Welded Joint Design

Second edition

J.G. HICKS

Consultant in welded design,
fabrication and quality assurance

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Introduction

The first edition of this book was written mainly for draughtsmen and engineers whose work involved designing steel structures and components, but it was recognised that it would also be of value to students as a link between the theory and practice of design. This second edition has been written for people in the same activities but recognises that in the intervening years there have been changes in attitudes, in the wider implementation of fracture mechanics testing, and in the approach to matters of quality.

The chapter on brittle fracture has been expanded to include descriptions of fracture mechanics tests and their significance to the designer. Due to the implementation of research findings catastrophic brittle fractures are fortunately increasingly rare, although not unknown, as a picture in the chapter illustrates. The lesson must be that the possibility of fracture always exists unless design, materials and welding are considered comprehensively at the design stage.

The chapter on fatigue has been expanded to include the performance of joints in tubular structures, the understanding of which has been enhanced by the attention which has been necessary for fixed offshore structures. Minor changes have been made to the chapter on the effect of welding on materials, which it is hoped will make it more easily reconciled with the approach to quality.

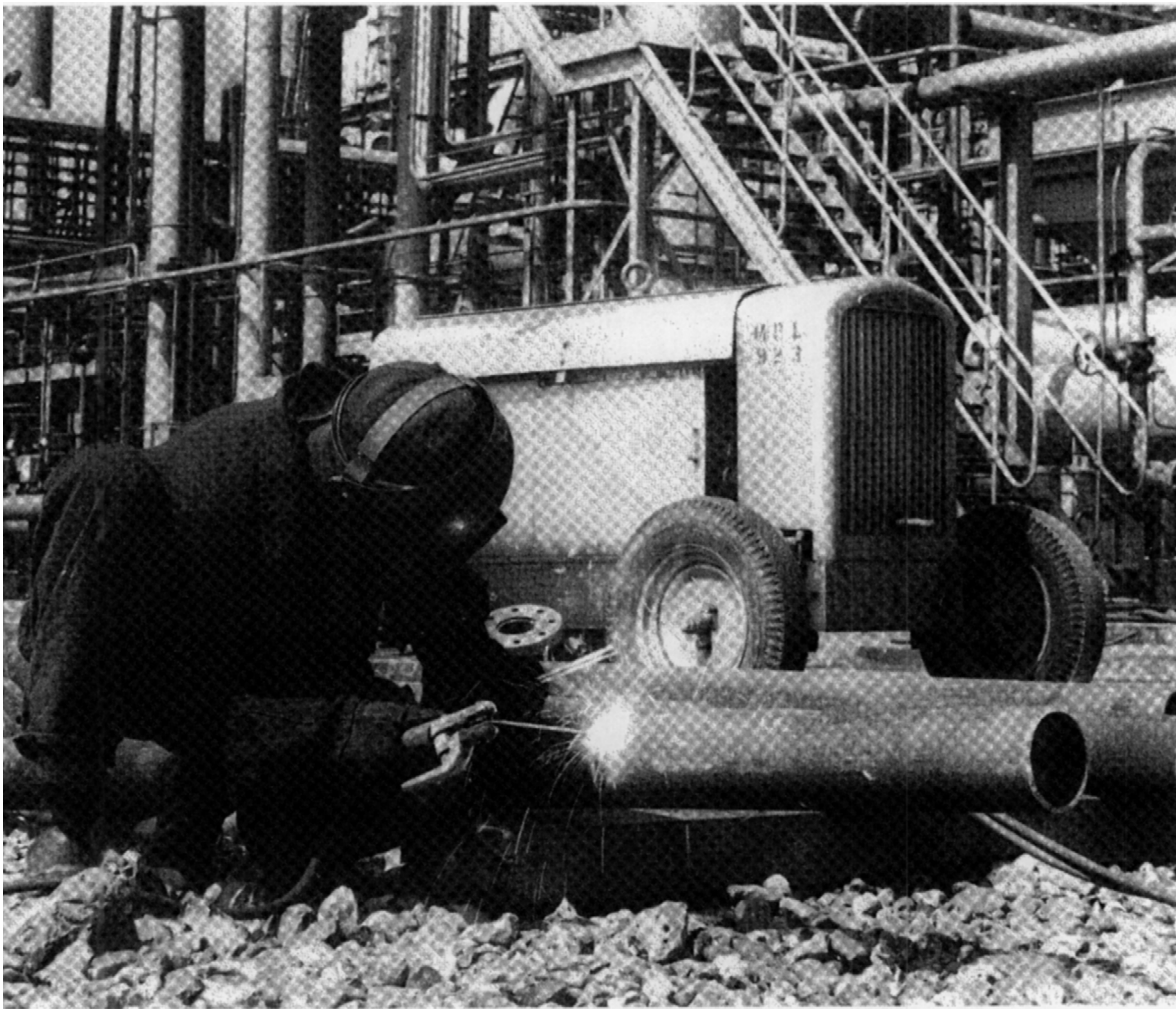
A totally new field introduced in this second edition is the subject of quality assurance. Until the late 1970s this activity, in a formalised sense, was pursued in only a few industries, notably for defence and nuclear power applications. However, since then the potential benefits of formalised quality systems have been recognised in an increasingly large number of industries. The treatment in this book is elementary but sufficient to point out the implications of this trend to the individual designer inasmuch as it affects the approach to welded products.

Comments made to the author by people for whom the first edition was written confirmed that its scope was appropriate; the changes incorporated in this second edition should ensure its continued relevance to their work.

1987 J. G. Hicks

Acknowledgements

This book, in common with many other textbooks, represents the experience of the author in interpreting the engineering knowledge and data relevant to the activity of designing welded joints. In preparing the book the author has received valuable guidance and assistance from a number of organisations and individuals. Acknowledgement is made to the British Standards Institution upon whose standard specifications some of the weld symbols and preparations are based; to GKN Lincoln Electric Limited for illustrations of welding equipment; and to The Welding Institute for various illustrations. Personal thanks are offered to Mr R. P. Newman, until his retirement Education Executive, and Mr L. M. Gourd, Manager, Training Services at The Welding Institute. The late Dr A. A. Smith gave extensive guidance on the chapter dealing with welding processes in the first edition; a measure of his contribution is that Mr J. C. Needham, Chief Control Engineer at The Welding Institute has confirmed that at the level at which this book is directed in this area no changes to the text are necessary in this second edition.



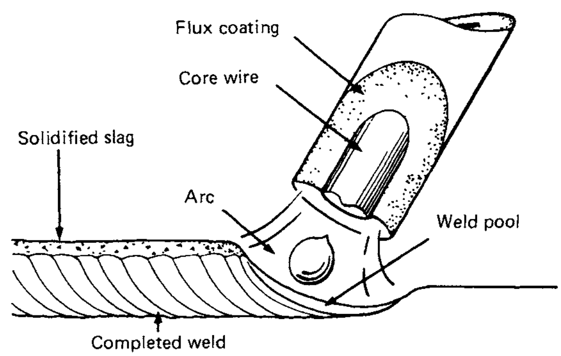
CHAPTER 1

Arc Welding Processes

Most steel welding is done with one of three processes which are briefly described here.

Manual Metal Arc

This is colloquially known as stick electrode welding or even just stick welding. The welder uses a stick or rod, which is a metal electrode with a fusible mineral coating, in a holder connected to an electrical supply. An arc is struck between the electrode and the work piece which completes the return circuit to the electricity supply which may be AC or DC depending on the type of electrode and the welding technique being used. The arc melts both the electrode and a superficial area of the work piece.



Electromagnetic forces created in the arc help to throw drops of the molten electrode on to the molten area of the work piece where the two metals fuse to form the weld pool. The electrode coating, or flux, contributes to the content of the weld pool by direct addition of metal and by metallurgical reac-

Manual metal arc welding of pipework. The simplicity of the equipment can be seen. Note also the earth lead clamped to a flange behind the welder and the bevel preparation on the end of the pipe ready for the next joint. The welder wears stout leather gloves to protect his hands and arms from ultra-violet radiation, heat and weld spatter. A mask protects his face and neck and holds a dark glass screen which filters out the intense ultra-violet radiation but allows him to see the arc and weld pool.
Photograph by courtesy of GKN Lincoln Electric Ltd.

tions which cleanse and refine the molten metal before it solidifies into the weld bead. The flux coating also generates a local gaseous atmosphere which contributes to the stability of the arc and prevents absorption of atmospheric gases by the weld metal.

Electrodes for manual metal arc welding are made with core wire diameters from 2 mm to 10 mm although the range generally used is from 2.5 to 6 mm in lengths of between 200 and 450 mm.

There are many types of electrodes. The main differences between them are in the flux coating. There are three principal groups of electrode for carbon and carbon-manganese steels used in most conventional fabrications.

Rutile electrodes have a high proportion of titanium oxide in the flux coating. They are relatively easy to use and might be termed general-purpose electrodes for applications which do not require strict control of mechanical properties. The steels on which they are used should have good weldability (see Chapter 2).

Basic electrodes have a coating which contains calcium and other carbonates and fluorspar. They are more difficult to use than the rutile electrodes but can produce welds with better strength and notch toughness. If they are dried in a properly controlled manner they produce welds with low amounts of hydrogen and can be used to weld the more *hardenable* steels without the risk of cracking (see Chapter 2).

Cellulosic electrodes have a high proportion of combustible organic materials in their coating. The arc produced by this type of electrode is very penetrating and is often used for the root runs in pipeline welding and occasionally in structural work. The high quantities of hydrogen which are released from the coating require that precautions be taken to prevent cracking in the steel after welding.

Both the rutile and the basic electrodes can have iron powder added to the coating. This improves productivity by producing more weld metal for the same size of core wire and hence the same welding current. The larger weld pool which is created means that the iron powder electrodes cannot be so readily used in all positions as the plain electrode.

Submerged Arc

This welding process uses a bare wire electrode and a flux added separately in the form of granules or powder over the arc and weld pool.

The flux has four principal functions:

(*a*) To protect the molten metal by forming a protective slag layer.
(*b*) To stabilise the arc.
(*c*) To cleanse the molten metal, particularly when there is rust on the surface.
(*d*) To control the composition of the weld metal.

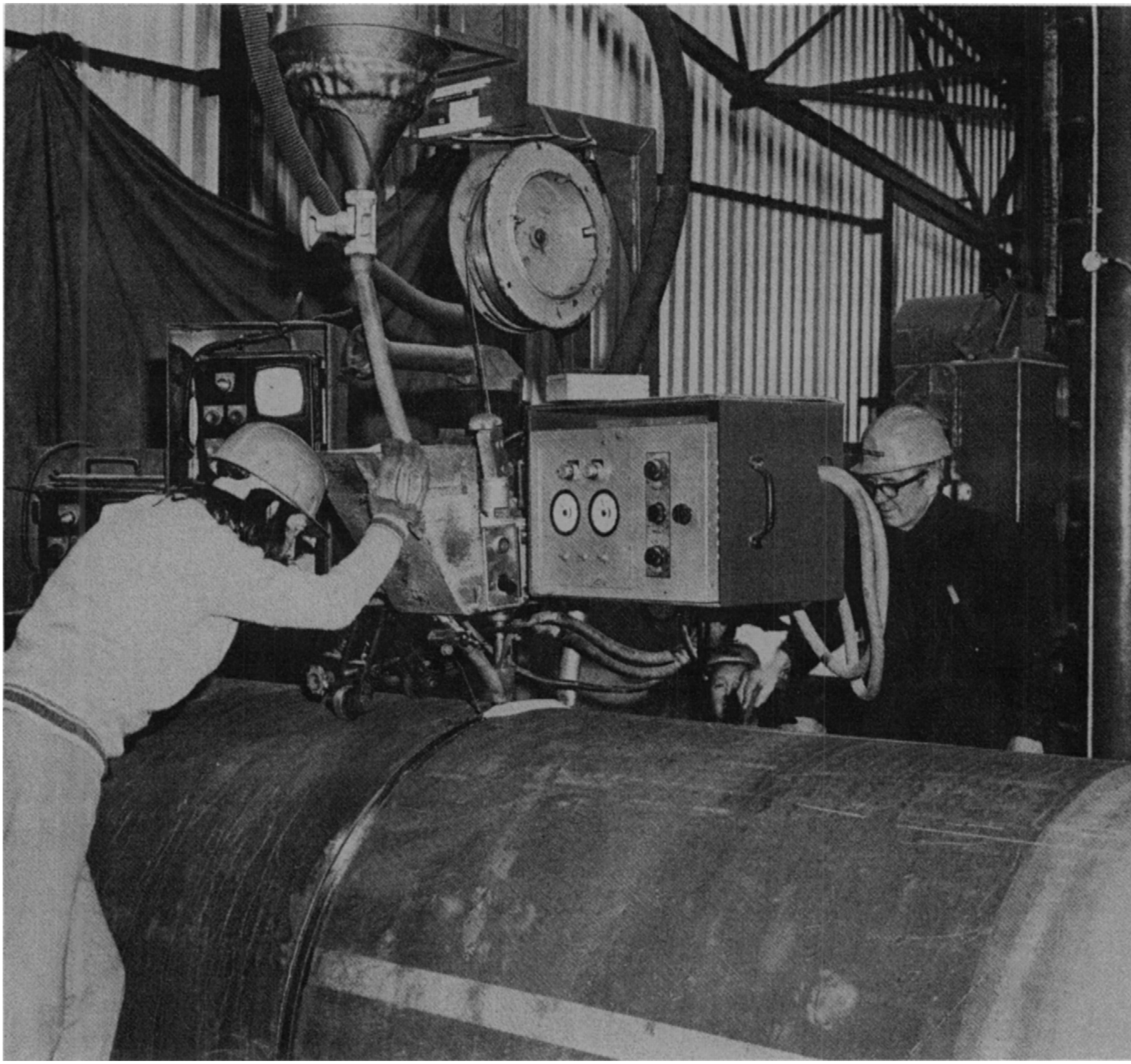
Fluxes can be classified by their method of manufacture and their chemical characteristics. Flux may be made by melting the constituents together and then grinding the solidified mix when it has cooled, by bonding the constituents together, or by simply mixing the component minerals.

The chemical characteristics range from the acid types, containing manganese or calcium silicates together with silica, to the basic types again containing calcium silicate, but with a lower proportion of silica than the acid types.

The acid fluxes are used for general-purpose welding, whereas the basic fluxes are used for welds requiring control of fracture toughness and, for steels of high hardenability, to prevent cracking. The electrode wire is usually of a 0.1 per cent carbon steel with a manganese content of between 0.5 and 2 per cent and with a relatively low silicon content (0.2 per cent).

The arc is completely enclosed, and high current can be used without the risk of air entrainment or severe spatter. A high current gives the weld pool a deep penetration into the parent metal and thicker sections can be welded without edge preparation than with manual metal arc welding.

The process is used mainly in a mechanised system feeding a continuous length of electrode from a coil on a tractor unit, which carries the welding head along the joint. Alternatively, the welding head may be fixed and the job traversed or rotated under it. A welding head may feed several wires, one behind the other, so that in effect a multi-run weld can be made in one pass. AC or DC can be used in submerged arc welding, and with a multi-head unit DC and AC may be used with the different wires – DC on the leading wire to give deep penetration and AC on the other wires to provide a high weld metal deposition rate. Welding currents of up to 1000A per wire can be used, but where mechanical properties are to be controlled a weld can be made with a number of small runs. Manually operated versions of the submerged arc welding



A 39mm thick, 2.3 m diameter steel tube, part of an oil production platform for BP's North Sea Forties Field, being welded by a submerged arc welding installation at the Graythorp, Hartlepool, works of Laing Pipelines Offshore.

Note that the operator needs only normal industrial clothing, the arc is screened by the flux.

Some 43 km of welding holds together the 25,000 tonnes of steel tube that makes up the platform and flotation raft. The platform stands in 122 m of water in the North Sea.

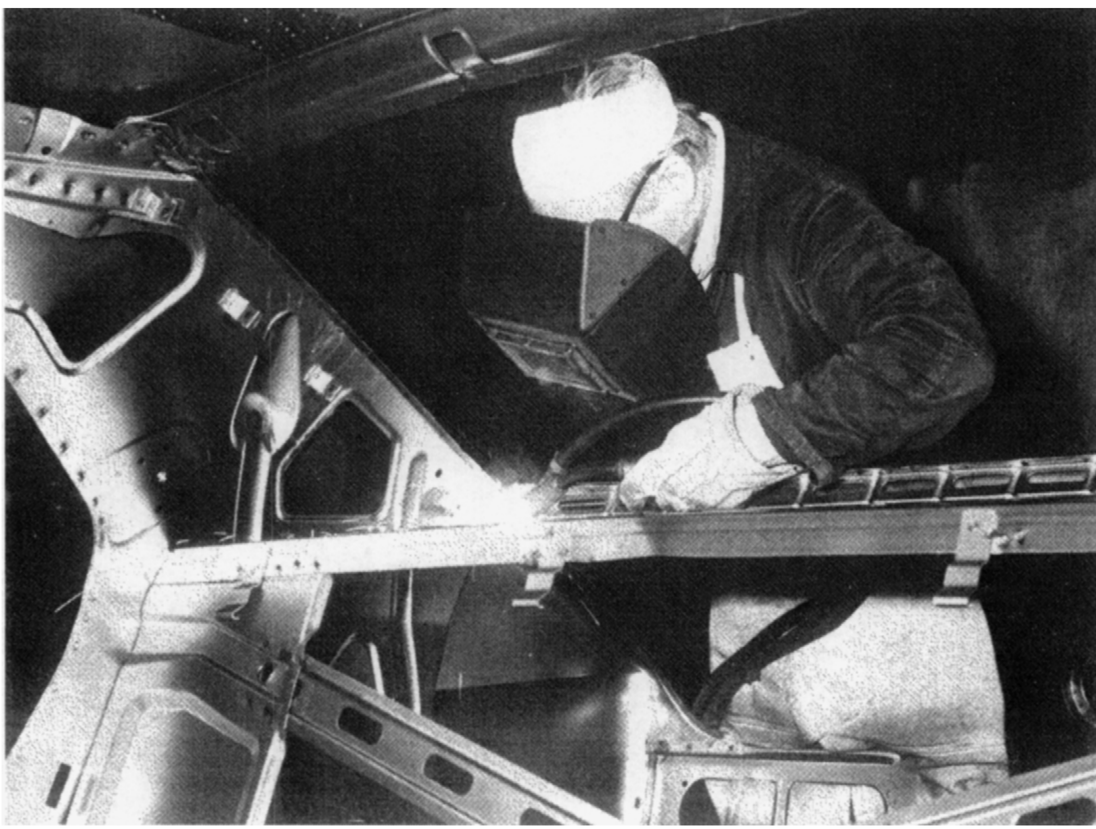
Photograph by courtesy of GKN Lincoln Electric Ltd.

process are used in which current levels are limited to about 400A.

As a mechanical process, submerged arc welding is capable of greater consistency and productivity than manual welding, although to balance this the process is not suitable for areas of difficult access and multiposition work *in situ*. Because the wire and flux are separate, the welding engineer can choose a combination which will give the required weld metal properties and can exercise further control with the heat input and welding speed.

Gas Shielded Welding

In this process a bare wire electrode is used, and a shielding gas is fed around the arc and weld pool. This gas prevents contamination of the electrode and weld pool by air, and provides a local atmosphere giving a stable arc. The process is known as MIG (metal inert gas) when argon or helium gases are used – generally for non-ferrous metals such as aluminium, titanium, and nickel alloys. For carbon and carbon manganese steels, the gas commonly



Welding a vehicle body with the gas shielded welding process. The welder wears leather gloves and a leather apron to protect him from heat and spatter and looks at the weld through a mask with a dark glass screen. The tube coming away from the welding gun above the welder's hand is extracting the fumes produced at the point of welding.
Photograph by courtesy of GKN Lincoln Electric Ltd.

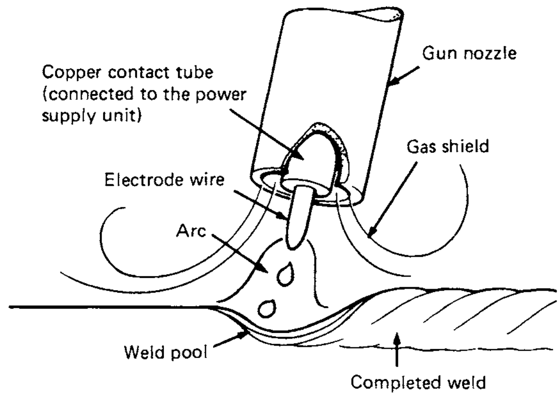
employed is carbon dioxide (CO_2) or a mixture of argon and carbon dioxide, and the process is then called MAG (metal active gas).

The welding wire contains about 1 per cent manganese and 1 per cent silicon, de-oxidising elements which combine readily with the 'active' oxygen part of the shielding gas and protect the molten steel from chemical reactions which would cause porosity in the weld. At present the process operates only on DC, although it has been shown that AC can be used and this mode may be developed in the future.

The range of currents covers that of both the manual metal arc process and the lower ranges of the submerged arc welding process. The electrode is fed from a coil to a welding head or gun which may be hand held or mounted on a mechanised system. The electrode wire may be a solid wire or may contain a flux core which affords further control of the weld metal properties and expands the range of applications of the process. The necessity for providing gas and wire feed conduits (and for high current work, cooling water hoses) makes the process less flexible in its manual form than the manual metal arc systems, although it is used satisfactorily on some construction sites. The gas-shielded solid wire process has benefits in production line welding as it leaves virtually no slag on the weld surface and is relatively clean.

The MIG/MAG process can operate in two modes – at low currents the transfer of metal from electrode to weld pool takes place after short circuits caused by the electrode actually touching the weld pool, intermittently. At high currents the transfer is by a stream of droplets propelled across the arc. The low current or dip transfer mode is used for sheet metal work, root runs and for positional work whereas the high current or spray transfer mode is used for downhand filling passes in thicker plate. A wider control of metal transfer characteristics can be achieved by pulsing the welding current using a special power source. This permits, amongst other things, a wider range of conditions for positional welding but cannot be used with CO_2 as a shielding gas. It is, therefore, restricted in practice to welding with argon or argon–CO_2–oxygen mixtures as the shielding gas.

Another variant of the MIG/MAG process employs a wire which has a core with constituents which give off CO_2 when heated in the arc. No separate shielding gas supply is then needed, and



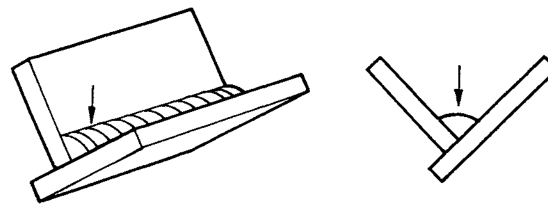
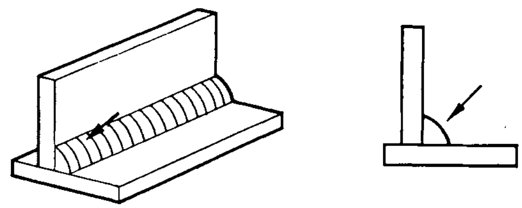
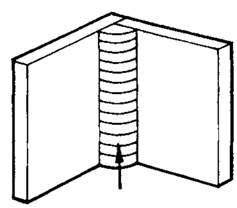
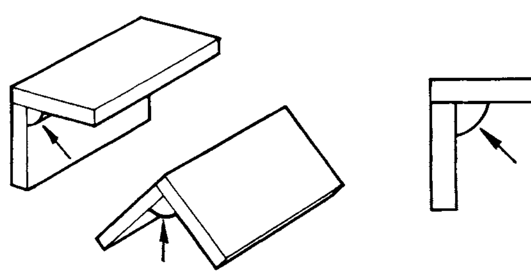
the gun can be lighter in construction and less restrictive on access than the conventional gun.

For thin sheet work and precision welding of components to close tolerances. TIG (Tungsten Inert Gas) welding can be used. This process employs inert argon or helium gas to protect the weld pool and the arc is struck between the work and a non-consumable tungsten electrode.

Filler can be added to the joint, although most applications employ joint designs not requiring filler (autogenous welds). AC is usually used for aluminium alloys and DC for ferrous metals.

Welding in Practice

Welds can be made in all positions and with few or many passes. Welding positions are defined according to standard nomenclatures.
Note. In the figure it is the position of the joint which is described, not that of the welder!

B.S. 499 Definition	A.W.S. No.	
Flat position	1	
Horizontal–vertical position	2	
Vertical position	3	
Overhead position	4	

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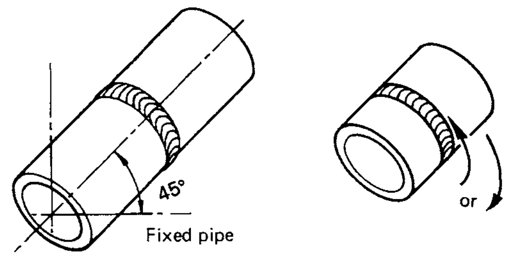
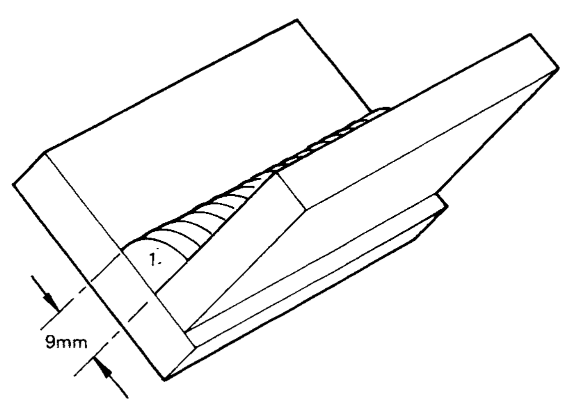
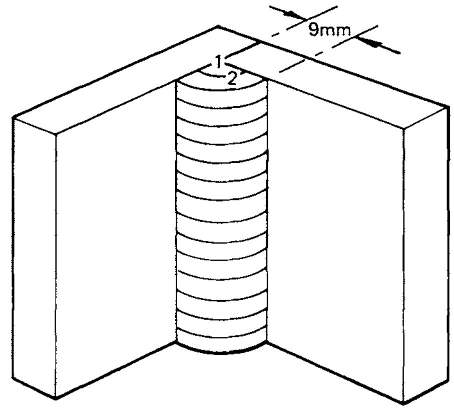


The limits of intermediate positions are given in the relevant Standard, e.g. B.S. 499: Part 1: 1983. A.W.S. D1. 111–86. The rate at which weld metal can be placed and, therefore, the speed of welding depends on the current drawn. The size of the weld pool, the arc forces, and the heat dissipated place a top limit on the current at which a welder can produce a consistently sound weld; a practical maximum amperage for manual work in the flat position is about 400A. The mechanical properties of the welded joint are influenced by the heat input and can place a limit on the current and therefore the size of the weld bead.

