5 Welding design

5.1 Introduction

In all constructional applications where welded connections are used either a stress analysis is carried out or ample experience of acceptable performance exists for the specific joint design. The principles of stress analysis are outside the scope of this chapter – it deals instead with those shop-floor fabrication activities that the designer directly influences. There are many national and international specifications dealing with the design aspects of specific structures. For instance, BS 8118 deals with the structural use of aluminium, as does the US specification D 1.2. Pressure vessel design is covered by BS PD 5500 and ASME VIII. For advice on the design of such structures the designer can do no better than consult the relevant specifications. For a list of relevant specifications see Appendix A at the end of this book.

The objective of the designer is to provide an assembly with adequate strength for the specific application with the least amount of weld metal and the minimum number of joints. This requires the designer to plan for a smooth flow of stresses through the joint, to compensate for any strength loss due to welding, to design the component such that there is sufficient access for welding and to select the metal to be welded with optimum weldability in mind. As mentioned in Chapter 2 there is little that can be done to improve the strength of the weldment to match that of the cold worked or precipitation-hardened alloy. All that the designer can do to compensate for the loss is to thicken the component, either overall or locally, or to move the weld to an area of low stress. For advice consult British Standard BS 8118 or the AWS Structural Design Code D 1.2, as mentioned above.

There are a number of factors that the designer needs to take into account that are specific to designs in aluminium. Some of these have been mentioned in earlier chapters and include such physical properties as the high coefficients of thermal conductivity and expansion, the major loss of strength of certain alloys in the HAZ and the low Young's modulus. In addition, the designer must consider access for both welding and inspection, joint design to enable high-quality welds to be made, the effects and minimisation of distortion and the effect of welding on stress concentrations and fatigue.

The ease with which a weld can be made is crucially dependent on joint design and this will have a direct effect on fabrication costs. It is thus essential that the designer is aware of certain fundamentals of welding practice in order to achieve the objectives of the lightest structure capable of performing its desired function at the lowest cost.

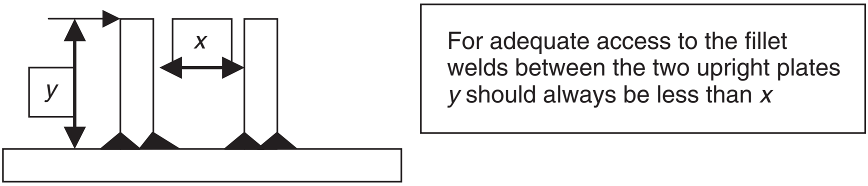
There are a number of 'golden rules' that the designer should keep in mind when detailing the drawings:

- Remember that weld metal is very expensive. Do not over-specify fillet weld throat thickness and specify the narrowest weld preparation angle that is consistent with quality. Specify these sizes clearly.
- Keep welding to a minimum – use formed sections instead of welded plate, keep stiffeners to a minimum. The cheapest weld of all is the one you do not make!
- Specify welds to be made in the flat position.
- Allow adequate access for the welder – see below.

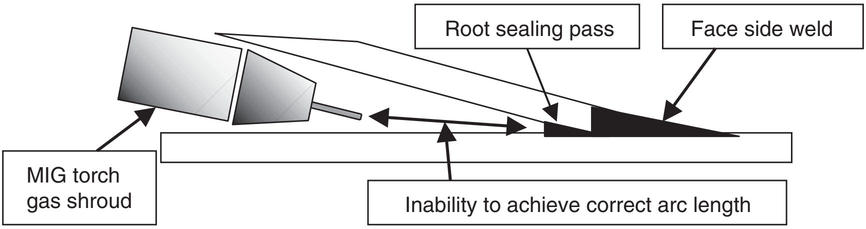
5.2 Access for welding

The two most common design faults are failing to recognise that full vision of the weld pool is essential for manual welding and that the weld must be at a comfortable distance from the operator, neither too close nor at a distance where the welder's arm is at full stretch. These errors can frequently be recognised at the design stage and the benefits of requiring an experienced welding engineer to review draft drawings cannot be overemphasised. The distance from the operator's head to the weld can easily be checked on drawings. Ideally this distance should be in the region of 200 mm minimum to 450 mm maximum. It should be remembered that the diameter of the welder's helmet is about 300 mm and that this will affect the access requirements.

For a joint to be accessible for manual welding welders must be able comfortably to position themselves and their equipment if high-quality welds are to be produced. This requires sufficient space to permit free movement of the welding torch or electrode and to enable the torch to be presented to the weld pool at the correct angle. Detail design must also take into account the proximity of adjacent material which should be such that the welder is allowed an unrestricted view of the arc. The amount of space required will depend on the size of the equipment to be used, in particular the size of the torch. Welding aluminium with the gas shielded processes



5.1 Access requirements for welding.



5.2 Access problems of angled plates or pipes.

requires a large diameter gas shroud and a short arc length. This means that the welder's view of the weld pool is more restricted than when welding a similar configuration in steel. The sketch in Fig. 5.1 illustrates a situation that is often encountered in practice where the designer has failed to take into account the need for adequate access. As a rule of thumb the distance between the plates should be as shown. A further limitation for TIG welding is the need to add a filler wire that restricts further the welder's view of the arc and the ease of manipulation as both of the welder's hands need to be in the work area.

The welding of attachments or nozzles to plates or pipes can present problems when the nozzle is presented to the surface at an angle less than 45°. Access into the acute angle is difficult, resulting in lack-of-fusion defects in the root of the weld as illustrated in Fig. 5.2.

5.3 Welding speed

Aluminium is normally welded at higher travel speeds than when welding steels, particularly when using the MIG process. The implication of this is that abrupt changes of direction are to be avoided. It is, for example, impossible to weld around a 90° corner as the MIG torch cannot be moved rapidly enough to keep the correct lead angle. It is also difficult to weld around small diameter bosses fixed in position. In this sort of application the boss needs to be rotated with the torch held stationary. Such comments do not necessarily apply when fully mechanised or robotic equipment is used.

Automation or the use of robots enables torch positioning and motion to be controlled with the precision required for the production of quality welds.

5.4 Welding position

Welding in the flat or downhand position is preferred for all arc welding activities. It is easier for the welder to deposit high-quality weld metal at high deposition rates in the flat position than in any of the other positions. The weld pool is larger in this position with slower solidification and cooling rates, permitting gases to evolve from the pool and reducing the amount of porosity. The force of gravity in positions such as the horizontal–vertical, however, means that the weld pool tends to sag, making it more difficult to achieve an acceptable weld profile. These effects are more marked with MIG than with TIG. Flat position welding therefore gives the best quality weld metal at the lowest cost.

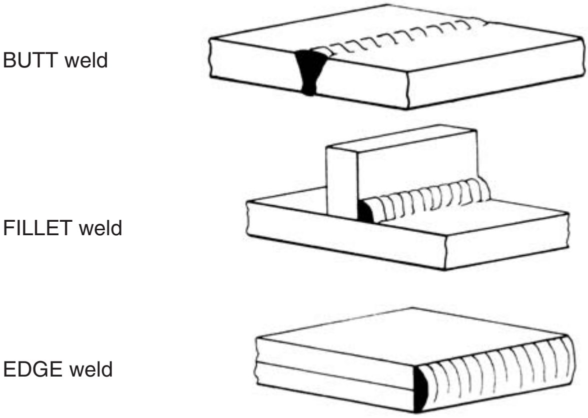
The designer should take these points into account when considering the design of a structure. Wherever possible welding should be performed in the flat position. This may require the fabrication of sub-assemblies that are more easily manipulated. Manipulating equipment such as rotators or face-plate manipulators are useful for items too large for manual handling. The use of this equipment, however, may require the welding of temporary attachments to the component to facilitate fitting the component to the manipulator. As much care must be taken with the welding and removal of these attachments as is applied to the permanent joints – formal welding procedures should be considered in order to exercise control over this sometimes haphazard activity.

