A GUIDE TO DESIGNING WELDS

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Foreword

Welding is rightly the responsibility of professional welding engineers and it would be unrealistic for designers to presume to know as much about the craft. But it is acknowledged that there are some whole industries and parts of others into which the profession of welding engineer has not penetrated, and designers in some industries are, through no fault of the individuals, often not aware of what good practice represents. As a result, they may be guided into courses of action by fabricators, for which they themselves are ultimately responsible.

This book is written with the design and welding interface in mind and is intended to inform designers not only what they should perhaps know about welding for design purposes, but primarily to set out what information the designer should give to the welding engineer or fabrication superintendent so that the designer's aims can be achieved, in terms of engineering performance, safety, reliability, cost and appearance.

John Hicks
August 1989

Introduction

Joints

Joints are made between two or more pieces of material for a variety of reasons:

- Limitations on maximum size of raw material;
- Complexity of shape;
- Combination of raw materials;
- Limitations on size of component parts for transport;
- Combination of manufacturing methods;
- Ease of replacement in service.

Joints can be made mechanically using bolts, rivets or keys; made using adhesives or by welding. Welding in this context is the joining of parts to form a continuous metal to metal bond. This definition can include techniques such as soldering and brazing but these are excluded here by requiring that the parts to be joined are fused together, usually by some heating process which melts adjacent parts. There are special cases such as solid state joining which do not fit this definition and will also be excluded from the scope of this book.

From the point of view of engineering performance, any joint is a nuisance. Whether it be mechanical or of any other form it is always difficult to get the same set of mechanical properties from a joint as from the parent material. In that sense the designer's aim may be to minimise the number of joints. Against this, production requirements need joints so that manufacturing costs can be optimised whilst maintenance is facilitated by mechanical joints for both access and replacement of parts. Therefore, although a joint may be a costly feature to manufacture in itself, its expense may be offset by the cheapness of sub-assemblies and the production rate inherent in being able to handle or sub-contract such sub-assemblies. Total cost of ownership has now become more important than first cost in some users' minds and ease of maintenance is a significant contribution to keeping the total cost down.

It is important, therefore, to be able to make a rational decision on whether a joint should be used, and if so what type and where. The basic information required to be able to make such a rational decision may not be available at the design stage. Where an explicit decision is avoided, designers follow conventional practice and use their experience until there arises some totally new product or some initiative in the guise of 'value engineering', 'design review' in a quality system or some other such external stimulus.

The choice of a specific type of joint and joining process is directed by the designer's knowledge of joining techniques and the state of development of material forms. This fluctuates under various influences, both commercial and technological. Most metals and their alloys are available in a variety of forms such as sheet, plate, rolled sections, forgings and castings whilst a few have particular properties such as the aluminium alloys which can be extruded.

Fashion also plays a part in this business for there is no doubt that perceived trends influence so called technical judgements and result in attention being paid to popular techniques of the time.

Welded joints

A welded joint is made by melting together two or more parts with or without the addition of a filler metal. Once made, this joint is not a set of separate parts like bolts and the holed members they join, and so it is impossible to draw a welded joint as separated numbered parts as might be shown in a drawing of a bolted assembly. There is, in between the action of fitting up the parts to be welded and their union, the activity of welding, the stages of which cannot be shown explicitly on a drawing in the way a bolted joint can.

Few designers are faced with the task of designing a totally new product or designing in a material completely new to them, so it would be naive in this book to suggest that all the ramifications of arriving at the design of a welded joint could be set out in a number of sequential chapters. Everyone enters the subject at a different point and the reader should therefore use this book like a roundabout, getting on at the place of interest and getting off again when that interest is satisfied, or when the matter cannot be resolved by consulting this book. As on a roundabout one can go back or go forward, sometimes without getting off and the reader is advised to use the contents list as a basis for the search for information and guidance.

In a way analogous to a designer's knowledge of the response of materials to working loads and environment, so a welding engineer has knowledge of the response of materials to welding processes in terms of the mechanical properties of the metal in the welded joint and its soundness as well as of the physics and mechanics of welding machinery. In this book the bases are described on which designers and welding engineers have to work to achieve the aims of their professions, that is to say, a product which is both suited to its function and is competitive in terms of cost.

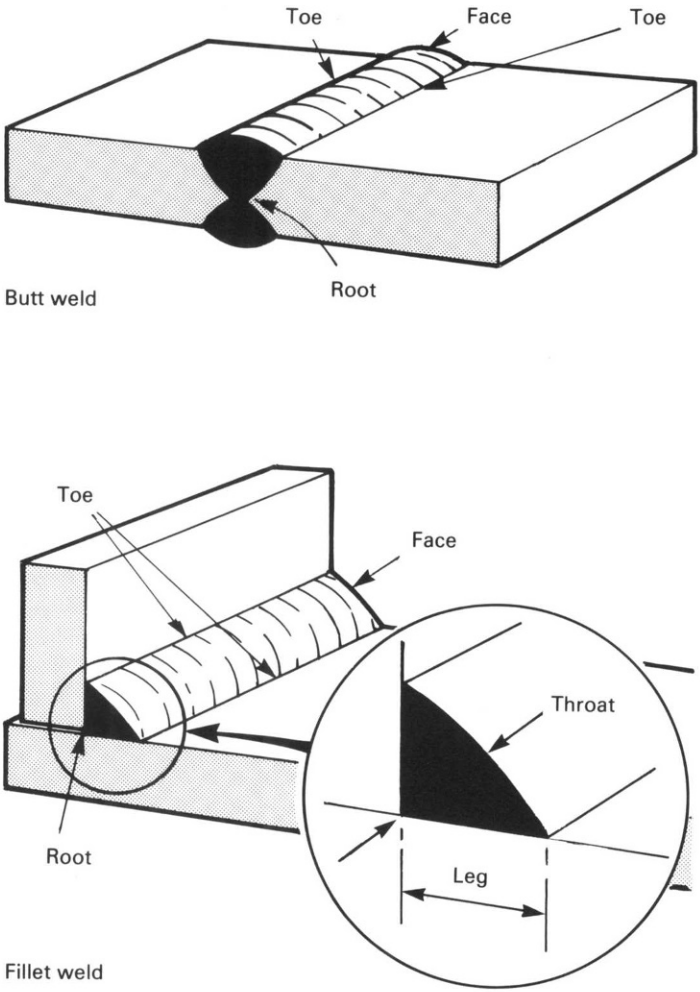
CHAPTER 1

Definitions

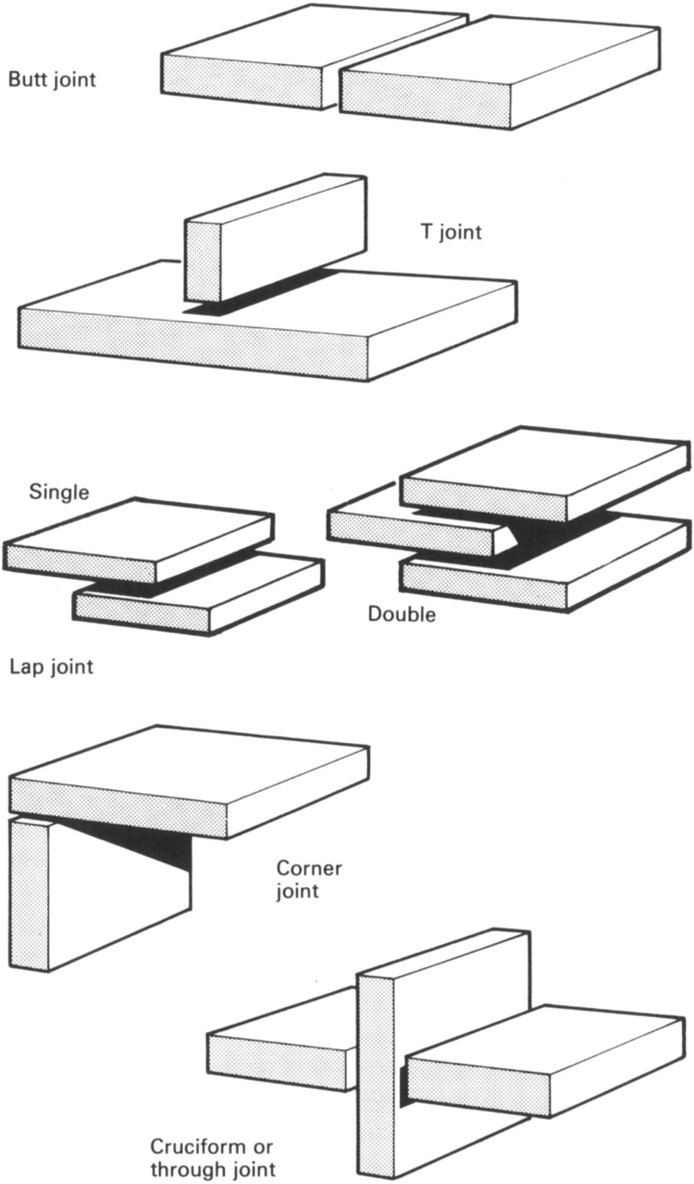
To understand the subject of this book it is important that the author and reader use the same words to mean the same thing. There are standards for terminology; an example is BS 499 for British terminology, and there are equivalent documents in other countries. For interpreting between languages the reader can use the 'Multilingual collection of terms' published by the International Institute of Welding (IIW).

A few basic definitions of terms which are in everyday use in design and fabrication are shown in Fig.1 and 2. These definitions are explained here by sketches but the reader should be aware that in drawing office practice the standard symbols, of which a few are given in Chapter 2, should be used.

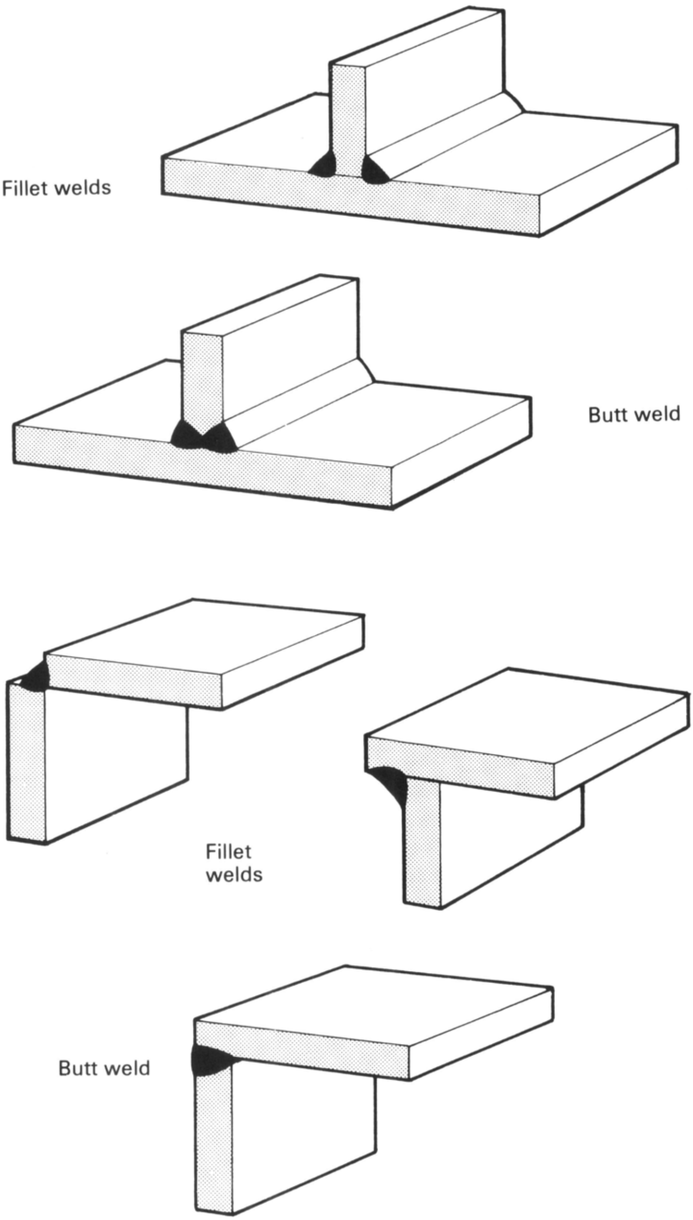
The two basic types of weld shown (fillet and butt) can be used to make a variety of joints, as shown in Fig.3. The use of partial penetration butt welds is shown in Fig.4 and welds made from one side only in Fig.5. One sided butt welds should not be used where the weld is put under a bending load, especially when it puts the root in tension. This also applies to T joints made with one fillet weld (Fig.5*c*). Various joints which can be used for welding tubes are shown in Fig.6, including tube to tubeplate joints.