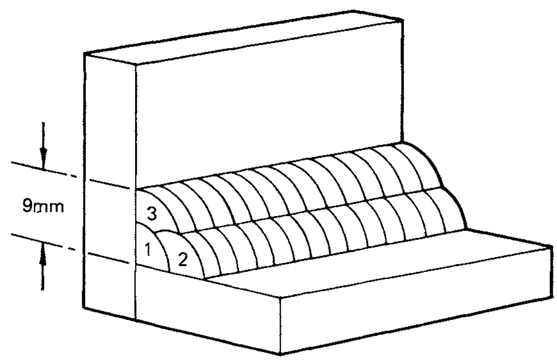
Welding in the flat position allows a greater rate of weld metal deposition than the other positions, in which the maximum size of weld run is limited by the tendency of the molten weld metal to run out of the joint. In these positions the weld may have to be built up by depositing a number of smaller runs. *For example* with a 9 mm leg length weld made with manual metal arc rutile or basic coated electrodes:

Flat position – one run

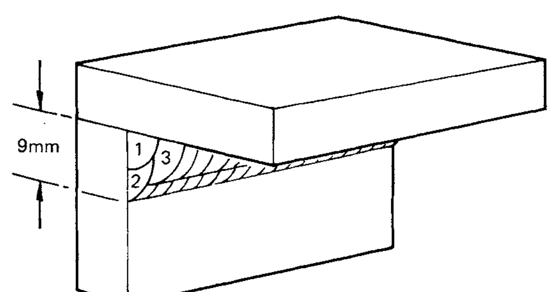




Vertical position – two runs



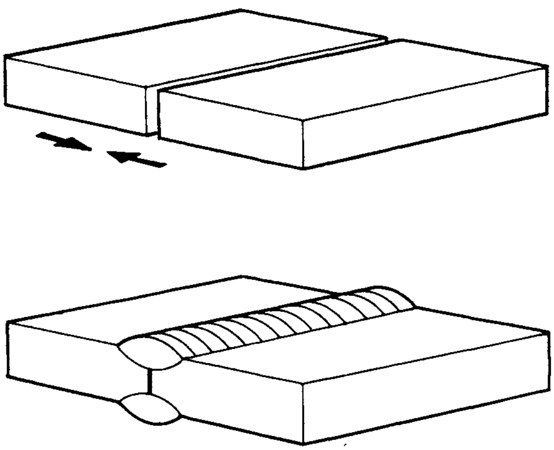
Horizontal–vertical position – three runs

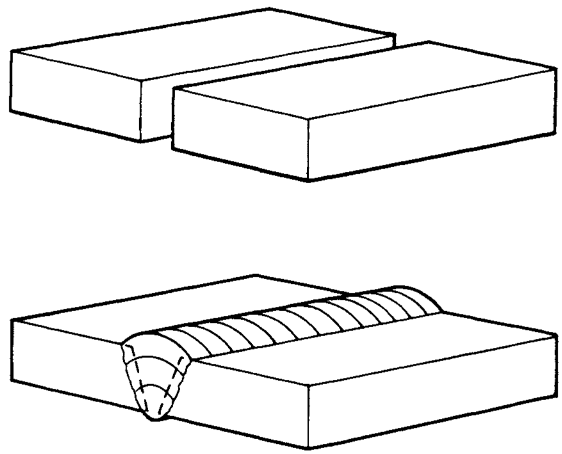


Overhead position – three runs

This limitation on operating current also affects the depth of penetration into the parent plate. If two plates with square edges are butted together without a gap (a *close square butt joint*) and one run is deposited on each side, the centre of the joint will be unfused in thicknesses greater than about 3 mm.

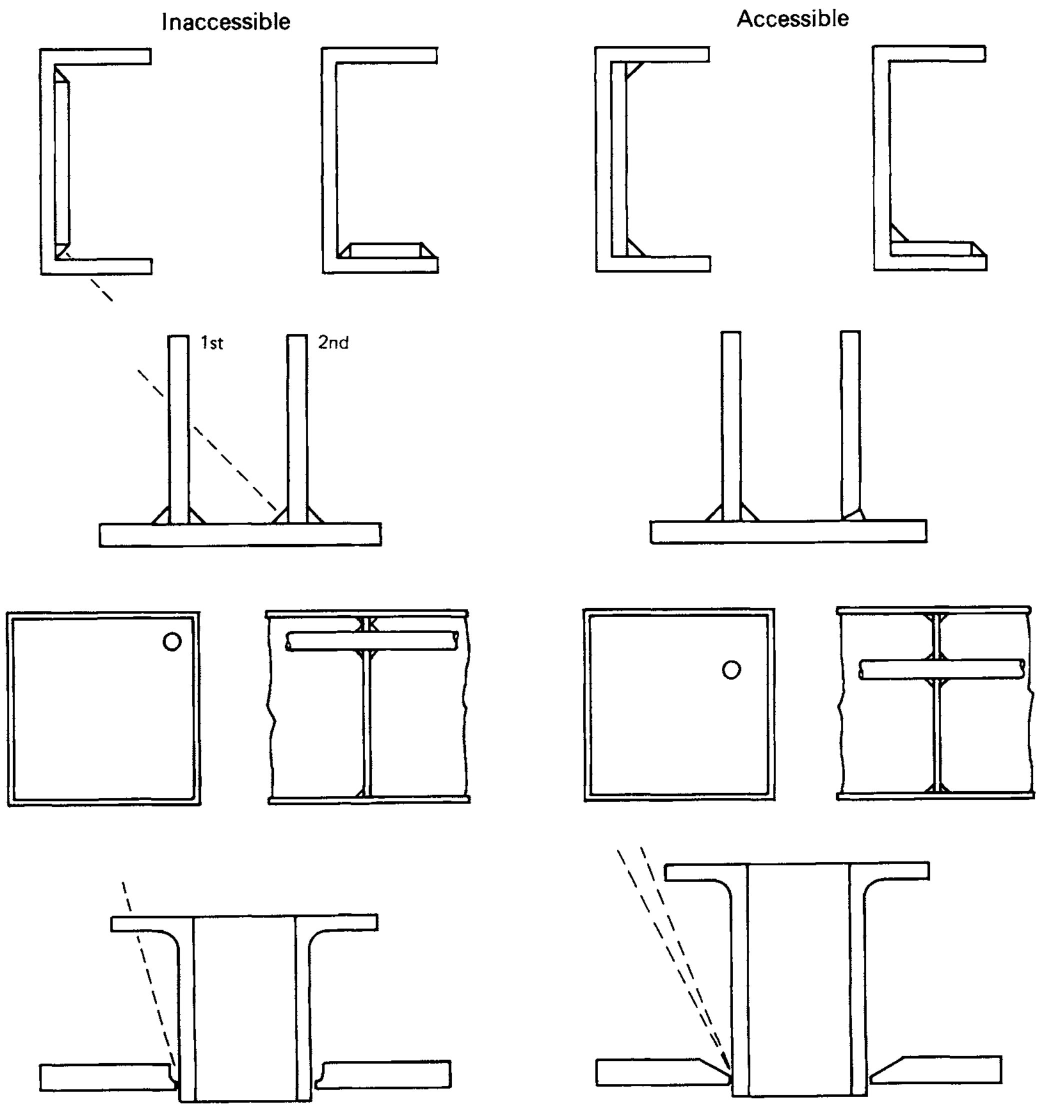
Full joint penetration is made possible by leaving a gap between the abutting edges (*open square butt joint*). The gap should be about half the plate thicknesses. Above 6 mm thickness the gap becomes impracticable and instead the edges are bevelled. The vee so formed is then filled by depositing a number of runs. The shape and dimensions of the prepared edges will depend on a number of factors which are discussed in Chapter 5.





Access

All welding operations require space in which to operate the equipment, whether it be manual or mechanised. In addition, for manual operations at least, the welder must be able to see the joint he is making, so there needs to be space for his head and a face mask as well as the hand held rod or gun. The arc must be capable of being struck on the faces to be fused so that there has to be clear space over a sector around the joint corresponding to the gun or electrode angle. Some examples of inaccessible details together with suitable redesigns will illustrate the restraints on joint design arising from access requirements.



CHAPTER 2

Steels and their Weldability

Chemical Composition

The commonly used mild and high yield strength steels consist of iron, carbon and manganese with some additional alloying elements such as nickel, chromium and vanadium. They may also contain such elements as copper which come from scrap steel used in some steelmaking plants. Iron ore contains sulphur and phosphorus which also show up in the final product. A typical structural steel might have the following composition:

	C	Mn	Si	Ni	Cr
% wt	0.16	1.6	0.3	0.2	0.1

	V	Cu	S	P
% wt	0.05	0.1	0.003	0.005

So steel is 98 per cent iron and it is only the odd 2 per cent of other elements which give it strength and which can also create problems for the fabricator.

The Effects of Welding on Steel

The welding arc is a very concentrated source of heat and, although it melts only a small amount of metal in its passage, it creates quite extensive changes in the nature of the steel in and adjacent to the weld. Provided that the welding is properly planned and conducted, the resulting joint will be sound. If such attention is not given, it is possible that defects will be produced in the weld and some of the more common ones will be described here.

Weld Defects

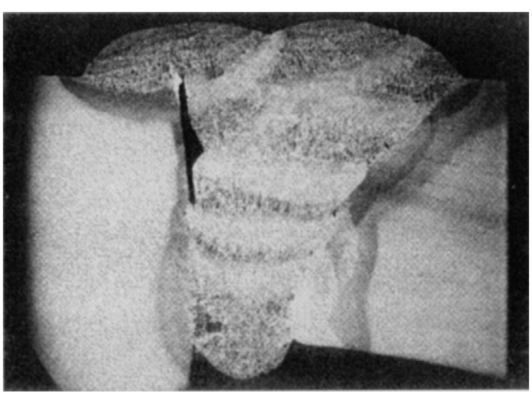
The designer should not be deceived into believing that weld defects are inevitable, but materials by their nature are inhomogeneous, and indeed metals derive their strength from being full of defects in the form of discontinuities on a microscopic or even atomic level. In the engineering sense a discontinuity is a defect when it is considered to be potentially damaging to the integrity of the component, or even if it represents a standard of manufacture which is below that achievable by competent workmanship.

Weld defects may be broadly divided into two groups labelled as:

(*a*) operator-induced defects, that is to say, defects introduced by incorrect working or lack of skill. or

(*b*) metallurgical defects which are a result of incorrect selection of materials or welding procedure.

Operator-induced defects are generally confined to lack of penetration and lack of fusion although the more cosmetic but still important root bead and weld face shape are under the control of the welder. Such defects can be more difficult to avoid if the design prevents good access for welding or if irrationally established dimensional tolerances give rise to poor fit between parts.



Welded joint with gross lack of sidewall fusion, note also the mismatch at the bottom of the joint.
Photograph by courtesy of the Welding Institute

The metallurgical defects generally occur during the cooling-down phase of the weld thermal cycle. They can occur in the weld metal, that is, the metal which has been molten at some stage in the process, or in the parent metal which has remained solid throughout, albeit quite hot. The most likely weld metal defect is hot cracking, also called solidification cracking. This happens as the metal is cooling from liquid to solid, when non-metallic substances such as sulphides in the weld metal freeze at lower temperatures than the metal and remain liquid whilst the steel becomes hard. This liquid takes the form of thin films between the grains of steel and forms a plane of weakness which under the stress of cooling down is pulled apart to be seen as cracks.

A similar phenomenon can occur in the parent metal where the non-metallic inclusions in the steel can melt whilst the steel is solid and produce cracks in the same way except that they are known as liquation cracks. These types of cracks are less common than they used to be due to the advances in steelmaking technology which reduces the amount of sulphides in the steel below that which existed a few years ago.

Probably the other most common type of crack is the hydrogen-induced crack in the heat-affected zone of the parent metal or in the weld metal.

The welding arc is a very concentrated source of heat, and it melts only a small volume of metal in its passage. This line of hot metal loses its heat to the rest of the metal; the rate at which the hot metal cools down depends on the temperature difference between the locally heated metal and the bulk of the metal.

If the rate of cooling is high, the metal is quenched and hardened in the same way that steel cutting edges may be hardened by heating and then plunging them into oil or water. If the rate of cooling is low, then the metal may not be hardened very much at all. This quenching produces the heat affected zone (H.A.Z.). The hardness which is produced by a certain cooling rate or *quench severity* depends on the *hardenability* of the steel which, in simple terms, is a function of the chemical composition.

Carbon is the principal element affecting hardenability; a low carbon content, say 0.10 per cent, will give a low hardenability, whereas a high carbon content, say 0.4 per cent, will give higher hardenability. Carbon is not the only hardening constituent; manganese (Mn) is effective as are other elements such as nickel (Ni), vanadium (V), or chromium (Cr). For practical purposes, the hardening effect of each of these elements is expressed in terms of the amount of carbon which would give the same effect.

The sum of all these effects is called the carbon equivalent (Ceq), and this can be calculated from very simple formulae, one form of which is:

$$Ceq = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}$$

If the quantities of the various elements are given in percentage weights, the Ceq is a percentage. Typical values for a mild steel would be:

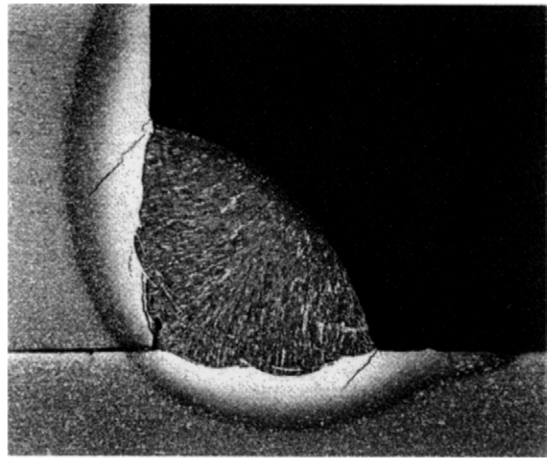
	% wt	Ceq
C	0.13	0.13
Mn	1.2	0.20
Ni	0.06	0.004
V	0.1	0.02
Cr	0.03	0.006
		0.36

The cooling rate is affected by the following:

(*a*) The heat sink – this depends on the thickness and number of parts meeting at the joint.

(*b*) The heat input from the welding process.

(*c*) The temperature of the metal away from the weld before and during welding.



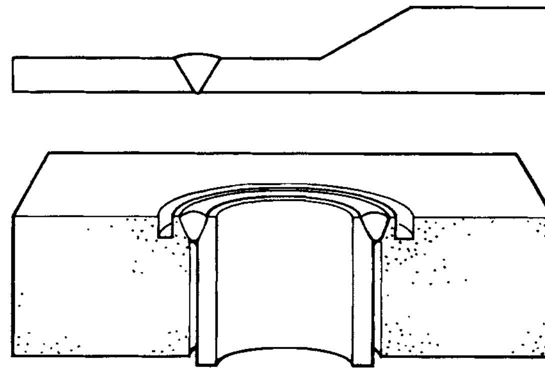
Hydrogen cracking in a fillet welded joint.
Photograph by courtesy of the Welding Institute

Now why should the local hardness of the metal be important? Carbon and carbon-manganese steels can absorb hydrogen, and provided that the steels are fairly soft this has no effect; but when the steel is hardened it cannot so easily accommodate the hydrogen and high internal stresses are set up which can cause cracks.

Hydrogen can come into the steel from a number of sources during welding. Water, oil, grease and paint on the steel surface will produce quantities of hydrogen on heating in an arc. The welding fluxes may also generate hydrogen. Naturally, cracks are undesirable in any structure and the welding technique has to be worked out to prevent their happening.

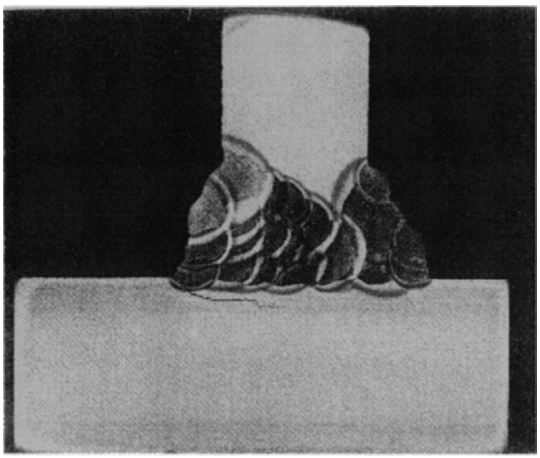
There are several ways in which hydrogen cracking can be prevented and as many reasons for the suitability: see the table below.

In most steel fabrication work methods 1, 2 and 3 are commonly used. Method 4 would be used for large components or for alloy steels of high hardenability following a preheat sequence. In marginal cases the joint can be covered with blankets to maintain the heat put in by welding and this provides a self-contained post heat. The designer can help to reduce fabrication costs in this area by not specifying unnecessarily high strength steels and by ensuring that steel thicknesses are not greater than required for the purpose. Local thinning of metal is sometimes adopted, as is the introduction of grooves to reduce the available heat path.



Method	Technique	Practical Implications
1. Limit the amount of hydrogen	Ensure cleanliness of steel before welding and use *low hydrogen* processes, e.g. MIG/MAG low hydrogen MMA electrodes, basic submerged arc fluxes.	Requires clean, dry conditions, electrode drying ovens. MIG/MAG may not be suitable or available. Submerged arc not necessarily suitable.
2. Control Carbon Equivalent	Steelmaker limits steel composition.	More expensive steel, difficult to maintain strength in thicker steel, i.e. thicker than 75 mm.
3. Reduce cooling rate	(*a*) employ high welding currents or slow welding speeds to increase rate of heat input to joint and so reduce cooling rate. (*b*) Heat steel before welding, i.e. preheat. (*c*) Optimise steel thickness in design.	Restricts positional welding. Low speeds increase costs. Low productivity. Unable to achieve high notch ductility in weld metal. Requires time, energy consumption, manpower and equipment.
4. Eliminate hydrogen *after* welding	Do not let job cool down after welding and keep hot for one or two hours after welding – *post heat*. This releases some hydrogen.	Delays completion of job, requires energy, manpower and equipment.

Two other features influence the risk of hydrogen cracking: the first is the rigidity of the joint which can restrain the material from expanding and contracting, and increases local stresses; the second is the fit up in fillet welded joints, there being a tendency for poor fits to encourage hydrogen cracking.

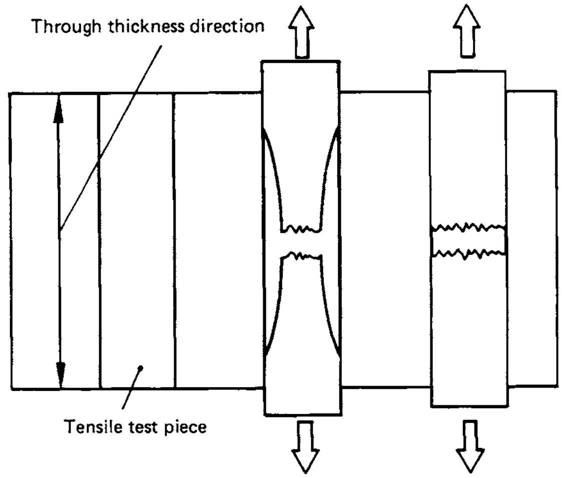


Lamellar tearing in a T joint
Photograph by courtesy of the Welding Institute

A second form of cracking is lamellar tearing, which can occur beneath welds in rolled steel plate fabrications. This is caused by:
(*a*) Low ductility in the 'through thickness' direction, also known as the 'short transverse' direction.
(*b*) High joint restraint.

The main reason for low through thickness ductility is the inclusion content of the plate. All common structural steels contain large numbers of inclusions which consist of non-metallic substances produced in the steelmaking process. They are formed as spheres, films, or small angular particles in the ingot as it cools down after being cast from the molten steel.

When the ingot is rolled to make steel plate the inclusions deform into plates or discs parallel to the plate surface. Different types of inclusions deform in different ways and break up during rolling.

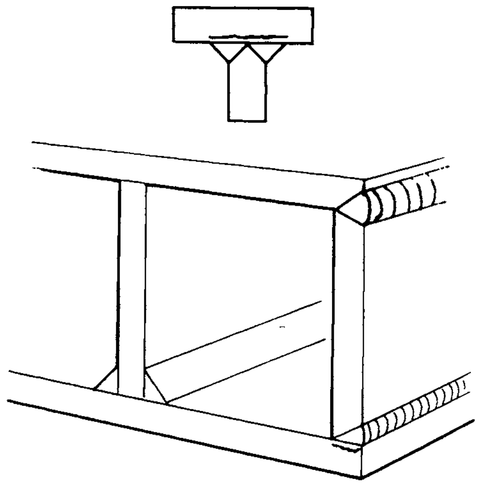


It is the form, distribution and density of the inclusions in a rolled plate which leads to varying ductility in the through thickness direction, and only a small percentage of steel plates is susceptible to tearing. Only a small number of these susceptible plates are incorporated into the critical joints and structures which satisfy the other two conditions which encourage lamellar tearing. Certain steelmaking techniques produce steels of such cleanness that the through thickness ductility is high and the susceptibility to lamellar tearing is low. Such steels are sold under various trade names and specifications but do, of course, tend to cost more than steels made to less demanding specifications.

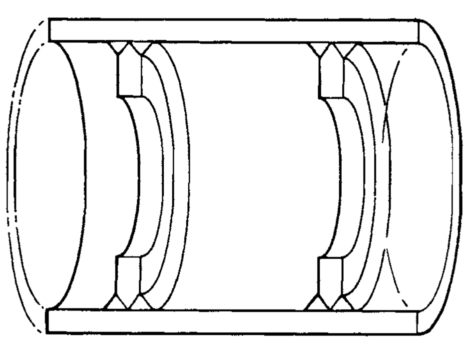
Restraint is defined as the resistance to contraction and expansion in a joint or structure by reason of its configuration. Welding causes local thermal expansion and contraction which will set up high stresses in a restrained situation. If these are at right angles to the surface of a susceptible plate the risk of lamellar tearing will be high.

The assembly and welding sequence can sometimes be planned to minimise the restraint at various stages of fabrication.

Corner joints are common in box sections and the intermediate plate occurs in some more complex



structures. Lamellar tearing risks in these types of joints can be reduced by modifying the details so that the stresses are spread across the plate section rather than being reacted on the surface. This technique is widely used but it is not without disadvantages. A large angle giving the minimum lamellar tearing risk requires more weld metal to fill than the small angle in which the tearing risk is higher. A compromise has to be reached and this can really only be made by the fabricator on the basis of experience. Both hydrogen cracking and lamellar tearing are basically avoided by decisions regarding steel composition and welding procedure. The designer can, however, make the fabricator's task easier by bearing the foregoing explanations in mind. Other types of restrained joints in which lamellar tearing has occurred include:



(*a*) Ring stiffeners or diaphragms in tubular structures.

(*b*) Penetrations in webs or pressure vessels.

Lamellar tearing can be a problem in joints of low restraint if the material is sufficiently susceptible, i.e. if it has a low through thickness ductility. For this reason items such as lifting lugs welded on to plates and stressing the plate in the through thickness direction should receive special attention either by thorough inspection after fabrication or by the specification of plate of a guaranteed minimum through thickness ductility. Joint design can influence the risk of lamellar tearing by the way in which it exposes a plate to welding stresses in the through thickness direction. Full penetration T joints, either single sided or double sided, tend to give a higher risk of lamellar tearing than T joints made with twin fillet welds. The cruciform joint is a more severe form of the T joint since the susceptible plate is restrained against bending in the region of the weld.

CHAPTER 3

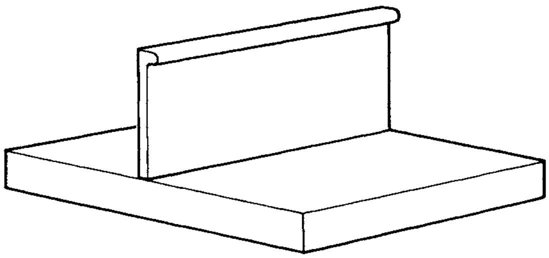
Distortion and Residual Stresses

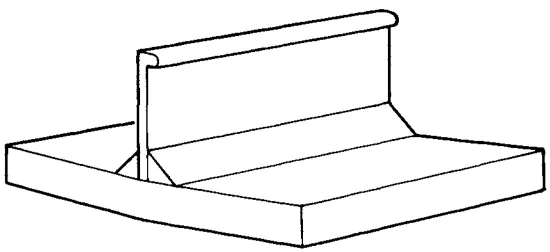
Engineers are used to working to tolerances. These are allowances for the fact that it is impossible to produce items to exactly the size and shape required, or to produce a number of items which are exact copies of each other. Components which fall outside the established tolerances can cause a number of problems. They may not fit into mating parts, they may cause misalignment in machinery, and they may cause a structure to have a strength lower than the design strength. We can make allowances in some cases by performing certain operations after assembly, for example line reaming of shaft-bearing housings. There are some circumstances in which we can take no action - a large column or a shaft which is not within the specified straightness tolerances cannot readily be straightened, so the job must be done within the tolerance allowed from the outset.

The intense heat of the welding arc and the molten steel which is deposited both conspire to distort the welded fabrication by thermal expansion and contraction. We know of course that thermal expansion and contraction do not always create distortion. If an object is heated uniformly it expands uniformly and increases in size and then contracts again on cooling. This feature has been used for centuries in engineering for obtaining tight fits; metal tyres for wooden wheels are an early example. Conversely, when we want to remove a tight-fitting flywheel from a shaft we can heat it up so that it expands and releases its grip.

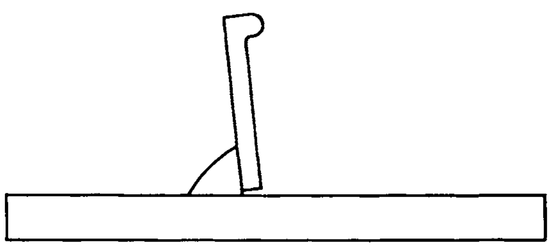
The welding arc moves along the joint, both heating the metal and depositing more molten metal. If this is done on one side of a plate - for example when welding a stiffener to a web or a ship's frame to the plating - the plate will bend.

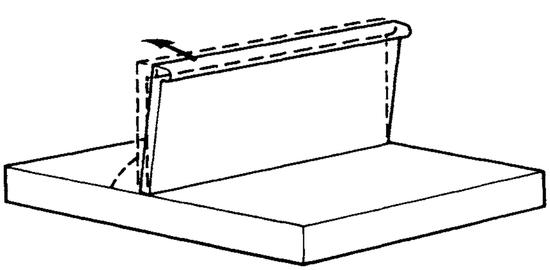
There are really two effects here; firstly the heating and cooling of the plate surface, and secondly the contraction of the hot filler metal. If a





one-sided fillet weld is used the stiffener will end up out of square because it will have been pulled over by the contraction of the weld metal on cooling. This effect can be allowed for by presetting the stiffener

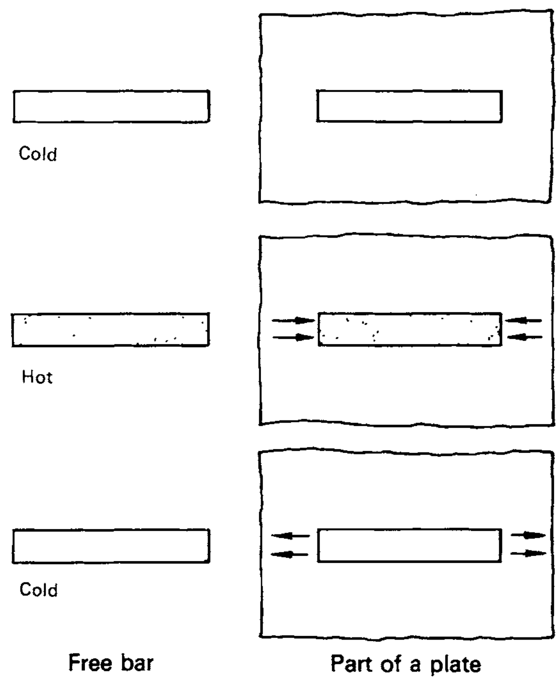




and allowing it to be pulled into its correct position, but this will still leave distortion in the plate.

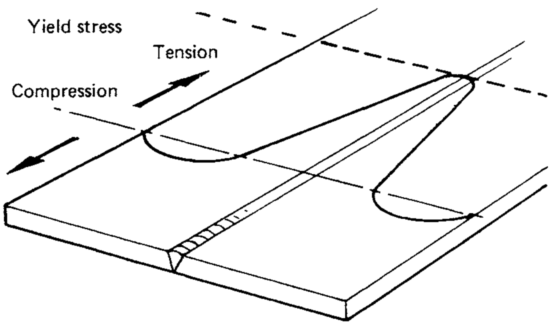
It is very difficult to predict and therefore prevent distortion. The degree of distortion depends on the weld heat input, the welding travel speed, the number of runs and also on the residual stresses which may be in steel plate and rolled sections.

Heating only part of a metal object may cause internal stresses. The hot area wants to expand but is restrained by the surrounding cool metal. The diagram shows the difference between the behaviour of a free bar of metal and part of a large plate. Both pieces are unstressed when cold. When they are hot the free bar is longer and is still stress free, but the hot part of the plate is prevented from expanding by the surrounding plate. The result is that compressive stress is set up in the hot metal.