5.5 Edge preparation and joint design

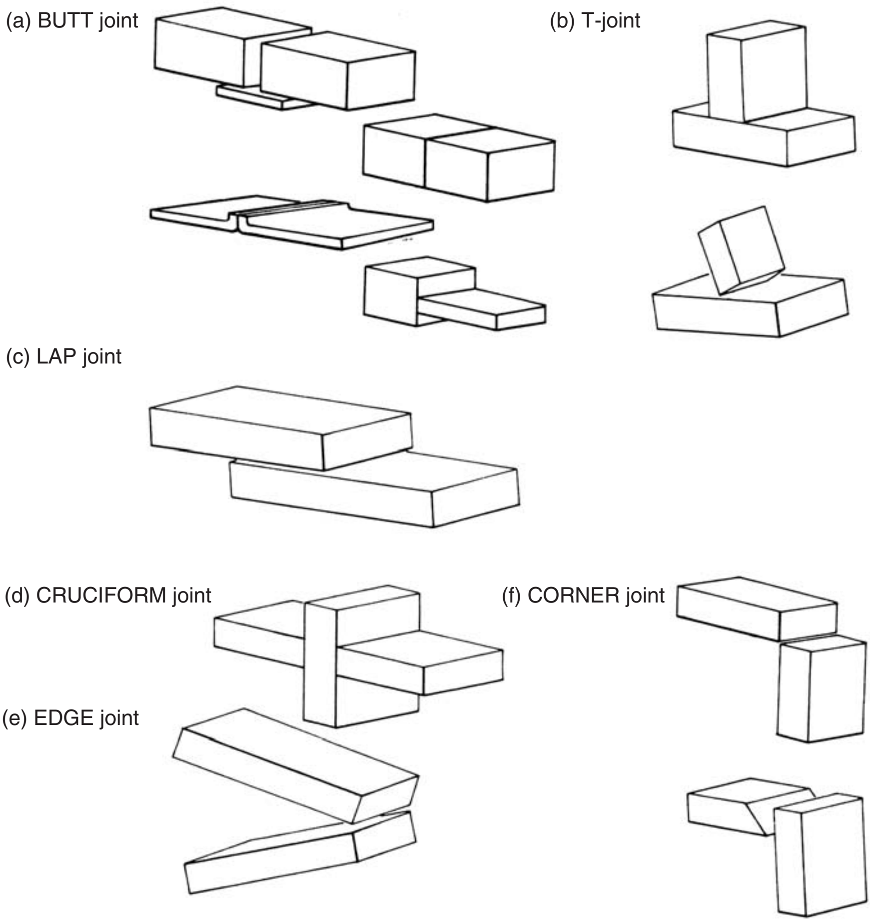
There are few more important decisions that affect the success of welding than that of correct joint design. Problems with weld quality or performance can often be attributed to the wrong design of edge preparation. Joint design is determined by the strength requirements, the alloy, the thickness of the material, the type and location of the joint, the access for welding and the welding process to be used.

There are three fundamental forms of weld, the butt, the fillet and the edge weld, illustrated in Fig. 5.3, from which can be developed six basic joint types. These are the butt, T-joint, corner, cruciform, edge and lap joint, illustrated in Fig. 5.4.

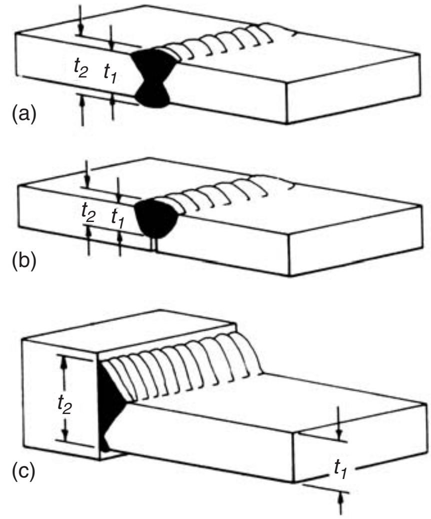
The static tensile strength of these weld types is determined by the *throat thickness* (Fig. 5.5). The size of a fully penetrated butt weld is determined by the thickness of weld metal deposited within the plane of the plate or



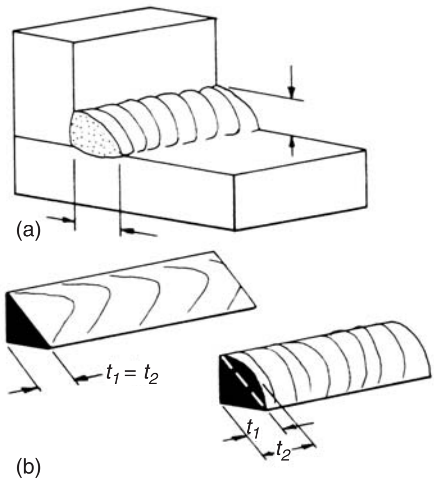
5.3 Butt, fillet and edge welds.



5.4 Joint types developed from the butt, fillet and edge weld.

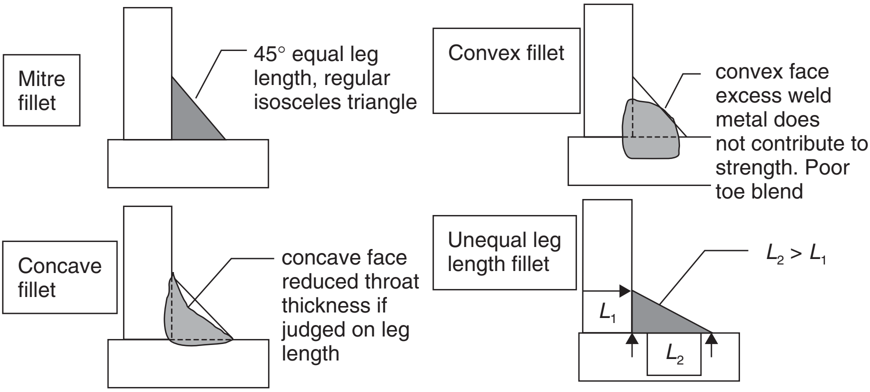


5.5 Throat thickness in a butt weld: (a) full pen butt weld; (b) partial pen butt weld; (c) T-butt weld.



5.6 Throat thickness in a fillet weld: (a) fillet weld; (b) mitre and convex fillet weld.

pipe, t_1 in Fig. 5.5. No credit is taken in calculating permissible static design stress of either a butt or fillet weld for the excess weld metal, i.e. that above the surface of the parent metal for a butt or outside the isosceles triangle of a fillet weld as given by $(t_2 - t_1)$.



