base metals occurs in brazing; only the filler melts. In brazing the filler metal (also called the

brazing metal), has a melting temperature (liquidus) that is above 450°C (840°F) but below the melting point (solidus) of the base metal(s) to be joined. If the joint is properly designed and the brazing operation has been properly performed, the brazed joint will be stronger than the filler metal out of which it has been formed upon solidification. This rather remarkable result is due to the small part clearances used in brazing, the metallurgical bonding that occurs between base and filler metals, and the geometric constrictions that are imposed on the joint by the base parts.

Brazing has several advantages compared to welding: (1) any metals can be joined, including dissimilar metals; (2) certain brazing methods can be performed quickly and consistently, thus permitting high cycle rates and automated production; (3) some methods allow multiple joints to be brazed simultaneously; (4) brazing can be applied to join thin-walled parts that cannot be welded; (5) in general, less heat and power are required than in fusion welding; (6) problems with the heat-affected zone in the base metal near the joint are reduced; and (7) joint areas that are inaccessible by many welding processes can be brazed, since capillary action draws the molten filler metal into the joint.

Disadvantages and limitations of brazing include (1) joint strength is generally less than that of a welded joint; (2) although strength of a good brazed joint is greater than that of the filler metal, it is likely to be less than that of the base metals; (3) high service temperatures may weaken a brazed joint; and (4) the color of the metal in the brazed joint may not match the color of the base metal parts, a possible aesthetic disadvantage.

Brazing as a production process is widely used in a variety of industries, including automotive (e.g., joining tubes and pipes), electrical equipment (e.g., joining wires and cables), cutting tools (e.g., brazing cemented carbide inserts to shanks), and jewelry making. In addition, the chemical processing industry and plumbing and heating contractors join metal pipes and tubes by brazing. The process is used extensively for repair and maintenance work in nearly all industries.

30.1.1 BRAZED JOINTS

Brazed joints are commonly of two types: butt and lap (Section 29.2.1). However, the two types have been adapted for the brazing process in several ways. The conventional butt joint provides a limited area for brazing, thus jeopardizing the strength of the joint. To increase the faying areas in brazed joints, the mating parts are often scarfed or stepped or otherwise altered, as shown in Figure 30.1. Of course, additional processing is usually required in the making of the parts for these special joints.

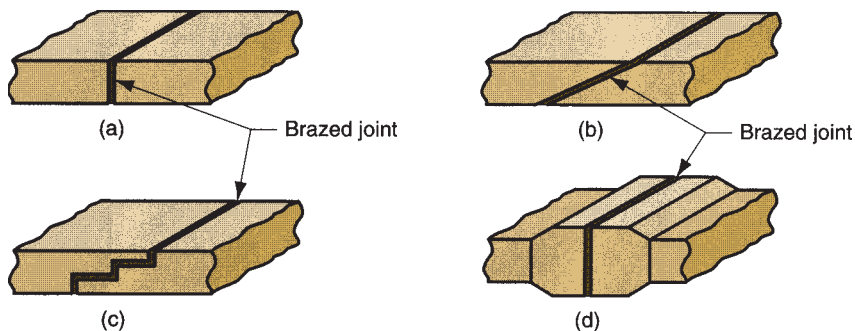


FIGURE 30.1
(a) Conventional butt joint, and adaptations of the butt joint for brazing: (b) scarf joint, (c) stepped butt joint, (d) increased cross section of the part at the joint.

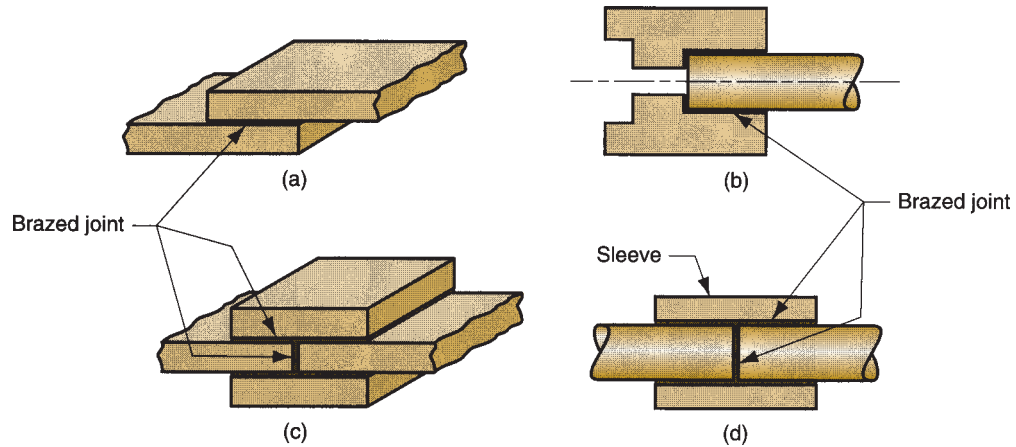


FIGURE 30.2 (a) Conventional lap joint, and adaptations of the lap joint for brazing: (b) cylindrical parts, (c) sandwiched parts, and (d) use of sleeve to convert butt joint into lap joint.

One of the particular difficulties associated with a scarfed joint is the problem of maintaining the alignment of the parts before and during brazing.

Lap joints are more widely used in brazing, since they can provide a relatively large interface area between the parts. An overlap of at least three times the thickness of the thinner part is generally considered good design practice. Some adaptations of the lap joint for brazing are illustrated in Figure 30.2. An advantage of brazing over welding in lap joints is that the filler metal is bonded to the base parts throughout the entire interface area between the parts, rather than only at the edges (as in fillet welds made by arc welding) or at discrete spots (as in resistance spot welding).