Now steels have a much lower yield stress when they are hot than when they are cold and can then easily be deformed or squashed. The hot area in the plate yields under the effect of the compressive stress with the result that when it cools down it tries to contract and goes into tension but at the lower temperature the yield stress is so much higher that the tensile stress remains in the plate.

A similar effect occurs in welded joints in which there is, after welding, a tensile stress along the



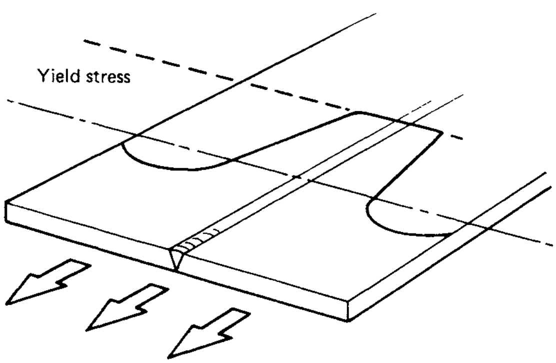
weld and, to a lesser extent, across it. Such stress is called residual stress and generally has little effect on the strength of the welded component. In fact a small part of the joint is at a stress equal to the yield stress before any external load is applied; when the external load is added it causes this part of the joint to yield. It is, of course, still capable of carrying the load because the amount of yielding is limited to the elastic strain of the surrounding steel; on removing the load the peak residual stress level will have been found to have been reduced.

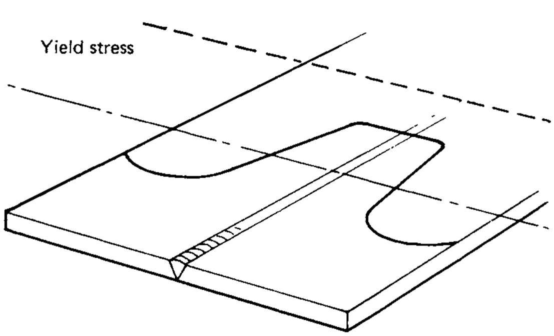
Residual stresses are sometimes undesirable. Two examples of this are where they enhance the risk of brittle fracture (see Chapter 9) and where they can facilitate certain types of corrosion. In these situations the residual stresses are reduced by heating the welded steel components in an oven to a low red heat (about 600°C). At this temperature the yield stress is very low and the residual stress pattern relaxes so that the peak residual stress is less than a quarter of its initial level. The heating and cooling rates during this *thermal stress relief* must be carefully controlled otherwise further residual stress patterns may be set up in the component. There is a practical limit to the size of a structure which can be thermally stress relieved both because of the size of the ovens required and because of the risk of the structure distorting under its own weight when it is in a low strength condition.

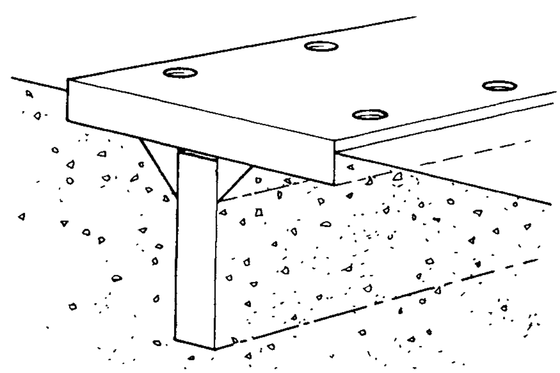
Individual joints in a large structure can be heat treated by placing specially tailored ovens around the joints or by using electrically heated elements in contact with the steel.

Two examples will illustrate the effects of distortion and will also show how the designer can help to minimise distortion and its effects.

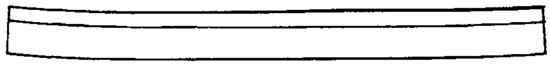
A beam for supporting a heavy machine must provide support at a constant level. The T section is welded up but some distortion is bound to occur to the top of the flange must be machined. However the removal of metal, which is in compression due



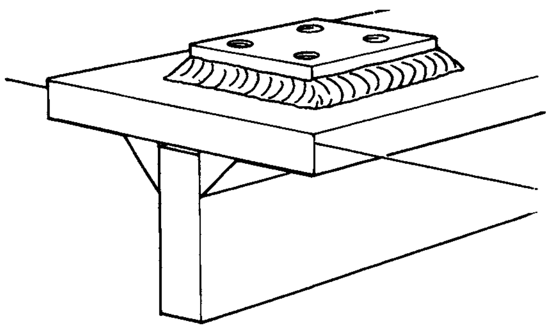




to the stresses set up by welding, makes the distortion worse – the diagram illustrates this. There

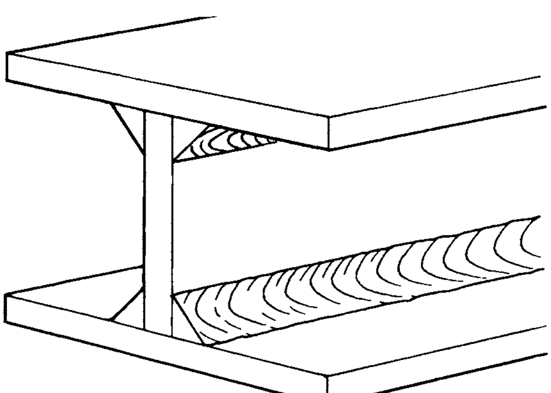


are two ways of easing this situation. One is to thermally stress relieve the beam before machining. The machining operation then causes no further distortion. The second way is to accept that distortion will occur during welding and, to avoid machining the cross section of the T, local pads are welded to the base. These pads can be machined –

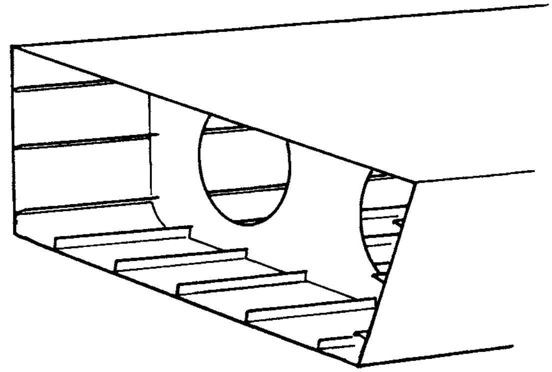


now a much shorter operation because of the reduced area and no metal is taken off the flange to unbalance the stress system.

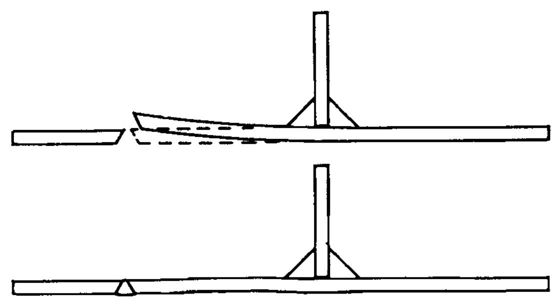
Note that the use of a symmetrical beam section would prevent much of the distortion. The welding sequence can be planned to keep distortion under control and the section is much stiffer so that the machining operation causes far less distortion.



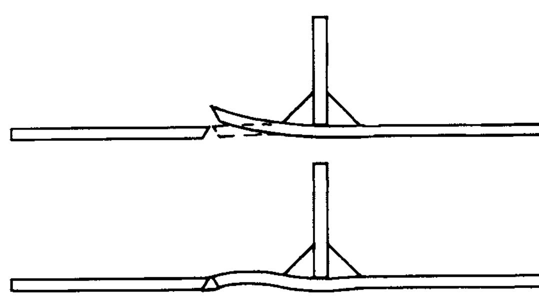
A box girder is to be made from sections to be welded together on site. Diaphragms are welded



into the box; these may cause some distortion, particularly to the free edge of the box which then has to be welded to its neighbour. Now if the diaghragm is well away from the free edge the flexibility of the plate will allow it to be pulled into place and welded to give a fairly smooth box contour.



If the diaphragm is close to the free edge it is more difficult to deal with. It may even result in a permanent kink in the box panels.

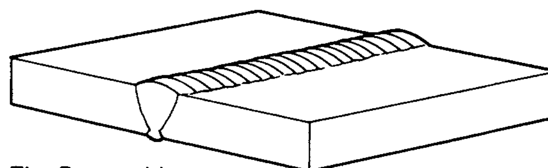


CHAPTER 4

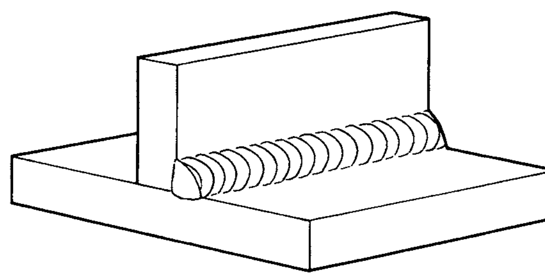
Terms and Definitions

Welds and Joints

The terms *weld* and *joint* are often confused in arc welding, two basic types of weld can be made:

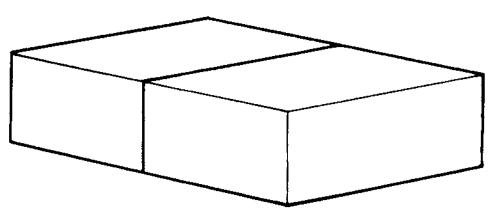


The Butt weld

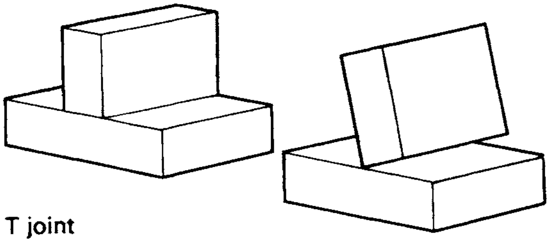


The Fillet weld

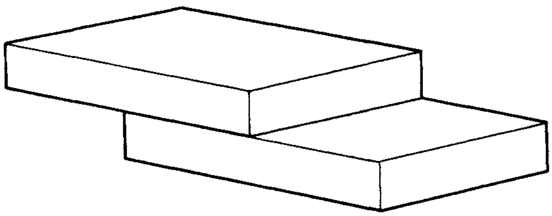
It is the configuration of the connected parts that determines the type of joint. Typical joint forms are:



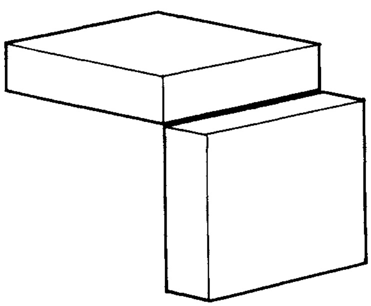
Butt joint



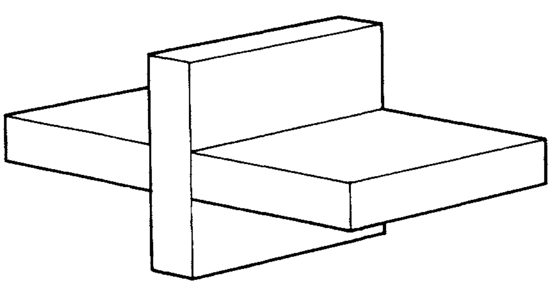
T joint



Lap joint

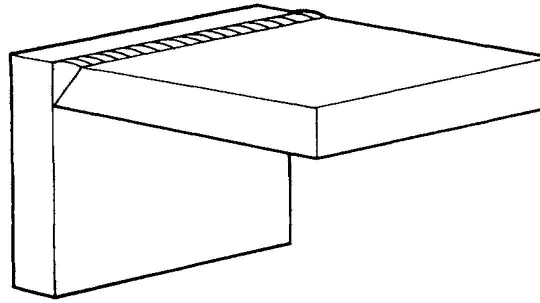


Corner joint

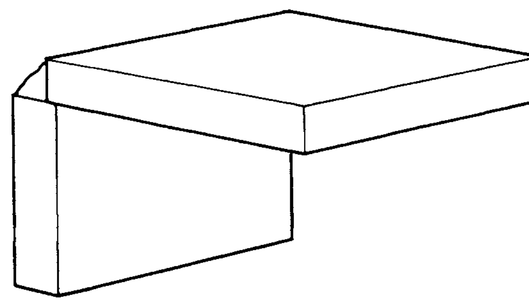


Cruciform joint

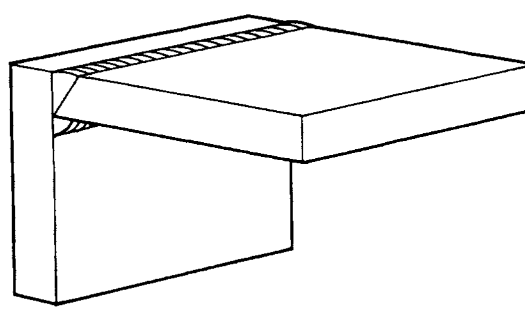
One type of joint may be made with different types of weld – the corner joint provides a good exercise in the choice of the correct terms:



Butt weld



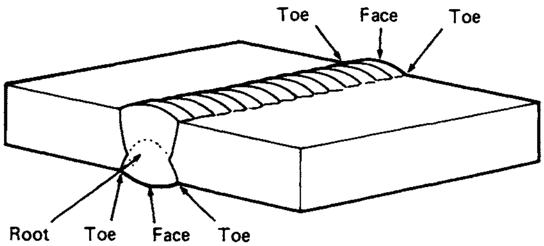
Fillet weld



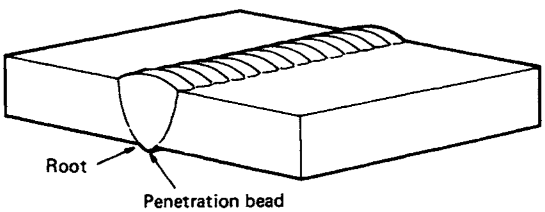
Butt and Fillet weld

Features of the Completed Weld

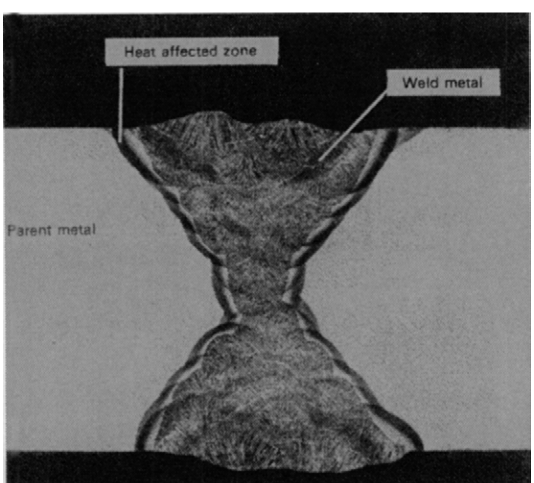
A butt weld in plate, made by welding from both sides, has two weld faces, four toes. In a full penetration weld made from one side. The protrud-



ing weld on the underside is the penetration bead. Note that the position of the weld root has changed. This feature is defined as follows. 'The zone on the side of the first run furthest from the welder.'



If a weld is sectioned, polished and etched, differences in metallurgical structure can be seen.



The heat affected zone (H.A.Z.) is metal which has not been melted but has been rapidly heated and cooled by the passage of the welding arc. The metal between the heat affected zones is weld metal, a mixture of deposited metal and some of the parent metal which has been melted.

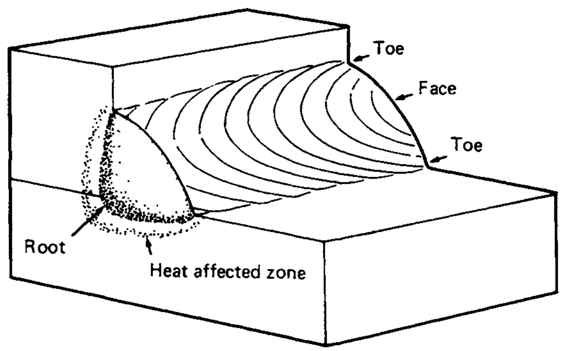
Fillet welds also have:

Toes.

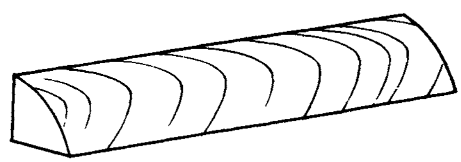
A weld face.

A root.

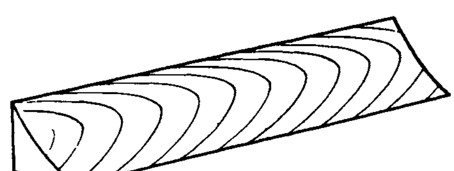
A heat affected zone.



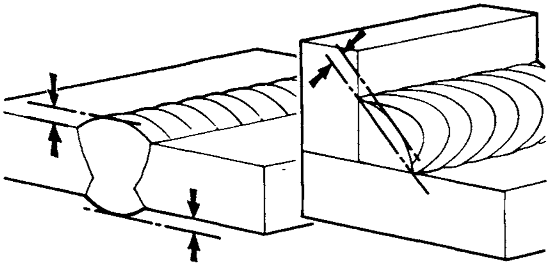
The shape of a fillet weld in cross-section is described by one of two terms.



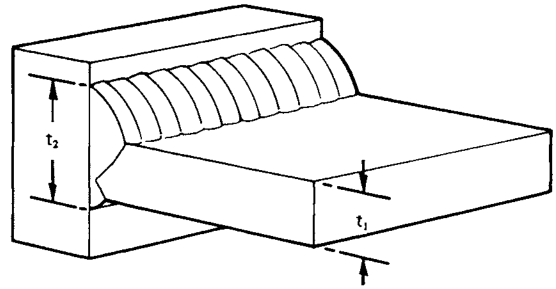
Convex fillet



Concave fillet



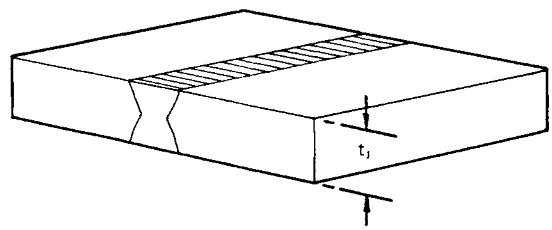
Excess weld metal, as illustrated, is often referred to as weld reinforcement. This does not mean it necessarily strengthens a joint; a better term is overfill.



In a butt weld ground flush, obviously $t_2 = t_1$. For full penetration butt welds, the general rule is: design throat thickness, t_1 = thickness of the thinner part joined.

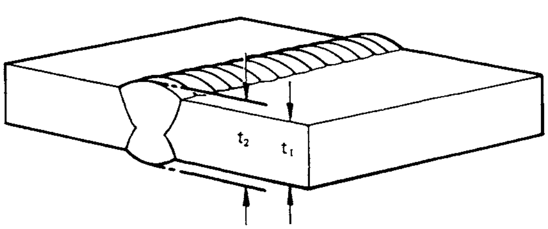
Size of Weld

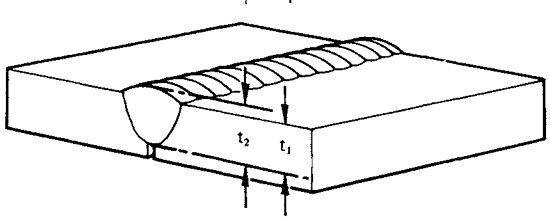
The size of welds is specified as follows:
For butt welds: throat thickness.
For fillet welds: leg length or throat thickness.
For design purposes it is necessary to refer to the *effective* size of welds.



Butt Welds

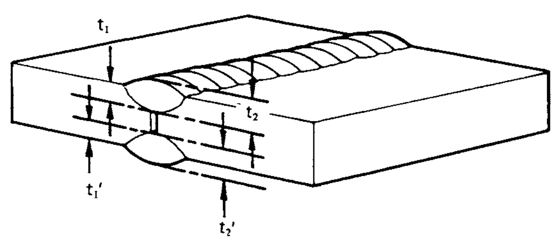
Effective size – design throat thickness, t_1. Note that in the three illustrations shown; $t_1 < t_2$, where t_2 is the actual throat thickness. In each case the thickness of the overfill weld metal is deducted.



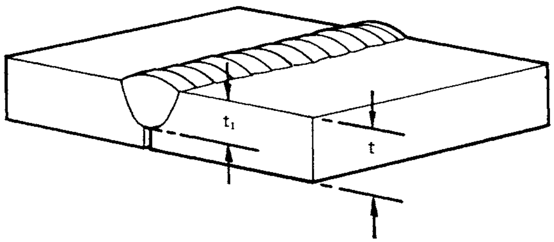


Partial Penetration Butt Welds

The term partial penetration strictly implies butt welds that are designed to have less than full penetration. Failure to achieve full penetration when it is wanted should be listed as the defect *incomplete penetration* and is dealt with in Chapter 10.



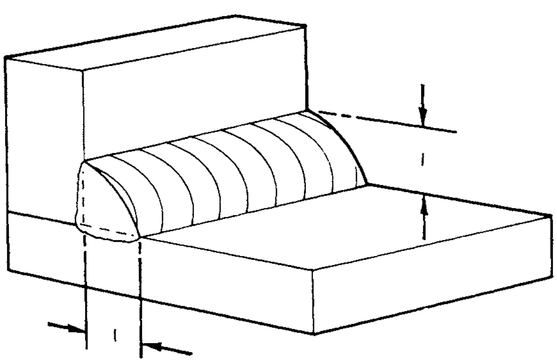
The throat thickness of a partial penetration weld is $t_2 + t_2'$, and the design throat thickness $t_1 + t_1'$. Note that the degree of penetration must be accurately known.



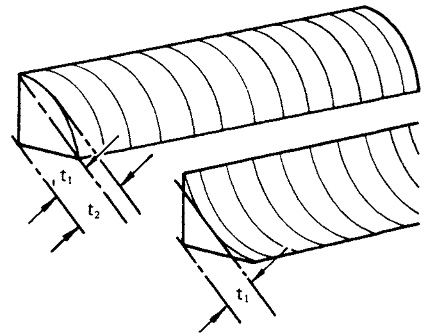
Warning: There are considerable objections to the use of unsealed welds, especially when service conditions involve:
(*a*) Fatigue loading.
(*b*) The possibility of corrosion attack.

Fillet Welds

Fillet weld sizes are calculated by reference to allowable shear stress on the throat area, i.e. throat area = design throat thickness × length of weld. The size required is specified on drawings in terms of leg length, *l*, or throat thickness, *t*.

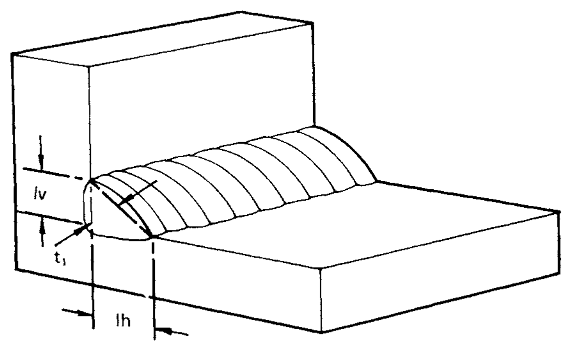


For fillet welds with equal leg lengths 1 = 1.4t_1 is as defined for mitre and convex fillets.



This does not hold for concave fillets.

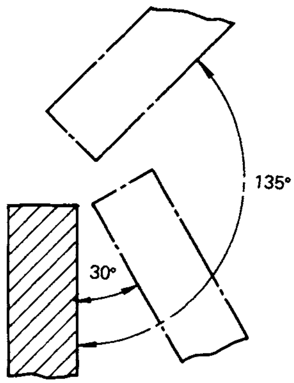
If an asymmetrical fillet weld is required, both leg lengths are specified and t_1 is taken as the minimum throat dimension.



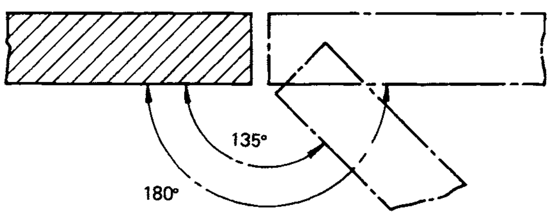
Practical Applications and Interpretation

Structural members and components can meet at all angles and there are limits to the definitions of joints and welds. Distinction between the different welds is important because allowable design stresses are often defined on the basis of the weld type.

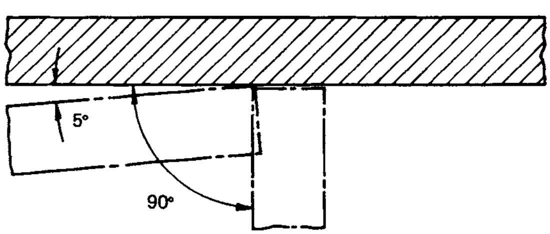
These are the limits of a corner joint:



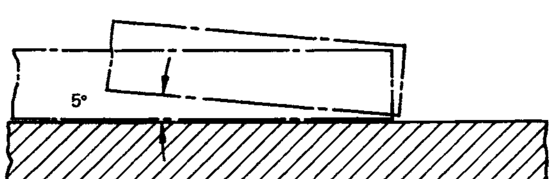
So a butt joint lies between these limits.



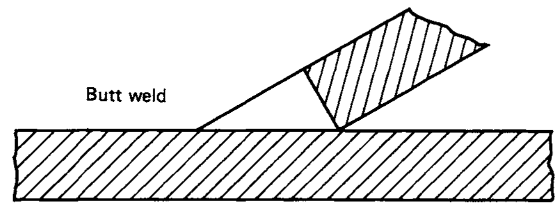
A T-joint is made when the angle between the parts being joined is between 5° and a right angle.



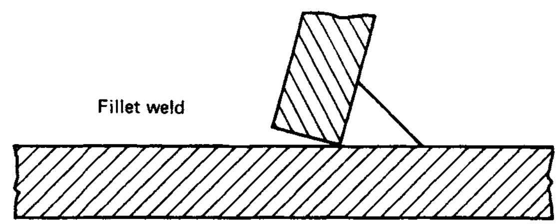
And a lap joint has an angle of 5° or less.



There has been no really satisfactory all-purpose definition of a butt weld. In some cases, for example in plate members joined at their edges, the definition is self-evident. In other cases – the corner joint is one – the distinction between a fillet weld and butt weld becomes blurred. It seems from common usage that a butt weld is one which substantially maintains the cross-section of the joined members



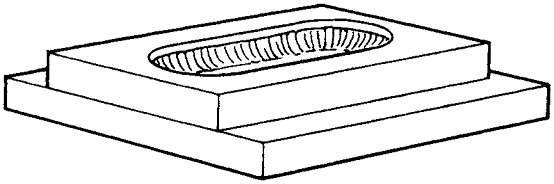
across its throat, or in the case of a weld between members of differing thickness the cross-section of the thinner member, and is contained within the shape of the members being joined, whereas a fillet weld can be just an external addition to the joint. In practice most butt welds extend outside the basic joint envelope to some degree.



As a further aid to definition, a fillet weld is always a fillet in the sense of being a triangular filler in the corner between two faces at an angle and its size does not depend on the thickness of other parts being joined.

The Slot Lap Joint

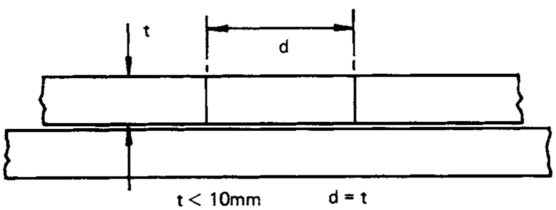
This is also known as a slot weld, and is a means of providing joint area between two flat members – as for example on a cover plate to a beam flange. It is really just a fillet welded lap joint, and the slot width to plate thickness ratio should be greater than three but the slot should never be less than 25 mm wide. The ends of the slot should be circular to allow a continuous and sound weld.