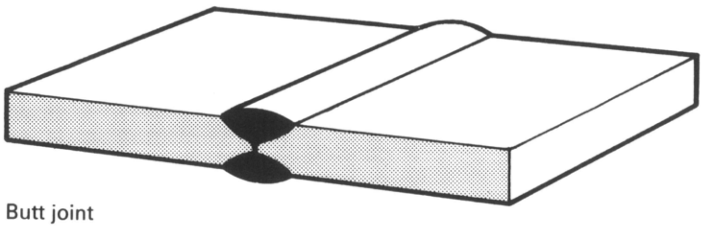
1 *Butt and fillet welds.*

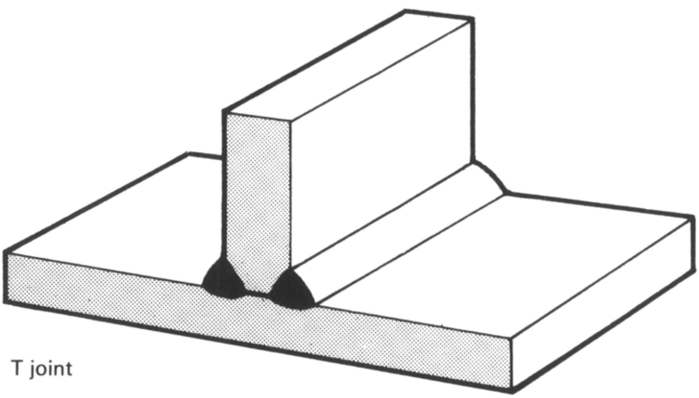


2 *Joints used for welding.*

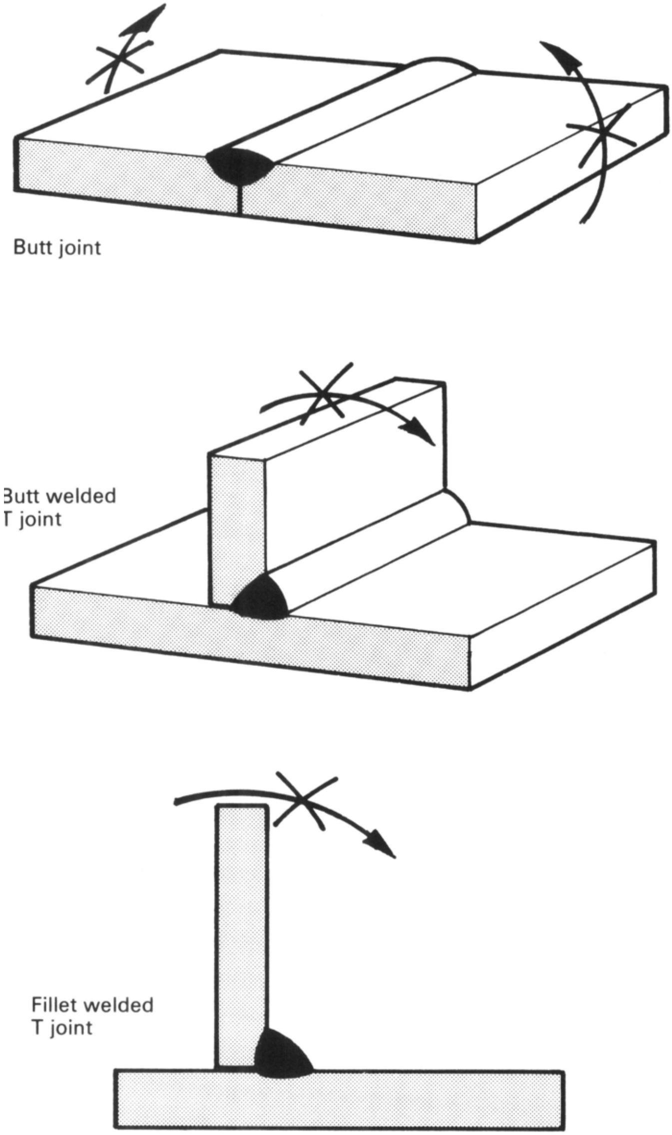


3 *Use of fillet and butt welds to make*: a) *T joints*; b) *Corner joints.*

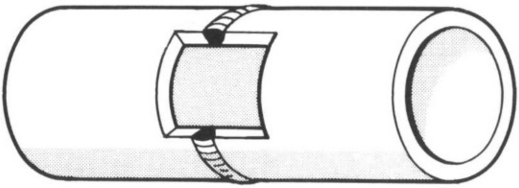




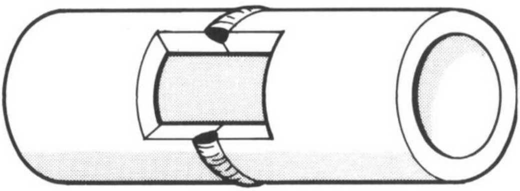
4 *Use of partial penetration butt welds.*



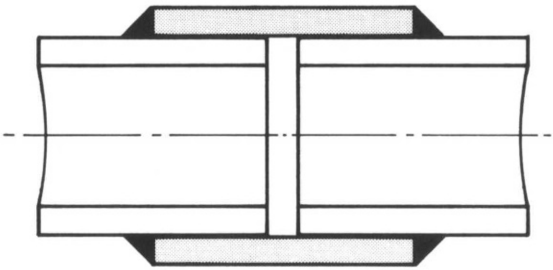
5 *Welds made from one side only. The crossed out arrows indicate the direction in which bending loads must not be applied.*



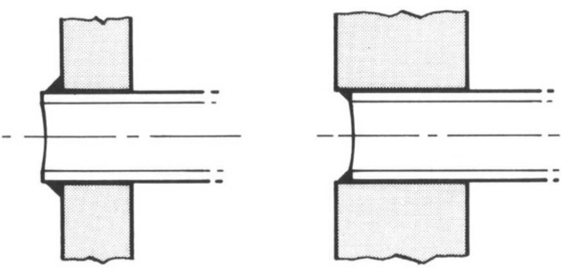
Full penetration butt weld



Partial penetration butt weld



Fillet welded sleeve



Fillet welded flange or tube plate

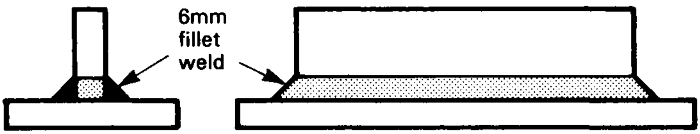
6 *Joints for welding tubes together.*

CHAPTER 2

Indicating welds on drawings

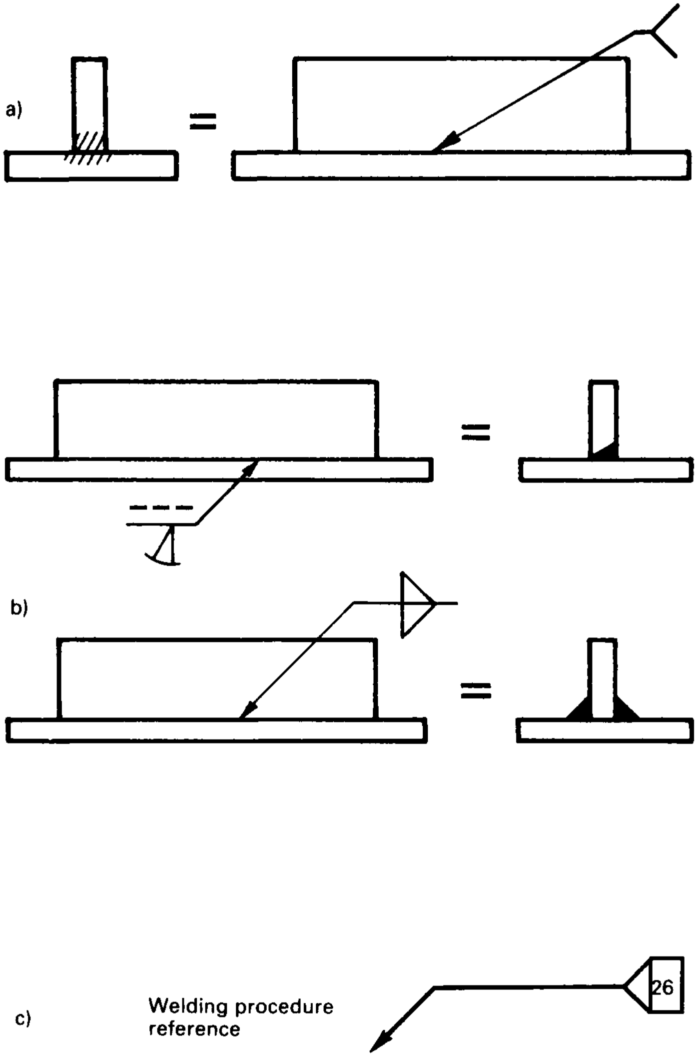
It is sometimes assumed by designers that fabricators automatically know what type or size of weld is to be used. This is not the case and responsibility for the weld type and size is that of the designer.

Welds can be shown on drawings as pictures of what they look like and for simple items this may be clear and unambiguous (Fig.7). For more complicated parts and assemblies this can soon become confusing and it is then wise to turn to a set of conventional symbols as in BS EN 22553/ISO 2553. A draughtsman unused to these symbols may be as baffled by them as a fabricator who has not seen them before. At first sight they do not appear to indicate what they are said to, but some practice will soon reveal their rationality.



7 *Drawings indicating a simple fillet weld.*

A draughtsman should approach their use in two stages. The first stage is to show where the welded joint is to be and the second is what sort of joint is to be used (Fig.8). There are further stages which are within the scope of the welding engineer's task and should not be the concern of the draughtsman. The essence of the BS EN 22553/ISO 2553 system is shown here but that document, or any other which may be used should be referred to for full details (*e.g.* 'Weld symbols and drawings', published by The Welding Institute, ISBN 0 85300157X).



