7. WELD METALLURGY

A wide range of mechanical and physical properties can be developed in a single engineering material of given composition by altering the microstructure. Such properties are said to be structure sensitive. The control of microstructure, through appropriate processing, allows the engineer to obtain the required material performance. However, there are usually several processing options available for achieving a given value of an engineering property. For example, the same hardness can be achieved in a given low carbon steel having several different microstructures. These are developed by a combination of cold work and heat treatment to achieve a range of grain size in tempered martensites, or a variety of pearlitic or bainitic structures.

In the welding of like materials, a primary aim is to approximate selected engineering properties of the bulk components in the region of the weldment. This cannot be done by preventing microstructural changes, but it can be achieved by careful attention to the weld and HAZ metallurgy, although we must recognize that only some of the properties will be retained.

We first consider the local effects of geometry, residual stress and thermal history in the weld bead. Previous discussion of these factors covered the macroscopic effects, on the scale of the component dimensions, while the present analysis is on the mesostructural scale, defined by the size of the weld pool and the width of the HAZ. This is first followed by a description of the microstructural morphology in the weld bead (the region which underwent solidification), and then an analysis of the complex microstructural changes which occur in the HAZ. Once more, the emphasis is on steel, although much of the discussion applies to welds formed in other metals and alloys. The weld is assumed to be between two like components of similar bulk composition and microstructure.

7.1 GENERAL CONSIDERATIONS

The local weld topology is dictated by the processing history, which may involve several heating cycles (multipass welding) and post-welding heat treatment. This is illustrated in Fig. 7.1. A simple weld between two bevelled plates is first tackwelded in position by a series of spaced spot-welds. The structural weld is then made in a single pass, to give a structure with a mirror symmetry plane passing through the centre of the weld and perpendicular to the plane of the welded plates.

The second example is a multipass weldment between thick bevelled plates. The smaller bevel is welded first, in either one or two passes, and, welding is then continued on the reverse side by multipass welding along the larger bevel. Each weld pass modifies the microstructure -of both the previously-cast weld metal and the neighbouring bulk metal (in the HAZ). The residual stress pattern is also modified with each weld pass, and interdiffusion between the filler metal and the HAZ occurs during the repeated heating and cooling cycles.

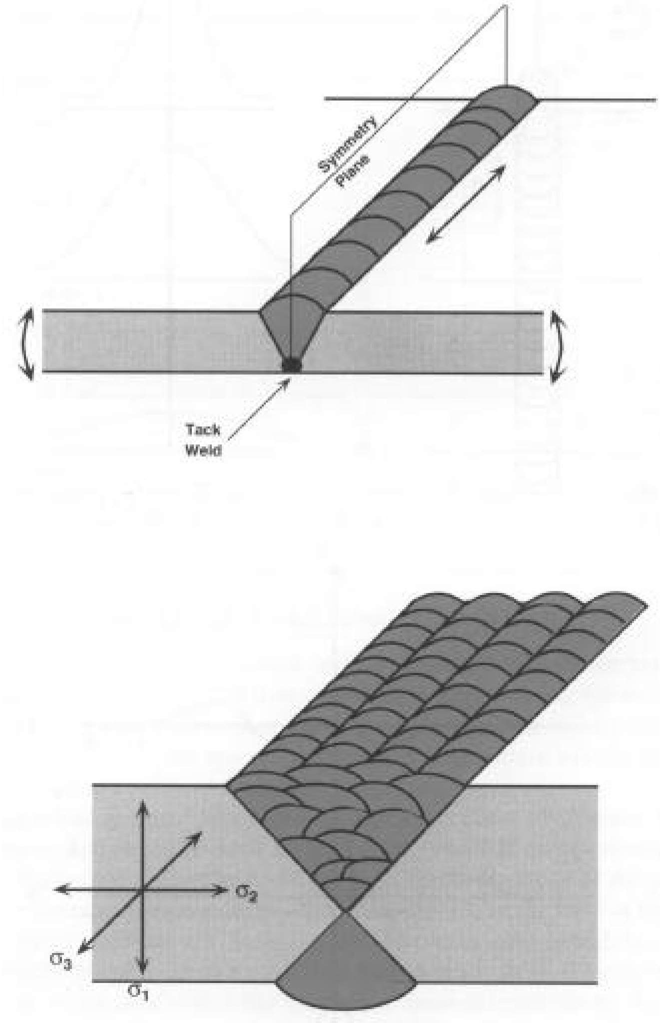

Fig. 7.1
In a single pass weld the longitudinal shrinkage stresses and the transverse bending. moment dominate the residual stress pattern. In a multipass weld the triaxial stress pattern is complex and varies throughout the welded zone.

