32.4 Adhesive-bonding

One of the most versatile joining process is the use of **adhesives** between two surfaces, generally using a rubber or polymer as the filler material. A common example of *adhesive-bonding* is plywood, where several layers of wood are bonded with wood glue. Modern plywood was developed in 1905, but the practice of adhesive-bonding of wood layers, using animal glue, dates back to 3500 B.C.

Adhesive-bonding has gained increased acceptance in manufacturing ever since its first use on a large scale: the assembly of load-bearing components in aircraft during World War II (1939–1945). Adhesives are available in various forms: liquid, paste, solution, emulsion, powder, tape, and film. When applied, adhesives typically are about 0.1 mm thick.

QR Code 32.1 Adhesive Bonding Processing. (*Source:* Courtesy of EWI)

To meet the requirements of a particular application, an adhesive may require one or more of the following properties (Table 32.3):

- Strength: shear and peel
- Toughness
- Resistance to various fluids and chemicals

TABLE 32.3

Typical Properties and Characteristics of Chemically Reactive Structural Adhesives

	Epoxy	Polyurethane	Modified acrylic	Cyanoacrylate	Anaerobic
Impact resistance	Poor	Excellent	Good	Poor	Fair
Tension-shear strength, MPa	15–22	12–20	20–30	18.9	17.5
Peel strength*, N/m	<523	14,000	5250	<525	1750
Substrates bonded	Most	Most smooth, nonporous	Most smooth, nonporous	Most non-porous metals or plastics	Metals, glass, thermosets
Service temperature range, °C	−55 to 120	−40 to 90	−70 to 120	−55 to 80	−55 to 150
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	None	None	0.5	0.25	0.60
Odor	Mild	Mild	Strong	Moderate	Mild
Toxicity	Moderate	Moderate	Moderate	Low	Low
Flammability	Low	Low	High	Low	Low

*Peel strength varies widely depending on surface preparation and quality.

- Resistance to environmental degradation, including heat and moisture
- Capability to wet the surfaces to be bonded

32.4.1 Types of Adhesives and Adhesive Systems

Several types of adhesives are available, and more continue to be developed that provide good joint strength, including fatigue strength (Table 32.4). The three basic types of adhesives are:

1. **Natural adhesives**, such as starch, soya flour, animal products, and dextrin (a gummy substance obtained from starch)
2. **Inorganic adhesives**, such as sodium silicate and magnesium oxychloride
3. **Synthetic organic adhesives**, which may be thermoplastics (used for nonstructural and some structural bonding) or thermosetting polymers (used primarily for structural bonding)

Because of their strength, synthetic organic adhesives are the most important adhesives in manufacturing operations, particularly for load-bearing applications. They are classified as:

- **Chemically reactive:** Polyurethanes, silicones, epoxies, cyanoacrylates, modified acrylics, phenolics, and polyimides; also included are anaerobics (which cure in the absence of oxygen), such as Loctite® for threaded fasteners; see also Case Study 32.1
- **Pressure sensitive:** Natural rubber, styrene–butadiene rubber, butyl rubber, nitrile rubber, and polyacrylates
- **Hot melt:** Thermoplastics (such as ethylene–vinyl acetate copolymers, polyolefins, polyamides, and polyester) and thermoplastic elastomers
- **Reactive hot melt:** A form of thermoplastic, with a thermoset portion (based on urethane's chemistry), with improved properties; also known as hot glue
- **Evaporative or diffusion:** Vinyls, acrylics, phenolics, polyurethanes, synthetic rubbers, and natural rubbers