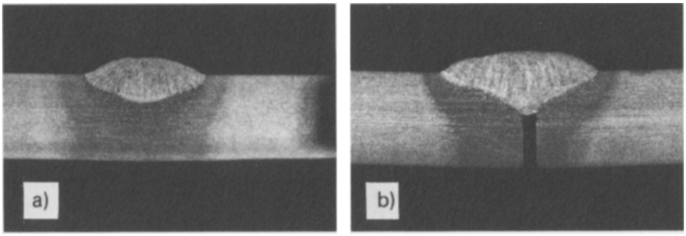
8 *Conventional symbols used to indicate the position and type of weld to be used as well as welding and inspection procedures*: a) *Stage* 1, *showing position of weld*; b) *Stage* 2 *showing weld type*; c) *Stage* 3, *giving welding procedure.*

CHAPTER 3

Edge preparations

When a weld is made with a manual welding process such as manual metal arc (MMA) or low current gas shielded welding, the melted electrode or wire fuses with the surface of the metal, but despite the apparently fierce power of the arc little of the parent metal is actually melted.

A cross section of a weld bead laid on a piece of steel plate is shown in Fig.9*a*, and compared with the same weld bead laid over the abutting edges of two plates as if they were to be joined (Fig.9*b*). There is little weld metal joining the two parts and it will have little strength. If the plates are turned over and a weld placed on the other side, the joint will be stronger but certainly not good enough for proper engineering purposes.

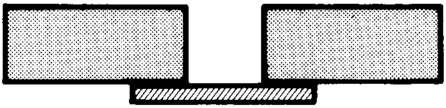


9 *Fusion of parent plate on welding*: a) *Bead-on-plate*; b) *Butt weld made using the same welding conditions.*

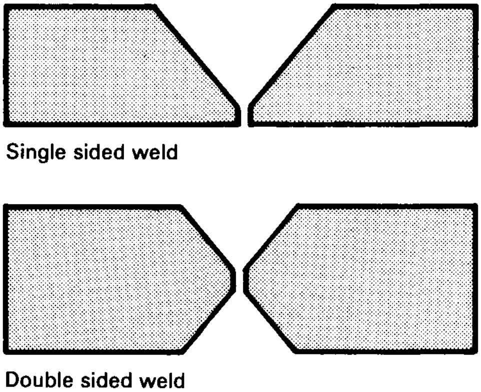
If the metal is thin, say 2mm, then it is possible to make a full penetration weld between abutting edges; indeed sheet metal can be welded in this way. For anything thicker, a gap between the pieces to be joined has to be left. There are several ways of proceeding from there.

Use of a parallel sided gap with a backing strip is quite convenient for thicknesses up to 10mm. The strip stays as part of the joint (Fig.10).

Alternatively, the edges can be bevelled and a small gap left at the bottom. This gap can be filled from the same side as the rest of the weld or it can be left until the end when it can be cleaned out by grinding and welded over in one pass.



10 *Parallel sided gap with backing strip, suitable for joining thicknesses up to 10 mm.*



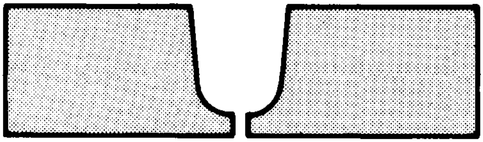
11 *Bevelled weld preparations.*

With increasing thickness the amount of weld metal becomes greater and it is then convenient to put a bevel on each side (Fig. 11). The quantity of weld metal can also be reduced by using a curved edge preparation (Fig. 12). Although this can be made by air arc or flame gouging it is usually made by machining which is more costly than the flame cutting method used for straight bevels. Machining is often easier on tubes than plates because it can be done on a lathe. Again, increasing thickness leads to double sided preparations and choice of preparation has to be made by the welding engineer to suit the welding equipment and the welding position.

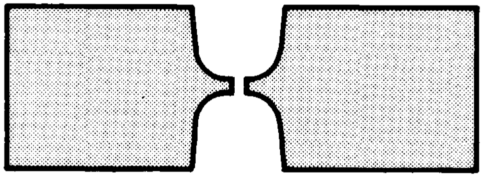
Dimensional tolerances

The absolute dimensions of an edge preparation are not usually critical and reasonable tolerances can be given. Consistency is really more important than actual shape. However, when the parts are to be fitted together, any required gap between them is critical, particularly if the weld is to be made from one side only. Drawings showing fit-up must show tolerances on such gaps and on alignment (Fig. 13).

For assembly or erection of sub-assemblies use of a backing strip offers flexibility for absorbing final tolerances (Fig. 14). Alternatively, for

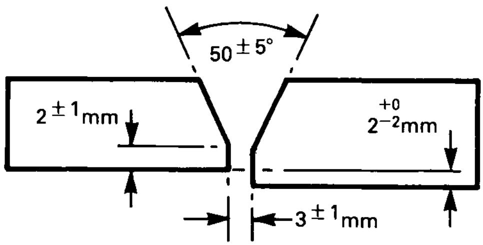


Single sided weld



Double sided weld

12 *Curved edge preparations*: a) *For single sided weld*; b) *For double sided weld.*

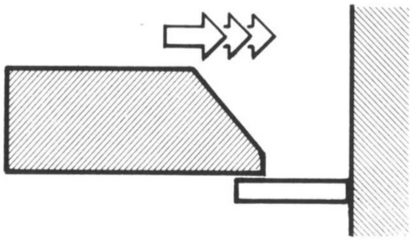


13 *Tolerances indicated on gaps and alignment.*

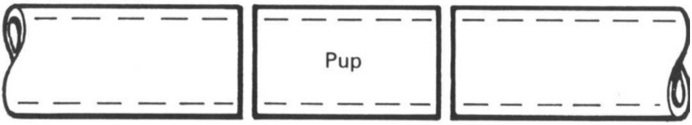
tubular structures, a final 'pup piece' may be cut to length and inserted after measurement of the actual dimension (Fig. 15).

Processes which use high currents such as submerged-arc and gas shielded welding in a mechanised form can penetrate more deeply into the metal than the manual processes and it is possible to use a shallower edge preparation (Fig. 16). It is sometimes possible to make a weld in one pass from each side without edge preparation (Fig. 17). This is confined to the flat position and is generally used only on fabricated beams and large pipes which can be conveniently positioned.

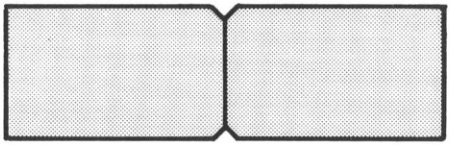
For large thicknesses of metal, developments of the gas shielded or submerged-arc processes are sometimes used with only a small weld preparation to be filled; these are called 'narrow gap' processes and edge preparations need to be designed in close co-operation with welding engineers (Fig. 18).



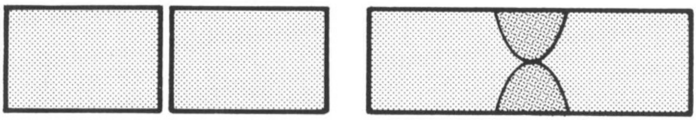
14 *Use of a backing strip to absorb final tolerances.*



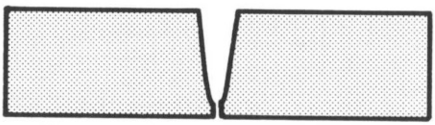
15 *Pup piece used in the assembly of pipe.*



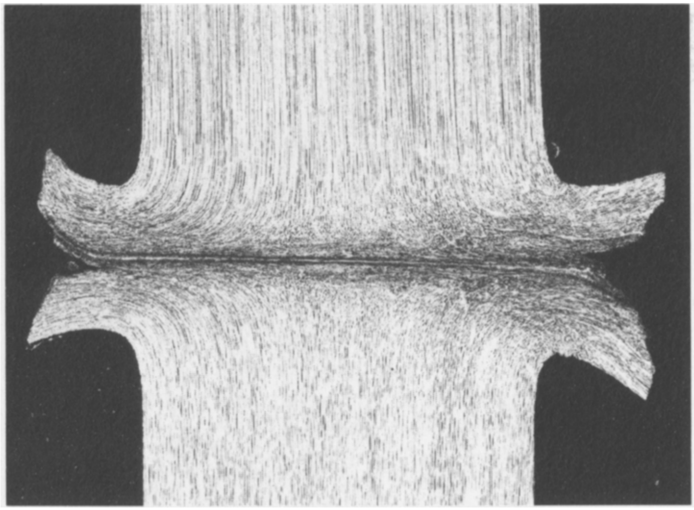
16 *Shallow edge preparation for use with high current welding processes.*



17 *Two sided weld made without edge preparation.*



18 *Narrow gap weld preparation.*



19 *Section through a friction weld in stainless steel.*

Some high energy density welding processes such as electron beam and laser can be used to make butt welds in parts without any edge preparation but these are restricted at present to specialised applications. A more commonly used process, friction welding, can also be used to make welds without preparations. Its use is restricted to items of compact cross section; it is therefore used mainly in joining pipe, tube and bar sections. Bars can be circular or rectangular in section (Fig.19).

Designers should appreciate that the selection of a shape for any particular item depends on a number of factors outside their control and it is wise to agree edge preparations with the fabricator before shop drawings are approved.

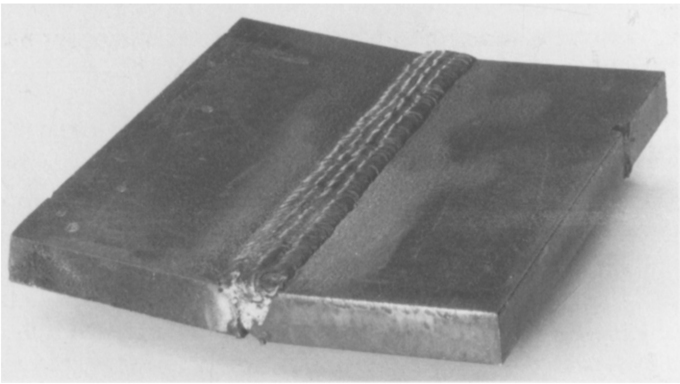
CHAPTER 4

Distortion

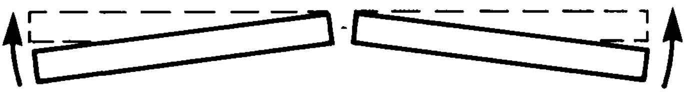
The heating and cooling occurring during welding and the accompanying expansions and contractions have the effect of distorting the shape of parts being welded. Preventing or minimising this distortion is the job of the welding engineer but the design of products can make distortion more or less likely and the designer also has to recognise at what level practical dimensional tolerances can be set.

A weld bead in a plate will distort it (Fig.20). In this example it would be possible to straighten the plate in a press. A weld run on the opposite side of the plate would also help. This latter idea gives the basis for one approach in plate structures which is to use two sided welding wherever possible. An alternative is to preset the parts so that distortion brings the parts into line (Fig.21).

Multipass welds create more distortion than single pass welds. Heavier welds create more distortion than smaller welds so that distortion can be reduced by careful planning of the welding sequence by the welding engineer.