5.7 Mitre, convex, concave and unequal leg length fillet.

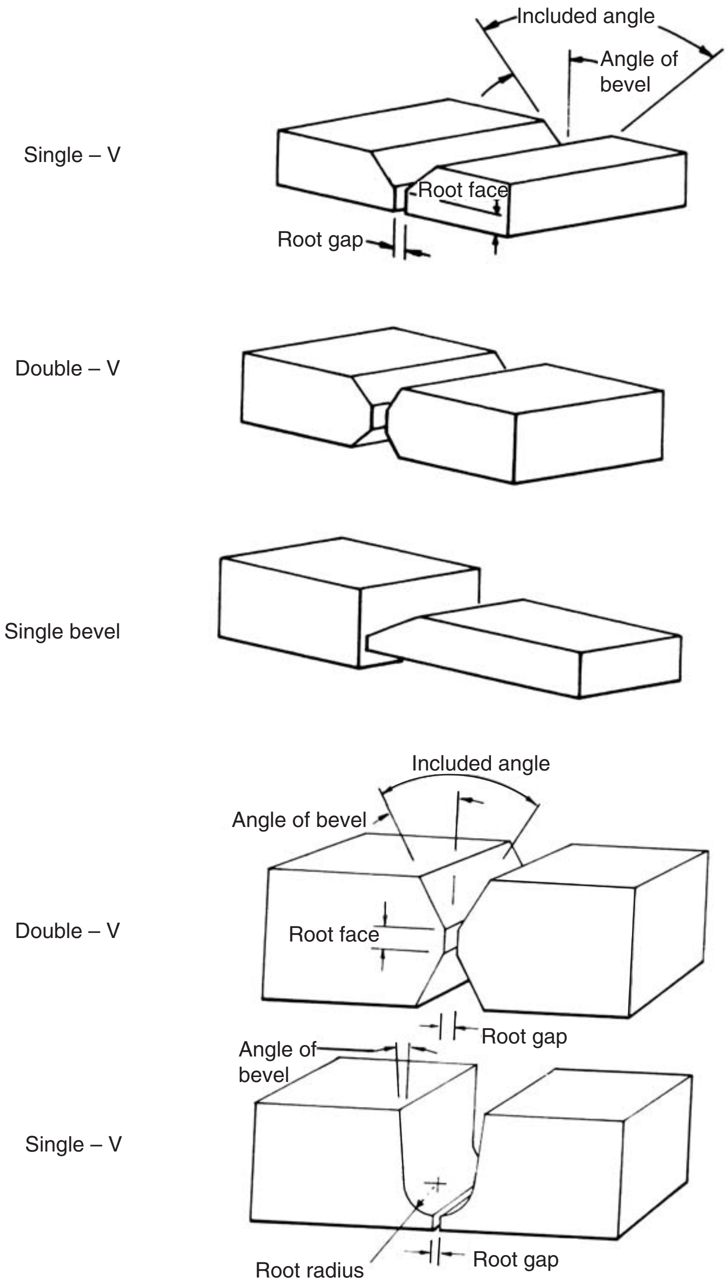
For the fillet weld the shape of the weld and the amount of penetration into the root will affect the throat thickness. The *effective* throat thickness is t_1 in Fig. 5.6. The size of the fillet weld must be determined by the designer and should be of sufficient size to carry the load. The throat may therefore be completely different from the material thickness.

The fillet weld may also be described as a *mitre*, a *concave* or a *convex* fillet. In addition the fillet weld may have unequal *leg lengths*. These four types of fillet weld are illustrated in Fig. 5.7.

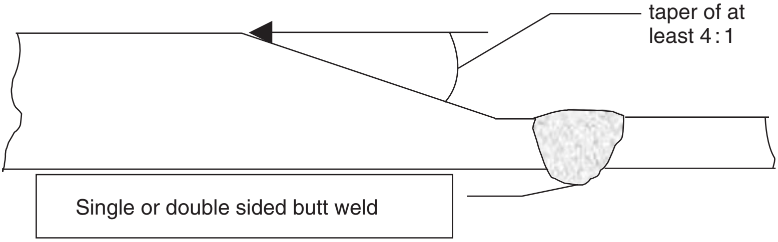
5.5.1 The butt weld

The butt weld, typical forms of which are illustrated in Fig. 5.8, is a simple and easily designed joint which uses the minimum amount of material. Figure 5.8 also includes definitions of some of the features of a *weld preparation* such as 'root face', 'angle of bevel' and 'included angle'. Butt welds, as illustrated in Fig. 5.5, may also be classified as *full penetration* or *partial penetration*.

With the conventional fusion welding processes of TIG and MIG penetration of weld metal into the surface of a flat plate from a bead-on-plate run is typically 3 mm and 6 mm respectively. To achieve a full penetration butt weld at thicknesses over these it is necessary for the two close square-butted edges to be bevelled, although leaving a small gap between the edges will increase penetration. Typical weld preparations for the various processes will be found in the relevant process chapter. Butt joints may be single or double sided – if double sided it is often necessary to back-gouge or back-grind the first side to be welded to achieve a joint that is free of any lack of penetration.



5.8 Various forms of the butt weld.

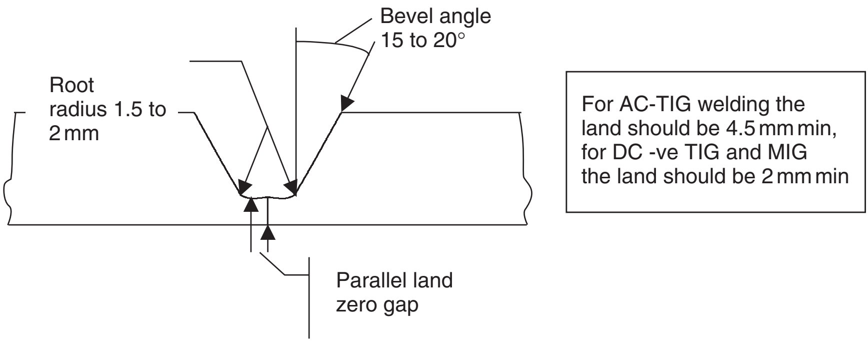


5.9 Suggested design for the joining of dissimilar thickness plates.

The effective size of a full penetration butt weld equals the design throat thickness, essentially the plate/pipe thickness of the thinner component. As mentioned elsewhere no credit is taken for the weld metal cap height or root penetration bead. Although not often used in aluminium fabrications because of the need to match joint strength and base metal strength, in lightly loaded joints a partial penetration joint (Fig. 5.5b), may be acceptable. Partial penetration can be achieved by the use of a close square butt joint or a thick root face. There are cost benefits associated with the partial penetration joint as little or no edge preparation is required, it is economical on filler metal and it is easy to assemble since the root gap does not need to be controlled. The limitations are that radiographic interpretation is difficult due to the lack of penetration, the fatigue life is compromised and static mechanical strength is reduced. The effective size in the case of the partial penetration weld is the throat of the weld minus the cap height.

Where two sections of unequal thickness are to be welded the welder's task will be eased and the best properties, particularly fatigue, will be achieved if the thicker of the two is bevelled or tapered to match the thinner. The taper on the thicker component to achieve this should be in the region of 4 to 1 to reduce the stress-raising effects of an abrupt change in thickness (Fig. 5.9).

The weld preparation shape may be selected to achieve root penetration and a sound root, to permit the required pass sequence or to control weld metal dilution from the parent metal. The MIG process can, but with difficulty, be used to produce a sound, defect-free penetration bead – for a sound joint either a backing bar or strip needs to be used or the weld must be cut-back and a second side weld made. These techniques are dealt with in greater detail elsewhere. The TIG process can be used to make a sound, fully penetrated root bead without a cut back or backing strip. A 'landed' bevel joint (Fig. 5.10) is designed to enable the highest quality root penetration bead to be made using the TIG process. This is of use in applications such as pipe butt welding, where the welds need to be single sided and to have a smooth root bead that will not hinder flow in the pipe.



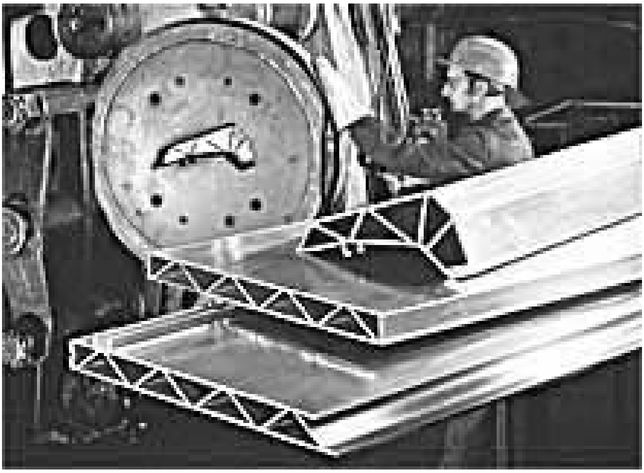
5.10 'Landed' single-V butt weld.

The strength of a sound, defect-free butt weld generally matches that of the filler metal or the annealed strength of the parent metal, as discussed in Chapter 2. The butt joint is the best in a dynamic loading environment, particularly if the excess weld metal is dressed flush. To achieve the best properties the two component parts require accurate alignment, which implies adequate tacking, jigging and fixturing.