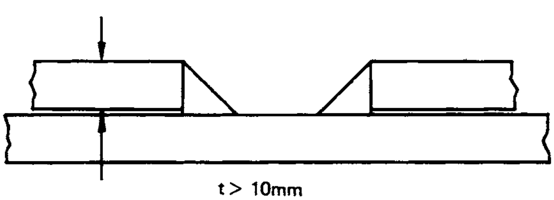
Note: It is not intended that the slot be filled with weld metal.

The Plug Weld

This is a weld made in a circular hole in one member on to another member underneath it. For structures with plate thickness less than 10 mm the weld may



be puddled in with no specific attention to root fusion in the corners – this happens automatically. For thicker material the slot weld technique should be used, with only a fillet weld in the corner of a circular hole whose diameter should be not less than three times the plate thickness, but never less than 25 mm (B.S. 5135).



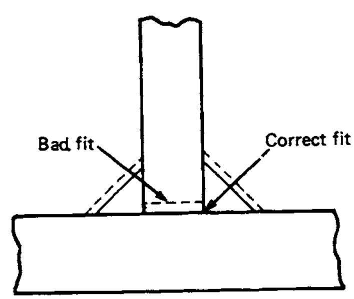
The A.W.S. Structural Welding Code, requires the following.

For plug welds the hole diameter should not be less than the plate thickness plus 8 mm and not greater than 2.25 times the plate thickness.

For slot welds the width should be greater than the plate thickness plus 8 mm, but not greater than 2.25 times the plate thickness. The slot length should not be greater than ten times the plate thickness and the end radius not less than the plate thickness. The spacing between slots should not be less than four times the slot width.

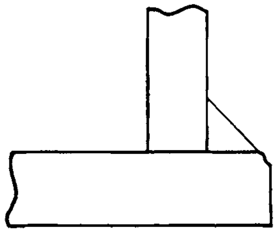
Practical Design Limitations

One of the more important points which is frequently ignored at the design stage is the effect of tolerances. Parts which do not match up can cause difficulties in welding unless the weld design specifically allows for tolerances. The simplest case is in a fillet welded joint where a gap between the parts to be welded will cause the throat thickness to be less than that expected from the leg length. If such a gap is to be allowed for the leg length of the weld should be increased by the maximum gap to be tolerated, to maintain the required weld throat. There is, of course, a maximum gap which should be permitted. For manual metal arc welding the gap should be no greater than 3 mm (except for sheet steel, where there should be a good fit). Where it is impossible to prevent such a gap – as in the final assembly of a large structure – the gap may be packed with the same material as the parts being



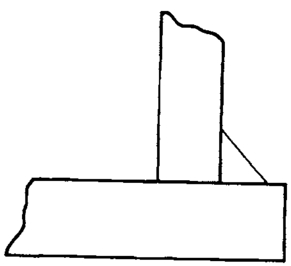
joined. The fillet weld can then be made correctly but its size should allow for the thickness of the packing. Mismatch between parts to be butt welded can be more difficult to overcome. A skilled welder can deal with a certain amount but beyond that a defective weld is almost certain to result as can be seen in the illustration on page 12.

The size of a fillet weld on an external corner weld is limited by the width of the outstanding plate but it is important to appreciate that the weld cannot be



Attempt to make weld to plate edge

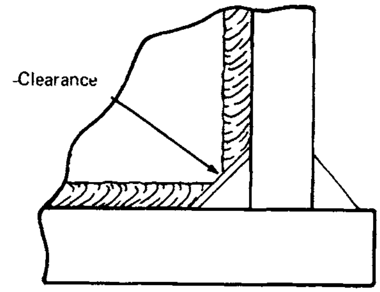
made to exactly this width. Any attempt to do this will result in the melting away of the corner and a subsequent loss of weld size. The weld leg length should be at least 2 mm less than the available plate width.



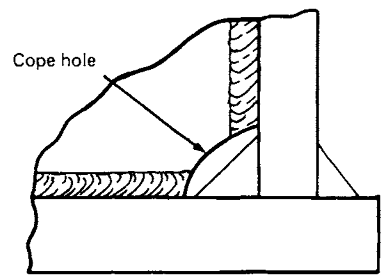
Correct design

The fitting of web stiffeners to welded I beams and stiffening diaphragms into welded box sections requires an appreciation of the practical problems. If the main box welds are made first the corners of the stiffeners must be cut back to clear these welds. Because the weld size will vary, it is difficult to fit the stiffener exactly. It is more practicable to allow a definite clearance over the weld and not to weld the stiffener to the beam at this point.

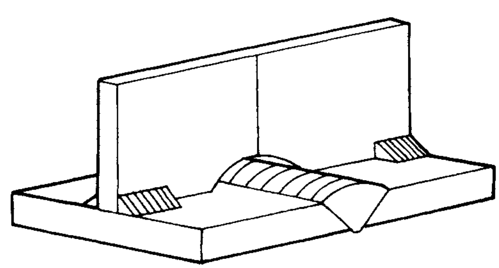
If the stiffeners are welded to the beam members prior to the welding together of the latter (a useful procedure which jigs the members) there are two procedures for the main welds. One is to stop these welds at each stiffener leaving a discontinuous attachment. The other is to cut back the corners of the stiffener to form a cope hole (or mouse hole) through which the main weld can be made continuous. A similar technique is used where a beam is to be spliced. A cope hole is cut in the web over the



flange splice to permit a sound, continuous butt weld to be made. Generally speaking, these cope holes are best left unfilled, but where they are to be watertight, plates can be fillet welded to each side.



Attempts to butt weld a patch into the hole can give rise to problems which can outweigh the apparent advantage of structural continuity. Note that in this type of joint the flange welds are usually made first and the web welds second. When the joint is fitted up ready for welding there should be a gap between the web edges; this gap will close up as the flange welds are completed and leave the web edge preparations almost touching. The amount of movement to be allowed for will depend on the flange weld procedure.



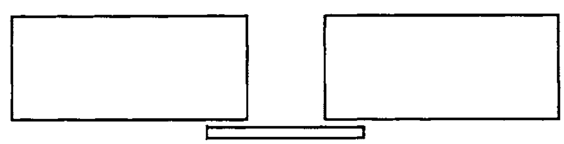
Cope hole in web over flange weld

CHAPTER 5

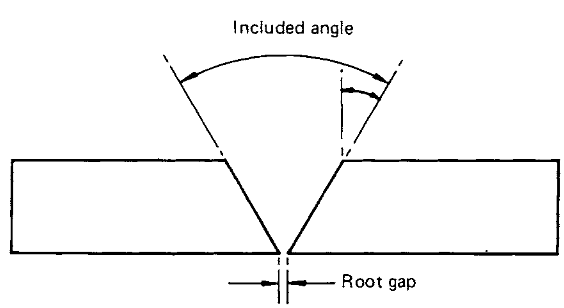
Weld Preparations

The reasons for weld preparations are outlined in Chapter 1, and a more detailed guide will be given here. The type of preparation will depend on the welding process and the fabrication procedure so it may not even be feasible for the designer to put weld preparations on the engineering drawings. Details will then appear on the shop drawings or on the welding procedure sheet. In some industrial situations the weld preparation may never be drawn at all but this leaves room for errors due to misunderstandings and is not a practice to be recommended.

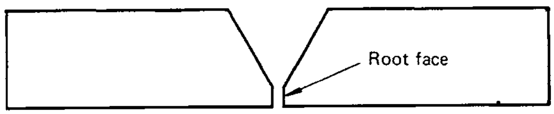
An open square butt can be used, but there is a risk that the restriction on electrode manipulation will produce defects by failure to completely melt the plate edge (in this context called the *side wall*.) In any case a backing strip will be needed to provide a base from which to work in thickness greater than 6



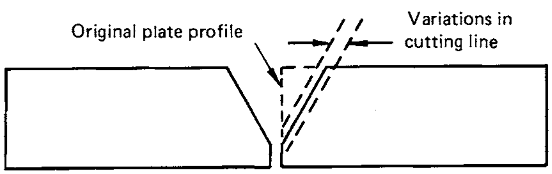
mm. To make sure of fusion the joint is opened up into a V or other suitable shape. If the face is simply bevelled a feather edge is produced. This can cause



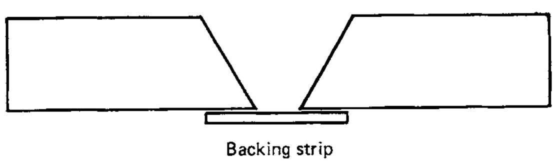
several problems, notably by its propensity to melt away at the first weld run, so letting the weld metal drop through unless very low welding currents are used; in addition any wander in the line of the cut edge will give a varying gap. These snags can be avoided by leaving a root face. This provides a solid *nose* which will fuse but at the same time hold up



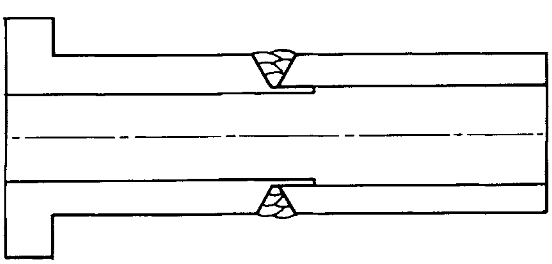
the weld metal. It also acts as a buffer for cutting tolerances by maintaining a constant root gap.



If, because of the effect of overall structural tolerances, a suitably small gap cannot be maintained, then the design should deliberately aim for a large gap in conjunction with a backing strip. In this

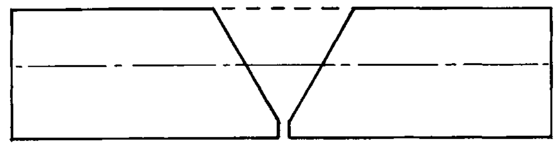


case a root face is not essential since the backing strip will hold up the weld. A backing can be incorporated into one of the parts being joined.

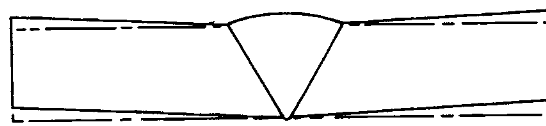


Warning: Backing strips give a built-in crevice susceptible to corrosion and give a lower fatigue life than the simple butt weld.

The single bevel preparation, as it is called, requires a volume of weld metal roughly propor-

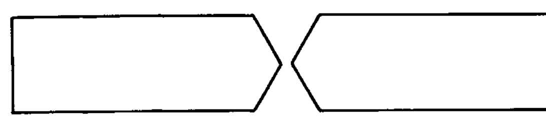


tional to the square of the plate thickness and its lack of symmetry can give rise to distortion. Other

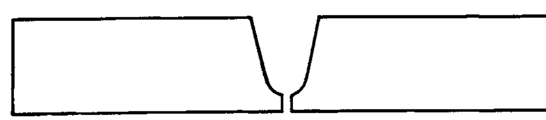


preparations are designed to both reduce the amount of weld metal and the potential distortion. These include:

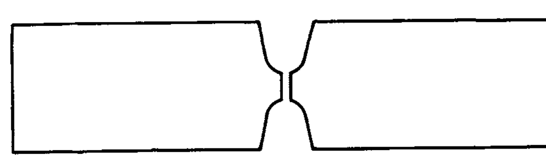
The double bevel



The single U

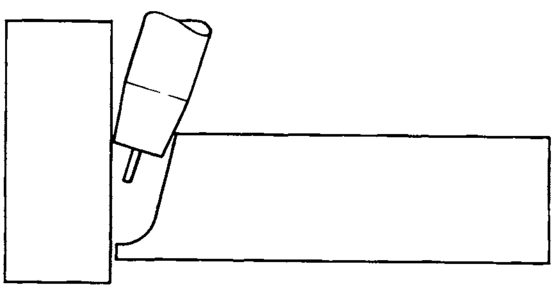


The double U

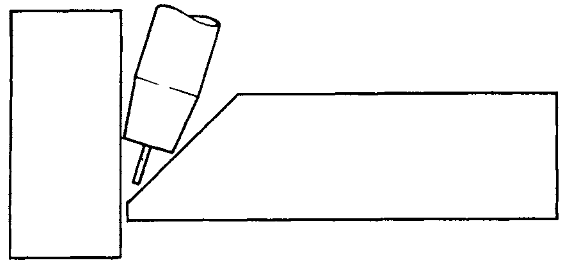


and other more or less complicated shapes. The double-sided preparation requires access to both sides. If the joint is horizontal the work must perhaps be turned over, a difficult job with large structures. The U preparation requires a machining operation whereas the bevel can be gas cut – a cheaper and quicker technique.

The T-joint made with a butt weld requires preparation, and the same considerations arise but are compounded in some cases by access considerations. Although a stick electrode can be used satisfactorily in a J preparation, the size of the nozzle of a MIG/MAG gun may prevent adequate root access and give rise to defects in the root and possibly at the side wall.



The single V will probably be better for the MIG/MAG gun. High current submerged arc welding will allow a larger root face and the possibility of no root gap. This makes the fabricator's setting up task



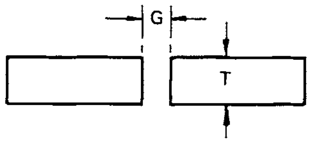
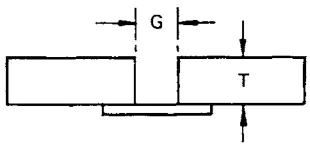
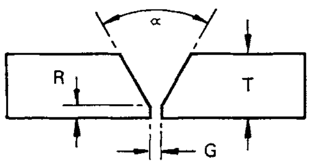
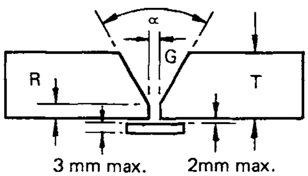
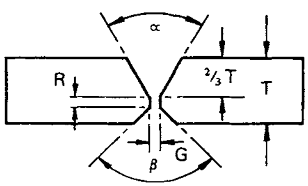
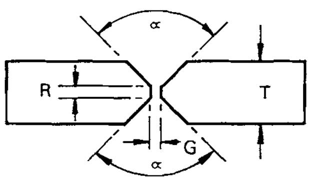
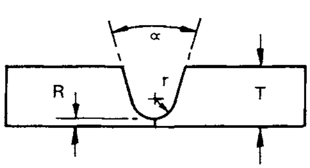
easier, but this approach must be used with caution because, if a gap does occur somewhere along the joint, the arc may blow through and give an erratic weld underbead. The designer must be aware that the root of a single-sided weld is the potential site of lack of penetration and other defects unless special techniques are used.

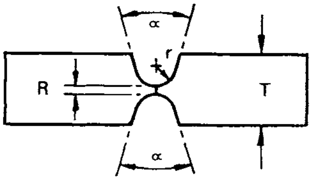
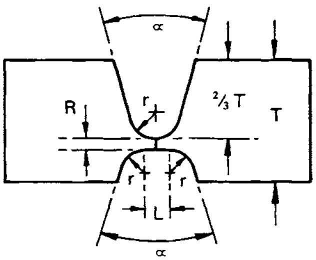
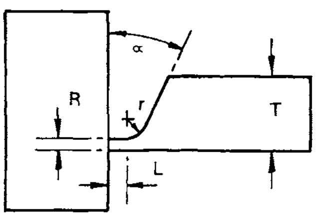
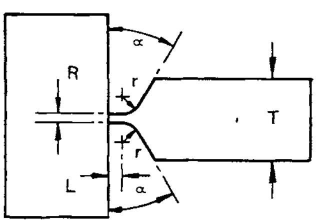
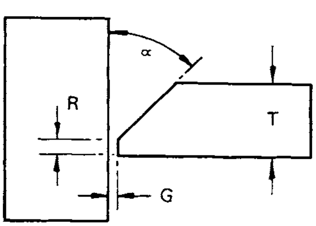
It will be clear that the choice of edge preparation cannot be made solely at the drawing board although hopefully the choice made will be recorded there.

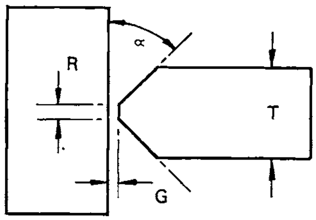
Note: A fillet weld joint needs no edge preparation — a big point in its favour.

There can be no fixed rules for joint preparations but a selection of those most commonly used in plate and rolled sections is shown overleaf.

These basic joint preparation shapes are suitable for most purposes although modification may be necessary depending on the position and accessibility of the joint.

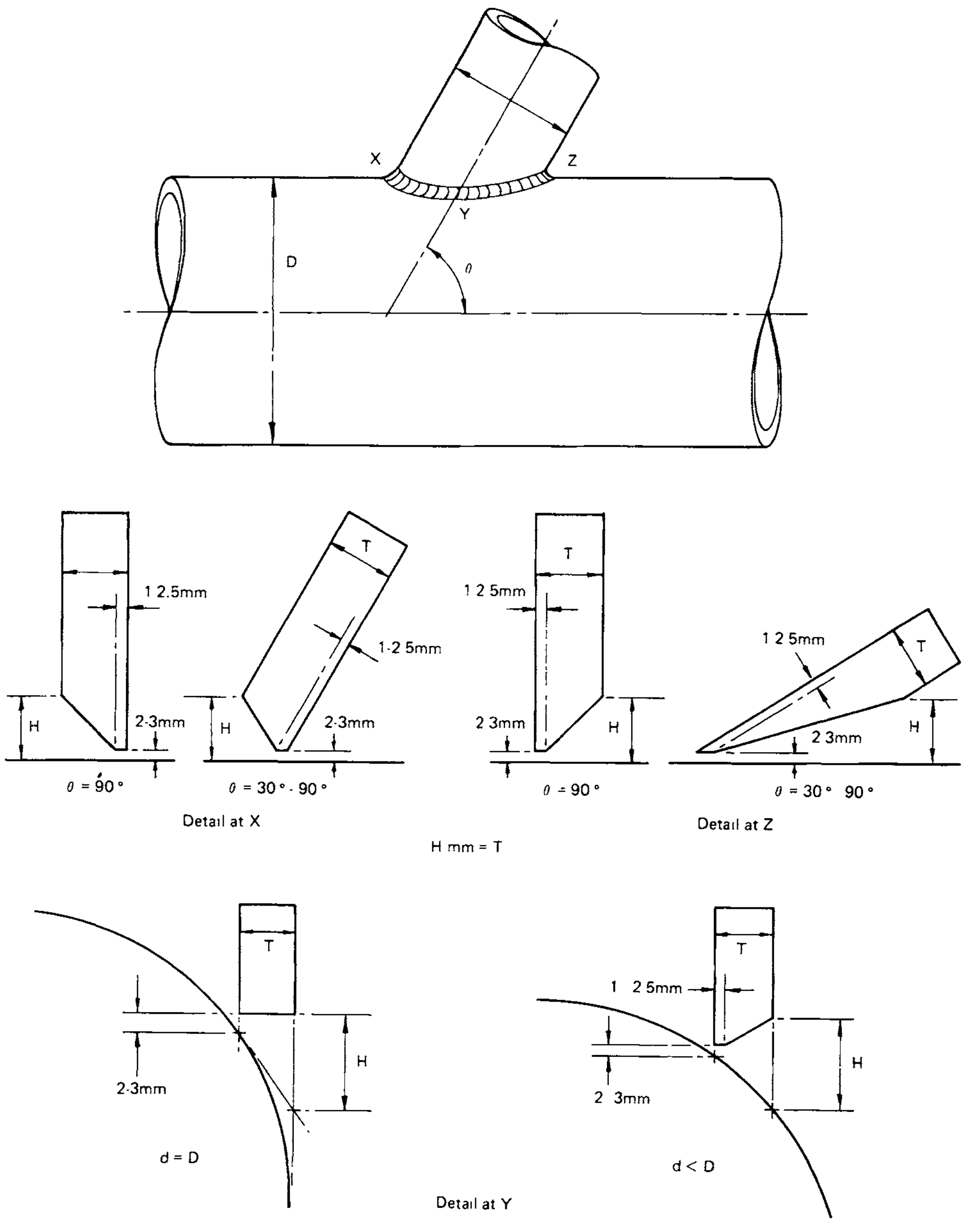
Weld Detail	Thickness mm	G mm	α	β	R mm	L mm	r mm	Position	Notes
	3–6 3–5	3 3	— —	— —	— —	— —	— —	Flat Horizontal-vertical or vertical	Welded from both sides
	3–5 5–8 8–16	6 8 10	— — —	— — —	— — —	— — —	— — —	All	Welded from one side with steel backing strip
	5–12 Over 12	2 2	60° 60°	— —	1 2	— —	— —	All	Welded from both sides or one side only
	Over 10	6 10	45° 20°	— —	0 0 +2 −0	— —	— —	All	Single root run Double root run Welded from one side with steel backing strip
	Over 12	3	60°	60°	2	—	—	All	Welded from both sides
	Over 12	3	60°	—	2	—	—	All	Welded from both sides
	Over 20	—	20°	—	5	—	5	All	Welded from both sides

Weld Detail	**Thickness** mm	**G** mm	α	β	**R** mm	**L** mm	**r** mm	**Position**	**Notes**
	Over 40	—	20°	—	5	—	5	All	Welded from both sides
	Over 30	—	20°	—	5	6	5	All	Welded from both sides
	Over 20	—	20°	—	5	5	5	All	Welded from both sides
	Over 40	—	20°	—	5	5	5	All	Welded from both sides
	5–12 Over 12	3 3	45° 45°	— —	1 2	— —	— —	All	Welded from both sides

Weld Detail	Thickness mm	G mm	α	β	R mm	L mm	r mm	Position	Notes
	Over 12	3	45°	—	2	—	—	All	Welded from both sides
TOLERANCE Except where shown otherwise	Up to 12	±1	V ± 5°		±1	±1	±1		Unless application specification states otherwise
	Over 12	±2	U + 10° - 0° J + 10° - 0°		±2	±2	- 0 +1 - 0		

Tubular joints require particular consideration because not only does the geometry of the intersection vary around the joint but positional welding means that welding conditions may change around the joint. Complex profiles have been developed which follow the general principles presented in this chapter, and typical recommendations are given here.

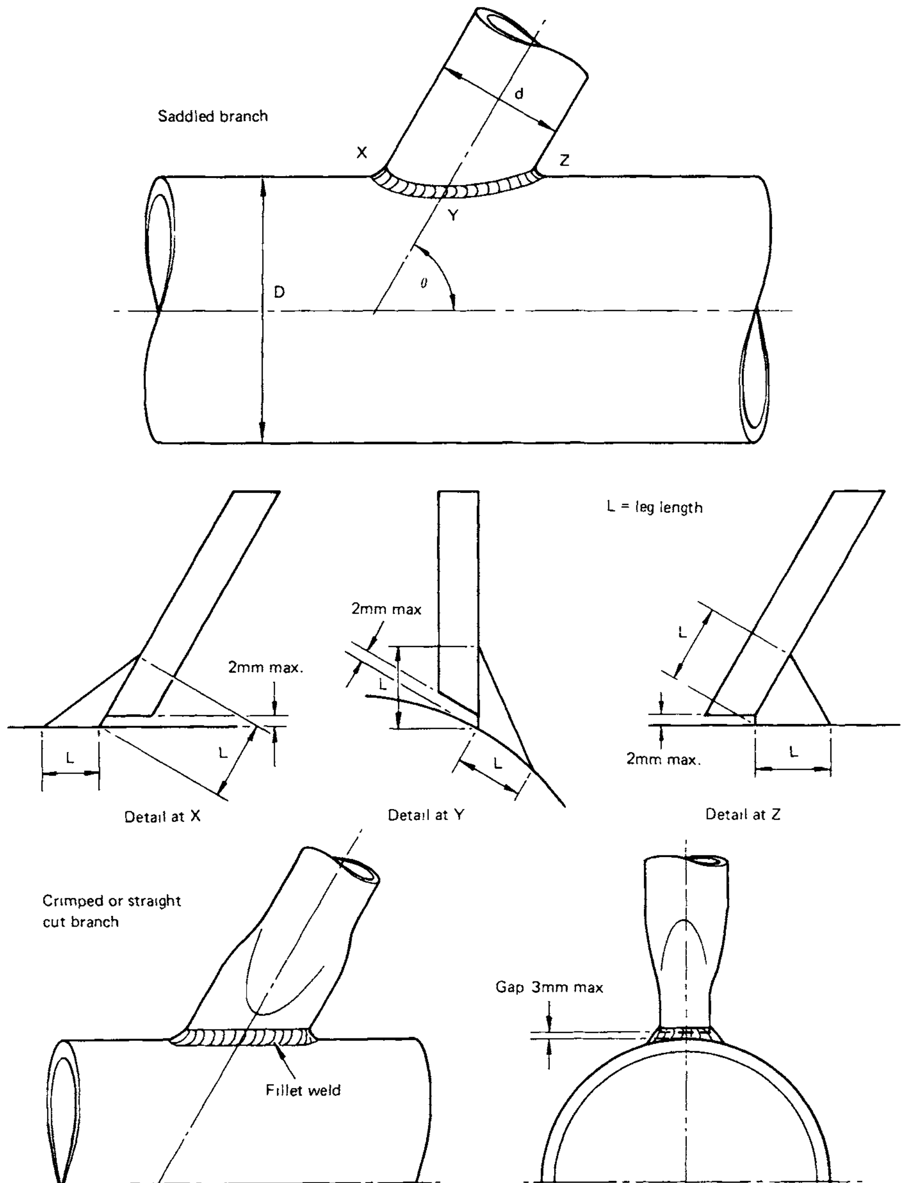
Typical details for branch connections for structural hollow sections
Circular structural hollow sections: butt welds (thickness up to 30 mm)



Note: The angle of intersection θ of the axes of the circular hollow sections should not be less than 30° unless adequate efficiency of the junction has been demonstrated.

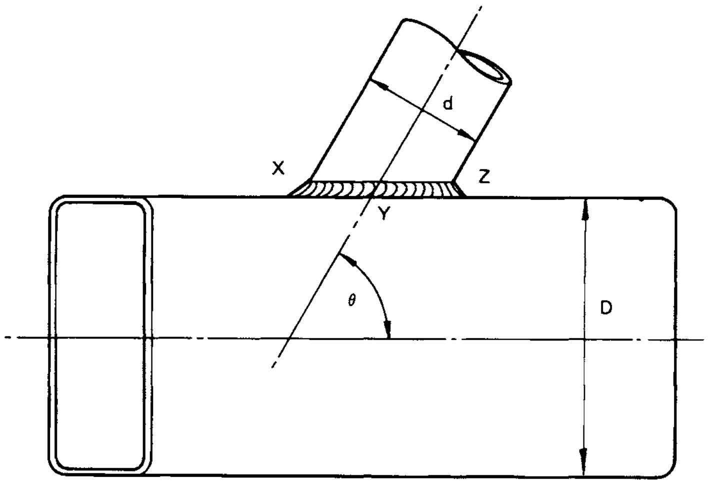
Circular structural hollow sections: fillet welds

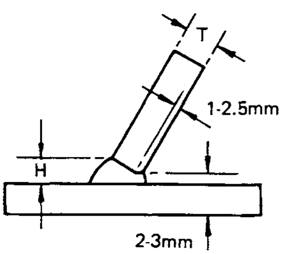
Leg lengths should be such that the stresses in fillet welds are in accordance with the permissible stresses given in the relevant specification and that the welds will transmit the loads in the member.



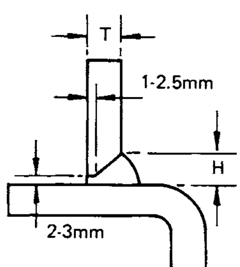
Note: The angle of intersection θ of the axes of the circular hollow sections should not be less than 30° unless adequate efficiency of the junction has been demonstrated.

