Joining Processes, Advanced

Welding and joining are literally where all parts of the manufacturing process come together. As such, these processes are essential to virtually every manufactured product. Nonetheless, these processes often appear to consume greater fractions of the product cost and to create more of the production difficulties than rightfully might be expected. There are a number of reasons for this.

First, welding and joining are multifaceted, both in the variations of the process (fastening, adhesive bonding, soldering, brazing, arc welding, diffusion bonding, resistance welding, etc.) and in the disciplines which must be brought to bear to solve a problem (mechanics, materials science, physics, chemistry, electronics, etc.). It requires an engineer with unusually broad and deep training to bring so many disciplines together and to apply them in depth to such a variety of processes. Second, when welding or joining difficulties arise, they usually happen well into the manufacturing stream where the relative value of scrapped parts is high. A final reason why welding and joining processes are important to manufacturing is that a very large percentage of product failures occur at joints. Joints are often the weakest part of the assembly and usually are located at the most highly stressed points. Careful attention to the joining processes can produce great rewards in manufacturing economy and product reliability.

There are very many joining processes. One of the greatest difficulties for the manufacturing engineer is to determine which will produce acceptable properties at the lowest cost. There are no simple answers. A change in the part geometry, the material, the value of the end product, the size of the production run, or the availability of joining equipment can influence the choice of joining method. On small lots of complex parts, fastening is often the best choice, whereas on long production runs, welds are often stronger and less expensive.

The perfect joint is indistinguishable from the material surrounding it. Some processes, such as diffusion bonding, come very close to this ideal; however, these processes are either expensive or restricted to a few materials. There is no universal process that will perform adequately on all materials in all geometries. Nevertheless, virtually any material can be joined in some way if one is willing to pay the price, although joint properties equal to those of the bulk material cannot always be achieved.

Economical joining processes often place a limitation on the usefulness of the material. Aluminum is used extensively in aircraft and is joined by adhesives, fasteners, and welding; yet none of these processes has proven economical enough for aluminum to replace steel in the frames of automobiles. The rise in the use of composites in aircraft is limited in large part by an inability to achieve adequate strength in the joints or to achieve acceptable joining technologies for repair of the structure. It is essential for the manufacturing engineer to work with the designer from the conception of a product, so that compatible materials, processes, and properties are selected for the final assembly. Too often a designer leaves the problem of joining the parts to the manufacturing engineer, with a resultant escalation in costs and decrease in reliability. If the design has been planned carefully and the parts have been produced accurately, the jointing process becomes much easier and cheaper, and the quality and reliability of the product are enhanced.

Apart from fasteners, each of the other joining processes involves the formation of a bond between the parts. These processes include the use of adhesives, solders, brazes, and welds.

Generally, any two solids will bond if the surfaces are brought into intimate contact. Unfortunately, two factors inhibit this contact. The first is surface contamination. Any freshly produced surface exposed to the atmosphere will adsorb oxygen, water vapor, carbon dioxide, and hydrocarbons very rapidly. Assuming that each molecule that hits the surface will be adsorbed, the pressure–time product to produce a monolayer of contamination is $10^{-9}$ atm s (1.013 25 × 10^{-3} N m^{-2} s). For example, at 10^{2} atm (1.013 25 N m^{-2}) pressure, the contamination time is 1 ms, and at 1 atm (1.013 25 × 10^{2} N m^{-2}) it is only 10 ns.

The second reason why two surfaces will not bond when placed in contact is that the solid surfaces do not mate perfectly. On an atomic scale, the smoothest surface contains numerous peaks and valleys, hence the true contact area is usually less than 10% and rarely more than 30% of the apparent contact area. This has been confirmed by tests in ultrahigh vacuum and in space. At such low pressures, the surface contamination time increases to minutes or hours. Two freshly cleaned surfaces placed in contact in such an environment will bond with approximately 10% of the bulk material strength. In this sense, the principles of bonding are the opposite of the principles of lubrication. In bonding, contamination must be prevented; in lubrication, the proper type of contamination is added to the surface to prevent bonding.
Joining Processes, Advanced

The contamination and the partial contact area can be considered as chemical and geometric barriers to bonding, respectively. Any successful bonding process must overcome both of these problems.