20 *Plate distorted by weld bead.*



21 *Presetting of parts so that weld distortion will bring them into line.*

Effects of distortion

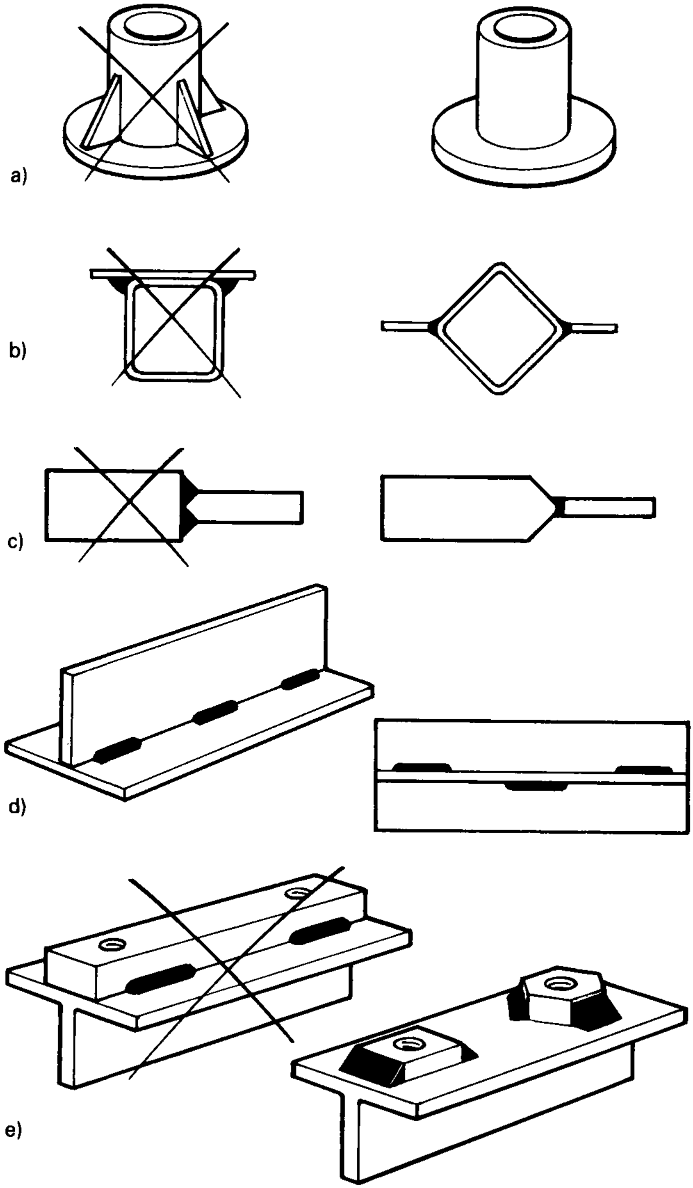
Distortion is the deviation of the shape of an item from the shape required by the design. This can have the following effects:

- Fit-up between mating parts is not achieved;
- Loss of straightness or flatness can reduce buckling strength;
- Increased local stresses caused by misalignment at joints can increase risks of failure under static or fatigue loading;
- Alignment of items such as shaft bearings is lost;
- Surface smoothness loss can affect fluid flow in pipes or over ship and aircraft structures;
- Deviation from design shape may detract from the required appearance, *e.g.* of motor car and railway coach bodies, bridge facings and soffits, exposed building frames or cladding.

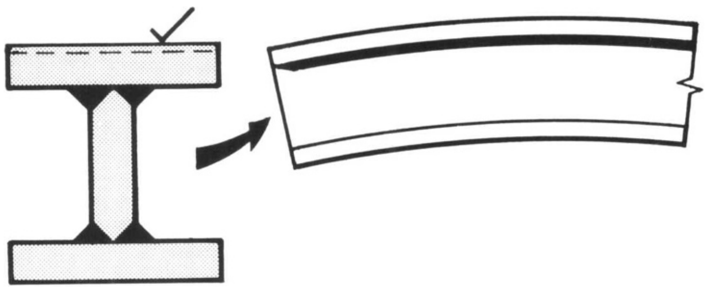
The first step is to decide whether distortion is important to the item in question. If it is, then there are some actions which the designer can take to help minimise it:

1. Put in as few welded joints as possible (Fig.22*a*);
2. Distribute welds equally about neutral axes (Fig.22*b*);
3. Minimise weld sizes; this can be assisted by reducing thick members where they are joined to thinner members (Fig.22*c*);
4. Where possible use intermittent welds (Fig.22*d*); or even intermittent parts (Fig.22*e*).

The rest is up to the welding engineers but designers should be aware that even though attention to design and control of distortion in fabrication produces an item to the required shape, it may still distort during subsequent manufacturing operations and in service. This can happen because welding leaves stresses locked up in the metal which can be relaxed by repeated loadings or released if part of an item is machined or cut away (Fig.23).



22 *Reduction of distortion by*: a) *Reducing number of welds*; b) *Distributing joints about a neutral axis*; c) *Reducing the size of a weld*; d) *Using intermittent welds*; e) *Using intermittent parts.*



23 *Distortion of a welded component following machining.*

It is not only welding which produces residual stresses. Rolled steel sections contain residual stresses which are clearly demonstrated if a beam is slit down its centre.

Residual stresses can be reduced by thermal stress relief, also called post-weld heat treatment. This entails heating welded fabrications or beams slowly in a furnace to about 600°C, a red heat, and leaving for about one hour for each 25mm of the thickness of the metal. After this, items are cooled in the furnace at a controlled rate to about 250°C when they can be put out into still air to cool completely. Unfortunately, if the residual stress patterns are not balanced, items may distort during stress relieving. It must therefore be carried out before machining so that components will be stable during machining and subsequently in service. Post-weld heat treatment can improve resistance to brittle fracture in some products such as pressure vessels, offshore platforms or any thick material where the as-welded notch toughness is considered inadequate for service duty. Thermal stress relieving is a costly operation and leaves the steel surface in a scaled condition so that a cleaning operation such as grit blasting has to be used to obtain a sound surface for subsequent painting. Residual stresses have also been reduced by vibration in specific modes but this process is not well documented.

Lest it be thought that welding is the only joining process which induces inconvenient residual stresses, it should be noted that riveting also produces distortion and the sequence of riveting aircraft structures, for example, has to be planned to maintain the correct shape.

CHAPTER 5

Calculating the static strength of welded joints

It is a widely held and totally erroneous view that weld metal is not as strong as the metal it joins. In ordinary structural steels, weld metal is almost always stronger than the steel. In high strength steels the weld metal, if chosen correctly, will be at least as strong as the steel.

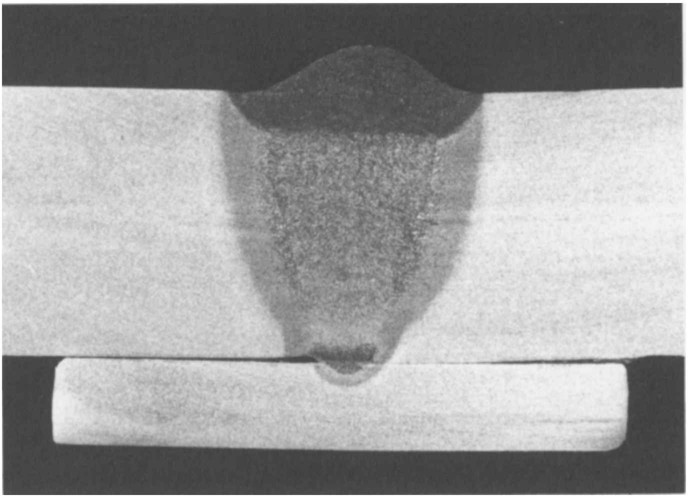
Butt welded joints

For welds made with matching weld metal (see Chapter 9) the strength of a full penetration butt weld (Fig.24) in steel is the same as the parent metal. As a result, product specifications based on an allowable stress philosophy usually consider butt welds to be as strong as the parent metal except for some pressure vessel specifications which reduce the allowable stress in a butt weld depending on the level of inspection. A similar approach has been taken with more recent specifications and codes using the 'limit state concept' where the design strength of a butt weld is taken as equal to the design strength of the weaker parts joined.

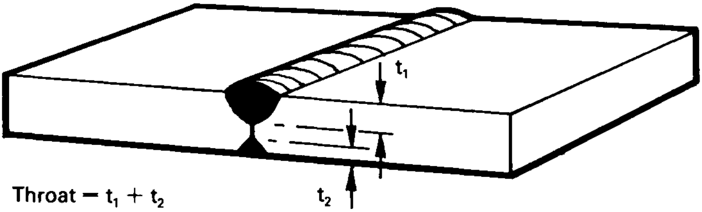
Partial penetration weld strengths are calculated on the size of their throat as shown in Fig.25. It is important to be able to confirm throat size either by inspection or by production weld tests on a statistical basis. For this reason, partial penetration welds used in tension or shear should be subject to a conservative design stress. Such welds are, of course, useful in compression joints if the two abutting members are in contact so that the load is transferred in bearing (Fig.26). The welds may then be considered as simply locating the two parts. They must, however, be designed to a size which is compatible with achievement of a sound weld. Any doubt about the ability to transmit full bearing should be cause for designing a load carrying weld.

Fillet welded joints

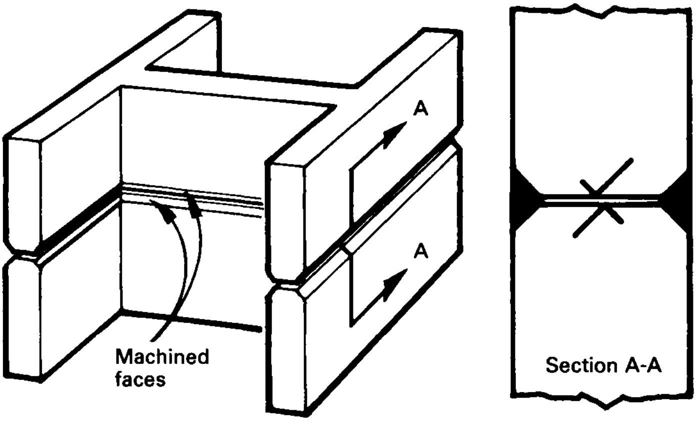
The design strength of a fillet weld is calculated from its size as measured by its throat thickness. Whether a joint is in tension, compression or



24 *Full penetration butt weld.*



25 *Throat size of a partial penetration weld.*



26 *Partial penetration weld used in the compression joint of a building column.*

shear, the allowable stress given in specifications and codes is the same and varies only with the strength of the weld metal or the parent metal. It is generally equal to a proportion of the shear strength of the metal at the yield point.

The stress on a fillet weld can be calculated simply by dividing the load by the throat area (Fig.27). This is not always physically correct but extensive tests in research programmes have shown this to be a valid estimation of the strength.

It is convenient to have a table or chart giving the strength of fillet welds in terms of load per millimetre or per metre rather than a stress (Fig.28). Such a chart can be compiled by any design office for repetitive work or be inserted into computer programs.

Intermittent fillet welds are used in some work where the loads are small. They reduce the cost of welding and also reduce distortion. Calculation of their strength is carried out in the same way as for continuous fillets. It is sometimes the practice to ignore a length at each end of such welds equal to the weld leg length because that may not have the full profile, see Fig.29.

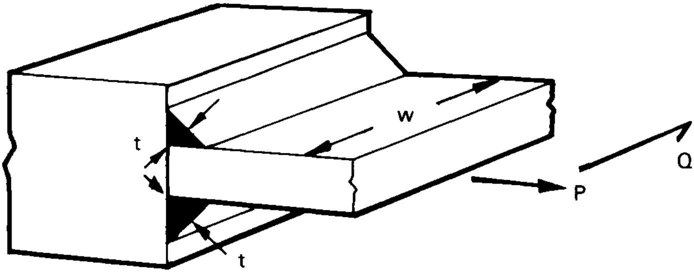
Unequal leg fillets are used occasionally if two parts of different thicknesses are being joined. The weld throat size is calculated from the geometry and the remainder of the strength calculation is the same as for equal leg welds (Fig.30).