Clearance between mating surfaces of the base parts is important in brazing. The clearance must be large enough so as not to restrict molten filler metal from flowing throughout the entire interface. Yet if the joint clearance is too great, capillary action will be reduced and there will be areas between the parts where no filler metal is present. Joint strength is affected by clearance, as depicted in Figure 30.3. There is an

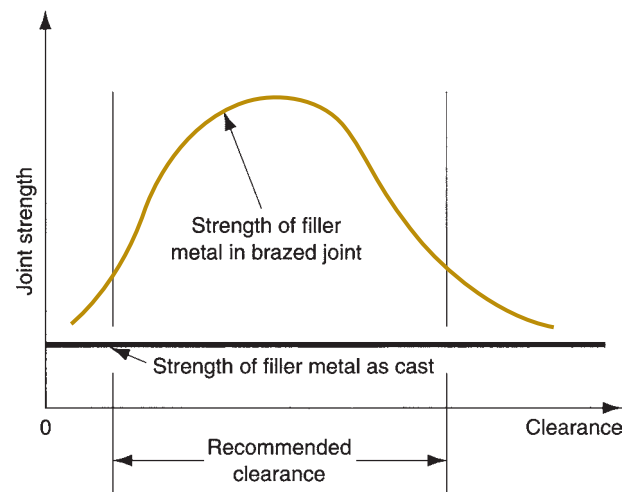


FIGURE 30.3 Joint strength as a function of joint clearance.

optimum clearance value at which joint strength is maximized. The issue is complicated by the fact that the optimum depends on base and filler metals, joint configuration, and processing conditions. Typical brazing clearances in practice are 0.025 to 0.25 mm (0.001–0.010 in). These values represent the joint clearance at the brazing temperature, which may be different from room temperature clearance, depending on thermal expansion of the base metal(s).

Cleanliness of the joint surfaces prior to brazing is also important. Surfaces must be free of oxides, oils, and other contaminants in order to promote wetting and capillary attraction during the process, as well as bonding across the entire interface. Chemical treatments such as solvent cleaning (Section 28.1.1) and mechanical treatments such as wire brushing and sand blasting (Section 28.1.2) are used to clean the surfaces. After cleaning and during the brazing operation, fluxes are used to maintain surface cleanliness and promote wetting for capillary action in the clearance between faying surfaces.

30.1.2 FILLER METALS AND FLUXES

Common filler metals used in brazing are listed in Table 30.1 along with the principal base metals on which they are typically used. To qualify as a brazing metal, the following characteristics are needed: (1) melting temperature must be compatible with the base metal, (2) surface tension in the liquid phase must be low for good wettability, (3) fluidity of the molten metal must be high for penetration into the interface, (4) the metal must be capable of being brazed into a joint of adequate strength for the application, and (5) chemical and physical interactions with base metal (e.g., galvanic reaction) must be avoided. Filler metals are applied to the brazing operation in various ways, including wire, rod, sheets and strips, powders, pastes, preformed parts made of braze metal designed to fit a particular joint configuration, and cladding on one of the surfaces to be brazed. Several of these techniques are illustrated in Figures 30.4 and 30.5. Braze metal pastes, shown in Figure 30.5, consist of filler metal powders mixed with fluid fluxes and binders.

Brazing fluxes serve a similar purpose as in welding; they dissolve, combine with, and otherwise inhibit the formation of oxides and other unwanted byproducts in the

TABLE • 30.1 Common filler metals used in brazing and the base metals on which they are used.

Filler Metal	Typical Composition	Approximate Brazing Temperature		Base Metals
		°C	°F	
Aluminum and silicon	90 Al, 10 Si	600	1100	Aluminum
Copper	99.9 Cu	1120	2050	Nickel copper
Copper and phosphorous	95 Cu, 5 P	850	1550	Copper
Copper and zinc	60 Cu, 40 Zn	925	1700	Steels, cast irons, nickel
Gold and silver	80 Au, 20 Ag	950	1750	Stainless steel, nickel alloys
Nickel alloys	Ni, Cr, others	1120	2050	Stainless steel, nickel alloys
Silver alloys	Ag, Cu, Zn, Cd	730	1350	Titanium, Monel, Inconel, tool steel, nickel

Compiled from [5] and [7].

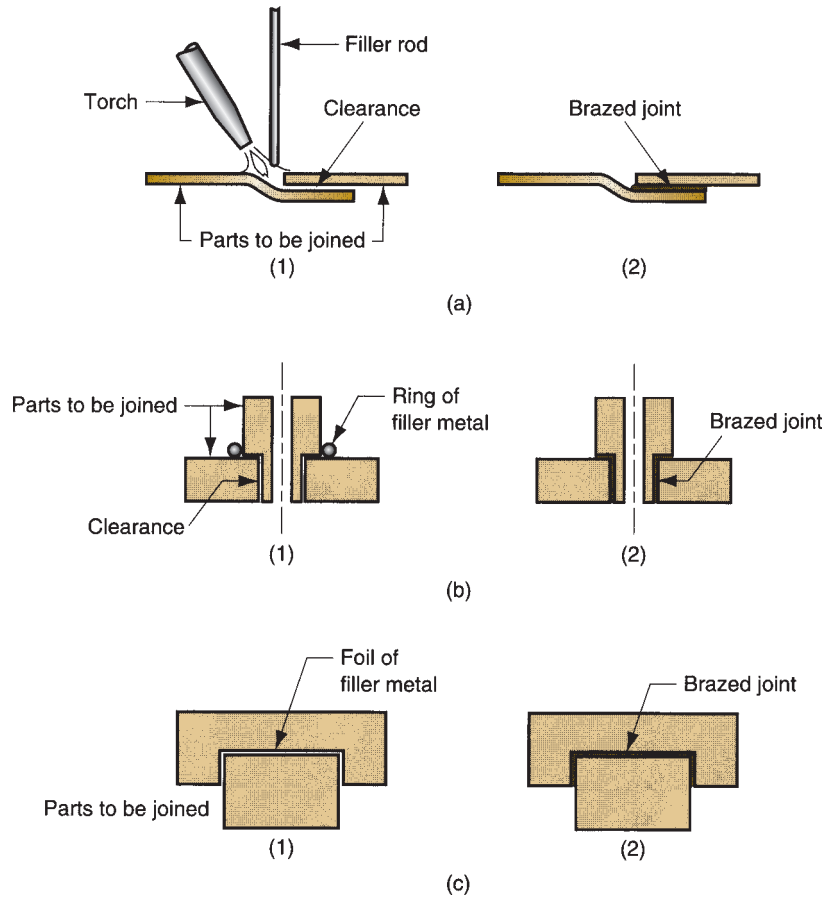


FIGURE 30.4 Several techniques for applying filler metal in brazing: (a) torch and filler rod; (b) ring of filler metal at entrance of gap; and (c) foil of filler metal between flat part surfaces. Sequence: (1) before, and (2) after.

brazing process. Use of a flux does not substitute for the cleaning steps described above. Characteristics of a good flux include (1) low melting temperature, (2) low viscosity so that it can be displaced by the filler metal, (3) facilitates wetting, and (4) protects the joint until solidification of the filler metal. The flux should also be easy to remove after brazing. Common ingredients for brazing fluxes include borax, borates, fluorides, and chlorides. Wetting agents are also included in the mix to reduce surface tension of the molten filler metal and to improve wettability. Forms of flux include powders, pastes, and slurries. Alternatives to using a flux are to perform the operation in a vacuum or a reducing atmosphere that inhibits oxide formation.

