Chapter 5
SHAPING AND FORMING

5. SHAPING

THE SHAPING and forming of aluminium alloy semi-finished products for use in shipbuilding and marine applications comprises all of the operations prior to assembly by welding, riveting and bonding. These are:

- marking out prior to cutting, if required,
- cutting to shape and size before assembly,
- forming.

The development of computer software for naval architecture and ship design has made it possible to automate metal cutting operations. These operations may be carried out by the shipyard or by a sub-contractor who specialises in this activity.

This preparatory phase of forming must be conducted with extreme care, especially with regard to cutting. Cutting must be both as accurate as possible to ensure a good fitup of components that will be welded together, and as regular as possible to prevent any sites of crack initiation. Cutting quality is one of the parameters that determines the fatigue strength of welded joints.

The surface hardness of aluminium is less than that of steel. This factor must be taken into consideration when handling semis, when clamping components in machine jaws and during certain forming operations, to prevent scoring or bruising to the metal. Aluminium sheet must never be dragged along the ground, placed in the path of handling equipment such as stacker trucks, or walked on.

Aluminium alloy semis must be protected from metal particles discharged by the forming or shaping (grinding, machining etc.) of other metals such as steels or copper alloys. Such particles can cause superficial micro-pitting in the presence of moisture if allowed to become embedded in the surface of the aluminium.

The tools and forming techniques used for aluminium alloys do not differ greatly from those used for stainless steel. However certain settings (or arrangements) of tooling are different, for example bending radii or the angles of sawteeth.

1. RECEIVING AND STORAGE OF SEMIS

Packaging to the size of the finished product is made of timber or steel pallets on which sheets are stacked. These may be separated from one another by liners made from special moisture-absorbent paper.

The packs of aluminium sheet are wrapped in polyethylene film and Kraft paper and strapped to the pallet (figure 53).

COASTGUARD CP 280

AND FORMING

1.1 Receiving packs

Polymer film and Kraft paper can tear, which means that these packaging materials are not watertight and incoming packs of aluminium alloy semis must be unwrapped under cover.

Aluminium sheet must be handled with care and precautions taken to protect its clean surface condition to ensure the good quality of weldments and the general appearance of aluminium alloy structures.

1.2 Storage

There is no compelling need to remove aluminium semi products from their original packaging before they are actually needed. They just have to be protected from water and damp environments at their place of storage.

However if sheets or shapes are removed from their original packaging and stored flat, they must be placed on wooden blocks several centimetres thick to prevent any direct contact with the ground, even if this is cemented.
When sheets or shapes are laid flat without any liners between them (paper or board or even wooden blocks), whitish or greenish stains on facing surfaces will usually be observed after a certain period of time (1). These stains are due to the effect of moisture seeping in between the sheets or shapes by capillary action.

Prolonged storage of unpacked semis in the open air can lead to superficial changes on the surface of the material. These will usually be very superficial micro-pits (a few microns in size), stains or even general tarnishing (2).

While such alterations have no effect on the metal's subsequent resistance to corrosion, when they are in service on the ship they represent moisture "traps" that must be carefully removed before any welding. They will affect the general appearance of the semis however, though this is less critical when the products are painted or cannot be seen from the outside.

PACKING "MARINE" GRADE SHEET

Figure 53

Note: Ideal storage is in a covered room protected from the weather, with semis stocked upright and sheets or shapes spaced apart to prevent moisture penetrating between them. When stored flat, semis should be spaced apart using wooden blocks.

(1) These stains will have the same shape on both of the facing surfaces. They are symmetrical about the axis parallel with the sides of the sheets (or shapes).

(2) It goes without saying that these changes will be made worse in aggressive atmospheres highly polluted by industrial emissions, smoke etc.

FLYINGCAT 3

2. CUTTING TO SHAPE

The basic tools used for cutting aluminium alloys are the same as for steel. These are:

- plate or crocodile shears,
- bandsaw,
- circular saw,
- plasma,
- fluid jet.

The first three tools (and plasma) are used for manual cutting, whereas plasma and fluid jet are the preferred media when cutting is automated using programmes created with naval construction software.

The contours of the parts must first be traced on the semi before they are cut out. Metal scribing tools should not be used for tracing as they can leave marks in the material which could become crack initiation sites under the effect of stresses in service.

It is preferable to use a medium hard pencil (e.g. 5H) (3) that makes lines which are very visible and easy to erase if corrections are necessary.

2.1 Plate and crocodile shears

These shears are used for making straight-line cuts. Aluminium alloys are cut with machines of the same power as for unalloyed steel E24.

The surface condition of the edge of the shear blade must also be as clean as possible. A roughness Ra of less than 0.1 micron on a steel blade of type Z160CDV12 minimises the risks of seizing.

A suitable "cutting gap" or clearance should be set between the blade and the frame of the shear to protect sheet from distortion. The optimum setting will increase with the metal's shear strength; the gap will also be smaller for annealed sheet than for strain hardened sheet.

The use of shears to cut sheet more than 10 mm thick is not advisable in practice, as cutting introduces stresses on the sheared edges that can ultimately lead to severe pitting corrosion and also cause cracks.

2.2 Bandsaw

A bandsaw is essential for cutting sheet more than 10 mm thick and for shapes.

Sawblades used for cutting aluminium are special – their teeth have a greater pitch (i.e. there is more space between adjacent teeth) and a wider throat than blades used to saw steel (figure 54) so as to assist chip fragmentation and removal.

The pitch of the teeth must be such that two teeth are engaged in the thickness of the metal at all times, so there is a minimum thickness of material that is suitable for cutting with this tool.

The rate at which aluminium is sawn is greater than for steel, and may attain 1000 $mm.min^{-1}$. Lubrication using soluble oil or cutting oil is essential for long lengths and high cutting rates.

Sawing will produce cut edges that are clean and burr-free provided the sawblade is suitable for aluminium and the cutting parameters are set correctly.

Note: Jigsaws can be used to cut thin sheet less than 6 mm thick; jigsaws have the advantage of being very easy to handle and can be used to cut relatively complex shapes as well as straight lines.

BANDSAW

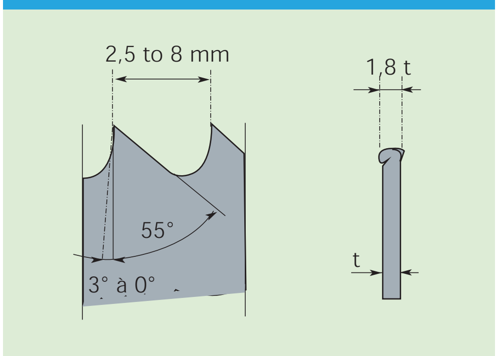


Figure 54

(3) Graphite markers should not be used on surfaces which will be in contact with water or moisture.