5.5.2 Backing bars and backing strips

Although it is possible to deposit a sealing run on the reverse side of a butt weld without a back-gouge, this cannot be relied upon to give a sound, defect-free weld. Single sided joints may be welded by TIG to produce a sound root pass but the conventional (non-pulsed) MIG process often requires either permanent or temporary backing on which to deposit the MIG root pass. The purpose of the backing bar or strip is to support the root pass where conditions make the control of the bead difficult. Conventionally, a backing *bar* is temporary and can be lifted away as soon as the weld has been completed, and a backing *strip* is a permanent part of the joint. A backing bar or strip can greatly simplify the task of setting up the joint – for example, root gap variations are easily coped with and joints can be self-jigging, good root bead appearance can be achieved and costs can be reduced.

A grooved temporary backing bar will produce good penetration bead shape, the groove being used as a mould for the molten weld metal. This will provide a better dynamic performance than a permanent backing strip. Backing bar material can be an inexpensive mild steel but a longer life can be obtained from the bar with less risk of contamination if stainless steel is used. Ceramic backing, provided as a flexible strip of tiles or on adhesive tape, can also be used. Copper or copper alloys should be avoided because



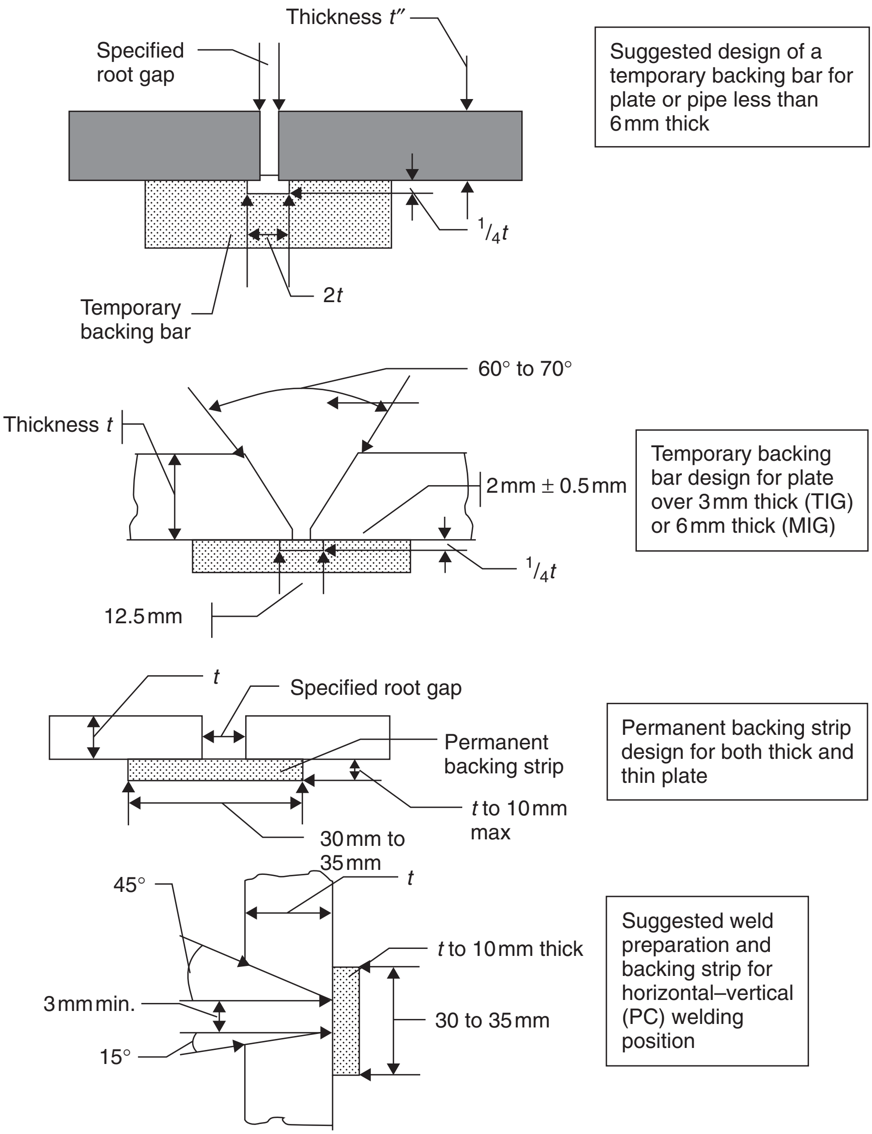
5.11 Typical self-jigging extrusions. Courtesy of ALCAN.

of the risk of contamination. An ungrooved backing bar will need the root pass to be back-ground and perhaps a sealing pass to be deposited to produce a sound weld. If TIG welding using a backing bar the weld should be made with no root gap. This is necessary to prevent the TIG arc acting directly on and perhaps melting the backing material.

The permanent backing strip is fused into the root pass and care must be taken to select an alloy that is compatible with the parent metal and the filler. The strip should be in the region of 4–6 mm thick and tacked in position. Many extrusions in aluminium, however, can be produced with the backing strip incorporated and in this way joint set-up is simplified. It is possible to design the extrusions with both the backing strip built in and of such a shape that the joint is self-jigging, as illustrated in Fig. 5.11.

The crevices associated with permanent backing strips result in local stress concentrations. These may reduce both impact and fatigue resistance if the root is in a highly stressed area. The crevice may also give rise to localised corrosion although even in marine environments this has not been reported as a major problem when the correct alloy has been chosen. Despite these potential drawbacks, permanent backing strips are a common feature in many structures used in challenging applications.

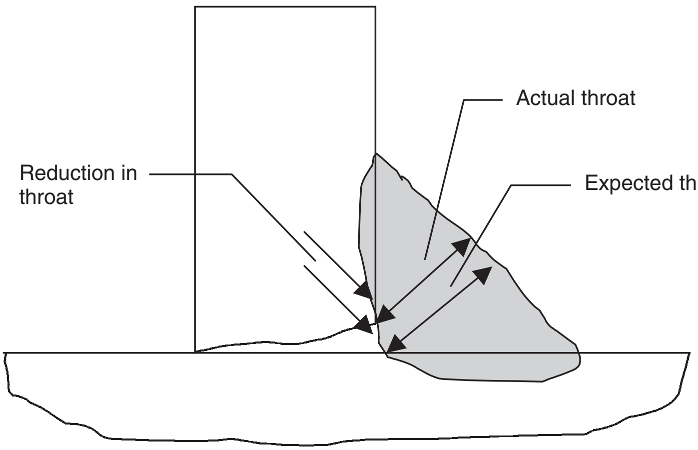
Inert gas backing can be used for critical applications such as food processing or pharmaceutical process pipework or vessels and is very useful when there is no access to the back of the weld to back-gouge and seal. An argon purge will prevent oxidation of the root penetration bead and oxide films being fused into the joint, giving a smooth, even TIG root bead. Typical designs of backing bars and strips are given in Fig. 5.12.



5.12 Backing bar and strip designs.

5.5.3 The T-joint

As the name infers, the T-joint (Fig. 5.4b) is one where one member is positioned at approximately right angles to its partner with the most usual applications being plate to plate or branch connections. The upright of the T may be joined by a butt weld, by a fillet weld or welds or by a combination of



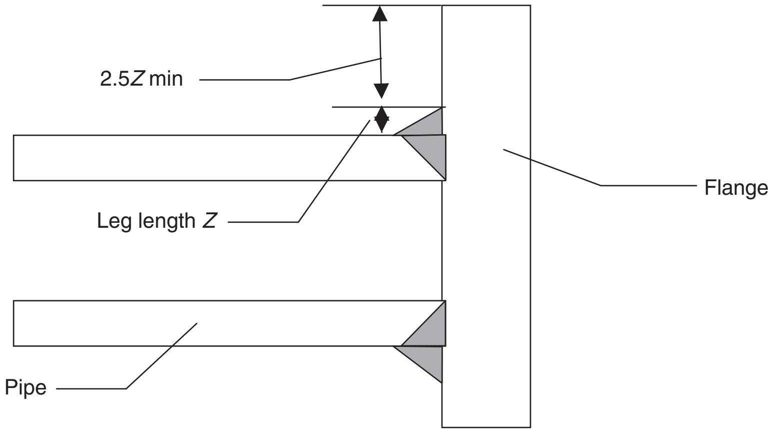
5.13 Effect of an irregular cut edge on the fillet weld throat thickness.

the two weld types (Fig. 5.5c). The T-joint is a simple, easily designed weldment which, except in the case of the T-butt, requires little or no edge preparation. The accuracy of the fit-up depends to a great extent on the accuracy with which the edge of the upright of the T is prepared. An irregular cut will give a variable gap, which may result in an inadequate throat thickness as illustrated in Fig. 5.13.