30.1.3 BRAZING METHODS

There are various methods used in brazing. Referred to as brazing processes, they are differentiated by their heating sources.

Torch Brazing In torch brazing, flux is applied to the part surfaces and a torch is used to direct a flame against the work in the vicinity of the joint. A reducing flame is typically used to inhibit oxidation. After the work part joint areas have

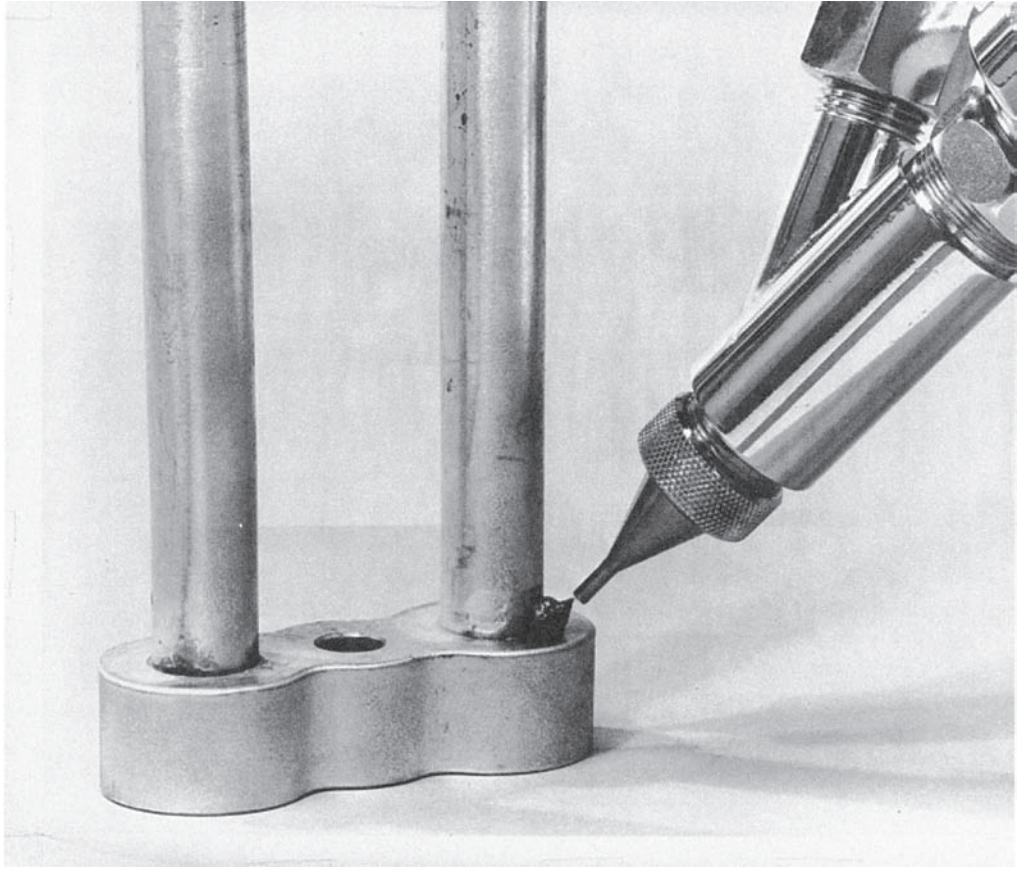


FIGURE 30.5 Application of brazing paste to joint by dispenser. (Courtesy of Fusion, Inc.)

been heated to a suitable temperature, filler wire is added to the joint, usually in wire or rod form. Fuels used in torch brazing include acetylene, propane, and other gases, with air or oxygen. The selection of the mixture depends on heating requirements of the job. Torch brazing is often performed manually, and skilled workers must be employed to control the flame, manipulate the hand-held torches, and properly judge the temperatures; repair work is a common application. The method can also be used in mechanized production operations, in which parts and brazing metal are loaded onto a conveyor or indexing table and passed under one or more torches.

Furnace Brazing Furnace brazing uses a furnace to supply heat for brazing and is best suited to medium and high production. In medium production, usually in batches, the component parts and brazing metal are loaded into the furnace, heated to brazing temperature, and then cooled and removed. High-production operations use flow-through furnaces, in which parts are placed on a conveyor and are transported through the various heating and cooling sections. Temperature and atmosphere control are important in furnace brazing; the atmosphere must be neutral or

reducing. Vacuum furnaces are sometimes used. Depending on the atmosphere and metals being brazed, the need for a flux may be eliminated.

Induction Brazing Induction brazing utilizes heat from electrical resistance to a high-frequency current induced in the work. The parts are preloaded with filler metal and placed in a high-frequency AC field—the parts do not directly contact the induction coil. Frequencies range from 5 kHz to 5 MHz. High-frequency power sources tend to provide surface heating, while lower frequencies cause deeper heat penetration into the work and are appropriate for heavier sections. The process can be used to meet low- to high-production requirements.

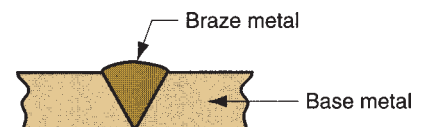
Resistance Brazing Heat to melt the filler metal in this process is obtained by resistance to flow of electrical current through the parts. As distinguished from induction brazing, the parts are directly connected to the electrical circuit in resistance brazing. The equipment is similar to that used in resistance welding, except that a lower power level is required for brazing. The parts with filler metal preplaced are held between electrodes while pressure and current are applied. Both induction and resistance brazing achieve rapid heating cycles and are used for relatively small parts. Induction brazing seems to be the more widely used of the two processes.