Rectangular structural hollow sections: butt welds

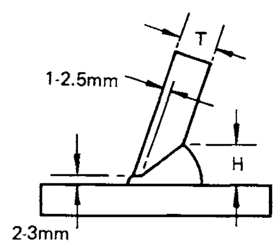




Detail at X

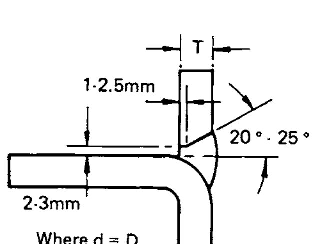


Where d < D



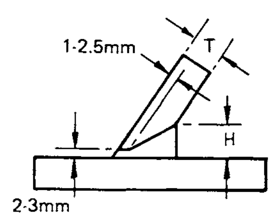
$\theta = 60° - 90°$

H min. = T



Where d = D

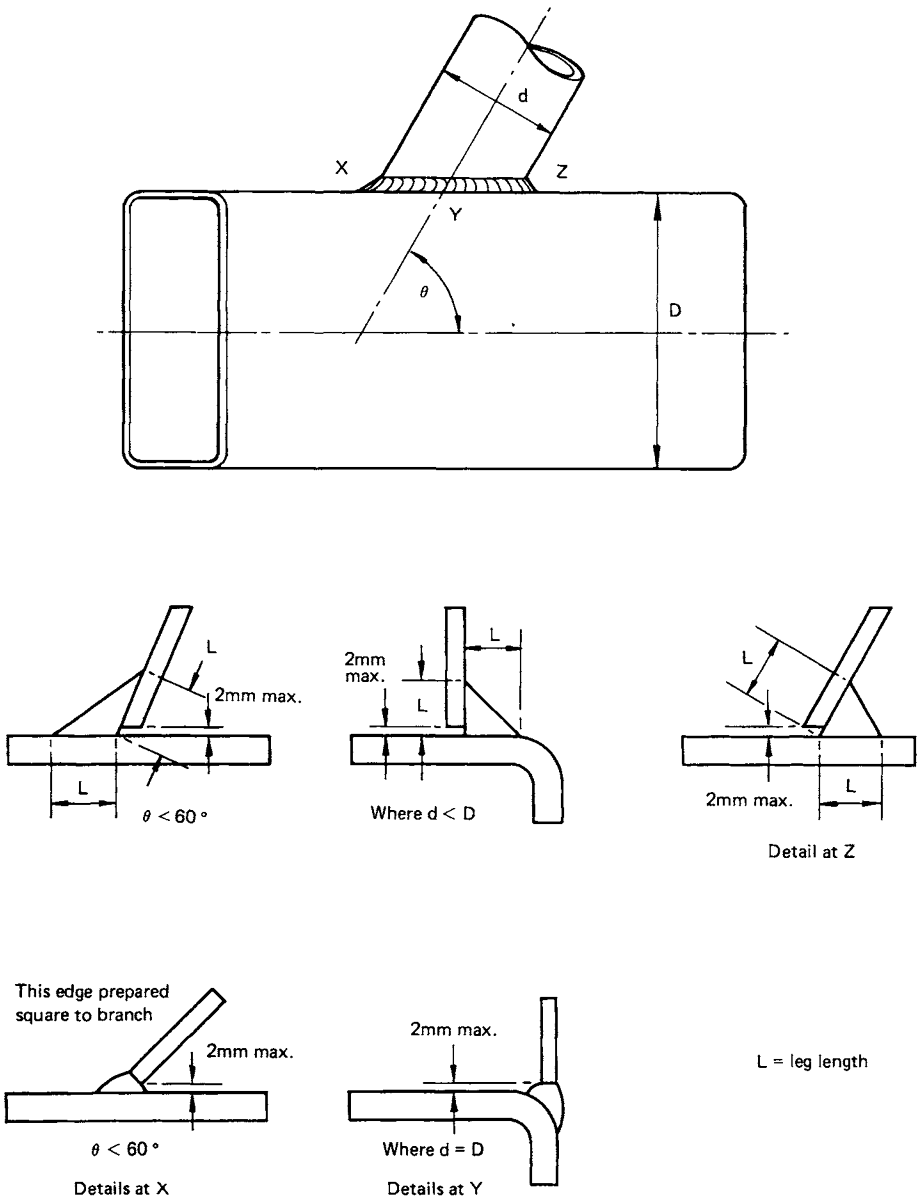
Details at Y



$\theta < 60°$

Details at Z

Rectangular structural hollow sections: fillet welds



Note: The angle of intersection θ of the axes of the rectangular hollow sections should not be less than 30°, unless adequate efficiency of the junction has been demonstrated.

CHAPTER 6

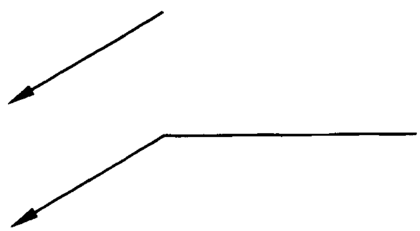
Weld Symbols on Drawings

Engineering drawings are descriptions of manufactured objects in terms of shape, surface, finish and material. In many industries it is customary to draw the shape of the component without indicating how that shape is achieved. The drawing is a description of a requirement produced by the designer for the instruction of the manufacturer. In theory, the manufacturer knows best how to produce an object with the resources he has. In practice, of course, the designer compromises and produces designs which are capable of production by the techniques of which he is aware. For example, a round hole can be drilled, bored or punched, and can be finished by reaming, but whichever method is used, the lines on the drawing are the same and whichever method is used, the material is not changed in its characteristics.

A welded joint offers a range of considerations which do not arise in other forms of manufacture. Firstly, there are far more techniques for making a welded joint than in many other manufacturing operations. This means that the designer has far less chance of foreseeing the manufacturer's methods. Secondly, the properties and integrity of the joint will depend on the manner in which the weld is made. Despite this, the designer can still indicate the type of joint he requires, provided that he is prepared to accept that he may not be able to completely define the joint in the earlier stages of a design.

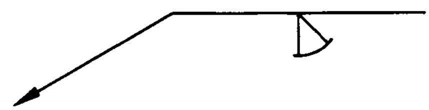
In some industries it is customary for the manufacturer to produce shop drawings which contain details of weld preparations and reference to established welding procedures not shown in detail on the designer's drawings. This chapter describes the range of British Standard symbols which can be used on a drawing to indicate a weld detail. The draughtsman or engineer has to make up his mind as to how much detail can be usefully put on to the drawing. Other systems of drawing symbols are used in the world and it is essential to indicate on the drawing which system is used.

The American Welding Society weld symbols are described in A.W.S. specification A2.4 *Symbols for welding and non-destructive testing.* The basic features of the B.S. 499 weld symbol system are the arrow, which points to the welded joint, and a horizontal line, the reference line, on which the various weld symbols are drawn.

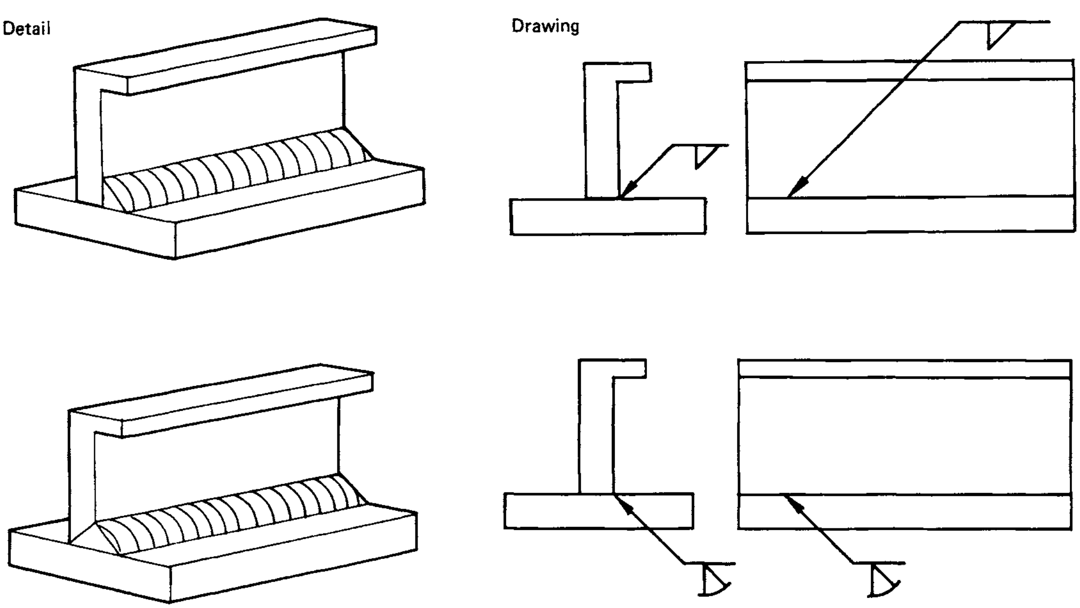


This is the symbol for a fillet weld:

A butt weld (single-sided bevel):

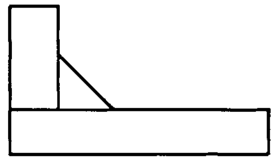
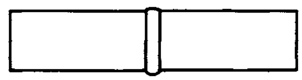
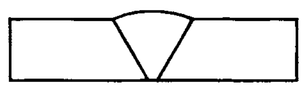
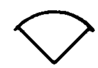
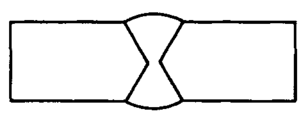
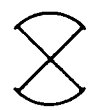
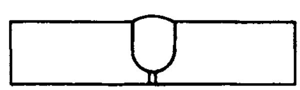
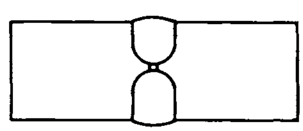


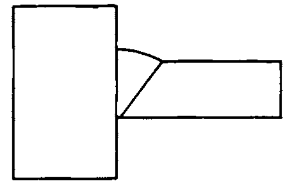
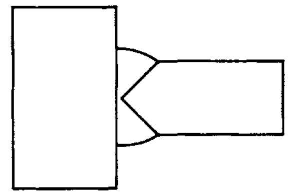
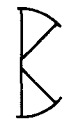
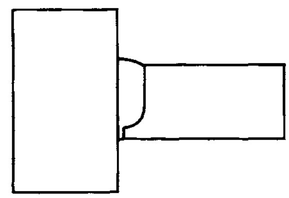
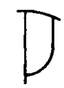
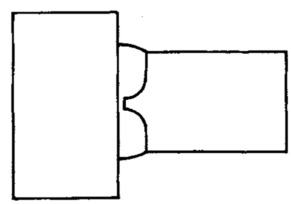
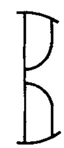
In practice, the two symbols shown above right would be used as follows:

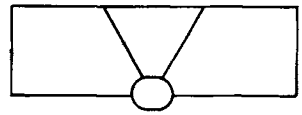
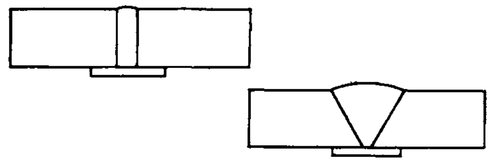
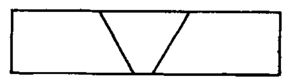


NOTE: The arrow points towards the prepared edge

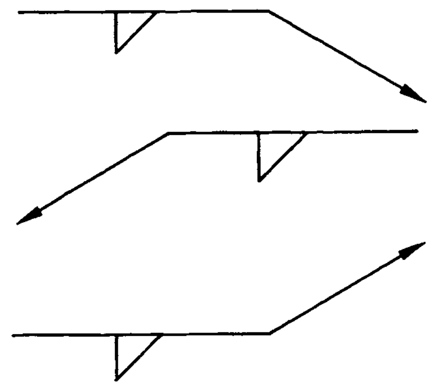
Symbols are available for a variety of weld types.

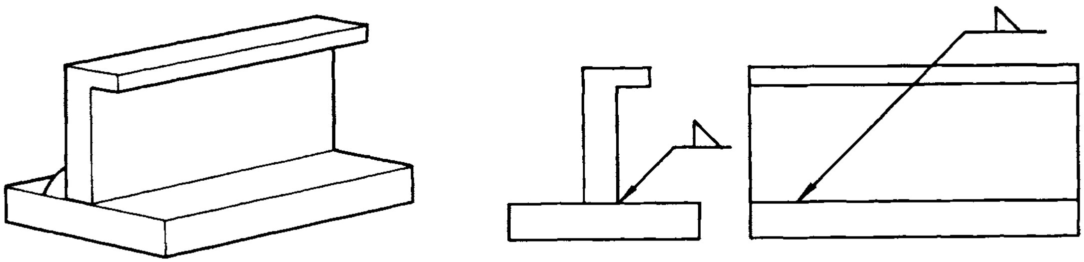
Fillet		
Square butt		
Single-V butt		
Double-V butt		
Single-U butt		
Double-U butt		

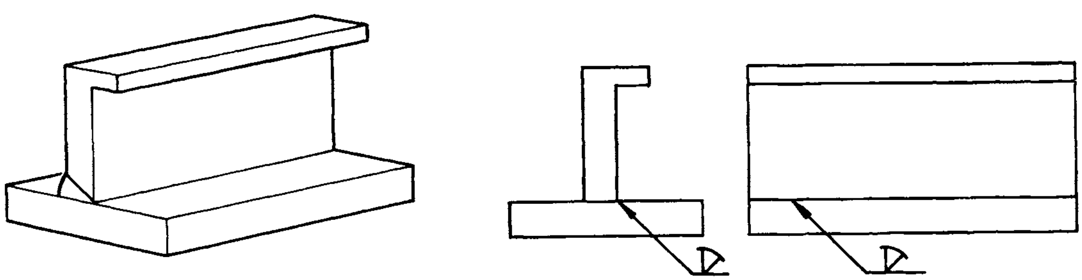
Single-bevel butt		
Double-bevel butt		
Single-J butt		
Double-J butt		

Some extra details **Sealing run**		○
Backing strip		═
Dressed flush		—
– and a very useful symbol **Full penetration butt weld by a welding procedure to be agreed**		

The weld symbol is always drawn the same way round regardless of the layout of the arrow and the reference line. The position of the symbol on the reference line has significance. A symbol below the reference line means that the weld is made from that side of the joint indicated by the arrow. A symbol above the reference line means that the weld is made from the opposite side of the joint to the arrow.



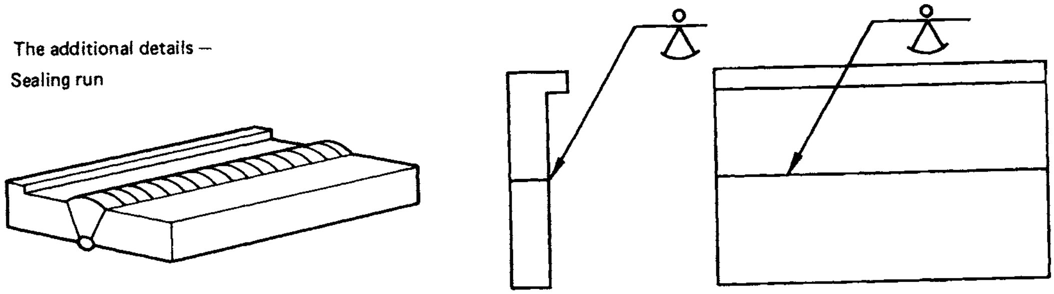




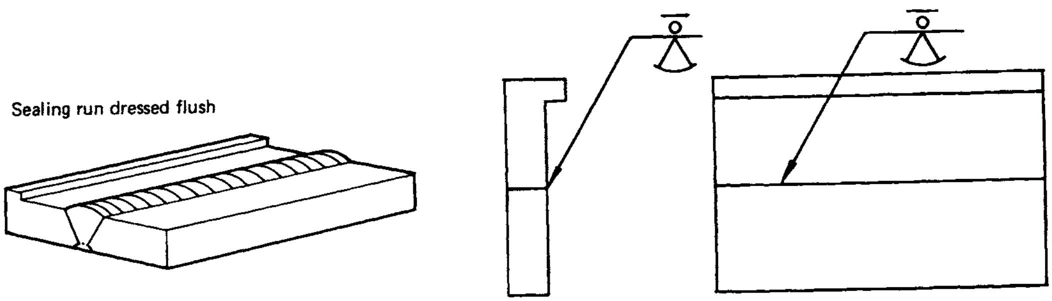
Note: The arrow points towards a prepared edge.

The additional details –

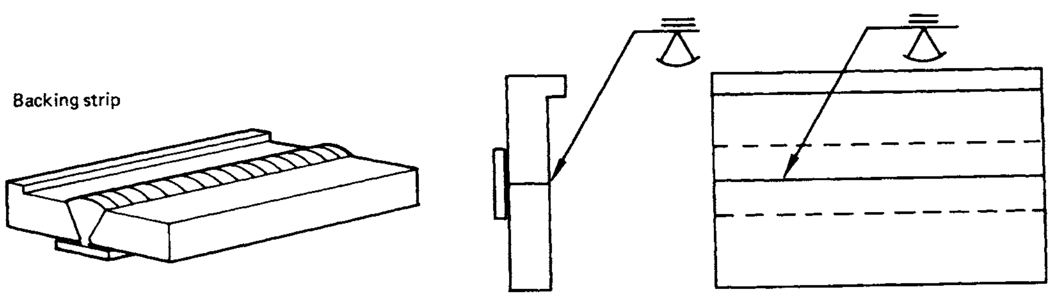
Sealing run



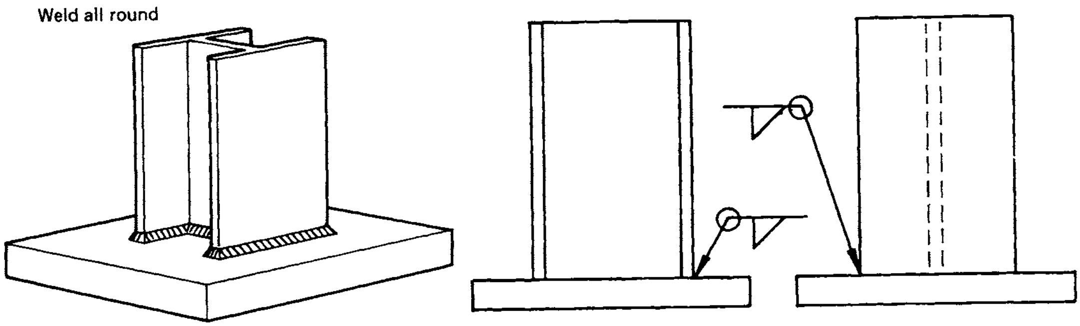
Sealing run dressed flush



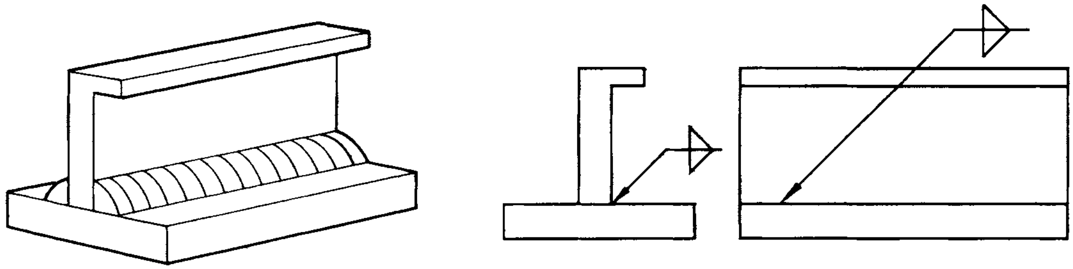
Backing strip

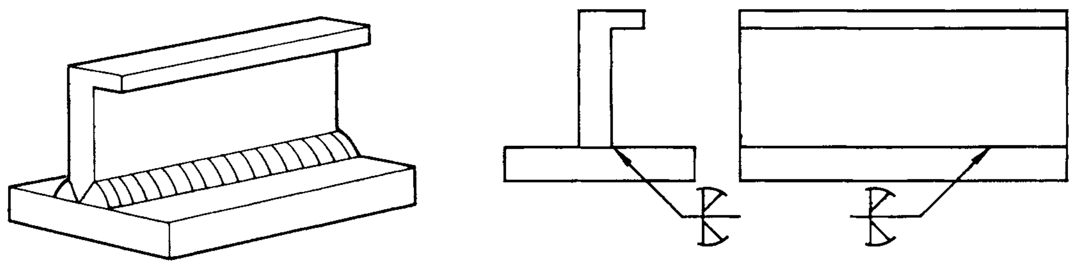


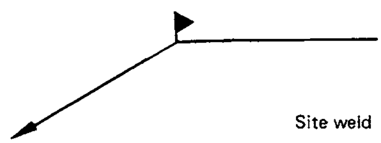
Weld all round



A joint made from both sides has a symbol on each side of the reference line:

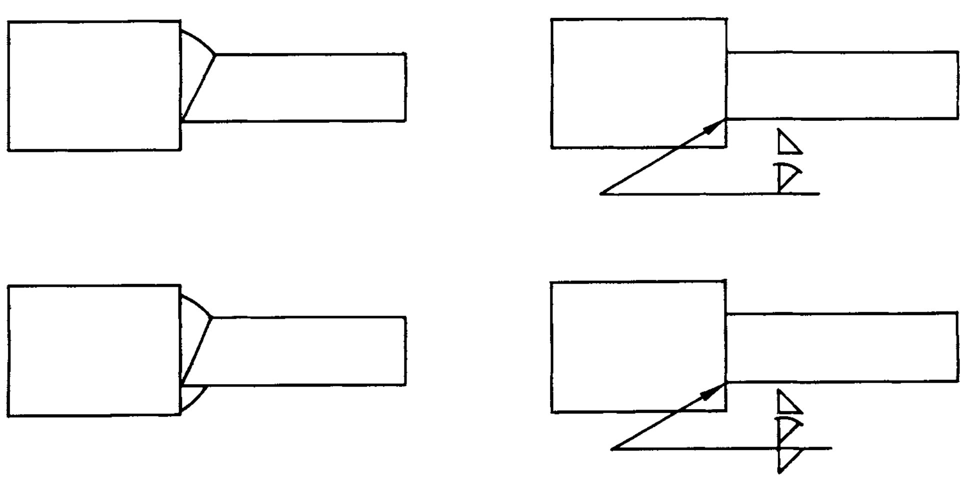




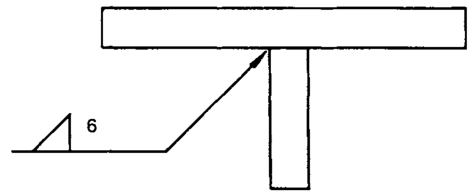


Site weld

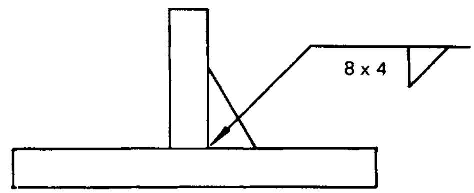
Compound welds



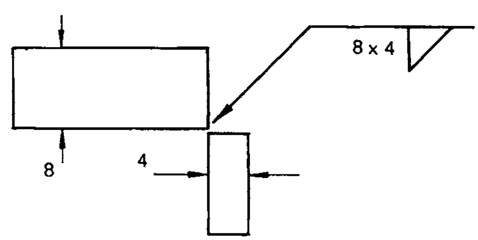
Weld size can be indicated on the symbol.
6 mm fillet weld.
The drawing must state whether a throat or leg dimension is quoted.



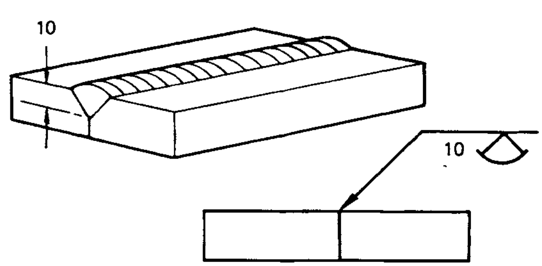
Unequal leg fillet weld.
This must be defined by leg length.
A diagram of weld shape is required here.



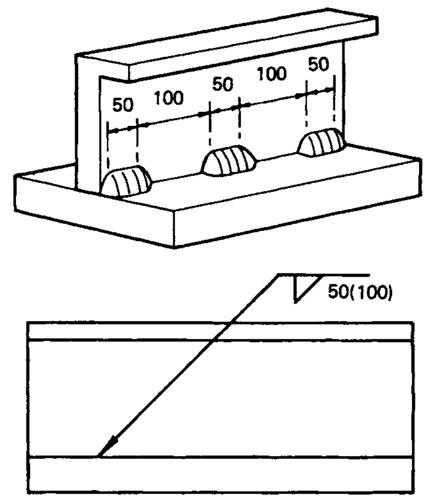
A diagram is not required here because the size of the members indicates the weld orientation.



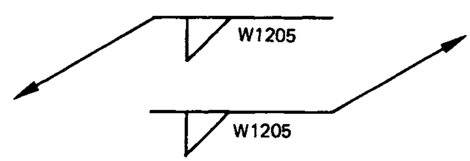
Partial penetration butt weld, plate preparation 10 mm deep on the arrow size only.



Information other than weld size may be written to the right of the symbol.
Intermittent welds.
The figure in brackets is the space length, 50 before (100) indicates that the weld is at the beginning. (100) 50 would indicate a space first then a weld although such an arrangement would not represent good practice.



Welding procedure reference, e.g. Welding procedure sheet W1205.
Note: The position of written information remains the same regardless of the arrow.



CHAPTER 7

Static Strength of Welded Joints

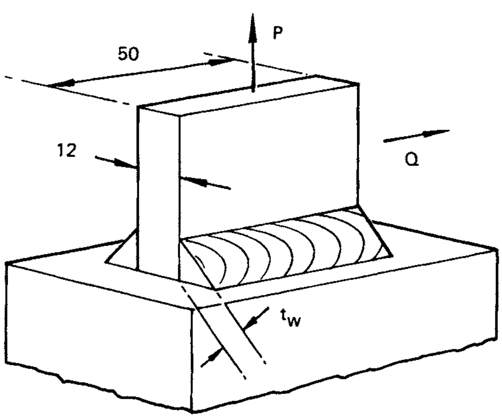
The strength of steel is expressed in terms of its yield stress and tensile strength. These terms come from tensile tests on steel in which a test specimen in the form of a bar is pulled in a test machine. The strain (extension per unit length) is measured against the stress on the nominal cross-section of the bar. Up to a certain stress the strain increases in proportion to the stress and if the load is removed the strain reverts to zero as the bar goes back to its original length. This is termed elastic behaviour and the ratio of the applied stress to the strain is called the elastic modulus or Young's modulus; because strain has no units, Young's modulus has the same units as stress. The most commonly used symbol for Young's modulus is E.

As the load is increased, there comes a point when the specimen strain increases without a proportionate stress increase. This is the *yield stress*, and the steel is now said to behave plastically although if the load is now reduced, the steel will again behave elastically but it will have been permanently stretched. If on reaching the yield stress the load is maintained, the strain increases until there comes a point at which the steel begins to work harden and the load must be increased to cause any further strain. Again, removal of the load allows an elastic contraction and upon reloading the steel will behave elastically up to the previous maximum stress. If the load is increased indefinitely, a point is reached where the specimen fractures and the stress at maximum load is called the *tensile strength*.

In a tensile test piece of relatively small diameter or thickness, the fracture will be preceded by severe necking or thinning of the specimen. The amount by which the specimen reduces in cross-section is a measure of the *ductility* of the steel as is also the elongation to the point of fracture. The final fracture is at an angle to the cross-section and is a failure by shear. A round bar produces a *cup and cone* fracture, a rectangular bar will produce a single or double shear face.

Weld metals are usually selected so that they are slightly stronger than the steels they join and we can calculate the strength of a butt-welded joint using the strength of the parent material. The throat thickness and the mode of loading are all that we need to know. The throat of a full penetration butt weld was shown to be the same as the thickness of the part being joined, whether under axial load, shear, or bending, and if the design is checked for stress there is no need to do special calculations for the weld.

There are several methods of calculating the size or strength of fillet welds. The simplest method assumes that the throat is in shear for all types of load, and the shear stress in the throat is the load divided by the throat area as in the following example.