In the strength calculation shown in Fig.30, the loads were either parallel to or at right angles to the direction of the welds. In practice loads can be applied in combination. One way of dealing with this is to calculate the resultant of the loads and divide this by the weld throat area and use the conventional allowable stress to gauge the adequacy of the weld size.

Practical limitations on fillet weld size

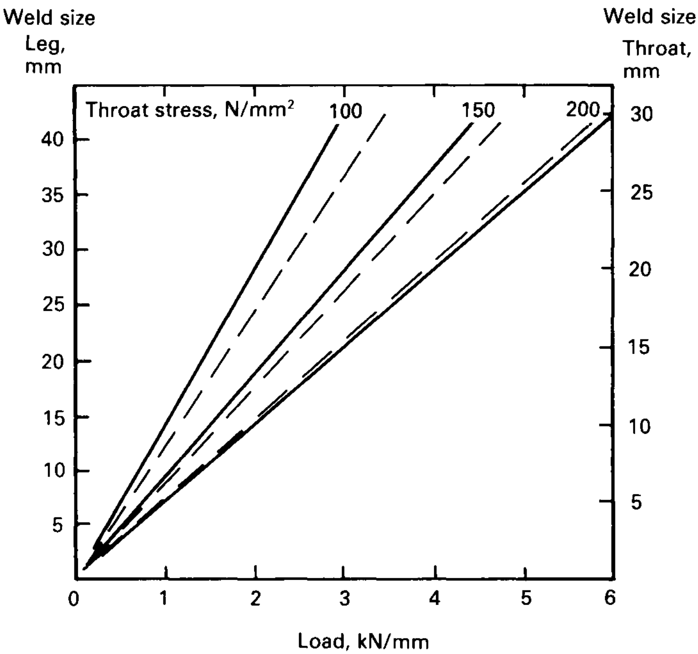
The calculated weld size may satisfy structural theory but there may be practical reasons why it is not suitable for fabrication purposes:

1. For any material thicker than about 10mm there needs to be a minimum weld heat input to achieve fusion and to avoid cracking in the heat affected zone. As in a single run weld the heat input is a function of weld size it follows that the smallest practical weld will be decided by this feature;
2. Another limitation on minimum weld size is fit-up between the parts. If there is a gap between the parts, the effective weld size is reduced: to allow for this, the size of the weld should allow for the tolerance on fit-up (Fig.31).

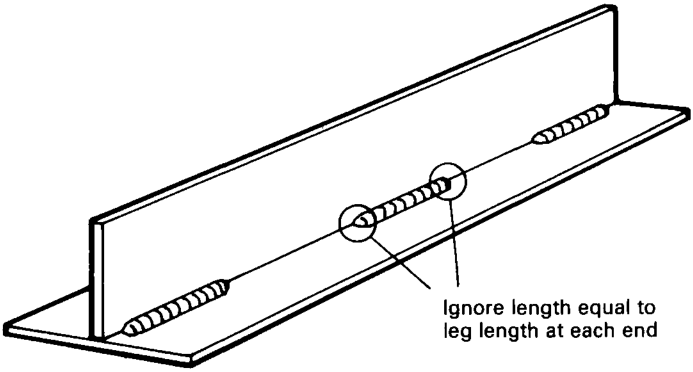


Weld throat area = t × w
Weld stress for tension load P = P/2tw
Weld stress for shear load Q = Q/2tw

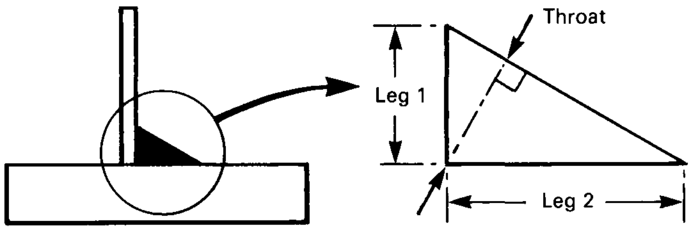
27 *Calculation of stress on a fillet weld.*



28 *Fillet weld design chart, showing strength of fillet welds in terms of load/mm.*



29 *An intermittent fillet weld showing lengths, x, to be ignored at the ends for strength calculations.*

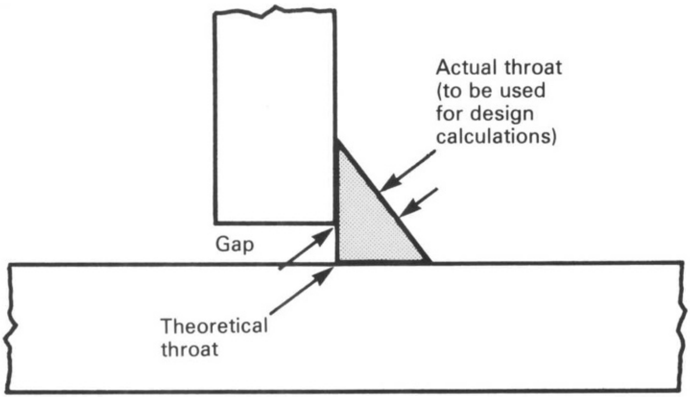


30 *Calculation of weld throat size for unequal leg fillets.*

There is no theoretical upper limit to the size of a fillet weld; more weld passes add to the size of the weld. However, the larger the weld the more the distortion; costs also need to be taken into account and there is a size at which a fillet weld is uneconomic compared with a butt weld and the latter can be used with advantage.

For example, compare the welds shown in Fig.32 for the same loading, using typical design strengths for mild steel as given in BS 5950. With a parent metal design stress of 265 N/mm^2 in the thinner plate for both joints, the figures given below apply for butt and fillet welds:

	Butt	Fillet
Weld design stress, N/mm^2	265	215
Throat size, mm	t	tw



31 *Reduction of throat size because of the presence of a gap.*

For the fillet weld (Fig.32*a*):

Load = weld design stress × throat area
= 215 × 2tw
= 430tw

For the butt weld (Fig.32*b*):
Load = weld design stress × throat area
= 265 × t

Therefore, for the same load:

430tw = 265t

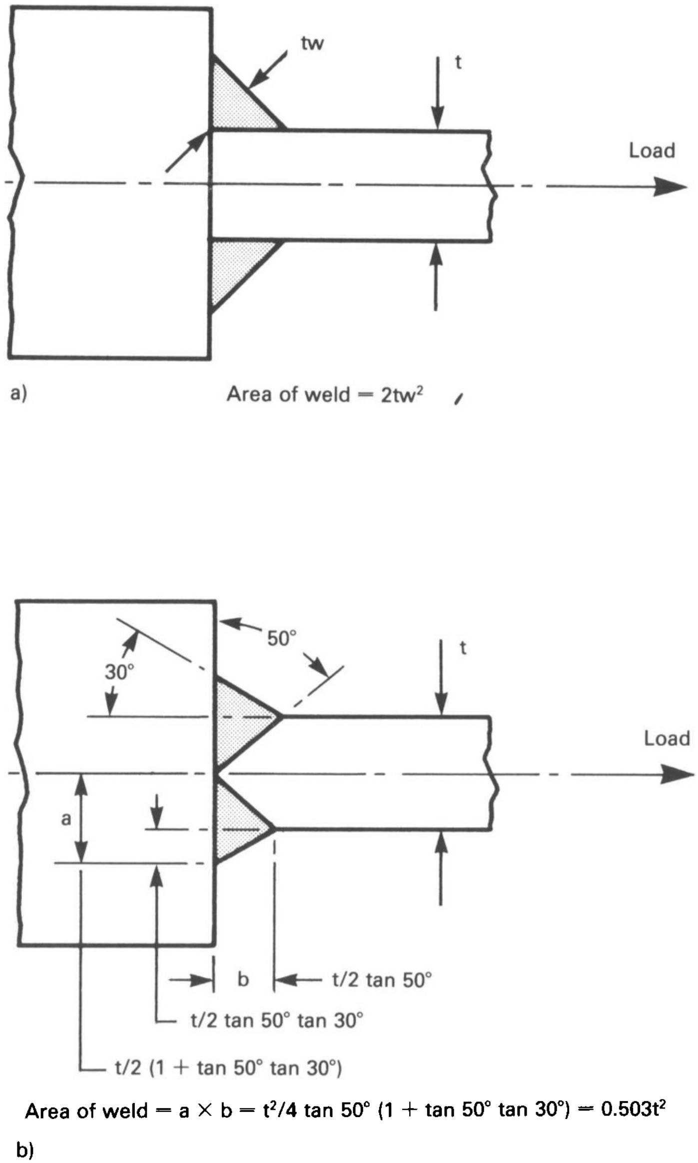
$$\therefore \text{tw} = \frac{265}{430}\text{t} = 0.62\text{t}.$$

The volume of weld metal in a fillet weld per unit length of weld is $2tw^2$ (Fig.32*a*):

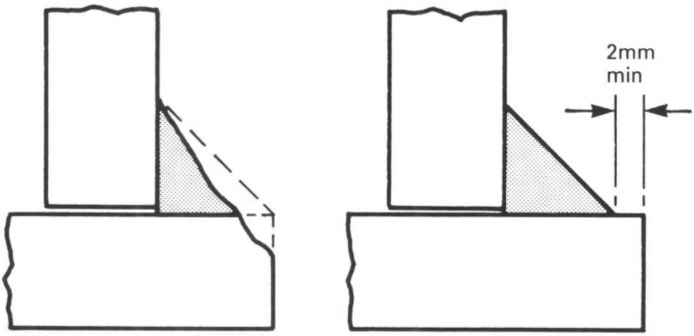
$= 2 \times (0.62t)^2$

$= 0.76t^2$.

As the volume of weld metal in a butt weld per unit length of weld is $0.503t^2$ (Fig.32*b*), this shows that there is about 50% more weld metal in a fillet weld than in a butt. This implies a similarly longer welding time and larger cost for a fillet weld, although the time taken to prepare the edges for a butt weld must also be taken into account.



32 *Calculation of volume of weld metal per unit length of weld for*:
a) *Fillet weld*; b) *Butt weld.*



33 *Making a fillet weld on a corner section. An allowance of about 2mm should be left to prevent melting away of the edge.*

The reader may find it interesting to repeat this calculation for welds made from one side only as in a tube-to-plate joint. As a practical note, it should be remembered that a fillet weld cannot be made on the corner of a section because the edge melts away and reduces the fillet size. A land of, say, 2mm should be left for most practical purposes (Fig.33).

CHAPTER 6

Welding procedures

The phrase 'welding procedures' occurs so often in talk about welded products that it is important that its meaning is understood. British Standard 499 defines a welding procedure as 'a specific course of action followed in welding, including a list of materials and, where necessary, tools to be used'.

A welding procedure for a particular joint is described in a document called a 'welding procedure specification', WPS for short. The WPS is prepared by the welding engineer and includes all the information necessary to make the weld. This information will include, but may not be restricted to, the following:

- Parent metal;
- Type of joint;
- Type of welding process;
- Type of welding electrode, wire, flux, *etc*;
- Weld preparation;
- Welding position;
- Sequence of weld passes;
- Welding current, voltage and travel speed;
- Preheat temperature;
- Inspection and non-destructive testing requirements.

