WELDING TECHNOLOGY

JOINING & ASSEMBLY PROCESSES FUNDAMENTALS OF WELDING

***JOINING* - welding, brazing, soldering, and adhesive bonding to form a permanent joint between parts**
***ASSEMBLY* - mechanical methods (usually) of fastening parts together**
Some of these methods allow for easy disassembly.

- **WELDING** – A joining process of two materials that coalesced at their contacting (faying) surfaces by the application of pressure and/or heat.
  – Weldment – The assemblage
  – Sometime a filler material to facilitate coalescence.
- **ADVANTAGE**: portable, permanent, stronger than the parent materials with a filler metal, the most economical method to join in terms of material usage and fabrication costs .
- **DISADVANTAGE**: Expensive manual Labor, high energy and dangerous, does not allow disassemble and defects

APPLICATIONS

- Constructions, Piping, pressure vessels.
- Boilers and storage tanks, Shipbuilding, Aerospace.
- Automobile and Railroad.
- Automation - Machine, Automatic and Robotic welding.

PHYSICS OF WELDING

• Coalescing Mechanism: Fusion via high-density energy
• Process plan to determine the rate at which welding can be performed, the size of the region and power density for fusion welding
• Powder density (PD):PD=P/A
where *P* = power entering the surface, W (Btu/sec); and
A = the surface area, mm2 (in2)
– With too low power density, no melting due to the heat conducted into work
– With too high power density, metal vaporizes in affected regions
– Must find a practical range of values for heat density.
• In reality, pre & post-heating and nonuniform
• For metallurgical reason, less energy and high heat density are desired.

- The estimated quantity of heat:

$$U_M = KT^2_M \text{ where } K = 3.33\text{x}10^{-6}$$

- Heat waste:

– Heat transfer efficiency, f1, between heat source and surface

- Heat problem: Oxyfuel gas welding is inefficient while Arc welding is relatively efficient.

– Melting efficiency, f2 , due to the conduction of a work material

- Conduction problem: Al and Cu have low f2
- Net Heat Available for Welding: $H_W = f_1 f_2 H$
- Balance between energy input and energy for welding:

$$H_W = U_M V$$

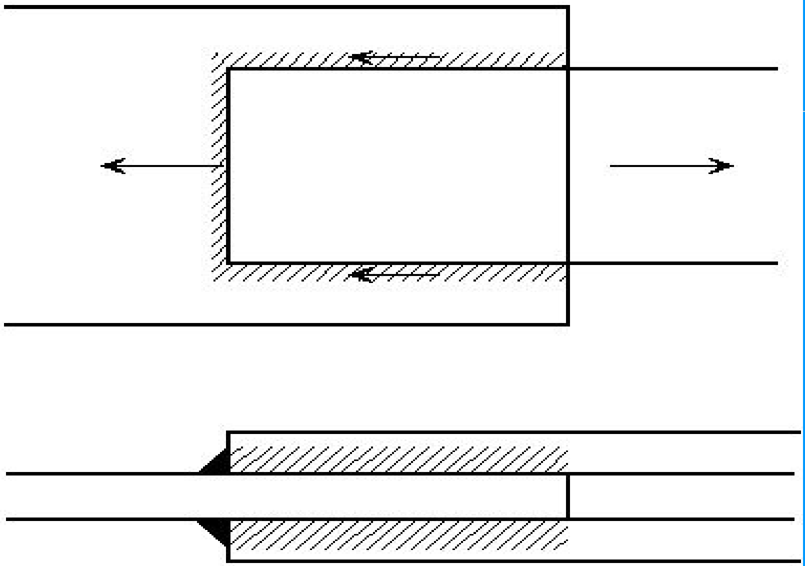
- Rate Balance: $HR_W = U_M WVR$

$$= f_1 f_2 H\ R = U_M A_W V$$

where WVR=volume rate of metal welded

TYPES OF Weld Joint AND WELDS

- Types of Joints
  - Butt joint
  - Corner joint
  - Lap joint
  - Tee joint
  - Edge joint
- Types of Welds
  - Fillet weld
  - Groove weld
  - Plug and slot welds
  - Spot and Seam welds
  - Flange and Surfacing welds



The welds are assumed to carry forces proportional to their strength

Figure 2 Lap joint.

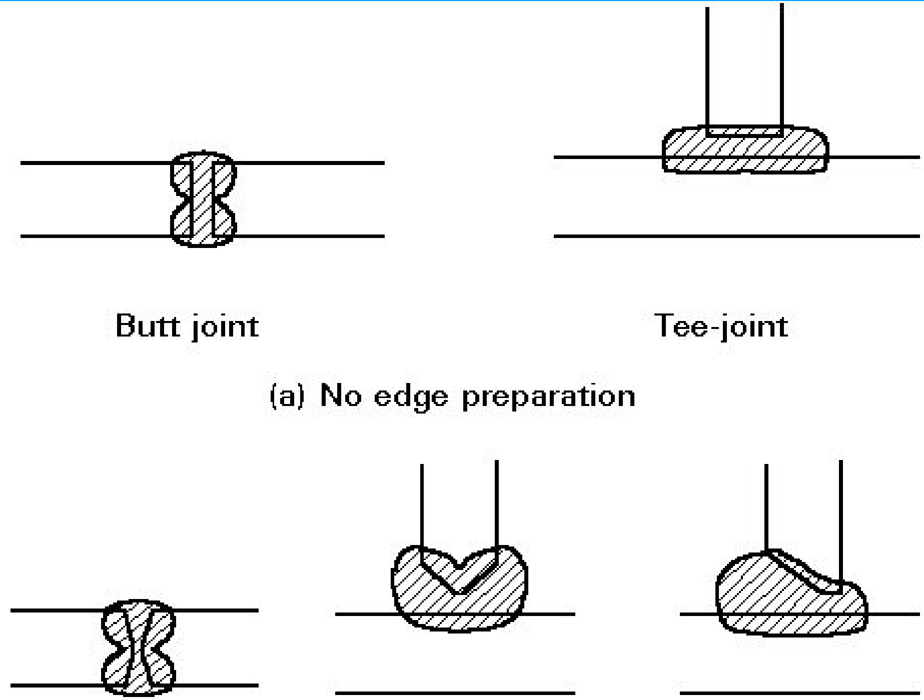
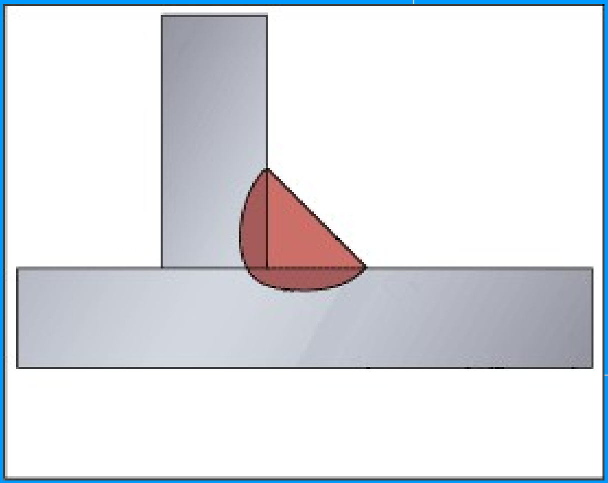


Figure 4 Butt welds with full penetration



-----T joint----

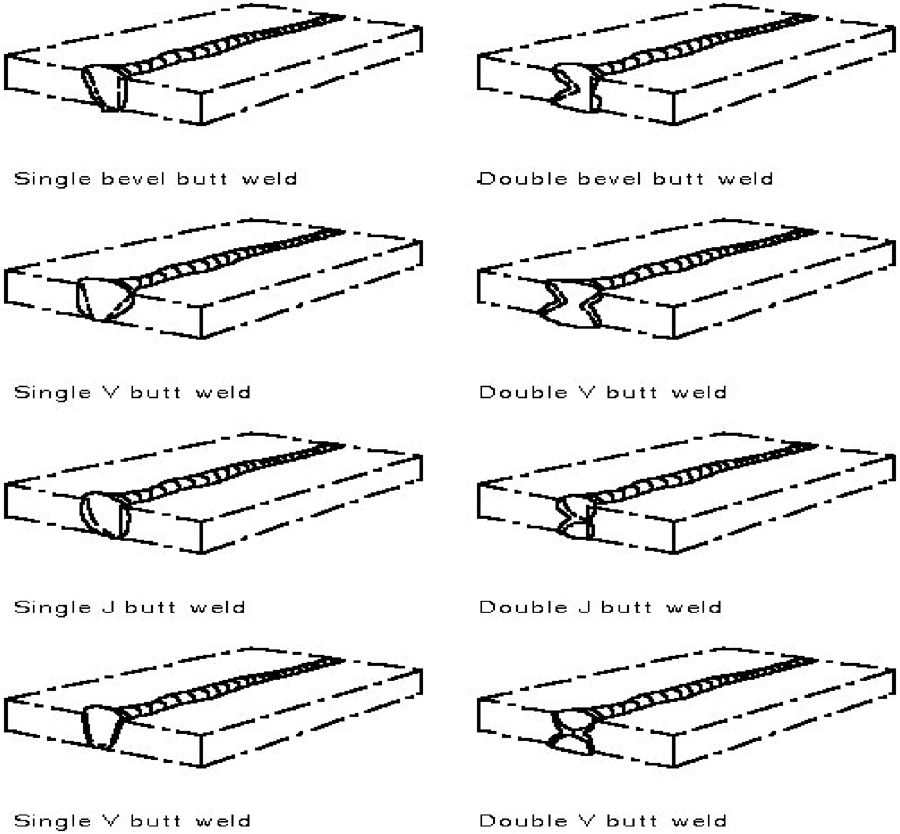


Figure 5 Types of bevelled edges

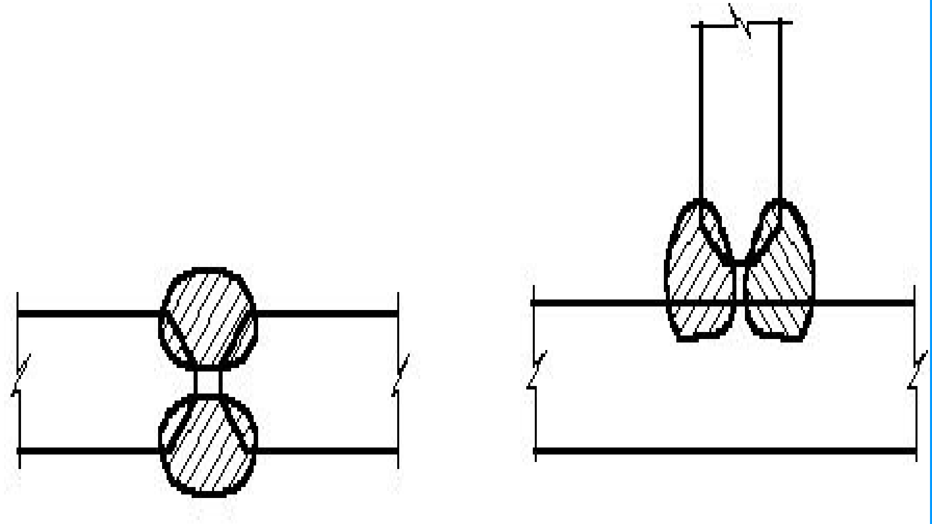


Figure 6 Butt welds with partial penetration

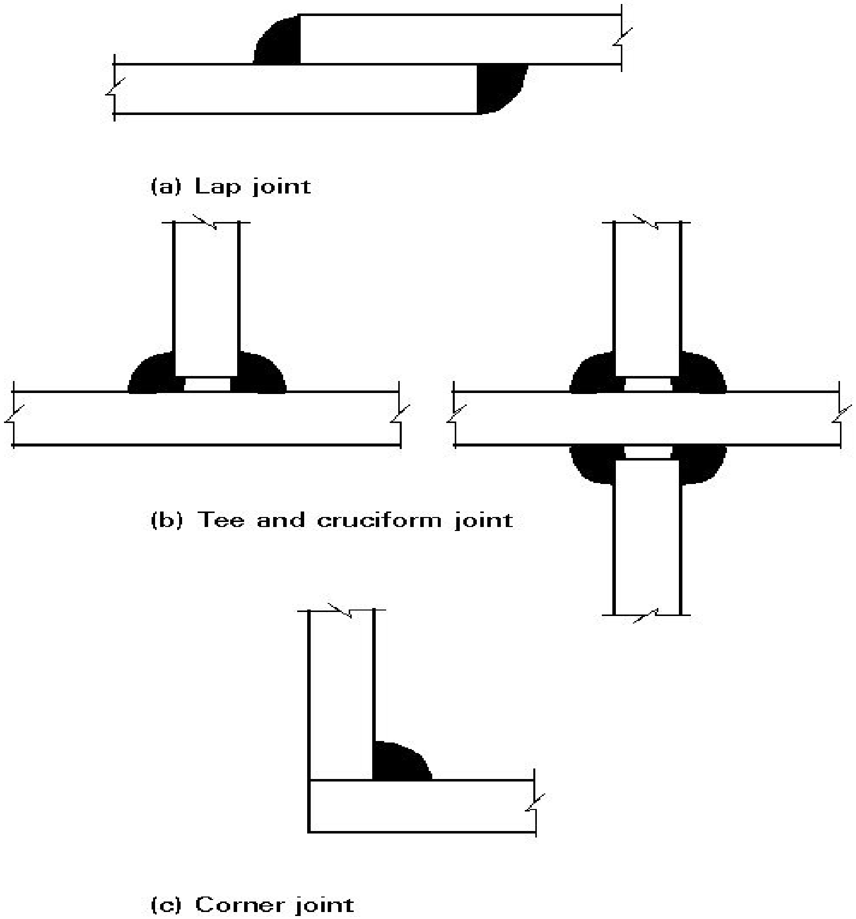


Figure 7 Fillet welds

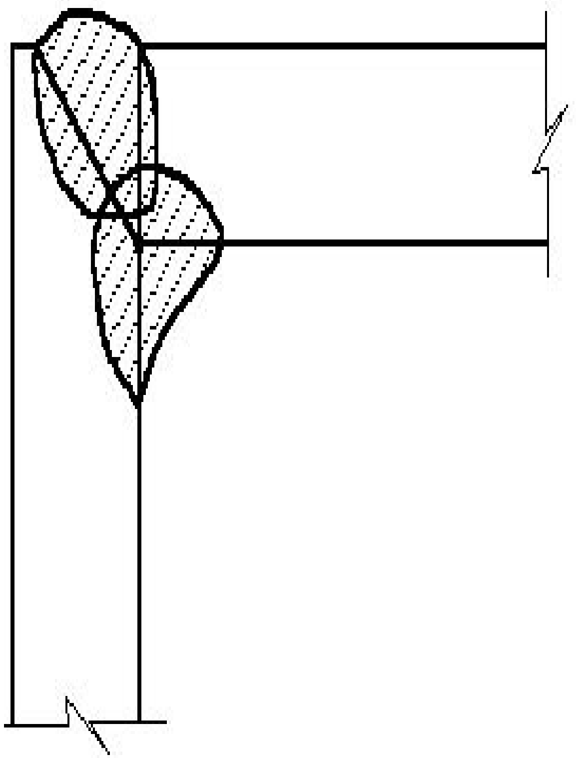
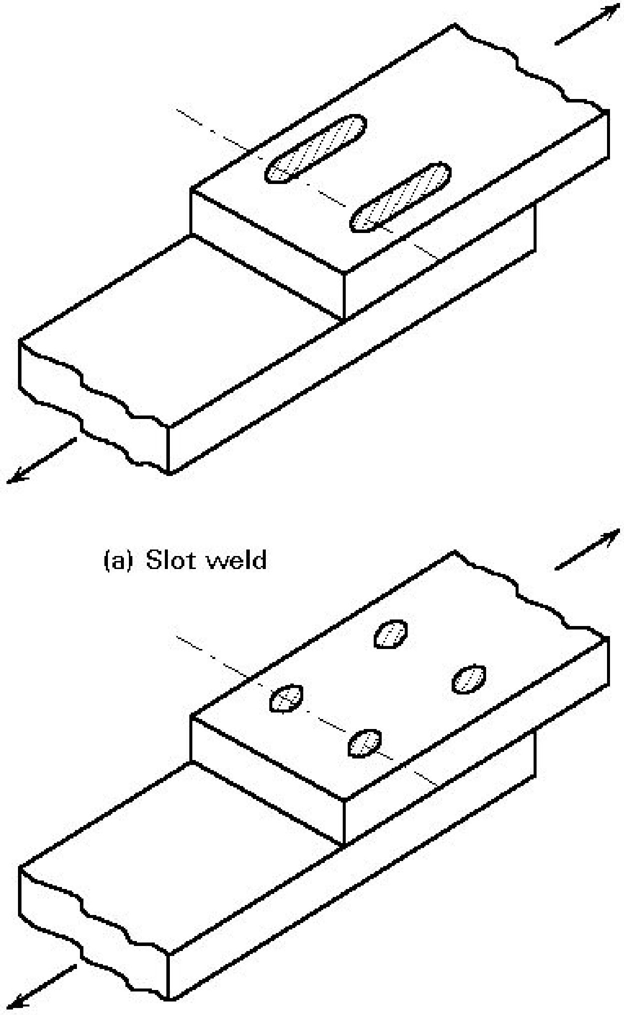


Figure 8 Corner joint with butt and fillet welds



(a) Slot weld

(b) Plug weld

Figure 9 Slot and plug welds

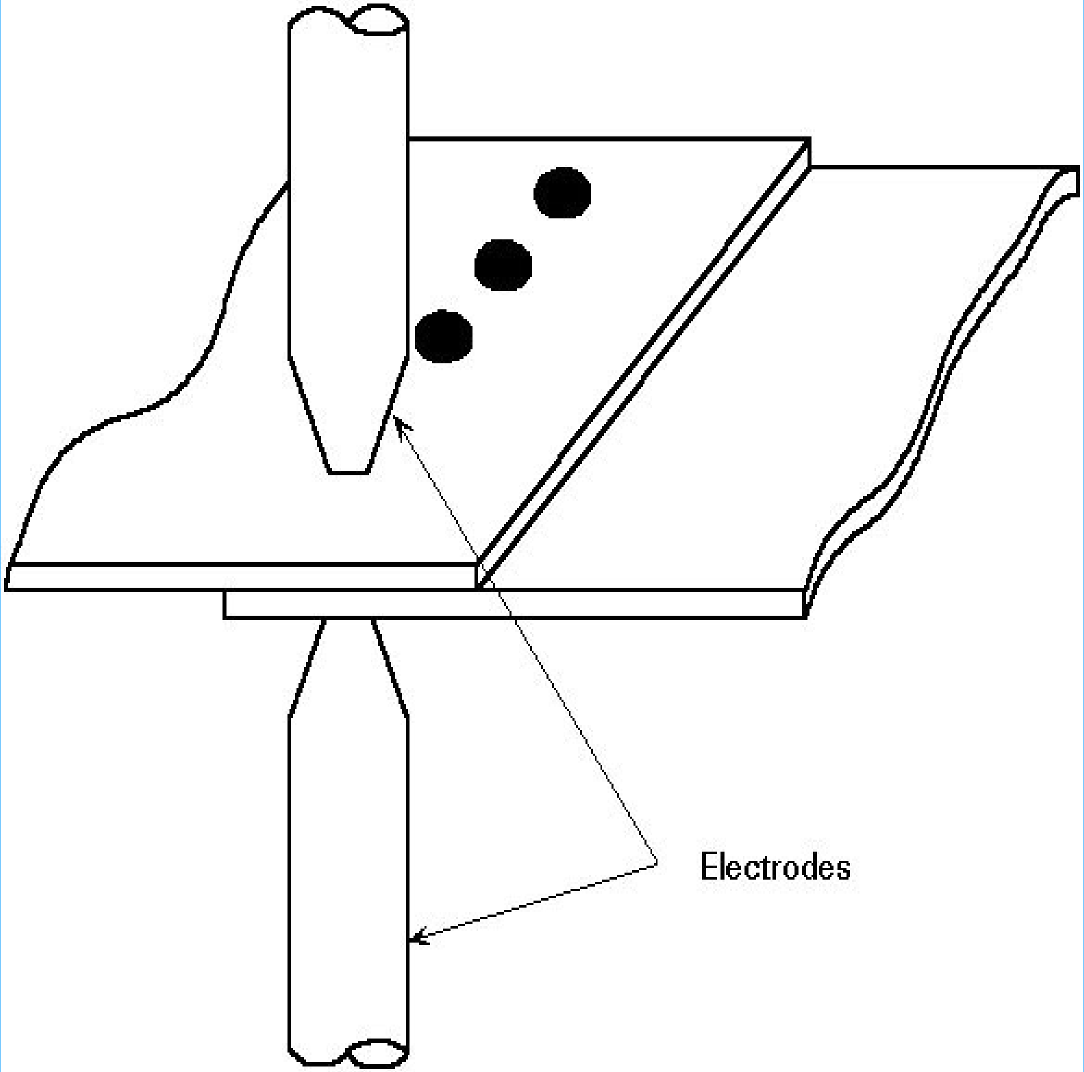


Figure 10 Spot welds

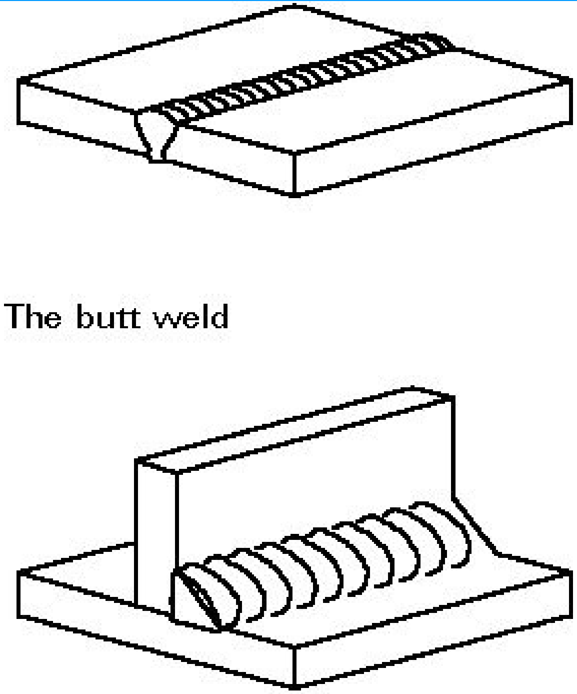
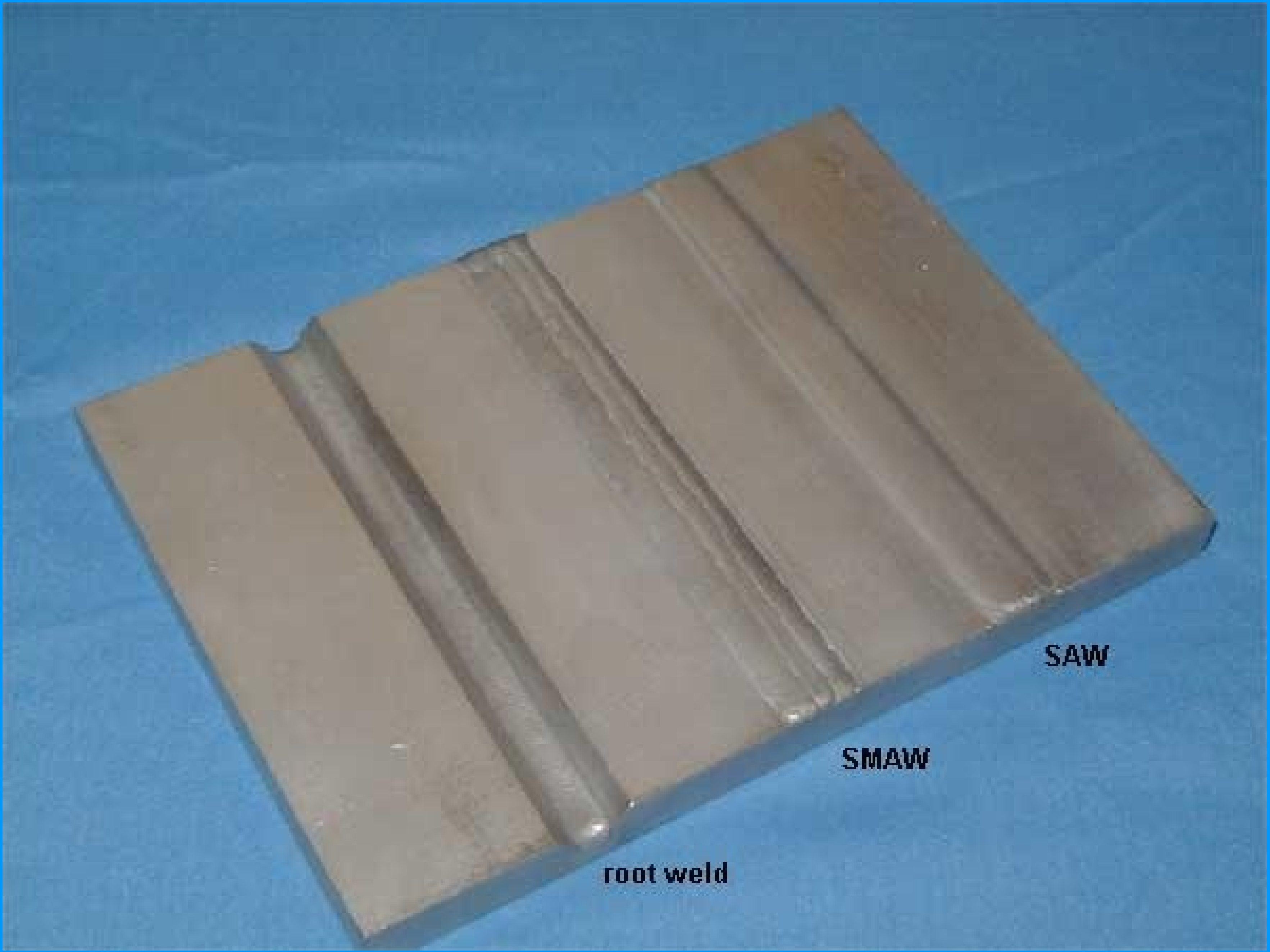


Figure 1 The two basic types of weld

Butt welds : A butt weld is made between two pieces of metal usually in the same plane, the weld metal maintaining continuity between the sections. weld metal is generally contained within the profiles of the welded elements

Fillet welds : These welds are roughly triangular in cross section and between two surfaces not in the same plane and the weld metal is substantially placed alongside the components being joined. Deposited weld metal is external to the profile of the welded elements


SAW
SMAW
root weld

VARIOUS PARTS OF WELDS

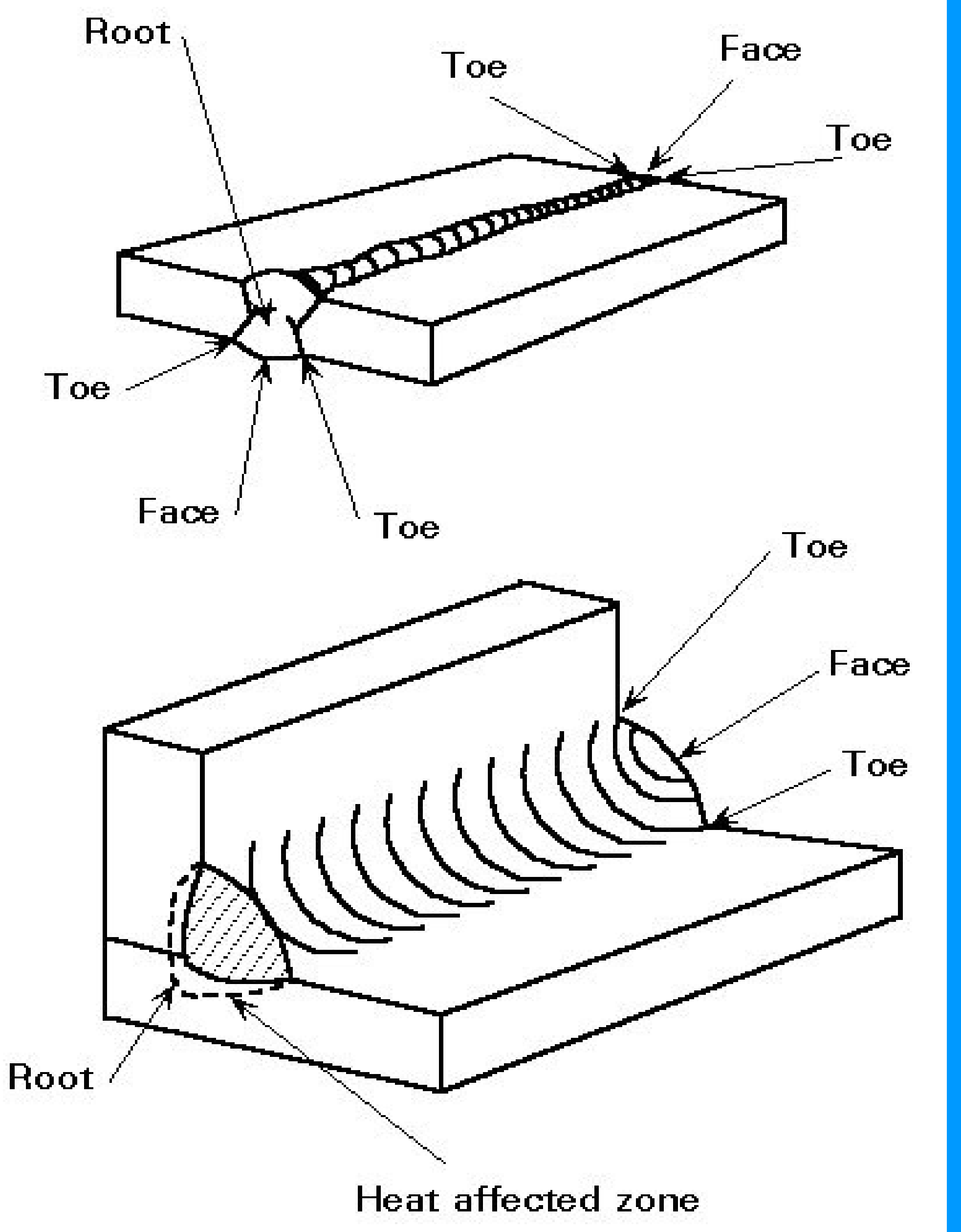
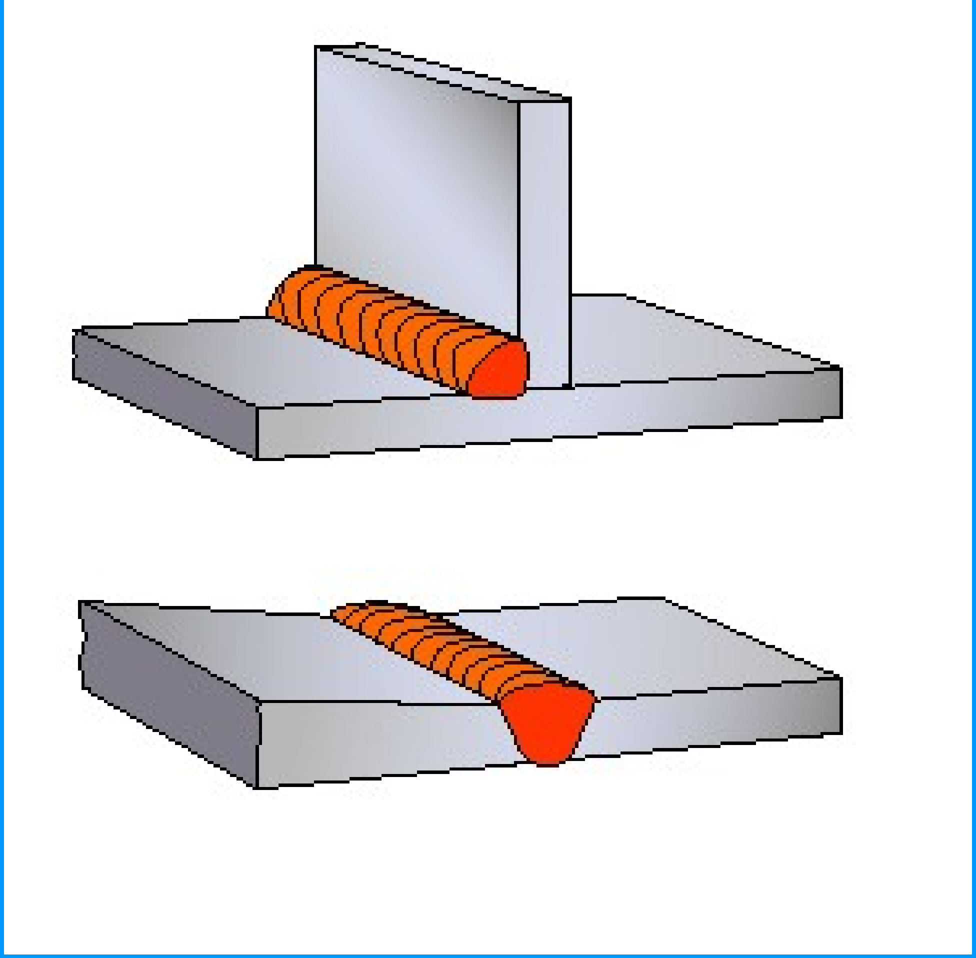


Figure 11 Various parts of welds

WELD JOINT PREPARATION.