7.1.1 Localized Residual Stress & Distortion

The residual stresses in the vicinity of a weld develop as a function of the thermal history, starting at the trailing edge of the weld pool (Fig. 7.2a). We confine ourselves to a qualitative discussion of the development of the axial stress distribution parallel to the weld line and in the plane of the surface, as the weld pool moves away. The temperature distribution across the weld line is illustrated in Fig. 7.2b. At the edge of the melt (section I) the axial stress must be zero (Fig. 7.2c). A compressive stress is developed in the hot zone near the solidification front, as a result of local thermal expansion. This is balanced by a tensile stress in the adjacent, comparatively cooler, bulk metal. At a later stage, section II, thermal shrinkage of the solidified weld metal imposes a tensile stress in the weld bead, while the tensile stress in the developing HAZ is decreased, relieved by thermal expansion. When cooling is nearly complete (section H1) the axial stress in the weld zone is characterized by residual tension, while that in the HAZ is dominated by residual compression. Shear stresses are a result of the tensile stress gradient, and are a maximum in the transition zone between the cast weld bead and the HAZ. It is not difficult to predict that embrittlement of the weld metal will lead to cracking across the line of the weld bead, while loss of ductility in the HAZ will lead to cracking parallel to the line of the weld and close to the region of maximum shear stress.

The major volume changes are associated with the liquid to solid transformation in the weld pool and the thermal contraction which occurs on cooling from the melting point, but phase changes in the solid state are additional sources of residual stress. The transition from the face-centred cubic, austentitic structure of steel, to the body-centred cubic, ferritic structure is accompanied by a small increase in volume (Fig. 7.3). It follows that, in a ferritic steel, we can expect two regions within the HAZ, an inner region, near the weld bead, which has been heated sufficiently during the welding cycle to transform to austenite, and an outer region, adjacent to unaffected bulk material, which has remained ferritic throughout.

Distortion of the welded assembly is a side effect of residual stress and is dependent on the constraints imposed by the geometry of the welded structure. It is useful to distinguish between bending moments, which reflect the through-thickness weld asymmetry and give rise to bowing (Fig. 7.4a), and tensile stresses, confined to the plane of the welded components, which give rise to both radial and longitudinal shrinkage (Fig. 7.4b).