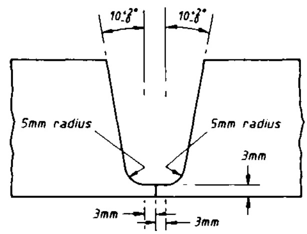
In principle this WPS could be given to a welder and from it he would be able to make the weld required. In practice, many of the items are not within the control of individual welders, such things as the welding process and the type of electrode are chosen by the practice within the works. To keep paperwork to a minimum it is common to issue welders, or their supervisors, with an abbreviated document called a weld data sheet; this contains only the information on matters over which the welder has control such as welding current, electrode size, preheat temperature, welding speed, *etc.*

In industries where the strength and other properties of the weld are important to the integrity of the product, a weld simulating that to be

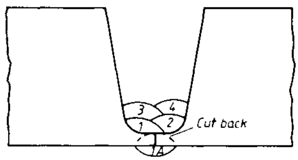
TECHNOLOGY — **WELDING PROCEDURE SHEET** — **WELPRO**

Company name	Contract	Welding procedure no **WPA2.8/A1/1/100**
Order no.	Material BS 4360 Grade 43 (max CE 0.40)	
Joint type: Full penetration butt		Drawing no

Weld preparation



Run sequence



Run no	Process	Welding position	Electrode/wire Specification	Electrode/wire Tradename	Size mm	Flux/gas and flow rate	Electrode polarity	Welding current A	Arc voltage V	Travel speed mm/min Run out length mm	Wire feed rate m/min	Arc energy kJ/mm
1-2	MMA	1G	E6013		4		AC	160 – 180	OCV 80	170 – 190		1.7 – 2.0
3-6	MMA	1G	E6013		5		AC	230 – 250	OCV 80	260 – 280		1.8 – 2.0
7 –	MMA	1G	E6013		6		AC	310 – 330	OCV 80	360 – 380		2.0 – 2.1
1A	MMA	1G	E6013		5		AC	230 – 250	OCV 80	260 – 280		1.8 – 2.0

Notes 1 Combined thickness up to 70mm 15°C, more than 70mm 80°C

NDT As per contract spec

Preparation method Flame cut and dress or machine	Preheat temperature, °C See note 1
Weld finish Not dressed	Interpass temperature, °C N/A
Proposed by Date	Revisions

34 *Example of a welding procedure specification from The Welding Institute's WELPRO system.*

made in the product is made using the welding procedure as described in the WPS. This weld is then inspected for quality by visual means as well as perhaps by radiography and ultrasonics. It will then be cut up for examination and hardness testing and if of a suitable shape, test-pieces for tensile strength and notch toughness will be made. If the results of these tests show that the weld meets the requirements of the product specification it can be approved for use. Test results are recorded on a document called a 'procedure qualification record' (PQR for short) and requirements for these welding procedure tests are given in standards and codes such as BS EN 288 and ASME IX.

To give a customer confidence that the WPS is suitable, an inspector may be sent to monitor the welding and the tests, alternatively welding and testing may be witnessed by an independent inspection company who will confirm that the tests have been properly carried out.

An example of a WPS is shown in Fig.34; what is of relevance to the designer is to see that the details of the weld preparation are included. This means that if the WPS number is referred to on the drawing it may not be necessary to detail the edge preparations but if they are detailed, they must be consistent with the WPS detail. The need to detail preparations on a drawing depends on the circumstances of manufacture. If the parts are manufactured by one firm and welded by another, then putting the preparations on the drawing is more convenient. If the preparations are to be machined, then it is also more convenient to put the details on the drawing. Perhaps the most obvious situation where the preparations need not be detailed on the drawing is where parts are cut and welded in the same shop.

In some industries, civil engineering for example, the design engineer's drawings show only the type of weld required at any joint, and for fillet and partial penetration butt welds, the size: the fabricator's draughtsman puts the details of the welds on the shop drawings including weld preparations if necessary.

CHAPTER 7

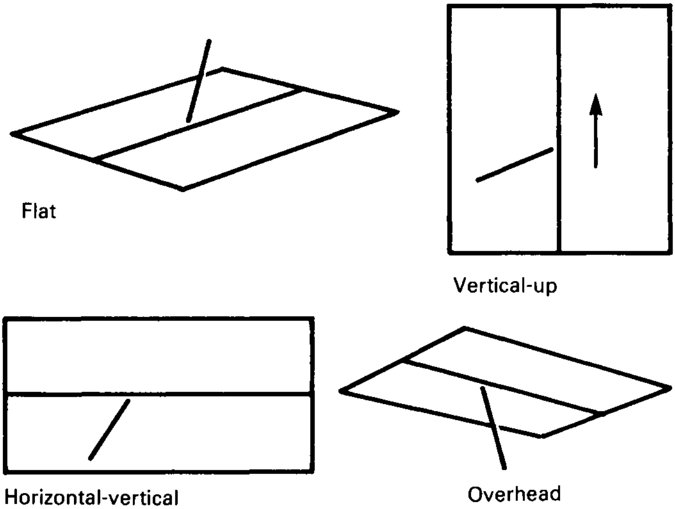
Access for welding

Welds can be made in any position (Fig.35). An essential is that joints be accessible to the welder or welding machine. There are a few basic configurations which cannot be satisfactorily welded by conventional manual or mechanised welding processes. Examples of these are shown in Fig.36, together with methods by which the difficulties can be overcome.

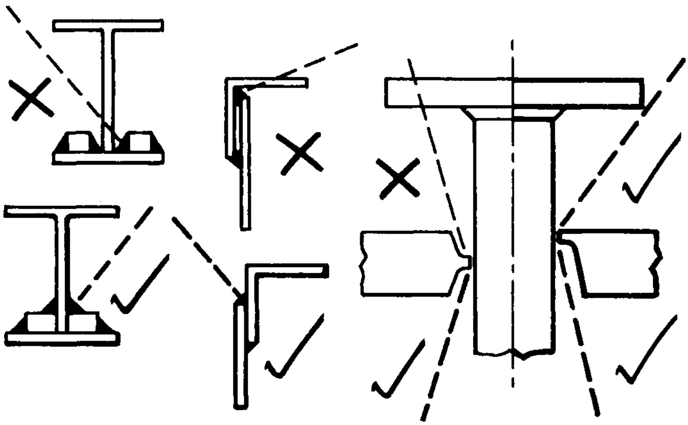
There are configurations where although a welding rod or gun can be directed at the joint, the angle between the parts is so small that the tip of the rod or wire is insufficiently close to the joint line to allow proper fusion into the root of the joint. This problem (Fig.37) is related to weld preparation which is dealt with in Chapter 4.

The advent of robotic welding machines has given the opportunity for installation of equipment which has more 'wrists and elbows' than a human being. These developments mean that welded joints can be made in locations where a human or conventional machine welder could not reach. Nonetheless, designers should appreciate that the more accessible a welded joint, the more likely it is to be of good quality, and, of equal importance, accessible for inspection and, if necessary, repair. The last point is of some importance for if a defective weld is found on inspection it will have to be taken out and remade, a procedure which may not lend itself to robotics. Naturally, there are methods of reaching points of limited access which are used when the situation demands it but the cost can be astronomical especially if the product is already in service.

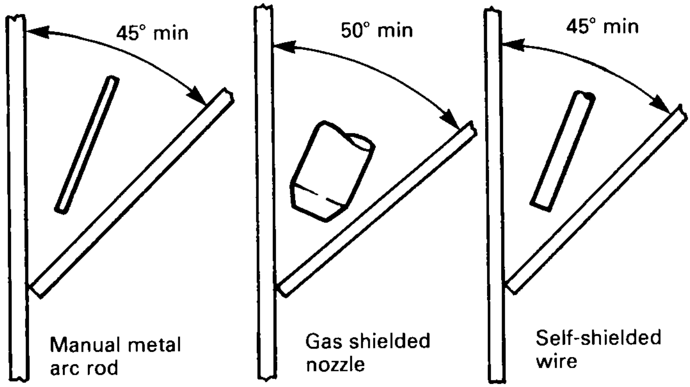
The nuclear power industry has devised some ingenious techniques for remote controlled welding in areas where humans cannot go (Fig.38), but most designers are looking at manufacturing and repair costs which are orders of magnitude below that which this type of intervention demands.



35 *Various welding positions.*



36 *Joint configurations which cannot be welded by conventional processes* (×), *and alternatives used to overcome the difficulties* (√).



37 *Angular limits for joint preparations for various welding techniques.*

38 *Remote controlled welder in use at The Welding Institute.*

Site welding

Welds made on site can be as good as those made in the shop but there must be good access and shelter from wind, rain and cold. Good welding requires a welder to have both feet on a firm base and room to move around the joint whilst making the weld. Welding from ladders is not good practice nor is it safe for the welder. The actual welding operation on site is usually more expensive than the shop equivalent because of the need to erect scaffolding, shelter, possibly heating, and the bringing on site of welding equipment and storage for welding consumables. Against this must be balanced the lower cost of transporting sub-assemblies, *etc.*

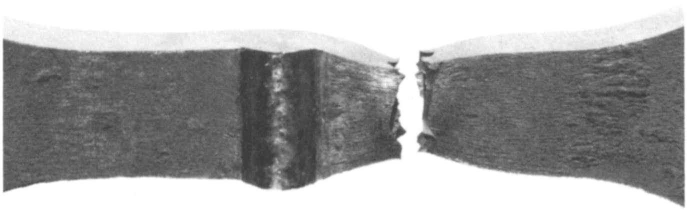
Bolted joints are frequently used for site erection but they often require flanges, butt straps or local thickening which are not always convenient, and they may impair the performance, *e.g.* for flow of solids or liquids, or be architecturally unsatisfactory.

CHAPTER 8
Engineering properties of welds

Strength

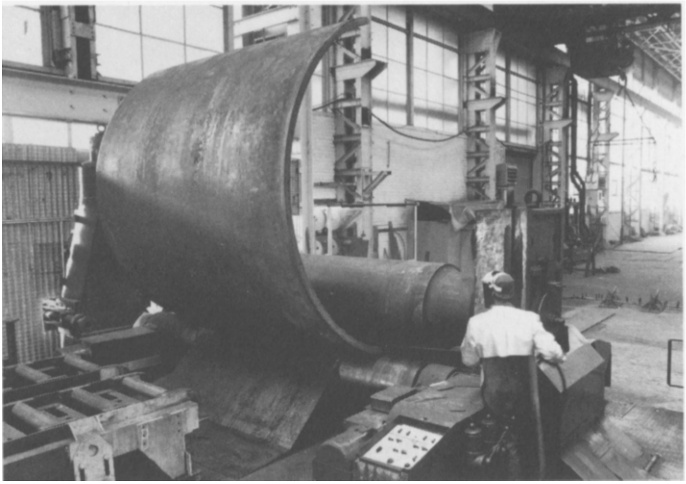
The most common property required of any load bearing item is strength. In steels this may be the yield strength or the ultimate strength and these quantities are measured as stresses in tensile tests. In such tests a sample of the steel is put under load and the extension of the sample is measured against the load (Fig.39).

Of particular importance is the amount by which the steel stretches plastically between the yield strength and the tensile strength. This plastic behaviour is a particular feature of mild and high yield steels and accounts for their ability to be used in structures based on the plastic theory of design. The capacity for deformation also makes such steels easy to roll or bend into tubes or sections without heating, (Fig.40).



39 *Tensile test specimen.*

If the steel itself has to have these properties, then it is essential that the welded joints also behave in the same way, otherwise the joints will represent weak points in the design. Weld metals designed to have properties equal to the parent metal are said to 'match' the parent metal.