Dip Brazing In dip brazing, either a molten salt bath or a molten metal bath accomplishes heating. In both methods, assembled parts are immersed in the baths contained in a heating pot. Solidification occurs when the parts are removed from the bath. In the *salt bath method*, the molten mixture contains fluxing ingredients and the filler metal is preloaded onto the assembly. In the *metal bath method*, the molten filler metal is the heating medium; it is drawn by capillary action into the joint during submersion. A flux cover is maintained on the surface of the molten metal bath. Dip brazing achieves fast heating cycles and can be used to braze many joints on a single part or on multiple parts simultaneously.

Infrared Brazing This method uses heat from a high-intensity infrared lamp. Some IR lamps are capable of generating up to 5000 W of radiant heat energy, which can be directed at the work parts for brazing. The process is slower than most of the other processes reviewed above, and is generally limited to thin sections.

Braze Welding This process differs from the other brazing processes in the type of joint to which it is applied. As pictured in Figure 30.6, braze welding is used for filling a more conventional weld joint, such as the V-joint shown. A greater quantity of filler metal is deposited than in brazing, and no capillary action occurs. In braze welding, the joint consists entirely of filler metal; the base metal does not melt and is therefore not fused into the joint as in a conventional fusion welding process. The principal application of braze welding is repair work.

FIGURE 30.6 Braze welding. The joint consists of braze (filler) metal; no base metal is fused in the joint.



30.2 Soldering

Soldering is similar to brazing and can be defined as a joining process in which a filler metal with melting point (liquidus) not exceeding 450°C (840°F) is melted and distributed by capillary action between the faying surfaces of the metal parts being joined. As in brazing, no melting of the base metals occurs, but the filler metal wets and combines with the base metal to form a metallurgical bond. Details of soldering are similar to those of brazing, and many of the heating methods are the same. Surfaces to be soldered must be precleaned so they are free of oxides, oils, and so on. An appropriate flux must be applied to the faying surfaces, and the surfaces are heated. Filler metal, called **solder**, is added to the joint, which distributes itself between the closely fitting parts.

In some applications, the solder is precoated onto one or both of the surfaces—a process called **tinning**, irrespective of whether the solder contains any tin. Typical clearances in soldering range from 0.075 to 0.125 mm (0.003–0.005 in), except when the surfaces are tinned, in which case a clearance of about 0.025 mm (0.001 in) is used. After solidification, the flux residue must be removed.

As an industrial process, soldering is most closely associated with electronics assembly (Chapter 34). It is also used for mechanical joints, but not for joints subjected to elevated stresses or temperatures. Advantages attributed to soldering include (1) low energy input relative to brazing and fusion welding, (2) variety of heating methods available, (3) good electrical and thermal conductivity in the joint, (4) capability to make air-tight and liquid-tight seams for containers, and (5) easy to repair and rework.

The biggest disadvantages of soldering are (1) low joint strength unless reinforced by mechanical means and (2) possible weakening or melting of the joint in elevated temperature service.

30.2.1 JOINT DESIGNS IN SOLDERING

As in brazing, soldered joints are limited to lap and butt types, although butt joints should not be used in load-bearing applications. Some of the brazing adaptations of these joints also apply to soldering, and soldering technology has added a few more variations of its own to deal with the special part geometries that occur in electrical connections. In soldered mechanical joints of sheet-metal parts, the edges of the sheets are often bent over and interlocked before soldering, as shown in Figure 30.7, to increase joint strength.

For electronics applications, the principal function of the soldered joint is to provide an electrically conductive path between two parts being joined. Other design considerations in these types of soldered joints include heat generation (from the electrical resistance of the joint) and vibration. Mechanical strength in a soldered electrical connection is often achieved by deforming one or both of the metal parts to accomplish a mechanical joint between them, or by making the surface area larger to provide maximum support by the solder. Several possibilities are sketched in Figure 30.8.

30.2.2 SOLDERS AND FLUXES

Solders and fluxes are the materials used in soldering. Both are critically important in the joining process.

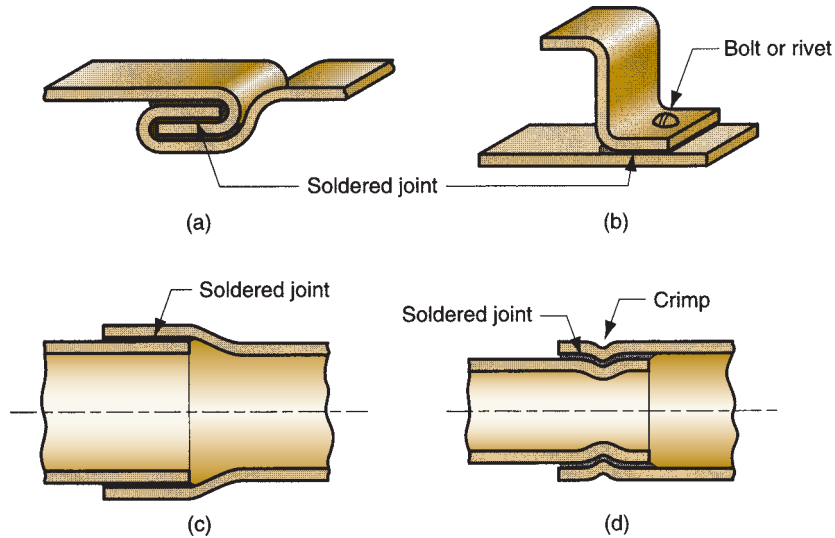


FIGURE 30.7 Mechanical interlocking in soldered joints for increased strength: (a) flat lock seam; (b) bolted or riveted joint; (c) copper pipe fittings—lap cylindrical joint; and (d) crimping (forming) of cylindrical lap joint.

Solders Most solders are alloys of tin and lead, since both metals have low melting points (see Figure 6.3). Their alloys possess a range of liquidus and solidus temperatures to achieve good control of the soldering process for a variety of applications. Lead is poisonous and its percentage is minimized in most solder compositions. Tin is chemically active at soldering temperatures and promotes the wetting action required for successful joining. In soldering copper, common in electrical connections, intermetallic compounds of copper and tin are formed that strengthen the bond. Silver and antimony are also sometimes used in soldering alloys. Table 30.2 lists various solder alloy compositions, indicating their approximate soldering temperatures and principal applications. Lead-free solders are becoming increasingly important as legislation to eliminate lead from solders is enacted.