TABLE 32.4

General Characteristics of Adhesives

Type	Comments	Applications
Acrylic	Thermoplastic; quick setting; tough bond at room temperature; two components; good solvent; chemical and impact resistance; short work life; odorous; ventilation required	Fiberglass and steel sandwich bonds, tennis racquets, metal parts, and plastics
Anaerobic	Thermoset; easy to use; slow curing; bonds at room temperature; curing occurs in absence of air; will not cure where air contacts adherents; one component; not good on permeable surfaces	Close-fitting machine parts, such as shafts and pulleys, nuts and bolts, and bushings and pins
Epoxy	Thermoset; one or two components; tough bond; strongest of engineering adhesives; high tensile and low peel strengths; resists moisture and high temperature; difficult to use	Metal, ceramic, and rigid plastic parts
Cyanoacrylate	Thermoplastic; quick setting; tough bond at room temperature; easy to use; colorless	"Krazy Glue"; bonds most materials; especially useful for ceramics and plastics
Hot melt	Thermoplastic; quick setting; rigid or flexible bonds; easy to apply; brittle at low temperatures; based on ethylene vinyl acetate, polyolefins, polyamides, and polyesters	Bonds most materials; packaging, book binding, and metal can joints
Pressure sensitive	Thermoplastic; variable strength bonds; primer anchors adhesive to roll tape backing material—a release agent on the back of web permits unwinding; made of polyacrylate esters and various natural and synthetic rubbers	Tapes, labels, and stickers
Phenolic	Thermoset; oven cured; strong bond; high tensile and low impact strength; brittle; easy to use; cures by solvent evaporation	Acoustical padding, brake lining and clutch pads, abrasive grain bonding, and honeycomb structures
Silicone	Thermoset; slow curing; flexible; bonds at room temperature; high impact and peel strength; rubberlike	Gaskets and sealants
Formaldehyde (urea, melamine, phenol, resorcinol)	Thermoset; strong with wood bonds; urea is inexpensive, is available as powder or liquid, and requires a catalyst; melamine is more expensive, cures with heat, and the bond is waterproof; resorcinol forms a waterproof bond at room temperature. Types can be combined	Wood joints, plywood, and bonding
Urethane	Thermoset; bonds at room temperature or oven cure; good gap-filling qualities	Fiberglass body parts, rubber, and fabric
Water-based (animal, vegetable, rubbers)	Inexpensive, nontoxic, and nonflammable	Wood, paper, fabric, leather, and dry-seal envelopes

- **Film and tape:** Nylon, epoxies, elastomer epoxies, nitrile phenolics, vinyl phenolics, and polyimides
- **Delayed tack:** Styrene–butadiene copolymers, polyvinyl acetates, polystyrenes, and polyamides
- **Electrically** and **thermally conductive**: Epoxies, polyurethanes, silicones, and polyimides. Electrical conductivity is obtained by the addition of fillers, such as silver (used most commonly), copper, aluminum, and gold. Fillers that improve the electrical conductivity of adhesives generally also improve their thermal conductivity.

Adhesive Systems. These systems may be classified on the basis of their specific chemistries:

- **Epoxy-based systems:** These systems have high strength and high-temperature properties, to as high as 200°C; typical applications include automotive brake linings and bonding agents for sand molds for casting.
- **Acrylics:** Because the adhesive acts as a solvent, these adhesives are more tolerant of contaminants on surfaces.
- **Anaerobic systems:** Curing of these adhesives is done under oxygen deprivation, and the bond is usually hard and brittle; curing times can be reduced by external heat or by ultraviolet (UV) radiation.
- **Cyanoacrylate:** The bond lines are thin and the bond sets within 5 to 40 s.
- **Urethanes:** These adhesives have high toughness and flexibility at room temperature; used widely as sealants.
- **Silicones:** Highly resistant to moisture and solvents, these adhesives have high impact and peel strength; however, curing times are typically in the range from 1 to 5 days.

Many of these adhesives can be combined to optimize their properties, such as the combinations of *epoxy–silicon*, *nitrile–phenolic*, and *epoxy–phenolic*. The least expensive adhesives are epoxies and phenolics, followed, in affordability, by polyurethanes, acrylics, silicones, and cyanoacrylates. Adhesives for hightemperature applications, in a range up to about 260°C, such as polyimides and polybenzimidazoles, are generally the most expensive. Most adhesives have an optimum temperature, ranging from about room temperature to about 200°C, for maximum shear strength.