2.3 Circular saw

Also called a milling saw by some, it operates with an action similar to milling.

The characteristics of circular saw blades for aluminium are shown in figure 55.

With semi-finished products in the 5000 and 6000 series, cutting speeds can attain 600 to 1000 mm/min. with high speed steel (HSS) blades and 800 to 1500 mm/min. using carbide blades.

As with the bandsaw blade, lubrication is essential for long cuts and high cutting speeds.

The values of p and h will depend on the diameter of the saw

Note: Portable circular saws may be used on products not more than 20 mm thick.

2.4 Plasma cutting

The industrial use of plasma cutting for metals began in the Nineteen Fifties.

In this process, the cutting of the metal is achieved with a combination of the thermal and kinetic effects of a plasma arc which is generated by a special torch whose path follows the contours of the piece that is to be cut.

The plasma arc is obtained by passing an electric current through a stream of gas, also known as plasmagen gas, that has been brought up to ionisation temperature.

To obtain the characteristics that are required for cutting, the plasma arc is passed through a small diameter energy-cooled aperture or nozzle, the containing effect of which is to greatly increase the temperature and velocity of the resulting jet of plasma arc.

As an indication, the current flowing in the column of plasma arc can be between 10 and 1000 Amps, the diameter of the jet emerging from the nozzle ranges from several tenths of a millimetre to several millimetres, the temperature inside the jet from 15,000 to 30,000 K and the discharge velocity at the exit from the nozzle from Mach 1 to Mach 2.

The process of the plasma cutting of metal materials is based on a transferred arc, which means that an arc is established between a refractory electrode (– pole) and the piece to be cut (+ pole) (figure 56).

This highly rigid and extremely hot stream of plasma fuses the metal over its full thickness and ejects it outside the cut thanks to the kinetic energy generated by the plasma's very high velocity.

The choice of gas depends on the thickness of the material that is to be cut and on other criteria such as the quality of cut, productivity and running costs (table 45, p. 78).

Plasma cutting can be manual with the compressed air and argon/hydrogen processes, or automatic (on machines).

Manual plasma cutting is used primarily on site to make unplanned cuts, e.g. breaches for pipes through bulkheads, partitions etc. A template should be used for accurate cutting. Material up to 50 mm thick can be cut manually and with a limited amount of skill.

CIRCULAR SAW

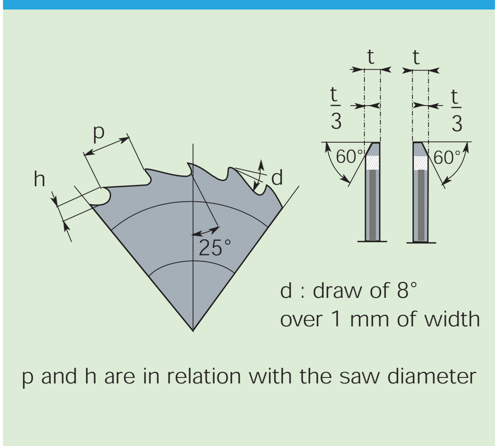


Figure 55

PLASMA CUTTING

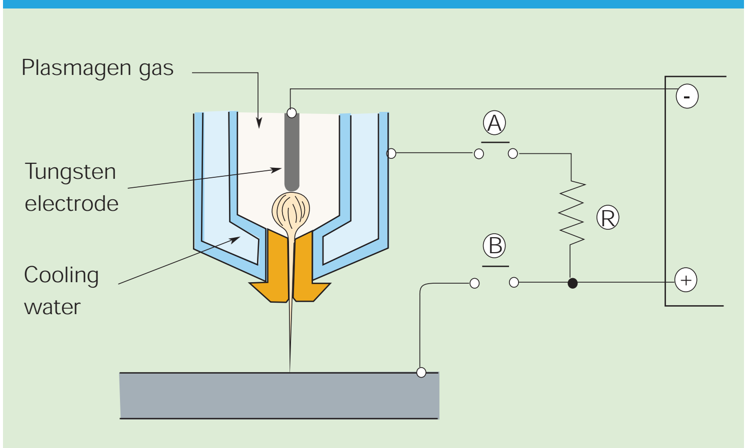


Figure 56

Automatic plasma cutting is done on straight or contoured cutting tables (such as numerically controlled (NC) X-Y machines or multiple jointed robots). The path of the plasma torch is controlled by machine axis control programmes; these run in conjunction with software that defines the geometry of the components and their interfaces with other parts so as to minimise waste by optimising both the position of the component within the sheet format and the paths of the torch.

There are two plasma cutting techniques (figure 57):

- "dry" plasma cutting on a table, in air. The draft may be as much as 5° with a plasmagen gas mixture of argon and hydrogen,

- water vortex plasma, in which the sheet to be cut is placed in a tank filled with water. The torch itself is partially submerged. The cutting draft is smaller, in the region of 2 to 3° (4).

Water vortex plasma allows higher cutting speeds than argon/hydrogen plasma cutting which is done in air. It demands more electrical power for the same thickness of cut however. Argon/hydrogen can be used to cut material thicknesses of up to 150 mm, and the geometrical accuracy of the cut pieces is in the region of 1 millimetre.

Given the high energy input that takes place during the localised fusion of the metal, heat is diffused to a width of around one millimetre on either side of the cut whatever the alloy and whatever its thickness. As happens with arc welding (5), this "heat affected zone" is annealed (in the metallurgical sense).

This zone can be removed by machining more than 2 mm from the cut edge, although this operation is obviously pointless when the piece has been cut to size and shape for subsequent arc welding.

Note: The process of oxygen cutting with the *oxy-acetylene torch* which is used widely for mild steel is not at all suitable for aluminium.

(4) During water vortex plasma cutting, the fine particles of aluminium can react with the water and give off hydrogen. It is therefore essential to avoid any build-up of this gas which can cause local explosions.

(5) Cf. Chapter 6.