Soldering Fluxes Soldering fluxes should do the following: (1) be molten at soldering temperatures, (2) remove oxide films and tarnish from the base part surfaces, (3) prevent oxidation during heating, (4) promote wetting of the faying surfaces,

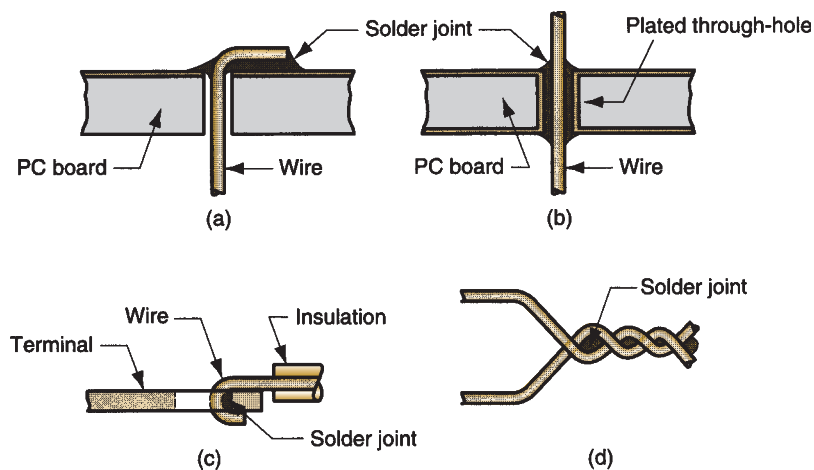


FIGURE 30.8 Techniques for securing the joint by mechanical means prior to soldering in electrical connections: (a) crimped lead wire on printed circuit board (PCB); (b) plated through hole on PCB to maximize solder contact surface; (c) hooked wire on flat terminal; and (d) twisted wires.

TABLE • 30.2 Some common solder alloy compositions with their melting temperatures and applications.

Filler Metal	Approximate Composition	Approximate Melting Temperature		Principal Applications
		°C	°F	
Lead-silver	96 Pb, 4 Ag	305	580	Elevated temperature joints
Tin-antimony	95 Sn, 5 Sb	238	460	Plumbing and heating
Tin-lead	63 Sn, 37 Pb	183 ^a	361 ^a	Electrical/electronics
	60 Sn, 40 Pb	188	370	Electrical/electronics
	50 Sn, 50 Pb	199	390	General purpose
	40 Sn, 60 Pb	207	405	Automobile radiators
Tin-silver	96 Sn, 4 Ag	221	430	Food containers
Tin-zinc	91 Sn, 9 Zn	199	390	Aluminum joining
Tin-silver-copper	95.5 Sn, 3.9 Ag, 0.6 Cu	217	423	Electronics: surface mount technology

Compiled from [2], [3], [4], and [13].
Eutectic composition — lowest melting point of tin–lead compositions.

(5) be readily displaced by the molten solder during the process, and (6) leave a residue that is noncorrosive and nonconductive. Unfortunately, there is no single flux that serves all of these functions perfectly for all combinations of solder and base metals. The flux formulation must be selected for a given application.

Soldering fluxes can be classified as organic or inorganic. **Organic fluxes** are made of either rosin (i.e., natural rosin such as gum wood, which is not water-soluble) or water-soluble ingredients (e.g., alcohols, organic acids, and halogenated salts). The water-soluble type facilitates cleanup after soldering. Organic fluxes are most commonly used for electrical and electronics connections. They tend to be chemically reactive at elevated soldering temperatures but relatively noncorrosive at room temperatures. **Inorganic fluxes** consist of inorganic acids (e.g., muriatic acid) and salts (e.g., combinations of zinc and ammonium chlorides) and are used to achieve rapid and active fluxing where oxide films are a problem. The salts become active when melted, but are less corrosive than the acids. When solder wire is purchased with an **acid core** it is in this category.

Both organic and inorganic fluxes should be removed after soldering, but it is especially important in the case of inorganic acids to prevent continued corrosion of the metal surfaces. Flux removal is usually accomplished using water solutions except in the case of rosins, which require chemical solvents. Recent trends in industry favor water-soluble fluxes over rosins because chemical solvents used with rosins are harmful to the environment and to humans.

30.2.3 SOLDERING METHODS

Many of the methods used in soldering are the same as those used in brazing, except that less heat and lower temperatures are required for soldering. These methods include torch soldering, furnace soldering, induction soldering, resistance soldering, dip soldering, and infrared soldering. There are other soldering methods, not used in brazing, that should be described here. These methods are hand soldering, wave soldering, and reflow soldering.

Hand Soldering Hand soldering is performed manually using a hot soldering iron. A *bit*, made of copper, is the working end of a soldering iron. Its functions are (1) to deliver heat to the parts being soldered, (2) to melt the solder, (3) to convey molten solder to the joint, and (4) to withdraw excess solder. Most modern soldering irons are heated by electrical resistance. Some are designed as fast-heating **soldering guns**, which are popular in electronics assembly for intermittent (on-off) operation actuated by a trigger. They are capable of making a solder joint in about a second.

Wave Soldering Wave soldering is a mechanized technique that allows multiple lead wires to be soldered to a printed circuit board (PCB) as it passes over a wave of molten solder. The typical setup is one in which a PCB, on which electronic components have been placed with their lead wires extending through the holes in the board, is loaded onto a conveyor for transport through the wave-soldering equipment. The conveyor supports the PCB on its sides, so that its underside is exposed to the processing steps, which consist of the following: (1) flux is applied using any of several methods, including foaming, spraying, or brushing; (2) preheating (using light bulbs, heating coils, and infrared devices) to evaporate solvents, activate the flux, and raise the temperature of the assembly; and (3) wave soldering, in which the liquid solder is pumped from a molten bath through a slit onto the bottom of the board to make the soldering connections between the lead wires and the metal circuit on the board. This third step is illustrated in Figure 30.9. The board is often inclined slightly, as depicted in the sketch, and a special tinning oil is mixed with the molten solder to lower its surface tension. Both of these measures help to inhibit buildup of excess solder and formation of “icicles” on the bottom of the board. Wave soldering is widely applied in electronics to produce printed circuit board assemblies (Section 35.3.2).