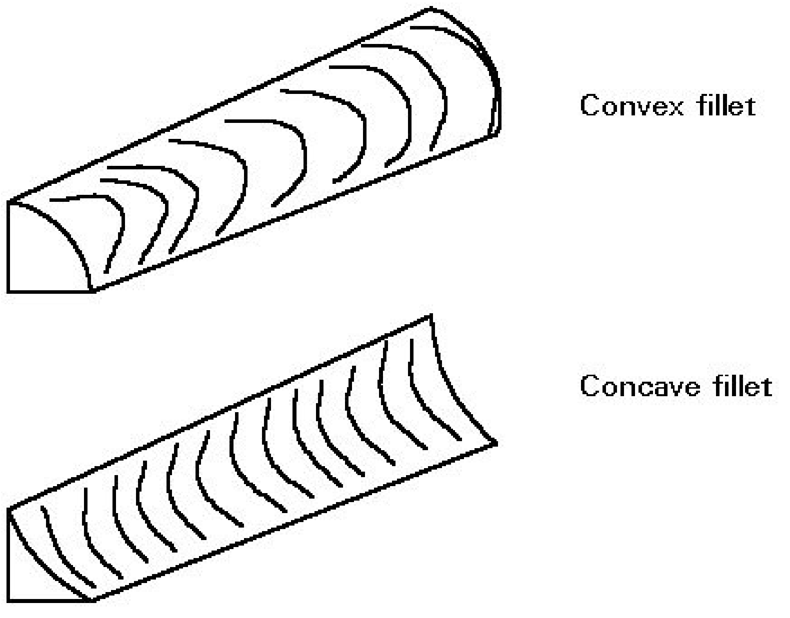


Figure 12 Convex and concave fillets

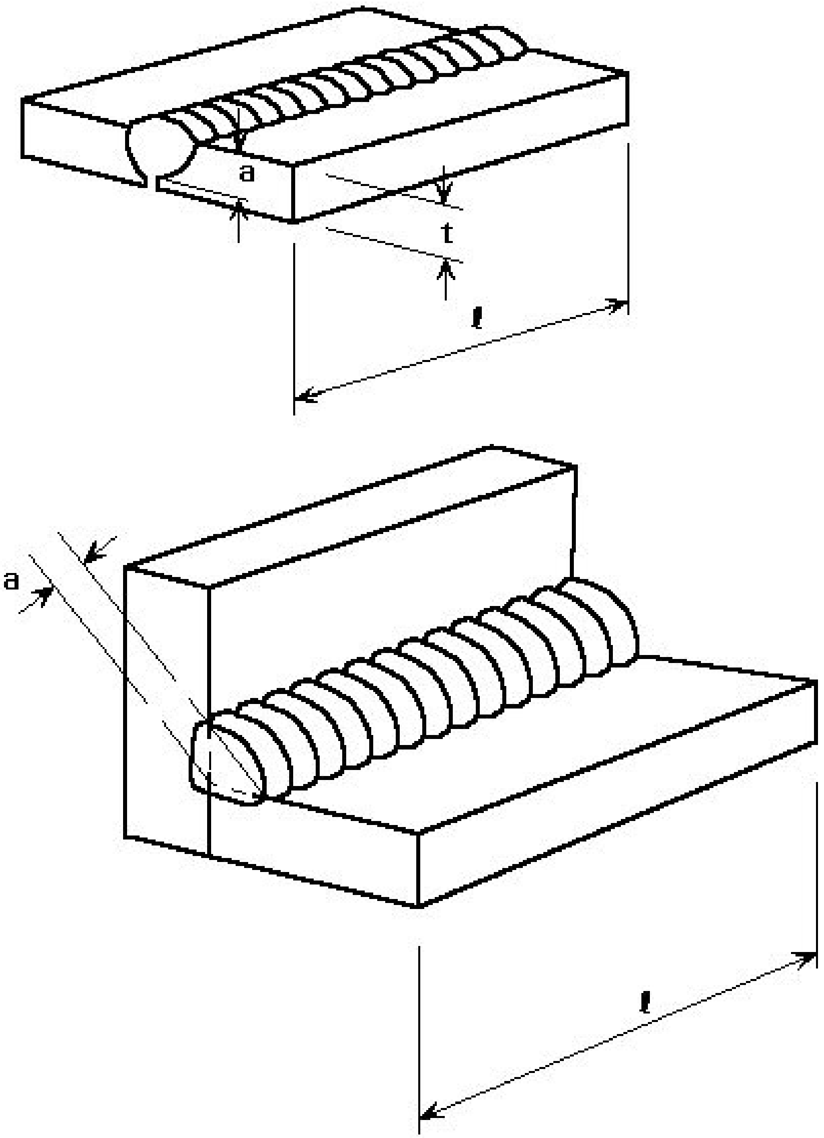


Figure 13 Throat thickness of welds

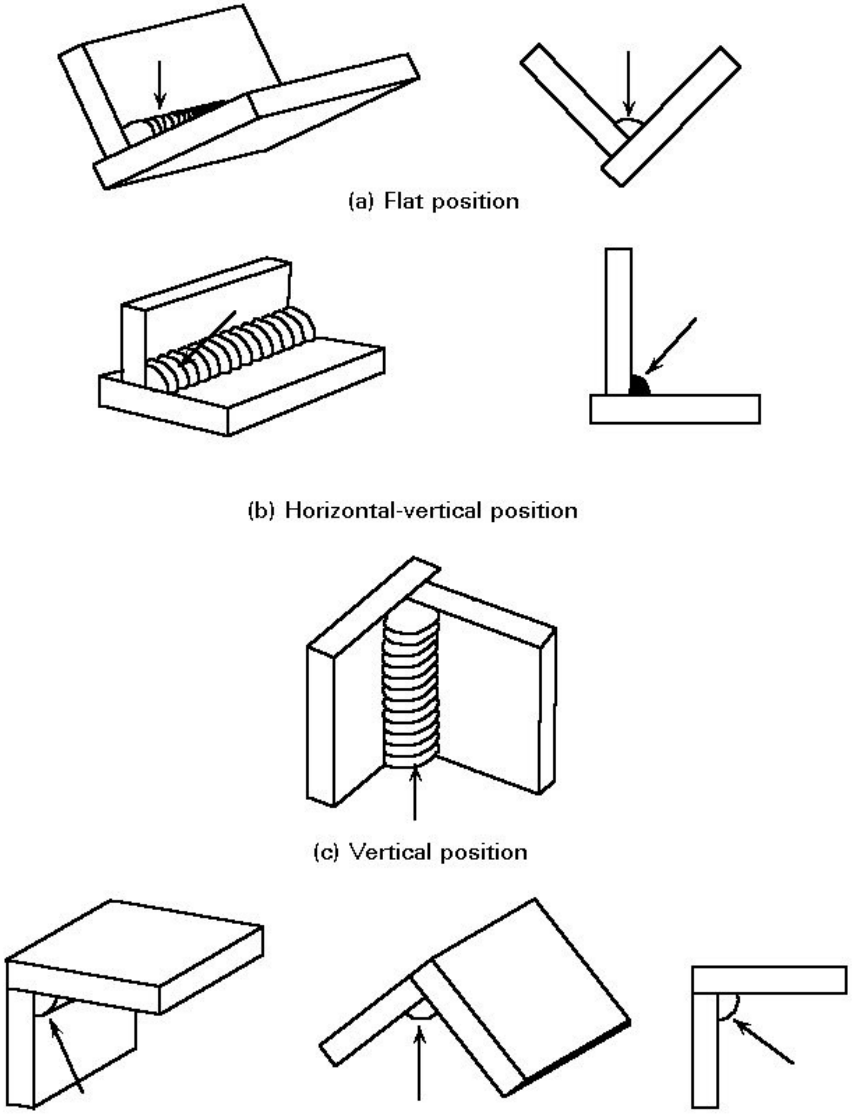


Figure 14 Weld positions

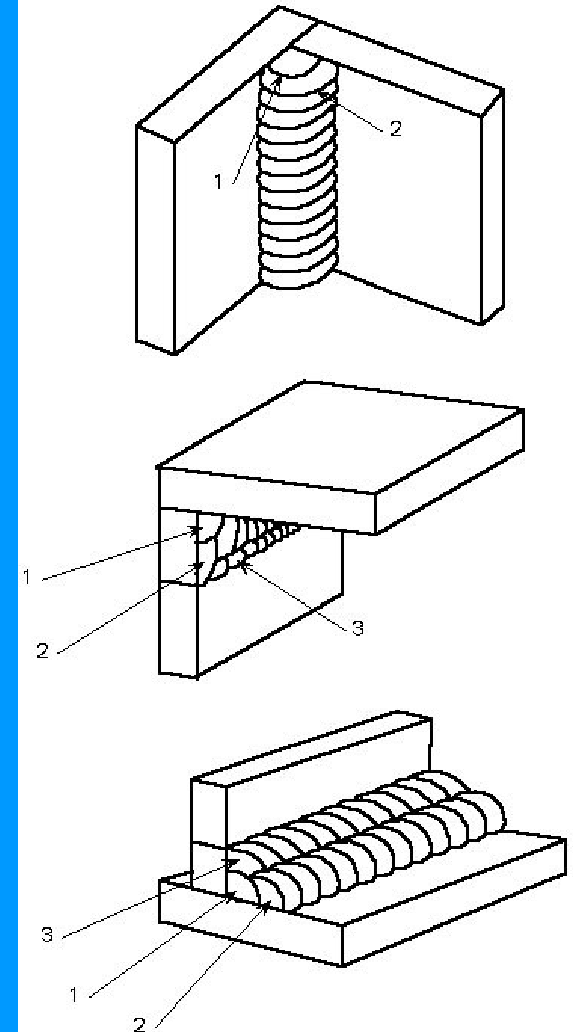
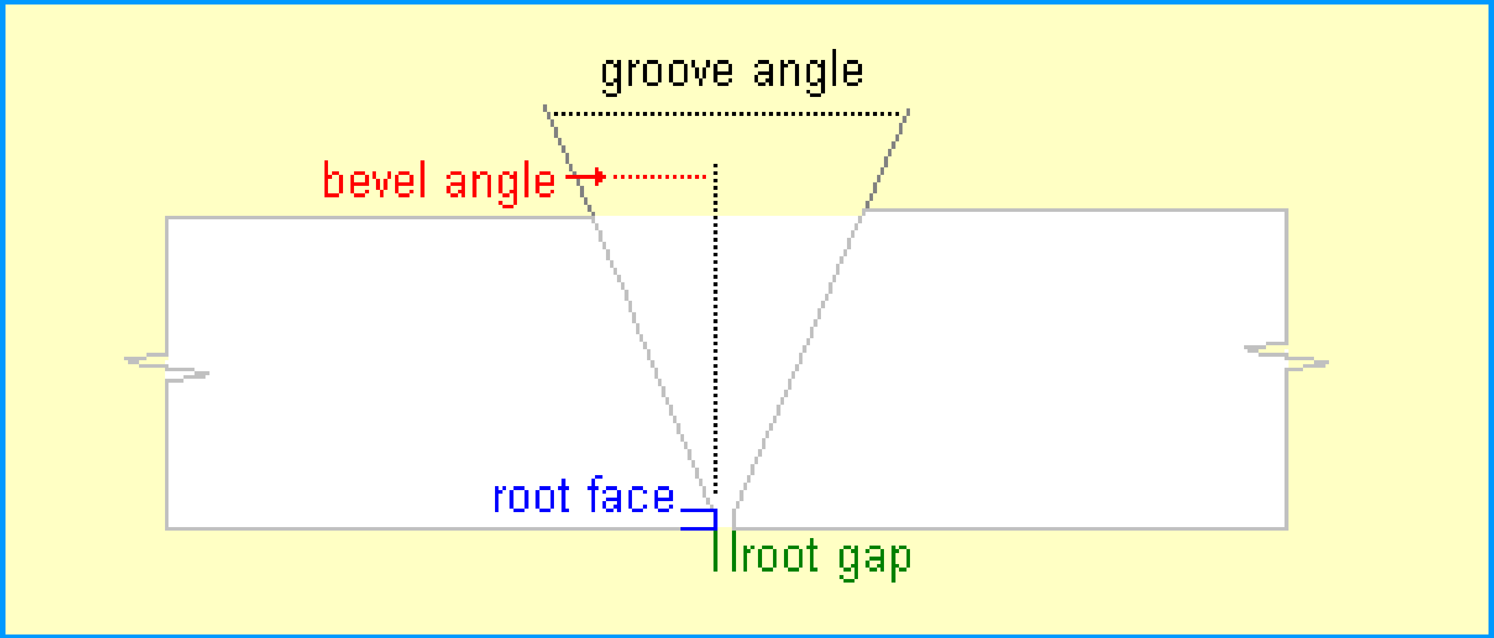
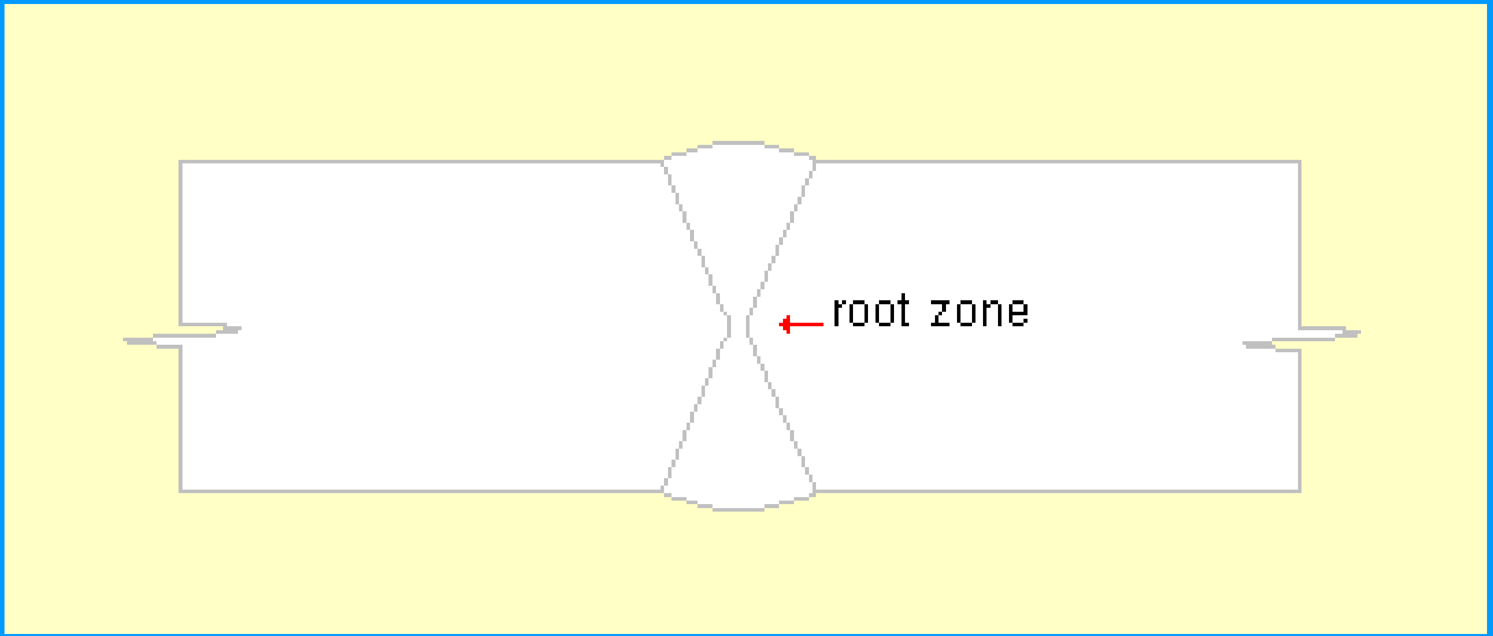


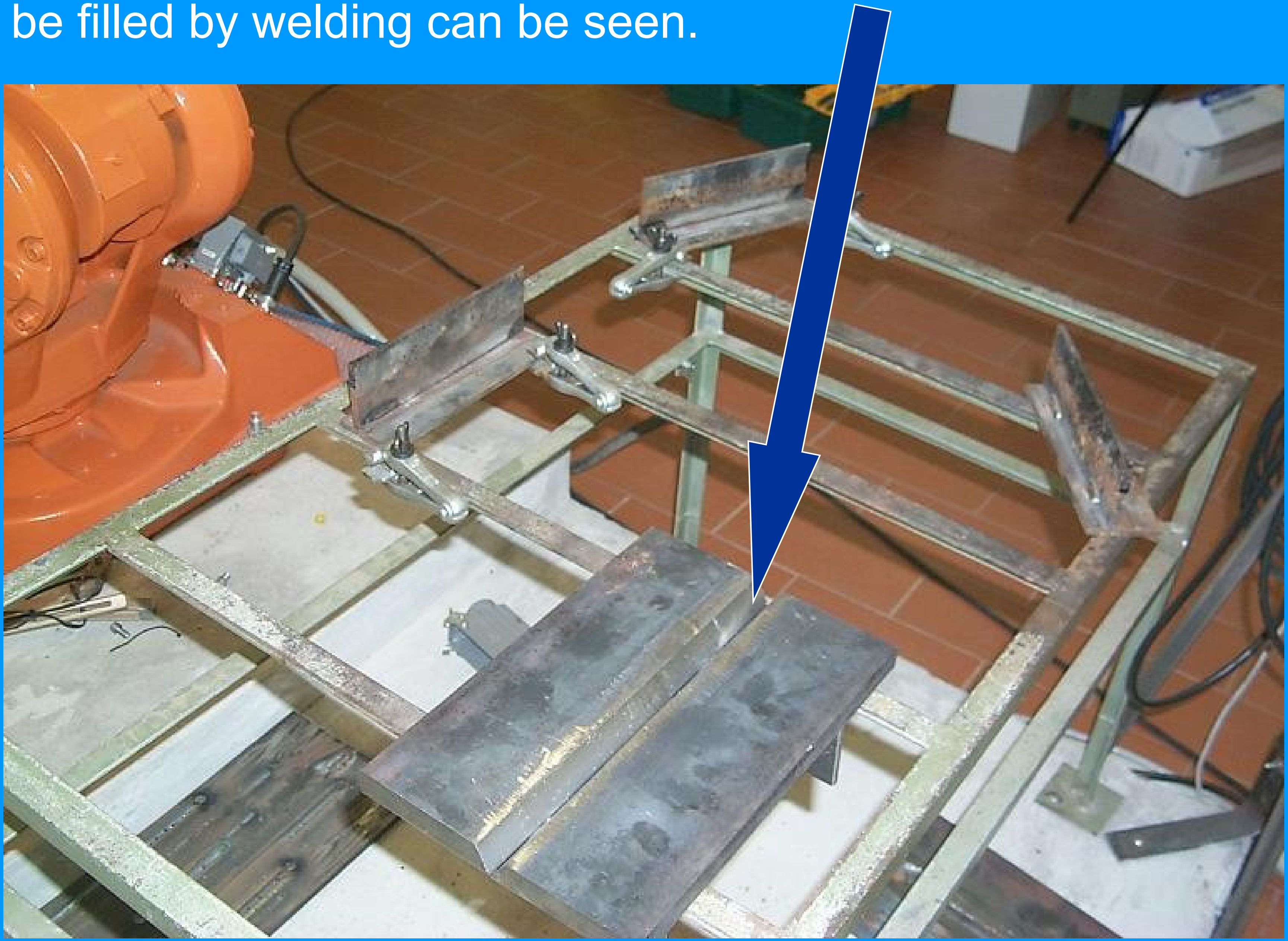
Figure 15 Welds with successive runs

Weld joint preparation





Weld joint fit up before welding. The weld groove which is to be filled by welding can be seen.



Weld joint fit up for a pipe to reducer joint, the root gap is clearly visible.

Double Vee Weld groove fit up for plates bend in to pipes

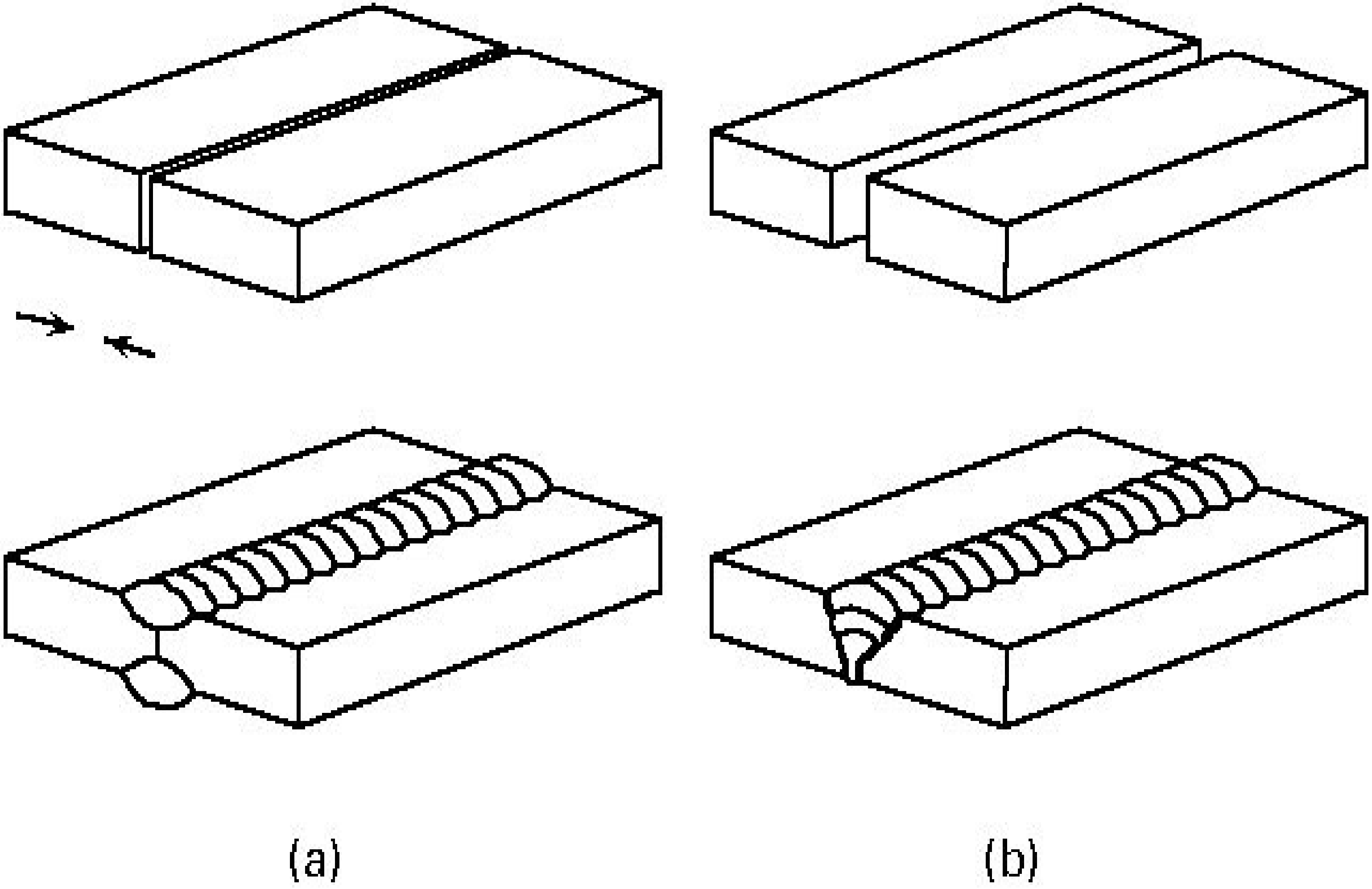
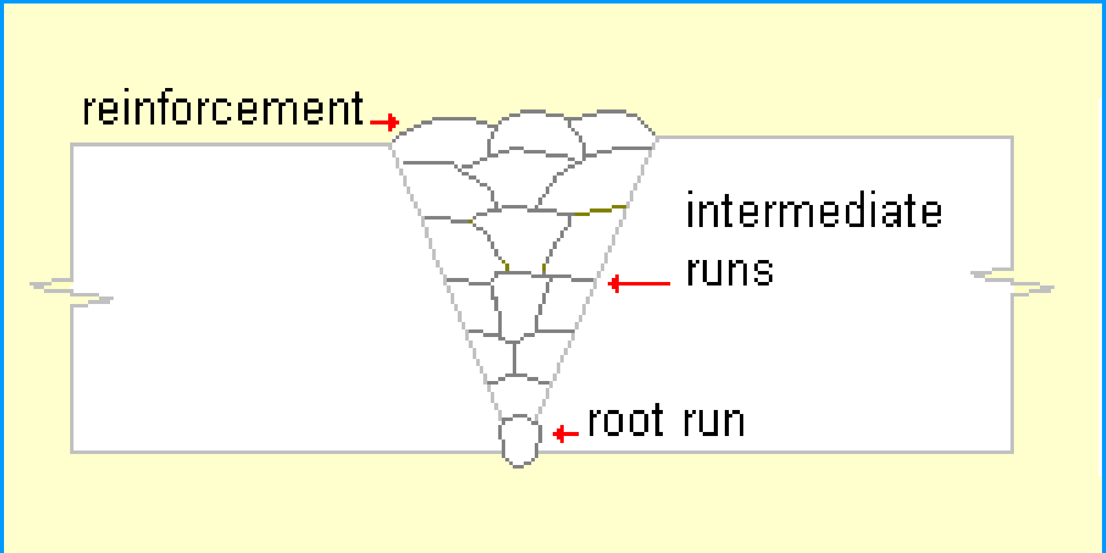
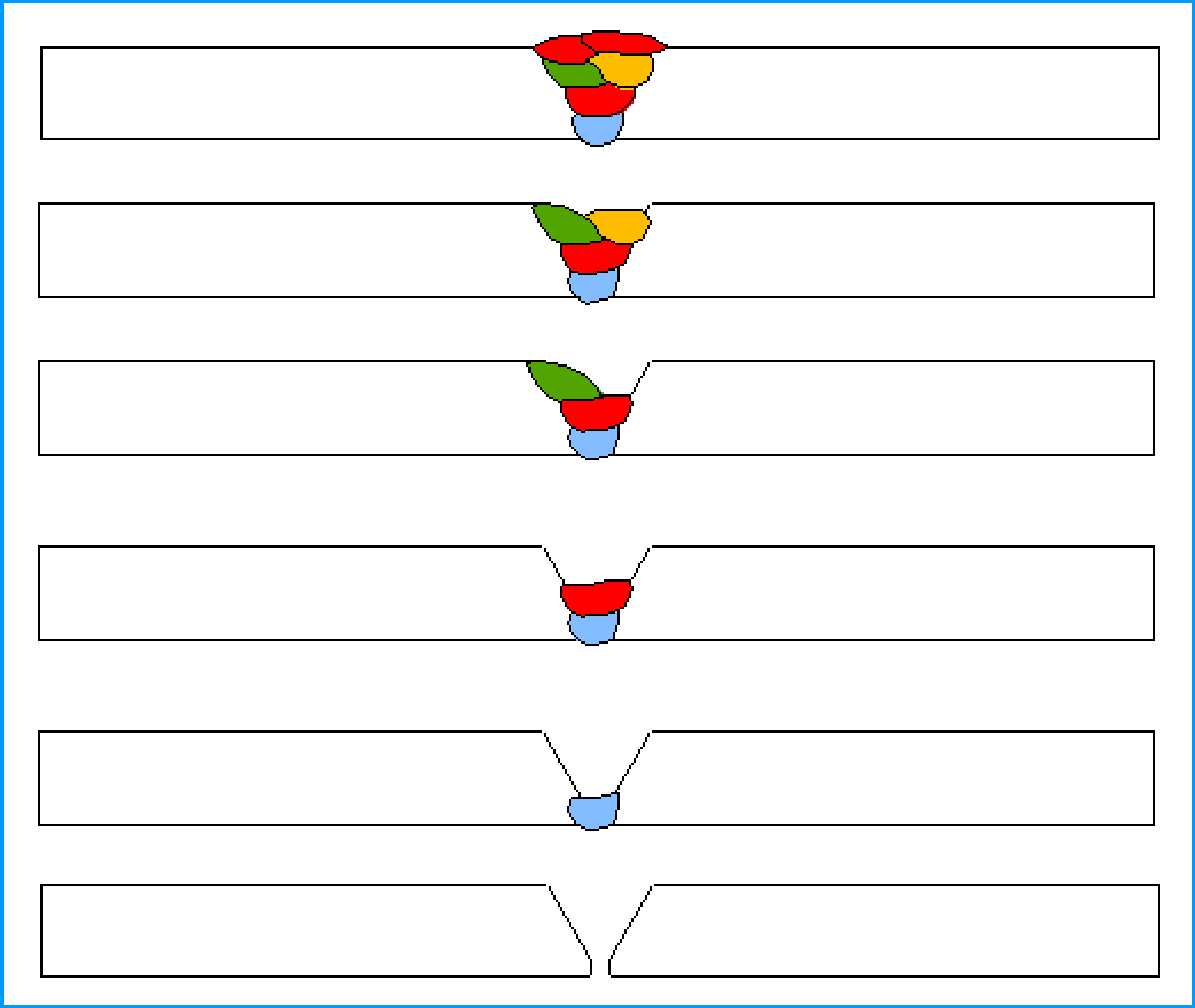


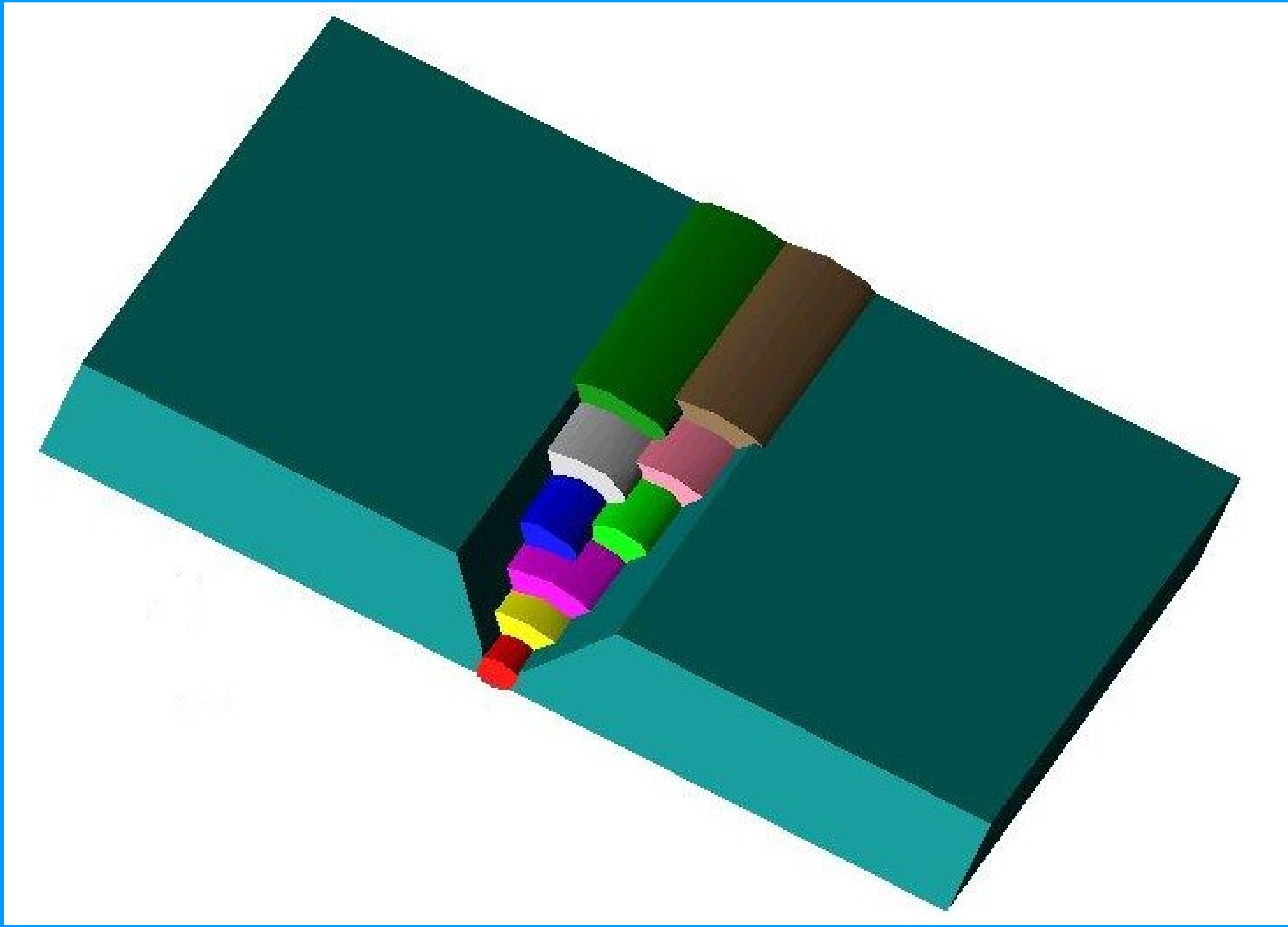
Figure 16 Effects of the gap on weld penetration



Welding sequence :



Welding sequence



Welded layers

HEAT AFFECTED ZONE

When the weld pool is cooling and solidifying, the majority of the heat flows through the parent metal alongside the joint. The steel is thus subjected to heating and cooling cycles similar to those experienced in heat treatment practice.

As shown in Figure 7, the structure of the steel will be changed in this region (called the heat affected zone, HAZ)

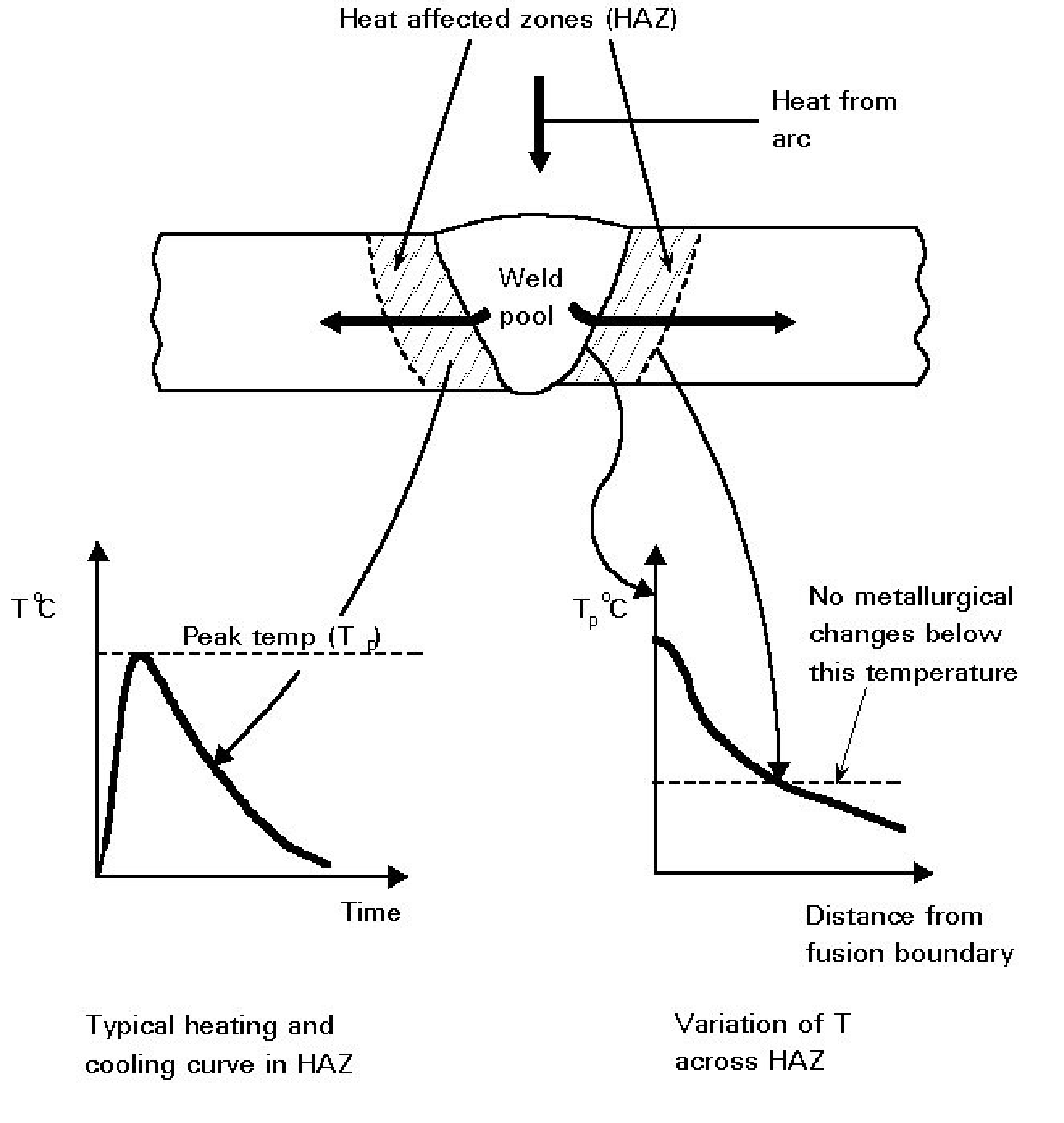


Figure 7 Formation of heat affected zone (HAZ)

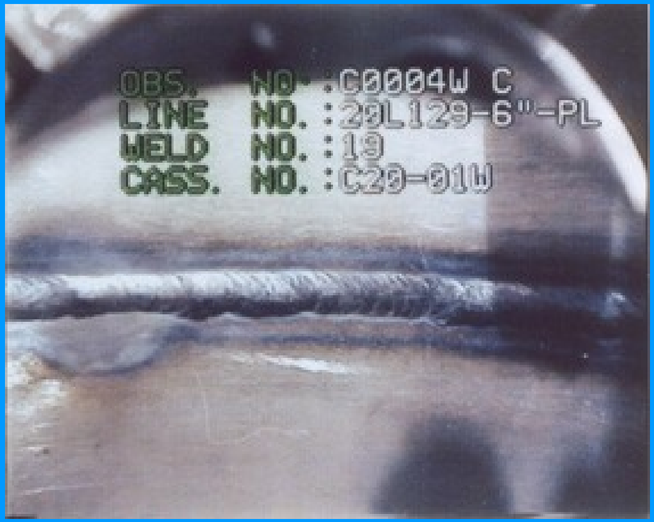
HEAT AFFECTED ZONE

The structure of the HAZ will be controlled by:

- the composition of the steel (carbon equivalent).
- the cooling rate in the HAZ.

In turn the cooling rate is determined by:

- arc energy, i.e. heat input to the joint.
- type of joint.
- thickness of steel.
- temperature of steel plate or section prior to welding, e.g. preheat



TYPES OF WELDING

- **Fusion** Welding – melting base metals

– Arc Welding (AW) – heating with electric arc

– Resistance welding (RW) – heating with resistance to an electrical current

– Oxyfuel Welding (OFW) – heating with a mixture of oxygen and acetylene (oxyfuel gas)

– Other fusion welding – electron beam welding and laser beam welding

- **Solid State** Welding – No melting, No fillers

– Diffusion welding (DFW) – solid-state fusion at an elevated temperature

– Friction welding (FRW) – heating by friction

– Ultrasonic welding (USW) – moderate pressure with ultrasonic oscillating motion

- SHIELDED METAL ARC WELDING(SMAW)
- GAS SHIELDED ARC WELDING(GSAW)
- FLUX CORE ARC WELDING(FCAW)
- SUBMERGED ARC WELDING(SAW)
- ELECTROSLAG AND ELECTROGAS WELDING
- OXYACETYLENE WELDING(OAW)
- RESISTANCE WELDING(RW)

Shielded Metal Arc Welding (SMAW)

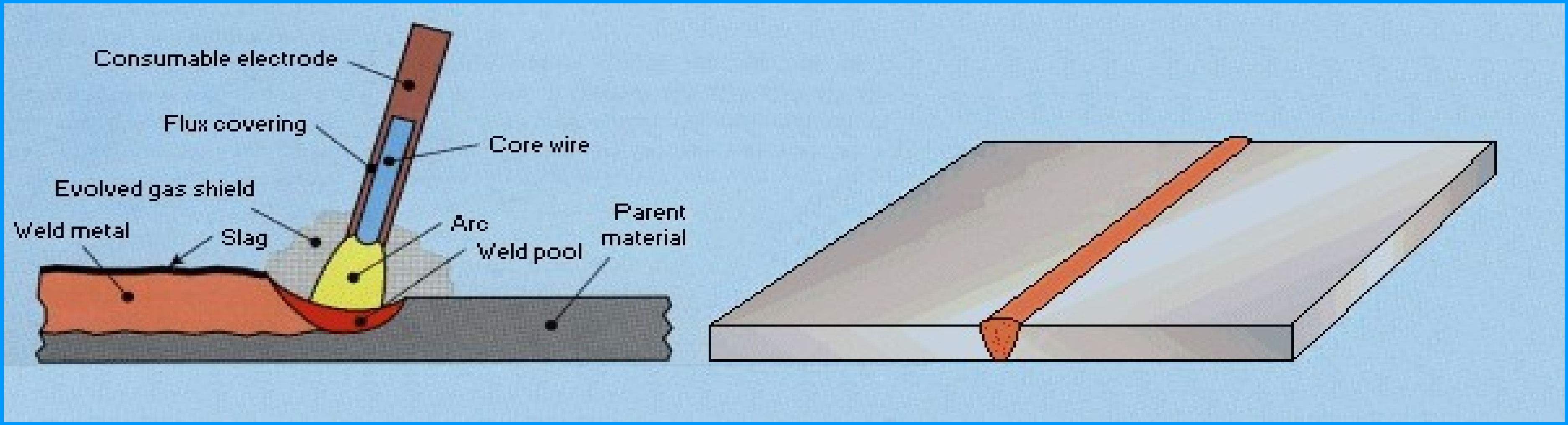
– A consumable electrode – a filler metal rod coated with chemicals for flux and shielding (230-460mm long and 2.5-9.4mm in diameter)

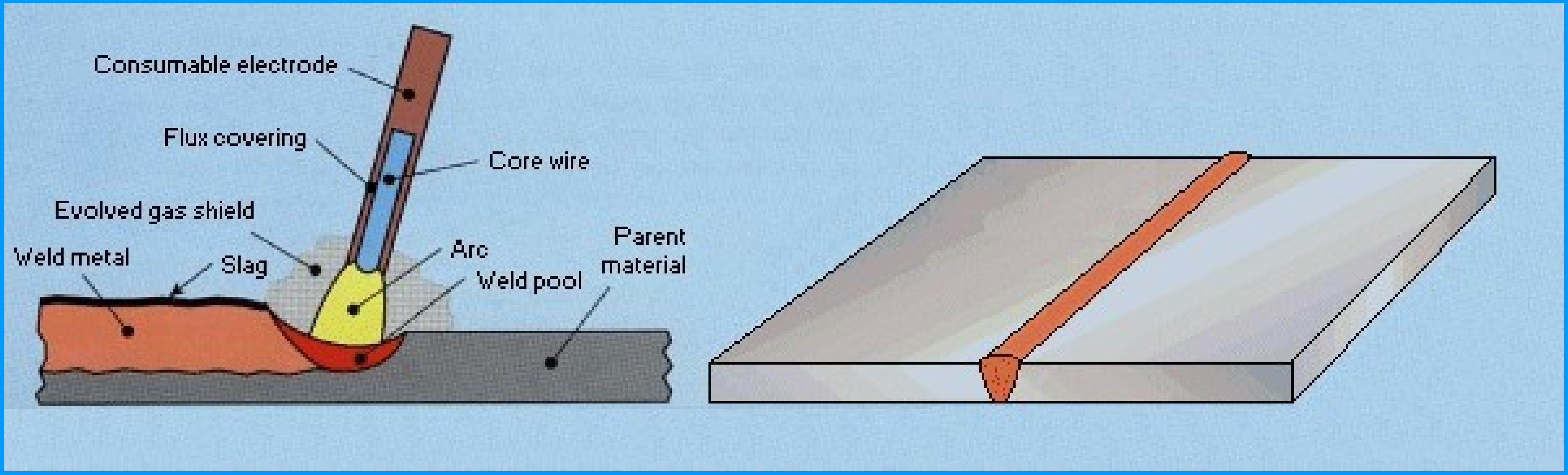
– The filler metal must be comparable with

– Current: 30-300A and Voltage: 15-45V

– Cheaper and portable than oxyfuel welding

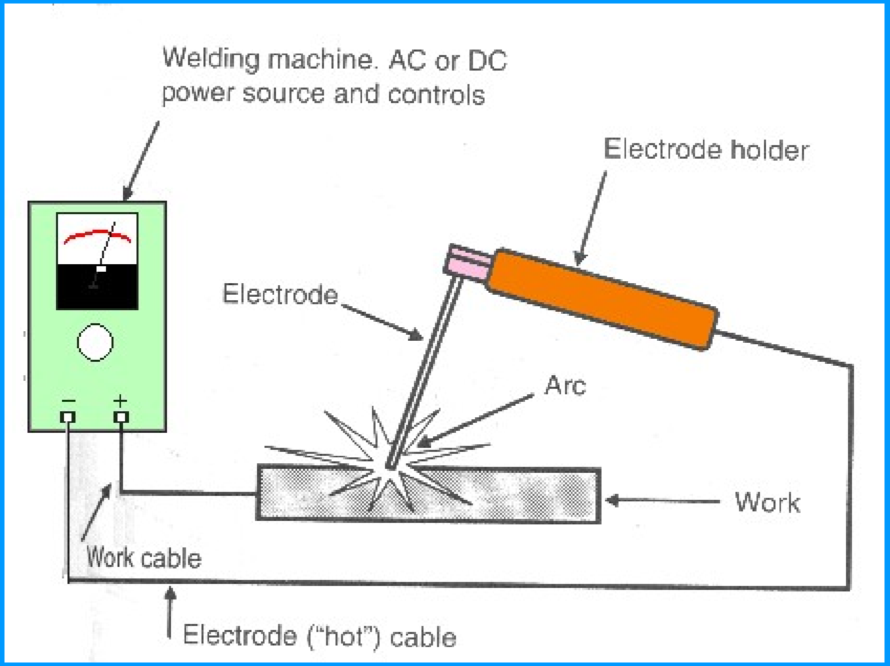
– Less efficient and variation in current due to the change in length of consumable electrodes during the process.