1. Welding Using Interfacial Shear

If two materials, usually metals or plastics, are placed in contact and the interface is sheared in a manner which disrupts the surface contamination while also mechanically excluding the atmosphere, a bond will be formed. This is important in joining of wires to integrated circuits or sealing metal cans around such circuits. The interfacial shear is essential, as experience shows that merely pressing two surfaces together without sliding between the surfaces will not produce a bond. Cone-shaped or beveled punches are often used to produce adequate interfacial shear.

Studies have also shown that metals with a high ratio of oxide hardness to metal hardness are easiest to cold bond. In practice, this means that indium is the easiest material to bond, followed by aluminum or tin. In fact, steel cans for encasing semiconductors are often tin- or indium-plated to improve cold bonding.

Ultrasonic welding, in which a 10–75 kHz vibration is imposed on two parts placed in contact, is another form of cold welding. The vibrations create microscopic shear, which generates new uncontaminated surface area without macroscopic deformation of the part; however, it must be remembered that the contamination is merely redistributed and is not displaced from the joint. As a result, this rarely produces more than a 50% actual bond area. Ultrasonic bonding can be applied to any material which has enough ductility to deform locally without fracturing. This includes most metals, plastics, and polymer matrix composites.

The key to cold welding is the production of significant interfacial sliding. In most cases, the ability to generate such shear is strongly dependent on the part geometry. If cold bonding is practical, it is often economical, especially in high-volume production, as no filler material is needed and the process is rapid. In addition, the absence of heat reduces distortion of the overall part and simplifies tooling and automation.

Yet another process which uses interfacial shear is friction welding. In thermoplastic materials, which have low heat diffusivity, sliding of the interface can generate enough heat to soften or even melt a thin zone. The contamination is displaced, hence producing intimate contact of the polymer with a resultant bond. In metals, with much higher heat diffusivities and melting temperatures, much more sliding is necessary to soften the metal. Typically, circular parts rotating at hundreds of rpm with respect to one another are pressed together under high axial pressure. With steel or other high-melting alloys, the interface rapidly becomes red hot and begins to deform. The rapid shear and the mechanical exclusion of the atmosphere produce intimate metal contact. If all of the contamination is removed from the interface by extruding hot metal out of the weld zone, a full-strength, nearly perfect weld can be formed. A relatively new process, linear-friction welding (rather than rotational), is being used to join intermetallic turbine blades to turbine disks, thus reducing the weight of this attachment.

2. Adhesive Bonding

Adhesives consist of fluids (many of them very viscous) which fill the hills and valleys of the solid surfaces. The adhesive bond is created by surface tension forces or mechanical interlocking of the adhesive in the pores and valleys of the solid. This produces bonds which are weaker than the interatomic bonds formed during welding. As a result, adhesives work best when joining materials of high surface-to-volume ratio such as sheets, fibers, or small particles. The large joint surface area provides strength and distributes the forces over a large area, thus reducing stress concentrations in the assembly. The adhesive can also serve as an electrical insulator or a hermetic seal in some applications. Virtually any combination of materials can be joined rapidly in a manner which is easy to automate. The cost can vary greatly from much less than US$1 per pound for common adhesives to hundreds of dollars per pound for the most exotic types, which are resistant to moisture and maintain strength at elevated temperatures.

Adhesive bonding is unusual among the bonding processes in that all of the chemical contamination of the surface need not be removed. Indeed, some surfaces, such as chromated aluminum or phosphated steel, are purposely “contaminated” with porous surface films that enhance the bonding of the adhesive.

The most critical property of an adhesive is the surface energy (equivalent to surface tension), which determines the wetting angle between the fluid adhesive and the solid adherend. A low angle represents good wetting and a high angle represents poor wetting. Generally, contact angles of less than 30° are necessary for bonding.