Reflow Soldering This process is also widely used in electronics to assemble surface mount components to printed circuit boards (Section 35.4.2). In the process, a solder paste consisting of solder powders in a flux binder is applied to spots on the board where electrical contacts are to be made between surface mount components and the copper circuit. The components are then placed on the paste spots, and the board is heated to melt the solder, forming mechanical and electrical bonds between the component leads and the copper on the circuit board.

Heating methods for reflow soldering include vapor phase reflow and infrared reflow. In **vapor phase reflow soldering**, an inert fluorinated hydrocarbon liquid is vaporized by heating in an oven; it subsequently condenses on the board surface

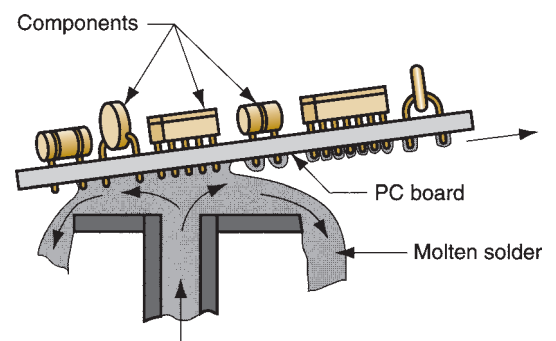


FIGURE 30.9 Wave soldering, in which molten solder is delivered up through a narrow slot onto the underside of a printed circuit board to connect the component lead wires.

where it transfers its heat of vaporization to melt the solder paste and form solder joints on the printed circuit boards. In ***infrared reflow soldering***, heat from an infrared lamp is used to melt the solder paste and form joints between component leads and circuit areas on the board. Additional heating methods to reflow the solder paste include use of hot plates, hot air, and lasers.

30.3 Adhesive Bonding

Use of adhesives dates back to ancient times (Historical Note 30.1) and adhesive bonding was probably the first of the permanent joining methods. Today, adhesives are used in a wide range of bonding and sealing applications for joining similar and dissimilar materials such as metals, plastics, ceramics, wood, paper, and cardboard. Although well-established as a joining technique, adhesive bonding is considered a growth area among assembly technologies because of the tremendous opportunities for increased applications.

Historical Note 30.1 *Adhesive bonding*

Adhesives date from ancient times. Carvings 3300 years old show a glue pot and brush for gluing veneer to wood planks. The ancient Egyptians used gum from the Acacia tree for various assembly and sealing purposes. Bitumen, an asphalt adhesive, was used in ancient times as a cement and mortar for construction in Asia Minor. The Romans used pine wood tar and beeswax to caulk their ships. Glues derived from fish, stag horns, and cheese were used in the early centuries after Christ for assembling components of wood.

In more modern times, adhesives have become an important joining process. Plywood, which relies

on the use of adhesives to bond multiple layers of wood, was developed around 1900. Phenol formaldehyde was the first synthetic adhesive developed, around 1910, and its primary use was in bonding of wood products such as plywood. During World War II, phenolic resins were developed for adhesive bonding of certain aircraft components. In the 1950s, epoxies were first formulated. And since the 1950s a variety of additional adhesives have been developed, including anaerobics, various new polymers, and second-generation acrylics.

Adhesive bonding is a joining process in which a filler material is used to hold two (or more) closely spaced parts together by surface attachment. The filler material that binds the parts together is the ***adhesive***. It is a nonmetallic substance—usually a polymer. The parts being joined are called ***adherends***. Adhesives of greatest interest in engineering are ***structural adhesives***, which are capable of forming strong, permanent joints between strong, rigid adherends. A large number of commercially available adhesives are cured by various mechanisms and suited to the bonding of various materials. ***Curing*** refers to the process by which the adhesive's physical properties are changed from a liquid to a solid, usually by chemical reaction, to accomplish the surface attachment of the parts. The chemical reaction may involve polymerization, condensation, or vulcanization. Curing is often motivated by heat and/or a catalyst, and pressure is sometimes applied between the two parts to activate the bonding process. If heat is required, the curing temperatures are relatively low, and so the materials being joined are usually unaffected—an advantage for adhesive bonding. The curing or hardening of the adhesive takes time, called ***curing time*** or ***setting time***. In some cases this time is significant—generally a disadvantage in manufacturing.

Joint strength in adhesive bonding is determined by the strength of the adhesive itself and the strength of attachment between adhesive and each of the adherends. One of the criteria often used to define a satisfactory adhesive joint is that if a failure should occur due to excessive stresses, it occurs in one of the adherends rather than at an interface or within the adhesive itself. The strength of the attachment results from several mechanisms, all depending on the particular adhesive and adherends: (1) chemical bonding, in which the adhesive unites with the adherends and forms a primary chemical bond upon hardening; (2) physical interactions, in which secondary bonding forces result between the atoms of the opposing surfaces; and (3) mechanical interlocking, in which the surface roughness of the adherend causes the hardened adhesive to become entangled or trapped in its microscopic surface asperities.

For these adhesion mechanisms to operate with best results, the following conditions must prevail: (1) surfaces of the adherend must be clean—free of dirt, oil, and oxide films that would interfere with achieving intimate contact between adhesive and adherend; special preparation of the surfaces is often required; (2) the adhesive in its initial liquid form must achieve thorough wetting of the adherend surface; and (3) it is usually helpful for the surfaces to be other than perfectly smooth—a slightly roughened surface increases the effective contact area and promotes mechanical interlocking. In addition, the joint must be designed to exploit the particular strengths of adhesive bonding and avoid its limitations.

30.3.1 JOINT DESIGN

Adhesive joints are not generally as strong as those by welding, brazing, or soldering. Accordingly, consideration must be given to the design of joints that are adhesively bonded. The following design principles are applicable: (1) Joint contact area should be maximized. (2) Adhesive joints are strongest in shear and tension as in Figure 30.10(a) and (b), and joints should be designed so that the applied stresses are of these types. (3) Adhesive bonded joints are weakest in cleavage or peeling as in Figure 30.10(c) and (d), and adhesive bonded joints should be designed to avoid these types of stresses.