SHIELDED METAL ARC WELDING : Several welding processes are based on heating with an electric arc, the oldest and simple is the shielded metal arc welding [SMAW] or stick welding. In this process an electrical machine [which may be DC or AC] supplies current to an electrode holder which carries an electrode. An earth cable connects the work piece to the welding machine to provide a return path for the current. The weld is initiated by tapping [striking] the tip of the electrode against the work piece which initiates an electric arc. The high temperature generated [about 6000^{o}C] almost instantly produces a molten pool and the end of the electrode. The electrode continuously melts into this pool and fills the groove. The operator needs to control the gap between the electrode tip and the work piece while moving the electrode along the joint.

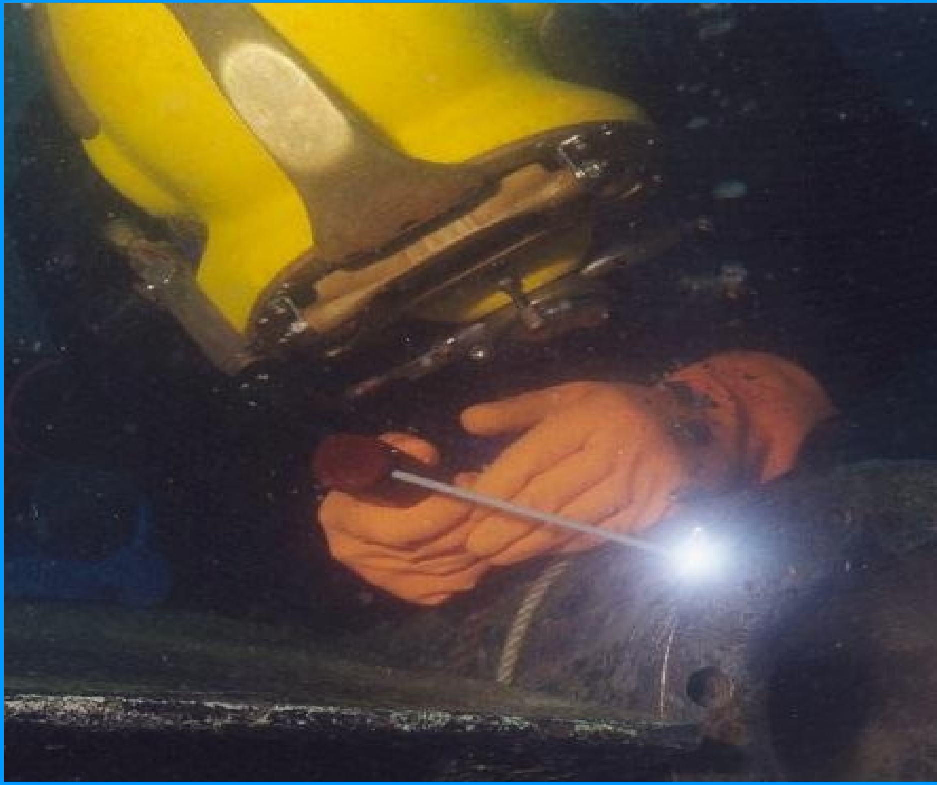
In the shielded metal arc welding process [SMAW] the 'stick' electrode is covered with an extruded coating of flux. The heat of the arc melts the flux which generates a gaseous shield to keep air away from the molten pool and also flux ingredients react with unwanted impurities such as surface oxides, creating a slag which floats to the surface of the weld pool. This forms a crust which protects the weld while it is cooling. When the weld is cold the slag is chipped off.



Major defects in this process are

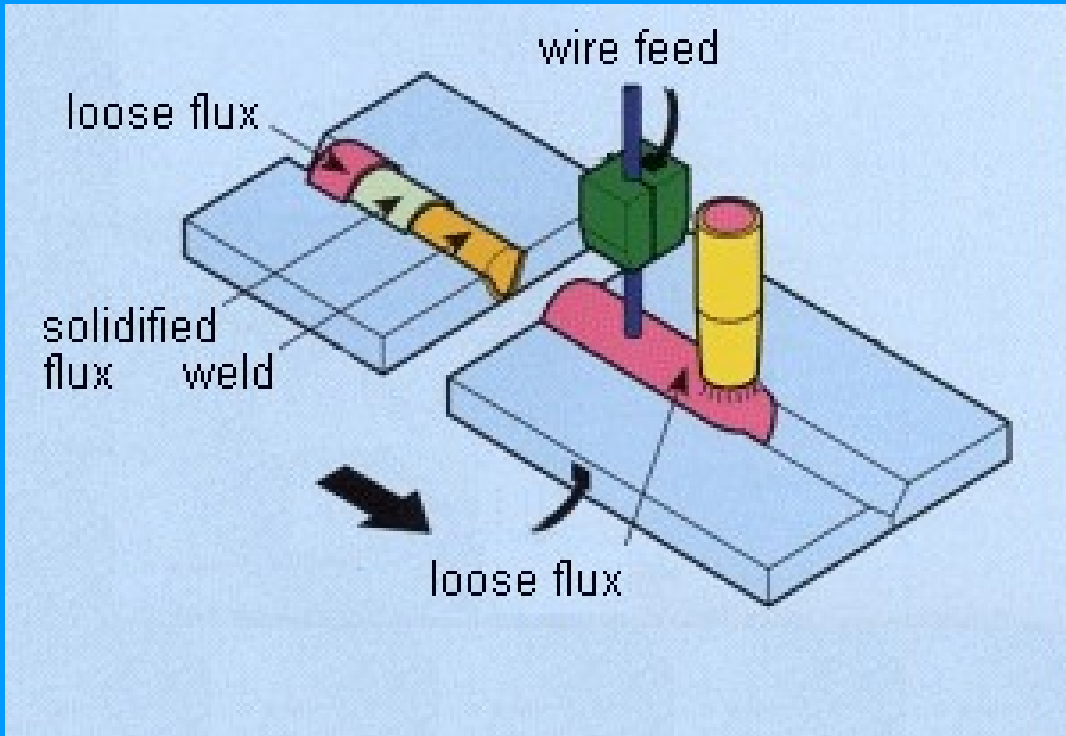
Undercutting, Incomplete penetration, incomplete fusion, Porosity, Slag Inclusions, Cracks, burn through.

Shown in the picture is the electrode and it's holder. The cover on the electrode is flux. An old electrical power source can also be seen in the behind. The SMAW process can not be used on steel thinner than about 3mm and being a discontinuous process it is only suitable for manual operation. It is very widely used in fabrication shops and for on site steel construction work. A wide range of electrode materials and coatings are available enabling the process to be applied to most steels, heat resisting alloys and many types of cast iron.



A SMAW deposit and cover blanket of the slag. The flux covering the electrode melts during welding. This forms the gas and slag to shield the arc and molten weld pool. The slag must be chipped off the weld bead after welding. The flux also provides a method of adding scavengers, deoxidizers, and alloying elements to the weld metal.

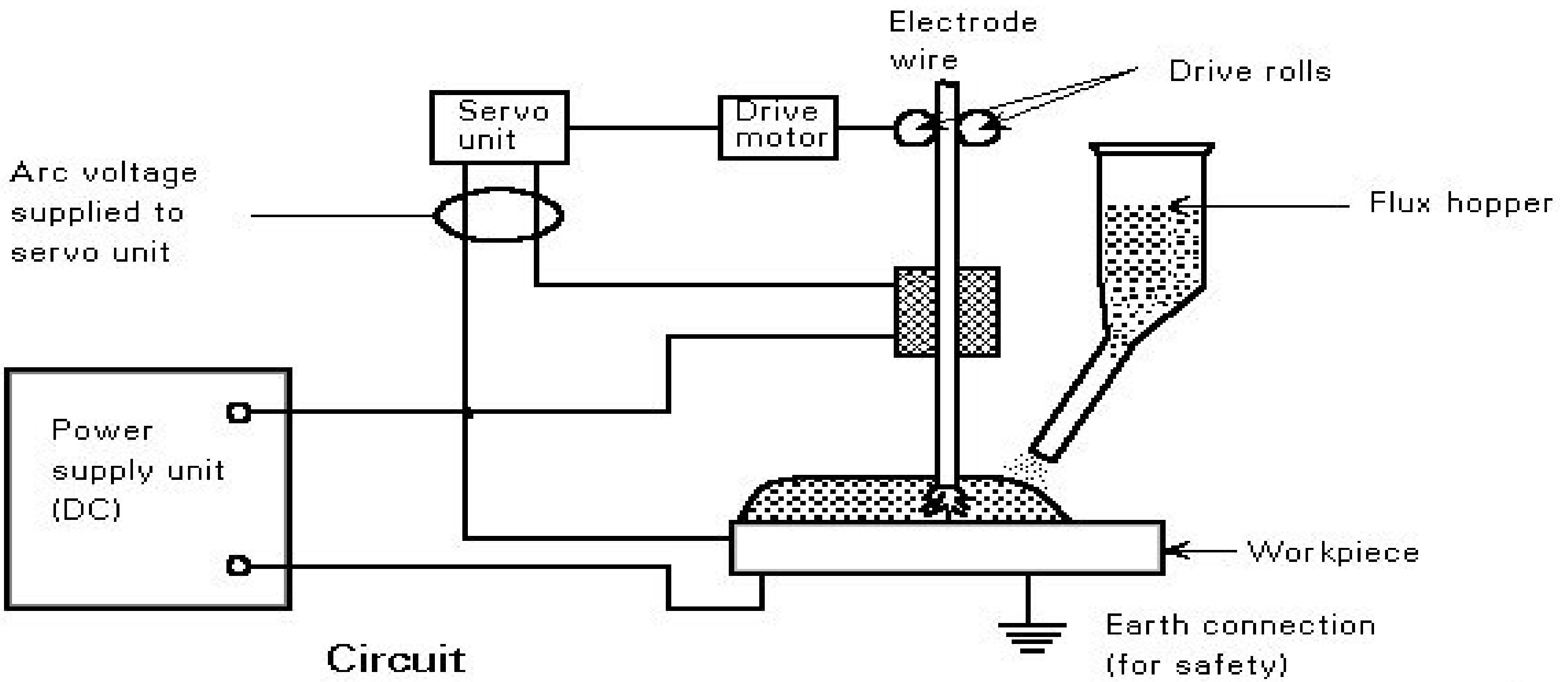
The covering slag removed from the finished weld and the weld bead exposed.



SUBMERGED ARC WELDING [SAW]

It is a high quality, very high deposition rate welding process. The electric arc is submerged below the loose granular flux which is poured into the groove separately. This method is used for, fast, large scale welding of thicker plates in fabrication shops.

Common defects in Submerged Arc Welding : Solidification Cracking, Hydrogen Cracking , Incomplete penetration, Incomplete fusion, Slag inclusion, Porosity.



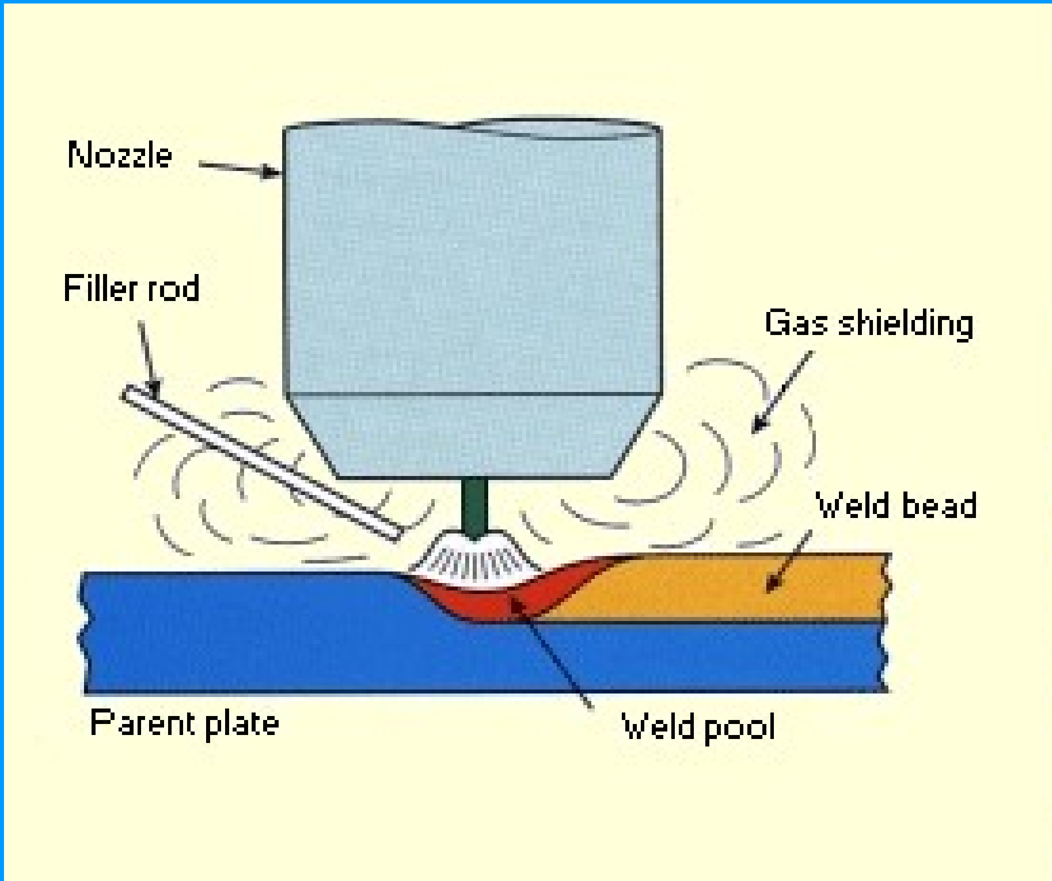
Circuit

Electrode : Bare wire; 2,4 to 6 mm diam.

Flux : Fused (silicate) or agglomerated (basic)

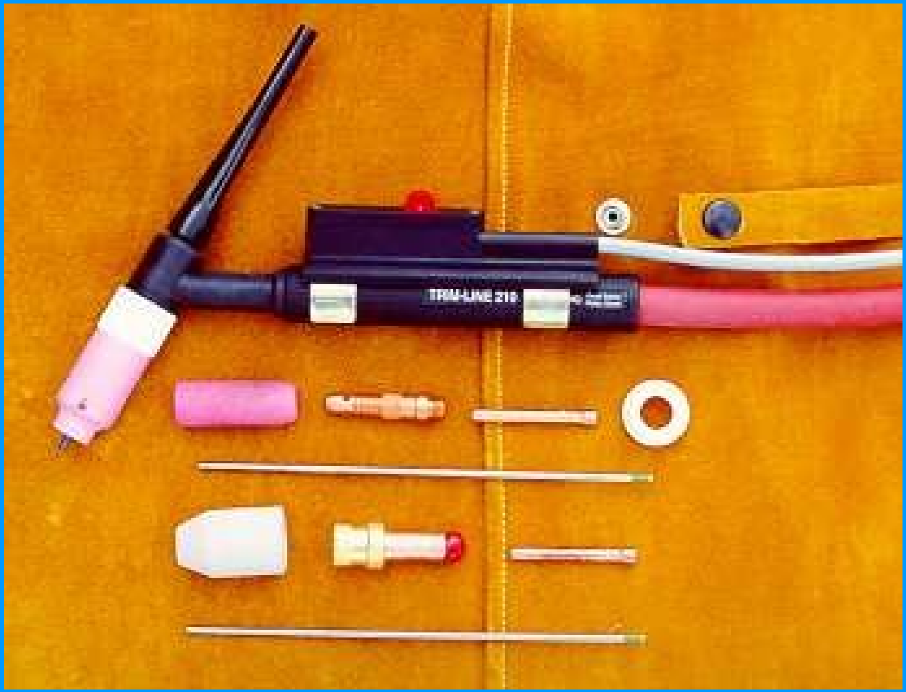
Controls : Current - maintained at preset values
Voltage - by servo-unit
Electrode feed
Travel speed - preset on traverse unit. Can be altered during welding

The arc is formed between a continuously-fed wire electrode and the workpiece, and the weld is formed by the arc melting the workpiece and the wire. The layer of flux generates the gases and slag to protect the weld pool and hot weld metal from contamination. Flux plays an additional role in adding alloying elements to the weld pool.



Gas Tungsten Arc Welding : In this process the arc is formed between a pointed tungsten electrode and the work piece in an inert atmosphere of argon or helium. The small intense arc provided by the pointed electrode is ideal for high quality and precision welding, specially useful for thin joints. If filler wire is used, it is added to the weld pool separately. GTAW has played a major role in the acceptance of aluminium for high quality welding and structural applications.

The process is well suited to joining non - ferrous metals, including aluminum, magnesium, refractory and special metals and is effective for joining thin section metals. A high degree of skill is needed, but high quality welds can be produced.



Helium is generally added to increase heat input. Hydrogen will result in cleaner looking welds and also increase heat input, however, Hydrogen may promote porosity or hydrogen cracking. Because the electrode is not consumed during welding, the welder does not have to balance the heat input from the arc as the metal is deposited from the melting electrode. Undercutting, Tungsten inclusions, Porosity, Weld metal cracks, Heat affected zone cracks are the common defects.

GTAW

MIG welding :

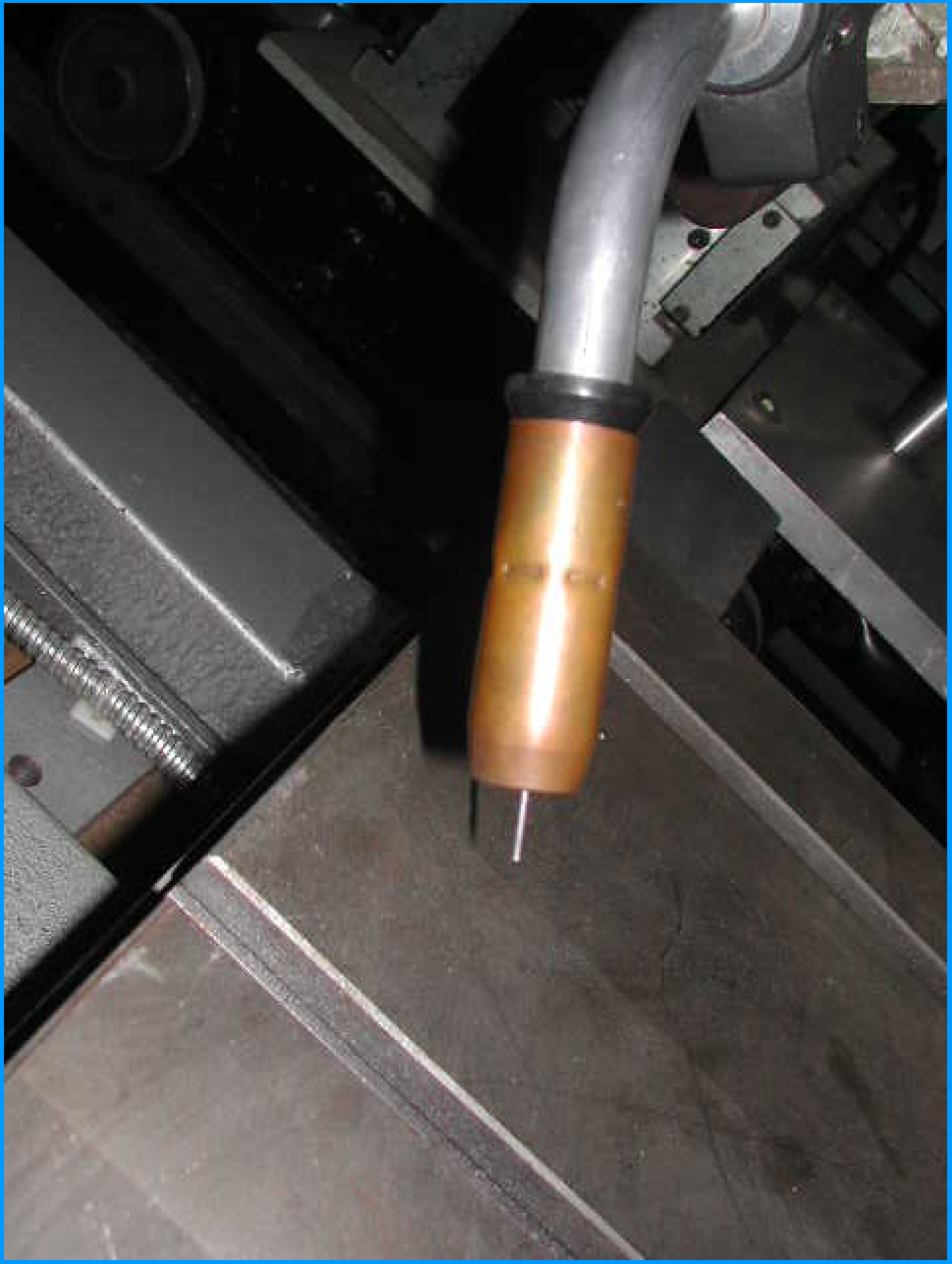
In MIG the arc is formed between the end of a small diameter wire electrode fed from a spool, and the work piece. The shielding gas, Argon or CO_2 forms the arc plasma, stabilizes the arc on the metal being welded, shields the arc and molten weld pool, and allows smooth transfer of metal from the weld wire to the weld groove. Main equipment components are :

power source

Wire feed system

Conduit

Gun



In MIG welding, a shielding gas is fed into the welding torch and exits around the filler wire. The arc and the weld pool are protected from the atmosphere by this gas shield. This enables bare wire to be used without a flux coating. However, the absence of flux to 'mop up' surface oxide places greater demand on the welder to ensure that the joint area is cleaned immediately before welding. This can be done using either a wire brush for relatively clean parts, or a hand grinder to remove rust and scale. The other essential piece of equipment is a wire cutter to trim the end of the electrode wire. In this process a filler metal is stored on a spool and driven by rollers [current is fed into the wire] through a tube into a 'torch'. The large amount of filler wire on the spool means that the process can be considered to be continuous and long, uninterrupted welds can easily be made. In this process they key issues are selecting the correct shielding gas and flow rate and the welding wire speed and current. MIG process can readily be automated and MIG welding is <u>now commonly carried out by robots</u>. This welding process is widely used on steels and on aluminium. Although the inert gas shield keeps the weld clean, depending upon the process settings, there may be spatter of metal globules adjacent to the weld which detracts from its appearance unless they are removed.

Metal Inert Gas Welding machine :

Common defects in MIG welding are ;

Undercutting, Excessive melt-through, Incomplete fusion, Incomplete joint penetration, Porosity, Weld metal cracks, Heat affected zone cracks.

The primary shielding gasses used are ;

Argon, Argon - 1 to 5% Oxygen, Argon - 3 to 25% $CO_{2,}$ Argon / Helium. CO_2 is also used in its pure form in some MIG welding processes. However, in some applications the presence of CO_2 in the shielding gas may adversely affect the mechanical properties of the weld.

FLUX CORED ARC WELDING

FCAW is a commonly used high deposition rate welding process that adds the benefits of flux to the welding simplicity of MIG welding. The welding wire is continuously fed from a spool. FCAW uses the same types of wire feeders and power sources as the GMAW process. However, the FCAW process uses a tubular electrode with its core (inner) containing the deoxidizers, scavengers, and (protectant) slag and vapor forming ingredients. Its overall efficiency is about the same as the GMAW process, but significantly better than the SMAW process. FCAW is adaptable to welding both thick and thin Steels. If used under windy conditions, the FCAW-G (added external gas shielding) process requires some barriers to prevent the gas from being dissipated. The FCAW-S (self shielded - from the core) process is commonly used on mild steel, but the electrodes can be manufactured to contain a number of alloying elements in the core for welding stainless steels and other low-alloys.

Self shielding flux cored arc welding wires are available or gas shielded welding wires may be used. Flux cored welding is generally more forgiving than MIG welding. Less precleaning may be necessary than MIG welding. However, the condition of the base metal can affect weld quality. Excessive contamination must be eliminated. Flux cored welding produces a flux that must be removed.

Common defects are

Undercutting, Incomplete fusion , Slag inclusions, Porosity, Cracks.

FLUX CORED ARC WELDING PROCESS

FCAW uses the same types of wire feeders and power sources as the GMAW process. However, the FCAW process uses a *tubular electrode with its core (inner)* containing the deoxidizers, scavengers, and (protectant) slag and vapor forming ingredients.

If used under windy conditions, the FCAW-G (added external gas shielding) process requires some barriers to prevent the gas from being dissipated. The FCAW-S (self shielded - from the core) process is commonly used on mild steel, but the electrodes can be manufactured to contain a number of alloying elements in the core for welding stainless steels and other low-alloys.

FCAW is noted for its high-deposition rates and somewhat forgiving arc characteristics. Its overall efficiency is about the same as the GMAW process, *but significantly better than the SMAW process.* It is a versatile process, adaptable to welding both thick and thin Steels.

Welding Defects

Any of these defects are potentially disastrous as they can all give rise to high stress intensities which may result in sudden unexpected failure below the design load or in the case of cyclic loading, failure after fewe

Welding defects include the following:

Porosity
Trapped slag
Lack of fusion
Lack of penetration or excess penetration
Undercut
Hot cracking
Hydrogen induced HAZ cracking
Lamellar tearing

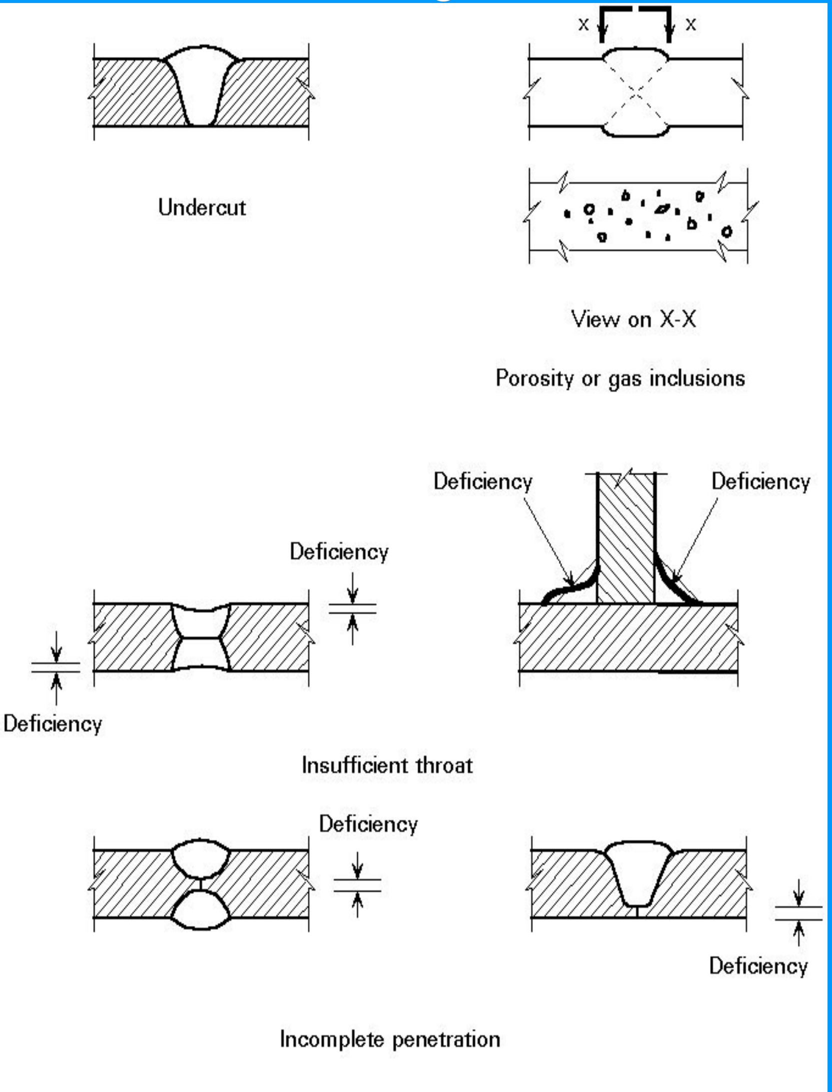
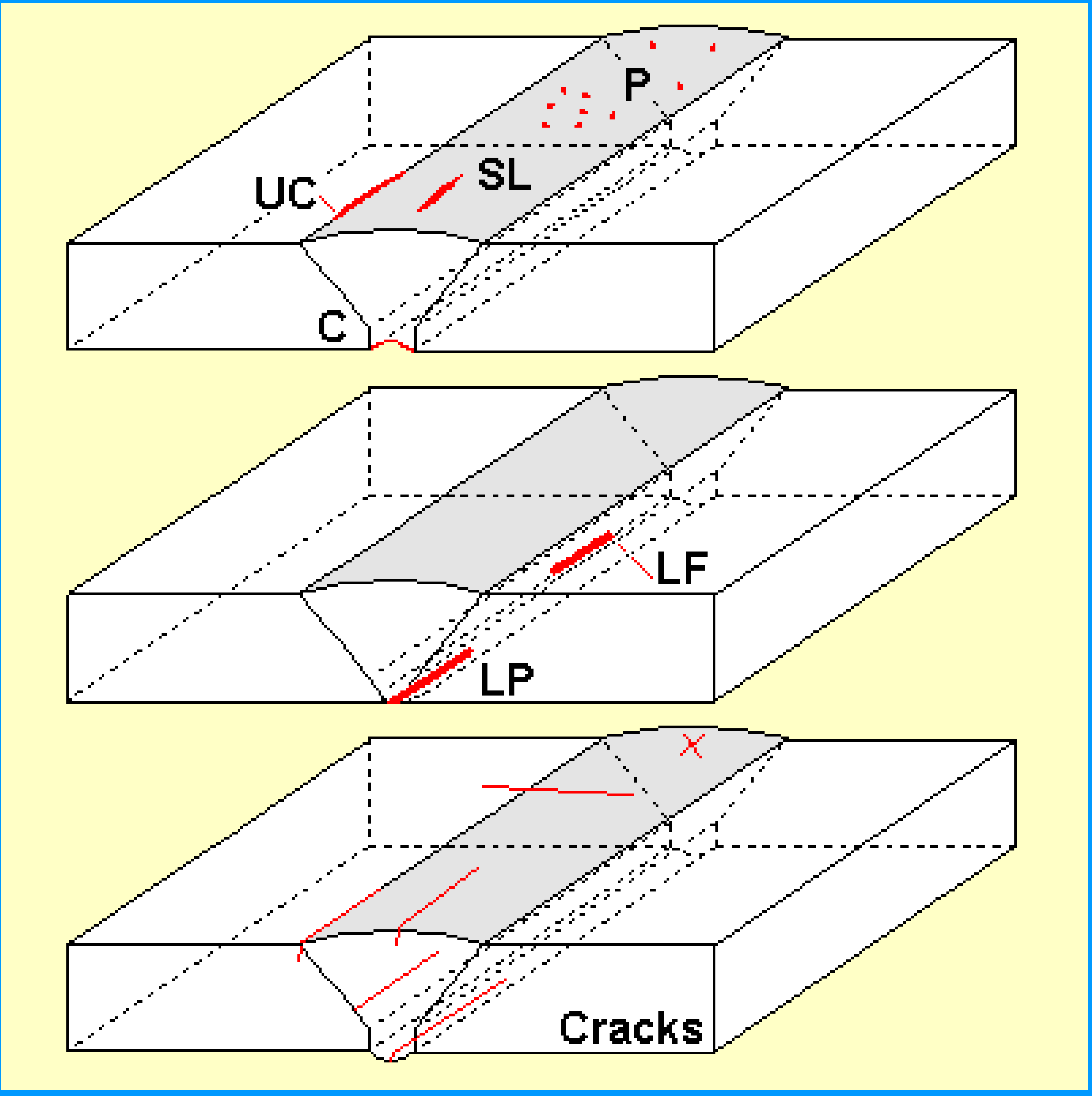


Figure 17 Examples of weld defects

Welding Defects

Essentially a discontinuity or flaw is called a defect if it exceeds the acceptance limits established by engineering based on Fitness for Service criteria.



POROSITY

Porosity is the presence of cavities in the weld metal caused by the freezing in of gas released from the weld pool as it solidifies. The porosity can take several forms:

- distributed
- surface breaking pores
- wormhole
- crater pipes

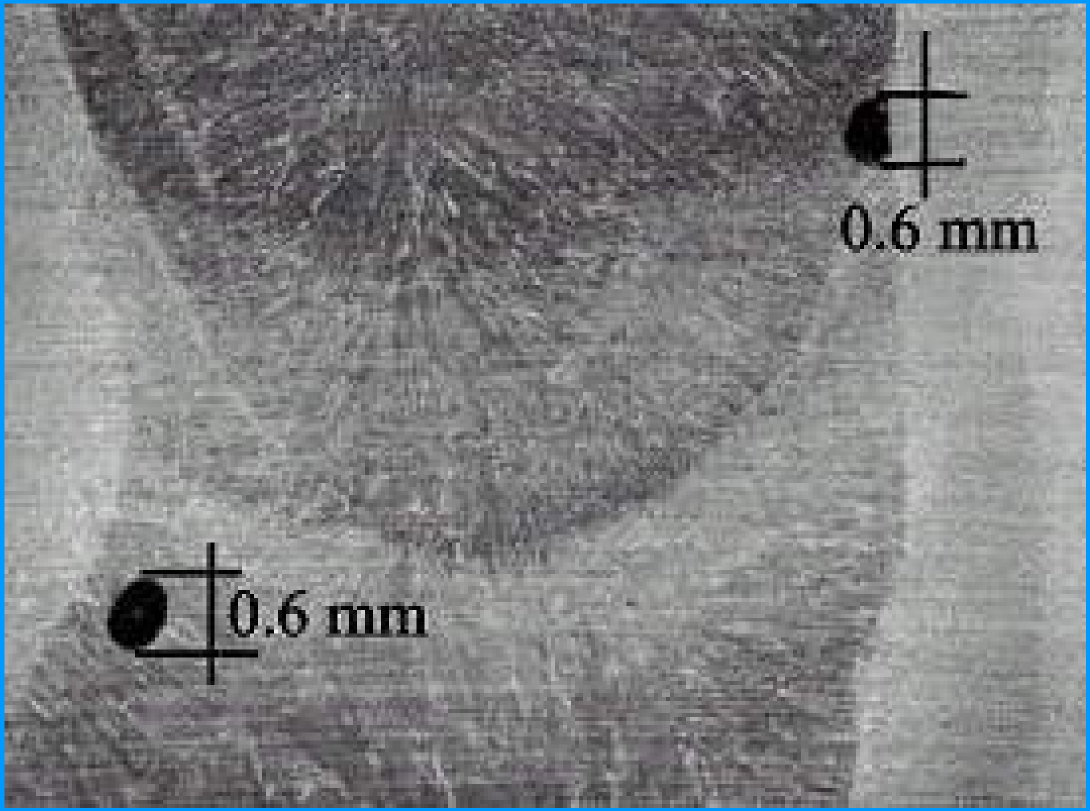
Porosity is caused by the absorption of nitrogen, oxygen and hydrogen in the molten weld pool which is then released on solidification to become trapped in the weld metal.

Nitrogen and oxygen absorption in the weld pool usually originates from poor gas shielding. As little as 1% air entrainment in the shielding gas will cause distributed porosity and greater than 1.5% results in gross surface breaking pores. Leaks in the gas line, too high a gas flow rate, draughts and excessive turbulence in the weld pool are frequent causes of porosity.

Hydrogen can originate from a number of sources including moisture from inadequately dried electrodes, fluxes or the workpiece surface. Grease and oil on the surface of the workpiece or filler wire are also common sources of hydrogen.

Surface coatings like primer paints and surface treatments such as zinc coatings, may generate copious amounts of fume during welding. The risk of trapping the evolved gas will be greater in T joints than butt joints especially when fillet welding on both sides. Special mention should be made of the so-called weldable (low zinc) primers. It should not be necessary to remove the primers but if the primer thickness exceeds the manufacturer's recommendation, porosity is likely to result especially when using welding processes other than MMA.

Porosity is a collective name describing cavities or pores caused by entrapment of gas in molten metal during solidification. Contaminants, moisture or inadequate shielding may stand at its origin. Hydrogen can diffuse in molten aluminum and is rejected upon solidification causing porosity.



Relatively large bubbles or diffused clusters of small pores or pinholes, spherical or elongated can appear. Shrinkage voids can also saw a similar aspect. The effects of porosity on performance depend upon quantity, size, alignment and orientation. When clustered at the center of a weld, they are not considered dangerous fatigue promoters, or highly detrimental to fatigue resistance, although they may reduce the static stress carrying capacity of the welded member.