40 *Rolling steel plate to form a cylinder.*

Notch toughness

Another welded joint property which is sometimes required to match that of the parent metal is notch toughness. This is a measure of the steel's resistance to brittle fracture. There are a number of different types of tests which are used to measure this property although this subject will not be dealt with in this book. The reader is referred to a book by K G Richards ('Brittle fracture of welded structures', The Welding Institute, 1971). In high temperature applications, the creep strength of the weld metal is important but again that is a specialised matter which can be studied in other books.

Setting these property requirements should really be the responsibility of the designer, but some of the standard welding procedure tests described in Chapter 6 inherently check that some of the weld properties such as strength and ductility are comparable with those of the parent metal.

Selecting welding consumables such as covered electrodes or wires and fluxes to meet these requirements is a task for the welding engineer not only because it requires specialised knowledge but also because the properties depend on the way the weld is made. This is described in the welding procedure specification which, as we have already seen, is the welding engineer's responsibility. It should then not be necessary for the designer to be concerned about these matters but he is of course entitled to demand evidence, in the form of welding procedure tests, that the materials and methods to be used will be satisfactory.

Fatigue strength

Fatigue cracking can occur in all materials under fluctuating loads. In welded items made of any one type of metal, the occurrence of this cracking is not a function of material properties but of the detail design and quality of fabrication. A number of standard specifications and codes of practice give rules for the design of welded products which operate under fluctuating loads such as bridges, cranes, offshore structures, *etc.* The designer must become familiar with these rules if a successful design is to be produced because the form of the welded joints has a primary influence on the life of the item or, conversely, it may have the effect of reducing the allowable stress in the member or joint well below that which may be used with static loads. In addition, weld defects which would cause no problem under static loading can severely reduce the life under fluctuating loads by starting fatigue cracks well before they would occur in a sound joint. A designer with this responsibility should consult the fatigue clauses of the specification or code appropriate to the product and also become familiar with works of reference such as Gurney T R: 'Fatigue of welded structures' (Cambridge University Press).

CHAPTER 9

Steels for welded construction

Steels required for welded construction have to be able to tolerate the rapid heating and cooling which accompanies arc welding without undergoing great changes in their metallurgical structure and mechanical properties and without cracking.

It is important that in choosing steels for welded construction the word 'weldable' is identified in the standard specification if one is to be used. This means that the composition of the steel has been designed so that it can be welded by conventional methods and in accordance with good practice which may itself be the subject of a standard specification. Only those designers with access to a metallurgist or a welding engineer should use steels which are not labelled as weldable. Such steels can be welded but they require specific procedures which may be outside the competence of some fabricators and may be costly.

Weldable structural steels are the subject of national, regional and international specifications. These specifications commonly offer a number of steel grades based on yield and tensile strength with subdivisions within those grades based on notch toughness. Limitations on chemical composition, and sometimes the steelmaking process, may be associated with the different grades and sub-grades. Some specifications relate to specific applications such as pressure vessels; often such an application will demand greater levels of assurance of consistency of properties. This is achieved through more extensive testing than is accepted for a less demanding application. The actual steel may be the same for each application and any price difference may just reflect the cost of the additional testing and documentation.

Specifications will be found in many series of standards for steel forgings and castings as well as cold formed sheet, concrete reinforcing bar and other product forms. For specific uses the designer should refer to the standards catalogue relevant to the project.

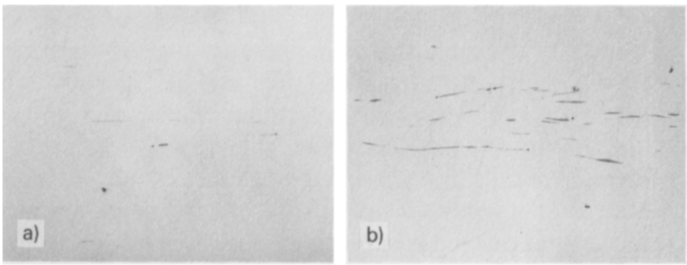
Outside the range of steels made to these standard specifications are those offered by most of the world's steel companies. Some of these are made to meet other national standard specifications and some are proprietary steels made by one particular company.

It should be recognised that a specification is a set of requirements to be met and is not a label for a particular type of steel. Especially within the commonly used grades most structural steel made around the world conforms to common structural steel standards. If a plate is labelled as conforming to some other specification the difference may be only in the type and amount of testing required by this other specification and perhaps closer examination will show it to meet the user's requirements.

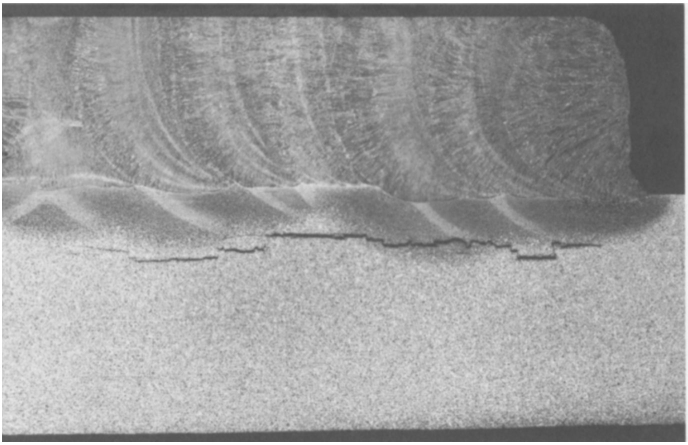
Apart from properties of strength and notch toughness it is sometimes necessary to place a control on other characteristics. One of these is the occurrence of inclusions — non-metallic materials which arise as part of the steelmaking process and which the steelmaker tries to exclude from steel to be rolled into sections or plate. Layers of such inclusions (laminations) represent a plane of weakness in the steel which is undesirable where loads act at right angles to the plate surface.

It is possible to specify levels of distribution of laminations or small patches of inclusions of non-metallic substances. An example of a specification is BS 5996 which gives three levels of lamination or inclusion content as measured by ultrasonic testing. Unfortunately for designers there is little guidance available anywhere as to which level is suitable in a particular circumstance and the choice must be somewhat arbitrary, based on the amount of stress and the consequence of failure. An alternative approach used by many companies is to use untested plate but to examine ultrasonically those areas on to which attachments are to be welded.

Another characteristic of steel plate which may be specified is its resistance to lamellar tearing as measured by the ductility of a tensile test-piece taken from the through-thickness direction of a plate. Lamellar tearing is a form of cracking which occurs if the steel has too high a non-metallic inclusion content (Fig.41) distributed on a microscopic



41 *Steels with differing inclusion contents*: a) *Clean steel* (*low inclusion content*); b) *Dirty steel* (*high inclusion content*).



42 *Lamellar tear induced on welding steel with a high non-metallic inclusion content.*

scale (not the same as laminations which are on a far larger scale). These inclusions can induce a weakness in the steel during welding of attachments to the surface (Fig.42).

Tests to measure this susceptibility are described in BS 5135 'Process of arc welding of carbon and carbon-manganese steels'. (The title of this standard is a misnomer as it is about welding procedures and not processes.) Guidance is given in this standard to the ductility levels which are considered acceptable on the basis of testing and experience in fabrication.

The text so far has dealt entirely with steels whose principal alloying elements are carbon and manganese. These steels, mild steel being the most elementary description of the lower strength grades, do not have good resistance to corrosion and start to lose their strength at temperatures above about 200°C. Under either of these circumstances the designer will look for other materials.

If there is a need for atmospheric corrosion resistance the first step might be to look at so called weather resistant grades of steel. These have a small proportion of copper in them which causes the surface to develop a firmly attached form of rust which resists further corrosion. Such steel has been used in unclad building frames, bridges and electricity transmission towers. The appearance is not to everyone's taste as it has connotations of ordinary rust and associated lack of maintenance, but in suitably chosen sites and with appropriate architectural treatment it has been used successfully.

For resistance to corrosion, where cleanness is important, the choice of material will probably move towards stainless steels. There are many alloy combinations under this generic name but the most commonly seen one is that containing 18%Cr-8%Ni. This is used for catering equipment as well as for chemical process plant; it is easily welded using the proper procedures and can be polished to a bright surface. However, a warning should be given that it is not resistant to corrosion in all environments and specialist advice should be sought in choosing this or any of the other stainless steels.

In high temperatures, such as the conditions prevailing in steam power generating equipment, a range of creep resisting steels is used embodying elements such as nickel and chromium in different proportions as well as molybdenum and vanadium. These steels retain their strength at higher temperatures than the ordinary carbon-manganese steels but their successful use requires specialised knowledge.

CHAPTER 10

Weld defects — what are they and do they matter?

The definition of a weld defect can be derived from two points of view. For the designer it may be a feature of a weld which is sufficient in size, shape and location to prevent the joint performing according to its design requirements. For the welding engineer it may be any feature which interrupts the uniformity of the weld. This could range from a small gas pore in the weld metal to a gross area of lack of fusion.

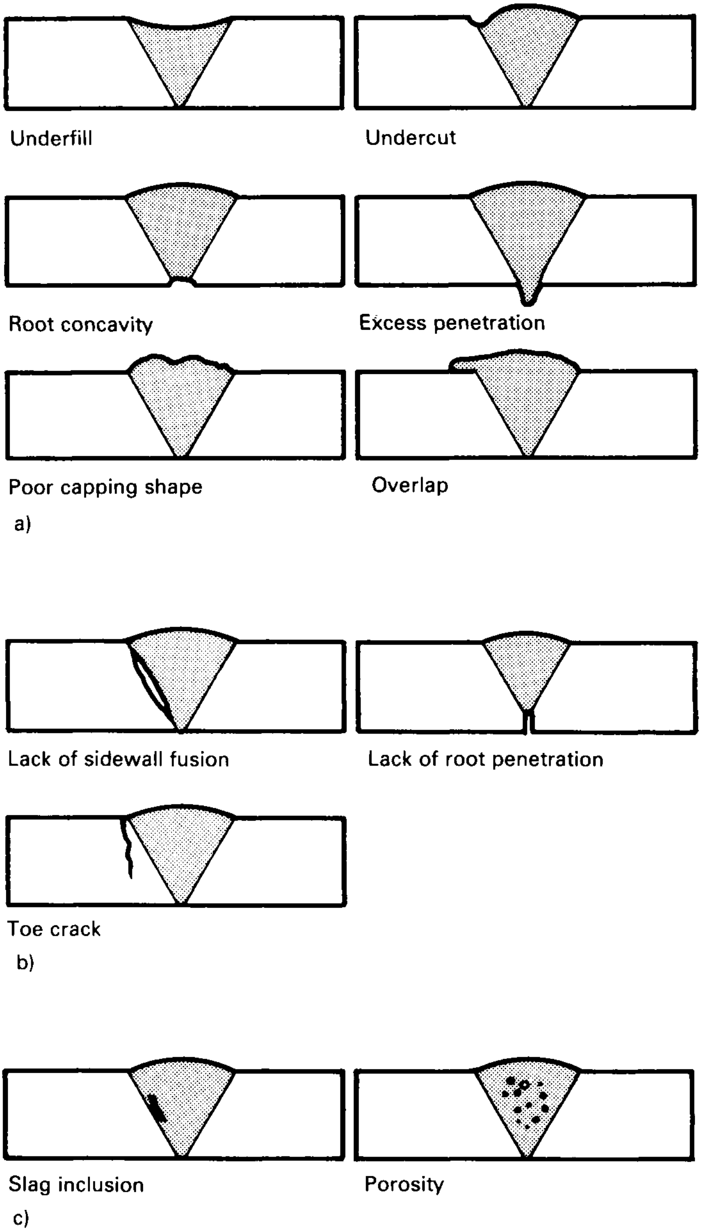
In practice, a weld defect is generally defined as any unintentional discontinuity at the surface or within the body of the weld which is potentially detrimental to the performance of the welded joint, or which is evidence of a standard of workmanship lower than that expected. This general definition would be difficult to employ if a decision had to be made whether a certain defect could be allowed to remain. To overcome this, 'acceptance levels' for various types of defect in certain products have been established in standard specifications.

