6. WELDING

In welding two components are joined by heating the region at the interface above the melting point of one or other of the components. Welding is distinguished from soldering and brazing, in which a low melting point filler metal is used to make the join, as well as from diffusion bonding, in which the temperature at the interface is kept below the melting points of all the phases present.

In addition to welding as a term to describe bonding by localized melting, the term solid state welding is used to describe at least two processes in which the melting point of the components is not exceeded at the interface. The first of these is friction welding, in which bonding relies on the heat generated by friction at a sliding interface subjected to compression. The frictional heating raises the temperature at the interface to the point at which extensive plastic flow occurs to relieve the compressive stress. The second process is explosive welding, in which a flyer plate travelling at high velocity impacts a stationary component to generate hydrostatic pressures which exceed the Hugoniot elastic limit, the pressure above which dynamic plastic flow accompanies a ballistic shock front. Hugoniot pressures are typically in the range of 5 to 100GPa, at least an order of magnitude greater than the static yield stress. The bonded interface formed in both friction welding and explosive welding is a region of intense turbulent flow, where surface defects and contamination are extruded from the bonded zone by the high plastic strains resulting in a strong joint of high integrity. Both processes are characterized by a high gradient of plastic strain at the joint, which limits the width of the zone affected. Both processes are also limited in their applications by some fairly severe restrictions on joint geometry.

6.1 WELDING SCIENCE

In the present chapter we are primarily concerned with the scientific principles of welding, in particular the basic transport processes that determine mass and heat transfer during welding. We also outline some engineering solutions to problems of weld design and describe the more important sources of heat for welding technology. Since an electric arc is one of the commonest of these, we describe the physical characteristics of an electric arc. Finally, we outline the nature and characterization of welding defects.

It is as well to appreciate why, despite the high temperatures and large power inputs required, welding remains one of the most versatile and effective means available for the assembly of individual components into larger modules for both large and small engineering systems. At one extreme, the outer shell of a welded reactor pressure vessel may have a thickness of the order of 0.5 m. Welded armour plate for a battle-tank is also massive (at least 0.2 m). At the other extreme, ultrasonically welded conducting wires for microelectric assemblies may have a diameter of less than 15μm, and submicron device technologies are attempting to reduce this. The range of linear dimensions for welded structures thus covers over 4 orders of magnitude.

Welded assemblies are able to carry loads similar to those supported by the individual components from which they are constructed, without requiring the addition of appreciable mass or volume to the overall assembly. It is the high strength to weight ratio (at reasonable processing costs) that compensates for the high processing temperatures and environmental hazards associated with welding. No mechanical bond can compete in its strength to weight ratio with this load-carrying efficiency of a welded joint. No adhesive bond can match the tensile and shear strength of a welded joint. If disassembly is not a requirement, then welding is very often the joining method of first choice.

6.1.1 Weld Geometry

Any weld design must aim at ensuring the integrity of the weld and, effectively the same thing; minimize the effects of welding defects. There are two major considerations. Firstly, the control of the dimensions and thermal history of the molten metal in the weld pool. Secondly, the analysis of the geometrical constraints imposed by the system and the effect of these constraints on the development of residual stresses during the welding cycle.

Welding generally approximates one or other of two limiting cases of heat transfer. In the first case welding stresses and heat transfer are two-dimensional (Fig. 6.1a). The temperature is assumed constant in the through-thickness direction and varies only in the plane of the components being welded. The component is in a state of biaxial stress throughout the welding cycle, with no stress component in the through-thickness direction. That is, welding is accomplished in plane stress. The welding of a thin sheet in a single weld pass approximates this situation.

In the second limiting case the components being welded behave as though the through-thickness dimension were infinite, the components filling the whole of half-space below the heat source and the weld pool (Fig. 6.1b). In the multipass welding of thick components, the final weld passes approximate this situation. Heat transfer is three-dimensional in the half-space beneath the weld pool and the stress distribution is triaxial. It follows that triaxial residual stresses are likely to be retained in the welded component.

As for geometrical constraints, spot welding a wire to a surface (typical of a microelectronic assembly, Fig. 6.2a) gives a join which is only loosely constrained along the axis of the wire, while butt welding a bar involves a more complex geometry with considerable bending constraint (Fig. 6.2b). If the bar is butt-welded into a ring, then residual longitudinal stresses can be retained around the circumference of the ring. The additional stresses may be introduced during setting up the components for welding (elastic strains imposed by the jig), or they may be a result of differential thermal shrinkage on cooling after welding. In either case, cutting the ring after welding will serve to demonstrate the presence and extent of these stresses.

Additional mechanical constraint will be present in seam-welded tube, since now the stresses are biaxial. Thermal stresses are likely to be more significant, both along the length of the tube and tangential to the seam weld (Fig. 6.3a). On the other hand, welding two tubes together involves a different constraint geometry (Fig. 6.3b).