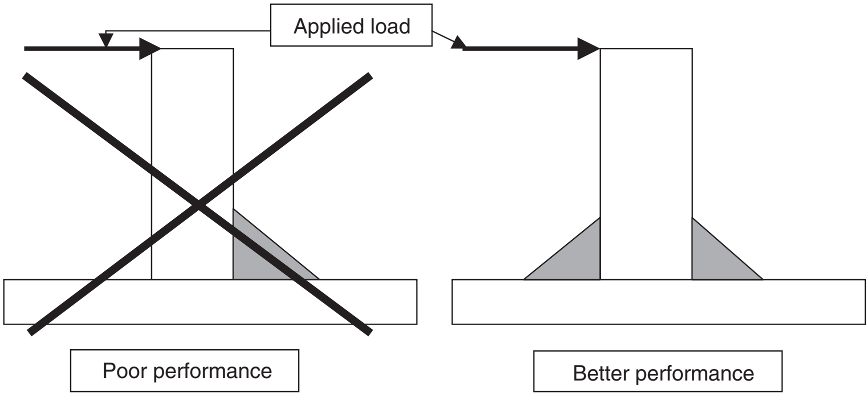
A fillet weld can present difficulties in achieving full penetration into the root, resulting in a void being formed in the corner. This is regarded as undesirable, particularly in critical applications, as this lack of fusion acts as a stress raiser in the root and also reduces the throat thickness. The welder needs to be made aware of this problem as the main cause is incorrect welder technique.

If the T-butt is a flanged joint, sufficient metal must be left that the weld does not melt away the corner of the flange and to allow for variations in fit-up. As a rule of thumb, some 2.5 to 3 times the fillet weld leg length is regarded as being adequate (Fig. 5.14). This may not prevent the edge of the flange from buckling due to distortion from the heat of welding, particularly where the fillet size is large in proportion to the flange thickness.

The strength of a fillet welded T-joint is determined by the shear strength of the fillet weld or welds, the strength of a butt-welded T-joint by the strength of the weld metal or the HAZ. If the joint is subjected to transverse shear loads the bending stresses in the joint can lead to premature failure, particularly if the joint is fillet welded on one side only. Fillet welds on both sides or a full penetration T-butt joint will permit substantially increased loads before failure occurs (Fig. 5.15). Dynamic performance of T-joints is not good: the change in section from the horizontal to vertical



5.14 Recommended distance of weld toe from the flange edge.



5.15 Redesign of side loaded fillet welds for improved performance.

member gives rise to high stresses at the weld toes, drastically shortening the fatigue life.

5.5.4 The corner joint

The corner joint may be regarded as a butt joint and is used to join two plates at right angles to each other (Fig. 5.4f). It can be difficult to assemble and maintain correct alignment, particularly in thin flexible sheet. The root of a single-sided weld when loaded in tension is very weak and for the highest strength the corner joint needs to be welded from both sides. The single-sided weld may also have a crease containing oxides along the centre line of the penetration bead, further reducing the strength of the weld. Pulsed AC-TIG has been found to be effective in reducing the occurrence of this feature. The corner joint is most often found in low load-carrying applications and in sheet metal work.

5.5.5 The edge joint

The edge joint (Fig. 5.4e) is simple to assemble and to hold in position during welding. Like the corner weld, it is weak in loading situations that put the root in tension and is rarely used in a structural application, being confined to non-load-carrying applications in thin sheet metal. Melting of the corners of the edges being joined can be a problem and may result in a shallow, low throat thickness weld.

5.5.6 The lap joint

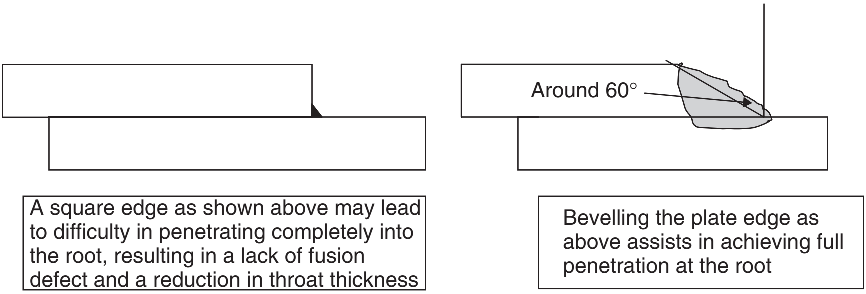
The lap joint is perhaps the easiest joint of all to assemble. It comprises two overlapping plates joined by a fillet weld (Fig. 5.4c). Variations in component sizes are easily accommodated and no edge preparation is required, although a bevel, as in Fig. 5.16, may be used to guarantee full root fusion.

The joint is uneconomical in terms of material as the overlapping material is waste. The overlap should be at least three times the thickness of the thinner plate. Care also needs to be taken to ensure that the weld does not melt away the corner of the upper plate as this results in a reduction in the effective throat thickness of the fillet.

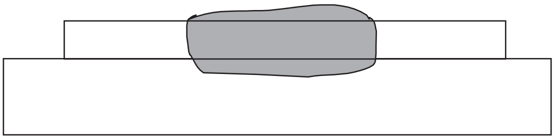
The joint strength is set by the shear strength of the fillet weld. Weld sizes and lengths should be specified by the designer to guarantee adequate load-carrying capacity.

5.5.7 Spot, plug and slot welds

Arc welded plug and spot welds are illustrated in Fig. 5.17. Both the TIG and MIG processes are capable of fully penetrating 2–3 mm through the upper sheet of a lap type joint to provide an acceptable weld. Laser and



5.16 Bevelling the plate edge in a lap joint to improve penetration.



5.17 Plug and spot welds using TIG or MIG welding.

electron beam welding are capable of spot and 'stake' welding through a substantial plate thickness, in the case of electron beam up to 200 mm.

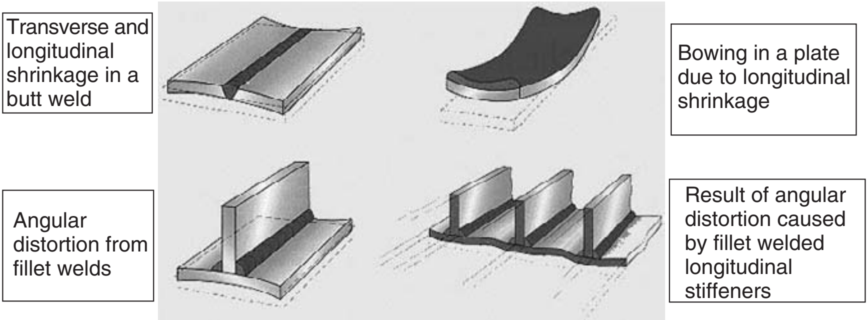
TIG welding tends to be confined to thin sheet, less than 2 mm thick, and finds only a very limited application in production. The bulk of spot welding is performed using MIG welding and is covered in greater detail in Chapter 7. The designer must be aware, however, of the variable quality of the spot weld which results in low strength and poor fatigue performance. The high restraint inherent in this weld form almost always results in distortion, particularly when the welds are close pitched, and may produce hot cracks in the HAZ. These features limit the applications of spot welding.