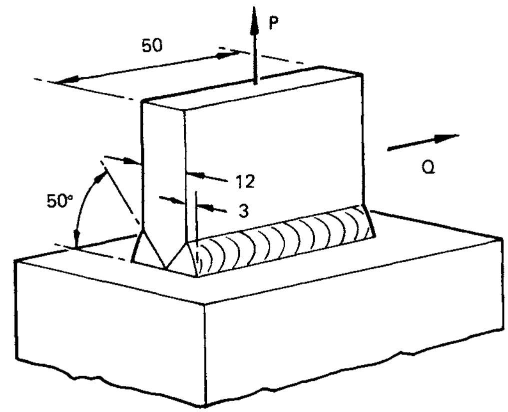
Weld throat area = $50 \times 2 \times t_w = 100\ t_w$
(Allowable stress (B.S. 449) = 115 N/mm^2 for mild steel and E43 electrodes.)

For maximum allowable stress in the welds under a load P = 90 kN.

$$100t_w \times 115 = 90\,000$$
$$t_w = 7.82 \text{ mm}$$

Leg length ≈ 11 mm
The volume of weld metal is 6060 mm^3

For comparison the corresponding butt-welded joint can be calculated as follows.



Weld throat area = $50 \times 12 = 600$ mm^2
Under load P = 90 kN.

$$\text{Stress} = \frac{90\,000}{600} = 150 \text{ N/mm}^2$$

(Allowable stress (B.S. 449) = 155 N//mm^2)

The volume of weld metal is 3218 mm^2.

Note that the fillet weld has almost twice as much weld metal as the butt weld. The fillet weld leg length is almost as large as the plate thickness and is really not a good design for this particular example.
For maximum allowable stress in the fillet weld

Under load Q = 65 kN
$$100\ t_w \times 115 = 65\,000$$
$$t_w = 5.65 \text{ mm}$$

Leg length ≙ 8 mm

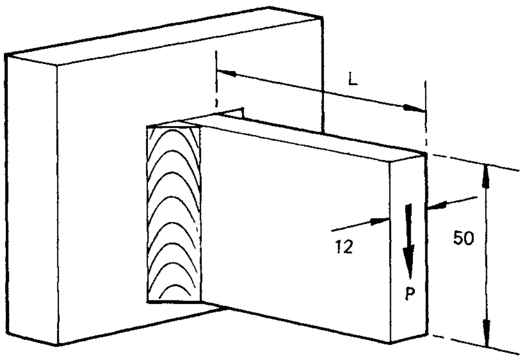
The volume of weld metal is now 3200 mm^3

$$\text{Stress in butt weld} = \frac{65\,000}{600} = 108 \text{ N/mm}^2$$

Allowable shear stress (B.S. 449) = 115 N/mm^2

The volume of weld metal is still 3218 mm^3

So the fillet weld is much more efficient in carrying shear loads than axial loads.



When there is a load system giving a combination of axial load and shear it is necessary to calculate their effect. The load P produces a moment and a shear at the joint. The weld throat stress due to these effects can be calculated by a simple method in which the throat stress for each type of load is calculated separately and then added vectorially to produce the combined stress which is to be compared with the allowable weld throat stress.

The weld throat stress due to shear load is:

$$P = \frac{P}{100t_w}$$

The bending moment is PL and this is resisted by the weld. The effective modulus of the weld throat as the effective width.

$$Z_w = 1/_{12}\ \frac{2t_w \times 50^3}{25}$$

The maximum weld throat stress is then

$$\frac{PL}{833.3t_w}$$

The combined stress is then:

$$\sqrt{\left[\left(\frac{P}{100t_w}\right)^2 + \left(\frac{PL}{833{\cdot}3t_w}\right)^2\right]} = \frac{P}{t_w}\sqrt{\left[\left(\frac{1}{100}\right)^2 + \left(\frac{L}{833{\cdot}3}\right)^2\right]}$$

For $P = 10$ kN and $L = 100$ mm this becomes:

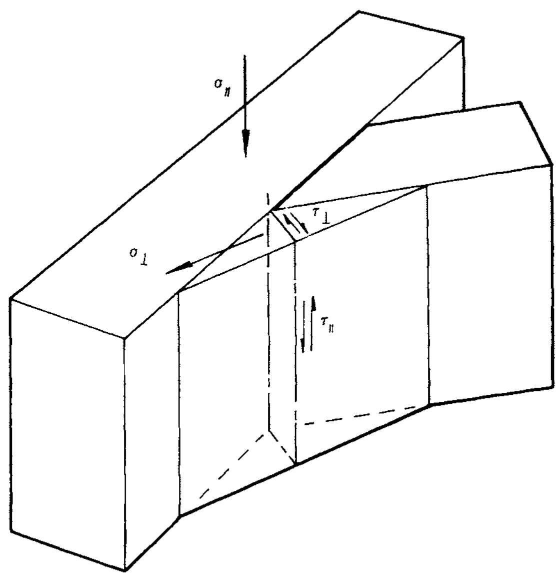
$$\frac{10000}{t_w}\sqrt{(0.0001 + 0.0144)} = \frac{1204}{t_w}$$

With an allowable stress of 115 N/mm²

$$t_w \simeq 10 \text{ mm}$$

This method of combining stresses in two directions is rather conservative and may lead to the calling up of larger fillet welds than are necessary.

A more refined approach proposed by the International Institute of Welding employs a rather more complicated but still straightforward method in which the stresses are resolved across the weld throat. These components of the stress are a normal stress ($\sigma_\perp$) perpendicular to the throat, a shear stress



($\tau_{\parallel}$) acting in the throat parallel to the axis of the weld and a shear stress ($\tau_{\perp}$) acting in the throat transverse to the axis of the weld. Normal stress ($\sigma_{\parallel}$) along the axis of the weld has no effect on the strength of the weld.

An equation then allows us to check the weld size in terms of the allowable tensile stress in the steel. (P_a)

The equation is:

$$\beta \sqrt{[\sigma_\perp^2 + 3(\tau_{\parallel}^2 + \tau_\perp^2)]} \leqslant P_a$$

For mild steel, e.g. B.S. 4360 Grade 43. $\beta = 0.7$
For high yield steel, e.g. B.S. 4360 Grade 50, $\beta = 0.85$
The example on this page can be checked using this equation.

$\tau_{\parallel}$ is equal to the shear stress due to P and this is

$$\frac{10\,000}{500} = 20\ \text{N/mm}^2$$

$\tau_{\parallel}$ and $\sigma_{\perp}$ have to be calculated from the effect of the bending moment.

$$\frac{PL}{833{\cdot}3 t_w \sqrt{2}} = \frac{1\,000\,000}{833{\cdot}3 \times 10\sqrt{2}} = 84{\cdot}87\ \text{N/mm}^2$$

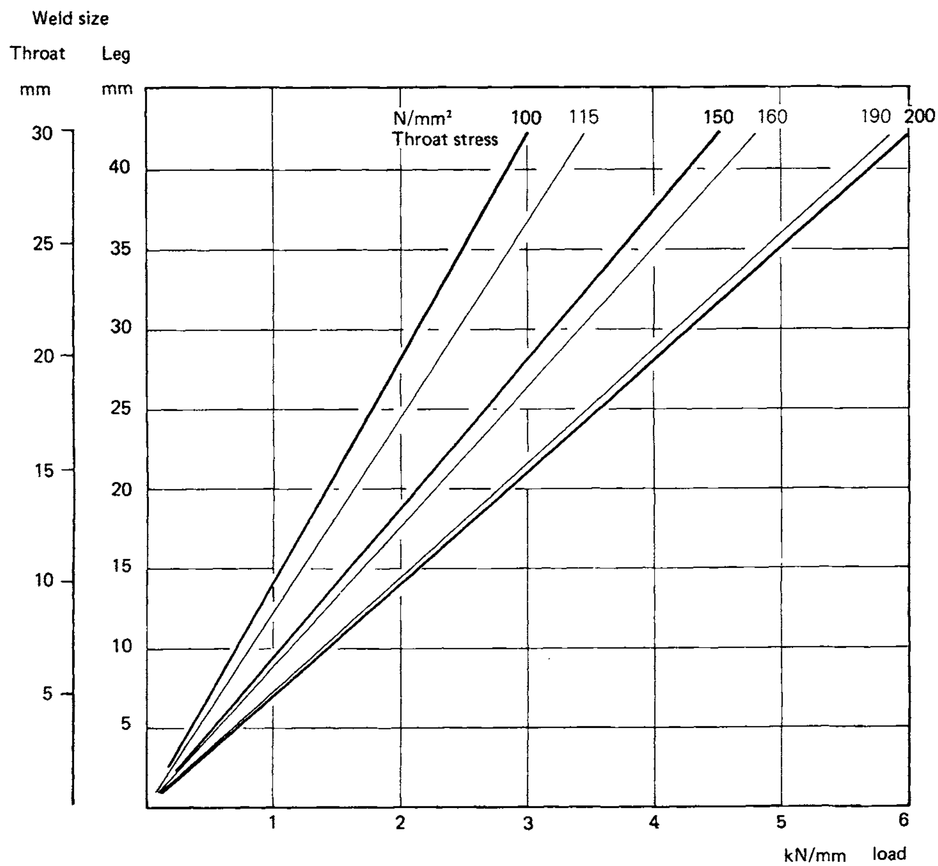
So $\quad 0{\cdot}7\sqrt{[84{\cdot}87^2 + 3\,(84{\cdot}87^2 + 20^2)]}$
$\quad = 121{\cdot}26\ \text{N/mm}^2$

This is less than the allowable tensile stress of 155 N/mm² and so we can reduce the weld size in proportion, and it can be

$$\frac{121.26}{155} \times 10 = 7.8\ \text{mm}$$

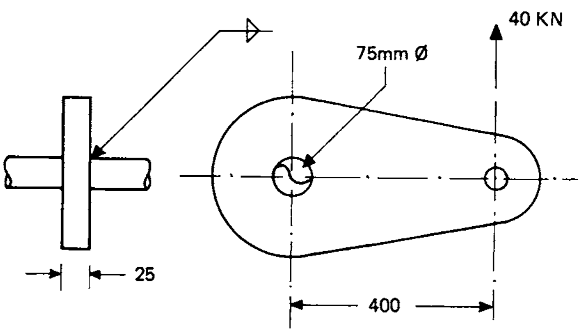
throat thickness compared with the previous size of 10.0 mm.

The fillet weld design chart below gives a quick method of calculating weld size from load per millimetre length of weld.



Fillet weld design chart

Two practical examples will clarify the way to calculate fillet welded joint strengths.



1. *A lever is mounted on a shaft*. What weld size is required? The force on the lever creates a torque of 16 kNm in the shaft. The welded joint transfers this torque to the shaft. We can take the weld length as $\pi \times 75$mm and this has a torque arm equal to the radius of the shaft. If the weld throat is t, since we have a twin fillet weld then with an allowable throat stress of 115 N/mm²

$$37.5 \times (\pi \times 75) \times 2t \times 115 = 16 \times 10^6$$

(10^6 is required to obtain equivalent dimensional units on each side of the equation)

so $$t = \frac{16 \times 10^6}{2\,032\,218} = 7.87 \text{ mm}$$

The leg length is then $7.38 \times \sqrt{2} = 11.13$ mm

In practice we might call for a 12 mm leg fillet weld on each side of the lever. We could refine the calculation and take the weld length measured along the centre of its throat. Reverting to the calculated value of 7.38 mm the diameter of the weld line is then

$$75 + \frac{7.38 \times 2}{\sqrt{2}} = 85.43 \text{ mm}$$

We can then write

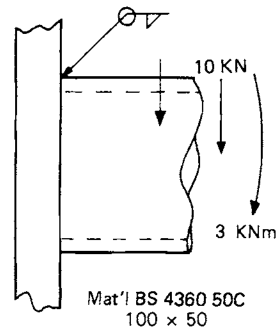
$$42.71 \times \pi \times 85.43 \times 2 \times 7.38\sigma = 16 \times 10^6$$

whence σ, the calculated throat stress,

$$= 94.57 \text{ N/mm}^2$$

We could then call for 10 mm leg length fillet welds which will be a saving in weld metal and so represent a cost saving.

2. *A connection between a hollow section and a plate*. What fillet weld size is required?



A simple method is to assume that the shear is taken on the vertical (web) welds and the moment is taken on the horizontal (flange) welds. For weld metal matching grade 50 steel the allowable throat stress is 160 N/mm² (B.S. 449).

Then for the web welds

$$200t \times 160 = 10\,000$$

$$\text{and } t = \frac{10\,000}{32\,000} = 0{\cdot}31 \text{ mm}$$

which is too small for practical welding.

For the flange welds

$$\frac{3 \times 10^6}{100} = 50 \times t \times 160$$

$$t = \frac{3 \times 10^6}{50 \times 100 \times 160} = 3{\cdot}75 \text{ mm}$$

$$\text{leg length} = 5{\cdot}3 \text{ mm}$$

In practice we would use a 6 mm leg length weld all round the joint.

A more refined calculation takes into account the effective bending modulus of the weld. The moment of inertia I is calculated using the weld throat as the section thickness.

Area	A mm²	Ay mm³	Ay^2 mm⁴	I mm⁴
Flange welds	$100t$	$100t \times 50 = 5000t$	$250\,000t$	—
Web welds	$200t$	—	—	$\frac{2t \times 100^3}{12} = 166\,667t$

Total $I = 416\,667$ mm⁴

$$\text{Then } Z = \frac{416\,667}{50} = 8333t \text{ mm}^3$$

so if stress in the flange is not to exceed 160 N/mm²

$$8333t = \frac{3 \times 10^6}{160}$$

$t = 2.25$ mm ignoring the shear load.
However if we take into account the shear load the weld stress is

$$\frac{3 \times 10^6}{8333t} \text{ due to bending}$$

$$\text{and } \frac{10 \times 10^3}{300t} \text{ due to shear.}$$

Resolving this we obtain the total shear stress

$$\sqrt{\left[\left(\frac{360}{t}\right)^2 + \left(\frac{33}{t}\right)^2\right]} = \frac{242}{t}$$

$$\text{then } t = \frac{361}{160} = 2{\cdot}25 \text{ mm}$$

Obviously the shear load in this case makes little difference. By using the weld modulus we now have a weld leg length of only 3.2 mm compared with the previously calculated 5.3 mm. In this type of example we can see the importance of employing a calculation method which fully acknowledges the contribution of all the welded joint. Note that because of the relative proportioning of the stresses due to shear and bending the use of the fillet weld strength calculation given on page 51 would not have made any significant difference to the answer.
Note: in this chapter the allowable stresses have been based on B.S. 449: Part 2: 1969. Other standard specifications quote different allowable stresses, and these must, of course, be used if the design is to one of these standards.

CHAPTER 8

Fatigue Life

Fatigue of metals is a very misunderstood subject if only because the very word fatigue is so inappropriate. It implies an exhaustion of some type, the loss of properties, when it is in fact nothing of the sort. The name arose in the nineteenth century from very inadequate observations and has been used ever since. What we call fatigue in metals is the starting and the progression of cracks under fluctuating loads. We often read of hairline cracks, this can mean any sort of crack, whether it be in a tea cup or a power station. The reader is here advised to cast aside all previous notions and build up a picture for himself on the following fundamentals.

1. Neither metals nor the welds joining them are as smooth as they look, they have pits, grooves and cracks.
2. Metals tear or fracture when they are stretched more than a certain amount.
3. The pits, grooves and cracks in a metal under load cause high strains over very small areas. Fluctuating loads will create small tears or fractures, which increase in length with each application of the load – a sort of ratchet effect develops because the metal around the crack is stretched and compressed plastically at each load application. The surrounding bulk of metal will control the amounts by which the crack can open.

At this stage the crack must be thought of as being so small that it does not affect the overall strength of the component in the same way that an oil hole in a shaft or a drainage hole in a girder will not influence the strength of those items. It is only when the fatigue crack becomes large enough to affect the component strength that we can start talking about *failure*. Conventionally a *fatigue failure* occurs when the crack has reduced the section so much that the tensile strength of the metal is reached on the remaining section or the crack is large enough to start a brittle fracture. In certain products a fatigue crack can be undesirable when it affects the operation of a unit without causing fracture. For example a fatigue crack which goes through the wall of a tank, pipeline, or pressure vessel will cause leakage even though there is no structural collapse. A crack can change the stiffness of a structure and make it liable to resonate at loading frequencies it was designed to avoid. The last two effects are, in fact, turned to advantage in some areas. The presence of cracks in helicopter rotor blades and the tubular jibs of very large draglines is detected by pressurising the hollow members and measuring pressure drops which occur if fatigue cracks are present. It has been proposed that cracks in offshore platforms could be detected by monitoring the natural frequencies of the platform which may change if cracks occur.

The rate at which a crack spreads, *propagates* is the commonly used word, depends on the size of the stress fluctuation in the cracked member and the size of the crack itself. These combine to produce the amount of plastic deformation, or stretch, at the crack tip.

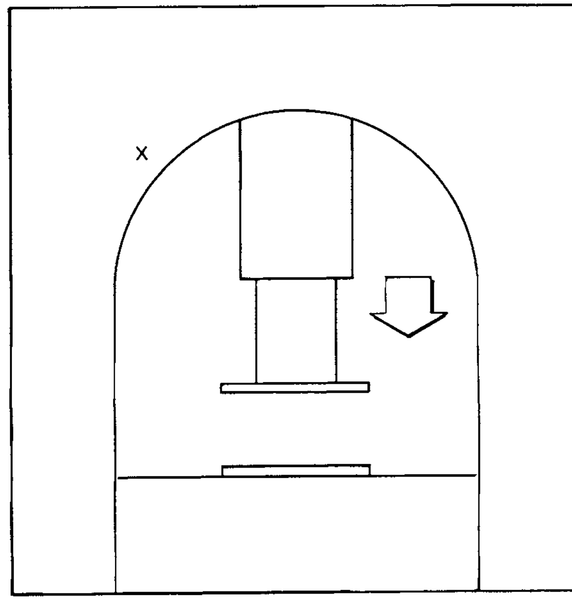
If, for the sake of argument, we assume that in welded components the cracks and grooves are all much the same size to start with, the only important effect is the stress fluctuation. The stress that the metal sees is the uniform stress magnified by any local shape changes, and the degree of magnification is called the stress concentration, caused by holes, grooves, steps and, of course, welds.

The number of stress fluctuations which a member will stand before failure is called the *fatigue life*. This can be described more clearly in a diagram showing the variation of stress with time, such as might occur in a hydraulic press or a conveyor pulley.

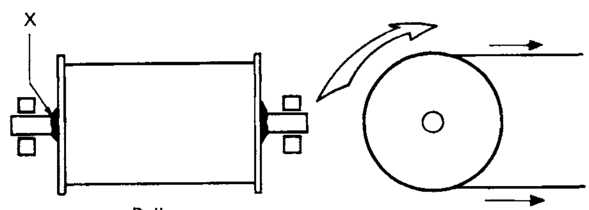
The stress in the press starts at zero and increases as the pressing, or forming operation proceeds and then dies away as the pressure is reduced. At any particular point on the pulley shaft the stress changes from tension to compression as it rotates.

In the press the stress *range* is equal to the maximum stress whereas in the pulley the stress range is twice the maximum stress. In welded components it is the stress range which decides the fatigue life and is, therefore, very important. The relation between stress range and fatigue life is most simply shown as a graph produced from experimental results.

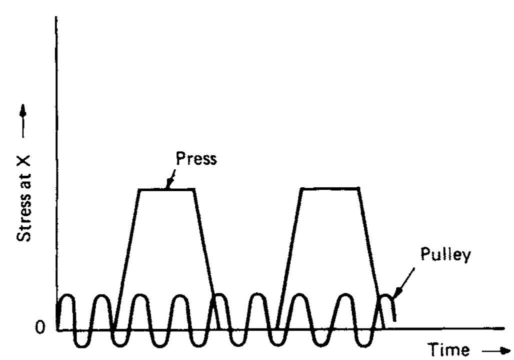
Such a graph is called an SN curve or a Wöhler

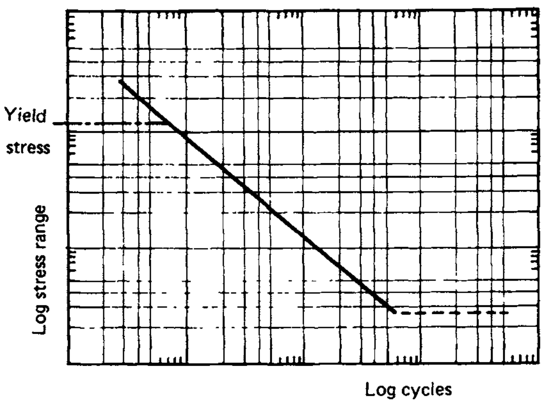


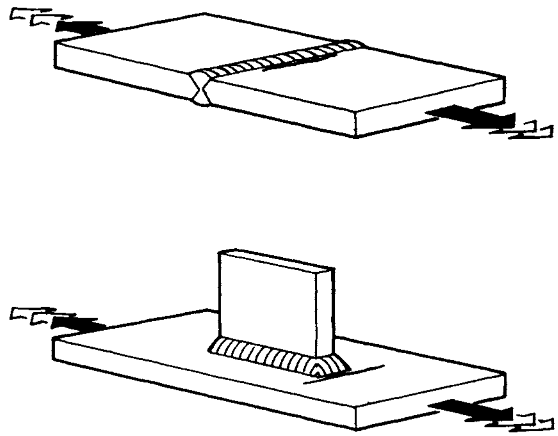
Press



Pulley







line. At very low stress ranges we might find that the pulleys did not fail at all so there is a cut off, shown dotted on the SN curve. At the high stresses we run into the region where the performance of the pulley is limited by the yielding of the steel so we have an upper limit beyond which this type of component cannot go. In practice, of course, the maximum allowable design stress is lower than the yield stress. In a structure like the hydraulic press there can be local stress concentrations, and although the main body of the structure will be working below the allowable design stress there will be areas of stress concentration working well above that level, so we need to know the whole of the SN curve.

Since the longest life will be obtained with the lowest stresses the best design will have the minimum of stress concentration and the whole structure will be evenly stressed. It is impossible to avoid all stress concentrations and the most difficult ones to avoid arise from welded joints have differing degrees of stress concentration and their relative fatigue lives are not always in the most obvious order. For example a butt weld in a plate might be expected to have a shorter fatigue life than an unjointed plate with a welded bracket carrying no load. Unfortunately if a butt-welded plate with a welded bracket is fatigue tested the fatigue failure will occur at the bracket weld. The crack will start at the toe of the weld and spread into the plate until failure occurs.

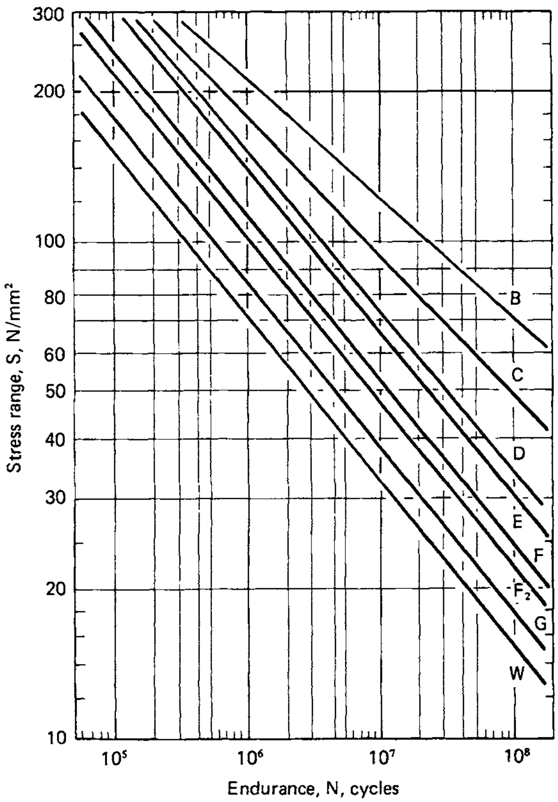
A whole range of welded joints has been tested and the results have been analysed to produce design SN curves. Joints having similar fatigue performance are grouped under categories to make life easier for the designer. The answers are not however clear cut.

Every specimen is slightly different as is each item from a production run and the fatigue test results show a great deal of scatter. A mean line can be drawn through test results but for practical purposes the designer needs to be sure that only an acceptable proportion of his products will fail before the design life.

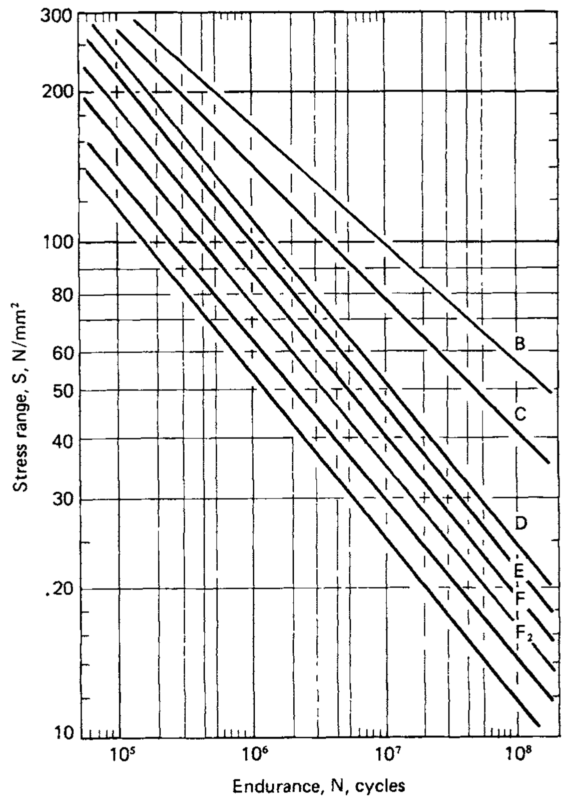
It is sometimes the practice to divide the mean life by a factor to make sure that early fatigue failures do not occur. This is a rather crude device and a more refined method is used in which the test results, and service experience, are analysed to give SN lines with a certain probability of failure. The mean line gives a situation where 50 per cent of the components designed for that life will have failed by the time that life has been reached. Any other line can be drawn with other probabilities of failure or, more positively, probabilities of survival.

The SN lines below are for the 50 and 97.5 per cent survival levels.

SN line for 50% survival



SN line for 97·5% survival



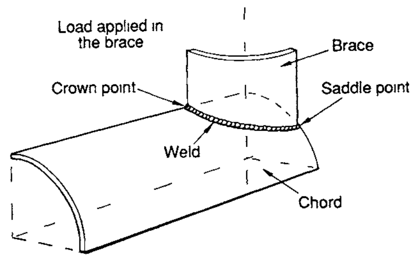
The table on pages 60–65 gives the classification of the more common types of welded joints to be used with the SN lines above. The table is based on the proposals by Dr T R Gurney of The Welding Institute which have been used to formulate the British Standard for Bridges (B.S. 5400) and the United Kingdom Department of Energy Guidance on the design of offshore installations. These documents should be consulted for fuller details in respect of those types of structure, although this design data in its basic form applies to any welded steel item. It will be seen that for offshore structures a correction to the SN curves has to be made if the thickness of the material is more than 22 mm. This is a result of research which shows that the thicker the material, the lower the fatigue life.

Steel tubes are often used as structural members in products as wide-ranging as building frames, cranes and offshore structures. The design of joints between tubular members requires special consideration because of the secondary stresses which are caused by local bending of the tube walls.

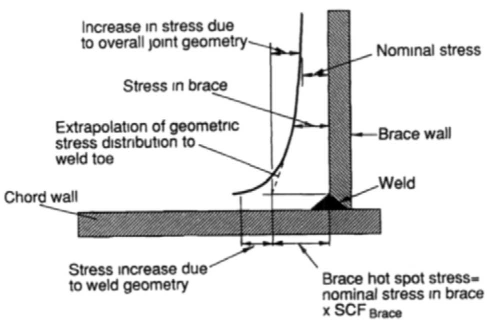
Most of the joints in structures made from tubes consist of one or more brace members joined to a main, or chord, member:

The secondary bending set up in the chord member means that the nominal stress in the members cannot be used with the SN curves above because the life would be seriously underestimated. Instead the greatest stress in the member at the toe of the weld has to be calculated; this is not an easy task because the stress varies around the joint.