Several strategies are possible for welding two large tubes together and these are illustrated in Fig. 6.4. All three start by tack-welding the two tubes in position. Thereafter we can use a continuous, single weld pass (Fig. 6.4a), two passes which start at the same spot but move in opposite directions around the perimeter (Fig. 6.4b), or two passes which start at the two ends of a diameter and move in the same direction around the tube (Fig. 6.4c). It is the last strategy, which is often preferred in welding large tubular structures, two welders working together to minimize the asymmetric thermal expansion about the tube axis. As in all welding of structures, minimizing the residual stresses developed both by the structural constraints and by the welding cycle is a major objective.

If a thick spherical shell is formed by welding together two hemispheres, then the mechanical constraint is still further increased, and will depend on the ratio of the shell thickness to the shell diameter. In this instance every precaution will be taken to allow residual stresses to relax, most commonly by a post-welding, stress relief heat treatment at a temperature which is sufficient to reduce the yield stress of the component, but not so high as to affect the microstructural integrity~

Weld geometries are frequently complex, and so far we have only mentioned simple spot-welds, butt-joints and seams. Edge welds require that the plates be bevelled to help control formation of the

weld pool (Fig. 6.5a). Thin plates can be edge-welded in a single pass, but it is easier to avoid weld defects in thicker plate and reduce the width of the heat-affected zone (the region either side of the weld line with properties and microstructure modified by the welding cycle) if several weld passes are made (multipass welding, Fig. 6.5b). Although the yield strength of weld filler metal may exceed that of the bulk component, the strength in the heat-affected zone (HAZ) will most probably have been reduced. It is common, practice to reinforce a weld by doubling or tripling the thickness with additional plates which are lap-welded to the assembly (Fig. 6.6a). Similar principles of reinforcement are involved in the welding of a reinforcing rib to a flat bar or plate in a T-joint (Fig. 6.6b).
One last word should be reserved for spot-welds, as opposed to continuous welding (seam-welds). Spot welding is an important process in its own right, especially in the automobile industry, and we have already mentioned the spot welding of electrical leads in microelectronic assemblies. Spot welding is also a frequently used method of setting up an assembly prior to structural welding. In particular, spot or tack welding can often be substituted for expensive jigging assemblies. However, spot-welds are sites of stress concentration, and hence potential sources of weakness.

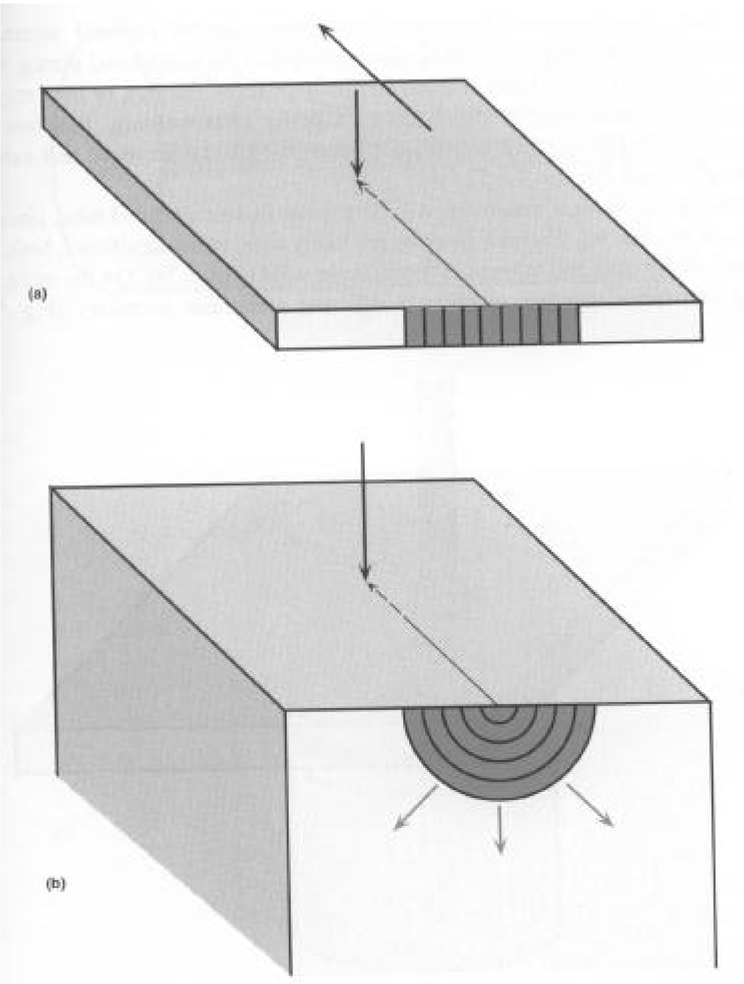

Fig. 6.1
Two limiting heat transfer conditions for a moving point source of heat.
a) two dimensional heat transfer.
b) three-dimensional heat transfer to an infinite half-space.

