CHAPTER 1

Introduction to Joining

JOINING COMPRISES a large number of processes used to assemble individual parts into a larger, more complex component or assembly. The individual parts of a component meet at the *joints.* Joints transmit or distribute forces generated during service from one part to the other parts of the assembly. A joint can be either temporary or permanent. The five joint types that are predominately used in the joining of parts are the butt, tee, corner, lap, and edge joints (Fig. 1.1).

The selection of an appropriate design to join parts is based on several considerations related to both the product and the joining process. Product-related considerations include codes and standards, fitness for service, aesthetics, manufacturability, repairability, reliability, inspectability, safety, and unit cost of fabrication. Joining process considerations include material types and thicknesses, joint geometry, joint location and accessibility, handling, jigging and fixturing, distortion control, productivity, and initial and recurring manufacturing costs. Additional considerations in-

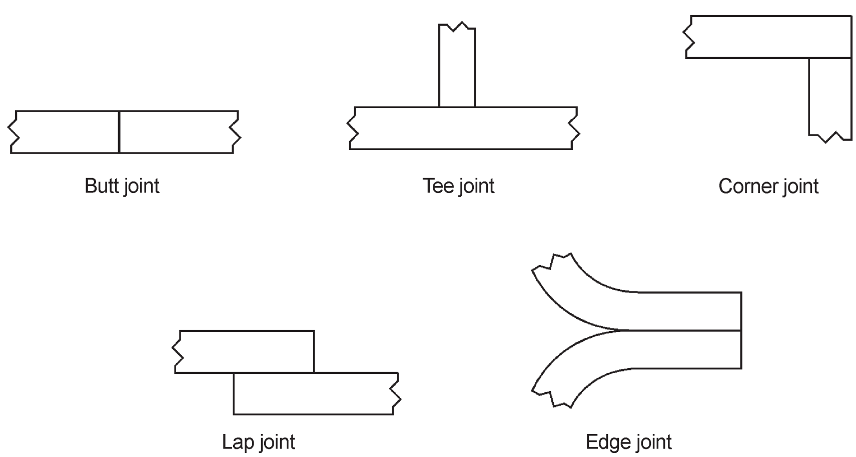

Fig. 1.1 Types of joints. Source: Ref 1.1

clude whether the joint is fabricated in a shop or at a remote site, possibilities for failure, and containment in case of a catastrophic failure (e.g., a nuclear reactor vessel).

The design or selection of appropriate joint type is determined primarily by the type of service loading the assembly will be exposed to during its service life. For example, in metallic structures, butt joints are preferred over tee, corner, lap, or edge joints for components subjected to fatigue loading, while a lap joint would be optimum for an adhesive-bonded structure. However, since high-strength adhesives are typically weak in peel, the lap joint should be loaded in shear. To effectively transfer loads through the adhesive, the substrates (or adherends) are overlapped so that the adhesive is loaded in shear. Typical adhesive-bonded joint designs are shown in Fig. 1.2. The specific joint design aspects, such as the size, length, and relative orientation of the joint, are based on stress calculations that are results of the anticipated service loads, properties of materials, properties of sections, and appropriate structural design requirements. An ideal joint is one that effectively transmits forces among the joint members and throughout the assembly, meets all structural design requirements, and can still be produced at a minimal cost. This involves selection and application of good design practices based on a thorough understanding of the available joining processes.

Assembly imposes constraints on the design. The parts must be designed so that they not only can be assembled and joined together to provide the needed function but also are easy to handle, insert, retain, and verify that they have been assembled correctly. Because assembly is an integrative process, problems with detail part designs often surface when they are assembled. For example, parts may not fit together properly, tools may not reach in the space provided, and parts may be incorrectly as-