PRINCIPLE OF PLASMA

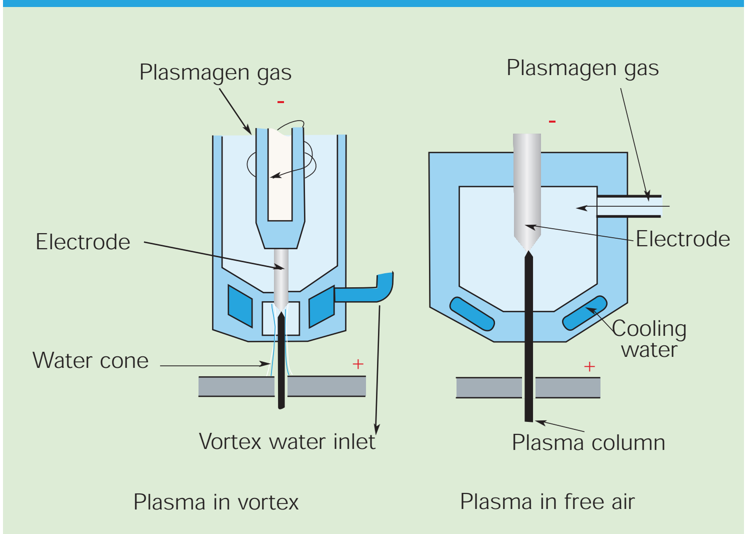


Figure 57

PLASMAGEN GASES

Thickness (mm)	Gas	Remarks
0,4 - 15	Oxygen	High cutting speeds
0,4 - 30	Compressed air	Low running costs
8 – 150	Mixture Argon (80 to 65 %) / Hydrogen (20 to 35 %)	Superior cut quality
1 – 70	Nitrogen + Post injection of water	Immersing the component in water reduces sources of nuisance (noise, fumes and radiation)

Table 45

2.5 Fluid jet cutting

In fluid jet cutting, the metal is cut by a calibrated jet of water charged with abrasive particles (granules of garnet, corundum or other very hard minerals). The water is projected at very high pressure - 3000 bars and more - through a nozzle onto the material which is in a tank filled with water (figure 58).

Water jet cutting produces a clean and extremely accurate cut without a draft.

On aluminium, the technique can be used to cut through thicknesses between 1 and 100 mm at speeds of 3500 and 30 mm/min respectively.

Unlike plasma cutting, there is no heat affected zone either side of the cut because no heat is transferred.

(6) For the meaning of the tempers, refer to section 4.3 in Chapter 3.

WATER JET CUTTING

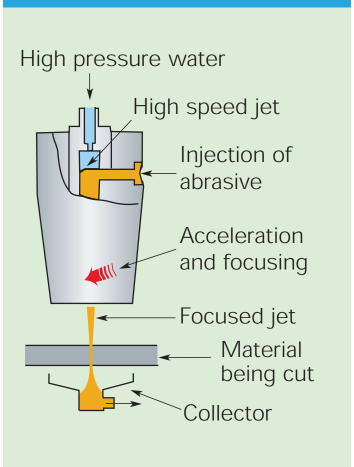


Figure 58

3. FORMING

In naval construction, forming consists essentially of the folding and forming of sheet and the bending of shapes.

Because forming requires the metal to be sufficiently plastic, it follows that the temper of aluminium alloy semis is an important parameter that must be taken into consideration for delivery and during the forming operations if these involve significant work hardening.

3.1 Influence of the temper

Most aluminium alloys used in shipbuilding and in coastal installations belong to:

- the 5000 series (aluminium-magnesium alloys), mainly in the form of sheet and plate. The most common alloys are: 5754, 5086, 5086, 5383. These alloys lend themselves very well to forming especially in the annealed tempers O and annealed flattened tempers H111. It is these tempers which should be preferred as having the best suitability for forming. This suitability decreases for the H116 temper and even more so for the H321.
- the 6000 series (aluminium—silicon-magnesium alloys), mainly in the form of shapes. The most common alloys are: 6005A, 6082 and 6061. As in all the 6000 series, these are age hardened alloys. Semis are delivered in the T6 or T5 tempers and less frequently in the T4 or T1 tempers (6). Even though these alloys lend themselves less well to forming in the artificially aged tempers (T6 or T5), they must nevertheless be formed cold and not hot. Heating would have a more or less marked annealing effect and hence a significant reduction in mechanical properties.

3.2 Sheet bending

Conventional table bending machines and bending presses are perfectly adequate provided the tools are free from unacceptable irregularities.

If for reasons of appearance the bent sheet must not display any clamp marks from the jaws, then the contact surfaces should be protected with kraft paper or plastic film.

For multiple bendings, holes should be drilled to mark their points of intersection to avoid the formation of cracks during bending (figure 59). The hole diameter will increase with the thickness of the material. It is 4 mm for sheet 1 mm thick and 6 mm for material 2 mm thick.

Aluminium alloys must never be bent at a sharp angle. The inside radius of bending is a function of the thickness of the sheet to be bent (table 46):

Note: Aluminium alloy sheet (or shapes) from which forms have already been cut out should never be formed. Cutouts must always be made after forming, using a jigsaw for example.

INTERSECTING BENDINGS

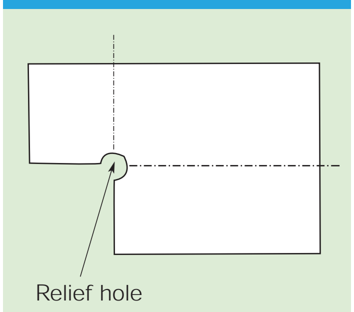


Figure 59

INSIDE RADII FOR COLD BENDING, AT 90 ° TYPICAL VALUES (*)				
Alloy	Thickness (mm)			
	Temper	1,5 - 3,0	3,0 - 6,0	6,0 - 12,5
5454	O and H111 H24 and H34	1,0 t 2,5 t	1,5 t 3,0 t	2,5 t 4,0 t
5754	O and H111 H24 and H34	1,0 t 2,0 t	1,0 t 2,5 t	2,0 t 3,0 t
5083	O and H111 H116 H24 and H34	1,0 t 2,0 t 2,5 t	1,5 t 2,5 t 3,5 t	2,5 t 4,0 t 4,5 t
5383	O and H111 H116 H24 and H34	1,0 t 2,0 t 2,5 t	1,5 t 2,5 t 3,5 t	2,5 t 4,0 t 4,5 t
5086	O and H111 H116 H24 and H34	1,0 t 2,0 t 2,5 t	1,5 t 2,5 t 3,5 t	2,5 t 3,5 t 4,5 t
6061	O T6 (**)	1,0 t 3,5 t	1,0 t 4,0 t	2,0 t 5,0 t
6082	O T6 (**)	1,0 t 3,5 t	1,5 t 4,5 t	2,5 t 6,0 t

(*) Taken from standard EN 485-2, December 2001.

(**) Sheet made from these alloys can be bent to significantly smaller radii on a "fresh quench".

Table 46

3.3 Non-machinable surfaces

All scoring or clamping marks left behind after cutting must be removed from the edges of sheet material to prevent the formation of cracks at points of deep deformation.