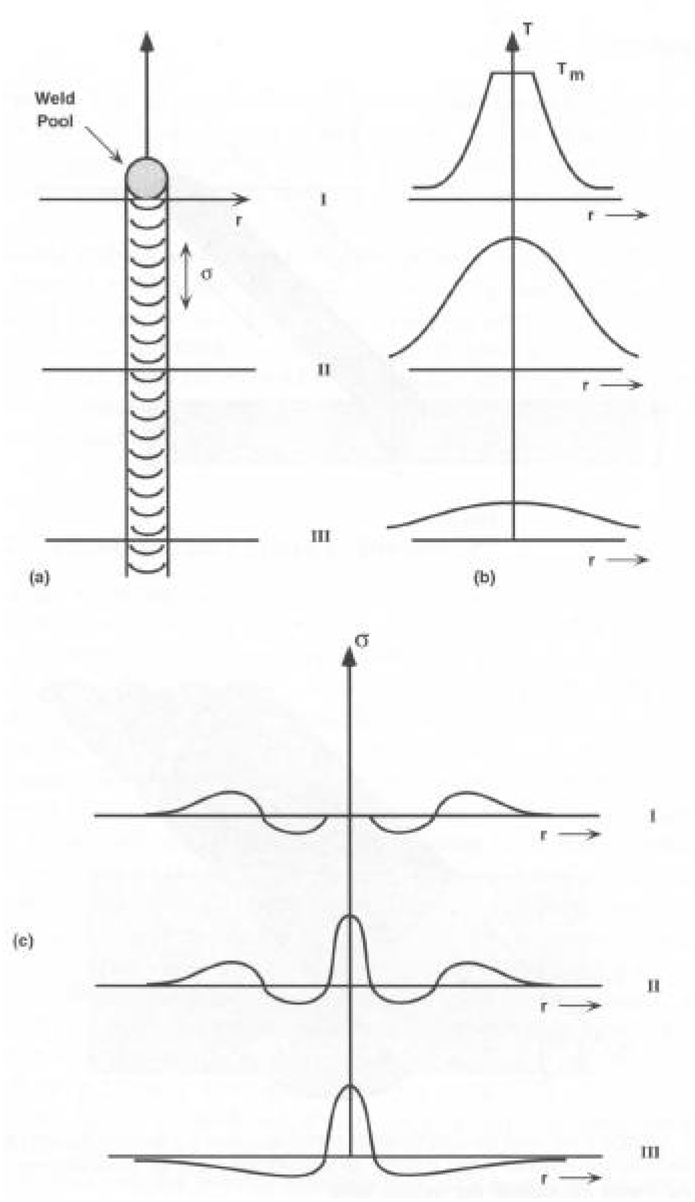

Fig. 7.2

a) The longitudinal residual stress distribution varies along the length of the weld pass.
b) Three residual stress zones can be distinguished by their temperature distribution: 1. The edge of the weld pool, 11. The fully-solidified zone behind the weld pool, 111. The final, fully-cooled weld.
c) In zone I thermal expansion puts the solid matrix into compression, and this is balanced by tensile stresses far from the weld line. In zone 11 solidification of weld metal leads to tensile stresses in the weld bead which are balanced by compressive stresses in the surrounding matrix, while the thermal gradient continues to generate a region of tensile stress far from the centre line. In zone 111 the maximum tensile stresses in the weld bead have relaxed somewhat and are balanced by a longitudinal compressive stress in the HAZ.

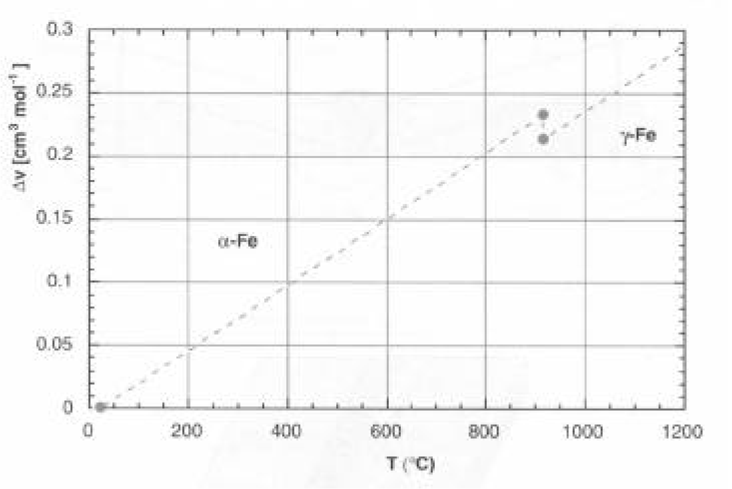

Fig. 7.3

The density of γ-Fe is higher than that of α-Fe, leading to an abrupt increase in specific volume as the metal is cooled through the transformation temperature ($910^{o}C$).