TRAPPED SLAG

Slag is normally seen as elongated lines either continuous or discontinuous along the length of the weld. Slag inclusions are usually associated with the flux processes, i.e. MMA, FCA and submerged arc, but they can also occur in MIG welding. As slag is the residue of the flux coating, it is principally a deoxidation product from the reaction between the flux, air and surface oxide. The slag becomes trapped in the weld when two adjacent weld beads are deposited with inadequate overlap and a void is formed. When the next layer is deposited, the entrapped slag is not melted out. Slag may also become entrapped in cavities in multi-pass welds through excessive undercut in the weld toe or the uneven surface profile of the preceding weld runs. As they both have an effect on the ease of slag removal, the risk of slag imperfections is influenced by

- Type of flux
- Welder technique

The type and configuration of the joint, welding position and access restrictions all have an influence on the risk of

TRAPPED SLAG

- they occur only in the weld metal
- they normally appear as straight lines along the centreline of the weld bead, as shown in Fig. 1, but may occasionally appear as transverse cracking depending on the solidification structure
- solidification cracks in the final crater may have a branching appearance
- as the cracks are 'open', they are easily visible with the naked eye On breaking open the weld, the crack surface in steel and nickel alloys may have a blue oxidized appearance, showing that they were formed while the weld metal was still hot
- Segregation of impurities to the centre of the weld also encourages cracking. Concentration of impurities ahead of the solidifying front weld forms a liquid film of low freezing point which, on solidification, produces a weak zone. As solidification proceeds, the zone is likely to crack as the stresses through normal thermal contraction build up. An elliptically shaped weld pool is preferable to a tear drop shape. Welding with contaminants such as cutting oils on the surface of the parent

TRAPPED SLAG

- The overriding cause of solidification cracking is that the weld bead in the final stage of solidification has insufficient strength to withstand the contraction stresses generated as the weld pool solidifies. Factors which increase the risk include:

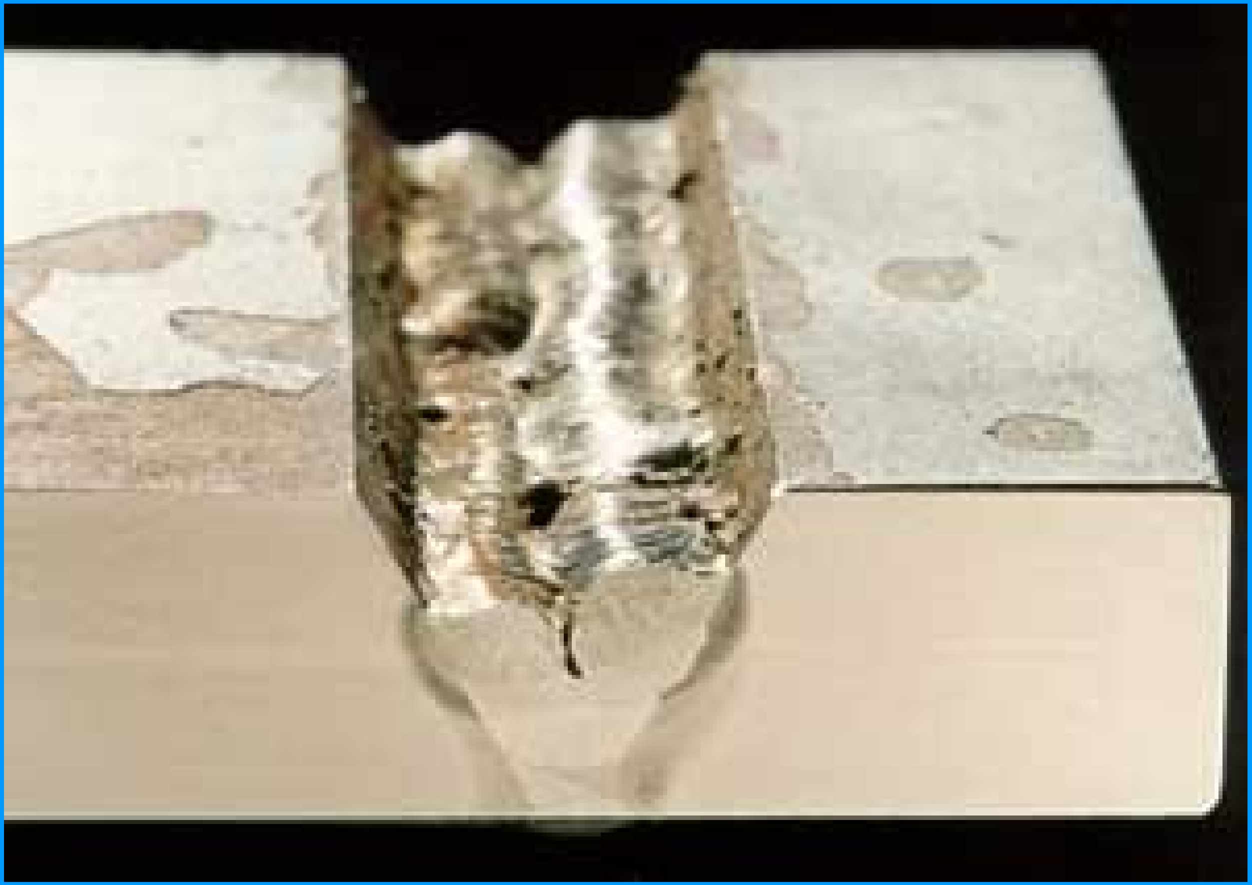
- insufficient weld bead size or shape

- welding under high restraint

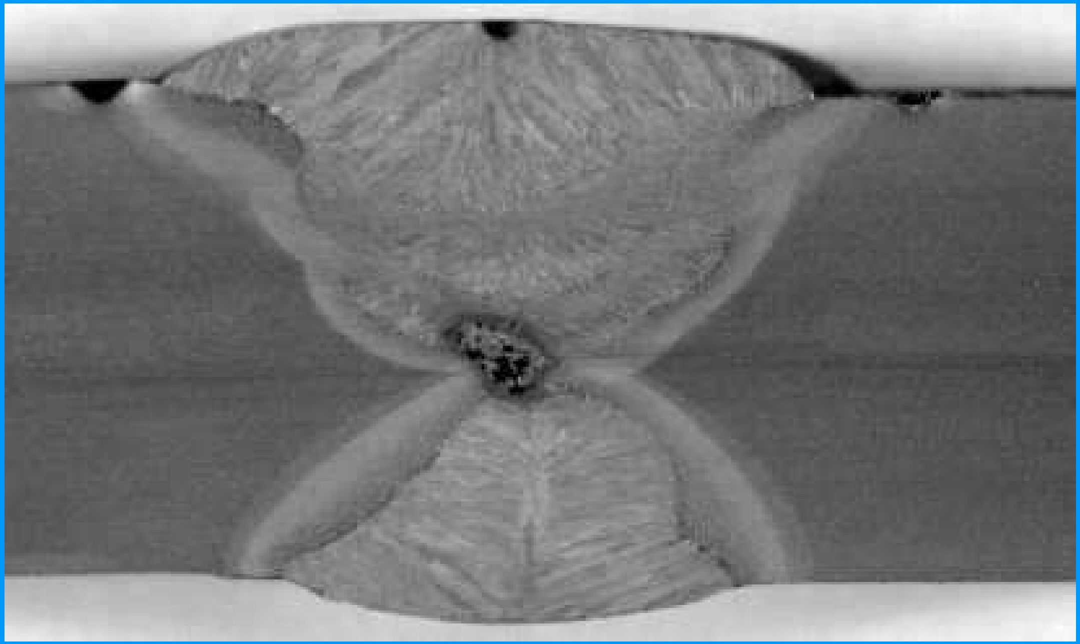
- material properties such as a high impurity content or a relatively large amount of shrinkage on solidification.

- Joint design can have a significant influence on the level of residual stresses. Large gaps between component parts will increase the strain on the solidifying weld metal, especially if the depth of penetration is small. Therefore, weld beads with a small depth-to-width ratio, such as formed in bridging a large gap with a wide, thin bead, will be more susceptible to solidification cracking, as shown in Fig. 2. In this case, the centre of the weld which is the last part to solidify, is a narrow zone with negligible cracking resistance.

- of the plate and the filler determine the weld metal composition



Lack of cleanliness traps slags in the weld.



Large slag inclusion creates fusion problem.

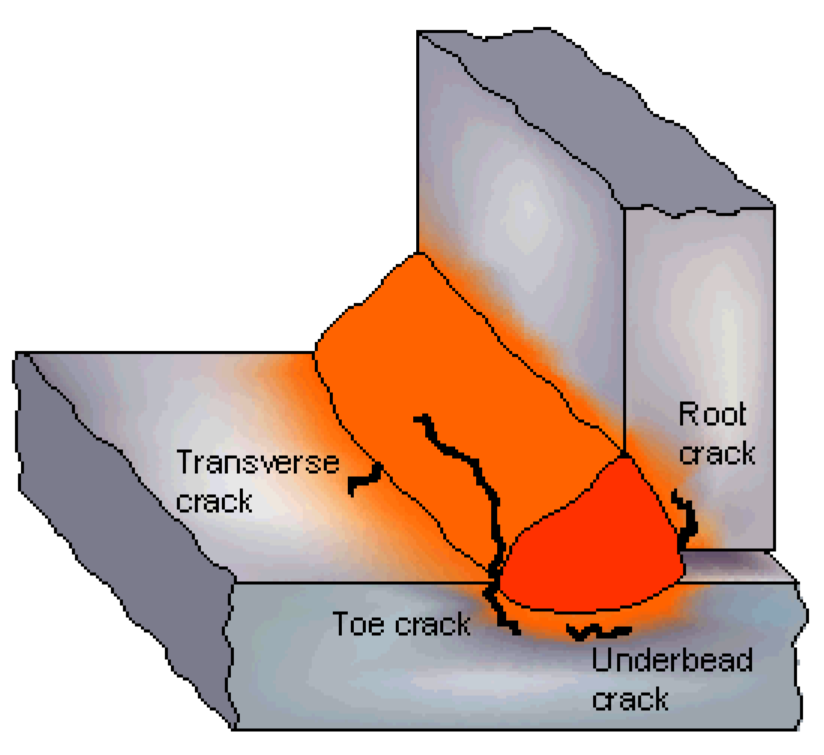
Inclusions are generated by extraneous material and disrupt the continuity of the base metal. They can be slag-, tungsten-, sulfide- or oxide-inclusions.

Tungsten Inclusion is a flaw consisting in a bit of tungsten electrode (from GTAW) embedded in weld metal. It can be found by x-ray and ultrasonic inspections.

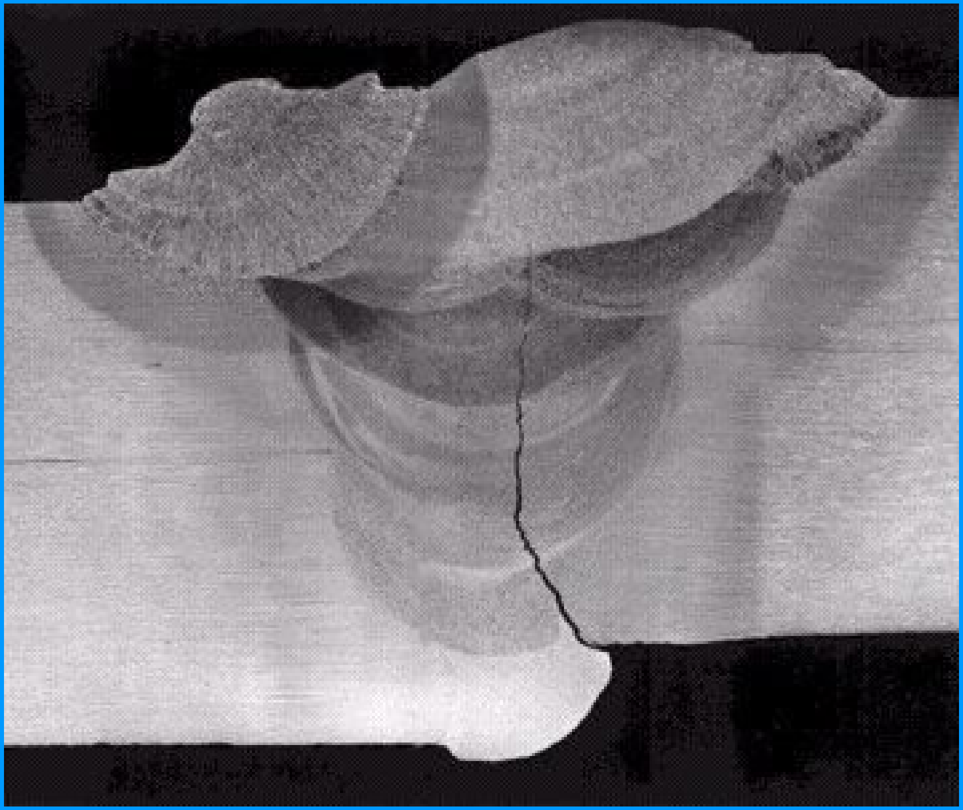
Display

Cracks

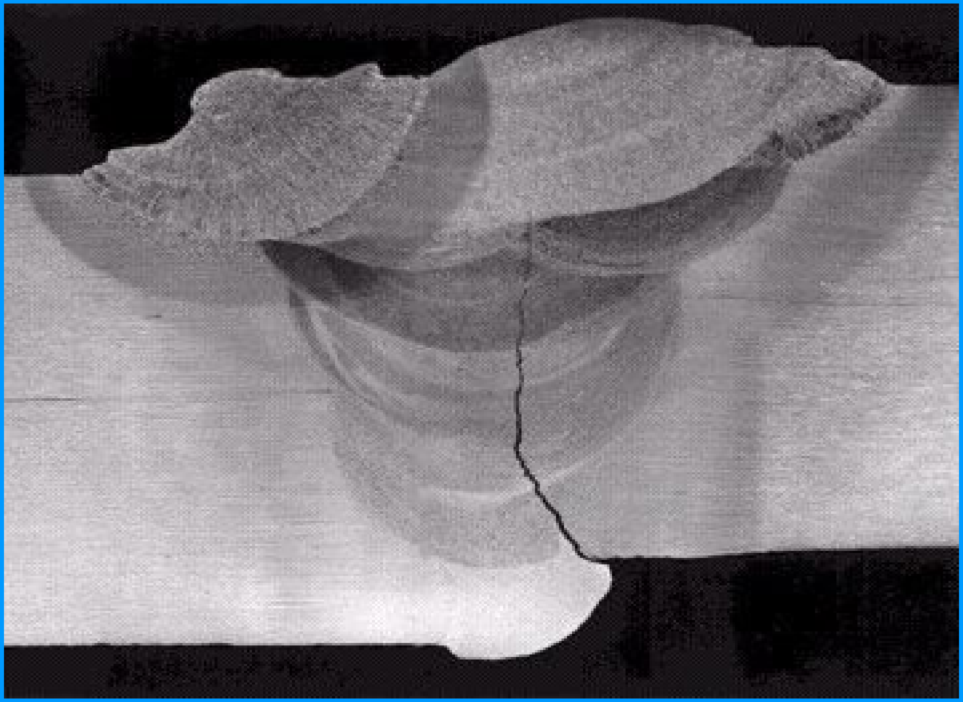
A crack is produced by a fracture which can arise from the stresses generated on cooling or acting on the structure. It is the most serious type of imperfection found in a weld and must be removed. Cracks not only reduce the strength of the weld through the reduction in the cross section thickness but also can readily propagate through stress concentration at the tip, especially under impact loading or during service at low temperature



Cracked weld. **Craters** are visually inspectable depressions indicating improper weld terminations, usually with the presence of radial cracks. They should be avoided or eliminated through improved welding skill or repaired if present. **Cracks** can appear of two different kinds. Hot cracks form when the material solidifies, generally because of the presence of low melting constituents. Cold cracks are generated later, when the material is cold and under stress, sometimes by the presence of dissolved atomic **hydrogen**. They are easily differentiated under the microscope, but anyhow, hot or cold they should not be allowed in a sound structure, otherwise the structure is in danger if not already failed altogether.



Cracks and planar discontinuities are the most dangerous, especially if fatigue loading conditions (i.e. successively increasing and decreasing) are present in service. Their shape extends mainly in two dimensions and constitutes stress raisers. In visual inspection only a linear indication may be visible.



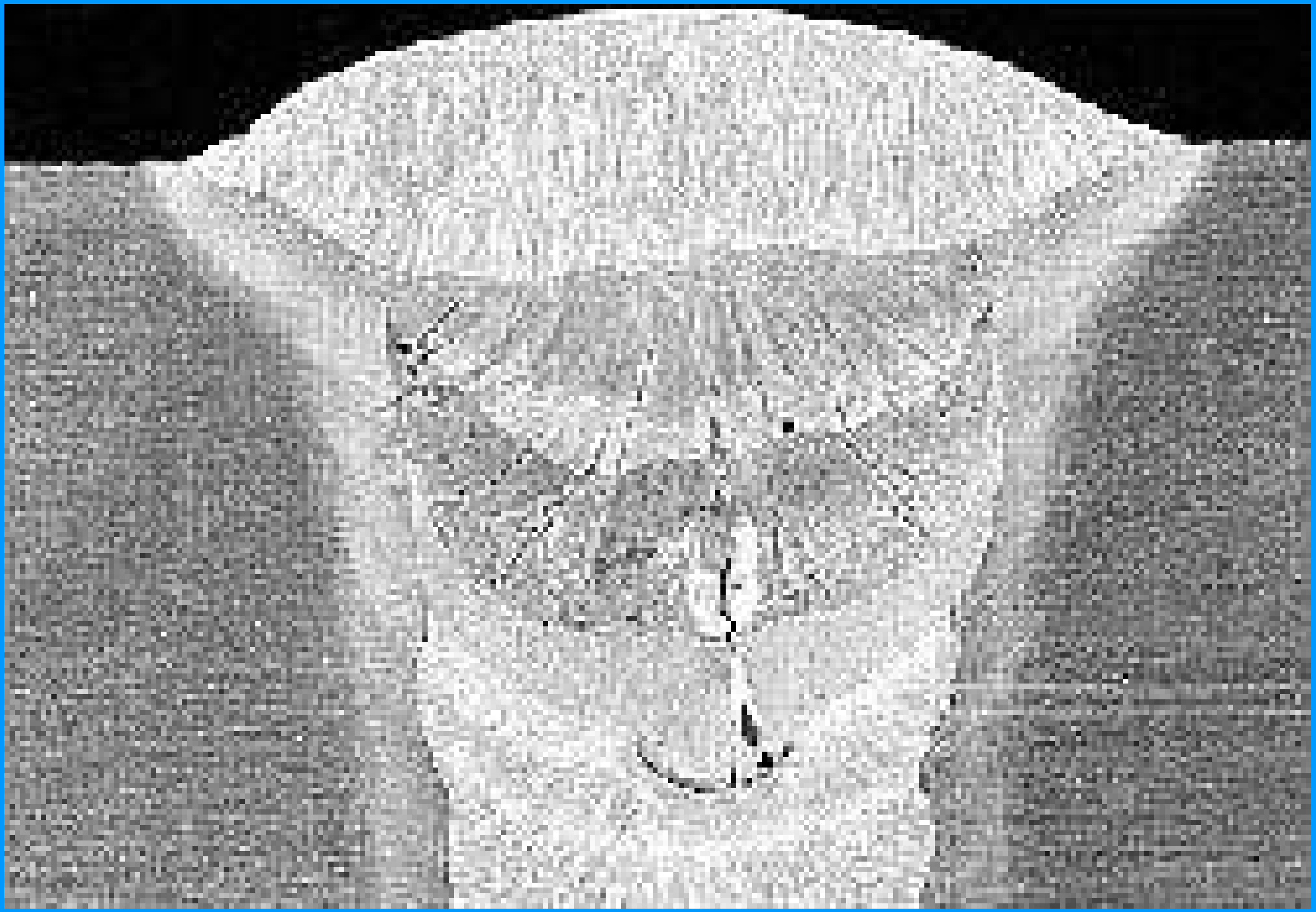
Different types of cracks are described. Usually none are tolerated (at the prescribed detection level), so that they must be removed by careful grinding (if superficial) or repaired by welding. The most insidious ones are those not open to the surface that may require specialized techniques to be detected and evaluated.

Globular volumetric three dimensional discontinuities, porosity or inclusions, are usually found deep inside the weld.

Craters are visually inspectable depressions indicating improper weld terminations, usually with the presence of radial cracks. They should be avoided or eliminated through improved welding skill or repaired if present.

Spatter (click for definition, then close new window to come back), consisting in the presence of metal drops expelled from the weld, which stick to surrounding surfaces should be minimized by correcting the welding conditions and should be eliminated by grinding when present. **Spatter**: the metal drops and particles expelled during arc or gas welding. They do not form part of the weld. Spatter loss is the metal lost due to spatter.

Arc strikes appear as localized remelted metal from inadvertent or careless arc manipulation. They must be avoided and any traces removed because small cracks and their localized heat affected zone may become the origin of dangerous fatigue failures.

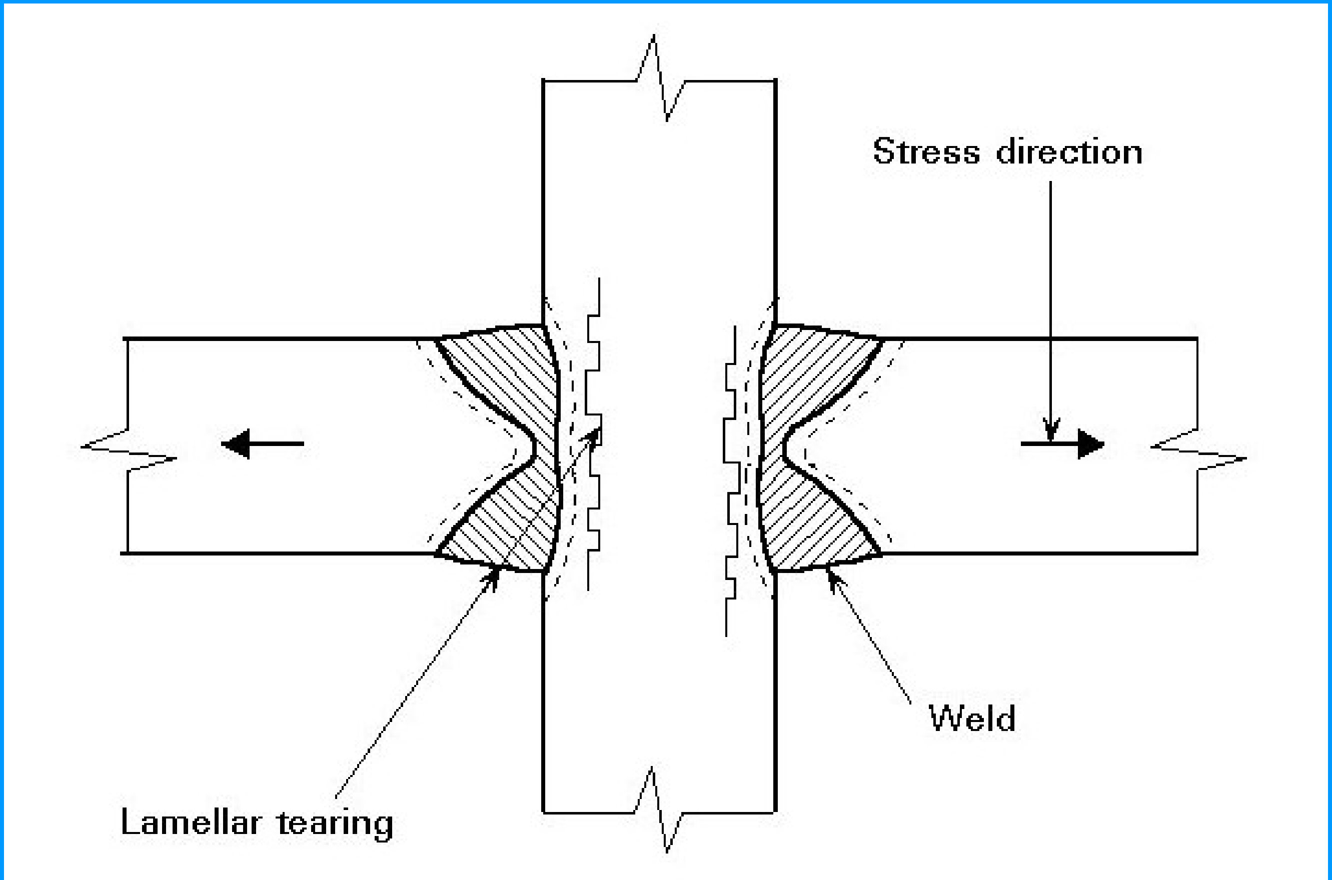


Cracks originated from copper inclusions in the weld metal:

Dendritic and coarse grain structure of stainless steel welds make testing difficult.

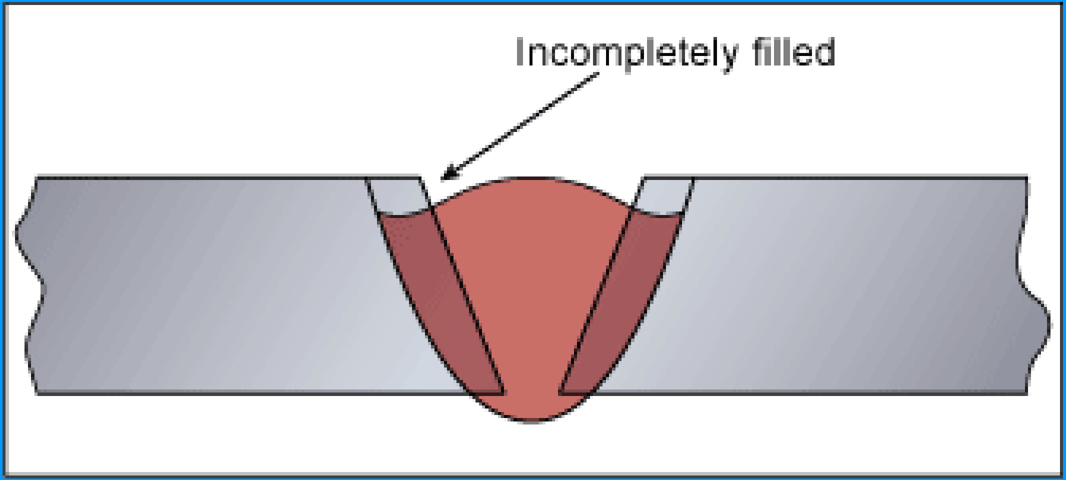
Lamellar Tearing

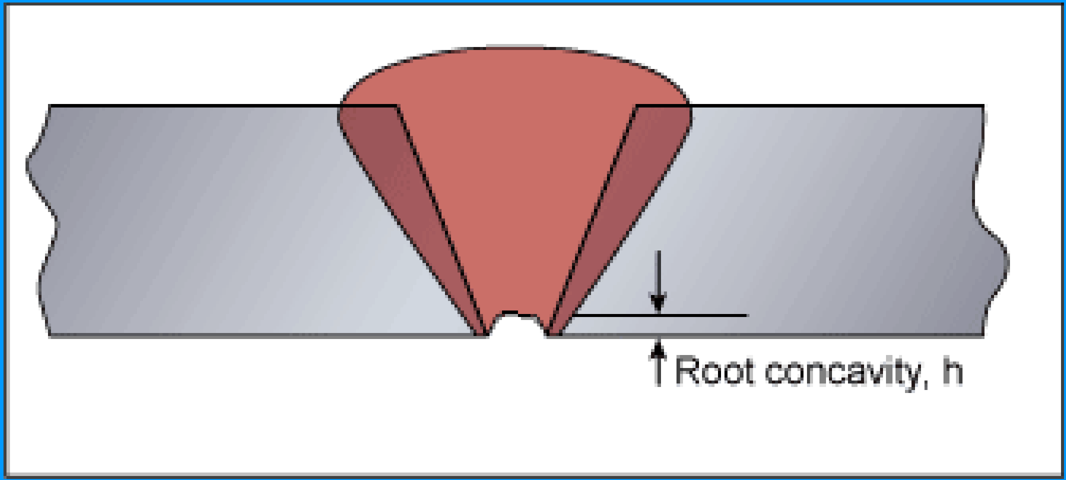
IT is a dangerous planar defect occurring when certain plate materials presenting laminations are welded to a perpendicular element. Tearing occurs in the base metal plate adjacent to welds due to high shrinkage stresses in the thickness direction, introduced by weld metal shrinkage in highly restrained joints. Tearing takes place along laminations. These internal cracks usually run parallel to the weld.



Geometrical imperfections :

It refers to those characteristic of the weld, like incorrect fit up, misalignment, and poor bead shape (undercut, underfill, overlap, melt through and distortion) as determined by visual inspection. They are an indication of inadequate workmanship and may be cause for concern if exceeding requirement limits.



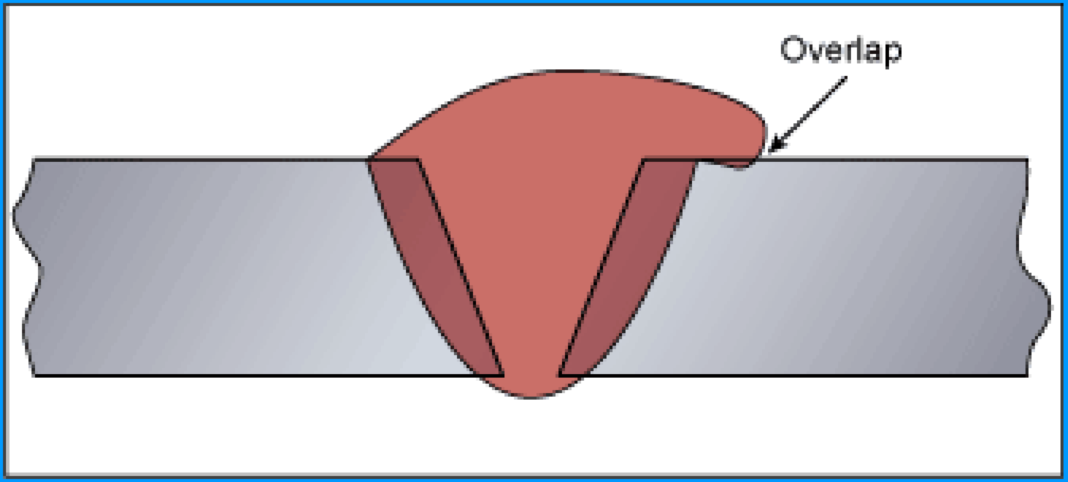


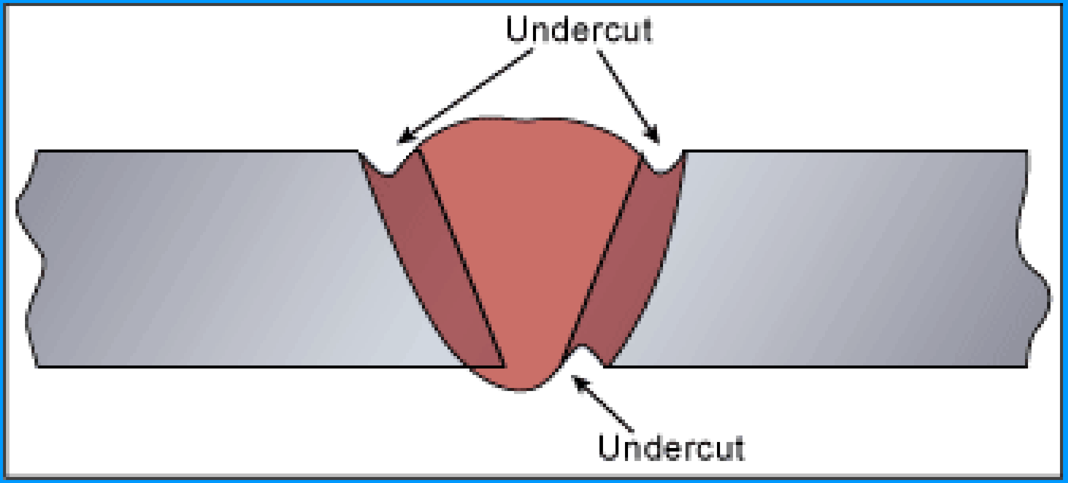
Under fill - A condition in which the weld face or root surface extends below the adjacent surface of the base metal.

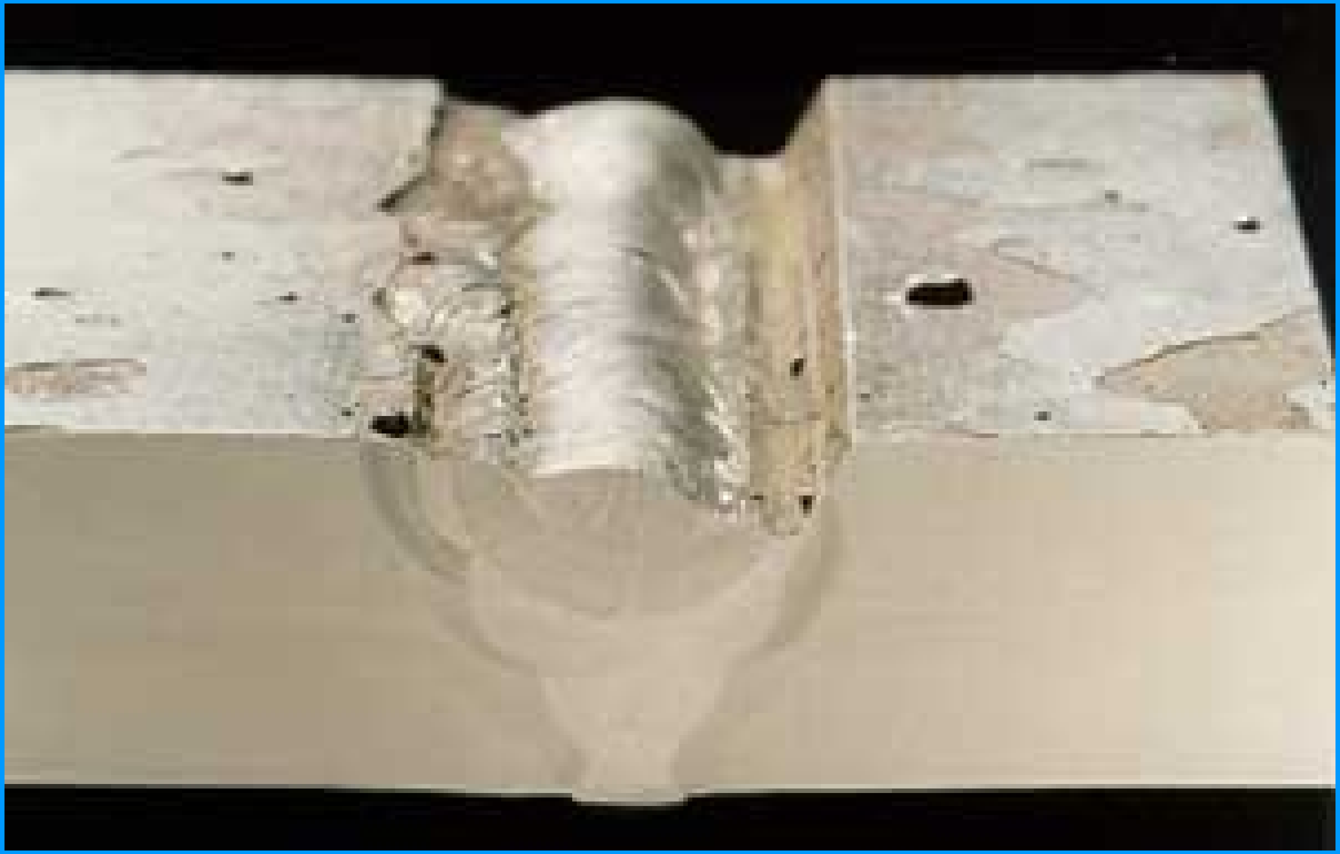
Root concavity -

Overlap - The protrusion of weld metal beyond the weld toe or weld root. There may be fusion problem.

Undercut - A groove melted into the base metal adjacent to the weld toe or weld root and left unfilled by weld metal.



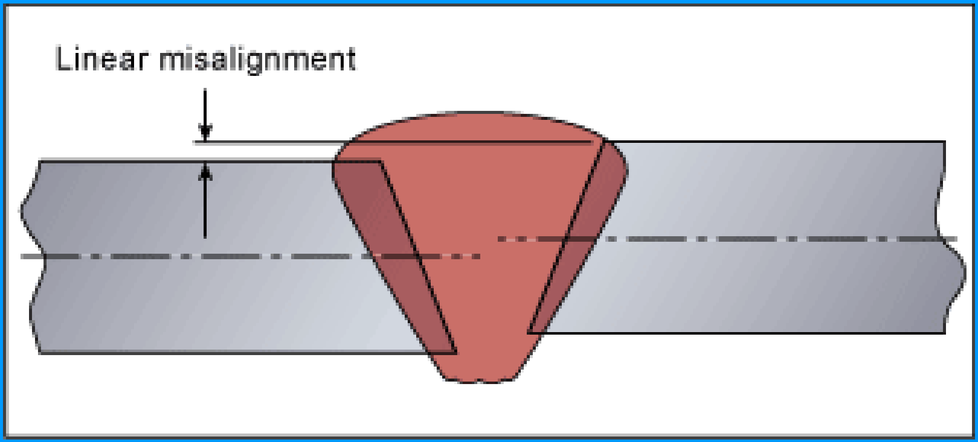


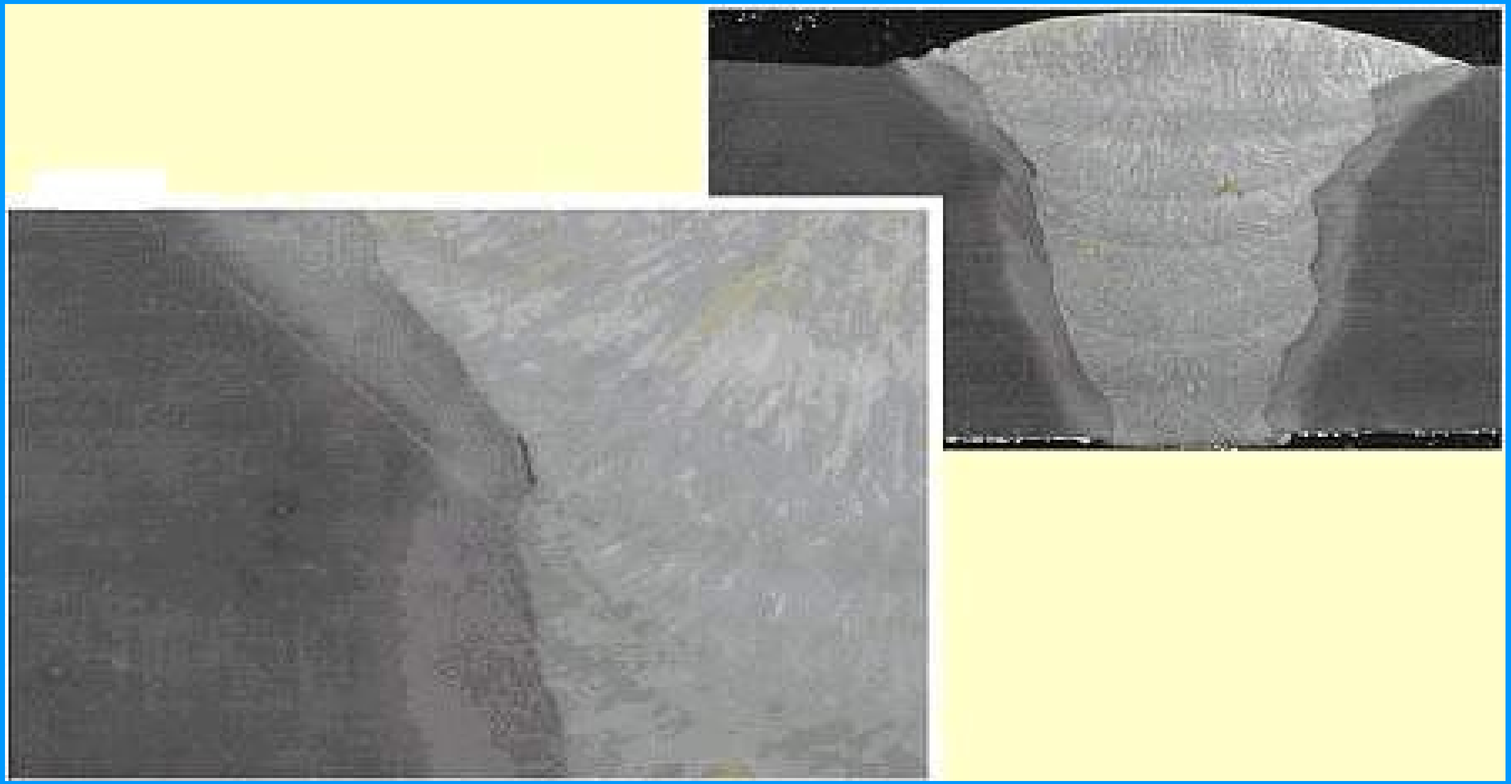


Undercut - A groove melted into the base metal adjacent to the weld toe or weld root and left unfilled by weld metal.

Clean weld but irregular melting of edges because of high welding current produce undercuts.

Misalignment -





Lack of side wall fusion

Lack of complete **fusion** or incomplete penetration are internal planar discontinuities difficult to detect and evaluate but most dangerous especially if low Impact Strength and elevated Transition Temperature are determined for the material in cause and if cold weather may occur to promote low Toughness and brittle fracture

Root LF

Concavity

Side wall LF

Root crack

Display

Porosity

Slag

Undercut

Crack

Display

Excess penetration

Incomplete Fill

Display

Weld defects/imperfections

The characteristic features and principal causes of common weld defects are described. General guidelines on best practice are given so that welders can minimise the risk of imperfections during fabrication.