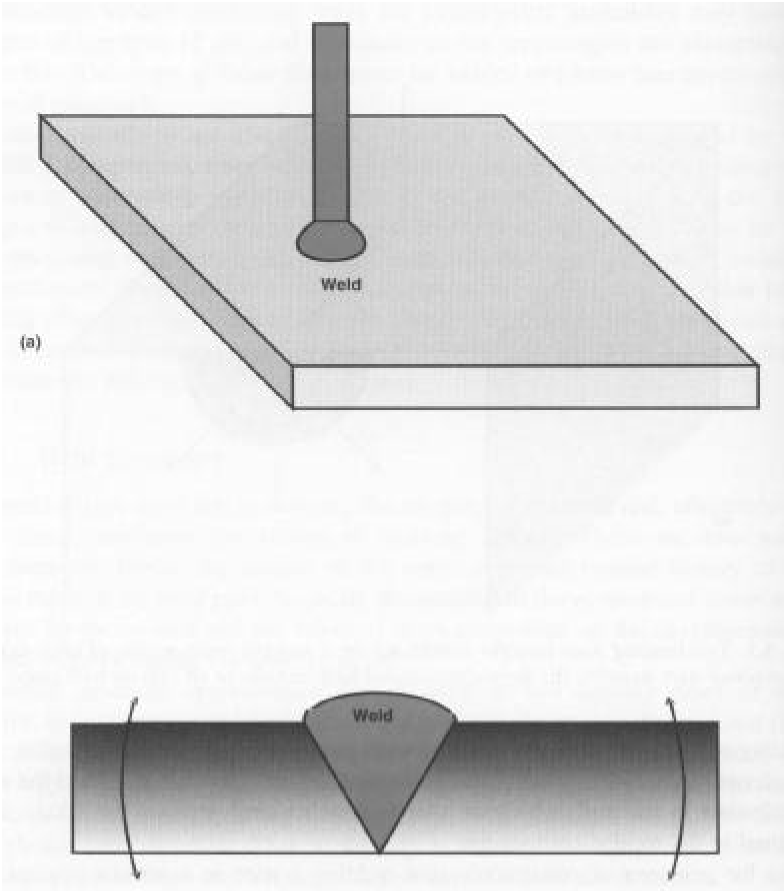

Fig. 6.2
Mechanical constraints dependon the weld geometry.
a) spot-welded wire experiences minimal constraint.
b) butt-welded bar is constrained in bending in two dimensions.

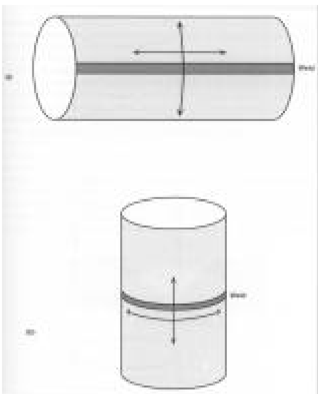

Fig. 6.3
Residual stresses in a thin-walled welded tube.
a) The axial and radial stresses are the principal stresses in a longitudinally welded tube.
b) Two tubes joined end to end by a circumferential weld will have a different pattern of residual stress.

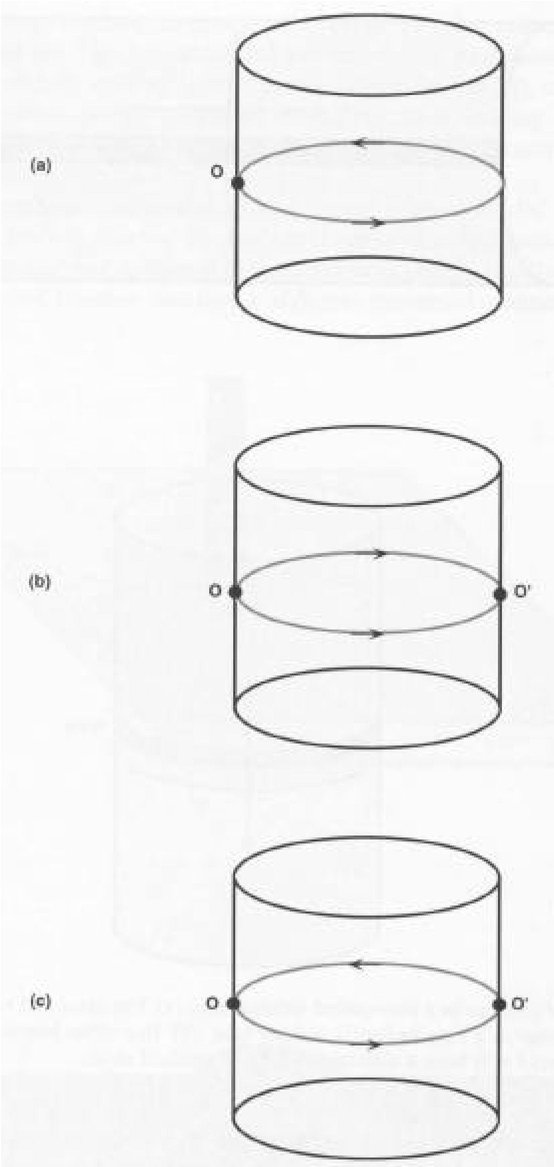

Fig. 6.4

The residual stresses in the circumferential welding of a tube will depend on the welding procedure.