If the material is so work hardened that shaping becomes difficult, intermediate annealing must be carried out either in the furnace or using an oxy-acetylene torch.

In this case the rise in temperature must be monitored. Tallow can be used as a temperature indicator – it turns brown around 340 °C – or use thermocolour pencils that change colour as the temperature changes.

3.4 Bending tubes and shapes

Bending can be carried out manually on timber templates for slender sections or steel templates for thicker sections. If necessary, tubes are filled with sand and shapes are internally reinforced to prevent collapse or distortion.

Bending can also be done on suitable presses (three-roll bending press etc.).

6000 series alloys in the T6 temper should be bent cold so as not to affect their mechanical properties in the delivery condition. If this is not possible, they will have to be bent in the quenched T1 or T4 temper and then artificially aged under the usual conditions of temperature and time.

HIGH INERTIA BEAM FABRICATED BY WELDING SHEETS

PATROL BOATS

Chapter 6
WELDING

6. WELDING

WELDING is the process by which two or more parts are joined by localised fusion of the metal to form a single component; the original contours of the initial parts disappear after assembly.

Arc welding is still by far the most widespread joining process and the one used most frequently in shipbuilding.

Technical advances in arc welding with pulsed MIG have helped improve the performance of welding machines and the quality of the weldments produced.

The development of other processes such as laser beam welding or friction stir welding (FSW) will further advance the design and fabrication of aluminium sub-assemblies for shipbuilding.

Whatever the welding technique that is used, the quality of workmanship of aluminium alloy weldments becomes increasingly important on very long ships as it determines the fatigue resistance of the most stressed areas of the vessel. The weld is a vital element in the fatigue strength of an assembly.

1. HISTORICAL REVIEW

The first attempts at welding aluminium were made in 1904, and gas welding was used at that time [1].

Up until the early Sixties, welding with the oxy-acetylene torch was the only method available for welding aluminium alloys. The use of this process was limited to flat welding and thin sheet.

For many years the presence of a natural oxide film on the surface of aluminium was a major obstacle to the welding of this metal. For aluminium to be welded correctly, this film must be removed and prevented from re-forming by shielding the weld pool from the surrounding atmosphere.

In oxy-acetylene welding, fluxes in the form of paste diluted in water were deposited on the edges to be welded and on the filler wire to eliminate the oxide film. These fluxes were based on chlorides and fluorides. To avoid any risk of corrosion from flux residues, these had to be removed by brushing or washing in water.

As with the arc welding of steel, rods of filler metal coated in flux for welding thicker products began to become available from 1925 onwards. One of the very first known applications of arc welding using coated rods came in France in 1934 with the construction of railway vehicles in 5056 (A-G5) alloy for the 'Cie Française des Chemins de Fer du Nord' [2]. This process was not developed to any great extent owing to the unsatisfactory quality of the weldments.

The first attempts at arc welding in a shielding gas (argon or helium) were made in the middle of the Nineteen Thirties [3]. This technique represented a major step forward, and eliminated the need for flux with its attendant risks of corrosion. It was now possible to weld at high speed and in all positions, making aluminium a "fully fledged" fabrication metal in its own right.

The industrial development of the TIG and MIG processes began in the early Fifties and advances and improvements in these processes have been made ever since. One such innovation came at the beginning of the Nineties with electronically controlled pulsed MIG welding.

WELDING A HATCHWAY FRAME

Up until the early Sixties, ships made from aluminium alloys – as well as aluminium alloy equipment on steel ships (superstructures, funnels etc.) – were assembled by means of riveting, as indeed steel ships still were.

The sailing ship "Morag Mhor", a 70 foot ketch made from aluminium-magnesium alloy (4 and 5 % magnesium) and designed by a British naval architect, was the first known boat to be constructed with MIG welding in 1953 [4].

2. SPECIFICS OF WELDING ALUMINIUM

Although the techniques used for welding semi-finished products made from aluminium alloys are very similar to and even the same as those used for carbon steel, the operating conditions are rather different. This is due to the presence of the oxide film (Al_2O_3) on the surface of the metal (1) and to the physical properties of aluminium alloys which are very different from those of steels (table 47, p. 87).

(1) Cf. Chapter 10.

(2) In arc welding with the continuous TIG process, the welded piece is always connected to the minus pole (–) to remove the oxide film.

(3) Although it is an electrical insulator, the film is too thin to stop the flow of electrical current in the same way as layers of anodising whose thickness is commonly 15 to 20 microns.

(4) Greases and lubricants are carbon chains with the general formula $C_nH_{2n}O$.

2.1 The oxide film

The natural film of oxide which permanently covers the surface of the metal is 50 to 100 nanometers thick. Its melting point is very high, 2052 °C, and it is insoluble in solid or liquid aluminium.

For welding purposes the film must be removed (2) and prevented from re-forming while the filler metal is being applied to the weld seam (3). This is why aluminium must be arc welded or laser welded in a controlled atmosphere consisting of an inert gas such as argon, helium or their mixtures.

Although the film is chemically stable (it is an oxide) it nevertheless reacts with its environment by adsorbing traces of rolling mill oils, shaping lubricants and the moisture present in the air. All of these elements are sources of hydrogen (4) when they are dissociated in the plasma of the electric arc.

LNG CARRIERS

2.2 Solubility of hydrogen in the fused metal

Given the very high solubility of hydrogen in liquid aluminium, it dissolves in the weld pool of the weld seam as it is formed (figure 60) (5).
However since hydrogen is soluble in solid aluminium, if cooling is too fast it will have a tendency to become trapped in the metal forming bubbles that will be porosities in the weld seam (6).

This is why it is so important to remove all possible sources of hydrogen on the metal that are present in moisture, in traces of grease and in the shielding gases.

2.3 Physical properties

Table 47 presents a comparative list of those physical properties of aluminium and steel which affect the welding of these metals. It is the thermal properties which account for the significant differences between the welding conditions for aluminium compared with those for steel.

Aluminium has a high calorific capacity (899 $J.kg^{-1}.K^{-1}$, compared with 420 for steel) and a higher thermal conductivity (229 $W.m^{-1}.K^{-1}$, against 78 for steel). This means that much of the energy input from the arc is used to heat up the pieces that are to be welded.

Aluminium's high effusivity (7) requires a very high level of welding energy. All other things being equal, the rise in temperature of aluminium parts to be welded will be greater than for steel parts.

Heat quickly dissipates in aluminium due to its high diffusivity (8) (0.9 compared with 0.2 for steel), and this must be compensated by the input of heat from the electric arc.

Aluminium's high coefficient of expansion (23.10^{-6}), its high diffusivity and the metal's high level of temperature mean that welding is accompanied by more strain in aluminium than in other metals.