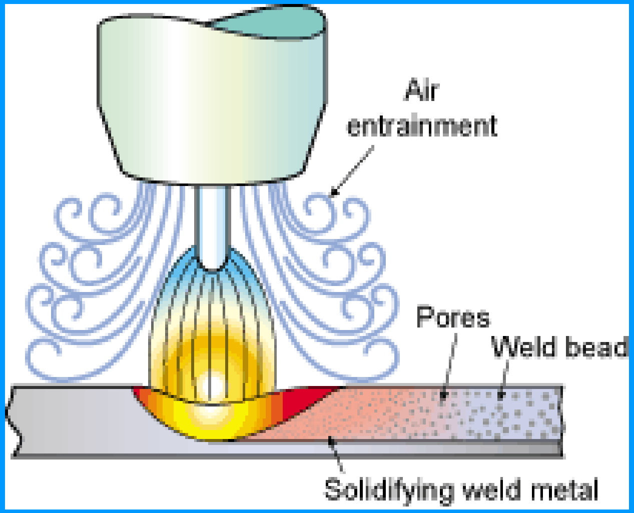
- Weld defects / imperfections - incomplete root fusion or penetration
- Weld defects / imperfections in welds - lack of sidewall and inter-run fusion
- Defects / imperfections in welds - porosity
- Defects / imperfections in welds - slag inclusions
- Defects - solidification cracking
- Defects - hydrogen cracks in steels - identification
- Defects - hydrogen cracks in steels - prevention and best practice
- Defects - lamellar tearing
- Defects - reheat cracking

POROSITY

Identification

Porosity is the presence of cavities in the weld metal caused by the freezing in of gas released from the weld pool as it solidifies. The porosity can take several forms:

- distributed
- surface breaking pores
- wormhole
- crater pipes



Cause and prevention

Distributed porosity and surface pores

Distributed porosity *(Fig. 1)* is normally found as fine pores throughout the weld bead. Surface breaking pores *(Fig. 2)* usually indicate a large amount of distributed porosity

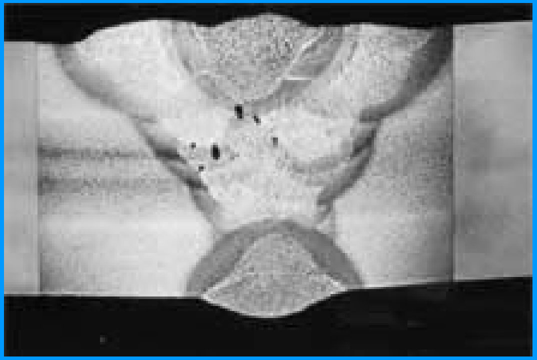


Fig. 1. Uniformly distributed porosity

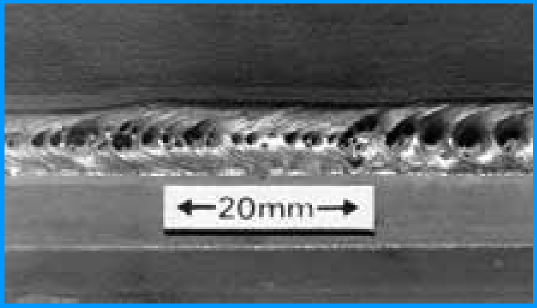


Fig. 2. Surface breaking pores (T fillet weld in primed plate)

POROSITY

Prevention

The gas source should be identified and removed as follows:

Air entrainment

- seal any air leak
- avoid weld pool turbulence
- use filler with adequate level of deoxidants
- reduce excessively high gas flow
- avoid draughts

Hydrogen

- dry the electrode and flux
- clean and degrease the workpiece surface

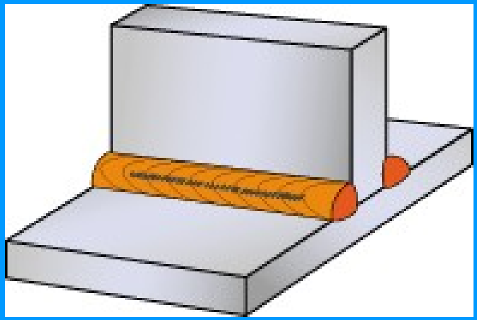
Surface coatings

- clean the joint edges immediately before welding
- check that the weldable primer is below the recommended maximum thickness

POROSITY

Wormholes

Elongated pores or wormholes



Characteristically, wormholes are elongated pores *(Fig. 3)* which produce a herring bone appearance on the radiograph.

Cause

Wormholes are indicative of a large amount of gas being formed which is then trapped in the solidifying weld metal. Excessive gas will be formed from gross surface contamination or very thick paint or primer coatings. Entrapment is more likely in crevices such as the gap beneath the vertical member of a horizontal-vertical, T joint which is fillet welded on both sides.

When welding T joints in primed plates it is essential that the coating thickness on the edge of the vertical member is not above the manufacturer's recommended maximum, typically 20µ, through over-spraying.

Prevention

Eliminating the gas and cavities prevents wormholes.

Gas generation

- clean the workpiece surfaces
- remove any coatings from the joint area
- check the primer thickness is below the manufacturer's maximum

Joint geometry

- avoid a joint geometry which creates a cavity

POROSITY

Crater pipe

A crater pipe forms during the final solidified weld pool and is often associated with some gas porosity.

Cause

This imperfection results from shrinkage on weld pool solidification. Consequently, conditions which exaggerate the liquid to solid volume change will promote its formation. Switching off the welding current will result in the rapid solidification of a large weld pool. In TIG welding, autogenous techniques, or stopping the wire before switching off the welding current, will cause crater formation and the pipe imperfection.

Prevention

Crater pipe imperfection can be prevented by removing the stop or by welder technique.

Removal of stop

- use run-off tag in butt joints
- grind out the stop before continuing with the next electrode or depositing the subsequent weld run

Welder technique

- progressively reduce the welding current to reduce the weld pool size
- add filler (TIG) to compensate for the weld pool shrinkage

Porosity susceptibility of materials

Gases likely to cause porosity in the commonly used range of materials are listed in the Table.

Principal gases causing porosity and recommended cleaning methods

Material	Gas	Cleaning
C Mn steel	Hydrogen, Nitrogen and Oxygen	Grind to remove scale coatings
Stainless steel	Hydrogen	Degrease + wire brush + degrease
Aluminium and alloys	Hydrogen	Chemical clean + wire brush + degrease + scrape
Copper and alloys	Hydrogen, Nitrogen	Degrease + wire brush + degrease
Nickel and alloys	Nitrogen	Degrease + wire brush + degrease

POROSITY

Detection and remedial action

If the imperfections are surface breaking, they can be detected using a penetrant or magnetic particle inspection technique. For sub surface imperfections, detection is by radiography or ultrasonic inspection. Radiography is normally more effective in detecting and characterising porosity imperfections. However, detection of small pores is difficult especially in thick sections.

Remedial action normally needs removal by localised gouging or grinding but if the porosity is widespread, the entire weld should be removed. The joint should be re-prepared and re-welded as specified in the agreed procedure.

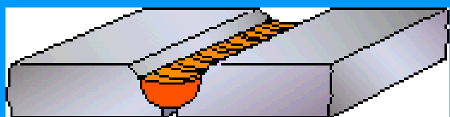
INCOMPLETE ROOT FUSION OR PENETRATION

Identification

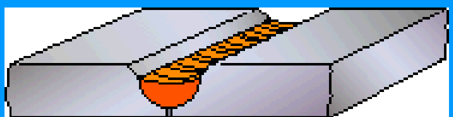
Incomplete root fusion is when the weld fails to fuse one side of the joint in the root. Incomplete root penetration occurs when both sides of the joint are unfused. Typical imperfections can arise in the following situations:

- an excessively thick root face in a butt weld (Fig. 1a)
- too small a root gap (Fig. 1b)
- misplaced welds (Fig. 1c)
- failure to remove sufficient metal in cutting back to sound metal in a double sided weld (Fig. 1d)
- incomplete root fusion when using too low an arc energy (heat) input (Fig. 1e)
- too small a bevel angle,
- too large an electrode in MMA welding (Fig 2)

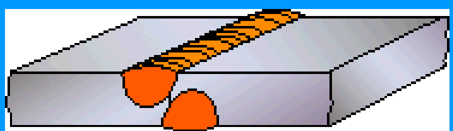
Fig. 1 Causes of incomplete root fusion



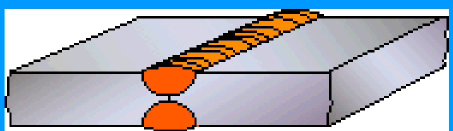
a)



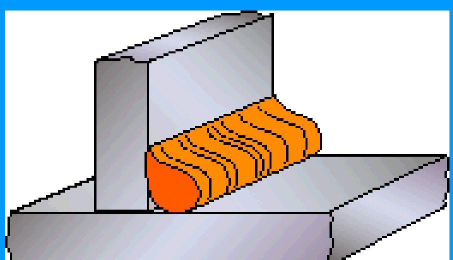
b)



c)



d)

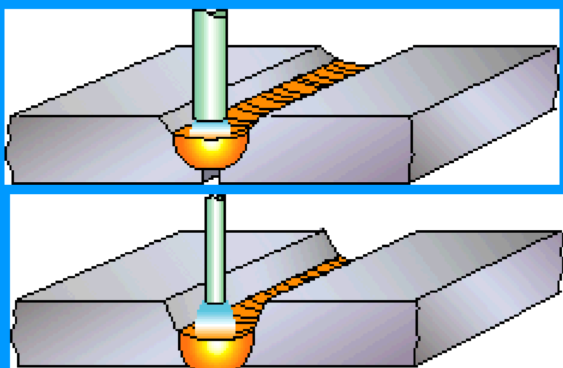


e)

a) Excessively thick root face
b) Too small a root gap
c) Misplaced welds
d) Power input too low
e) Arc (heat) input too low

INCOMPLETE ROOT FUSION OR PENETRATION

Fig. 2 Effect of electrode size on root fusion



a)

b)

a) Large diameter electrode
b) Small diameter electrode

INCOMPLETE ROOT FUSION OR PENETRATION

Causes

These types of imperfection are more likely in consumable electrode processes (MIG, MMA and submerged arc welding) where the weld metal is 'automatically' deposited as the arc consumes the electrode wire or rod. The welder has limited control of weld pool penetration independent of depositing weld metal. Thus, the non consumable electrode TIG process in which the welder controls the amount of filler material independent of penetration is less prone to this type of defect.

In MMA welding, the risk of incomplete root fusion can be reduced by using the correct welding parameters and electrode size to give adequate arc energy input and deep penetration. Electrode size is also important in that it should be small enough to give adequate access to the root, especially when using a small bevel angle (Fig 2). It is common practice to use a 4mm diameter electrode for the root so the welder can manipulate the electrode for penetration and control of the weld pool. However, for the fill passes where penetration requirements are less critical, a 5mm diameter electrode is used to achieve higher deposition rates.

In MIG welding, the correct welding parameters for the material thickness, and a short arc length, should give adequate weld bead penetration. Too low a current level for the size of root face will give inadequate weld penetration. Too high a level, causing the welder to move too quickly, will result in the weld pool bridging the root without achieving adequate penetration.

It is also essential that the correct root face size and bevel angles are used and that the joint gap is set accurately. To prevent the gap from closing, adequate tacking will be required.

INCOMPLETE ROOT FUSION OR PENETRATION

Best practice in prevention

The following techniques can be used to prevent lack of root fusion:

- In TIG welding, do not use too large a root face and ensure the welding current is sufficient for the weld pool to penetrate fully the root
- In MMA welding, use the correct current level and not too large an electrode size for the root
- In MIG welding, use a sufficiently high welding current level but adjust the arc voltage to keep a short arc length
- When using a joint configuration with a joint gap, make sure it is of adequate size and does not close up during welding
- Do not use too high a current level causing the weld pool to bridge the gap without fully penetrating the root.

INCOMPLETE ROOT FUSION OR PENETRATION

Acceptance standards

The limits for lack of penetration are specified in BS EN 25817 (ISO 5817) for the three quality levels.
Lack of root penetration is not permitted for Quality Level B (stringent). For Quality Levels C (intermediate) and D (moderate) long lack of penetration imperfections are not permitted but short imperfections are permitted.
Incomplete root penetration is not permitted in the manufacture of pressure vessels but is allowable in the manufacture of pipework depending on material and wall thickness.

Remedial actions

If the root cannot be directly inspected, for example using a penetrant or magnetic particle inspection technique, detection is by radiography or ultrasonic inspection. Remedial action will normally require removal by gouging or grinding to sound metal, followed by re-welding in conformity with the original procedure.

Relevant standards

EN 25817:1992 (ISO 5817) Arc welded joints in steel - Guidance on quality levels for imperfections.
EN 30042: 1994 Arc welded joints in aluminium and its weldable alloys - Guidance on quality levels for imperfections.

Lack of sidewall and inter-run fusion

Identification

Lack of fusion imperfections can occur when the weld metal fails

- to fuse completely with the sidewall of the joint (Fig. 1)
- to penetrate adequately the previous weld bead (Fig. 2).

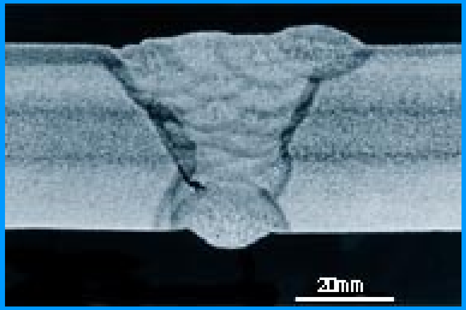


Fig. 1. Lack of side wall fusion

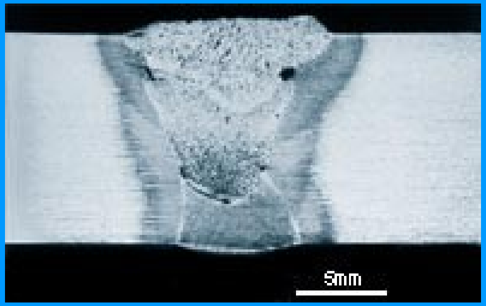


Fig. 2. Lack of inter-run fusion

lack of sidewall and inter-run fusion

Causes

The principal causes are too narrow a joint preparation, incorrect welding parameter settings, poor welder technique and magnetic arc blow. Insufficient cleaning of oily or scaled surfaces can also contribute to lack of fusion. These types of imperfection are more likely to happen when welding in the vertical position. **Joint preparation**

Too narrow a joint preparation often causes the arc to be attracted to one of the side walls causing lack of side wall fusion on the other side of the joint or inadequate penetration into the previously deposited weld bead. Too great an arc length may also increase the risk of preferential melting along one side of the joint and cause shallow penetration. In addition, a narrow joint preparation may prevent adequate access into the joint. For example, this happens in MMA welding when using a large diameter electrode, or in MIG welding where an allowance should be made for the size of the nozzle.

Welding parameters

It is important to use a sufficiently high current for the arc to penetrate into the joint sidewall. Consequently, too high a welding speed for the welding current will increase the risk of these imperfections. However, too high a current or too low a welding speed will cause weld pool flooding ahead of the arc resulting in poor or non-uniform penetration.

Welder technique

Poor welder technique such as incorrect angle or manipulation of the electrode/welding gun, will prevent adequate fusion of the joint sidewall. Weaving, especially dwelling at the joint sidewall, will enable the weld pool to wash into the parent metal, greatly improving sidewall fusion. It should be noted that the amount of weaving may be restricted by the welding procedure specification limiting the arc energy input, particularly when welding alloy or high notch toughness steels.

Magnetic arc blow

When welding ferromagnetic steels lack of fusion imperfections can be caused through uncontrolled deflection of the arc, usually termed arc blow. Arc deflection can be caused by distortion of the magnetic field produced by the arc current (Fig. 3), through:

- residual magnetism in the material through using magnets for handling
- earth's magnetic field, for example in pipeline welding
- position of the current return

The effect of welding past the current return cable which is bolted to the centre of the place is shown in Fig. 4. The interaction of the magnetic field surrounding the arc and that generated by the current flow in the plate to the current return cable is sufficient to deflect the weld bead. Distortion of the arc current magnetic field can be minimised by positioning the current return so that welding is always towards or away from the clamp and, in MMA welding, by using AC instead of DC. Often the only effective means is to demagnetise the steel before welding.

lack of sidewall and inter-run fusion

Fig. 3. Interaction of magnetic forces causing arc deflection

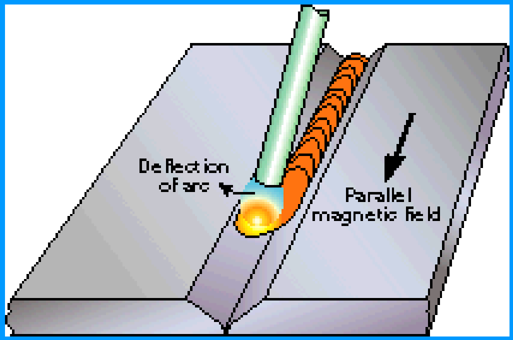


Fig. 4. Weld bead deflection in DC MMA welding caused by welding past the current return connection

Best practice in prevention

The following fabrication techniques can be used to prevent formation of lack of sidewall fusion imperfections:

- use a sufficiently wide joint preparation
- select welding parameters (high current level, short arc length, not too high a welding speed) to promote penetration into the joint side wall without causing flooding
- ensure the electrode/gun angle and manipulation technique will give adequate side wall fusion
- use weaving and dwell to improve side wall fusion providing there are no heat input restrictions
- if arc blow occurs, reposition the current return, use AC (in MMA welding) or demagnetise the steel

Acceptance standards

The limits for incomplete fusion imperfections in arc welded joints in steel are specified in BS EN 25817 (ISO 5817) for the three quality levels (see Table). These types of imperfection are not permitted for Quality Level B (stringent) and C (intermediate). For Quality level D (moderate) they are only permitted providing they are intermittent and not surface breaking.

For arc welded joints in aluminium, long imperfections are not permitted for all three quality levels. However, for quality levels C and D, short imperfections are permitted but the total length of the imperfections is limited depending on the butt weld or the fillet weld throat thickness.

lack of sidewall and inter-run fusion

Acceptance limits for specific codes and application standards

Application	Code/Standard	Acceptance limit
Steel	ISO 5817:1992	Level B and C not permitted. Level D intermittent and not surface breaking.
Aluminium	ISO 10042:1992	Levels B, C, D. Long imperfections not permitted. Levels C and D. Short imperfections permitted.
Pressure vessels	BS5500:1997	Not permitted
Storage tanks	BS2654:1989	Not permitted
Pipework	BS2633:1987	'l' not greater than 15mm (depending on wall thickness)
Line pipe	API 1104:1983	'l' not greater than 25mm (less when weld length <300mm)

Detection and remedial action

If the imperfections are surface breaking, they can be detected using a penetrant or magnetic particle inspection technique. For sub-surface imperfections, detection is by radiography or ultrasonic inspection. Ultrasonic inspection is normally more effective than radiography in detecting lack of inter-run fusion imperfections.

Remedial action will normally require their removal by localised gouging, or grinding, followed by re-welding as specified in the agreed procedure.If lack of fusion is a persistent problem, and is not caused by magnetic arc blow, the welding procedures should be amended or the welders retrained.

slag inclusions

Identification

Fig. 1. Radiograph of a butt weld showing two slag lines in the weld root

Slag is normally seen as elongated lines either continuous or discontinuous along the length of the weld. This is readily identified in a radiograph, *Fig 1.* Slag inclusions are usually associated with the flux processes, ie MMA, FCA and submerged arc, but they can also occur in MIG welding.

slag inclusions

Causes

As slag is the residue of the flux coating, it is principally a deoxidation product from the reaction between the flux, air and surface oxide. The slag becomes trapped in the weld when two adjacent weld beads are deposited with inadequate overlap and a void is formed. When the next layer is deposited, the entrapped slag is not melted out. Slag may also become entrapped in cavities in multi-pass welds through excessive undercut in the weld toe or the uneven surface profile of the preceding weld runs, *Fig 2.*

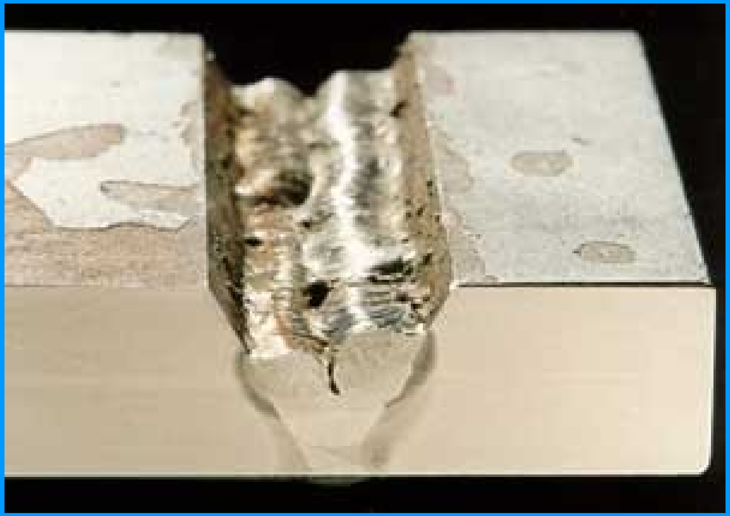
As they both have an effect on the ease of slag removal, the risk of slag imperfections is influenced by

- Type of flux
- Welder technique

The type and configuration of the joint, welding position and access restrictions all have an influence on the risk of slag imperfections.

slag inclusions

Fig. 2. The influence of welder technique on the risk of slag inclusions when welding with a basic MMA (7018) electrode



a) Poor (convex) weld bead profile resulted in pockets of slag being trapped between the weld runs

b) Smooth weld bead profile allows the slag to be readily removed between runs

slag inclusions

Type of flux

One of the main functions of the flux coating in welding is to produce a slag which will flow freely over the surface of the weld pool to protect it from oxidation. As the slag affects the handling characteristics of the MMA electrode, its surface tension and freezing rate can be equally important properties. For welding in the flat and horizontal/vertical positions, a relatively viscous slag is preferred as it will produce a smooth weld bead profile, is less likely to be trapped and, on solidifying, is normally more easily removed. For vertical welding, the slag must be more fluid to flow out to the weld pool surface but have a higher surface tension to provide support to the weld pool and be fast freezing.

The composition of the flux coating also plays an important role in the risk of slag inclusions through its effect on the weld bead shape and the ease with which the slag can be removed. A weld pool with low oxygen content will have a high surface tension producing a convex weld bead with poor parent metal wetting. Thus, an oxidising flux, containing for example iron oxide, produces a low surface tension weld pool with a more concave weld bead profile, and promotes wetting into the parent metal. High silicate flux produces a glass-like slag, often self detaching. Fluxes with a lime content produce an adherent slag which is difficult to remove. The ease of slag removal for the principal flux types are:

- Rutile or acid fluxes - large amounts of titanium oxide (rutile) with some silicates. The oxygen level of the weld pool is high enough to give flat or slightly convex weld bead. The fluidity of the slag is determined by the calcium fluoride content. Fluoride-free coatings designed for welding in the flat position produce smooth bead profiles and an easily removed slag. The more fluid fluoride slag designed for positional welding is less easily removed.

- Basic fluxes - the high proportion of calcium carbonate (limestone) and calcium fluoride (fluospar) in the flux reduces the oxygen content of the weld pool and therefore its surface tension. The slag is more fluid than that produced with the rutile coating. Fast freezing also assists welding in the vertical and overhead positions but the slag coating is more difficult to remove.

Consequently, the risk of slag inclusions is significantly greater with basic fluxes due to the inherent convex weld bead profile and the difficulty in removing the slag from the weld toes especially in multi-pass welds

slag inclusions

Welder technique

Welding technique has an important role to play in preventing slag inclusions. Electrode manipulation should ensure adequate shape and degree of overlap of the weld beads to avoid forming pockets which can trap the slag. Thus, the correct size of electrode for the joint preparation, the correct angle to the workpiece for good penetration and a smooth weld bead profile are all essential to prevent slag entrainment.

In multi-pass vertical welding, especially with basic electrodes, care must be taken to fuse out any remaining minor slag pockets and minimise undercut. When using a weave a slight dwell at the extreme edges of the weave will assist sidewall fusion and produce a flatter weld bead profile.

Too high a current together with a high welding speed will also cause sidewall undercutting which makes slag removal difficult.

It is crucial to remove all slag before depositing the next run. This can be done between runs by grinding, light chipping or wire brushing. Cleaning tools must be identified for different materials eg steels or stainless steels, and segregated.

When welding with difficult electrodes, in narrow vee butt joints or when the slag is trapped through undercutting, it may be necessary to grind the surface of the weld between layers to ensure complete slag removal.

slag inclusions

Best practice

The following techniques can be used to prevent slag inclusions:

- Use welding techniques to produce smooth weld beads and adequate inter-run fusion to avoid forming pockets to trap the slag
- Use the correct current and travel speed to avoid undercutting the sidewall which will make the slag difficult to remove
- Remove slag between runs paying particular attention to removing any slag trapped in crevices
- Use grinding when welding difficult butt joints otherwise wire brushing or light chipping may be sufficient to remove the slag.

slag inclusions

Acceptance standards

Slag and flux inclusions are linear defects but because they do not have sharp edges compared with cracks, they may be permitted by specific standards and codes. The limits in steel are specified in BE EN 25817 (ISO 5817) for the three quality levels. Long slag imperfections are not permitted in both butt and fillet welds for Quality Level B (stringent) and C (moderate). For Quality Level D, butt welds can have imperfections providing their size is less than half the nominal weld thickness. Short slag related imperfections are permitted in all three quality levels with limits placed on their size relative to the butt weld thickness or nominal fillet weld throat thickness.

Defects - solidification cracking

Weld repair on a cast iron exhaust manifold

A crack may be defined as a local discontinuity produced by a fracture which can arise from the stresses generated on cooling or acting on the structure. It is the most serious type of imperfection found in a weld and should be removed. Cracks not only reduce the strength of the weld through the reduction in the cross section thickness but also can readily propagate through stress concentration at the tip, especially under impact loading or during service at low temperature

solidification cracking

Identification

Visual appearance

Solidification cracks are normally readily distinguished from other types of cracks due to the following characteristic factors:

- they occur only in the weld metal
- they normally appear as straight lines along the centreline of the weld bead, as shown in Fig. 1, but may occasionally appear as transverse cracking depending on the solidification structure
- solidification cracks in the final crater may have a branching appearance
- as the cracks are 'open', they are easily visible with the naked eye

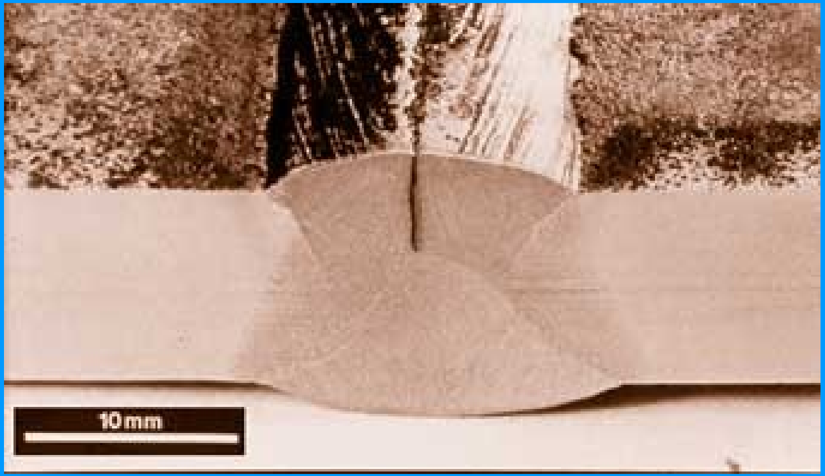


Fig. 1 Solidification crack along the centre line of the weld

On breaking open the weld, the crack surface in steel and nickel alloys may have a blue oxidised appearance, showing that they were formed while the weld metal was still hot.

Causes

The overriding cause of solidification cracking is that the weld bead in the final stage of solidification has insufficient strength to withstand the contraction stresses generated as the weld pool solidifies. Factors which increase the risk include:

- insufficient weld bead size or shape
- welding under high restraint
- material properties such as a high impurity content or a relatively large amount of shrinkage on solidification.

Joint design can have a significant influence on the level of residual stresses. Large gaps between component parts will increase the strain on the solidifying weld metal, especially if the depth of penetration is small. Therefore, weld beads with a small depth-to-width ratio, such as formed in bridging a large gap with a wide, thin bead, will be more susceptible to solidification cracking, as shown in Fig. 2. In this case, the centre of the weld which is the last part to solidify, is a narrow zone with negligible cracking resistance.

solidification cracking

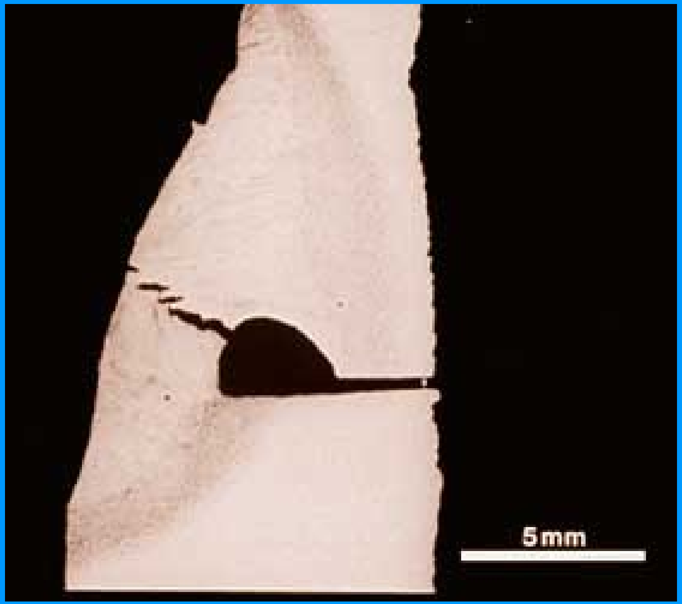


Fig. 2 Weld bead penetration too small

Segregation of impurities to the centre of the weld also encourages cracking. Concentration of impurities ahead of the solidifying front weld forms a liquid film of low freezing point which, on solidification, produces a weak zone. As solidification proceeds, the zone is likely to crack as the stresses through normal thermal contraction build up. An elliptically shaped weld pool is preferable to a tear drop shape. Welding with contaminants such as cutting oils on the surface of the parent metal will also increase the build up of impurities in the weld pool and the risk of cracking.

As the compositions of the plate and the filler determine the weld metal composition they will, therefore, have a substantial influence on the susceptibility of the material to cracking.

solidification cracking

Steels

Cracking is associated with impurities, particularly sulphur and phosphorus, and is promoted by carbon whereas manganese and silicon can help to reduce the risk. To minimise the risk of cracking, fillers with low carbon and impurity levels and a relatively high manganese content are preferred. As a general rule, for carbon-manganese steels, the total sulphur and phosphorus content should be no greater than 0.06%.

Weld metal composition is dominated by the consumable and as the filler is normally cleaner than the metal being welded, cracking is less likely with low dilution processes such as MMA and MIG. Plate composition assumes greater importance in high dilution situations such as when welding the root in butt welds, using an autogenous welding technique like TIG, or a high dilution process such as submerged arc welding.

In submerged arc welds, as described in BS 5135 (Appendix F), the cracking risk may be assessed by calculating the Units of Crack Susceptibility (UCS) from the weld metal chemical composition (weight %):

$UCS = 230C^* + 190S + 75P + 45Nb - 12.3Si - 5.4Mn - 1$

C^* = carbon content or 0.08 whichever is higher

Although arbitrary units, a value of <10 indicates high cracking resistance whereas >30 indicates a low resistance. Within this range, the risk will be higher in a weld run with a high depth to width ratio, made at high welding speeds or where the fit-up is poor. For fillet welds, runs having a depth to width ratio of about one, UCS values of 20 and above will indicate a risk of cracking. For a butt weld, values of about 25 UCS are critical. If the depth to width ratio is decreased from 1 to 0.8, the allowable UCS is increased by about nine. However, very low depth to width ratios, such as obtained when penetration into the root is not achieved, also promote cracking.

Aluminium

The high thermal expansion (approximately twice that of steel) and substantial contraction on solidification (typically 5% more than in an equivalent steel weld) means that aluminium alloys are more prone to cracking. The risk can be reduced by using a crack resistant filler (usually from the 4xxx and 5xxx series alloys) but the disadvantage is that the resulting weld metal is likely to have non-matching properties such as a lower strength than the parent metal.

Austenitic Stainless Steel

A fully austenitic stainless steel weld is more prone to cracking than one containing between 5-10% of ferrite. The beneficial effect of ferrite has been attributed to its capacity to dissolve harmful impurities which would otherwise form low melting point segregates and consequently interdendritic cracks. Therefore the choice of

Best practice in avoiding solidification cracking

Apart from the choice of material and filler, the principal techniques for minimising the risk of welding solidification cracking are:

- •Control joint fit-up to reduce gaps.
- •Before welding, clean off all contaminants from the material
- •Ensure that the welding sequence will not lead to a build-up of thermally induced stresses.
- •Select welding parameters and technique to produce a weld bead with an adequate depth to width ratio, or with sufficient throat thickness (fillet weld), to ensure the weld bead has sufficient resistance to the solidification stresses (recommend a depth to width ratio of at least 0.5:1).
- •Avoid producing too large a depth to width ratio which will encourage segregation and excessive transverse strains in restrained joints. As a general rule, weld beads whose depth to weld ratio exceeds 2:1 will be prone to solidification cracking.
- •Avoid high welding speeds (at high current levels) which increase the amount of segregation and the stress level across the weld bead.
- •At the run stop, ensure adequate filling of the crater to avoid an unfavourable concave shape.

Acceptance standards

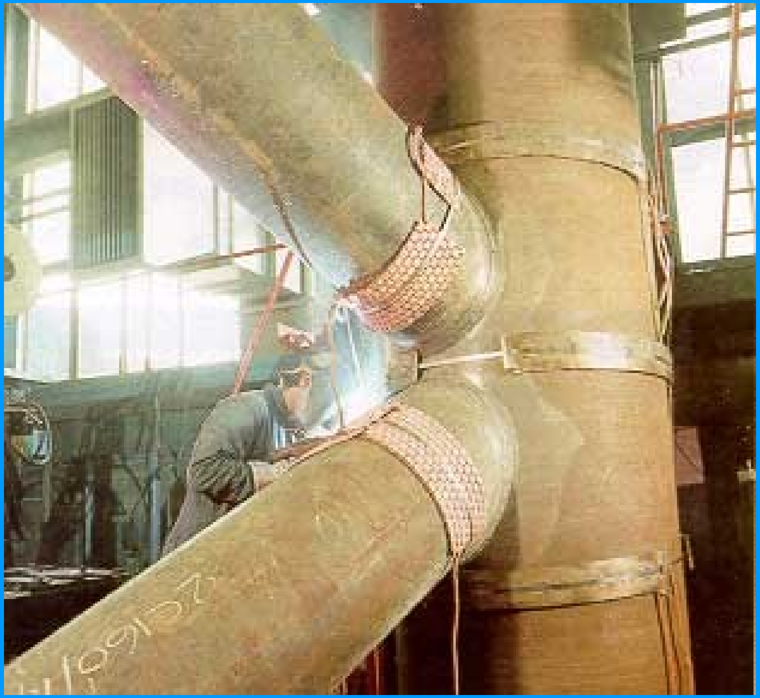
As solidification cracks are linear imperfections with sharp edges, they are not permitted for welds meeting the quality levels B, C and D in accordance with the requirements of BS EN 25817 (ISO 5817). Crater cracks are permitted for quality level D.

Detection and remedial action

Surface breaking solidification cracks can be readily detected using visual examination, liquid penetrant or magnetic particle testing techniques. Internal cracks require ultrasonic or radiographic examination techniques.

Most codes will specify that all cracks should be removed. A cracked component should be repaired by removing the cracks with a safety margin of approximately 5mm beyond the visible ends of the crack. The excavation is then re-welded using a filler which will not produce a crack sensitive deposit.

Hydrogen cracks in steels - identification



Preheating to avoid hydrogen cracking

Hydrogen cracking may also be called cold cracking or delayed cracking. The principal distinguishing feature of this type of crack is that it occurs in ferritic steels, most often immediately on welding or after a short time after welding.

Identification

Visual appearance

Hydrogen cracks can be usually be distinguished due to the following characteristics:

- •In C-Mn steels, the crack will normally originate in the heat affected zone (HAZ) but may extend into the weld metal *(Fig 1).*
- •Cracks can also occur in the weld bead, normally transverse to the welding direction at an angle of 45° to the weld surface. They are essentially straight, follow a jagged path but may be non-branching.
- •In low alloy steels, the cracks can be transverse to the weld, perpendicular to the weld surface, but are non-branching and essentially planar.

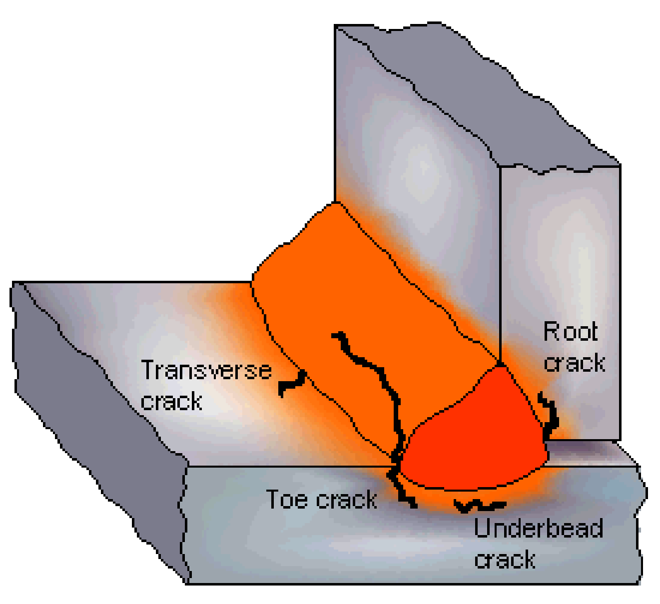


Fig. 1 Hydrogen cracks originating in the HAZ (note, the type of cracks shown would not be expected to form in the same Weldment)

On breaking open the weld (prior to any heat treatment), the surface of the cracks will normally not be oxidised,
even if they are surface breaking, indicating they were formed when the weld was at or near ambient temperature. A slight blue tinge may be seen from the effects of preheating or welding heat.

Hydrogen cracks in steels - identification

Metallography

Cracks which originate in the HAZ are usually associated with the coarse grain region, *(Fig 2).* The cracks can be intergranular, transgranular or a mixture. Intergranular cracks are more likely to occur in the harder HAZ structures formed in low alloy and high carbon steels. Transgranular cracking is more often found in C-Mn steel structures.

In fillet welds, cracks in the HAZ are usually associated with the weld root and parallel to the weld. In butt welds, the HAZ cracks are normally oriented parallel to the weld bead.

Fig. 2 Crack along the coarse grain structure in the HAZ

Hydrogen cracks in steels - identification

Causes

There are three factors which combine to cause cracking:

- hydrogen generated by the welding process
- a hard brittle structure which is susceptible to cracking
- residual tensile stresses acting on the welded joint

Cracking is caused by the diffusion of hydrogen to the highly stressed, hardened part of the weldment.