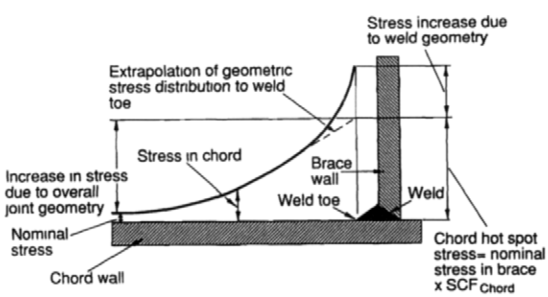
This greatest stress is called the hot spot stress and is usually calculated by using published formulae called parametric equations. These are empirical equations derived from experimental and theoretical work. They are at present limited in the complexity of joints which they can deal with, and even then are not very reliable; most of them err on the conservative side which is not always beneficial. More exact stresses can be calculated by the use of finite element computer programs, but these can be very costly to run for the complicated joints for which they are of the greatest benefit.



Nodal joint nomenclature

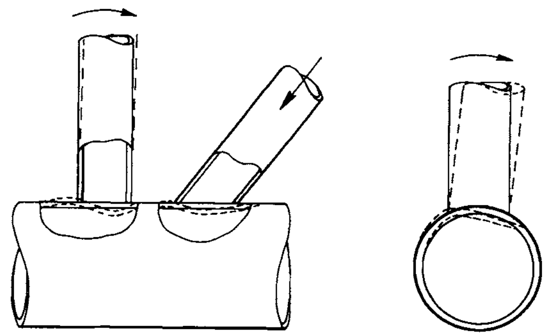


Stress distribution in brace



Stress distribution in chord

Hot spot stresses in a nodal joint



Local deformations in a tubular joint

Having calculated the hot spot stress, the engineer is then in a position to undertake a fatigue analysis. A special set of SN curves is used with these hot spot stresses. These curves are published in various codes, standard specifications and guidance. The example shown here is from Gurney and refers to circular section tubes. As with the SN curves for plates and sections, there is an adjustment in the curves to be made for the effect of the thickness of the material on the fatigue life. The curves shown here are for 97.5 per cent probability of survival which is the level commonly used in most industries.

This form of presentation has been extended to include rectangular section tubes and has been proposed for the Eurocode EC 3 Common unified code of practice for steel structures. A detailed discussion of the derivation of these curves has been prepared by Professor Wardenier of Delft University.

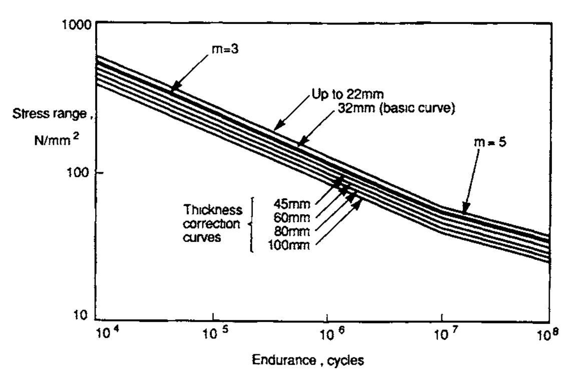
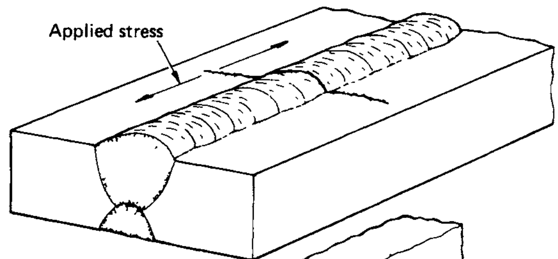


Diagram by permission of The Welding Institute

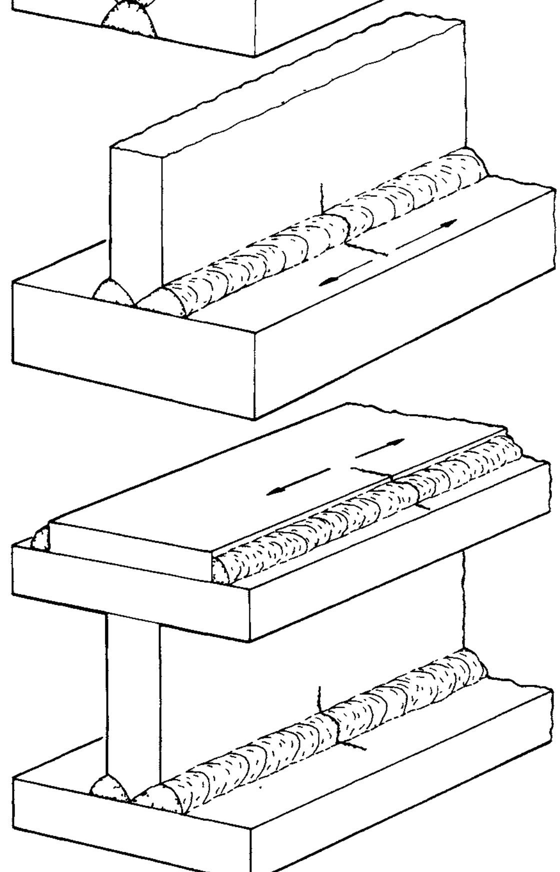
Class ***Description*** ***Location of Fatigue Cracks***

A. Plain steel surfaces polished and with no abrupt changes of section.

B. As-rolled steel with any flame cut edges dressed smooth.
Butt welds free of defects and with the faces dressed smooth and blended with the steel surface.

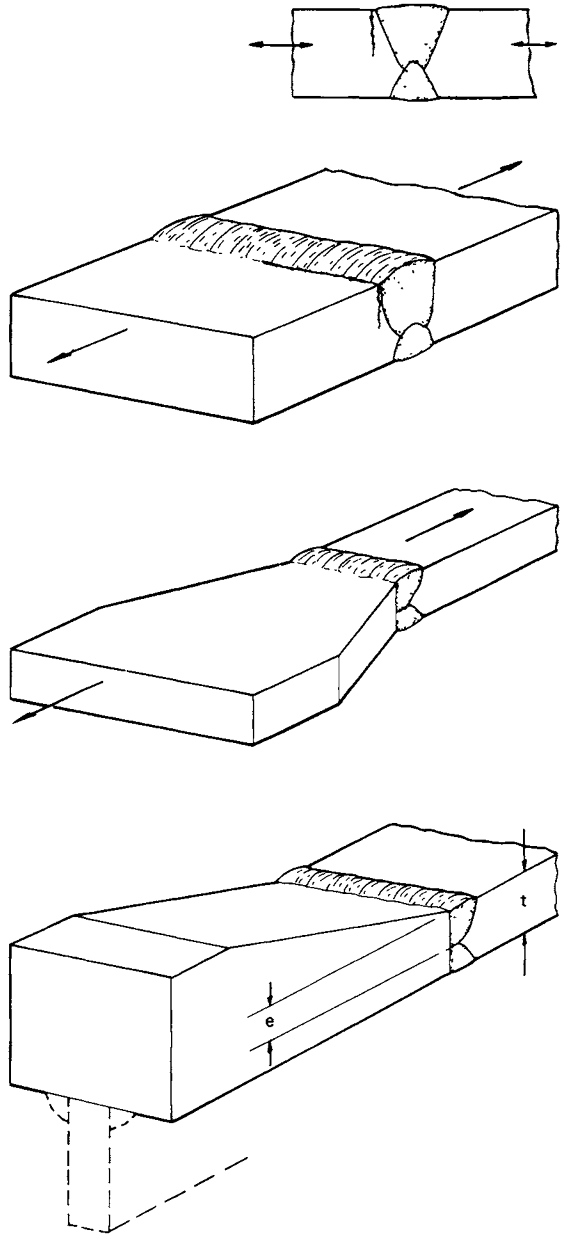


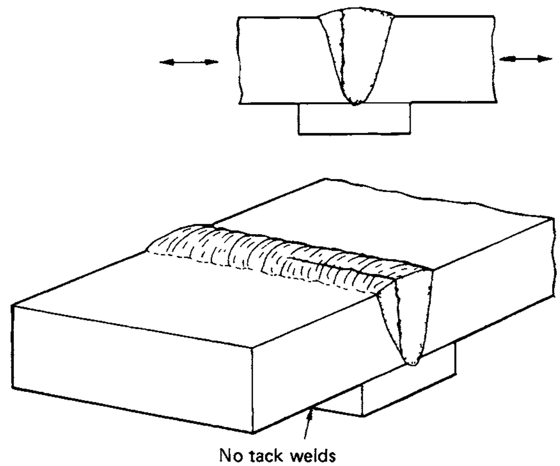
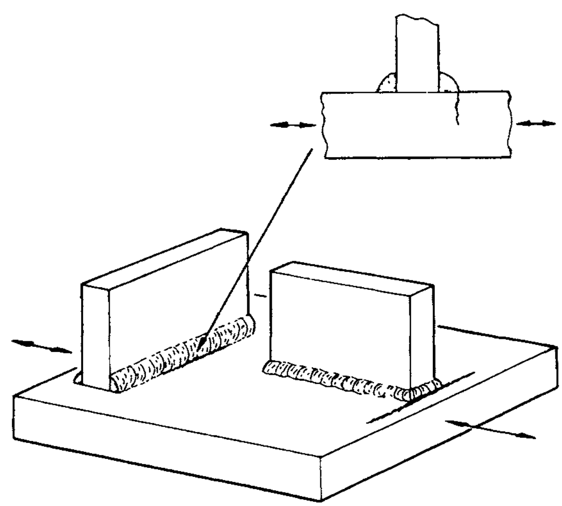
C. Full or partial penetration butt welds or fillet welds parallel to the direction of stressing, made by mechanical processes with no stop/start positions.

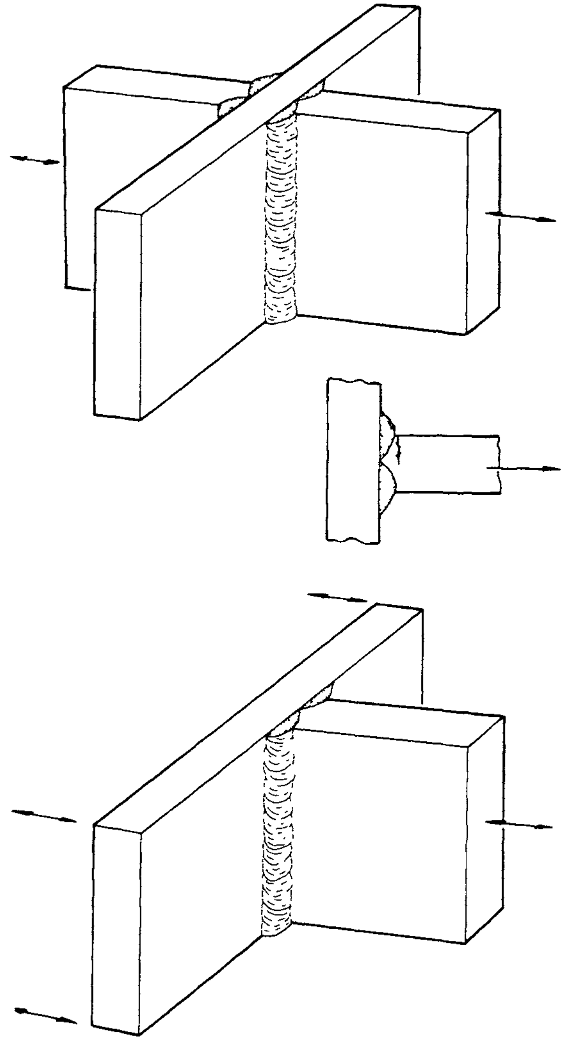


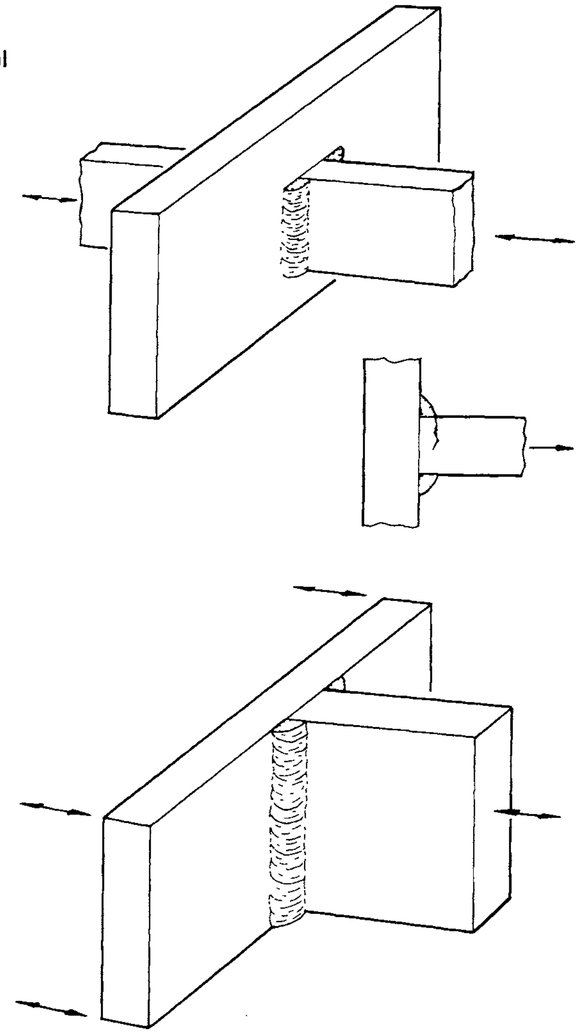
Class	***Description***
D.	Full or partial penetration butt welds or fillet welds parallel to the direction of stressing, made with manual processes or mechanical processes with stop/start positions. Full penetration butt welds transverse to the direction of stressing with a smooth transition between the weld surface and the parent material.

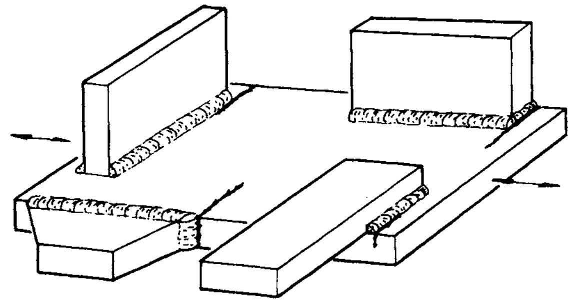
Location of Fatigue Cracks



Class	Description	Location of Fatigue Cracks
E.	Full penetration butt welds transverse to the direction of stressing with abrupt transition between the weld surface and the parent metal	
F.	Butt weld on a backing strip transverse to the direction of stressing.	
	Members with attachments welded to their surface.	

Class	***Description***	***Location of Fatigue Cracks***
F.	Cruciform or T-joints made with full penetration butt welds.	

Class	*Description*	*Location of Fatigue Cracks*
F2.	Cruciform or T-joints made with partial penetration butt welds or fillet welds.	

Class	*Description*	*Location of Fatigue Cracks*
G.	Members with attachments welded to their edges or close to the edges.	
W.	Weld metal in load-carrying joints made with partial penetration butt welds or fillet welds with the weld either parallel to or transverse to the direction of stressing. The stress used in calculating the fatigue life is the stress on the weld throat.	

Joints between tubular members can have very high stress concentrations which have to be allowed for. Their fatigue life can be predicted from the foregoing classification provided that the joints can be analysed or stresses measured.

When this is not practicable a simplified method based on the loads and the sizes of the members can be used. This is described in detail in the A.W.S. Structural Welding Code and is known as the *punching shear* method. So far this chapter has described situations where the stress fluctuations are always the same. Unfortunately this is not so for many, if not most, engineering products.

Vehicles on road, rail, sea and air are loaded in a random fashion by their motion. Towers and tall buildings suffer wind loading of varying intensity. Cranes lifting a range of loads from various positions will have difference fluctuations. Wave loadings on piers, jetties and offshore platforms cause a complicated stress history.

To calculate the fatigue life under such complicated loadings it is necessary to calculate or measure the number of cycles at various stress ranges. Use is made of the *linear cumulative damage rule* which can be explained by saying that if for a stress range S_1 the constant amplitude fatigue life is N_1 cycles, then n_1 cycles will use up a fraction n_1/N_1 of the fatigue life. In a stress history with stress ranges S_1, S_2, S_3, etc. occurring n_1, n_2, n_3, etc. times respectively failure will occur when

$$\frac{n_1}{N_1} + \frac{n_2}{N_2} + \frac{n_3}{N_3} + \ldots\ldots + \frac{n_i}{N_i} = \sum\frac{n}{N} = 1$$

As an example take a class F detail on an overhead travelling crane at a reinforced concrete plant. The crane does three basic lifts.

Movement	Load	Lifts/ Year	Stress at Welded Detail	Constant Amplitude Life
(*a*) Lift and transport skip full of concrete to casting bay	10 tons	6000	80 N/mm²	1 400 000
(*b*) Lift and transport empty skip back to batching plant	1 ton	6000	8 N/mm²	> 10^8
(*c*) Lift completed R C beam on to transporter	25 tons	1800	200 N/mm²	80 000

So for one year's operation.

$$\frac{n}{N} = \frac{6000}{1\,400\,000} + \frac{6000}{10^8} + \frac{1800}{80\,000}$$
$$= 0{\cdot}004\,29 + 0{\cdot}000\,06 + 0{\cdot}002\,250$$
$$= 0{\cdot}026\,85$$

the life of the detail will then be

$$\frac{1}{0{\cdot}026\,85} \approx 37 \text{ years.}$$

This is a very simple example and for the more complicated random load histories there are various methods of calculating fatigue damage which can be found in the literature.

It is possible to increase the design fatigue life of a welded joint over that indicated by these SN curves if one of a number of post-weld treatments is applied. The simplest one is to grind the whole of the weld profile smooth and blend it in with the parent metal. Almost as effective but not so easy to control is to grind only the toes of the weld. Shot blasting the joint will improve fatigue life, but the greatest improvement of all is achieved if the toe of the weld can be peened with an automatic hammer. This requires careful control and is not to be recommended without thorough attention to the details of the technique. Thermal stress relief will improve the fatigue life of a fabrication by a limited amount which depends on, amongst other things, the magnitude of compressive stress in the load history. Research has shown that painting weld joints with epoxy paints can improve their fatigue life, but there is no published information on any service experience with this technique. Melting the toe of the weld with a TIG welding torch has been shown to give a life extension.

This table shows the relative improvements which could be expected from some of these techniques.

Technique	Life multiplied by maximum of:
Painting	3
Toe grinding	8
Shot peening	8
Hammer peening	11
Stress relief	1.5

These figures are for a steel plate with a stiffener attached with a butt or fillet weld under a stress range, for which the life without treatment would be two million cycles. For higher lives many of the techniques give even greater improvements.

The reader may well ask why these techniques are not used extensively when such large increases in life are possible. There are two reasons. Firstly, except in the case of stress relief, the methods require manual operations which are costly. The finished detail requires throrough inspection for if even only a small length of weld remains untreated the joint will have the original fatigue life. Secondly, the improvements, again except in the case of stress relief, operate only on the surface of the weld so that in fillet welds and partial penetration butt welds the treatment will delay failure only until a crack starts from the weld root. A similar effect occurs with weld defects. For example, if a full penetration butt weld is to be ground to extend its fatigue life the weld quality standard will have to be improved so that previously acceptable defects do not cause premature cracking.

A limited range of structures in which the stress pattern is consistent can have their fatigue lives improved by overloading them before use, as in the proof stress applied to pressure vessels and cranes for other reasons. The press frame shown on page 56 could have its fatigue life improved if, before being put into production, a cycle of operation were carried out with the hydraulic pressure in excess of the normal operating pressure. The greater the excess the bigger the improvement, as long as the press isn't damaged in the process!

It is essential to be aware that this technique will not work if the structure doesn't have a consistent load history. The press and any pressure vessel are suitable because the loads are always in the same direction. On the other hand the runway girder of an overhead travelling crane sees both compressive and tensile stresses at the same point in the girder as the gantry passes over successive supports. In that case the method will not improve the life.

Some of the life extension methods can be used after the item has been in service. Grinding, hammer peening and TIG melting act directly on the potential fatigue cracking sites and so will still be effective even if small cracks have already developed. Overloading will still be effective as long as any cracks are not large enough to cause failure by brittle fracture.

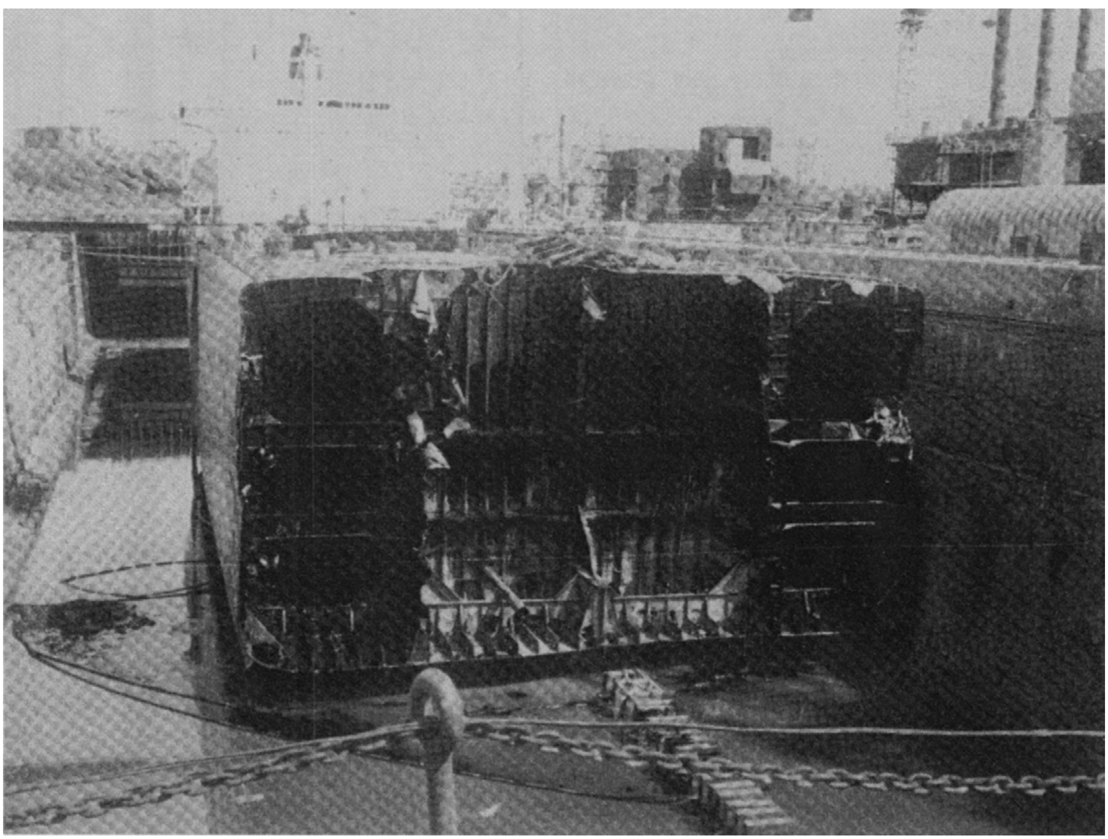
CHAPTER 9

Brittle Fracture

Chapter 7 described how steel under tension stretches elastically and then, when the stress is high enough, plastically. This sequence of properties is used to advantage in the rolling or forming of steel plates into various shapes, which would be impossible without this plastic property of steel. Consequently engineers have been surprised when steel structures and pressure vessels, items designed to conventional working stresses and operating under quite normal conditions, have literally flown apart or split in two.

The ship below broke in two at sea off the coast of Canada in 1979.

What is seen in this picture is what is called a 'brittle fracture'. It is a fast-moving fracture which gives the impression that the steel has lost its easy plastic property and has changed into a glass-like solid. This is not the case; what has happened is that a crack grew at high speed through the metal from some small irregularity. Welding can introduce irregularities such as slag inclusions, lack of fusion and cracks. When the welded steel is stressed, these irregularities interrupt the stress field and, like all such features, have the effect of a notch which locally increases the stress. In the case of the Kurdistan the origin of the fracture was a weld defect in the bilge keel.



Brittle fracture in a ship's hull – M. V. Kurdistan. *Photograph by courtesy of The Welding Institute*

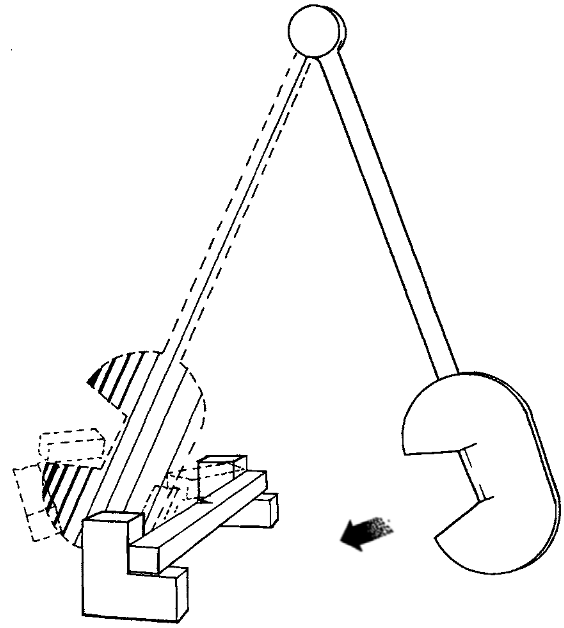
The strain across the tip of the notch is much higher than elsewhere, so that even if the steel is elastic in the main part of a steel plate it will be plastic around the tip of the notch. Now, because the plastic area is very small and is surrounded by elastic material, the strain cannot be relieved by relaxation over a larger area and in effect the steel which is highly strained begins to tear or crack and, like the splitting of a log with an axe, the crack goes on, driven by the elastic energy stored in the rest of the steel. Occasionally such a crack will stop, or be arrested, after it has exhausted the stored energy or when it has run into an area of the steel which has what is known as a high notch toughness.

Obviously this behaviour doesn't happen to every piece of steel under stress and there are three circumstances which must be present to make it happen. These are:

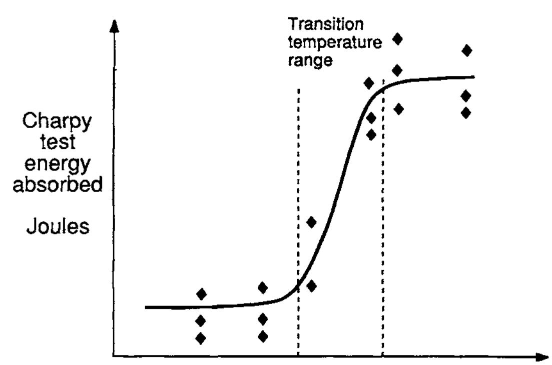
1. A stress concentrator.
2. A stress to be concentrated.
3. A low value of the property of the steel known as notch toughness.

The first two of these circumstances are well known to engineers but the third is not always so well known. This property of notch toughness represents the capacity of the steel for resisting brittle fracture from a notch. One of the most common measures of this property is the Charpy test. In this test, a bar machined out of the steel and notched half-way along its length is mounted between supports and struck by a weighted pendulum. This will usually break the bar and in so doing will absorb energy from the pendulum. A notch tough steel will absorb more energy than a notch brittle steel and the energy used in fracturing the bar is considered a measure of the notch toughness of the steel, in joules.

A feature of the carbon or carbon-manganese ferritic steels, i.e. those commonly used in structural engineering, is that their resistance to brittle fracture varies with temperature. When a series of Charpy tests is conducted at successively lower temperatures there comes a temperature at which the energy required to break the specimen falls rapidly and then remains at a more or less constant



Charpy impact test



Typical Charpy test results for steel plate level. The temperatures over which this change takes place are in the 'transition temperature range', a feature of these commonly-used structural steels.

The required level of Charpy energy to confirm resistance to brittle fracture at any service temperature is also a function of the thickness of the steel.