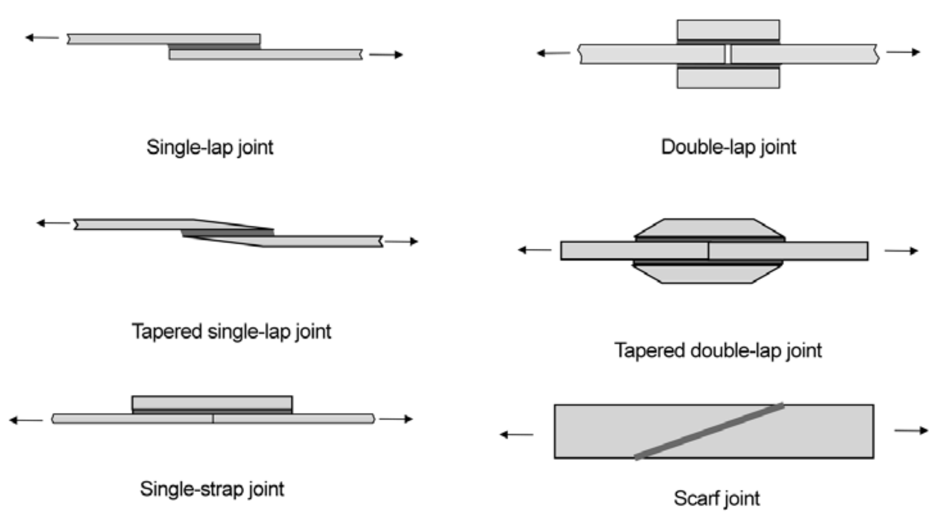

Fig. 1.2 Typical adhesive-bonded joint configurations. Note that the adhesive is loaded in shear in all configurations. Source: Ref 1.2

sembled. These problems often require extensive rework, resulting in costly schedule slippage and undesirable design compromises.

The importance of assembly as a design constraint has resulted in a greatly increased emphasis on assembly in the design process. Design and manufacturing practice now focuses on ensuring that parts conform to specifications and that variability and randomness are minimized, and on making non-value-added operations such as orienting and handling as simple and easy to perform as possible. Many product design departments now improve the ease with which products are assembled by using design for assembly (DFA) techniques, which seek to ensure ease of assembly by developing designs that are easy to assemble.

The aim of DFA is to simplify the product so that the cost of assembly is reduced. However, DFA techniques often result in improved quality and reliability, along with a reduction in production equipment and part inventory. These secondary benefits often outweigh the cost reductions in assembly.

General guidelines for DFA

- Minimize part count by incorporating multiple functions into single parts.
- Modularize multiple parts into single subassemblies.
- Assemble in open space, not in confined spaces; never bury important components.
- Make parts such that it is easy to identify how they should be oriented for insertion.
- Prefer self-locating parts.
- Standardize to reduce part variety.
- Maximize part symmetry.
- Eliminate parts that will tangle.
- Color code parts that are different but shaped similarly.
- Prevent nesting of parts; prefer stacked assemblies.
- Provide orienting features on nonsymmetries.
- Design the mating features for easy insertion.
- Provide alignment features.
- Insert new parts into an assembly from above.
- Eliminate reorientation of both parts and assemblies.
- Eliminate fasteners.
- Place fasteners away from obstructions; design in fastener access.
- Deep channels should be sufficiently wide to provide access to fastening tools; eliminate channels if possible.
- Provide flats for uniform fastening and fastening ease.
- Ensure sufficient space between fasteners and other features for a fastening tool
- Prefer easily handled parts.

Generally, a concept design is developed and then evaluated against each of these guidelines. Design modifications are then made to satisfy the guideline. There is no guarantee that a given guideline will apply to a particular design problem. Many of these guidelines are similar or the same as the rules of concurrent engineering:

Concurrent engineering rules

- Ensure that parts most likely to require maintenance are easily accessible.
- Ensure that the degree of maintenance of your product is consistent with your company's policy on making, stocking, and supplying spare parts.
- Ensure tools needed for installation and maintenance are as inexpensive and common as possible.
- The decisions made in the first 15% of a product development process fix 85% of the downstream quality and cost of the product.
- Include all experts actively.
- Resist making irreversible decisions.
- Continually optimize the designed product *and* the design process.
- Prefer concepts that are easy to manufacture.
- Prefer concepts that are easy to assemble.
- Integrate design and manufacturing.
- Do not overconstrain or underconstrain the design.
- Look ahead of the current state of the design to anticipate problems.
- Reduce the number of parts.
- Increase interchangeability of parts; standardize parts; minimize variation in parts.
- Modularize functions and subassemblies.
- Design multifunctional and multiple-use parts.
- Avoid flexible components.
- Avoid separate fasteners.
- Improve robustness.
- Allocate time/man power based on cost-benefit analysis of a proposed action.
- Maximize yield of existing equipment.
- Keep assemblies/components as independent as possible.
- Maximize tolerances.
- Test only what can be quantified; actively search for testable aspects of a design.
- Minimize machining setups and reorientations.
- Design parts for feeding and insertion into machines.
- Perform functional analysis.
- Tailor the manufacturing process to the character of the product.
- Study producibility and usability.
- Design the fabrication process.

- Design the assembly sequence for top-down assembly.
- Minimize assembly instructions.
- Use known/proven vendors and suppliers.
- Use new technologies only when necessary.
- Identify subassemblies as soon as possible in the design process.
- Do engineering changes in batches.
- Integrate quality control with assembly.
- Match assembly processes to tolerances.
- Operate on a minimum inventory.