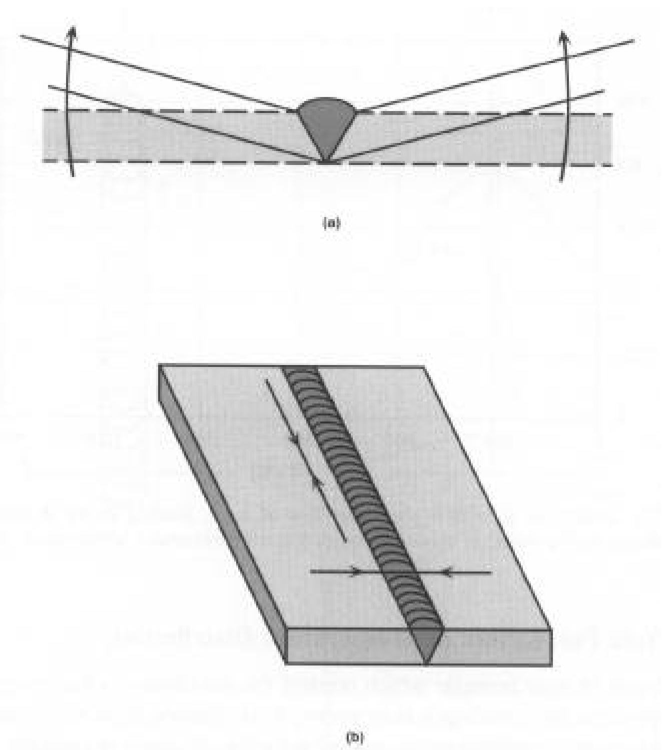

Fig. 7.4

a) Asymmetry perpendicular to the weld line leads to a residual bending moment about the weld axis.

b) The principal residual stresses in the plane of the surface are shrinkage stresses parallel and perpendicular to the weld line.

7.1.2 Weld Parameters & Temperature Distribution

The equations of heat transfer which control the distribution of temperature in the bulk components surrounding a heat source have already been discussed, but now we are concerned with the development of the microstructure in both the weld metal and the HAZ, and it is the thermal history and temperature profile in these local regions which will now be considered.

We discuss one geometry, the butt-welding of two plates of identical composition and thickness, and consider three factors: (i) the thermal conductivity of the bulk metal, (ii) the velocity of the heat source, and (iii) the thickness of the plate. Figure 6.5 shows schematic temperature profiles along the line of the weld at the surface of the plate. Three materials are compared: an aluminium alloy, which has the highest thermal conductivity, a carbon steel with intermediate thermal properties, and an austenitic stainless steel, which has the poorest thermal conductivity. As the thermal conductivity decreases the temperature profile around the moving point heat source becomes increasingly asymmetric. The same effect is produced by increasing the velocity of the heat source-the hot zone trails further behind the position of the source as the velocity increases. Increasing the plate thickness, on the other hand, reduces the axial asymmetry of the temperature profile, as more heat is then lost in the through-thickness direction and the governing heat transfer equations become increasingly 3-D rather than 2-D.

In summary, the final distribution of residual stress, the dimensions of the HAZ and the microstructural changes that occur in the HAZ and the weld bead depend on the weld parameters and the thermal properties of the material and the geometry of the components.

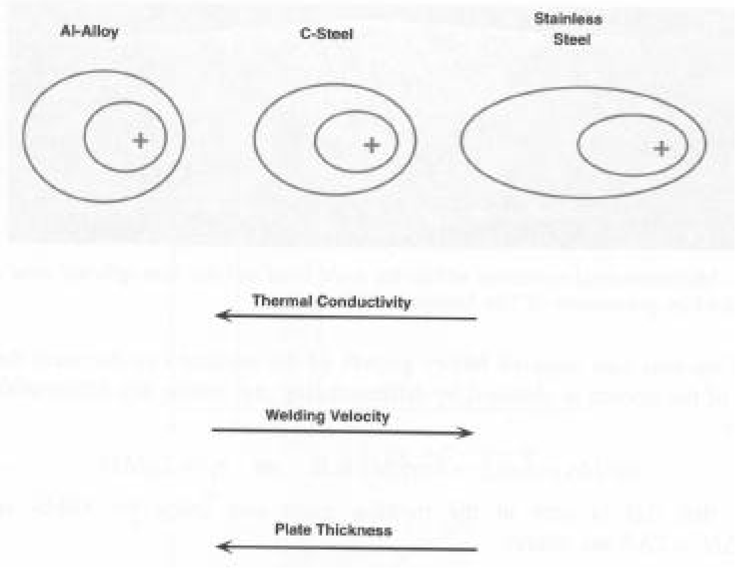

Fig. 7.5

The approximate shape of the free-surface isotherms as a function of thermal conductivity, welding velocity and plate thickness. The isotherms approximate the expected behaviour for an aluminium alloy, a plane carbon steel and a stainless steel.