Many factors influence this wetting angle, including surface roughness of the solid (better wetting) and surface contamination (poorer wetting). The wetting angle also can exhibit hysteresis, as the angle is often less when the liquid first flows onto the surface. As the fluid recedes, some adhesive is trapped on the surface of the solid and the wetting angle increases, sometimes producing a weaker bond on reapplication of the adhesive.

3. Diffusion Bonding

If some metals or ceramics are held together under high pressure at elevated temperatures for extended periods
of time, they will bond. The addition of heat permits deformation of the microscopic points of contact between the two materials, thus greatly increasing the true area of contact. If the surface contaminants are soluble in the base material, the contamination will diffuse away into the bulk, permitting true interatomic bonding at the interface. Thus, metals such as silver, the oxide of which is not stable at high temperatures, are very easy to bond by diffusion. Iron, titanium, and copper, although capable of forming stable oxides, are also easily bonded because the oxide will diffuse into the base metal at the elevated bonding temperatures. Aluminum and magnesium are difficult to bond by this method because their oxides are stable and are not readily soluble in the bulk metal.

The primary variables controlling diffusion bonding are pressure, temperature, surface finish, and surface cleanliness. Typical contact pressures are 500–5000 psi (≈350 × 10^3–3500 × 10^3 Pa) at temperatures of 60% or more of the absolute melting temperature of the metal. Contact times can be as short as a few minutes but are commonly ≈1 h or even tens of hours. As a result, diffusion bonding is generally an expensive process. Nonetheless, it can produce nearly ideal joints which are indistinguishable from the base metal. Many complex, inaccessible joints can be formed without distortion of the part or use of filler material, thus providing great precision in the assembly. A disadvantage is that the high temperatures will usually remove any strength in the base metal due to cold work or lower-temperature heat treatment; hence subsequent heat treatment may be required.

Diffusion bonding can be used to join many dissimilar materials which would otherwise be incompatible. The major problem with such dissimilar joints is the formation of residual stresses at the interface during cooling due to thermal expansion differences between the materials. For a difference in thermal expansion coefficient of 2 × 10^-5°C^-1 a temperature change of 100–300°C will usually produce yield-level residual stresses at the bond interface. Interlayer materials with intermediate expansion rates are sometimes used to reduce these stresses. Another potential problem is the formation of brittle intermetallic compounds with some material combinations. Again, interlayer materials can often be used to alleviate these problems.

An important variation of diffusion bonding is transient-liquid-phase (TLP) bonding. This has been used since ancient times, although in the late 1980s it has been patented, primarily for aerospace applications. In TLP bonding, a liquid is introduced between the two solids. This liquid fills the voids, thus providing nearly complete contact. This accelerates diffusion across the interface. As a result, TLP bonding is often much faster than diffusion bonding, requiring a few minutes to a few hours depending on the thinness of the liquid film. Since the liquid fills the joint without application of pressure, contact pressures of less than 10 psi (≈70 × 10^3 Pa) are required, essentially only for holding the parts in alignment. This greatly simplifies tooling.

The transient phase in TLP bonding is the liquid. The liquid must be a low-melting alloy in which one or more elements will diffuse rapidly into the base metal. As this component diffuses away the interfacial region becomes enriched in the non-diffusing elements, which solidify owing to loss into the bulk of the diffusing component. This is termed isothermal solidification, as the liquid freezes at constant temperature owing to a compositional change rather than the more usual athermal solidification which occurs at constant composition as the temperature is reduced. The patented process includes nickel–boron liquids in which the boron diffuses away, leaving a higher-melting nickel at the interface, but the process also occurs in other systems. For example, eutectic lead–tin soldered to copper will melt at 183°C, but during holding for 10 h at 200°C, the tin reacts with the copper, leaving a lead-enriched solid zone which maintains strength to 300°C even though the joint started as a liquid at 200°C.

The major problem with TLP bonding is that it is not applicable to all materials. There are a number of metallurgical restrictions such as a low-melting alloy, one component of which is soluble in the base metal, diffuses rapidly, is not harmful to mechanical properties of the base metal, and does not promote formation of brittle, intermetallic compounds at the interface. In addition, the bonding times are still relatively long, hence requiring use with high-value-added parts. Nonetheless, when TLP bonding is possible, it generally produces joints of excellent strength and high reliability.