In C-Mn steels, because there is a greater risk of forming a brittle microstructure in the HAZ, most of the hydrogen cracks are to be found in the parent metal. With the correct choice of electrodes, the weld metal will have a lower carbon content than the parent metal and, hence, a lower carbon equivalent (CE). However, transverse weld metal cracks can occur especially when welding thick section components.

In low alloy steels, as the weld metal structure is more susceptible than the HAZ, cracking may be found in the weld bead.

The effects of specific factors on the risk of cracking are::

- weld metal hydrogen
- parent material composition
- parent material thickness
- stresses acting on the weld
- heat input

Hydrogen cracks in steels - identification

Weld metal hydrogen content

The principal source of hydrogen is the moisture contained in the flux ie the coating of MMA electrodes, the flux in cored wires and the flux used in submerged arc welding. The amount of hydrogen generated is determined mainly by the electrode type. Basic electrodes normally generate less hydrogen than rutile and cellulosic electrodes.

It is important to note that there can be other significant sources of hydrogen eg moisture from the atmosphere or from the material where processing or service history has left the steel with a significant level of hydrogen. Hydrogen may also be derived from the surface of the material or the consumable.

Sources of hydrogen will include:

- oil, grease and dirt
- rust
- paint and coatings
- cleaning fluids

Parent metal composition

This will have a major influence on hardenability and, with high cooling rates, the risk of forming a hard brittle structure in the HAZ. The hardenability of a material is usually expressed in terms of its carbon content or, when other elements are taken into account, its carbon equivalent (CE) value.

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

The higher the CE value, the greater the risk of hydrogen cracking. Generally, steels with a CE value of <0.4 are not susceptible to HAZ hydrogen cracking as long as low hydrogen welding consumables or processes are used.

Parent material thickness

Material thickness will influence the cooling rate and therefore the hardness level, microstructure produced in the HAZ and the level of hydrogen retained in the weld.

The 'combined thickness' of the joint, ie the sum of the thicknesses of material meeting at the joint line, will determine, together with the joint geometry, the cooling rate of the HAZ and its hardness. Consequently, as shown in *Fig. 3,* a fillet weld will have a greater risk than a butt weld in the same material thickness.

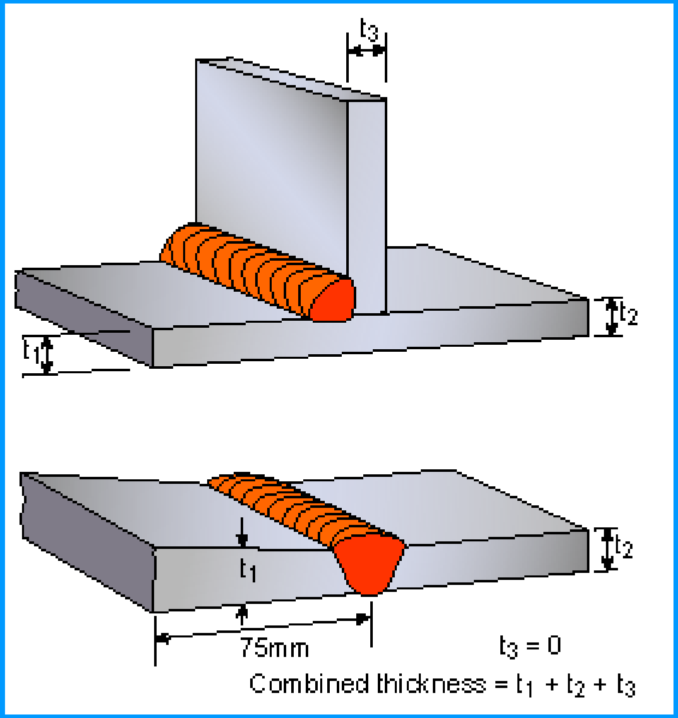


Fig.3 Combined thickness measurements for butt and fillet joints

Hydrogen cracks in steels - identification

Stresses acting on the weld

The stresses generated across the welded joint as it contracts will be greatly influenced by external restraint, material thickness, joint geometry and fit-up. Areas of stress concentration are more likely to initiate a crack at the toe and root of the weld.

Poor fit-up in fillet welds markedly increases the risk of cracking. The degree of restraint acting on a joint will generally increase as welding progresses due to the increase in stiffness of the fabrication.

Heat input

The heat input to the material from the welding process, together with the material thickness and preheat temperature, will determine the thermal cycle and the resulting microstructure and hardness of both the HAZ and weld metal.

A high heat input will reduce the hardness level.

Heat input per unit length is calculated by multiplying the arc energy by an arc efficiency factor according to the following formula:

$$\frac{V \times A \times 60 \times k}{1000 \times S} \ \text{kJ/mm}$$

V = arc voltage (V)

A = welding current (A)

S = welding speed (mm/min)

k = thermal efficiency factor

Hydrogen cracks in steels - identification

In calculating heat input, the arc efficiency must be taken into consideration. The arc efficiency factors given in BS EN 1011-1: 1998 for the principal arc welding processes, are:

Submerged arc (single wire)	1.0
MMA	0.8
MIG/MAG and flux cored wire	0.8
TIG and plasma	0.6

In MMA welding, heat input is normally controlled by means of the run-out length from each electrode which is proportional to the heat input. As the run-out length is the length of weld deposited from one electrode, it will depend upon the welding technique eg weave width /dwell

Hydrogen cracks in steels - prevention and best practice

Preheating of a jacket structure to prevent hydrogen cracking

Hydrogen cracks in steels - prevention and best practice

Preheating, interpass and post heating to prevent hydrogen cracking

There are three factors which combine to cause cracking in arc welding:

- hydrogen generated by the welding process
- a hard brittle structure which is susceptible to cracking
- residual tensile stresses acting on the welded joint

In practice, for a given situation (material composition, material thickness, joint type, electrode composition and heat input), the risk of hydrogen cracking is reduced by heating the joint.

Preheat

Preheat, which slows the cooling rate, allows some hydrogen to diffuse away and prevents a hard, crack-sensitive structure being formed. The recommended levels of preheat for carbon and carbon manganese steel are detailed in BS 5135. (Nb a draft European standard Pr EN 1011-2 is expected to be introduced in 2000). The preheat level may be as high as 200°C for example, when welding thick section steels with a high carbon equivalent (CE) value.

Hydrogen cracks in steels - prevention and best practice

Interpass and post heating

As cracking rarely occurs at temperatures above ambient, maintaining the temperature of the weldment during fabrication is equally important. For susceptible steels, it is usually appropriate to maintain the preheat temperature for a given period, typically between 2 to 3 hours, to enable the hydrogen to diffuse away from the weld area. In crack sensitive situations such as welding higher CE steels or under high restraint conditions, the temperature and heating period should be increased, typically 250-300°C for three to four hours.

Post weld heat treatment (PWHT) may be used immediately on completion of welding ie without allowing the preheat temperature to fall. However, in practice, as inspection can only be carried out at ambient temperature, there is the risk that 'rejectable,' defects will only be found after PWHT. Also, for highly hardenable steels, a second heat treatment may be required to temper the hard microstructure present after the first PWHT.

Under certain conditions, more stringent procedures are needed to avoid cracking than those derived from the nomograms for estimating preheat in BS 5135.

Appendix E of this standard mentions the following conditions:

- high restraint
- thick sections ($>$ approximately 50mm)
- low carbon equivalent steels (CMn steels with C $<$ 0.1% and CE $\leq$ approximately 0.42)
- 'clean' or low sulphur steels (S $\leq$ approximately 0.008%), as a low sulphur and low oxygen content will increase the hardenability of a steel.
- alloyed weld metal where preheat levels to avoid HAZ cracking may be insufficient to protect the weld metal. Low hydrogen processes and consumables should be used. Schemes for predicting the preheat requirements to avoid weld metal cracking generally require the weld metal diffusible hydrogen level and the weld metal tensile strength as input

Hydrogen cracks in steels - prevention and best practice

Use of austenitic and nickel alloy weld metal to prevent cracking

In situations where preheating is impractical, or does not prevent cracking, it will be necessary to use an austenitic consumable. Austenitic stainless steel and nickel electrodes will produce a weld metal which at ambient temperature, has a higher solubility for hydrogen than ferritic steel. Thus, any hydrogen formed during welding becomes locked in the weld metal with very little diffusing to the HAZ on cooling to ambient.

A commonly used austenitic MMA electrode is 23Cr:12Ni (eg from BS 2926:1984). However, as nickel alloys have a lower coefficient of thermal expansion than stainless steel, nickel austenitic electrodes are preferred when welding highly restrained joints to reduce the shrinkage strain. Figure 1 is a general guide on the levels of preheat when using austenitic electrodes. When welding steels with up to 0.2%C, a preheat would not normally be required. However, above 0.4%C a minimum temperature of 150°C will be needed to prevent HAZ cracking. The influence of hydrogen level and the degree of restraint are also illustrated in the figure.

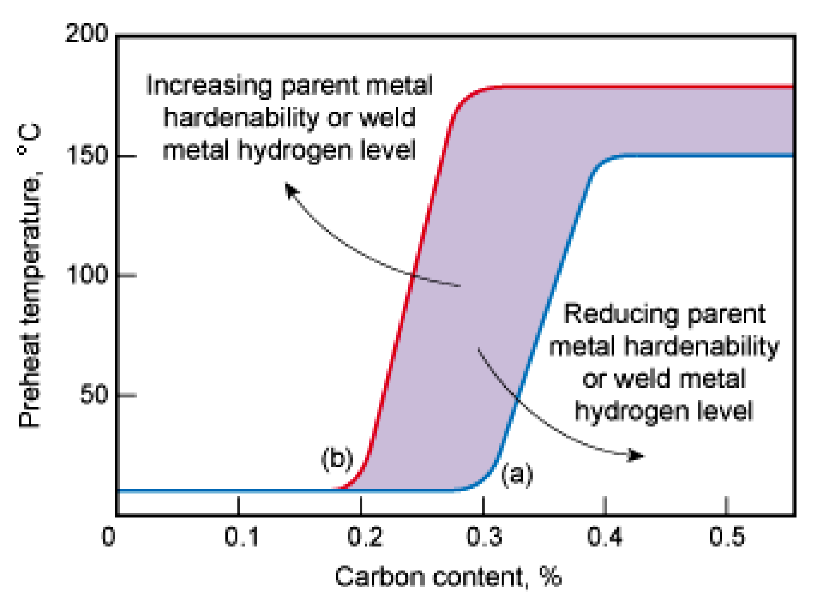


Fig.1 Guide to preheat temperature when using austenitic MMA

electrodes at 1-2kJ/mm
a) low restraint (e.g. material thickness <30mm)
b) high restraint (e.g. material thickness >30mm)

Hydrogen cracks in steels - prevention and best practice

Best practice in avoiding hydrogen cracking

Reduction in weld metal hydrogen

The most effective means of avoiding hydrogen cracking is to reduce the amount of hydrogen generated by the consumable, ie by using a low hydrogen process or low hydrogen electrodes.

Welding processes can be classified as very low, low, medium or high depending on the amount of weld metal hydrogen produced:

Very low	<5ml/100g
Low	5 - 10ml/100g
Medium	10 - 15ml/100g
High	>15ml/100g

Figure 2 illustrates the relative amounts of weld metal hydrogen produced by the major welding processes. MMA, in particular, has the potential to generate a wide range of hydrogen levels. Thus, to achieve the lower values, it is essential that basic electrodes are used and they are baked in accordance with the manufacturer's recommendations. For the MIG process, cleaner wires will be required to achieve very low hydrogen levels.

Hydrogen cracks in steels - prevention and best practice

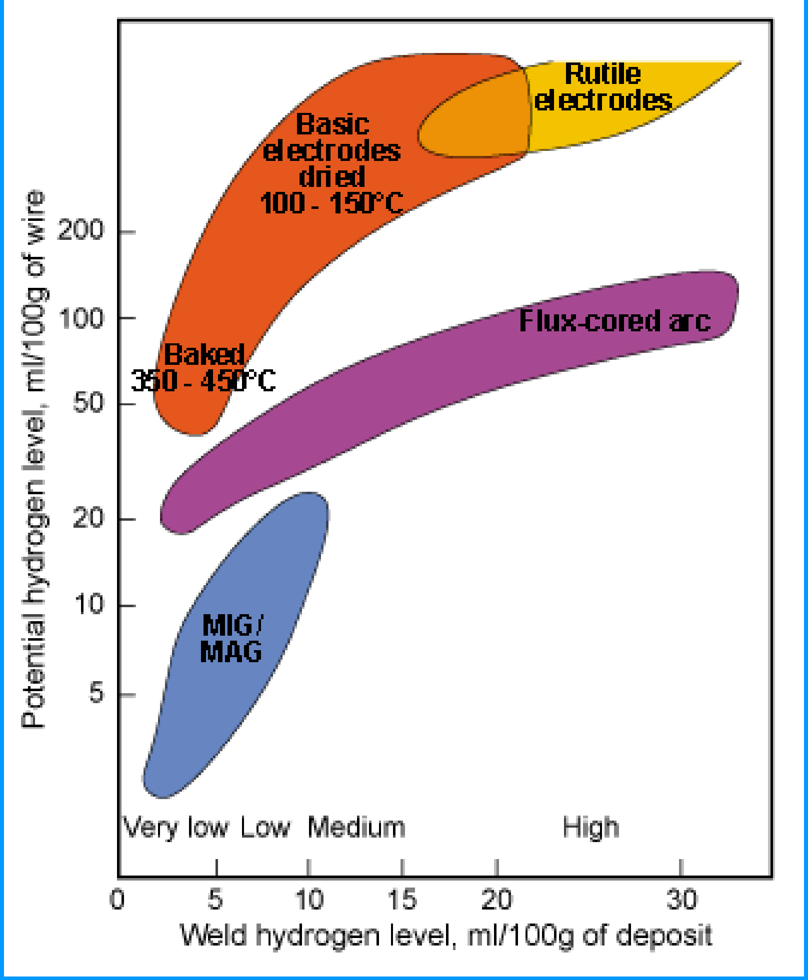


Fig.2 General relationships between potential hydrogen and weld metal hydrogen levels for arc welding processes

Hydrogen cracks in steels - prevention and best practice

General guidelines

The following general guidelines are recommended for the various types of steel but requirements for specific steels should be checked according to BS 5135 or BS EN 1011:

Mild steel (CE <0.4)

- readily weldable, preheat generally not required if low hydrogen processes or electrodes are used
- preheat may be required when welding thick section material, high restraint and with higher levels of hydrogen being generated

C-Mn, medium carbon, low alloy steels (CE 0.4 to 0.5)

- thin sections can be welded without preheat but thicker sections will require low preheat levels and low hydrogen processes or electrodes should be used

Higher carbon and alloyed steels (CE >0.5)

- preheat, low hydrogen processes or electrodes, post weld heating and slow cooling required.

More detailed guidance on the avoidance of hydrogen cracking is described in BS 5135.

Hydrogen cracks in steels - prevention and best practice

Practical Techniques

The following practical techniques are recommended to avoid hydrogen cracking:

- clean the joint faces and remove contaminants such as paint, cutting oils, grease
- use a low hydrogen process if possible
- dry the electrodes (MMA) or the flux (submerged arc) in accordance with the manufacturer's recommendations
- reduce stresses on the weld by avoiding large root gaps and high restraint
- if preheating is specified in the welding procedure, it should also be applied when tacking or using temporary attachments
- preheat the joint to a distance of at least 75mm from the joint line ensuring uniform heating through the thickness of the material
- measure the preheat temperature on the face opposite that being heated. Where this is impractical, allow time for the equalisation of temperature after removing the preheating before the temperature is measured
- adhere to the heat input requirements
- maintain heat for approximately two to four hours after welding depending on crack sensitivity
- In situations where adequate preheating is impracticable, or cracking cannot be avoided, austenitic electrodes may be used

Hydrogen cracks in steels - prevention and best practice

Acceptance standards

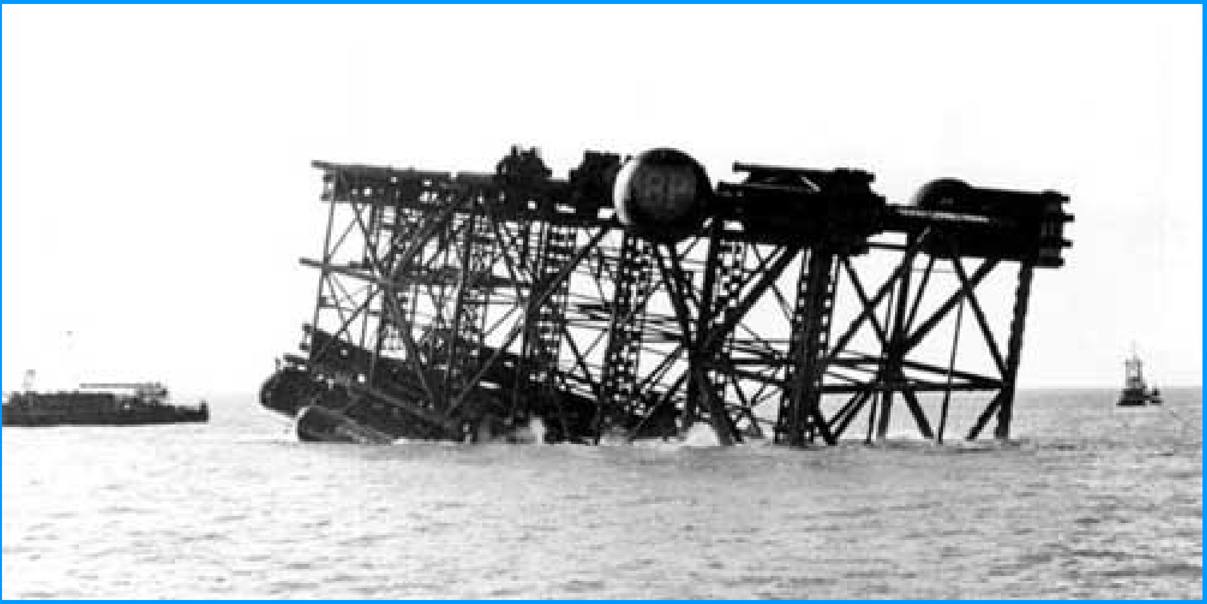
As hydrogen cracks are linear imperfections which have sharp edges, they are not permitted for welds meeting the quality levels B, C and D in accordance with the requirements of BS EN 25817 (ISO 5817).

Detection and remedial action

As hydrogen cracks are often very fine and may be sub-surface, they can be difficult to detect. Surface-breaking hydrogen cracks can be readily detected using visual examination, liquid penetrant or magnetic particle testing techniques. Internal cracks require ultrasonic or radiographic examination techniques. Ultrasonic examination is preferred as radiography is restricted to detecting relatively wide cracks parallel to the beam.

Most codes will specify that all cracks should be removed. A cracked component should be repaired by removing the cracks with a safety margin of approximately 5mm beyond the visible ends of the crack. The excavation is then re-welded.
To make sure that cracking does not re-occur, welding should be carried out with the correct procedure, ie preheat and an adequate heat input level for the material type and thickness. However, as the level of restraint will be greater and the interpass time shorter when welding within an excavation compared to welding the original joint, it is recommended that a higher level of preheat is used (typically by 50°C).

Lamellar tearing



BP Forties platform lamellar tears were produced when attempting the repair of lack of root penetration in a brace weld

Lamellar tearing can occur beneath the weld especially in rolled steel plate which has poor through-thickness ductility. The characteristic features, principal causes and best practice in minimising the risk of lamellar tearing are described.

Lamellar tearing

Identification

Visual appearance

The principal distinguishing feature of lamellar tearing is that it occurs in T-butt and fillet welds normally observed in the parent metal parallel to the weld fusion boundary and the plate surface , *(Fig 1).* The cracks can appear at the toe or root of the weld but are always associated with points of high stress concentration.

Fracture face

The surface of the fracture is fibrous and 'woody' with long parallel sections which are indicative of low parent metal ductility in the through-thickness direction, *(Fig 2).*

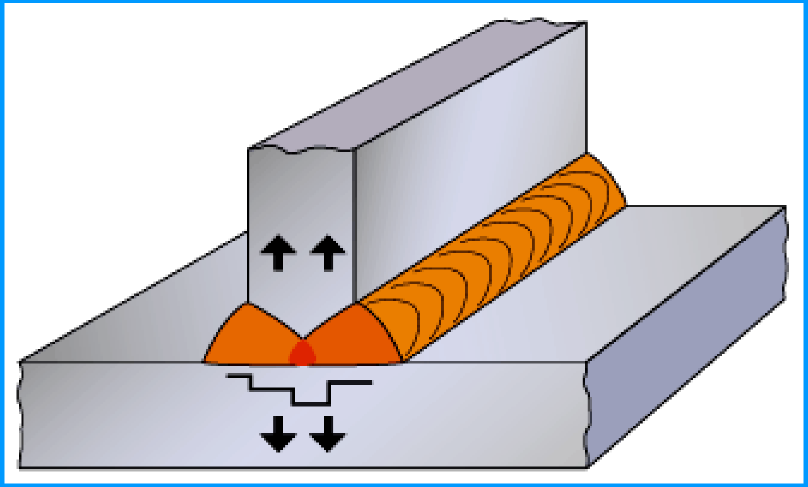


Fig. 1. Lamellar tearing in T butt weld

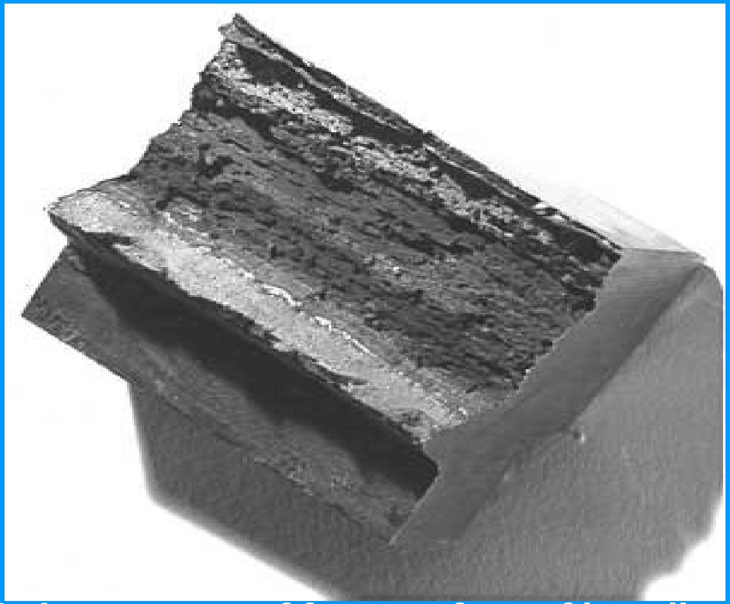


Fig. 2. Appearance of fracture face of lamellar tear

Lamellar tearing

Metallography

As lamellar tearing is associated with a high concentration of elongated inclusions oriented parallel to the surface of the plate, tearing will be transgranular with a stepped appearance.

Causes

It is generally recognised that there are three conditions which must be satisfied for lamellar tearing to occur:

1. Transverse strain - the shrinkage strains on welding must act in the short direction of the plate ie through the plate thickness

2. Weld orientation - the fusion boundary will be roughly parallel to the plane of the inclusions

3. Material susceptibility - the plate must have poor ductility in the through-thickness direction

Thus, the risk of lamellar tearing will be greater if the stresses generated on welding act in the through-thickness direction. The risk will also increase the higher the level of weld metal hydrogen

Lamellar tearing

Factors to be considered to reduce the risk of tearing

The choice of material, joint design, welding process, consumables, preheating and buttering can all help reduce the risk of tearing.

Material

Tearing is only encountered in rolled steel plate and not forgings and castings. There is no one grade of steel that is more prone to lamellar tearing but steels with a low Short Transverse Reduction in Area (STRA) will be susceptible. As a general rule, steels with STRA over 20% are essentially resistant to tearing whereas steels with below 10 to 15% STRA should only be used in lightly restrained joints *(Fig. 3).*
Steels with a higher strength have a greater risk especially when the thickness is greater than 25mm. Aluminium treated steels with low sulphur contents (<0.005%) will have a low risk.
Steel suppliers can provide plate which has been through-thickness tested with a guaranteed STRA value of over 20%.

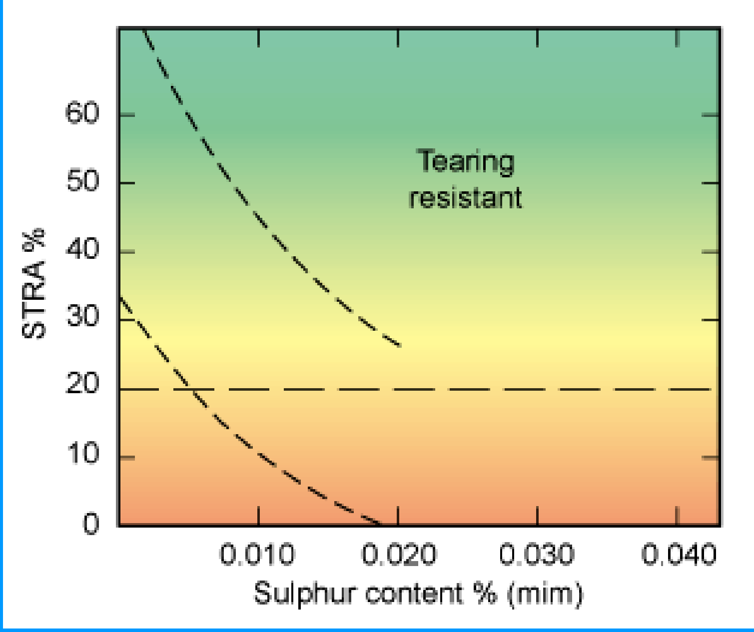


Fig. 3. Relationship between the STRA and sulphur content for 12.5 to 50mm thick plate

Lamellar tearing

Joint Design

Lamellar tearing occurs in joints producing high through-thickness strain, eg T joints or corner joints. In T or cruciform joints, full penetration butt welds will be particularly susceptible. The cruciform structures in which the susceptible plate cannot bend during welding will also greatly increase the risk of tearing.

In butt joints, as the stresses on welding do not act through the thickness of the plate, there is little risk of lamellar tearing.

As angular distortion can increase the strain in the weld root and or toe, tearing may also occur in thick section joints where the bending restraint is high.

Several examples of good practice in the design of welded joints are illustrated in *Fig. 4*

- As tearing is more likely to occur in full penetration T butt joints, if possible, use two fillet welds, *Fig. 4a.*

- Double-sided welds are less susceptible than large single-sided welds and balanced welding to reduce the stresses will further reduce the risk of tearing especially in the root, *Fig. 4b*

- Large single-side fillet welds should be replaced with smaller double-sided fillet welds, *Fig. 4c*

- Redesigning the joint configuration so that the fusion boundary is more normal to the susceptible plate surface will be particularly effective in reducing the risk, *Fig. 4d*

Lamellar tearing

Fig. 4 Recommended joint configurations to reduce the risk of lamellar tearing

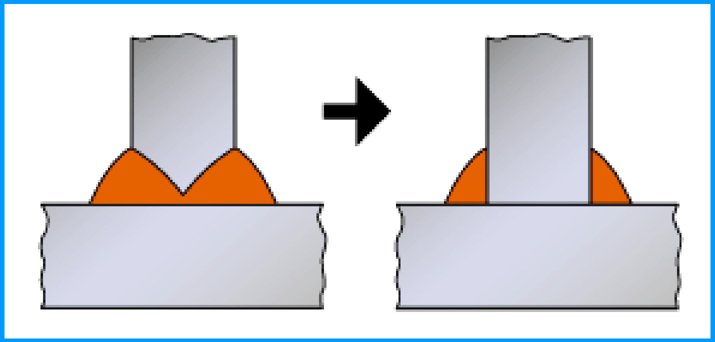


Fig. 4a

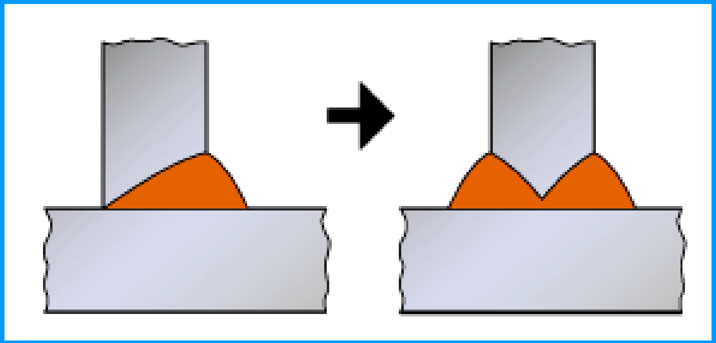


Fig. 4b

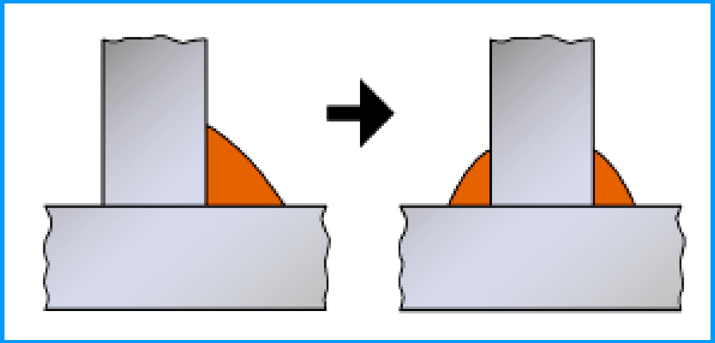


Fig. 4c

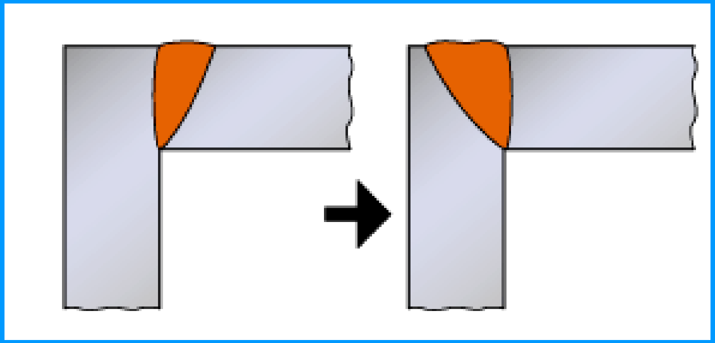


Fig. 4d

Lamellar tearing

Weld size

Lamellar tearing is more likely to occur in large welds typically when the leg length in fillet and T butt joints is greater than 20mm. As restraint will contribute to the problem, thinner section plate which is less susceptible to tearing, may still be at risk in high restraint situations.

Welding process

As the material and joint design are the primary causes of tearing, the choice of welding process has only a relatively small influence on the risk. However, higher heat input processes which generate lower stresses through the larger HAZ and deeper weld penetration can be beneficial.

As weld metal hydrogen will increase the risk of tearing, a low hydrogen process should be used when welding susceptible steels.

Consumable

Where possible, the choice of a lower strength consumable can often reduce the risk by accommodating more of the strain in the weld metal. A smaller diameter electrode which can be used to produce a smaller leg length, has been used to prevent tearing.

A low hydrogen consumable will reduce the risk by reducing the level of weld metal diffusible hydrogen. The consumables must be dried in accordance with the manufacturer's recommendations.

Preheating

Preheating will have a beneficial effect in reducing the level of weld metal diffusible hydrogen. However, it should be noted that in a restrained joint, excessive preheating could have a detrimental effect by increasing the level the level of restraint produced by the contraction across the weld on cooling.

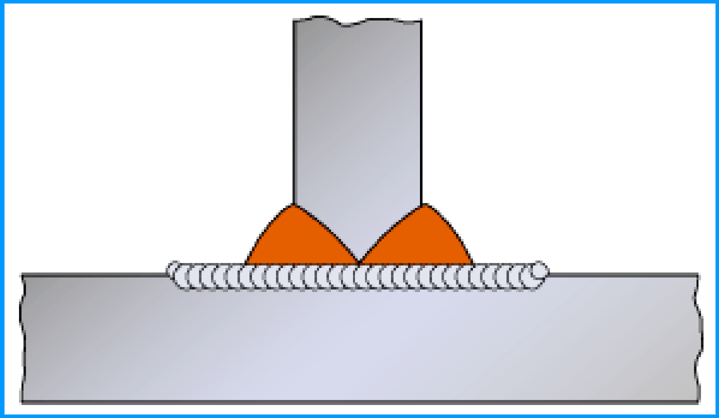
Preheating should, therefore, be used to reduce the hydrogen level but it should be applied so that it will not increase the amount of contraction across the weld.

Lamellar tearing

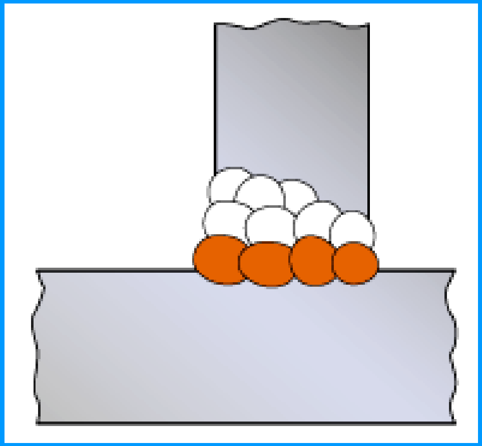
Buttering

Buttering the surface of the susceptible plate with a low strength weld metal has been widely employed. As shown for the example of a T butt weld *(Fig. 5)* the surface of the plate may be grooved so that the buttered layer will extend 15 to 25mm beyond each weld toe and be about 5 to 10mm thick.

Fig. 5. Buttering with low strength weld metal



a) general deposit on the surface of the susceptible plate



b) in-situ buttering

Lamellar tearing

Acceptance standards

As lamellar tears are linear imperfections which have sharp edges, they are not permitted for welds meeting the quality levels B, C and D in accordance with the requirements of BS EN 25817 (ISO 5817).

Detection and remedial action

If surface-breaking, lamellar tears can be readily detected using visual examination, liquid penetrant or magnetic particle testing techniques. Internal cracks require ultrasonic examination techniques but there may be problems in distinguishing lamellar tears from inclusion bands. The orientation of the tears normally makes them almost impossible to detect by radiography.

Reheat cracking

Brittle fracture in CrMoV steel pressure vessel probably caused through poor toughness, high residual stresses and hydrogen cracking

Reheat cracking

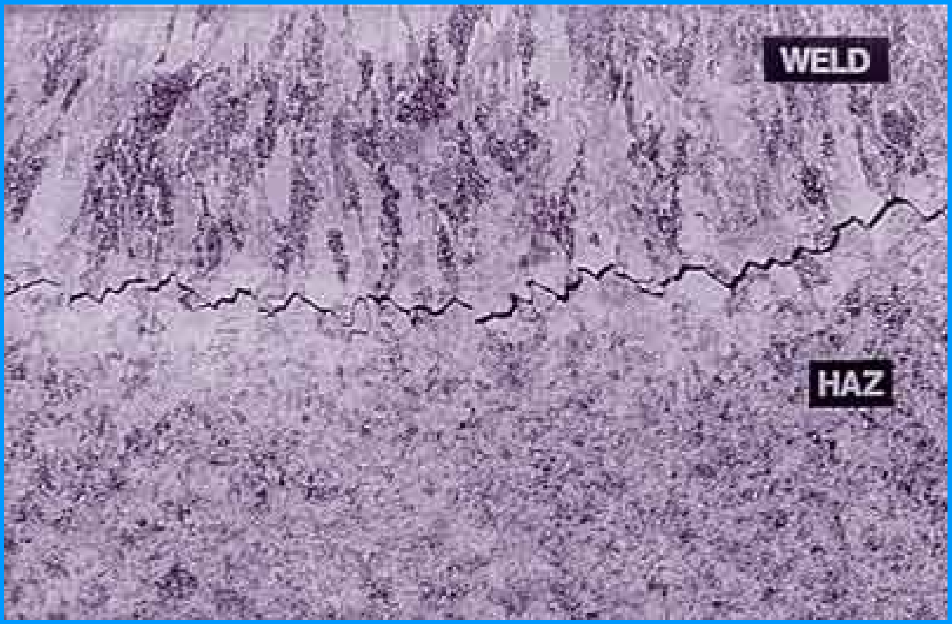
Identification

Visual appearance

Reheat cracking may occur in low alloy steels containing alloying additions of chromium, vanadium and molybdenum when the welded component is being subjected to post weld heat treatment, such as stress relief heat treatment, or has been subjected to high temperature service (typically 350 to 550°C).

Cracking is almost exclusively found in the coarse grained regions of the heat affected zone (HAZ) beneath the weld, or cladding, and in the coarse grained regions within the weld metal. The cracks can often be seen visually, usually associated with areas of stress concentration such as the weld toe.
Cracking may be in the form of coarse macro-cracks or colonies of micro-cracks.
A macro-crack will appear as a 'rough' crack, often with branching, following the coarse grain region, (*Fig. 1a*). Cracking is always intergranular along the prior austenite grain boundaries (*Fig. 1b*). Macro-cracks in the weld metal can be oriented either longitudinal or transverse to the direction of welding. Cracks in the HAZ, however, are always parallel to the direction of welding.

Reheat cracking



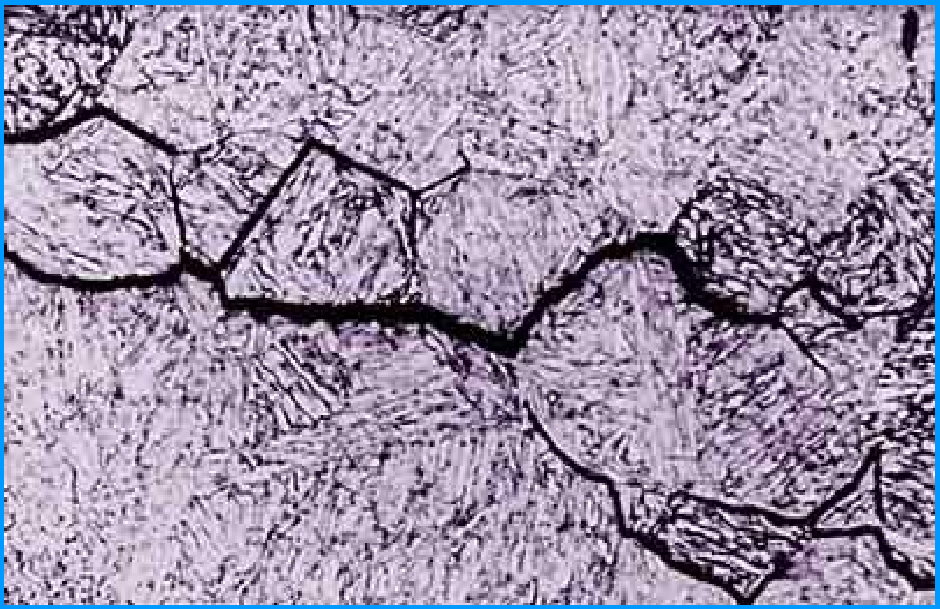


Fig.1a. Cracking associated with the coarse grained heat affected zone

Fig.1b. Intergranular morphology of reheat cracks

Micro-cracking can also be found both in the HAZ and within the weld metal. Micro-cracks in multipass welds will be found associated with the grain coarsened regions which have not been refined by subsequent passes.

Reheat cracking

Causes

The principal cause is that when heat treating susceptible steels, the grain interior becomes strengthened by carbide precipitation forcing the relaxation of residual stresses by creep deformation at the grain boundaries.