32.4.2 Electrically Conducting Adhesives

Although the majority of adhesive-bonding applications require mechanical strength, a relatively recent advance is the development and application of electrically conducting adhesives to replace lead-based solder alloys, particularly in the electronics industry. These adhesives require curing or setting temperatures that are lower than those required for soldering. Applications of electrically conducting adhesives include calculators, remote controls, and control panels. In addition, there are high-density uses in electronic assemblies, liquid-crystal displays, pocket TVs, and electronic games.

In these adhesives, the polymer is the matrix and contains conducting metals (fillers) in such forms as flakes and particles (see also Section 7.3 on electrically conducting polymers). There is a minimum proportion of fillers necessary to make the adhesive electrically conducting; typically, in the range of 40 to 70% by volume.

The size, shape, and distribution of the metallic particles, the method of heat and pressure application, and the individual conducting particle contact geometry can be controlled to impart isotropic or anisotropic electrical conductivity to the adhesive. Metals used are typically silver, nickel, copper, and gold, as well as carbon. More recent developments include polymeric particles, such as polystyrene, coated with thin metallic films of silver or gold. Graphite also can be used as a filler, usually to produce an electrically conductive adhesive that is nonmagnetic, and can provide electromagnetic interference (EMI) shielding for electronic components. Matrix materials are generally epoxies, although thermoplastics also are used and are available as film or as paste.

32.4.3 Surface Preparation, Process Capabilities, and Applications

Surface preparation is very important in adhesive-bonding, as joint strength depends greatly on the absence of dirt, dust, oil, and various other contaminants. This dependence can be observed when one is attempting to apply an adhesive tape over a dusty or oily surface. Contaminants also affect the wetting ability of the adhesive and prevent an even spreading of the adhesive over the interface. Thick, weak, or loose oxide films on workpiece surfaces are detrimental to adhesive-bonding. On the other hand, a porous or a thin and strong oxide film may be desirable, particularly one with some surface roughness to improve adhesion or to introduce mechanical locking. However, the roughness must not be too high, because air may be trapped, in which case the joint strength is reduced. Various compounds and primers are available that modify surfaces to improve adhesive-bond strength. Liquid adhesives may be applied by brushes, sprayers, or rollers.

Process Capabilities. Adhesives can be used for bonding a wide variety of similar and dissimilar metallic and nonmetallic materials and components with different shapes, sizes, and thicknesses. Adhesive-bonding also can be combined with mechanical joining methods (Section 32.5) to further improve bond strength. Joint design and bonding methods require care and skill. Special equipment is usually required, such as fixtures, presses, tooling, and autoclaves and ovens for curing.

Nondestructive inspection of the quality and strength of adhesively bonded components can be difficult. Some of the techniques described in Section 36.10, such as acoustic impact (tapping), holography, infrared detection, and ultrasonic testing, are effective testing methods for adhesive bonds.

Testing of Adhesives. Recall that adhesives are most successful when they support shear stresses, and are less successful under other loading condition. Many adhesives are weak when loaded by tensile stresses. Recognizing that loadings can be complex, a large number of test configurations have been used to evaluate adhesives, depending on the particular application and the stresses encountered (Fig. 32.9). Tapered cantilever and wedge tests are particularly useful for high-strain-rate evaluations; wedge tests can result in combined shear and normal stresses when the two members have different thicknesses.

QR Code 32.2 Peel test of an adhesive. (*Source:* Courtesy of Instron®)

The most common test is the peel test, shown in Figs. 32.9b and 32.10, which also illustrates the strengths and limitations of adhesives. Note, for example, how easy it is to peel adhesive tape from a surface, yet it is very difficult to slide it along the surface. During peeling, the behavior of an adhesive may be brittle or it can be ductile and tough, thus requiring high forces to peel the adhesive from a surface.