Typical joint designs for adhesive bonding that illustrate these design principles are presented in Figure 30.11. Some joint designs combine adhesive bonding with other joining methods to increase strength and/or provide sealing between the two components. Some of the possibilities are shown in Figure 30.12. For example, the combination of adhesive bonding and spot welding is called **weldbonding**.

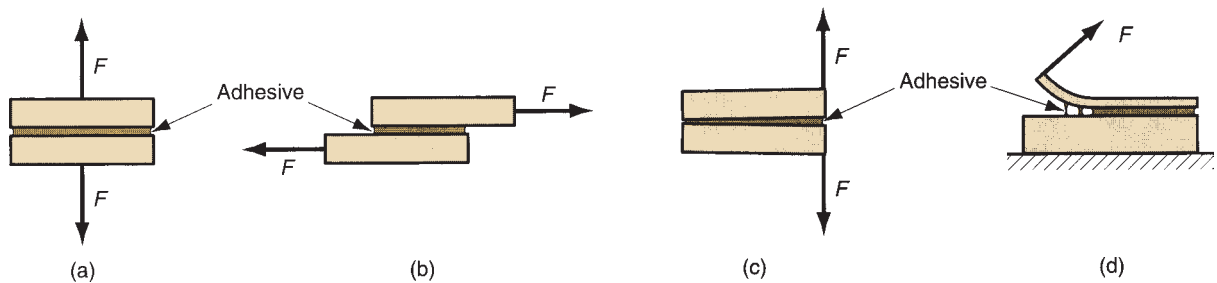


FIGURE 30.10 Types of stresses that must be considered in adhesive bonded joints: (a) tension, (b) shear, (c) cleavage, and (d) peeling.

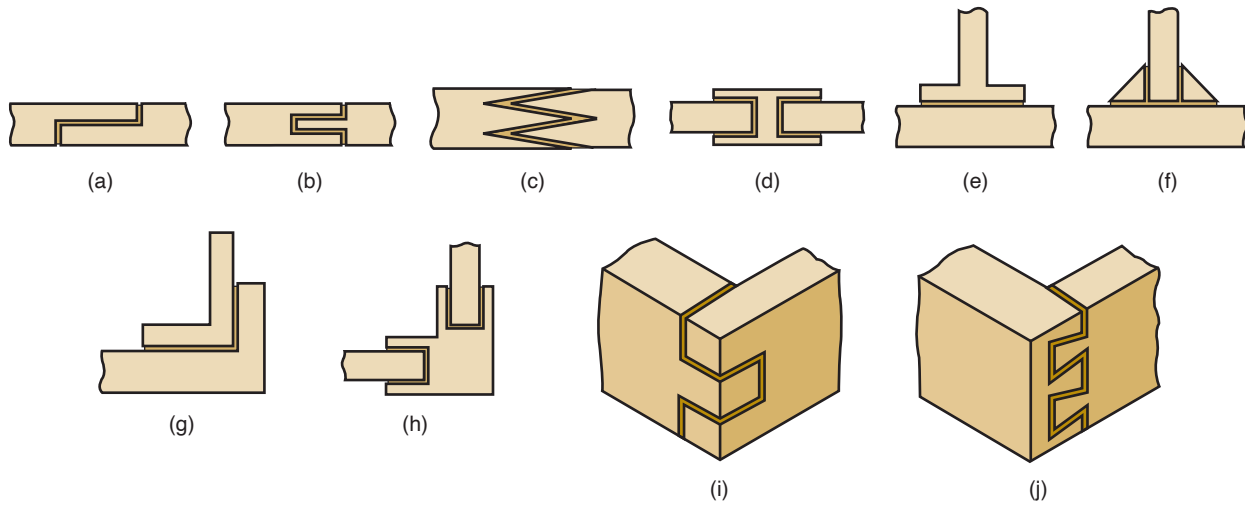


FIGURE 30.11 Some joint designs for adhesive bonding: (a) through (d) butt joints; (e) and (f) T-joints; and (g) through (j) corner joints.

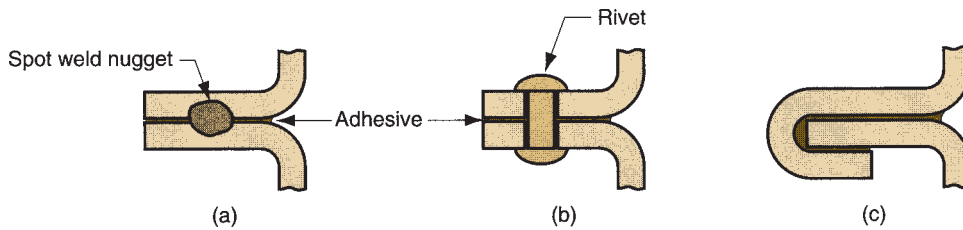


FIGURE 30.12 Adhesive bonding combined with other joining methods: (a) weldbonding—spot welded and adhesive bonded; (b) riveted (or bolted) and adhesive bonded; and (c) formed plus adhesive bonded.

In addition to the mechanical configuration of the joint, the application must be selected so that the physical and chemical properties of adhesive and adherends are compatible under the service conditions to which the assembly will be subjected. Adherend materials include metals, ceramics, glass, plastics, wood, rubber, leather, cloth, paper, and cardboard. Note that the list includes materials that are rigid and flexible, porous and nonporous, metallic and nonmetallic, and that similar or dissimilar substances can be bonded together.

30.3.2 ADHESIVE TYPES

A large number of commercial adhesives are available. They can be classified into three categories: (1) natural, (2) inorganic, and (3) synthetic.

Natural adhesives are derived from natural sources (e.g., plants and animals), including gums, starch, dextrin, soy flour, and collagen. This category of adhesive is generally limited to low-stress applications, such as cardboard cartons, furniture, and bookbinding; or where large surface areas are involved (e.g., plywood). **Inorganic adhesives** are based principally on sodium silicate and magnesium oxychloride. Although relatively low in cost, they are also low in strength—a serious limitation in a structural adhesive.

TABLE • 30.3 Important synthetic adhesives.