The presence of impurities which segregate to the grain boundaries and promote temper embrittlement eg sulphur, arsenic, tin and phosphorus, will increase the susceptibility to reheat cracking.
The joint design can increase the risk of cracking. For example, joints likely to contain stress concentration, such as partial penetration welds, are more liable to initiate cracks.
The welding procedure also has an influence. Large weld beads are undesirable as they produce a coarse grained HAZ which is less likely to be refined by the subsequent pass and therefore will be more susceptible to reheat cracking.

Best practice in prevention

The risk of reheat cracking can be reduced through the choice of steel, specifying the maximum impurity level and by adopting a more tolerant welding procedure / technique

Reheat cracking

Steel choice

If possible, avoid welding steels known to be susceptible to reheat cracking. For example, A 508 Class 2 is known to be particularly susceptible to reheat cracking whereas cracking associated with welding and cladding in A508 Class 3 is largely unknown. The two steels have similar mechanical properties but A508 Class 3 has a lower Cr content and a higher manganese content.

Similarly, in the higher strength, creep resistant steels, an approximate ranking of their crack susceptibility is as follows:

5 Cr 1Mo	lower risk
2.25Cr 1 Mo	
0.5Mo B	
0.5Cr 0.5Mo 0.25V	higher risk

↓

↓

Reheat cracking

Thus, in selecting a creep resistant, chromium molybdenum steel, 0.5Cr 0.5Mo 0.25V steel is known to be susceptible to reheat cracking but the 2.25Cr 1Mo which has a similar creep resistance, is significantly less susceptible.

Unfortunately, although some knowledge has been gained on the susceptibility of certain steels, the risk of cracking cannot be reliably predicted from the chemical composition. Various indices, including Δ G1, P_{SR} and Rs, have been used to indicate the susceptibility of steel to reheat cracking. Steels which have a value of ΔG of less than 2, P_{SR} less than zero or Rs less than 0.03, are less susceptible to reheat cracking

$$\Delta G1 = 10C + Cr + 3.3Mo + 8.1V - 2$$

$$P_{SR} = Cr + Cu + 2Mo + 10V + 7Nb + 5Ti - 2$$

$$Rs = 0.12Cu + 0.19S + 0.10As + P + 1.18Sn + 1.49Sb$$

Reheat cracking

Impurity level

Irrespective of the steel type, it is important to purchase steels specified to have low levels of trace elements (antimony, arsenic, tin and phosphorus). It is generally accepted that the total level of impurities in the steel should not exceed 0.01% to minimise the risk of temper embrittlement.

Welding procedure and technique

The welding procedure can be used to minimise the risk of reheat cracking by

- Producing the maximum refinement of the coarse grain HAZ
- Limiting the degree of austenite grain growth
- Eliminating stress concentrations

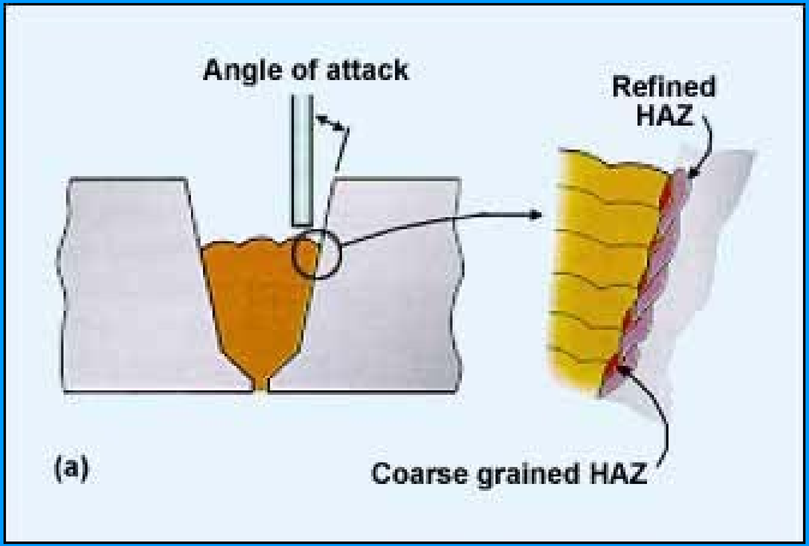


Fig.2a. Welding in the flat position - high degree of HAZ refinement

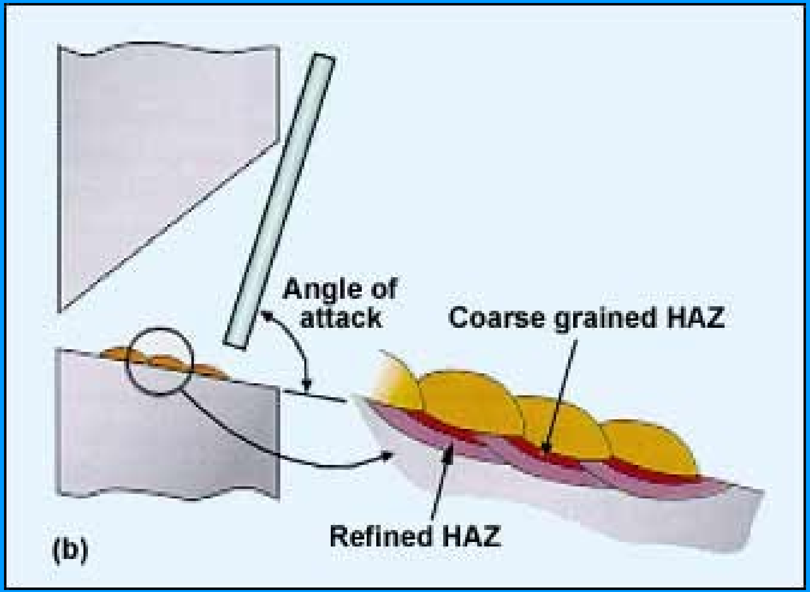


Fig.2b. Welding in the horizontal/vertical position - low degree of HAZ refinement

Reheat cracking

Refinement of the HAZ can be promoted by first buttering the surface of the susceptible plate with a thin weld metal layer using a small diameter (3.2mm) electrode. The joint is then completed using a larger diameter (4 - 4.8mm) electrode which is intended to generate sufficient heat to refine any remaining coarse grained HAZ under the buttered layer.

The degree of austenite grain growth can be restricted by using a low heat input. However, precautionary measures may be necessary to avoid the risk of hydrogen assisted cracking and lack-of-fusion defects. For example, reducing the heat input will almost certainly require a higher preheat temperature to avoid hydrogen assisted cracking.

The joint design and welding technique adopted should ensure that the weld is free from localised stress concentrations which can arise from the presence of notches. Stress concentrations may be produced in the following situations:

- welding with a backing bar
- a partial penetration weld leaving a root imperfection
- internal weld imperfections such as lack of sidewall fusion
- the weld has a poor surface profile, especially sharp weld toes

The weld toes of the capping pass are particularly vulnerable as the coarse grained HAZ may not have been refined by subsequent passes. In susceptible steel, the last pass should never be deposited on the parent material but always on the weld metal so that it will refine the HAZ.

Grinding the weld toes with the preheat maintained has been successfully used to reduce the risk of cracking in 0.5Cr 0.5Mo 0.25V steels

WELDING PROCEDURE SPECIFICATION

Job knowledge for welders

Standards - Approval of welding procedures, welders and welding operators

Routes to welding procedure approval

The key document is the Welding Procedure Specification (WPS) which details the welding variables to be used to ensure a welded joint will achieve the specified levels of weld quality and mechanical properties.

The WPS is supported by a number of documents (eg a record of how the weld was made, NDE, mechanical test results) which together comprise a welding approval record termed the WPAR (EN288) or PQR (ASME)

The essential variables are detailed in the relevant specification but include material type, welding process, thickness range and sometimes welding position.

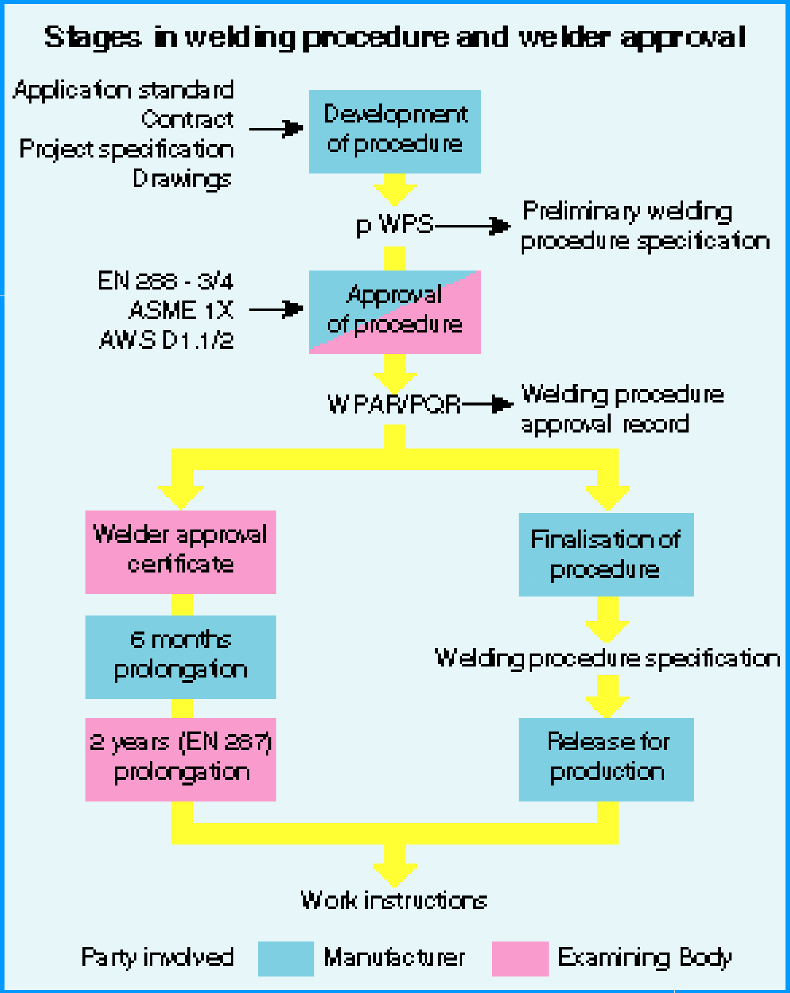


Fig. 1. Stages in welding and welder approval

The route followed to produce a WPS in EN 288 and the responsibilities of the manufacturer and the Examiner/Examining Body are shown in Fig. 1.

The most common method of gaining approval is to carry out an approval test as described in EN 288 Pt3 (steels) and Pt4 (aluminium and its alloys). The manufacturer initially drafts a preliminary welding procedure (PWPS) which is used by one of the manufacturer's competent welders to prove that it is capable of producing a welded joint to the specified levels of weld quality and mechanical properties. The welding procedure approval record (WPAR) is a record of this weld. If the WPAR is approved by the Examiner, it is used to finalise one or more WPSs which is the basis for the Work Instructions given to the welder.

It is noteworthy that the welder carrying out a satisfactory welding procedure approval test is approved for the appropriate range of approval given in the relevant standard (EN 287, ASME IX or AWS D1.1).

EN 288 also permits the following options for procedure approval:

- Welding procedure test
- Approved welding consumable
- Previous welding experience
- Standard welding procedure
- Pre-production welding test

The conventional procedure test (as specified in Parts 3 or 4) does not always need to be carried out to gain approval. But alternative methods have certain limits of application regarding, for example, welding processes, materials and consumables as specified in the appropriate application standard or contract agreement.

The welding procedure test method of approval is often a mandatory requirement of the Application Standard. If not, the contracting parties can agree to use one of the alternative methods. For example, a welding procedure specification can be approved in accordance with the requirements of Part 6 (previous experience) on condition that the manufacturer can prove, with appropriate documentation, that the type of joint has previously been welded satisfactorily.

The American standard, ASME IX requires a welding procedure test (PQR) but AWS D1.1 will allow the use of pre-qualified procedures within the limits detailed in the specification.

Welder approval

As the welder's approval test is carried out on a test piece which is representative of the joint to be welded, it is independent of the type of construction. ***The precise conditions, called 'essential variables', must be specified in the approval test eg material type, welding process, joint type, dimensions and welding position***. The extent of approval is not necessarily restricted to the conditions used for the test but covers a group of similar materials or a range of situations which are considered easier to weld

In EN 287, the certificate of approval testing is issued under the sole responsibility of the Examiner / Examining Body. The welder approval certificate remains valid subject to the requirements of the application standard. In EN 287, it can be extended at six monthly intervals by the employer for up to two years provided the welder has been successfully welding similar joints. After two years, prolongation of the welder's qualification will need approval of the Examiner who will require proof that his or her performance has been of the required standard during the period of validity. As the Examiner will normally examine the company's records on the welder's work and tests as proof that he has maintained his skill, it is essential that work records are maintained by the company.

Welding operator approval

As specified in EN 1418, approval of operators of equipment for fusion welding and resistance weld equipment setters can be based on:

- welding a procedure test
- pre-production welding test or production test
- production sample testing or a function test.

Prolongation of the welding operator approval is generally in accordance with the requirements of EN 287. The welding operator's approval remains valid for two years providing the employer/welding co-ordinator confirms that there has been a reasonable continuity of welding work (period of interruption no longer than six months) and there is no reason to question the welding operator's knowledge.

When working to ASME IX, operators for both mechanised and automatic welding equipment require approval. The essential variables are different to those in welder approval.

Relevant Standards

EN 287: Part 1. Steels
(Amendment 9665, August 1997)
(Amendment 9804, January 1998)
(Corrigenda No 1, April 1998)

Part 2.Aluminium and alloys
(Amendment No 9733, November 1997)
(Corrigenda No 1 June, 1998)

EN 288: Part 3. Steels
(Amendment No 9736, November 1997)
(Corrigenda No 1, June 1998)

EN 1418 : 1998 Welding personnel - Approval testing of welding operators for fusion welding and resistance weld setters for fully mechanised and automatic welding of metallic materials

Types of electrodes.

The main differences between them are in the flux coating

The three main classes of electrode are shown below:

- Cellulosic: The arc produced by this type of electrode is very penetrating. These electrodes have a high proportion of combustible organic materials in their coating. **Cellulosic electrodes** contain a high proportion of cellulose in the coating and are characterised by a deeply penetrating arc and a rapid burn-off rate giving high welding speeds. Weld deposit can be coarse and with fluid slag, deslagging can be difficult. These electrodes are easy to use in any position and are noted for their use in the 'stovepipe' welding technique.

Features:

- deep penetration in all positions
- suitability for vertical down welding
- reasonably good mechanical properties
- high level of hydrogen generated - risk of cracking in the heat affected zone (HAZ)

Types of electrodes.

2. Rutile: General purpose electrodes for applications which do not require strict control of mechanical properties. These electrodes contain a high proportion of titanium oxide in the flux coating.

   Rutile electrodes contain a high proportion of titanium oxide (rutile) in the coating. Titanium oxide promotes easy arc ignition, smooth arc operation and low spatter. These electrodes are general purpose electrodes with good welding properties. They can be used with AC and DC power sources and in all positions. The electrodes are especially suitable for welding fillet joints in the horizontal/vertical (H/V) position.

   Features:

- moderate weld metal mechanical properties
- good bead profile produced through the viscous slag
- positional welding possible with a fluid slag (containing fluoride)
- easily removable slag

Types of electrodes.

3. Basic: These electrodes produce welds with better strength and notch toughness than rutile. The electrodes have a coating which contains calcium carbonate and other carbonates and fluorspar.

Basic electrodes contain a high proportion of calcium carbonate (limestone) and calcium fluoride (fluorspar) in the coating. This makes their slag coating more fluid than rutile coatings - this is also fast-freezing which assists welding in the vertical and overhead position. These electrodes are used for welding medium and heavy section fabrications where higher weld quality, good mechanical properties and resistance to cracking (due to high restraint) are required.

Features:

- low weld metal produces hydrogen
- requires high welding currents/speeds
- poor bead profile (convex and coarse surface profile)
- slag removal difficult

Types of electrodes.

Metal powder electrodes

It contain an addition of metal powder to the flux coating to increase the maximum permissible welding current level. Thus, for a given electrode size, the metal deposition rate and efficiency (percentage of the metal deposited) are increased compared with an electrode containing no iron powder in the coating. The slag is normally easily removed. Iron powder electrodes are mainly used in the flat and H/V positions to take advantage of the higher deposition rates. Efficiencies as high as 130 to 140% can be achieved for rutile and basic electrodes without marked deterioration of the arcing characteristics but the arc tends to be less forceful which reduces bead penetration.

TEST FOR WELDED JOINTS

Compact tension and J integral tests

Fatigue testing

Bend testing

Crack Tip Opening Displacement (CTOD) test

Hardness Testing Part 1
Brinell Hardness Test
Vickers Hardness Test

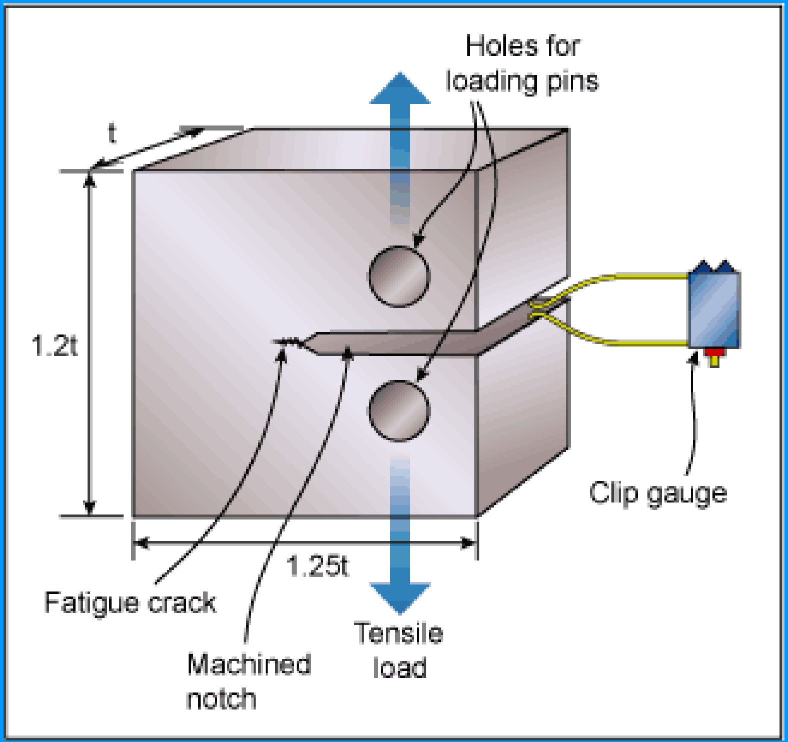
Hardness Testing Part 2
Micro-hardness testing :
Knoop test,Vickers test and the ultrasonic micro-hardness test.
portable hardness testing:

Mechanical testing - Tensile testing, Part 1
Mechanical testing - Tensile testing, Part 2

Compact tension Test

The compact tension specimen is a proportional specimen of full plate thickness containing a fatigue crack. The sides of the specimen are approximately twice the specimen thickness as illustrated in *Fig.1*. The specimen has a notch machined into one face in the area - weld, HAZ etc - to be tested and a fatigue crack is then grown from the tip of the machined notch to give a total 'crack' length approximately equivalent to the specimen thickness. The specimen is tested in tension with deformation measured by means of a clip gauge mounted across the mouth of the notch. Load and deformation are recorded and crack length is measured on the broken test piece. A decision may then be made as to the failure mode and the appropriate analysis tools then used to calculate toughness.

Fig.1. Compact tension specimen



Compact tension Test

The compact tension test has the advantage that the specimen is more economical in material and this can be important when thick plates are to be tested. For this reason the CT test is favoured by the nuclear industry, where safety is crucial and lower bound results are preferred.

J Integral test

The J integral is a third method of determining toughness and is based on the amount of energy required to propagate a crack. Both CTOD and J can be measured on the same specimen by using two clip gauges, one to measure CTOD, the other to measure J. To determine J the specimen is loaded at successively higher loads and the displacement and crack length at each load is measured. The area beneath the load/displacement curve gives the amount of energy required for fracture propagation to occur. Analysis of the results enables a J factor to be calculated as a measure of fracture toughness.

Fatigue testing

The premature failure of wagon axles led to Wohler in Germany investigating fatigue failure under rotating loading. This led to the design of the first standardised test - a reversing stress rotating specimen, illustrated in *Fig.1*.

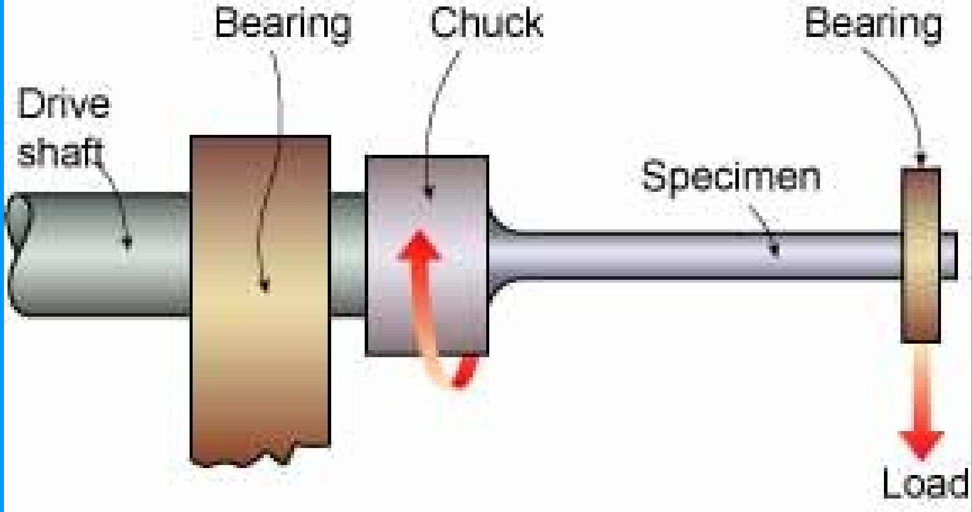


Fig.1. Wohler rotating fatigue test

There are many mechanisms that can lead to failure but fatigue is perhaps one of the most insidious since it can lead to a catastrophic failure with little or no warning - one well known example being the failure of the Comet aircraft in the 1950s

Fatigue testing

Failure can occur at a fluctuating load well below the yield point of the metal and below the allowable static design stress. The number of cycles at which failure occurs may vary from a couple of hundreds to millions. There will be little or no deformation at failure and the fracture has a characteristic surface, as shown in *Fig.2*.

The surface is smooth and shows concentric rings, known as beach marks, that radiate from the origin; these beach marks becoming coarser as the crack propagation rate increases. Viewing the surface on a scanning electron microscope at high magnification shows each cycle of stress causes a single ripple. The component finally fails by a ductile or brittle overload.

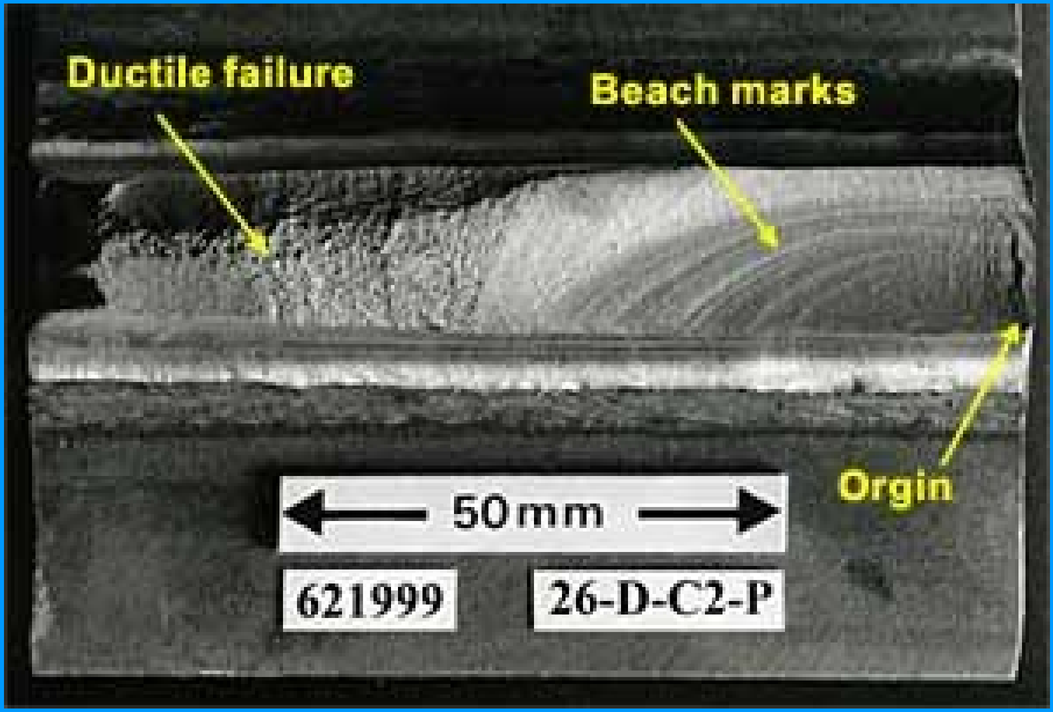


Fig.2. Typical fatigue crack fracture surface

Fatigue testing

Fatigue cracks generally start at changes in section or notches where the stress is raised locally and, as a general rule, the sharper the notch the shorter the fatigue life - one reason why cracks are so damaging.
There are two stages in the process of fatigue cracking - a period of time during which a fatigue crack is nucleated and a second stage where the crack grows incrementally leaving the ripples In an unwelded component the bulk of the life is spent in initiating a fatigue crack with a shorter period spent in crack propagation.
An unwelded ferritic steel component exhibits an endurance limit - a stress below which fatigue cracking will not initiate and failure will therefore not occur. This is not the case with most non-ferrous metals or with welded joints - these have no clearly defined endurance limit The reason for this is that in arc welded joints there is an 'intrusion' - a small defect at the toe of the weld, perhaps only some 0.1mm deep. Provided that the applied stress is sufficiently large a crack will begin to propagate within an extremely short period of time. The endurance limit for a welded joint is therefore dependent on the intrusion size that does not result in crack propagation at the applied stress range. In the case of a welded joint, therefore, a fatigue limit - a 'safe life' is specified, often the stress to cause failure at $2x10^{6}$ or 10^{7} cycles

Fatigue testing

To quantify the effect of these varying stresses fatigue testing is carried out by applying a particular stress range and this is continued until the test piece fails. The number of cycles to failure is recorded and the test then repeated at a variety of different stress ranges. This enables an S/N curve, a graph of the applied stress range, S, against N, the number of cycles to failure, to be plotted as illustrated in *Fig.3*. This graph shows the results of testing a plain specimen and a welded component. The endurance limit of the plain specimen is shown as the horizontal line - if the stress is below this line the test piece will last for an infinite number of cycles. The curve for the welded sample, however, continues to trend down to a point where the stress range is insufficient to cause a crack to propagate from the intrusion.

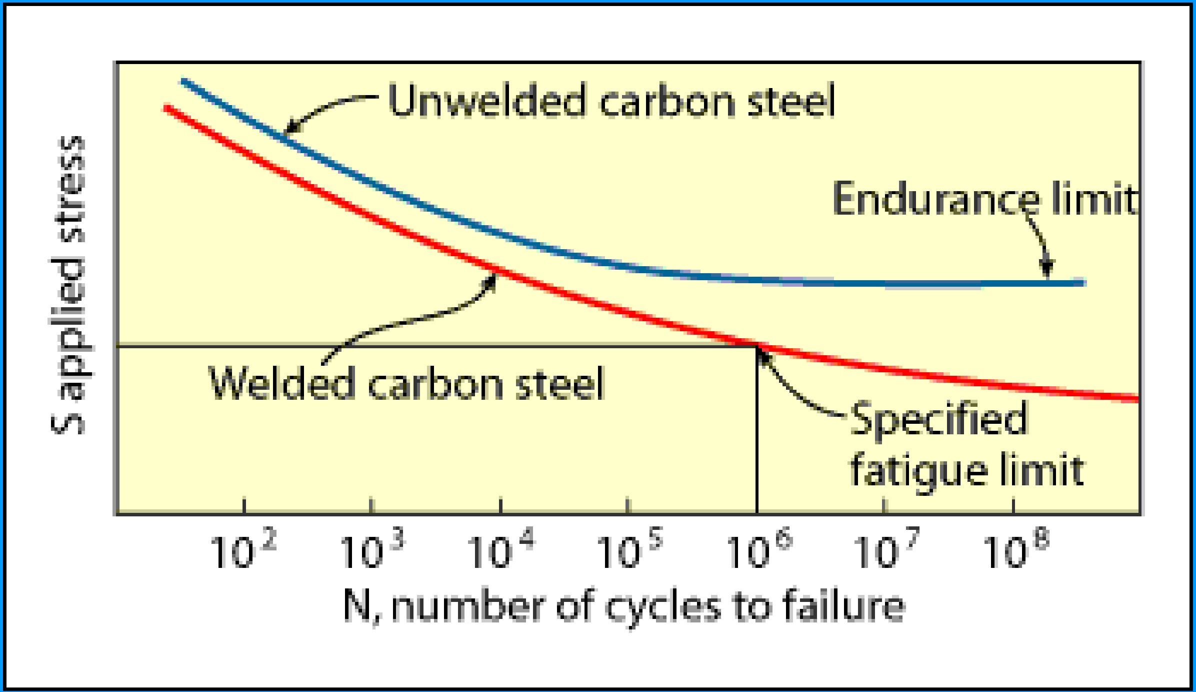


Fig.3. S/N curves for welded and unwelded specimens

Bend testing

The bend test is a simple and inexpensive qualitative test that can be used to evaluate both the ductility and soundness of a material. It is often used as a quality control test for butt-welded joints, having the advantage of simplicity of both test piece and equipment. It can be carried out on the shop floor as a quality control test to ensure consistency in production. The bend test uses a coupon that is bent in three point bending to a specified angle.The outside of the bend is extensively plastically deformed so that any defects in, or embrittlement of, the material will be revealed by the premature failure of the coupon.The bend test may be free formed or guided.

The guided bend test is where the coupon is wrapped around a former of a specified diameter and is the type of test specified in the welding procedure and welder qualification specifications. For example, it is a requirement in ASME IX, the EN 287 and EN 288 series of specifications and ISO 15614 Part 1

Bend testing

Typical bend test jigs are illustrated in *Fig.1(a)* and *1(b)*.

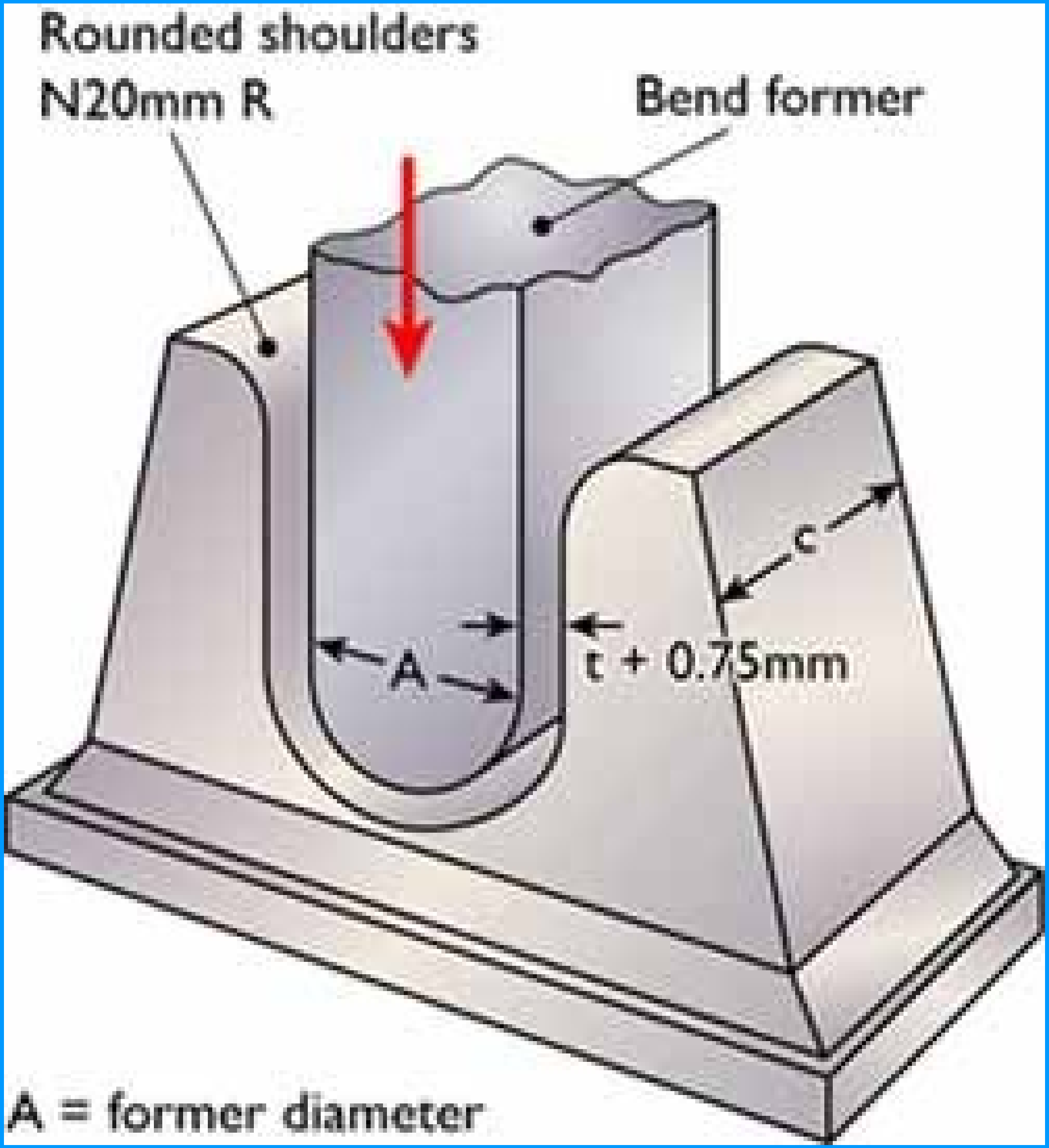


Fig.1(a) shows a guided bend test jig that uses a male and a female former, the commonest form of equipment

Bend testing

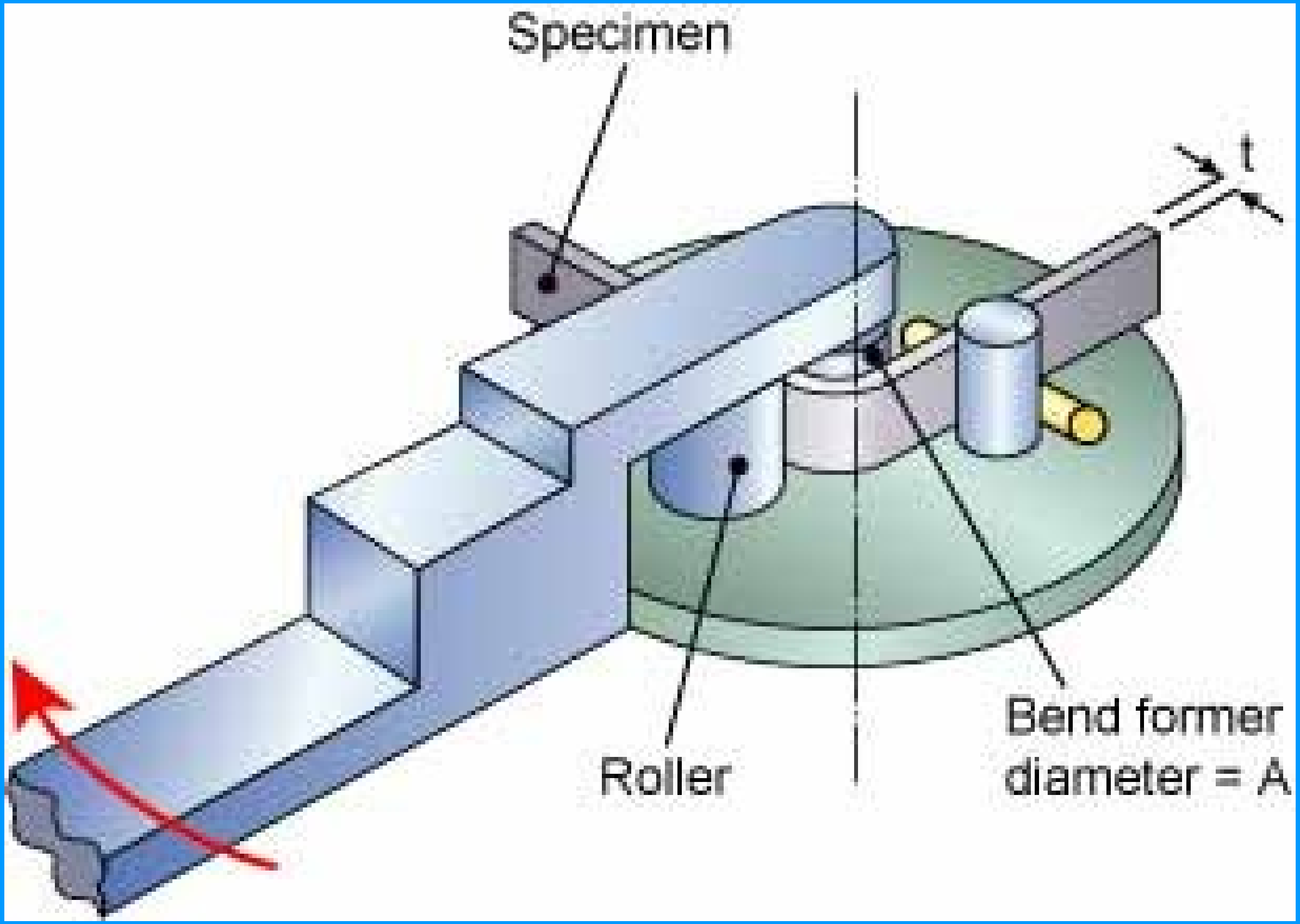


Fig.1(b) shows a wrap-around guided bend test machine that works on the same principles as a plumber's pipe bender

Bend testing

The strain applied to the specimen depends on the diameter of the former around which the coupon is bent and this is related to the thickness of the coupon 't', normally expressed as a multiple of 't' eg 3t, 4t etc.