Yet another variation of diffusion welding is activated diffusion bonding. In this process, the surface to be bonded is coated with another element which promotes rapid diffusion and decomposition of the surface contaminant. The most common activated layer is silver, which readily dissolves many metal oxides and is soft enough to promote large areas of interfacial contact. For example, steels can be diffusion bonded at temperatures as low as 200°C when a silver layer is introduced. No liquid phase is present and the silver remains as a thin layer in the final joint. In the absence of silver, the iron oxides would not decompose at such low temperatures, but with the silver, very strong bonds can be formed.

4. Soldering and Brazing

Soldering and brazing are identical processes differentiated only by the temperature at which they occur. Soldering is performed below 425°C whereas brazing is performed above this temperature. A heat source heats the base metal, a flux, and the solder. The flux dissolves the surface contamination, allowing the liquid
solder to contact the base metal directly. The solder must wet the metal and must have a sufficiently large surface tension to displace the molten flux, which must have a low surface tension. Molten metals have very high surface tensions, whereas organic compounds and inorganic salts have lower surface tensions; hence the solders are usually metals whereas the fluxes are organic or inorganic compounds. The base material can be either a metal or a ceramic. Indeed, brazing is one of the most useful methods for joining ceramics or glasses to other materials, particularly when the joint must operate at elevated temperatures.

Although rough surfaces are generally detrimental to most bonding processes, roughness usually enhances the wetting of the solder to the base metal. Increased bonding temperatures generally enhance the flux cleaning of the surface and increase the speed of bonding. Both soldering and brazing are readily automated and can often be accomplished at very high speeds.

Some materials, such as titanium or beryllium, have such stable oxides that no soldering flux has been developed. Aluminum solder fluxes have been produced but often create problems as their reactivity is marginal. Owing to the higher temperatures used in brazing, more aggressive fluxes are possible and virtually all metals and ceramics are brazable even if some are not solderable. Often brazing is carried out with a reactive gas such as hydrogen or in a vacuum, rather than with a flux. Figure 1 shows the relative stabilities of various metal oxides as a function of temperature, hydrogen dew point, and partial pressure of water vapor. Metals whose oxides decompose at lower temperatures are easier to braze or solder.

The strength of a solder joint is controlled primarily by the creep strength of the solder. This is, in turn, controlled by the melting temperature of the solder. A general rule suggests that solder joint stresses should not exceed 1000 psi (~7000 × 10^3 Pa) above 0.75 of the absolute melting temperature. This same limitation also applies to braze joints, although braze joints at room temperature are usually well below this creep limit, and strengths of 5000–10,000 psi (~35,000 × 10^3–70,000 × 10^3 Pa) are easily attainable in most brazes at room temperature. The actual strength can be much higher depending on the joint thickness, as shown in Fig. 2. As the joint becomes thinner, the braze metal is constrained from deforming due to the adjacent base metal. This produces a triaxial state of stress in the braze, which makes the entire joint stronger. This phenomenon is termed contact strengthening. In theory, contact strengthening will continue to increase as the joint becomes thinner. For example, thin silver-activated diffusion-bonded steel joints have produced failure stresses which are five times the strength of the bulk silver; however, in brazing, the strength usually peaks at an optimum joint thickness and decreases in thinner joints. This is due to the formation of defects such as porosity or entrapped flux in the thinnest joints. The optimum joint thickness varies for each braze alloy and must be developed empirically whenever maximum braze strength is required. When dissimilar materials are bonded, thicker joints sometimes act to relieve the differential thermal contraction stresses produced on cooling, thus shifting the optimum joint thickness to higher values.

5. Fusion Welding

In fusion welding, intimate interfacial contact is achieved by interposing a liquid of substantially similar composition to the base metal. The surface contamination, if soluble, is dissolved in the liquid and, if
insoluble, will float away from the solid–liquid interface.

Unfortunately, the melting created by fusion welding usually destroys the beneficial microstructure and properties of many advanced materials. Hence, although fusion-welding processes are commonly used for joining advanced materials, they rarely produce joints with a balance of properties matching those of the base material.