While some of these guidelines and rules may not always be applicable, and even occasionally contradict each other, they are certainly worth considering during the design process.

1.1 Overview of Joining Processes

Joining processes include welding, brazing, soldering, mechanical fastening, and adhesive bonding (Fig. 1.2). Mechanical fastening can be used to provide either temporary or permanent joints, while adhesive bonding, welding, brazing, and soldering processes are mainly used to provide permanent joints. Mechanical fastening and adhesive bonding usually do not cause metallurgical reactions. Consequently, these methods are often preferred when joining dissimilar combinations of materials and for joining polymer-matrix composites that are sensitive to extreme heat. Welding processes are divided into two broad classes: fusion welding and solid-state welding.

1.2 Fusion Welding

Fusion welding processes involve localized melting and solidification and are normally used when joining similar material combinations or materials belonging to the same family (e.g., joining one type of stainless steel with another type). In fusion welding, the weld can be made by simply melting the edges of the two workpieces and allowing them to fuse together on cooling. This type of weld is referred to as an *autogenous weld.* The other method is to add extra material during the welding process through the melting of an electrode or filler wire during the welding process. In both cases, the welded area will have a microstructure and properties that are different from the parent metal. The three predominant zones in a fusion weld are the fusion zone, a heat-affected zone (HAZ), and the base metal as shown in Fig. 1.3. The weld deposit itself will have a cast structure of often a complex composition. Between the weld deposit and the parent metal is an HAZ that did not melt during welding but reached very high temperatures. Grain growth due to the high temperatures is commonly encountered in the HAZ.

The types of welds commonly used with fusion welding processes are shown in Fig. 1.4. Joint designs and clearances that overwhelmingly trap the beam energy within the joint cavity are preferred for increased process efficiency. When joining thick sections, the preferred joint designs allow the weld metal to freely shrink without causing cracking. In addition, multipass welding is used for thick sections to provide for full penetration. The distinctive microstructure of a multipass weld compared to a single-pass weld is shown in Fig. 1.5. To maintain tolerances, distortion due to localized heating and cooling must be prevented or controlled during welding by the use of jigs and fixtures. Residual stresses can lead to distortion after welding and are often minimized by a stress-relief anneal after welding.

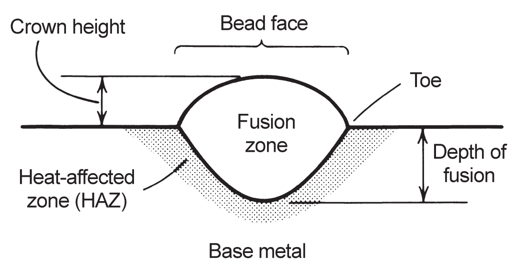

Fig. 1.3 Weld bead geometry showing fusion zone, heat-affected zone, and base metal. Source: Ref 1.3

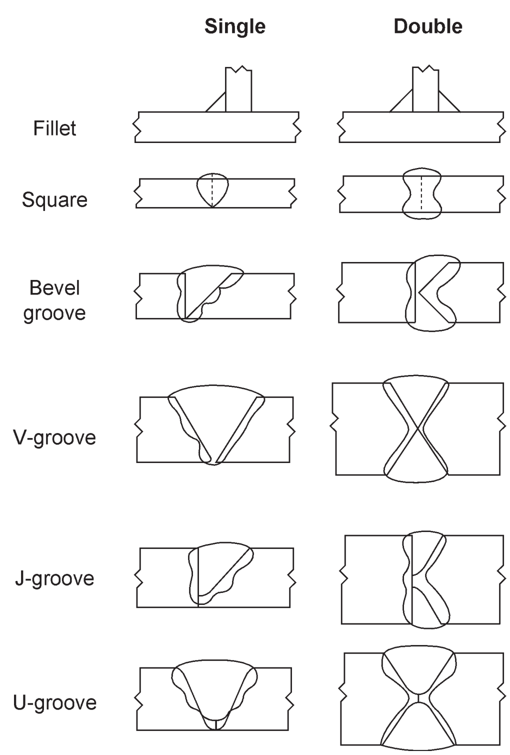

Fig. 1.4 Types of welds. Source: Ref 1.1

Thermal Welding. Heat is provided by an oxyfuel gas flame, mostly for manual welding, or by a thermit reaction for joining heavy sections such as rails. Portability is a great advantage.