It is convenient to group weld defects under the following headings (Fig.43):

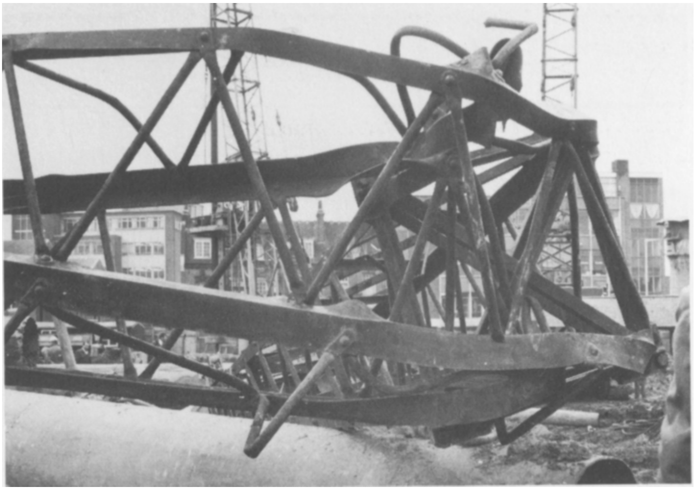
1 Weld profile;
2 Planar, *i.e.* flat with sharp edges;
3 Volumetric, *i.e.* three dimensional holes or lumps of non-metallic compounds.

Most of the limits on the allowable level of defects have been established arbitrarily and represent generally achievable levels of good workmanship by trained, skilled welders or welding machine operators. In most applications these levels are too low to damage the performance of the item. Indeed removal and repair of such defects has been known to leave a joint in a worse condition (Fig.44).

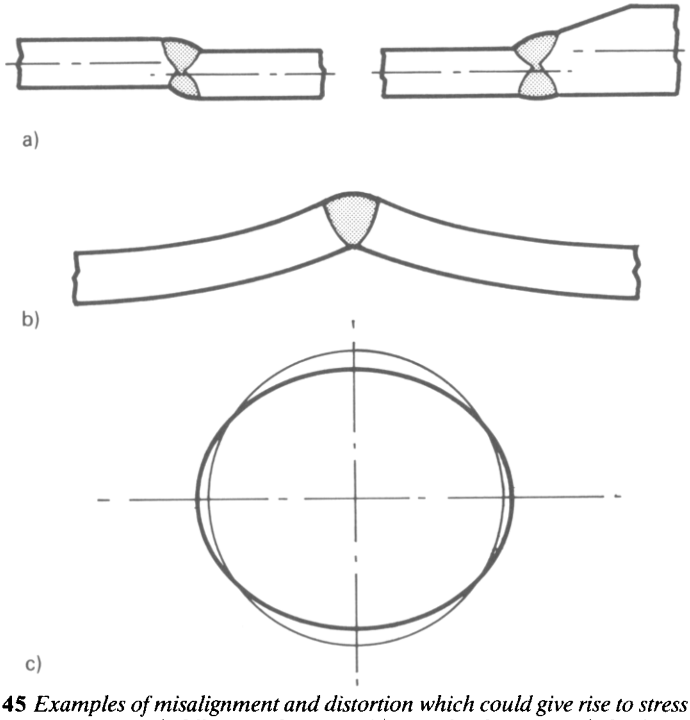
The most commonly found sets of standard acceptance levels for weld defects are in specifications for pressure vessels, the failure of which can



43 *Typical weld defects*: a) *Weld profile*; b) *Planar*; c) *Volumetric defects.*



44 *Overload failure of crane boom following weld repair.*



45 *Examples of misalignment and distortion which could give rise to stress concentrations*: a) *Offset misalignment*; b) *Angular distortion*; c) *Ovality.*

be catastrophic. Examples are to be found in BS 5500 and this standard has often been used for other products requiring established high levels of quality.

A drawback of this type of approach is that a higher level of quality may be required than is necessary, resulting in repair work which is both costly and not always beneficial as exemplified in Fig.44. As a result, work has been going on for a number of years to derive methods by which weld defect acceptance levels can be set to match the design conditions; this is known as engineering critical assessment (ECA). Like all refinements this requires that there is confidence in the calculated levels of stress and in the detection and measurement of defects. It demands specialist engineering staff at a level found only at present in the public utilities and large manufacturers and users of plant and structure.

The integrity of welded joints may also be reduced by poor alignment of the parts. This can induce local concentrations of stress which will not be predicted by calculations which assume proper alignment. This is referred to in Chapter 4 and examples are shown in Fig.45.

In any application, the decision regarding acceptable weld defect levels has implications for product manufacturing costs and the liability of customers and users. It is therefore necessary that the matter be dealt with at the highest technical and commercial levels in a firm and not left to individual engineers or draughtsmen.

CHAPTER 11

Non-destructive testing

This is a specialised activity with its own skills and technology. The designer would not necessarily be expected to know about the subject in any depth. Nonetheless, the methods by which defects can be found can have an impact on the configuration of the product and will also be reflected in the defect acceptance levels which can be employed.

The techniques used in non-destructive testing (NDT) can be divided broadly into two groups — those used to detect defects on the surface of the material and those used to detect defects lying entirely within it. The techniques commonly used for surface breaking and buried defects are listed below.

Surface breaking defects

Visual examination — this is not usually included in definitions of NDT but is vital in assessing not only the appearance of welds but that all the welds on a drawing have been completed.

Magnetic particle — to conduct this test, the weld area is magnetised and iron powder, dry or in liquid suspension, is sprayed on. This collects at surface cavities or cracks which concentrate the magnetic field and the concentrated powder appears as a line or point (Fig.46).

Dye penetrant — this is useful for non-magnetic materials, *e.g.* stainless steels or aluminium. Strong dye is sprayed on the joint and soaks into cracks, *etc.* The surplus is wiped off and after a short pause, a chalk powder suspension is sprayed on. This soaks out any dye in cavities which show as coloured patches or lines.

Buried defects

Radiography— X-rays from an X-ray tube or radiation from a radioactive isotope are used to produce images of welds on photographic film. The principle is simple in that where the metal is thinner or has a

46 *Detection of defects using magnetic particle inspection.*

47 *Using an ultrasonic probe to detect defects.*

cavity in it, more radiation passes through and affects the film which then appears dark in those areas after being developed. Interpretation of radiographs requires training, experience, knowledge of welding and careful viewing. The novice may miss significant images or fail to understand the nature of those which do appear. The technique is not sensitive to tightly closed cracks lying out of the plane of the direction of radiation. The use of radiographs requires that there be access to both sides of the joint, the film being placed on one side and the radiation source on the other. Use of the method therefore has to be taken into account at the design stage.

Ultrasonics — a beam of high frequency sound is transmitted into the material from a probe which is also able to detect any reflections of the beam from the opposite surface or from internal discontinuities such as weld defects. Progress of the beam is displayed on a cathode ray tube giving trained and experienced operators information from which, with a knowledge of the original weld preparation, they can indicate the position of the defect and its size. This is a far from exact technique but it is capable of being used in a multiplicity of directions which will, if pursued, enable an operator to give an opinion as to the nature of a defect (Fig.47).

Ultrasonics, if correct procedures are followed, can be used to detect tight cracks which radiography may fail to indicate. Information can also be obtained on the depth of a defect which cannot be obtained by radiography. Ultrasonic examination is not a feasible technique for welds in thin materials, say steel less than 6mm thickness.

Fillet welds are not easily examined by radiography or ultrasonics. Radiography is of limited efficacy in any configuration except in-line butt joints, whereas ultrasonics can be used on almost any configuration as long as there is access for the operator and equipment and also local room to allow the probe to scan across a sufficiently wide area. These last points emphasise those made in Chapter 7 about the need for access to welded joints which is a function of the design as well as the fabrication sequence. They are also a reminder that inspection is a matter to be taken into account at the design stage of a fabrication and not left until the job is completed.

There are some other specialised techniques which are employed in certain circumstances but the most usual are those listed above.

CHAPTER 12

Getting it together!

Throughout this book we have talked about a person called a designer and a person called a welding engineer. Such people do, of course, exist but their respective roles are not the same in all industries and they even differ within one industry. The essentials are that one group of people called designers have the job of taking a need and designing something to fulfil it; the other group, the welding engineers or people fulfilling their role if such qualified people are not employed, have the task of devising methods of welding the designed item. There are, of course, many other people involved in the business such as planners, purchasers, welding foremen, machine shop foremen, transport managers, *etc.*

The prime requirement for success at a competitive price is for a designer to be able to communicate clearly to the fabricator. This is usually done through the medium of an engineering drawing although in more complex products there may have to be some written specification of the requirements. How much detail is needed to convey the message depends on the closeness of the designer to the fabricator and on the similarity of successive jobs.

This book sets out the background knowledge which a designer ought to have to appreciate the type of information which the fabricator needs to make the required article. Quite often there are circumstances where the design goes through several stages. A conceptual design may be handed over to a detail designer to develop who may then pass it to the draughtsman who prepares the shop drawings so that there is no direct link between the original designer and the fabricator. At the other extreme, the draughtsman's office may open on to the shopfloor. In both cases it is important that clear instructions as to what is required are passed on and in so doing recorded for future use.

The minimum information which should pass from designer to fabricator can be summarised as follows:

- Material description;
- Type of welded joint;
- Dimensions and tolerances;
- Mechanical properties of welded joint (if not the same as the parent metal);
- Weld quality standards;
- Surface treatments and finishes.

In practice, more or less information is transmitted depending on the customs of the industry or the responsibilities of the parties.

A lot of people think they understand welding and some of them do. Of these, many have picked up knowledge secondhand or by hearsay. Some of it is out of date whilst some can be quite incorrect. The following table compares some of the myths of welding with the correct information.

Hearsay	Correct information
Welds should not be used in tension	Welds can be made as strong as required which is usually as strong as the metal being joined
Mild steel cannot be welded to high tensile steel	Most combinations of metals can be welded together provided that their melting points are not too different
CO_2 welding always gives lack of sidewall fusion	The quality of a weld depends on the establishment of a sound welding procedure and adherence to it in production, with properly maintained equipment
Welders are awkward people	Manual welding is an unusual skill often performed in unusually uncomfortable conditions. You have to be able to reach and watch a joint to be able to weld it. It requires a degree of concentration exceeded in few other crafts to avoid making mistakes which might not be visible and are expensive to find and correct
All welds can be X-rayed and ultrasonically tested	Many welds can be examined for internal defects by radiography or ultrasonics but the method must be chosen to suit the weld type
Welds should not cross	When welding over another weld, it may be necessary to grind the first weld to remove crevices which might give rise to defects
Residual stresses reduce the load carrying capacity of members	Residual stresses have no effect, of an engineering significance, on tension load capacity but may reduce buckling strength in some configurations
Heating steel with a flame drives moisture out of the metal	Water produced by combustion in the flame condenses on the cold metal. The flame must be directed at the metal for long enough to heat the metal and evaporate the condensed water