a) single weld pass starts and finishes at 0.

b) two weld passes are initiated at 0, travelling in opposite directions to meet at U.

c) two weld passes are initiated diagonally opposite each other, at 0 and 0', travelling in the same sense to finish at 0' and 0 respectively.

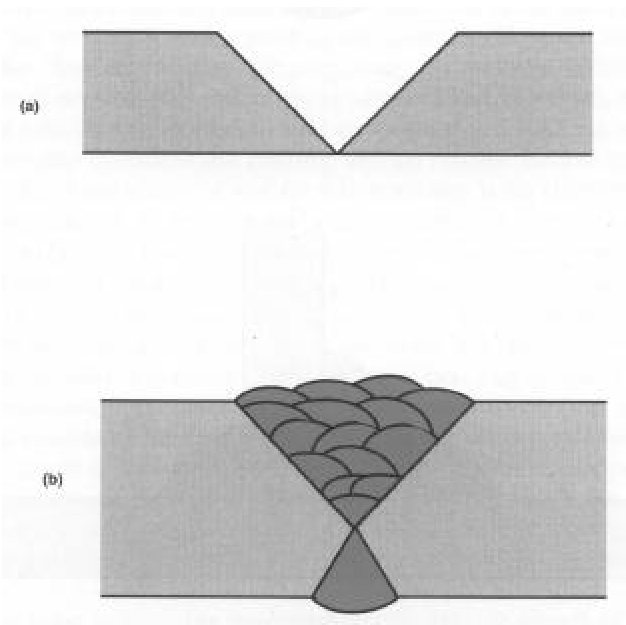

Fig. 6.5
a) Two thick plates to be joined by butt-welding are bevelled to accommodate molten filler metal, improve the tolerances associated with setting up and ensure full penetration of weld metal.
b) Very thick plate may be bevelled from both sides and fixed in position by a low energy, locating tack weld before being multipass welded, as indicated.

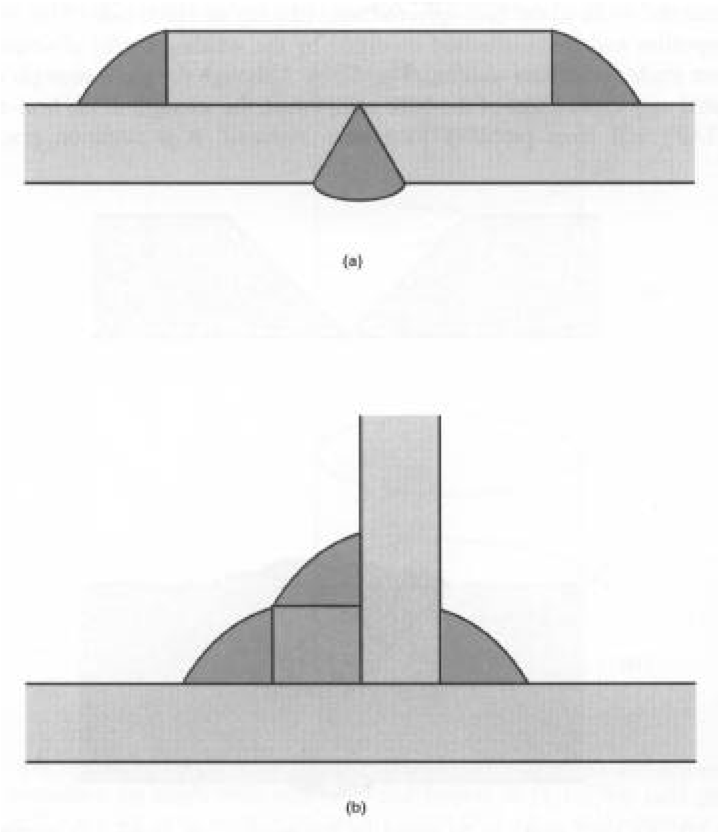

Fig. 6.6
Additional reinforcement may be needed to guarantee the integrity of a welded joint.
a) A reinforcing plate increases the load-bearing cross-section in the weld zone.
b) A reinforcing rib strengthens the weld at a T-junction.