Electric Arc Welding. Electric arc welding processes use electricity to produce the intense heat necessary for welding (Fig. 1.6). Some electric arc processes use a consumable electrode that melts and becomes part of the weld metal that is deposited, whereas others use a nonconsumable electrode that does not melt and does not become part of the weld deposit. Consumable electrode welding uses a filler rod as the electrode. Atmospheric protection of the molten weld metal is provided by a slag produced by the filler rod or by an externally supplied inert gas. Flux-cored wire allows a continuous and mechanized operation. The flux is supplied as a powder in submerged arc welding for horizontal welds, and a resistive slag pool protects the weld zone in electroslag welding of thick plates. Inert gas provides the protection in some welding processes, such as gas metal arc welding (GMAW) and gas tungsten arc welding (GTAW).

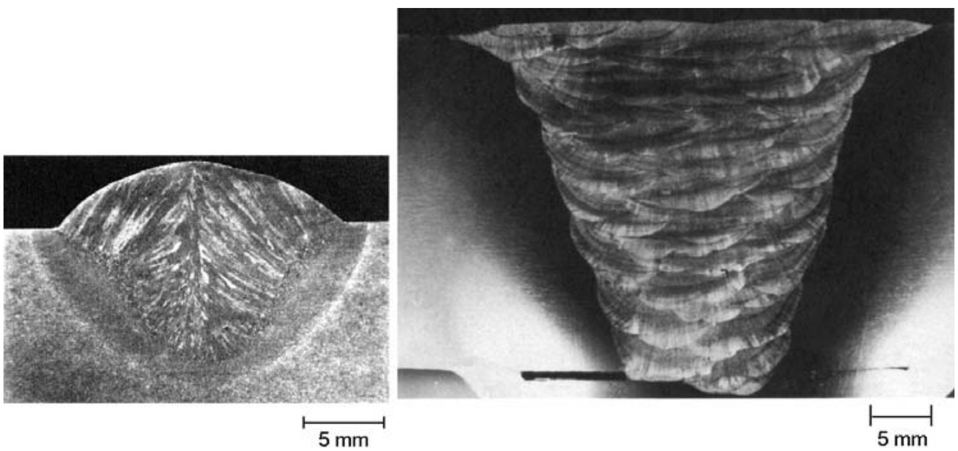

Fig. 1.5 Weld microstructures showing the fusion zone, heat-affected zone, and base metal for (a) single-pass bead-on-plate weld in A-710 steel and (b) multipass weld in 304 stainless steel. Source: Ref 1.3

Fig. 1.6 Welding using shielded metal arc welding process

Resistance Welding. After the two parts have been pressed together, electric current passes through the joint to heat and melt the interface. Pressure is kept on until solidification of the melt is complete. Spot welding is widely employed in building automotive bodies using welding robots. Seam welding, a continuous stream of spot welds, is used for making beams and box sections.

High-Energy Beam Welding. Highly concentrated beams of electrons impinge on the weld zone in electron beam (EB) welding. When the workpiece is enclosed with the gun in a vacuum chamber, a high vacuum protects the surfaces but increases cost and lowers production rates. Out-of-chamber welding is also possible. Gas (CO_2) or solid-state (Nd-YAG) lasers have seen increasing application for joining not only difficult metals and delicate parts but also sheets of different thicknesses for tailored blanks used in automobile body construction. All high-energy beam processes have the advantage that the HAZ is small, as shown in the EB weld microstructure in Fig. 1.7.

1.3 Solid-State Welding

Since solid-state welding processes do not involve melting and solidification, they are often suitable for joining not only similar but also dissimilar materials. Solid-state welding processes also have special joint design or part cross-section requirements. For example, continuous drive and inertia friction welding processes require that one of the parts exhibit a circular or near-circular cross section.

Diffusion bonding is a solid-state welding process that allows joining of a variety of structural materials, both metals and nonmetals. However, diffusion bonding requires an extremely smooth surface finish to provide intimate surface contact, a high temperature, and a high pressure, first to

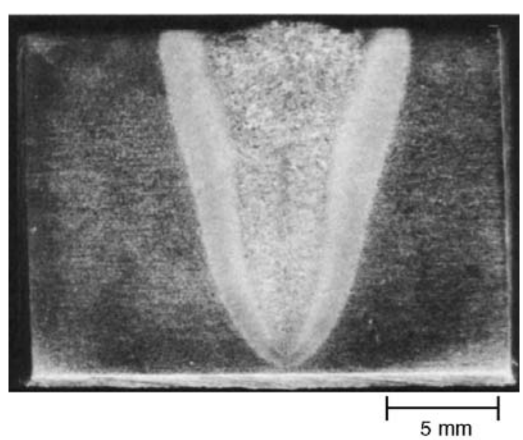

Fig. 1.7 25Cr-1Mo steel plate, single-pass electron beam weld. Macrostructure shows high depth-to-width ratio of the fusion zone, which is typical of high-energy-density welding processes. Source: Ref 1.3