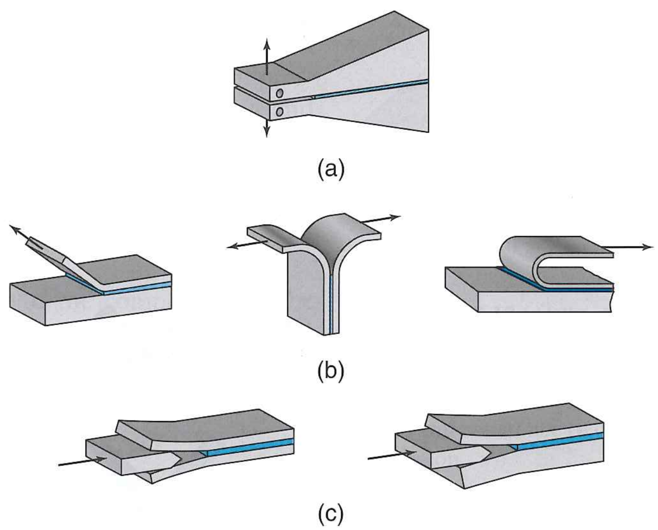

FIGURE 32.9 Common arrangements for evaluating adhesives: (a) tapered double cantilever beam, (b) peel test, and (c) wedge test.

Applications. Major industries that use adhesive-bonding extensively are the aerospace, automotive, appliances, and building-products industries. Applications include automotive brake-lining assemblies, laminated windshield glass, appliances, helicopter blades, honeycomb structures, and aircraft bodies and control surfaces.

An important consideration in the use of adhesives in production is curing time, which can range

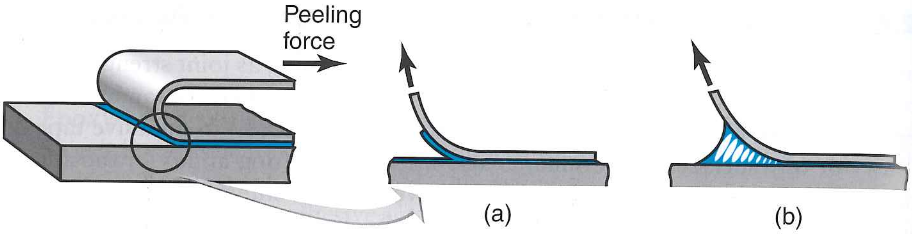

FIGURE 32.10 Characteristic behavior of (a) brittle and (b) tough adhesives in a peeling test; this test is similar to the peeling of adhesive tape from a solid surface.

from a few seconds (at high temperatures) to several hours (at room temperature), particularly for thermosetting adhesives. Thus, production rates can be low as compared with those of other joining processes. Moreover, adhesive bonds for structural applications rarely are suitable for service above 250°C.

The major advantages of adhesive bonding are:

- The interfacial bond has sufficient strength for structural applications, but is also used for nonstructural purposes, such as sealing, insulation, the prevention of electrochemical corrosion between dissimilar metals, and the reduction of vibration and of noise (by means of internal damping at the joints).
- Adhesive-bonding distributes the load at an interface, and thereby eliminates localized stresses that usually result from joining the components with mechanical fasteners, such as bolts and screws. Moreover, structural integrity of the sections is maintained (because no holes are required).
- The external appearance of the bonded components is unaffected.
- Very thin and fragile components can be bonded, without significant increase in their weight.
- Porous materials and materials of very different properties and sizes can be joined.

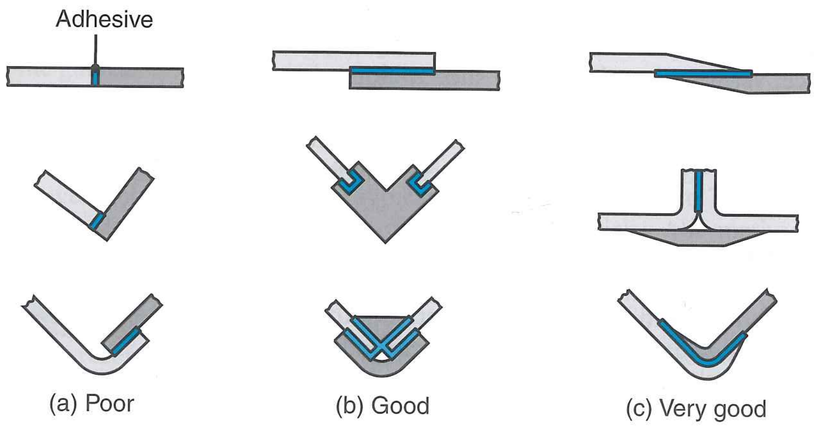

FIGURE 32.11 Various joint designs in adhesive-bonding; note that good designs require large contact areas between the members to be joined.