Plug welding is similar to spot welding except that the upper plate is cut to provide a hole which is either completely filled with weld metal or is fillet welded around its rim. This type of weld suffers from the same problems of variable quality and inadequate strength as do the spot welds. They both tend to be avoided when structural integrity is required.

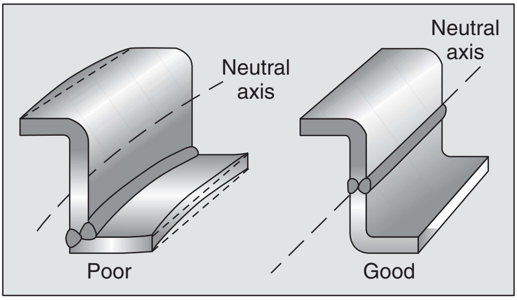
The slot weld is rather more useful in a structural application than the spot or plug weld since there is a reasonable length of weld to be deposited. This permits a stable weld pool to be established and a sound joint to be made. The weld may be a single pass completely filling the slot or it may be fillet welded both sides. For best quality the start and stop positions should be on the upper plate, clear of the slot. Fillet welded slots are preferred when the plate thickness exceeds 5 mm. The strength of a slot weld is determined by the shear strength of the weld deposit.

5.6 Distortion

Residual stress due to heating and cooling of the HAZs and the contraction of the weld metal as it cools from a molten state to ambient temperature is an unavoidable feature of welded joints. The stress deriving from this shrinkage results in distortion. This distortion may be localised, evenly distributed and acceptable or may render the entire structure unfit for its purpose. In a ship's hull, for instance, buckling of the hull plates can induce turbulence and increase drag; in piping it can restrict fluid flow; and in architectural applications it can be aesthetically unacceptable.



5.18 Longitudinal, transverse and angular distortion. Courtesy of TWI Ltd.



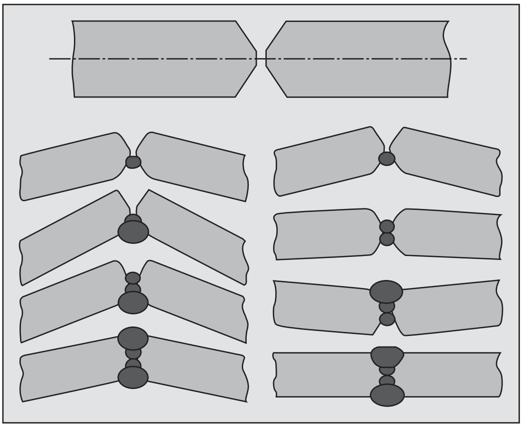
5.19 Welding around the neutral axis. Courtesy of TWI Ltd.

Distortion can appear as longitudinal shrinkage, transverse shrinkage, angular distortion, bowing or buckling. The various forms are shown in Fig. 5.18. The amount of distortion is affected by the heat input from the welding process, the welding sequence, joint design, the amount the joint is restrained, stresses in the parent metal and its physical characteristics.

Although the coefficient of thermal expansion of aluminium is about twice that of steel, its high thermal conductivity means that temperature gradients are less severe. However, the change that occurs when the weld metal solidifies is around a 5% volume shrinkage, compared with a 3% reduction in steel. The net result is that distortion in aluminium is somewhat greater than would be expected in a similar steel structure. If the metal is in a highly stressed state, such as being cold worked, this will also lead to greater distortion as these stresses are released by the heat of welding.

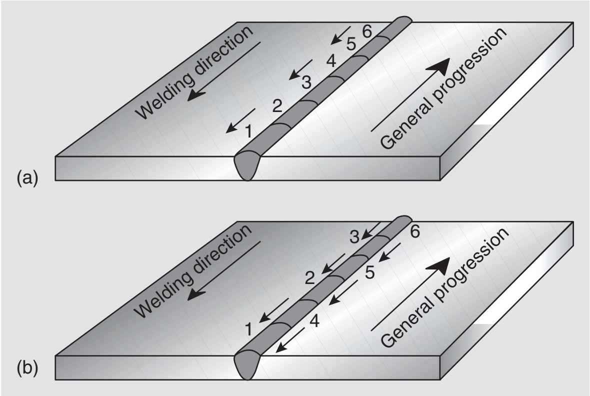
The measures that can be taken to minimise the problem are similar to those that would be used for steel:

- **Weld on or very close to the neutral axis**.
- **Balance the welds about the neutral axis of the component** (Fig. 5.19).

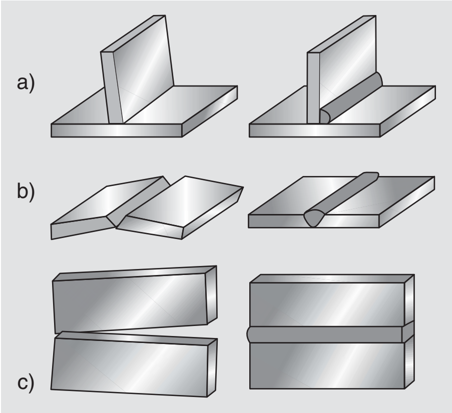


5.20 Balanced welding in a butt weld. Courtesy of TWI Ltd.

- Where appropriate **use a double-V preparation** and balance the welding about the plate centre line (Fig. 5.20).
- **Use the lowest heat input process and welding parameters**, consistent with achieving the required quality. Of the fusion welding processes the power beam processes – electron beam or laser welding – will give the least distortion.
- **Use the fewest number of weld passes to fill the joint**. This implies that a high heat input process will result in less distortion than a low heat input process. This may seem to be in conflict with the point above but it should be remembered that it is the *total* heat input to the joint that is significant. The sum of heat inputs from a large number of small passes will result in a higher total heat input than that from a small number of large beads for the same volume of weld metal. TIG welding, for instance, will almost always give more distortion than MIG welding the same component.
- On long welds, **weld from the centre towards the ends**. On items such as beams this will approximately halve the amount of bowing that would be expected if the beam was welded by starting at one end and welding through to the opposite end.
- **Use a 'back-step' sequence**, i.e. weld from a cold section of joint towards a hot section already welded (Fig. 5.21).
- **Break the construction down into sub-assemblies**, weld the individual sub-assemblies and assemble the complete item, balancing any distortion from the individual items to minimise the overall distortion.
- **Preset the components** (Fig. 5.22). If the amount of distortion is known or can be predicted, the items can be assembled and offset by the amount of expected distortion. On completion of welding the distortion



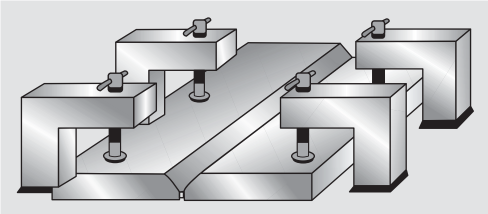
5.21 Backstep welding. Courtesy of TWI Ltd.



5.22 Presetting of components before welding. Courtesy of TWI Ltd.

has been used to pull the items to within tolerance. This technique is most easily used to cope with angular distortion on plates.

- **Use automatic welding**. This may enable faster travel speeds to be used and hence lower heat input to be achieved. Mechanised/automatic welding will also give more consistent distortion which enables the technique of pre-setting components to be used with greater confidence.
- **Use a planned welding sequence**. This is of use on fabrications such as lattice beams where a planned sequence can be of great benefit. The precise sequence to minimise distortion will vary from assembly to assembly and is best designed from experience. Staggered welds, back step and skip welding can also be employed.
- **Use adequate tack welds**. In a butt joint the contraction of the solidifying weld metal tends to pull together the two edges (Fig. 5.22). With thin



5.23 Jigging of plate to maintain flatness. Courtesy of TWI Ltd.

sheets this can result in the edges riding up over each other, requiring the tack welds to be more closely pitched. The length of tack welds should be in the region of 8 times the component thickness and spaced at intervals not greater than 35 times the thickness. They must be made with the same procedure and with as much care as the main weld. Tacks are expected to carry the assembly stresses and can therefore experience high loads that may well cause cracking problems. Incorporation of cracked tacks in the constructional weld will be an expensive problem to eliminate!