As with the fusion welding of conventional alloys, the optimization of the fusion microstructure and mechanical properties in advanced materials is dependent on the selection of a suitable welding process and process parameters. For example, the effective fusion welding of rapidly solidified aluminum and titanium alloys has been accomplished using high-energy-density laser and electron-beam welding processes. The rapid solidification and cooling rates achieved during these processes generate weld-zone microstructures comparable to those of the rapidly solidified particulate (which can be stronger than those of the consolidated and thermomechanically processed base material). The steep temperature gradients and rapid thermal cycles associated with these processes further minimize microstructural damage to the weld heat-effected zone. High-strength, porosity-free welds in rapidly solidified aluminum alloys containing high hydrogen contents have also been produced using the capacitor-discharge resistance-welding process, which provides extremely high fusion-zone solidification and cooling rates.

The electron-beam welding process has also been utilized effectively to join gamma-titanium aluminides without solid-state cracking. The production of crack-free welds required welding-parameter optimization, specifically the application of a high-weld-energy input that reduced weld-cooling stresses, which are a prerequisite for cracking.

6. Joint Preparation and Weld Defects

Economical joining requires consideration of the joining process from the initial design stage and selection of material. Not all materials are weldable, but all can be joined in some manner. Exotic metals, composites, and ceramics can be very difficult to join; hence the selection of these materials and the design geometry should be reviewed by a welding engineer early in the product planning. Although the assumption that any joining problem can be solved is generally true, it is not true that all of the solutions are economical. The costs of joining can exceed 50% of the total product cost in many complex assemblies; hence the joining process must be a specific part of the product design.

Once a joining process has been selected, accuracy in production of the components and attention to joint cleanliness can pay great dividends. Assembly inaccuracies of a few millimeters in large parts can require recutting, reforming, or deposition of excessive weld filler metal, any of which can result in a doubling of the cost of that operation. Dirty joints can result in weld defects such as porosity or cracking, the repair of which can be extremely costly or even impossible. Since joining usually occurs after most of the other work is already in the part, extra attention is warranted in order to avoid costly rework or scrap.

The thermal cycle created during fusion welding can produce many undesirable changes in the material. Segregation of alloying elements during solidification can produce hot cracking on cooling. Sometimes redesign of the joint geometry can reduce the stresses during cooling and thus prevent these defects, but in other cases no solution can be found. For this reason, many manufacturers place stringent chemical-composition requirements on incoming material. In addition, test welds are often required on sample material or special product geometries. In many cases, welding codes require the production and testing of trial welds before any production begins.

Even if a successful weld is produced, subsequent heat treatment can induce cracking. Certain high-strength steels are susceptible to reheat cracking during stress-relief heat treatments owing to metallurgical changes induced by the original weld thermal cycle. Some stainless steels, aluminum alloys, or nickel alloys can lose corrosion resistance owing to metallurgical changes induced by welding. Fortunately, producers and users of these alloys are generally familiar with problems caused during welding, and numerous sources exist to guide a designer or fabricator in the selection of the welding process and procedure. Unless one has extensive experience with both the joining process and the material, it is unwise to assume that no problems will arise. Successful joining is based on extensive industrial experience and cannot yet be categorized into a simple set of rules and formulas.

A number of metals, particularly steels and aluminum, are susceptible to defects if hydrogen is present during welding. Any source of hydrogen can be a problem—moisture, grease, hydroxides and others. These problems can be alleviated by maintaining strict cleanliness of the joint and welding materials and by preheating above room temperature to vaporize moisture and to allow the hydrogen to diffuse out of the metal before the defects form. Most materials suppliers can provide details of the preheating requirements and procedures necessary for successful welding.

See also: Adhesives; Joining of Advanced Materials: An Overview; Joining of Ceramics; Joining of Polymers and Composites

T. W. Eagar
[Massachusetts Institute of Technology, Cambridge, Massachusetts, USA]

W. A. Baeslack
[Ohio State University, Columbus, Ohio, USA]