As a result, product specifications will call for Charpy tests at temperatures which will depend not only on the service temperature but on the material thickness. These requirements have been drawn up on the basis of research and experience and their origins are not explicitly stated in the specifications.

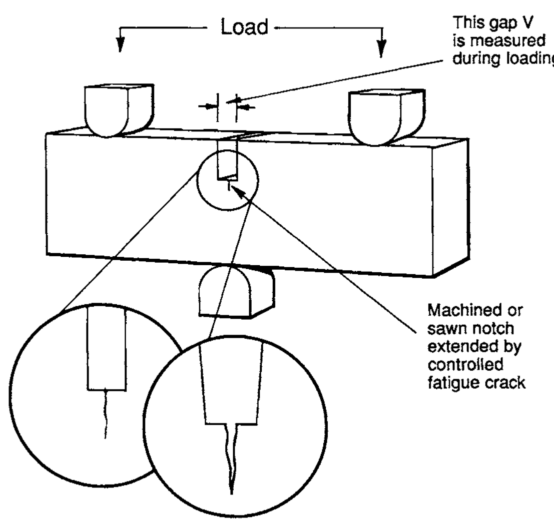
For some specialised areas of engineering the definition of notch toughness by the Charpy test is not considered sufficient, and a more discriminating approach is used, based on concepts called 'fracture mechanics' which examine the stress in the metal at the tips of cracks. In conventional engineering calculations the stresses in the item under load are derived, but the stress concentrating effect of such details as bolt holes is often neglected, although their cross sectional area may be deducted from the member section to give a net section. Rarely are the details of the stresses at the holes calculated because experience shows that under static load the steel will yield there and will not break.

For cracks the matter is not quite so simple; these induce very high changes of stress and strain over small areas which are not a function of the dimensions of the member but are related more to the size and shape of the crack. In a material like steel, where there is a change from elastic to plastic properties, the crack tip under load is surrounded by a plastic zone in which the stress defies conventional calculation. Specialists in this subject have approached the problem by saying that, in effect, the region around the crack tip is in a state of stress which is described by a quantity called a stress intensity factor, K, a quantity which summarises the effects of that stress rather than defining its distribution. The units are unusual being expressed in

$$\frac{\text{Newton}}{\text{millimetres}^{3/2}} \qquad (\text{Nmm}^{-3/2})$$

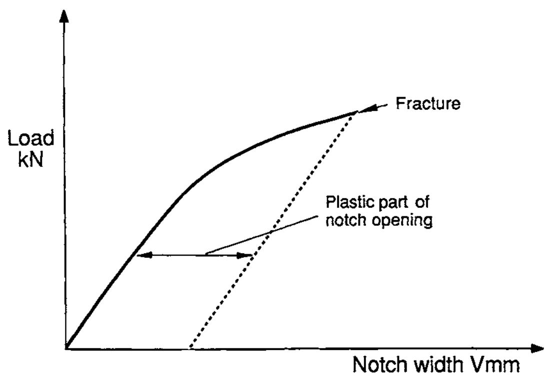
The value of the stress intensity factor which causes brittle fracture is called the 'critical stress intensity factor, Kc'. This concept is valid for low stresses, small cracks and brittle materials, but for notch ductile steels an alternative concept has to be used. One such concept is based on the extent to which a crack in the steel can be stretched open before brittle fracture or ductile failure occurs. The measure of this opening, is made on a standard type of test specimen and is called 'crack tip opening displacement', CTOD.

The CTOD specimen looks like this and is loaded in a conventional test machine:



CTOD test set up

The values of K or CTOD at which fracture occurs can be used, with a little mathematics, to define the fracture toughness of the material which is required to resist brittle fracture from a certain size of crack under a certain stress or strain level. Conversely they can be used to calculate whether a certain defect is likely to start a brittle fracture in a steel of known fracture toughness. This is the basis of the 'fitness for purpose' approaches which are used to set quality standards.



Record of CTOD test result

As with the Charpy test, the CTOD varies with temperature and a transition curve can be plotted. The CTOD specimen is of the same thickness as the steel in the structure and so the test value can be applied directly to the actual job.

Successful use of these concepts in material selection and in setting quality standards requires a far deeper knowledge and understanding of the subject than is given in this chapter. Nonetheless the engineer needs to know when this question of brittle fracture merits attention at the design stage. There is no direct answer to this except for those who are working to rigidly enforced specifications. In other circumstances the engineer will find it helpful to make a checklist as follows for any welded ferritic steel construction:

(*a*) Is the item under tensile stress greater than 25 per cent yield?

(*b*) Is it thicker than 5 mm?

(*c*) Is it to operate at temperatures below 5° C?

(*d*) Does the fabrication involve cold bending or forming?

(*e*) Would a sudden fracture have serious consequences?

If the answer to all of these questions is *no* then attention to notch toughness is not essential.

If the answer to any of the questions is *yes* then consideration should be given to controlling the risk of brittle fracture. There are two principal means of controlling this risk and a number of subsidiary actions which can be taken. The primary approach is to use steel and weld metals which have a notch toughness sufficient to avoid brittle fracture under the working conditions. This assumes that the quality of fabrication is of a minimum standard which must exclude any crack-like defects and the larger volumetric defects. Depending on the severity of the demands for controlling the risk of fracture, the achievement of this level of quality can be accepted on the basis of a quality assurance programme in which non-destructive testing methods appropriate to the risks to be accepted and the configuration of the welded joints may be included (see Chapter 12).

Steel of less demanding notch toughness can be employed if the second means of controlling the risk is employed in which the fabrication is post-weld heat treated, known as 'stress relieving'. This reduces residual stresses and can improve the notch toughness of the steel around any weld defects.

There are service temperatures so low, such as those at which liquefied gases are stored, that none of the conventional structural steels can give a low risk of brittle fracture. For such purposes it is the practice to use aluminium alloys or some of the stainless steels which do not have a change in notch toughness with temperature.

As the risk of brittle fracture under any particular set of circumstances is a function of the size of a crack-like defect, a method of avoiding fracture might be to make fabrications without any defects. However, there is no practical means of achieving and verifying a defect-free fabrication so that is an approach which is discounted in practice.

The setting of steel requirements in practice is a somewhat empirically-based matter and the knowledge and experience of specialist engineers and metallurgists in this field is the main source of specifications. Guidance in the use of some of the available methods is given in a document published by The British Standards Institution under the number PD 6493.

CHAPTER 10

Welding Procedures

The term 'welding procedure' has a very specific meaning when compared with other procedures. It is really a recipe for producing a welded joint defining the materials, the preparation of those materials, the operations to be performed and values of all the parameters which enter into the making of a weld.

This is a list of the items which are included in a welding procedure for the arc welding of steels:

(*a*) Parent material specifications and thickness.
(*b*) Joint configuration.
(*c*) Welding process.
(*d*) Welding consumables i.e. electrodes, wire, flux etc. and treatment, e.g. baking.
(*e*) Edge preparations and method, e.g. gas cutting, grinding.
(*f*) Weld preparation.
(*g*) Welding position.
(*h*) Pre-heat temperature and method of checking.
(*i*) For each pass (including tack welds):
type of consumables.
size of rod or wire.
welding voltage (DC or AC and polarity).
current (wire feed speed for MIG and MAG).
gas flow rate (TIG, MIG or MAG).
travel speed or run-out length.
direction of travel (vertical position).
electrode stick out (MIG, MAG and SAW).
weave width.
(*j*) Limits on interpass temperature.
(*k*) Sequence of weld passes.
(*l*) Method of cleaning or gouging, e.g. grinding, air-arc.
(*m*) Post-weld heat treatment.
(*n*) Inspection and non-destructive examination.

This information is recorded on a document called a Welding Procedure Specification, or WPS for short. In practice it is impossible to expect to define exact values of all these quantities, and tolerances are entered directly onto the WPS or by reference to a relevant standard specification.

Although this WPS can be used for any particular job, there are many situations where the customer demands that the Welding Procedure be tested to demonstrate that the required mechanical properties and integrity are actually produced. This entails welding a sufficiently representative joint that all the features which influence the properties and integrity of the joint are reproduced. This joint is then subjected to non-destructive testing and destructive testing to show its conformance with the desired characteristics. The record of the welding procedure test will include the exact values of the parameters which are listed on the WPS and the results of the inspection and tests. This record is called the Procedure Qualification Record or PQR for short. On it is entered the specification in accordance with which the test was carried out and the range of the variables for which it is valid. Examples of a WPS and PQR are shown on pages 75 and 76.

This information is important to the overall welding operation but many of the variables are outside the control of the production welder and for a particular product the range of variables may be unnecessary. It is then the practice in some industries to prepare a welding data sheet on which are recorded only those items which are under the direct control of the welder or his immediate supervisor. This will be a simple card which the welder can refer to for his instructions.

Great play is often made of 'approval' or 'qualification' of welding procedures. These words really mean the same, but are sometimes taken to indicate conformance with a standard specification when qualification is used and acceptance for use by a customer when approval is used respectively. It should be noted that third party inspection organisations are often used to witness tests but their role is not to give unlimited approval to the procedure. Their function in most circumstances is only to confirm that the tests are conducted in accordance with the appointed specification. Their terms of reference usually extend from identification of the materials to the conduct of the destructive tests and the reporting.

The use and testing of welding procedures are included in many standard specifications such as BS 5135, BS 4870, AWS-DI.I and the ASME Pressure Vessel Code.

Welding Procedure
specification

No

Contractor:

Address:

Contract

Joint location

Drawing No

Material spec(s) To

Thickness qualified mm

Consumable treatment

Edge prep. method

Pre-heat temp. °C
Method
Retention time hrs
Temp. check method
Max. interpass temp. °C

Weld preparation

Weld sequence & position

Gouge method
Gouge check method
Inter pass cleaning
Max. weave width
Electrode stick out mm
Welding progression
Weld finish

Notes

Pass No.	Process/ Polarity	Man/ Mech.	Electrode/Wire			Flux/Gas			A	V	Run Out Length/ Travel Speed mm or mm/min
			Trade Name	Spec.	Size mm	Trade Name	Spec.	Flow Rate 1/min			

PWHT
Heating Rate °C/h
Soaking Temp. °C
Time h
Cooling Rate °C/h
Withdrawal Temp. °C

NDT

	Signed	Date
Prepared by (Contractor) Approved for test (Client)		
Approved for construction To code/spec For 1. Contractor 2. Client 3. Certifying authority		

No	Description	Date	By	Chk	1	2	3
					Approved		

Revisions

Welding Procedure
Qualification Record

No

Contractor: Address: Contract	**Welding Procedure** Qualification Record No
Welders Name No Supervisor's Name	Date Welded Location
Material Spec(s) Thickness Thickness Qualified Steelmaker Test Certificate No	Witnessed for / Signed / Date Contractor Client Certifying Authority

Welding Process		Manufacturer	Batch No.
	Electrode/Wire		
	Flux/Gas		

	Type	Serial No.	Calibration Record No.
Power Source			
Welding Machine/Gun			

These sketches required only if different from Weld Proc. Spec.

Weld preparation	Weld sequence	Measured preheat temp. °C Max. measured interpass temp. °C

Test Results	Test House	Report No.(1)	Date	Pass/Fail	Witnessed for (2)		
					Contractor	Client	C.A.
Visual Magnetic particle Radiography Ultrasonic							
Cross weld tensile Weld metal tensile							
Root bend Face bend Side bend Nick break							
Macro Hardness							
Charpy COD							

Note 1 All NDT and mechanical test reports must be attached to this form and must carry witnesses' signature and stamps.
2 Names of witnesses in this part are for reference only.

	Signed	Date
Prepared by		
Checked by		

CHAPTER 11

Quality Management

Any product is built to serve a purpose, and the aim of those responsible for its specification, design and manufacture is to make sure that it does that. The product may fail to serve its purpose for a number of reasons, of which the following are examples:

1. The purpose may be wrongly defined.
2. The design may be wrong.
3. The product may be incorrectly made.
4. The product may be used incorrectly.
5. It may not be maintained properly.

The characteristics of a product which affect its ability to serve its purpose are summarised in a word – 'quality'. The attention to quality is directed by executing a number of activities which are collected together under the term 'quality assurance'. This is defined as all the activities concerned with the attainment of quality, and not only the actual provision of proof associated with the word 'assurance'. Above all, it must be recognised that the ultimate responsibility for quality rests with each individual working on a task.

A key feature of quality assurance is that it looks ahead, not behind; it entails defining what is needed and then planning activities to ensure that what is needed is what is produced. These activities are listed in what is called a 'quality programme' for any particular company or organisation, and in a 'quality plan' for a particular item or product. An essential point about a quality programme is that it is an integral part of the company's management programme.

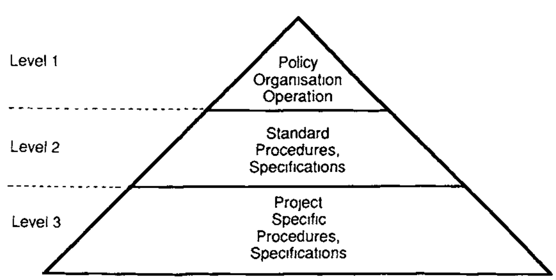
Some industries have been working in such ways for many years, but since the 1960s the more formalised approach conducted under the description of quality assurance has been introduced rapidly into a number of industries. Unfortunately in some instances the introduction has been conducted by personnel of insufficient vision and experience and has then been seen as a cosmetic operation involving much ineffective and costly bureacracy which has no effect on product quality.

Although the basic principles of quality assurance remain the same, their application to any particular industry or even any company within an industry must suit the way in which that industry or company operates. An attempt to force an unsuitable system onto an organisation will result in resistance from personnel, possible damage to quality and, without doubt, unjustifiable costs. A properly designed system will enhance product quality, motivate personnel, reduce costs and in the end satisfy customers to the benefit of all.

Written Procedures

Effective quality assurance can be pursued only by rigid attention to the way things are done, and in most cases this requires that the method be described in a written procedure. The method may then be examined on paper for its own correctness and may also be reviewed by others in adjacent activities. This 'interface' aspect is most important because there are few activities which do not impinge on others.

Procedures can be thought of as existing at several levels, as illustrated by the following diagram:



There is a recognised format for procedures; there are very good reasons for this particular type of sequencing of the contents:

(*a*) Scope: type of work or product.
(*b*) Purpose: what the procedure does.
(*c*) Definitions: special terms used in the procedure.
(*d*) Related procedures: other company procedures referred to.
(*e*) References: sources of information
(*f*) Responsibilities: *who* is responsible for executing the procedure.
(*g*) Narrative: the actual procedure.

The written procedure should say clearly and concisely what is to be done, but stop short of those activities which are part of a person's ordinary skills and tasks. If these are to appear anywhere they should be in the company's training manuals.

Quality Assurance in Welded Fabrication

Quality assurance principles are applied to welded fabrication in the same way as to other activities. In the terminology of quality assurance, welding is sometimes called a 'special process'. This is because it is not possible to measure all the qualities of a welded joint after it has been made. Contrast this with the simple operation of drilling a hole where a simple go-no go gauge will reveal whether the hole is the correct size.

The quality parameters which may be sought in a welded joint include:

(*a*) Static strength.
(*b*) Fracture toughness.
(*c*) Hardness.
(*d*) Freedom from unacceptable defects.
(*e*) Profile.

The only one of these parameters which can positively be measured after the weld is made is the profile. Weld defects such as cracks, porosity and lack of fusion which appear at the surface may be discovered by visual examination or, failing that, by the use of non-destructive testing techniques such as the magnetic particle or dye penetrant methods. Internal weld defects can be found only by the use of other non-destructive testing methods such as radiography or ultrasonics. Success in finding all the possible types and locations of defect by these methods cannot be guaranteed. Strength, fracture toughness and hardness can be measured only by destructive tests and so cannot be measured on a completed production joint.

To deal with the special case of welding, the achievement of the specified joint qualities is pursued by designing and proving a welding procedure to give the required properties, and then setting up and controlling the operation to ensure that the procedure is followed.

Welding Procedure Tests

To be confident that the completed production weld is likely to have the required characteristics, it is customary to conduct welding procedure tests in which a joint simulating the production joint is made under controlled conditions. The joint is then subjected to non-destructive and destructive tests with the intent of showing that the joint conforms to the specified requirements. The design and preparation of welding procedures is dealt with in detail in Chapter 10.

Welder Tests

Making welds of a consistent quality requires welders not only trained in the process to be used, but also with recent experience. That the welders have the skill and experience is determined by conducting welder approval, or qualification, tests. The test will require the welder to make a joint which requires similar skills to those needed for the actual job. This test joint is non-destructively examined and may be destructively tested by one of a number of means including a macro section or a bend test.

Material Identification

Chapter 2 has shown the importance of chemical composition in the weldability of steels. As the welding procedures will have been designed for a particular type of material, it is most important to ensure that the material delivered for the job is correct. Every steel plate leaving a steelworks is numbered so that it can be traced back to the tests which were carried out on the quantity of steel from which the plate came, and the results of these tests are recorded on a certificate often called a 'mill sheet'. When the plate is delivered to the fabricator, an inspector checks the plate numbers against the test certificates which accompany the steel. The fabricator's inspector, metallurgist or welding engineer will check that the test certificate shows that the steel comforms to the specification to which the steel was ordered. When the plate is cut up into parts to be fabricated, the plate number, or some other identifying number, is transferred to each part considered to be of sufficient importance. These identifications are then recorded on a drawing of the product.

These actions ensure that the specified type of material is used in the job. An additional benefit is that in the event of any problems in fabrication it can be helpful to know the history of the material or just the location of other pieces from the same plate.

Attention is also paid to the control of welding consumables. These are identified by the manufacturer on a batch basis, and a complete fabricator's record system will show where any batch of consumables was used, and by which welder.

Quality Control

Quality control is but one of the activities in a quality programme. In the context of a mass production industry using mechanised methods of manufacture, quality control entails measuring some feature of the product such as a dimension or a weight against the specified value. In the simplest approach a tolerance is allowed on this value and, if a value falls outside the permitted range, that item is rejected. In a better system there will be two or more tolerance levels, so that any item falling outside the first level will be accepted but a change will be made to the process to prevent further departures from the required value. This change may be performed manually by a machine setter or perhaps, in an automated system, by the machine itself.

This is a fairly traditional and simple activity if there is only one value to measure and one type of change to correct that value, for example, a lathe producing bolts. It is a very different matter for an operation with many variables and sources of variation, with some variations undetectable, particularly if the process is manually operated. Such is the case with welding, where management of quality cannot be achieved by a system based solely on examining the finished product. The implementation of a complete quality assurance programme is needed to give confidence that the specified product is produced.

Inspection Activities

The methods of inspection used for welded construction are described in Chapter 12, but how inspection fits into the overall pattern of quality assurance is explained here.

Inspection activities, like other tasks, need to be performed by personnel with training and experience. Inspection of welded joints tends to be broken down into visual inspection and non-destructive testing or examination. Visual examination requires an inspector with a sound knowledge of welding and the associated activities. The inspector's task before welding will entail:

(*a*) Checking of material type.
(*b*) Edge preparations and joint fit-up.
(*c*) Pre-heat temperatures.
(*d*) Other quantities which appear on the WPS.

On completion of the joint, the inspector will examine the surface profile of the weld and the compliance of the component with the drawing in respect of dimensions. Depending on the particular organisation, the welding inspector may direct and receive the results of any non-destructive testing. In some situations the NDT operator will say whether the weld is acceptable or not, an activity known as 'sentencing' in some quarters. In other situations the judgement on the acceptibility of the weld may be made by the welding inspector or other personnel.

Non-destructive testing in whatever form must be undertaken by personnel with the appropriate training and experience. Evidence of such training and experience is given by qualifications awarded by a number of bodies on the basis of examinations requiring demonstration of both practical ability in, and theoretical knowledge of, the particular technique. These bodies include CSWIP, the Certification Scheme for Weldment Inspection Personnel, administered from the United Kingdom, and ASNT, the American Society for Non-Destructive Examination, administered from the USA. Other schemes exist for specific industries but CSWIP and ASNT are the most widely accepted. Although the technical requirements are not substantially dissimilar, CSWIP and ASNT differ in that examinations for ASNT can be taken in the inspector's own organisation under ASNT qualified supervision from within the organisation, whereas CSWIP conducts its own independent examinations at various locations around the world.

Inspection Records

Each inspection or non-destructive testing activity is recorded in a report which should be listed in an inspection record and, depending on the practice of the type of industry, such a record may or may not be passed to the customer. In products for which statutory approval is required, the inspection records will form part of a package which has to be submitted to the authority before permission to use the product is given. This applies to such products as offshore platforms, aircraft, and nuclear power stations.

Standard Specifications for Quality Assurance

The British Standard most commonly used as the basis of quality systems in the United Kingdom is B.S. 5750 'Quality sytems'. This lists the following requirement of a quality system:

(*a*) Quality system.
(*b*) Organisation.
(*c*) Review of the quality system.
(*d*) Planning.
(*e*) Work instructions.
(*f*) Records.
(*g*) Corrective action.
(*h*) Design control.
(*i*) Documentation and change control.
(*j*) Control of inspection, measuring and test equipment.
(*k*) Control of purchased material and services.
(*l*) Manufacturing control.
(*m*) Purchaser-supplied material.
(*n*) Completed item inspection and test.
(*o*) Sampling procedures.
(*p*) Control of non-conforming material.
(*q*) Indication of inspection status.
(*r*) Protection and preservation of product quality.
(*s*) Training.

Another useful standard is the B.S. 4778 'Glossary of terms used in quality assurance'. For the nuclear power industry there is a specialised standard, B.S. 5882 'Specification for a total quality assurance system for nuclear installations'. There are standards published in other countries which cover similar ground.

CHAPTER 12

Inspection and Non-Destructive Testing

Inspection is an integral part of any manufacturing operation as a means of ensuring that only items made in accordance with the specification (and this includes drawings) are released for use. Inspections are made at various stages of the production process so that departures from the correct item are detected as early on as possible and wasteful work and repairs are minimised.

In the case of welded fabrication, inspection starts with the basic materials – the parent metal and the welding consumables. The parent material is inspected for identification, dimensions and surface quality; welding consumables for identification, cleanliness and damage.

After this, inspections may be made at the cutting, edge preparation and fit-up stages. Part of the inspector's task may be to check that the material identification is correctly transferred to individual parts. Pre-heat levels are the next item for inspection, followed by checking of welding consumables and welding conditions (voltage, current etc. as on the WPS or data sheet). When the weld is complete, the inspector will check it for profile and any surface defects such as porosity, undercut and lack of fusion; fillet welds will also be checked for size. All these inspection activities are performed mainly with the naked eye assisted by temperature-sensitive crayons or contact thermocouples for pre-heat, meters for current and voltage and gauges for size and profile. A dimensional check may also be made but this is not always conducted by the welding inspector.

A welded joint can be inspected visually to ascertain its apparent quality but it may contain unseen discontinuities, shown in Chapter 2, which detract from the integrity of the joint. Some of these defects are not visible to the naked eye even though they break the surface. Two commonly-used methods of enhancing the appearance of such discontinuities are the dye penetrant and the magnetic particle method. Both of these rely on simple principles.

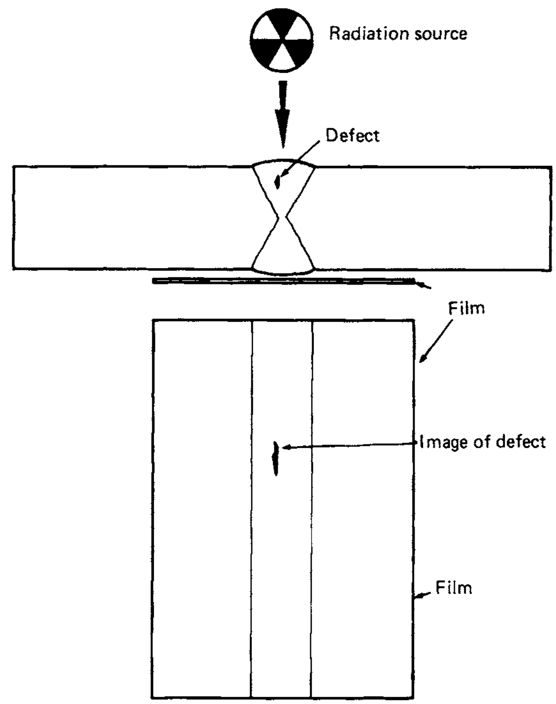
The dye penetrant method involves spraying a liquid dye onto the surface of the welded joint. This dye will be drawn into any crack or lack of penetration and remains there even when the surface is wiped clean. An absorbent powder is then sprayed onto the weld and absorbs the dye back to the surface, thereby revealing the position of any defects in the weld.

The magnetic particle method reveals crack-like defects by the way they concentrate lines of force in a magnetic field. In the most commonly-used form of this technique, the item being examined is temporarily magnetised by passing an electrical current through it. Iron powder suspended in paraffin is then sprayed on the area, which collects where the field is strongest and shows up as black lines over the cracks.

Other methods of non-destructive examination are necessary to detect the presence of defects below the surface of the weld which could never be seen with the naked eye. Such techniques include radiography and ultrasonics.

Other techniques than these are used but not as commonly and they will not be discussed in this book.

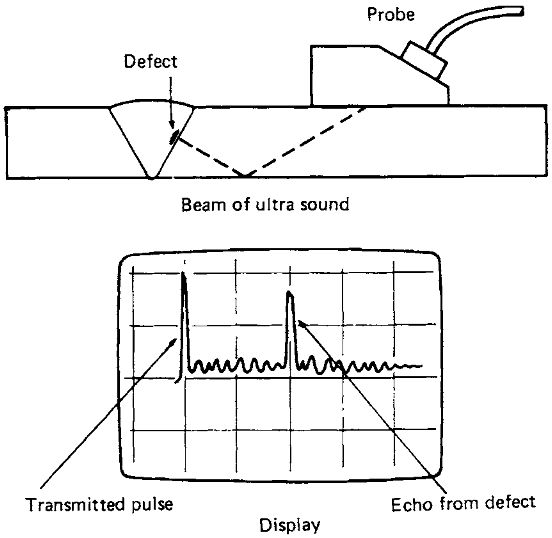
Radiography involves projecting radiation from an X-ray tube or a radioactive isotope through the item being examined to produce an image on a film. The item being examined will absorb radiation depending on its material and thickness and variations in thickness or material will produce an image which can be interpreted by trained personnel. The illustration shows a simplified layout of the components used in making a radiographic exposure of a welded joint. Of particular importance is the ability to have access to both sides of the welded joint although joints in small pipes can be radiographed by shooting through both walls at an angle to give an elliptical image. Effective examination can be made only on in-line butt joints between materials of comparable thickness; T-butt joints provide a poor subject and fillet welds are unsuitable.



Radiography is effective in showing up three-dimensional or volumetric weld defects, such as slag inclusions, porosity or lack of root penetration. Two-dimensional defects, such as cracks, can show up less well or not at all if they are not orientated in line with the radiation beam.

These limitations have provided the incentive to develop to a high degree of effectiveness the ultrasonic method of examination. In this method a beam of pulses of high frequency sound is projected by a probe through the item to be examined. The beam is reflected off discontinuities such as weld defects and this reflected signal is displayed on a cathode-ray tube on a time base of which the origin is the sending of the pulse. This time is a measure of the distance of the reflector from the probe and is used by the trained operator to locate the position of the reflector. By scanning the probe over the surface the operator can build up a picture of the shape of the reflector. This gives more information about the nature of a weld defect than the radiograph does, particularly in the through thickness direction which is often of importance to structural integrity.

Although access from both sides of a welded joint gives the ultrasonic operator more flexibility, one-sided access is not a serious bar to the use of the technique. Almost any joint configuration can be ultrasonically examined effectively. The question might be asked as to why radiography has not been superseded by ultrasonics. The answer to this at



present is that the radiograph is a permanent record which can be examined by any number of people, whereas the ultrasonic examination is recorded as the operator's written observations. These can be somewhat subjective and there is no permanent record of the signals. Some automatic ultrasonic systems with permanent records are in use but they are usually restricted to production lines for plate and pipe.

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Index