To maintain stable conditions therefore, aluminium must be welded at a rate higher than the rate at which the heat is propagated (figure 61).

If carbon steels are cooled too quickly they undergo a martensitic transformation that is accompanied by an increase in volume which in turn can cause cracks at the base of the weld seam.

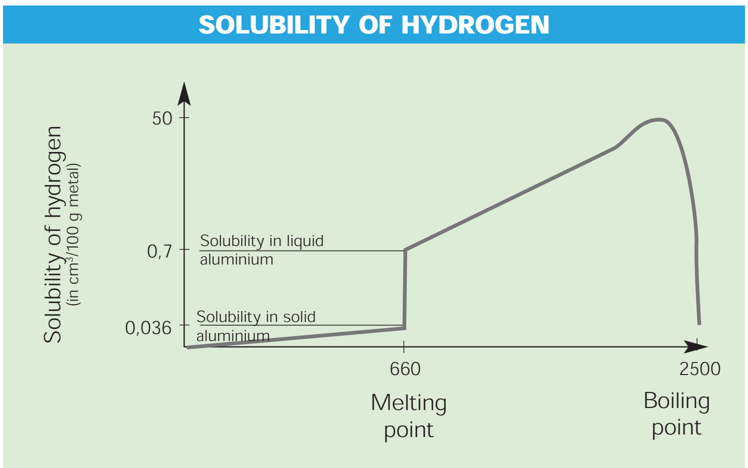


Figure 60

(5) *Contrary to what happens with certain steels, hydrogen does not embrittle aluminium and does not sensitise it to stress corrosion.*

(6) *Cf. table 54, pp. 104-105.*

(7) *(7) Effusivity "b" is the product of thermal conductivity λ by density ρ and by specific heat capacity* c_p*:*
$b = \sqrt{\lambda . p . C_p}$.
This variable describes the amount of heat which a heated zone receives by conduction, where:

λ = thermal conductivity

ρ = density

Cp = calorific capacity.

(8) *hermal diffusivity "a" is defined by the relation*
$a = \frac{\lambda}{\rho . Cp}$

HEAT FLOW DURING WELDING

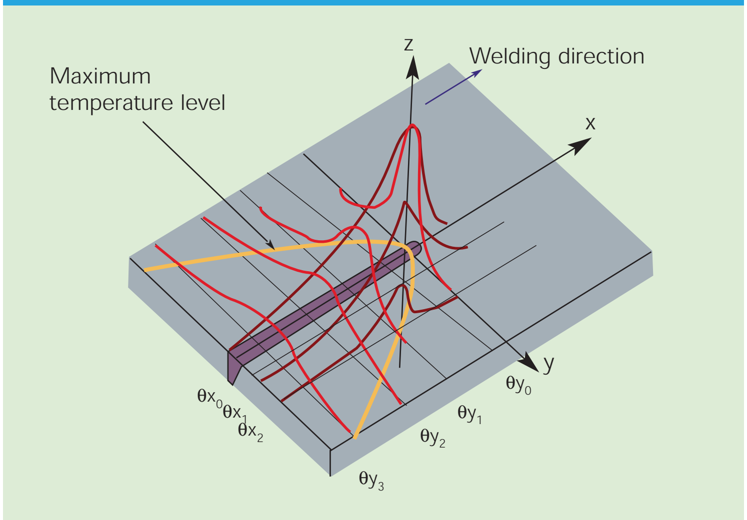


Figure 61

There are no such changes with aluminium alloys. As a result, the rapid cooling rate of the weld – between 100 and 1000 °C per second – does not cause any defect in the seam.

It is therefore not normally necessary to preheat aluminium prior to welding as can be done with steel (to prevent cracks in the weldment during cooling).

All of these factors must be allowed for when designing joints and executing the actual welds. This highly important aspect is discussed in Section 3.

(9) The mechanical properties of the weld seam itself are usually superior to those of the HAZ. When there is a crack, this usually occurs outside the weld seam.

2.4 The heat affected zone (HAZ)

With steels, changes of phase cause local hardening of the heat affected zone over a width of several millimetres. In contrast, the effect of heating is to soften aluminium alloys when they are:

- in the strain hardened condition as is the case with the 5000 alloys in the H116, H24, H32 and H34 tempers,
- thermally treated, e.g. 6000 alloys in the T5 or T6 tempers.

As figure 62, p. 88, shows, the material's mechanical properties change gradually from the weld seam outward to the edges of the HAZ (9).

As a result, the mechanical properties of the weldment are usually inferior to those of the parent metal. They are near to the annealed condition for strain hardened alloys and to the T4 temper for age hardening alloys.

PHYSICAL PROPERTIES OF ALUMINIUM AND STEEL E24

Property	Unalloyed Aluminium (1050A)	Steel E24	Ratio Al/Steel
Fusion interval (°C)	645/658	1 400/1 530	
Melting point of oxides (°C)	2 052	900	
Solidification shrinkage (%)	1,7	1,2	1,4
Density (kg.m-3)2 700	7 820	0,34	
Mass heat capacity Cp (J.kg^{-1}.K^{-1})	899	420	2,14
Latent heat of fusion (kJ.kg^{-1})	385	210	1,83
Thermal conductivity (W.m^{-1}.K^{-1})	229	54	4,24
Thermal diffusivity "a" (10^{-4}.m^{2}.sec^{-1})	0,9	0,2	4,5
Effusivity "b" (J. m^{-2}.K^{-1}.sec $^{-1/2}$)	24 000	16 000	1,5
Coefficient of linear expansion α (10^{-6}.K^{-1})	23,5	13,5	1,74
Electrical resistivity ρ (10^{-9} $\mu.\Omega$.m^{-1})	292	1010	0,29
Young's modulus (MPa)	70 000	210 000	0,33

Table 47

This is why for stress calculations, the design codes and regulations of the classification societies specify levels of yield strength of the annealed condition for strain hardening alloys and of the T4 temper for age hardening alloys.

In the case of butt welds, the HAZ is some 25 mm wide either side of the weld seam whatever the thickness of the parent metal and whether TIG or MIG welding is used.

The impact on the mechanical properties of the weldment must be minimised by:

- selecting the filler metal that is best suited to the parent alloy,
- establishing a welding cycle that is as rapid as possible to limit the size of the HAZ,
- designing the assembly so that the weldments are in the least stressed positions.

2.5 Weldable aluminium alloys

Most of the alloys belonging to the 1000, 3000, 5000 and 6000 series can be welded with the conventional TIG or MIG processes and by the other energy beam processes – electron beam, laser etc.