- Because adhesive-bonding is usually carried out at a temperature between room temperature and about 200°C, there is no significant distortion of the components or change in their original properties.

The major limitations of adhesive-bonding are:

- Limited range of service temperatures
- Bonding time can be long
- The need for great care in surface preparation
- Bonded joints are difficult to test nondestructively, particularly for large structures
- Limited reliability of adhesively-bonded structures during their service life, and significant concerns regarding hostile environmental conditions, such as degradation by temperature, oxidation, stress corrosion, radiation, or dissolution

The cost of adhesive-bonding depends on the particular operation. In many cases, however, the overall economics of the process make adhesive-bonding an attractive joining process, and sometimes it may be the only one that is feasible or practical. The cost of equipment varies greatly, depending on the size and type of operation.

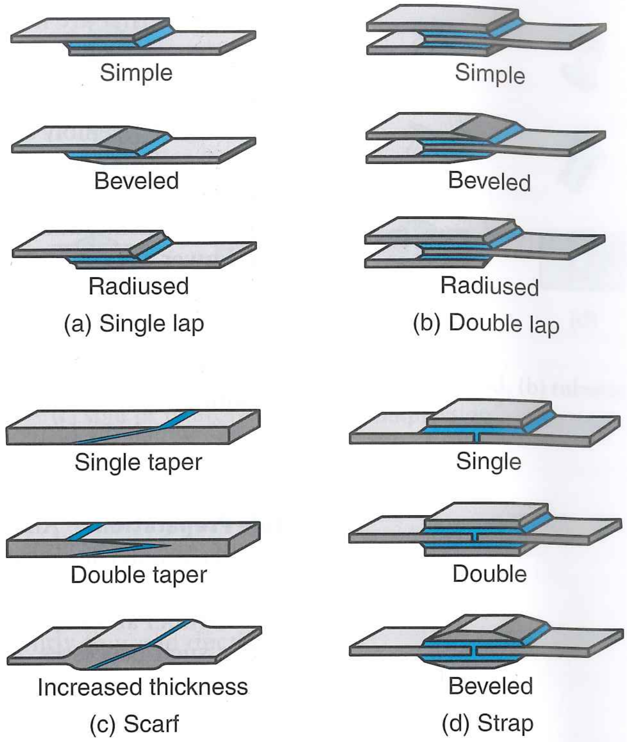

FIGURE 32.12 Desirable configurations for adhesively bonded joints.

32.4.4 Design for Adhesive-bonding

- Several joint designs for adhesive-bonding are shown in Figs. 32.11–32.13. They vary considerably in strength; hence, selection of the appropriate design is important and should include such considerations as the type of loading and the environment.
- Designs should ensure that joints are preferentially subjected only to compressive or shear forces, although limited tension can be supported. Peeling and cleavage should be avoided.
- Butt joints require large bonding surfaces; tapered (scarf) joints should be used when feasible. Simple lap joints tend to distort under tension, because of the force couple at the joint (see Fig. 31.9.). If this is a concern, double lap joints or straps can be used (Figs. 32.12b and d).
- The coefficients of thermal expansion (Table 3.1) of the components to be bonded should preferably be close to each other, in order to avoid internal stresses during adhesive-bonding. Situations in which thermal cycling can cause differential movement across the joint should be avoided.

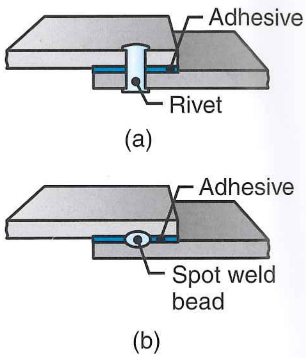

FIGURE 32.13 Two examples of combination joints, for purposes of improved strength, air of liquid tightness, and resistance to crevice corrosion.