- **Ensure that the joint fit-up is accurate**. This is perhaps one aspect where the importance cannot be over-emphasised. Large root gaps, for instance, will always result in large amounts of distortion as the root weld metal contracts.
- **Do not over-weld** and avoid the use of wide bevel angles, large root gaps and large amounts of excess metal. Fillet welds should be as small as permitted by design – for example, an 8 mm leg length fillet weld contains over 80% more weld metal than a 6 mm leg length fillet. It is worth remembering that not only does excess weld metal increase distortion, it also costs a lot of money to deposit it!
- **Use jigs and fixtures** (Fig. 5.23), to hold and retain the components in the correct alignment. The use of rigid restraints will give increased levels of residual stress and may increase the risk of cracking. Jigs need to be designed to provide good access for welding, to be rigid and robust, to be foolproof in use and to be well maintained to ensure that wear is taken into account and tolerances are achieved.

5.7 Rectification of distortion

If the measures listed above are not effective, remedial measures to rectify the distortion will be necessary. These may be based upon those used for steel but great care needs to be exercised if such techniques are used. The most effective methods are those that use some form of mechanical working or stretching as these will not significantly affect the mechanical properties of the base materials. Longitudinal bow in welded beams should preferably be done cold by pressing, and buckled plate may be pressed flat.

As a last resort, local spot or line heating may be used to heat-shrink items that have been distorted by the welding of, for instance, stiffeners. Some examples of how these techniques can be applied are illustrated in Fig. 5.24. The high thermal conductivity of aluminium means that local heating with an oxy-gas torch is not very effective. If this technique is to be used then electric induction heating is the most effective method of introducing sufficient heat into the component.

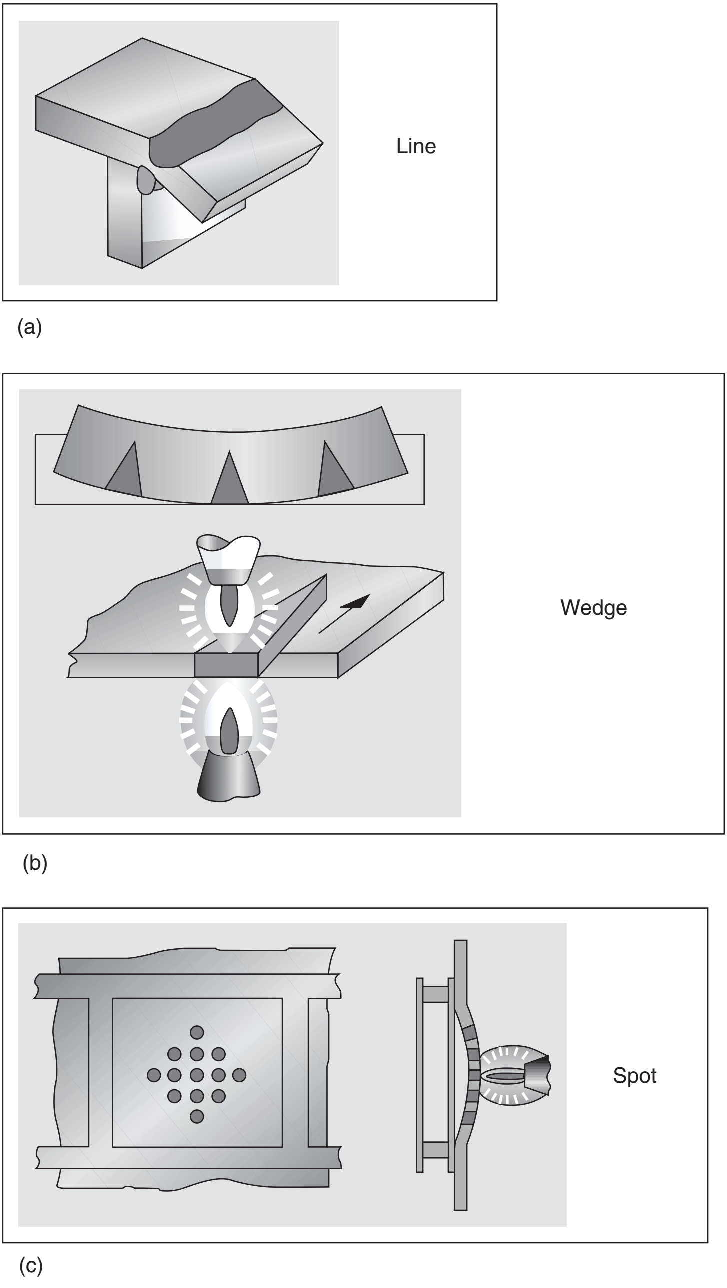
If heat must be used then this should not exceed 400 °C for the non-heat treatable alloys. Remember, though, that temperatures over 250 °C will produce full softening in the alloy if it is in the work-hardened condition. The age-hardened heat-treated alloys should not be heated to more than 150 °C as this will cause softening due to overageing of the precipitates.

Whenever these techniques are used then reference must be made to the design engineer to ensure that the potential loss of strength is taken into account.

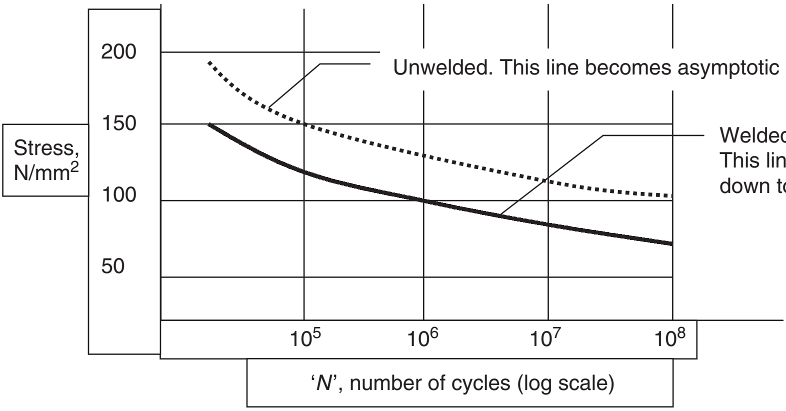
5.8 Fatigue strength of welded joints

Fatigue, as the name suggests, is a failure mechanism where the component fails after a period of time in service where it sees a repetitive cyclic stress. Failure may occur even if this stress is substantially below the yield strength of the metal as the other factor in causing failure is the number of stress cycles that the component experiences. Failure always occurs normal to the principal applied stress and the fracture surface is characterised by so-called 'beach marking' where changes in the stress level give different rates of crack propagation. This gives the surface a rippled appearance similar to a beach when the tide has ebbed away. The rate of crack propagation is proportional to the stress range and the crack length. Cracks in the early stages of growth tend to be very small and to grow slowly, making it easy for them to be missed during in-service inspection.

To be able to predict the fatigue life of a structure the designer needs accurate details of the full service loading conditions and accurate fatigue data on the performance of the component parts of the structure. The most common sites for initiation are weld toes, both root and face, drilled holes, machined corners and threaded holes. Of these sites the most significant are welds. Since welding has such a significant effect on fatigue life it will be necessary to specify welding details and controls rather more closely than for a statically loaded structure. This will, inevitably, have an effect on the cost of fabrication.



5.24 Rectification of distortion by (a) line, (b) wedge and (c) spot heating. Courtesy of TWI Ltd.



5.25 Stress/no. of cycles curve for alloy 5083.

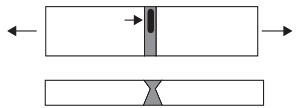
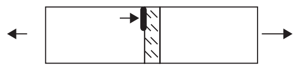
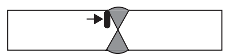
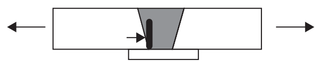
Fatigue performance can be represented graphically on an *S/N curve* where '*S*' is the stress and '*N*' the number of cycles to failure. For unwelded components a *fatigue limit* is reached where below a certain stress failure will not occur, irrespective of the number of cycles of stress it sees. A welded joint, however, does not exhibit a fatigue limit – failure will always occur if enough stress cycles are applied. These points are illustrated in the *S*/*N* curve in Fig. 5.25.