The 5000 series is the one that is most suitable for welding.

The wrought alloys *containing copper* in the 2000 and 7000 series (10) are not easy to arc weld (11). The presence of the copper causes cracking and shrinkage cracks on the weld seam.

The weldability of castings depends more on the method of casting than on the chemical composition of the alloy. Diecast parts cannot be welded as they may contain a lot of air that is introduced during the casting process.

Sand cast or chill cast parts can be welded provided they are "clean", i.e. free from porosities and shrink holes that produce blisters in the weld seam (12).

The 42100 (A-S7G) and 43300 (A-S10G) alloys can be welded with alloys in the 6000 series (13).

(10) The 7000 alloys without copper such as the 7020 can be welded but the HAZ is very sensitive to exfoliating corrosion (cf. Chapter 10).

(11) The welding regulations and construction codes such as Eurocode 9 and standard BS 8118 actually exclude these alloys from arc welded assemblies.

(12) Porosities in sand castings can be avoided by the use of metal heat sinks that improve the microstructure and prevent the formation of porosity.<0}

(13) The 5000 series cannot be welded with the 42000.

MECHANICAL CHARACTERISTICS OF THE HAZ

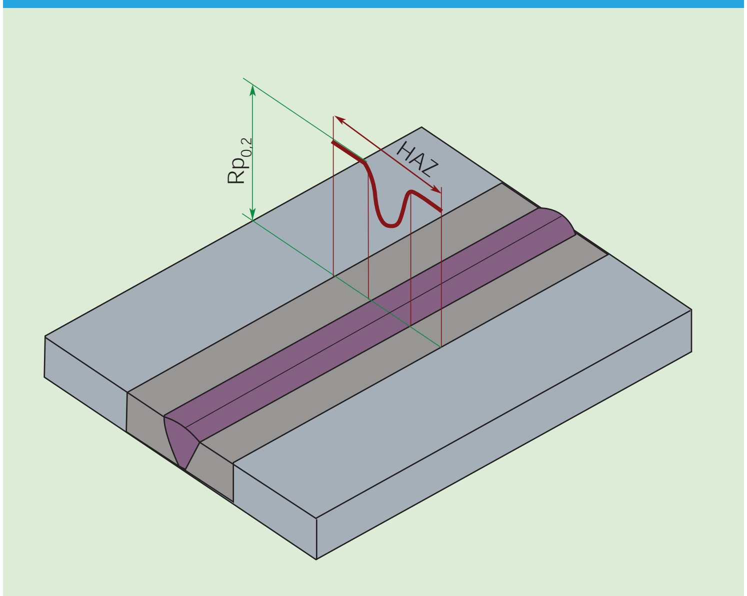


Figure 62

3. IMPLICATIONS FOR THE DESIGN AND EXECUTION OF WELDS

During welding, every point on a welded piece undergoes a heat cycle whose profile is a function of a number of parameters:

- the power of the heat source which depends on the process (MIG, TIG etc.),
- the geometry of the piece,
- the welding position (flat, vertical, horizontal, overhead),
- the diffusion coefficient of the material.

The result is a variety of different temperatures present in the component in the course of welding. These temperature differences translate into residual distortions of varying extent and which are due:

- to differences in expansion,
- to shrinkage as the weld seam solidifies.

3.1 Distortion

Distortion can be longitudinal or transverse:

- **longitudinal distortion** is caused by the contraction of the metal during the process of cooling which is not uniform. Stresses are set up along the weld seam (figure 63).
These stresses depend on the position of the weld – they are minimal or non-existent when the weld is on or near the neutral axis of the piece (figure 64) but very pronounced when the weld is asymmetrical. Concavity will follow the same orientation as the weld seams. On long components, distortion may manifest itself as a twist that will prove difficult to correct (figure 65).

As a general rule, distortion will be significant when the weld seams are asymmetrical relative to the piece.

- **transverse distortion** is due to a shortening of the weld seam – this is more pronounced at the surface of the seam than at its root and so creates a 'gripping' effect with angular deformation (figure 66).

This effect must be limited by balancing the stresses with a second weld: a double vee-groove weld on thick components and on the opposite side for fillet welds (figure 67).

LONGITUDINAL DISTORTION

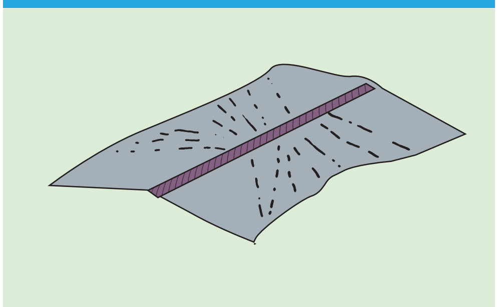


Figure 63

WELDS ON THE NEUTRAL AXIS

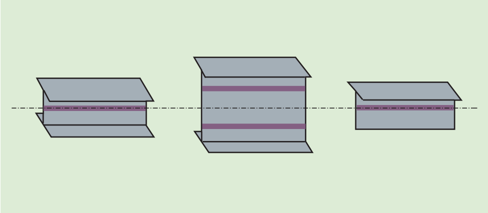


Figure 64

ASYMMETRICAL WELDS

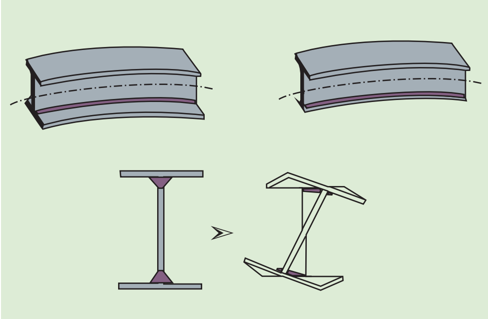


Figure 65

DISTORTION OF BUTT WELDS

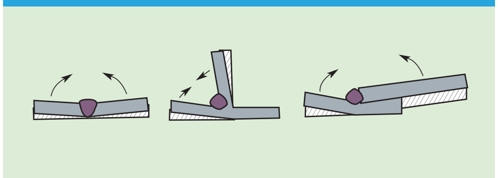


Figure 66

CORRECTION OF DISTORTION

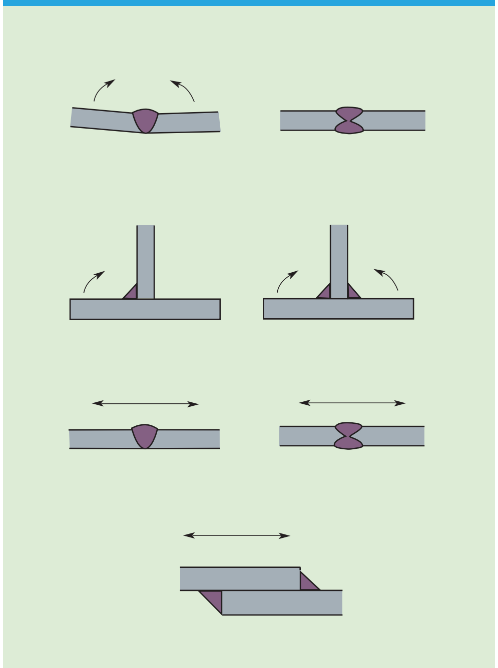


Figure 67

3.2 Stresses

Local levels of stress can exceed the yield strength of the metal, and are a function of:
- the shape of the piece,
- the layout of the weld seams,
- the weld sequence,
- positioning tools,
- clamping.