allow intimate contact of the parts along the bond interface, followed by plastic deformation of the microscopic surface asperities, and then to promote diffusion across the bond interface. The need to apply pressure while maintaining part alignment imposes a severe limitation on joint design. When perfectly clean surfaces are brought into intimate contact, interatomic bonds form a joint. Bond strength is greatest when the mating metals are mutually soluble, but good bonds can be obtained with dissimilar, not otherwise weldable metals and with highly differing thicknesses. When an exceptional surface finish is difficult to achieve, a metallurgically compatible, low-melting interlayer can be inserted between the parts to produce a transient liquid phase on heating. On subsequent cooling this liquid phase undergoes progressive solidification, aided by diffusion across the solid/liquid interfaces, and thereby joins the parts. This process is similar to a brazing process.

Cold Welding. Sufficient pressure must be exerted to establish conformance of surfaces. Sliding and deformation accompanied by surface expansion are needed to break up oxides and other adsorbed films. Cold welding processes differ only in the method of providing these conditions. Complex tubular parts such as refrigerator evaporator plates can be made by depositing a parting agent in a pattern to prevent welding. After roll bonding the passages may be inflated.

Forge Welding. As a generic term, forge welding applies to bonding by deformation at the hot-working temperature. Large surface extension in hot-roll bonding creates strong bonds for cladding, as in bonding copper-nickel surface layers to a copper core for some U.S. coins.

Friction Welding. Heat is produced by friction between a rotating and stationary part; again, some melt may form that is expelled together with oxidized metal. Localization of heat allows welding of dissimilar metals and of very different dimensions (e.g., a thin stem to a large head for an internal combustion engine valve).

From a metallurgical perspective, the application of both fusion welding and solid-state welding processes must be evaluated using appropriate weldability test methods for their ability to either recreate or retain base metal characteristics across the joint. When metallurgical reactions occur, they can either benefit or adversely affect the properties of the joint. These weldability evaluations need to combine material, process, and procedure aspects to identify combinations that would provide a weld joint with an acceptable set of properties.

1.4 Brazing

Brazing is a process for joining solid metals in close proximity by introducing a liquid metal that melts above 450 °C (840 °F). A sound brazed joint generally results when an appropriate filler alloy is selected, the parent metal surfaces are clean and remain clean during heating to the flow temperature of the brazing alloy, and a suitable joint design is used that allows capillary action. Strong, uniform, leak-proof joints can be made rapidly, inexpensively, and even simultaneously. Joints that are inaccessible and parts that may not be joinable at all by other methods can often be joined by brazing. Complicated assemblies comprising thick and thin sections, odd shapes, and differing wrought and cast alloys can be turned into integral components by a single trip through a brazing furnace or a dip pot. Metal as thin as 0.01 mm (0.0004 in.) and as thick as 150 mm (6 in.) can be brazed.

Brazed joint strength is high. The nature of the interatomic (metallic) bond is such that even a simple joint, when properly designed and made, will have strength equal to or greater than that of the parent metal. The fact that brazing does not involve any substantial melting of the base metals offers several advantages over other welding processes. It is generally possible to maintain closer assembly tolerances and to produce a cosmetically neater joint without costly secondary operations. Even more important is that brazing can join dissimilar metals (or metals to ceramics) that, because of metallurgical incompatibilities, cannot be joined by traditional fusion welding processes. If the base metals do not have to be melted to be joined, it does not matter that they have widely different melting points. Therefore, steel can be brazed to copper as easily as to another steel. Brazing also generally produces less thermally induced distortion, or warping, than does fusion welding. An entire part can be brought up to the same brazing temperature, thereby preventing the kind of localized heating that causes distortion in welding.

Finally, and perhaps most important to the manufacturing engineer, brazing readily lends itself to mass production techniques. It is relatively easy to automate because the application of heat does not have to be localized, as in fusion welding, and the application of filler metal is less critical. In fact, given the proper clearance conditions and heat, a brazed joint is not dependent on operator skill, as are most fusion welding processes. Automation is also simplified by the fact that heat can be applied to the joint by many means, including torches, furnaces, induction coils, electrical resistance, and dipping. Several joints in one assembly often can be produced in one multiple-braze operation during one heating cycle, further enhancing production automation.

1.5 Soldering

Soldiering is a joining process by which two substrates are joined together using a filler metal (solder) with a liquidus ≤450 °C (≤840 °F). The substrate materials remain solid during the bonding process. The solder is usually distributed between the properly fitted surfaces of the joint by capillary action.