Welding results in a substantial reduction in the fatigue life and an elimination of the fatigue limit. This is such a dominant effect that there is little difference in fatigue life between the various alloys and tensile strength in this context is, to a great extent, irrelevant. The presence of welding defects will have an additional adverse effect, particularly those defects that may be classified as planar. Abrupt changes in section, notches and corners all reduce the fatigue life. Poorly shaped welds where there is a poor toe blend with the excess weld metal meeting the parent metal at a sharp angle (see the convex fillet in Fig. 5.7 as an example) are significant stress raisers. For the best fatigue performance the welds should be smoothly blended with no abrupt changes on section.

The corollary of this is that the form and shape of the weld will have a major effect on fatigue performance. Many specifications categorise the various weld forms and the direction of loading with respect to the fatigue life as shown in Table 5.1 parts a and b.

Apart from the need to ensure that the welds are smooth and well blended the orientation of the welded item to the principal stress needs to be taken into account. Fatigue improvement techniques comprise, firstly, eliminating the weld if possible or moving it to an area of lower stress. Redesign to a joint type with a higher category should be considered. If this

Table 5.1a Fatigue classification of welded details

Description of detail	Explanatory comments	Examples showing crack sites	BS 8118 Classification	BS 5500 Classification
Transverse butt weld				
	Weld machined flush		42	D
	As welded with good profile, weld blends smoothly with the parent metal, eg automatic weld		35	D
	Less desirable profile, welds with peaky profile, multiple stop/starts		29	E
	Backing strip weld without tack welds, cracking from root		24	F

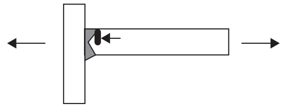
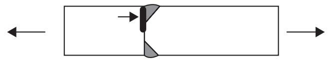
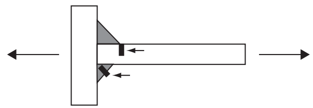
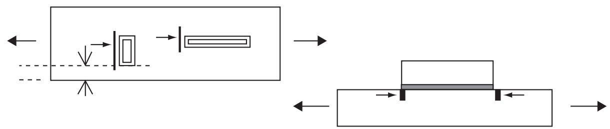
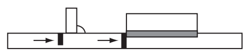
T-joint butt weld – full penetration			24	F
Butt weld – partial penetration.	Fatigue life determined on weld throat		14	W
Loadcarrying fillet welds				
T- or cruciform joints made with fillet welds	Cracking may be at the weld toe or in the weld throat		20	F2 if plate stress, W if weld throat stress
Non-loadcarrying attachments – butt or fillet welds				
Attachments not closer than 10 mm from edge of stressed member	Cracking starts at the weld toe.		24	F
As above but within 10 mm of edge of stressed member	Cracking starts at weld toe.		20	G

Table 5.1a (cont.)

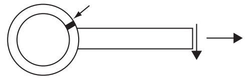
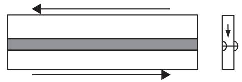
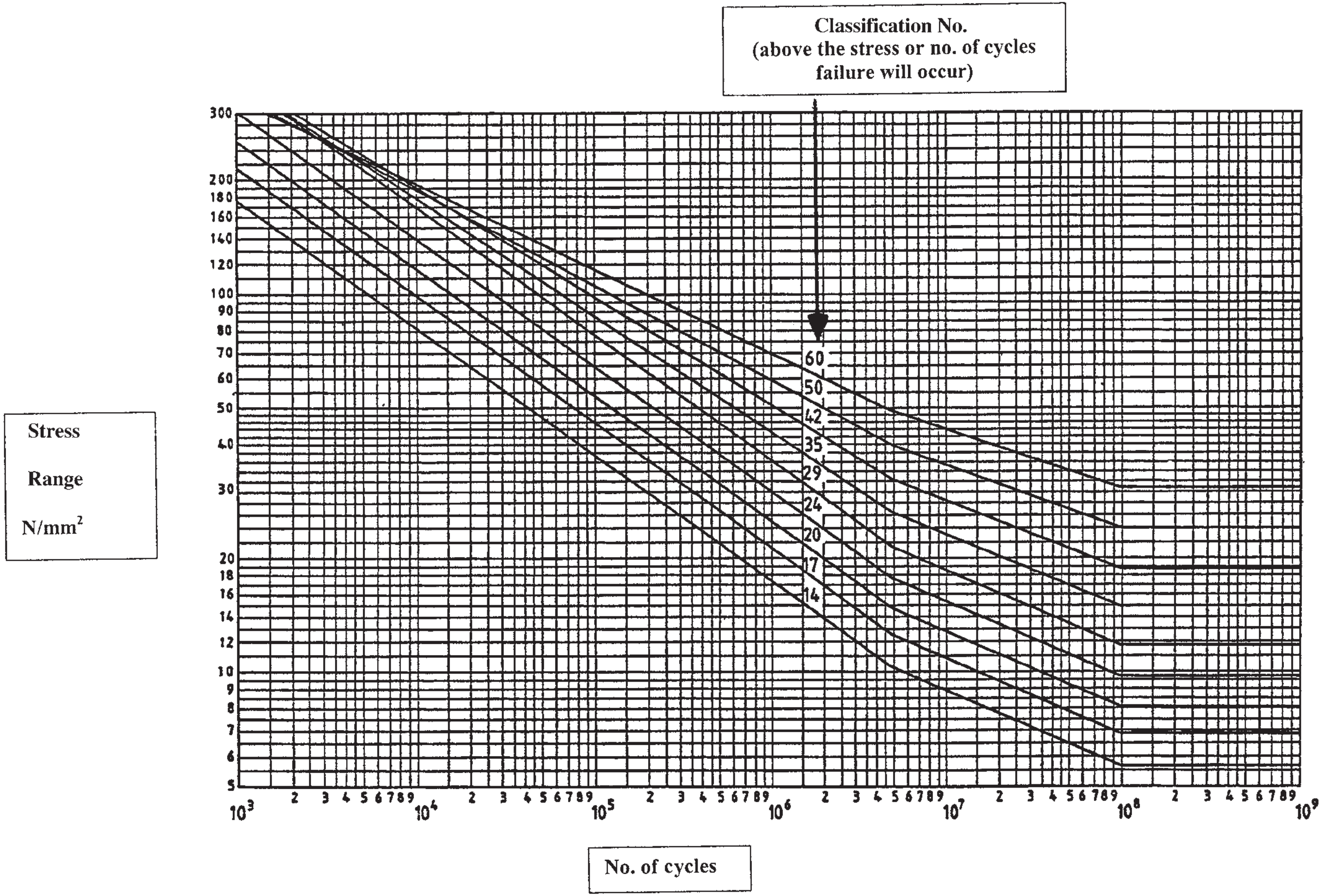
Description of detail	Explanatory comments	Examples showing crack sites	BS 8118 Classification	BS 5500 Classification
Fillet or butt welded nodal joint	Calculate peak stresses acting on the joint		24 (depends on loading regime)	F or W
Fillet and partial penetration butt welds in longitudinal shear	Weld throat is used to calculate stress	 	43 (automatic welds) 35 (multiple stop/starts)	W

Table 5.1b Fatigue life prediction for welded items from BS 8118



cannot be done then thickening the component will reduce the stress experienced by the weld. The fatigue life of the weld can be improved by inducing compressive stresses at the toe of the weld. Overstressing the joint or hammer peening the weld toe will both do this, although great care needs to be taken that an over-enthusiastic application of either technique does not introduce defects. Dressing of the weld toes has been found to be an effective method but, once again, over-enthusiastic grinding can reduce rather than improve fatigue life. If the weld toes are ground this should be carried out by fully trained personnel. Grinding should be performed transverse to the weld toes in order that the grinding marks are parallel with the principal stress.