Figure 68 indicates the level of longitudinal residual stress in sections fabricated by welding.

3.3 Controlling distortion

There are a number of factors by which distortion can be controlled:

- **Joint configuration**: so far as possible the designer should position the welds in a plane of symmetry of the component and on its neutral axes (14), and use specially designed shapes (15) where possible.

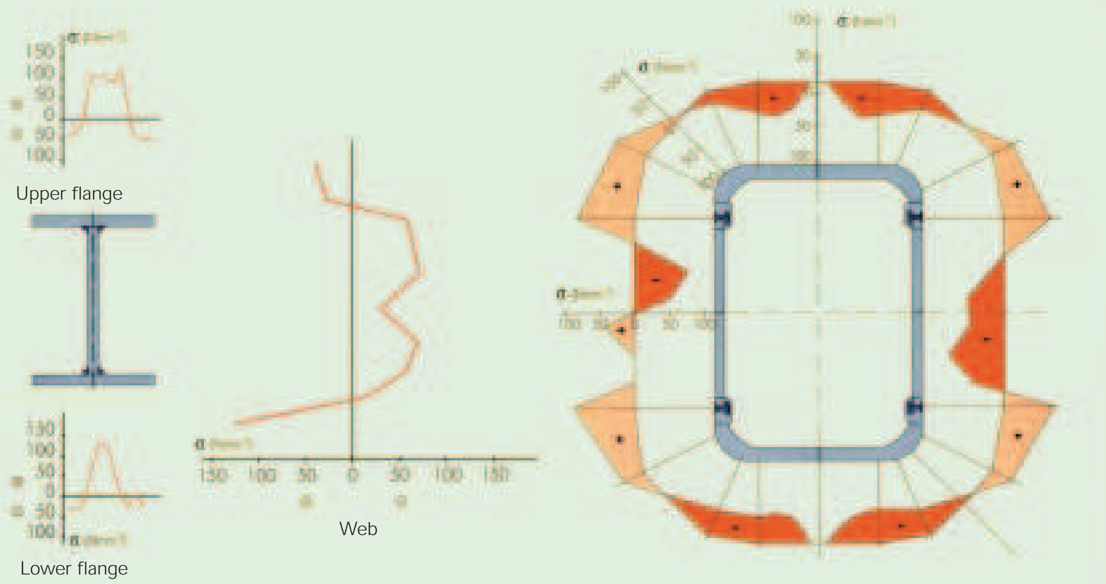
- **Careful forming** must be used to minimise clearances and offsets between the welded components and to eliminate fitup errors,

- **The welding sequence**: it is important to weld moving towards the outside edges to allow expansion to occur freely. The welds must be executed in reverse order of length, with the shortest first to better distribute any distortion. Distortion can be corrected more easily with long seams (figure 69).

Where possible, automatic welding with two torches is a very good way of reducing distortion (figure 70).

The distribution of internal stresses can be optimised by using a sequence of welds that

RESIDUAL STRESSES



Connection of plates in 5083 H111 and extrusions in 6082 T6

Figure 68

YACHT FRAME

WELD SEQUENCE

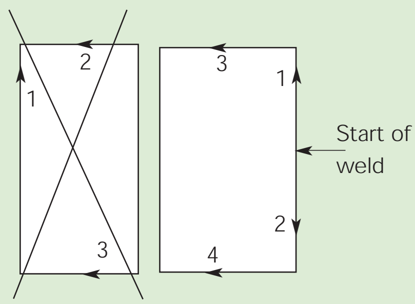


Figure 69

induces residual compression stresses in the weld seams that are stressed in tension (figure 71). This approach will very significantly improve the fatigue strength of the welded joints.

■ The purpose of **clamping** is to hold the parts in position. However clamps, fixtures etc. must not prevent expansion on the longest axes or components will be stressed (with an attendant risk of softening due to expansion Δl). Generally speaking, parts should not be clamped in the directions of greatest expansion as this will aggravate distortion square to the weld (figure 72).

On thick material, angular distortion can be avoided by attaching temporary stiffeners across the weld (figure 73).

■ **Welding parameters**: Distortion can also be caused by the solidification shrinkage of the weld seam. The greater the quantity of fused metal and the higher the temperature, the greater this shrinkage will be. Distortion can be limited by using high energy heat sources to weld as rapidly as possible – the faster the welding, the less time the heat has to dissipate

■ **Balance of heat flows:** Longitudinal distortion can be aggravated by a thermal imbalance between the welded pieces. This imbalance can be due to:
- the very different masses of the pieces that are to be joined,
- misalignment as the welding torch moves,
- poor contact with the support,
- etc.

Whenever possible therefore, the "thermal masses" must be balanced to achieve good thermal symmetry in the assembly (figure 74).

(14) This layout has a positive influence on the fatigue behaviour of the welded assembly, cf. Chapter 4.

(15) Cf. Figures 11 to 14, Chapter 2.