Adhesive	Description and Applications
Anaerobic	Single-component, thermosetting, acrylic-based. Cures by free radical mechanism at room temperature. Applications: sealant, structural assembly.
Modified acrylics	Two-component thermoset, consisting of acrylic-based resin and initiator/hardener. Cures at room temperature after mixing. Applications: fiberglass in boats, sheet metal in cars and aircraft.
Cyanoacrylate	Single-component, thermosetting, acrylic-based that cures at room temperature on alkaline surfaces. Applications: rubber to plastic, electronic components on circuit boards, plastic and metal cosmetic cases.
Epoxy	Includes a variety of widely used adhesives formulated from epoxy resins, curing agents, and filler/modifiers that harden upon mixing. Some are cured when heated. Applications: aluminum bonding applications and honeycomb panels for aircraft, sheet-metal reinforcements for cars, lamination of wooden beams, seals in electronics.
Hot melt	Single-component, thermoplastic adhesive hardens from molten state after cooling from elevated temperatures. Formulated from thermoplastic polymers including ethylene vinyl acetate, polyethylene, styrene block copolymer, butyl rubber, polyamide, polyurethane, and polyester. Applications: packaging (e.g., cartons, labels), furniture, footwear, bookbinding, carpeting, and assemblies in appliances and cars.
Pressure-sensitive tapes and films	Usually one component in solid form that possesses high tackiness resulting in bonding when pressure is applied. Formed from various polymers of high molecular weight. Can be single-sided or double-sided. Applications: solar panels, electronic assemblies, plastics to wood and metals.
Silicone	One or two components, thermosetting liquid, based on silicon polymers. Curing by room-temperature vulcanization to rubbery solid. Applications: seals in cars (e.g., windshields), electronic seals and insulation, gaskets, bonding of plastics.
Urethane	One or two components, thermosetting, based on urethane polymers. Applications: bonding of fiberglass and plastics.

Compiled from [8], [10], and [14].

Synthetic adhesives constitute the most important category in manufacturing. They include a variety of thermoplastic and thermosetting polymers, many of which are listed and briefly described in Table 30.3. They are cured by various mechanisms, such as (1) mixing a catalyst or reactive ingredient with the polymer immediately prior to applying, (2) heating to initiate the chemical reaction, (3) radiation curing, such as ultraviolet light, and (4) curing by evaporation of water from the liquid or paste adhesive. In addition, some synthetic adhesives are applied as films or as pressure-sensitive coatings on the surface of one of the adherends.

30.3.3 ADHESIVE APPLICATION TECHNOLOGY

Industrial applications of adhesive bonding are widespread and growing. Major users are automotive, aircraft, building products, and packaging industries; other industries include footwear, furniture, bookbinding, electrical, and shipbuilding. Table 30.3 indicates some of the specific applications for which synthetic adhesives are used. This section considers several issues relating to adhesives application technology.

Surface Preparation In order for adhesive bonding to succeed, part surfaces must be extremely clean. The strength of the bond depends on the degree of adhesion between adhesive and adherend, and this depends on the cleanliness of the surface.

In most cases, additional processing steps are required for cleaning and surface preparation, the methods varying with different adherend materials. For metals, solvent wiping is often used for cleaning, and abrading the surface by sand blasting or other process usually improves adhesion. For nonmetallic parts, solvent cleaning is generally used, and the surfaces are sometimes mechanically abraded or chemically etched to increase roughness. It is desirable to accomplish the adhesive bonding process as soon as possible after these treatments, since surface oxidation and dirt accumulation increase with time.

Application Methods The actual application of the adhesive to one or both part surfaces is accomplished in a number of ways. The following list, though incomplete, provides a sampling of the techniques used in industry:

- **Brushing**, performed manually, uses a stiff-bristled brush. Coatings are often uneven.
- **Flowing**, using manually operated pressure-fed flow guns, has more consistent control than brushing.
- **Manual rollers**, similar to paint rollers, are used to apply adhesive from a flat container.
- **Silk screening** involves brushing the adhesive through the open areas of the screen onto the part surface, so that only selected areas are coated.
- **Spraying** uses an air-driven (or airless) spray gun for fast application over large or difficult-to-reach areas.
- **Automatic applicators** include various automatic dispensers and nozzles for use on medium- and high-speed production applications. Figure 30.13 illustrates the use of a dispenser for assembly.



FIGURE 30.13 Adhesive is dispensed by a manually controlled dispenser to bond parts during assembly. (Courtesy of Nordson, Inc.)

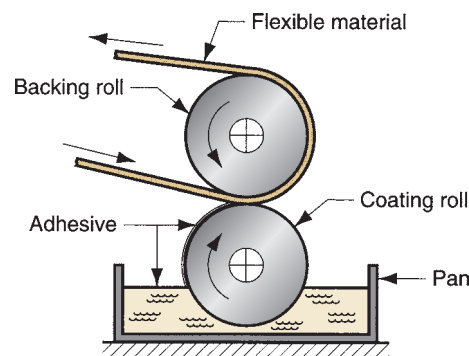


FIGURE 30.14 Roll coating of adhesive onto thin, flexible material such as paper, cloth, or flexible polymer.

- **Roll coating** is a mechanized technique in which a rotating roller is partially submerged in a pan of liquid adhesive and picks up a coating of the adhesive, which is then transferred to the work surface. Figure 30.14 shows one possible application, in which the work is a thin, flexible material (e.g., paper, cloth, leather, plastic). Variations of the method are used for coating adhesive onto wood, wood composite, cardboard, and similar materials with large surface areas.

Advantages and Limitations Advantages of adhesive bonding are (1) the process is applicable to a wide variety of materials; (2) parts of different sizes and cross sections can be joined—fragile parts can be joined by adhesive bonding; (3) bonding occurs over the entire surface area of the joint, rather than in discrete spots or along seams as in fusion welding, thereby distributing stresses over the entire area; (4) some adhesives are flexible after bonding and are thus tolerant of cyclical loading and differences in thermal expansion of adherends; (5) low temperature curing avoids damage to parts being joined; (6) sealing as well as bonding can be achieved; and (7) joint design is often simplified (e.g., two flat surfaces can be joined without providing special part features such as screw holes).

Principal limitations of this technology include (1) joints are generally not as strong as other joining methods; (2) adhesive must be compatible with materials being joined; (3) service temperatures are limited; (4) cleanliness and surface preparation prior to application of adhesive are important; (5) curing times can impose a limit on production rates; and (6) inspection of the bonded joint is difficult.

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