WELDING WITH TWO TORCHES

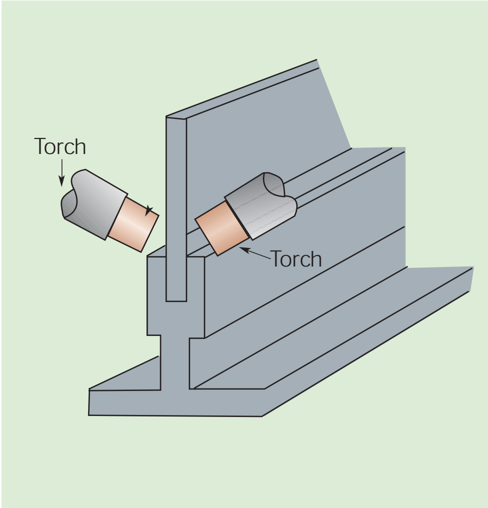


Figure 70

BUTT WELDING SHAPES

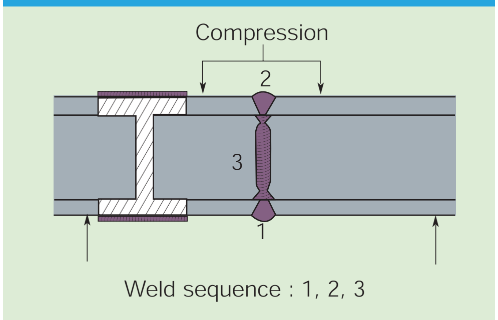


Figure 71

EFFECT OF CLAMPING

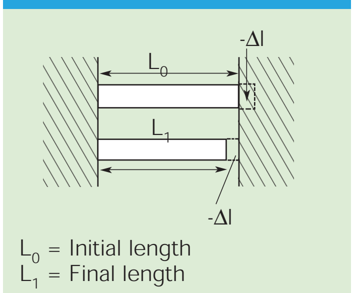


Figure 72

THERMAL BALANCE OF A WELD

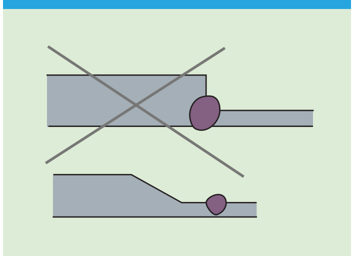


Figure 74

CLAMPING WITH STIFFENERS ACROSS THE WELD

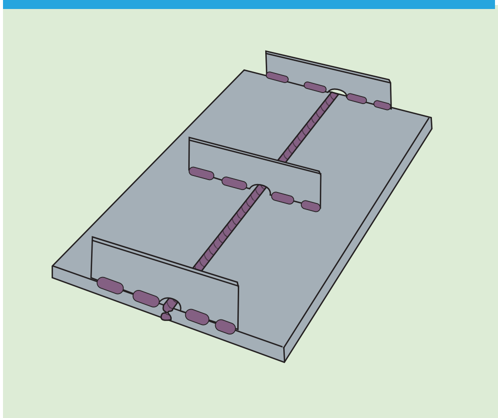


Figure 73

3.4 Use in the fabrication of a section with stiffeners

Figure 75 shows the optimum welding sequence (i.e. order in which the welds are made) for limiting distortion when welding the elements of the section illustrated in figure 76.

Welding starts in the centre of the panel and moves out towards the free edges to allow unimpeded expansion.

LIFTING ALUMINIUM SUB-ASSEMBLIES

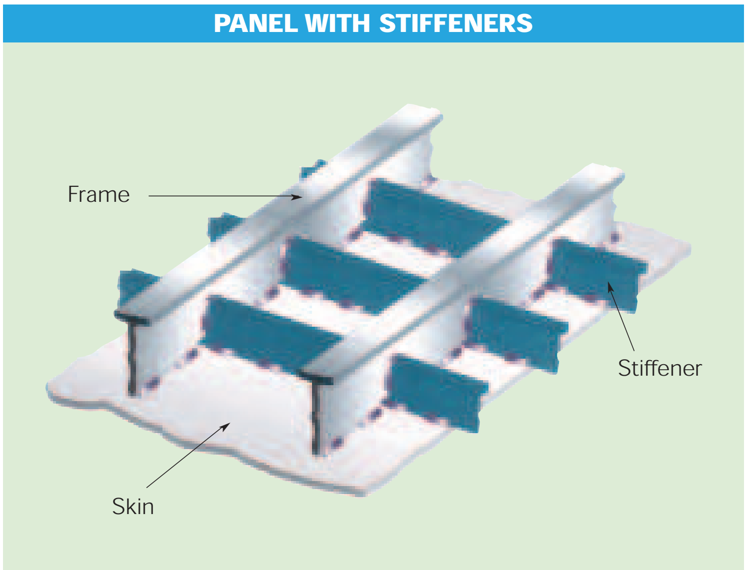


Figure 75

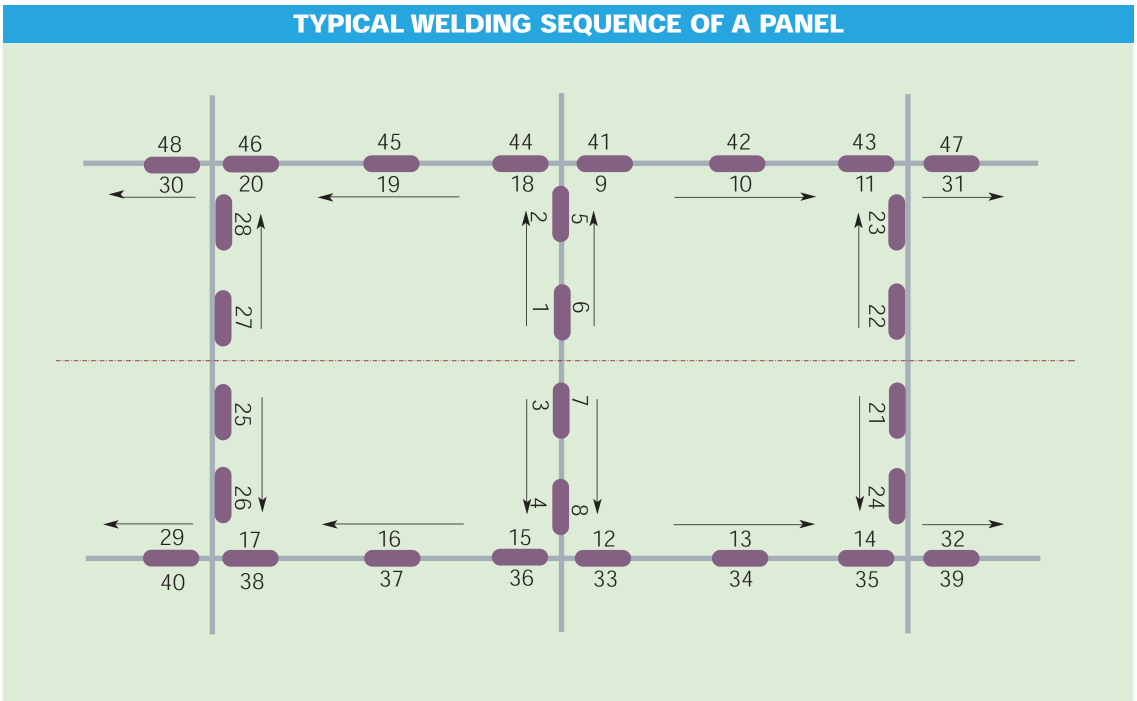


Figure 76