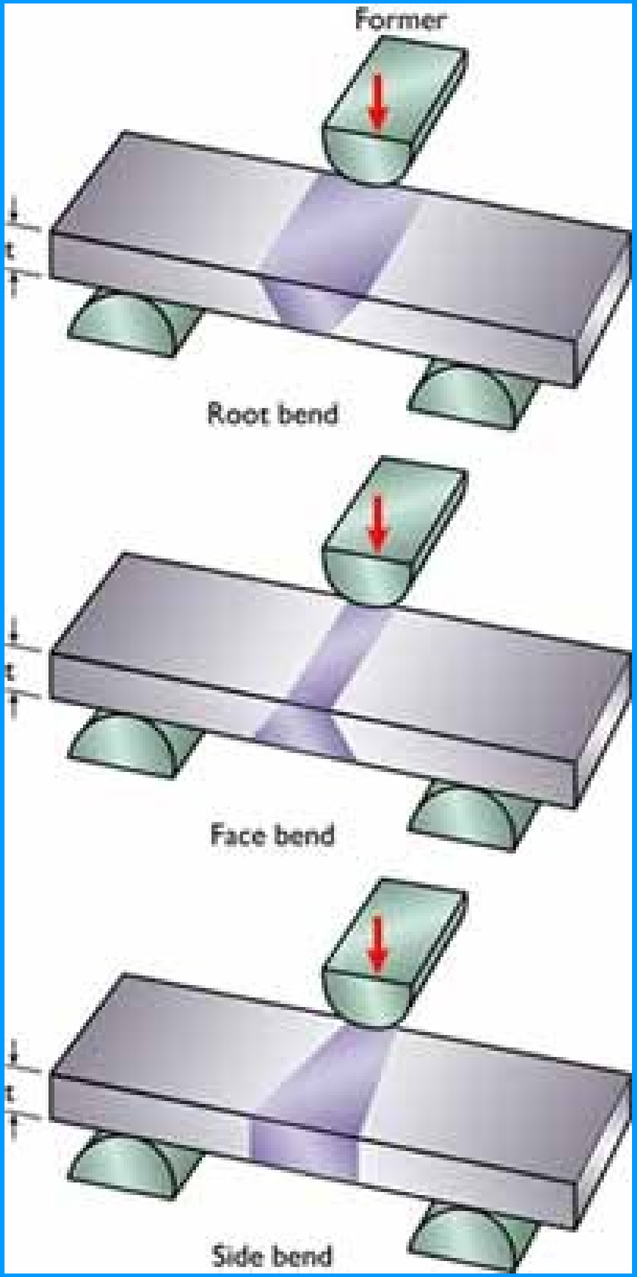
The former diameter is specified in the test standard and varies with the strength and ductility of the material - the bend former diameter for a low ductility material such as a fully hard aluminium alloy may be as large as 8t. An annealed low carbon steel on the other hand may require a former diameter of only 3t. The angle of bend may be 90°, 120° or 180° depending on the specification requirements.

On completion of the test the coupon is examined for defects that may have opened up on the tension face. Most specifications regard a defect over 3mm in length as being cause for rejection.

For butt weld procedure and welder qualification testing the bend coupons may be oriented transverse or parallel to the welding direction.

Bend testing

Below approximately 12mm material thickness transverse specimens are usually tested with the root or face of the weld in tension. Material over 12mm thick is normally tested using the side bend test that tests the full section thickness, *Fig.2*.
Conventionally, most welding specifications require two root and two face bend coupons or four side bends to be taken from each butt welded test piece.



Bend testing

The transverse face bend specimen will reveal any defects on the face such as excessive undercut or lack of sidewall fusion close to the cap. The transverse root bend is also excellent at revealing lack of root fusion or penetration. The transverse side bend tests the full weld thickness and is particularly good at revealing lack of side-wall fusion and lack of root fusion in double-V butt joints. This specimen orientation is also useful for testing weld cladding where any brittle regions close to the fusion line are readily revealed

Longitudinal bend specimens are machined to include the full weld width, both HAZs and a portion of each parent metal. They may be bent with the face, root or side in tension and are used where there is a difference in mechanical strength between the two parent metals or the parent metal and the weld. The test will readily reveal any transverse defects but it is less good at revealing longitudinally oriented defects such as lack of fusion or penetration

Bend testing

There are some features that may result in the test being invalid.

In cutting the coupon from the test weld the effects of the cutting must not be allowed to affect the result. Thus it is necessary to remove any HAZ from flame cutting or work hardened metal if the sample is sheared.

It is normal to machine or grind flat the face and root of a weld bend test coupon to reduce the stress raising effect that these would have. Sharp corners can cause premature failure and should be rounded off to a maximum radius of 3mm.

The edges of transverse bend coupons from small diameter tubes will experience very high tensile stresses when the ID is in tension and this can result in tearing at the specimen edges.

Weld joints with non-uniform properties such as dissimilar metal joints or where the weld and parent metal strengths are substantially different can result in 'peaking' of the bend coupon. This is when most of the deformation takes place in the weaker of the two materials which therefore experiences excessive localised deformation that may result in premature failure.

Bend testing

A dissimilar metal joint where one of the parent metals is very high strength is a good example of where this may occur and similar peaking can be seen in fully hard welded aluminium alloy joints.

In these instances the roller bend test illustrated in *Fig.1(b)* is the best method of performing a bend test as each component of the coupon is strained by a similar amount and peaking is to a great extent eliminated

Crack Tip Opening Displacement (CTOD) test

To determine the toughness of non-metallics such as weldable plastics. The CTOD test is one such fracture toughness test that is used when some plastic deformation can occur prior to failure - this allows the tip of a crack to stretch and open, hence 'tip opening displacement‘.

CTOD specimen may be the full thickness of the material, will contain a genuine crack and will be loaded at a rate more representative of service conditions. Conventionally three tests are carried out at the relevant temperature to ensure consistency of results.

Crack Tip Opening Displacement (CTOD) test

There are two basic forms - a square or a rectangular cross section specimen. If the specimen thickness is defined as 'W', the depth will be either W or 2W with a standard length of 4.6W. A notch is machined at the centre and then extended by generating a fatigue crack so that the total 'defect' length is half the depth of the test piece- see *Fig.1*. A test on a 100mm thick weld will therefore require a specimen measuring 100mm wide, 200mm deep and 460mm long - an expensive operation, the validity of which can only be determined once the test has been completed.

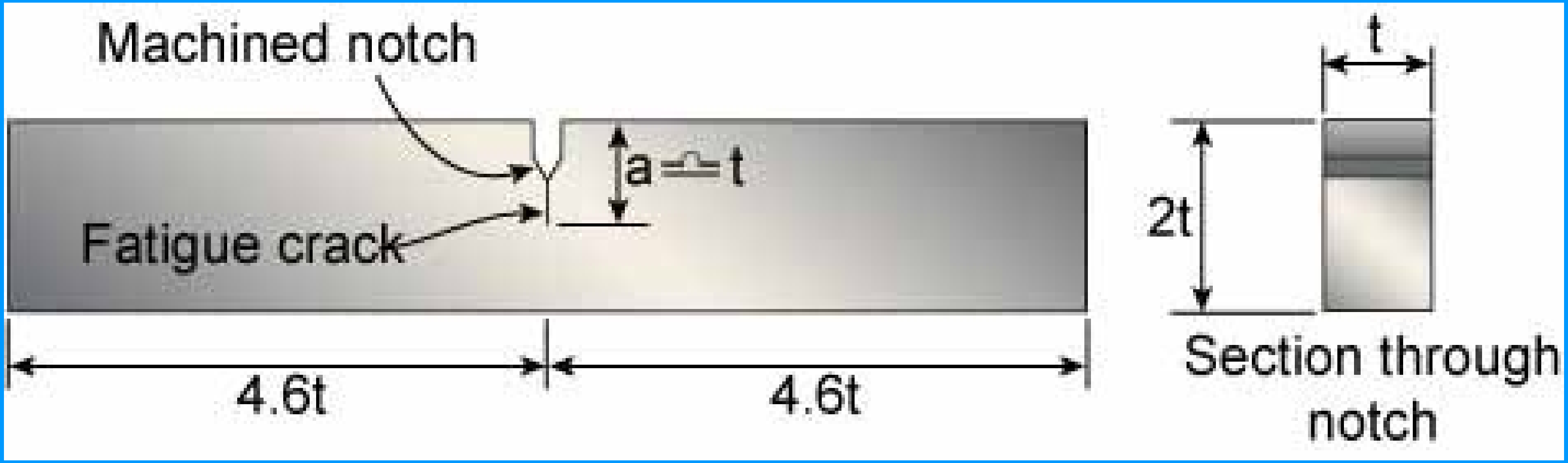


Fig.1. Proportional rectangular cross section CTOD specimen

Crack Tip Opening Displacement (CTOD) test

The test is performed by placing the specimen into three point bending and measuring the amount of crack opening. This is done by means of a strain gauge attached to a clip placed between two accurately positioned knife edges at the mouth of the machined notch (*Fig.2*)

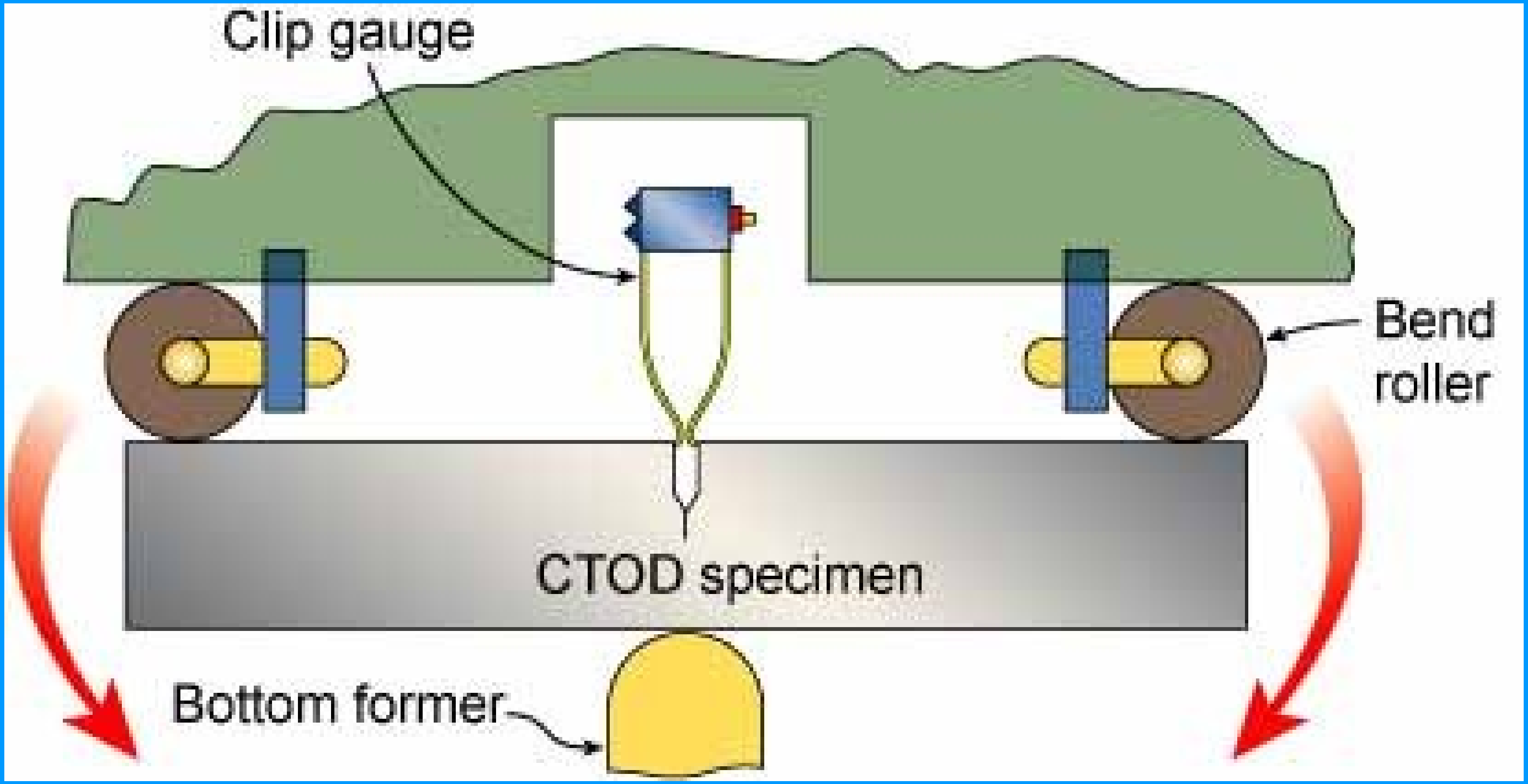


Fig.2. Typical test arrangement. The specimen can be easily immersed in a cooling bath

Crack Tip Opening Displacement (CTOD) test

As bending proceeds, the crack tip plastically deforms until a critical point is reached when the crack has opened sufficiently to initiate a cleavage crack. This may lead to either partial or complete failure of the specimen. The test may be performed at some minimum temperature eg the minimum design temperature or, more rarely, at a range of temperatures.

As a rule of thumb, a CTOD value of between 0.1mm and 0.2mm at the minimum service temperature is regarded as demonstrating adequate toughness.

The values that are required for the calculation of toughness are firstly the load at which fracture occurs and secondly the amount by which the crack has opened at the point of crack propagation (*Fig.3*).

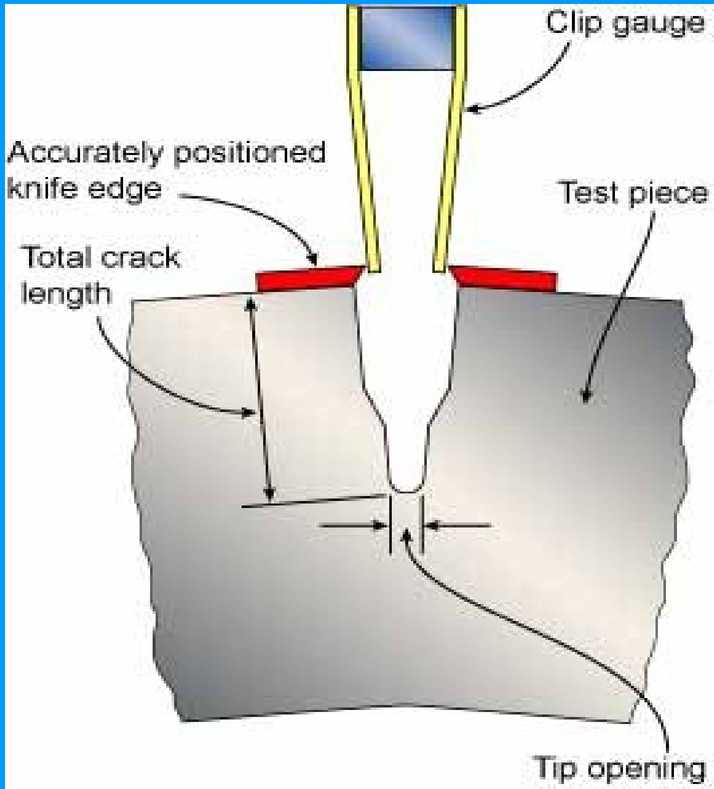


Fig.3. Position of CTOD specimen immediately prior to crack propagation

Crack Tip Opening Displacement (CTOD) test

Since the length of the crack and the opening at the mouth of the notch are known it is a simple matter to calculate the crack tip opening by simple geometry. The CTOD curve is a plot of stress versus strain (*Fig.4*). This illustrates the various shapes of curve that may be produced - (a) is a test where the test piece has fractured in a brittle manner with little or no plastic deformation. (b) exhibits a 'pop-in' where the brittle crack initiates but only propagates a short distance before it is arrested in tougher material - this may occur several times giving the curve a saw tooth appearance or after this one pop-in deformation may continue in a ductile manner as in (c) which shows completely plastic behaviour.

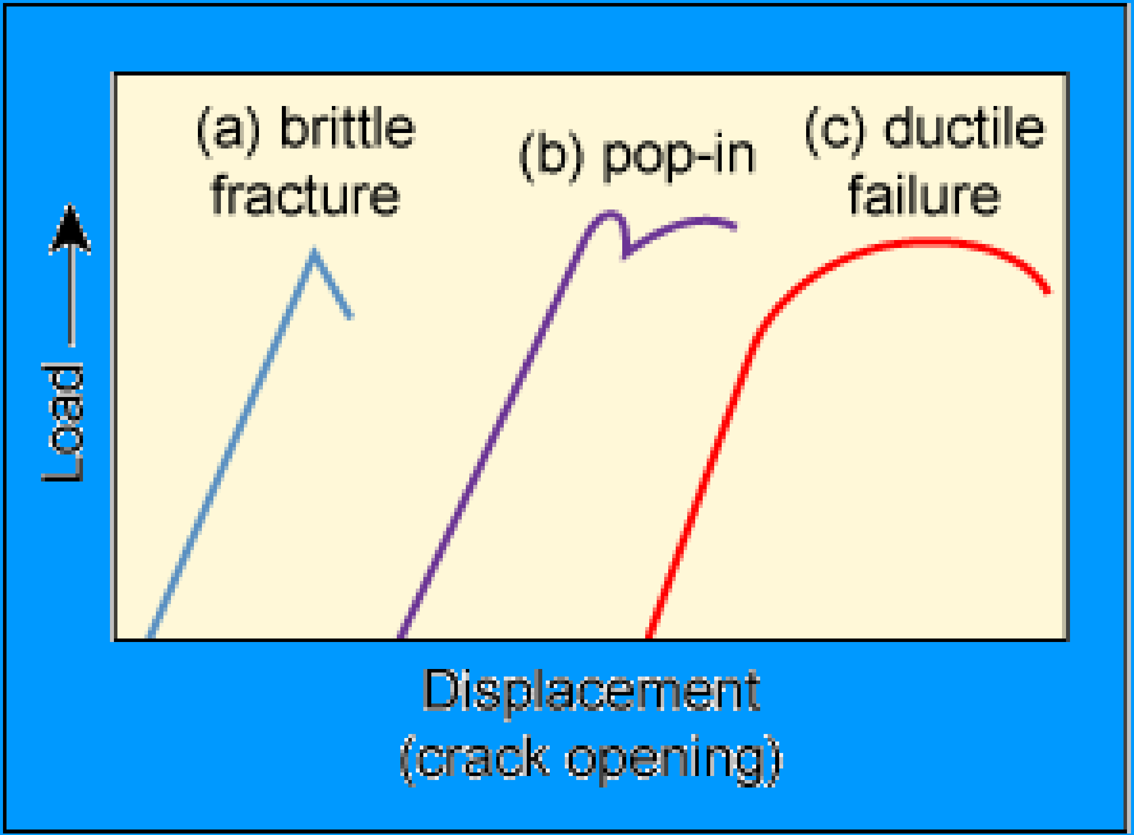


Fig.4. Load vs crack opening displacement curves showing three types of fracture behaviour

Crack Tip Opening Displacement (CTOD) test

The location of the notch in the weld HAZ or parent metal is important as an incorrectly positioned fatigue crack will not sample the required area, making the test invalid. To be certain that the crack tip is in the correct region, polishing and etching followed by a metallurgical examination are often carried out prior to machining the notch and fatigue cracking. This enables the notch to be positioned very accurately.

Once the sample is broken open the crack surface is examined to ensure that the fatigue crack has a reasonably straight front. The residual stresses present in a welded joint may cause the fatigue crack front to be irregular - if this is excessive the test may be invalid. To overcome this problem the test piece may be locally compressed at the machined notch tip to redistribute the residual stress.

Crack Tip Opening Displacement (CTOD) test

Two depressions each side of the sample can often be seen where this compression has been carried out. The fatigue cracking itself should be carried out using a low stress range. The use of high stresses to speed up the fatigue cracking process can result in a large plastically deformed area ahead of the fatigue crack and this will invalidate the results of the test.

Other causes of test failure can unfortunately only be determined once the test has been completed and the crack surface examined. The precise length of the fatigue crack is measured - this is required for the analysis - but if the length of the crack is not within the limits required by the specification the test is invalid. If the fatigue crack is not in a single plane, if the crack is at an angle to the machined notch or if the crack is not in the correct region the test will need to be repeated.

Hardness Testing

The hardness of a material can have a number of meanings depending upon the context, which in the case of metals generally means the resistance to indentation.

Brinell Hardness Test

Vickers Hardness Test

Micro-hardness Test

The Knoop test

The Vickers test

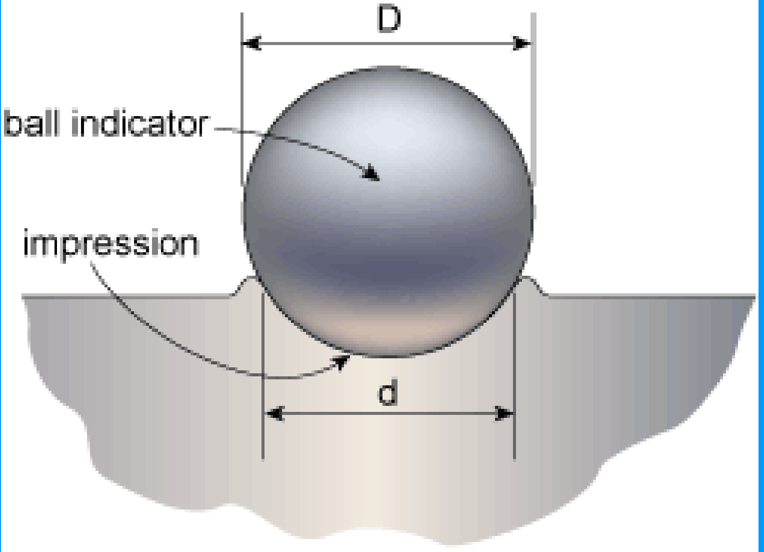
The ultrasonic micro-hardness test.

Portable hardness Test

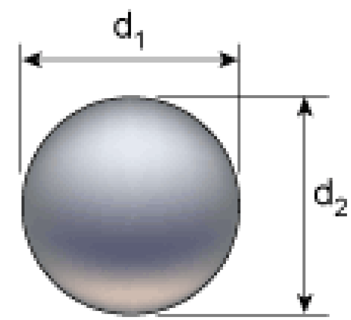
Hardness Testing

Brinell Hardness Test

The test comprises forcing a hardened steel ball indentor into the surface of the sample using a standard load as shown in *Fig.1(a)*. The diameter/load ratio is selected to provide an impression of an acceptable diameter. The ball may be 10, 5 or 1mm in diameter, the load may be 3000, 750 or 30kgf, The load, P, is related to the diameter, D by the relationship P/D^2 and this ratio has been standardised for different metals in order that test results are accurate and reproducible. For steel the ratio is 30:1 - for example a 10mm ball can be used with a 3000kgf load or a 1mm ball with a 30kgf load. For aluminium alloys the ratio is 5:1. The load is applied for a fixed length of time, usually 30 seconds. When the indentor is retracted two diameters of the impression, d_1 and d_2, are measured using a microscope with a calibrated graticule.and then averaged as shown in *Fig.1(b)*.



(a) Brinell indentation



(b) measurement of impression diameter

Hardness Testing

The Brinell hardness number (BHN) is found by dividing the load by the surface area of the impression.

The Brinell test is generally used for bulk metal hardness measurements - the impression is larger than that of the Vickers test and this is useful as it averages out any local heterogeneity and is affected less by surface roughness. However, because of the large ball diameter the test cannot be used to determine the hardness variations in a welded joint for which the Vickers test is preferred. Very hard metals, over 450BHN may also cause the ball to deform resulting in an inaccurate reading. To overcome this limitation a tungsten carbide ball is used instead of the hardened steel ball but there is also a hardness limit of 600BHN with this indentor.

Hardness Testing

Vickers Hardness Test

The Vickers hardness test operates on similar principles to the Brinell test, the major difference being the use of a square based pyramidal diamond indentor rather than a hardened steel ball. Also, unlike the Brinell test, the depth of the impression does not affect the accuracy of the reading so the P/D^2 ratio is not important. The diamond does not deform at high loads so the results on very hard materials are more reliable. The load may range from 1 to 120kgf and is applied for between 10 and 15 seconds.

Hardness Testing

The basic principles of operation of the Vickers hardness test are illustrated in *Fig.2* where it can be seen that the load is applied to the indentor by a simple weighted lever. In older machines an an oil filled dash pot is used as a timing mechanism - on more modern equipment this is done electronically.

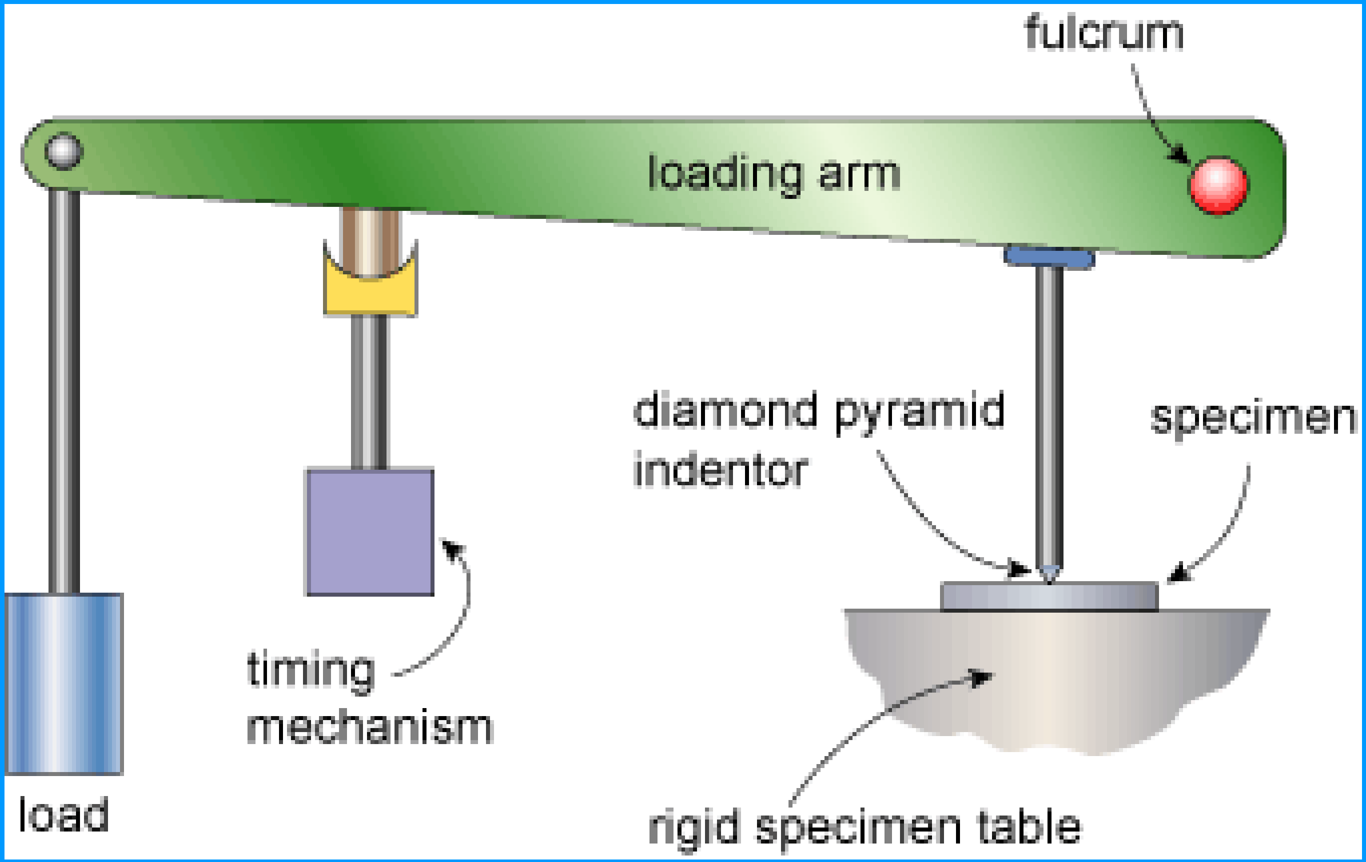


Fig.2. Schematic principles of operation of Vickers hardness machine

Hardness Testing

As illustrated in *Fig.3(b)* two diagonals, d_1 and d_2, are measured, averaged and the surface area calculated then divided into the load applied. As with the Brinell test the diagonal measurement is converted to a hardness figure by referring to a set of tables. The hardness may be reported as Vickers Hardness number (VHN), Diamond Pyramid Number (DPN) or, most commonly, Hv_{xx} where 'xx' represents the load used during the test.

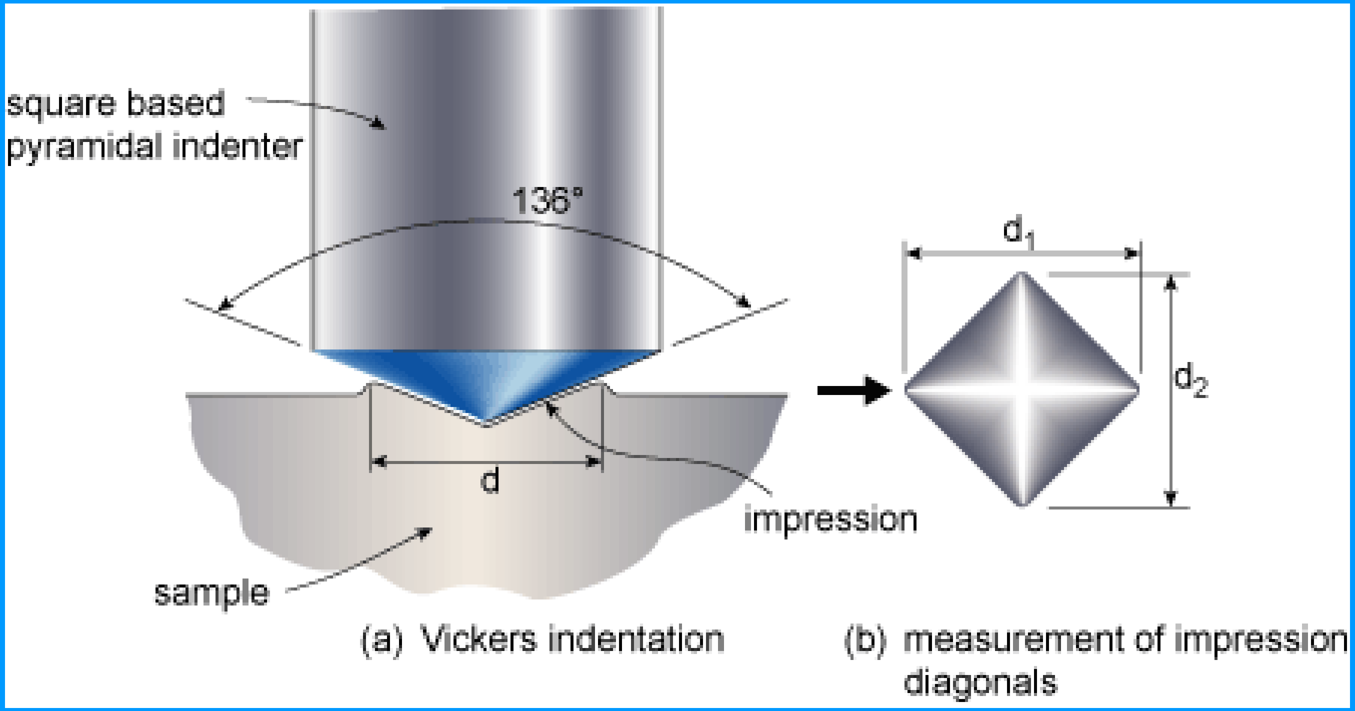


Fig.3. Vickers hardness test

Hardness Testing

The Vickers indentation is smaller than the Brinell impression and thus far smaller areas can be tested, making it possible to carry out a survey across a welded joint, including individual runs and the heat affected zones. The small impression also means that the surface must be flat and perpendicular to the indentor and should have a better than 300 grit finish.

Hardness Testing

Errors in Hardness Testing

There are many factors that can affect the accuracy of the hardness test. such as flatness and surface finish have already been mentioned above but it is worth

re-emphasising the point that flatness is most important - a maximum angle of approximately ± 1° would be regarded as acceptable.

To achieve the required flatness tolerance and surface finish surface grinding or machining may be necessary.

The condition of the indentor is crucial - whilst the Vickers diamond is unlikely to deteriorate with use unless it is damaged or loosened in its mounting by clumsy handling, the Brinell ball will deform over a period of time and inaccurate readings will result.

The specimen dimensions are important - if the test piece is too thin the hardness of the specimen table will affect the result. As a rule of thumb the specimen thickness should be ten times the depth of the impression for the Brinell test and twice that of the Vickers diagonal.

The specimen table should be rigidly supported and must be in good condition - burrs or raised edges beneath the sample will give low readings. Impact loading must be avoided.

Hardness Testing

Micro-hardness testing

Micro-hardness testing may be carried out using any one of three common methods and, as with the macro-hardness tests, measure the size of the impression produced by forcing an indentor into the specimen surface under a dead load, although many of the new test machines use a load cell system.

The three most common tests:

The Knoop test

The Vickers test

The ultrasonic micro-hardness test.

The Knoop test uses a pyramidal indentor that gives an elongated diamond shaped impression with an aspect ratio of around 7:1 The Knoop test is rarely used in Europe where the Vickers test is the preferred method. The loads used for the tests vary from 1gmf to 1kgf and produce impressions that need to be measured by using a microscope with magnifications of up to 100X, although modern machines may be equipped with an image analysis system that enables the process to be automated.

Hardness Testing

The ultrasonic hardness test does not rely upon measuring the size of an impression. Instead, the test uses a Vickers diamond attached to the end of a metal rod. The rod is vibrated at its natural frequency by a piezoelectric converter and then brought into contact with the specimen surface under a small load. The resonant frequency is changed by the size of the impression produced and this change can be measured and converted to a hardness value.

The size of the impression is extremely small and the test may be regarded as non-destructive since it is non-damaging in most applications.

Hardness Testing

The micro-hardness test has a number of applications varying from being a metallurgical research tool to a method of quality control. The test may be used to determine the hardness of different micro-constituents in a metal, as shown in *Fig.1*. Where an impression would be damaging, for instance on a finished product, micro-hardness tests, particularly the ultrasonic test, may be used for quality control purposes. Micro-hardness testing also finds application in the testing of thin foils, case hardened items and decarburised components

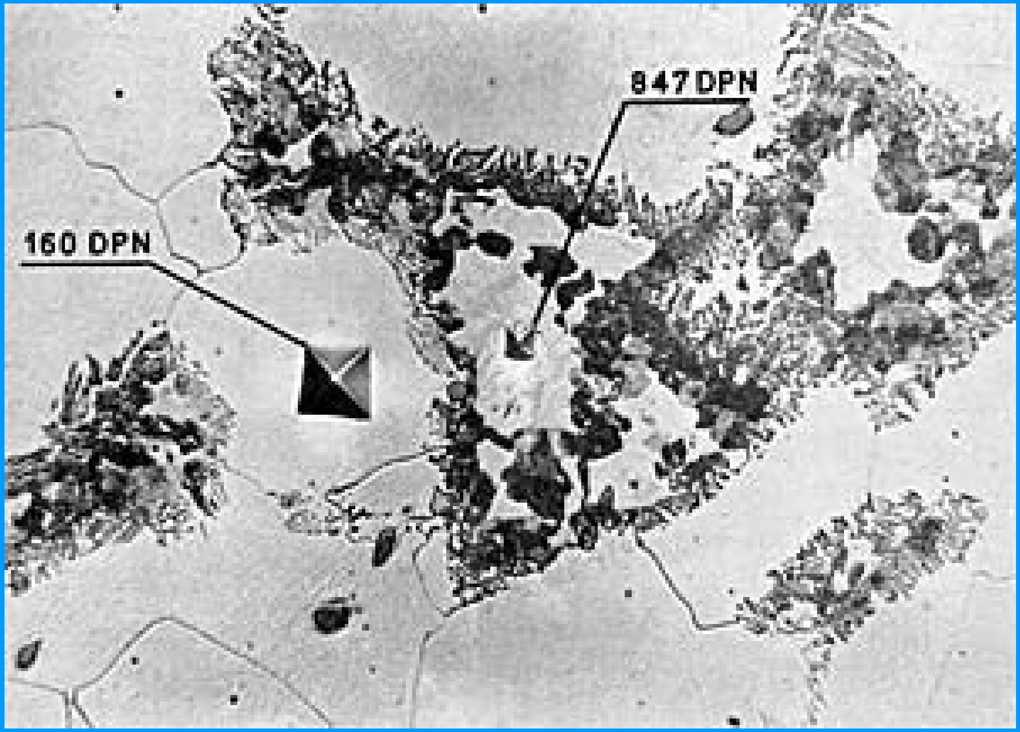


Fig.1. Micro-hardness test

Hardness Testing

Portable hardness tests may be used where the component is too large to be taken to the testing machine or in on-site applications. It is useful on-site, for example, for checking that the correct heat treatment has been carried out on welded items or that welded joints comply with the hardness limits specified by NACE for sour service. There are three principal methods - dynamic rebound, Brinell or Vickers indentation or ultrasonic testing

Hardness Testing

The Leeb hardness test uses dynamic rebound where a hammer is propelled into the test piece surface and the height of the rebound is measured. This gives a measure of the elasticity of the material and hence its hardness.

This type of test is typified by the 'Equotip' test, *Fig.2*, a trademark of Proceq SA. The 'Equotip' tester comprises a hand-held tube that contains a spring loaded hammer. The device is cocked by compressing the hammer against the spring, the device is then positioned vertically on the test surface and the release button is pressed. The hammer strikes the surface, rebounds and the result displayed digitally. Generally the average of five readings is taken.

Fig.2. Equotip test

To obtain a valid result, the position of the device, the flatness of the surface and the flexibility of the component all affect the accuracy of the results. Needless to say the skill and experience of the operator is one of the key factors in producing accurate hardness figures. The results are generally converted to give a hardness in Vickers or Brinell units

Hardness Testing

The other type of portable hardness test in common use is the ultrasonic method described above. Commercially available machines are typified by the Microdur unit supplied by GE Inspection Technologies as shown in *Fig.3*. This type of equipment is electronically based and can be programmed to give hardness readings of any type - Vickers, Brinell, or Rockwell. Needless to say, any of these methods of hardness testing require regular calibration of the equipment, fully trained operators and well prepared surfaces.

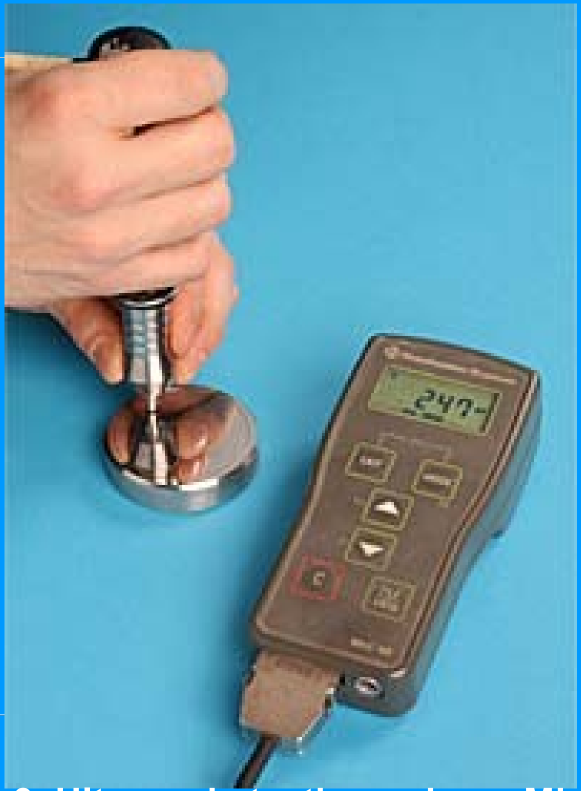


Fig.3. Ultrasonic testing using a Microdur unit

Hardness Testing

Hardness is related to tensile strength - multiplying the Vickers hardness number of a carbon steel by 3.3 will give the approximate ultimate tensile strength in N/mm ^{2} . A hardness traverse across a weld and its HAZs will therefore reveal how the tensile strength varies, as illustrated in *Fig.4* which is for a work hardened aluminium alloy. In carbon or low alloy steels a hardness of above approximately 380HV suggests that the hard brittle microstructure, martensite, has been formed leading to the possibility of cold cracking during fabrication or brittle fracture in service. This fact has been recognised in the specification EN ISO 15614 Part 1 so that a maximum hardness of 380HV is permitted on a hardness traverse of a macro-section from a carbon steel procedure qualification test.

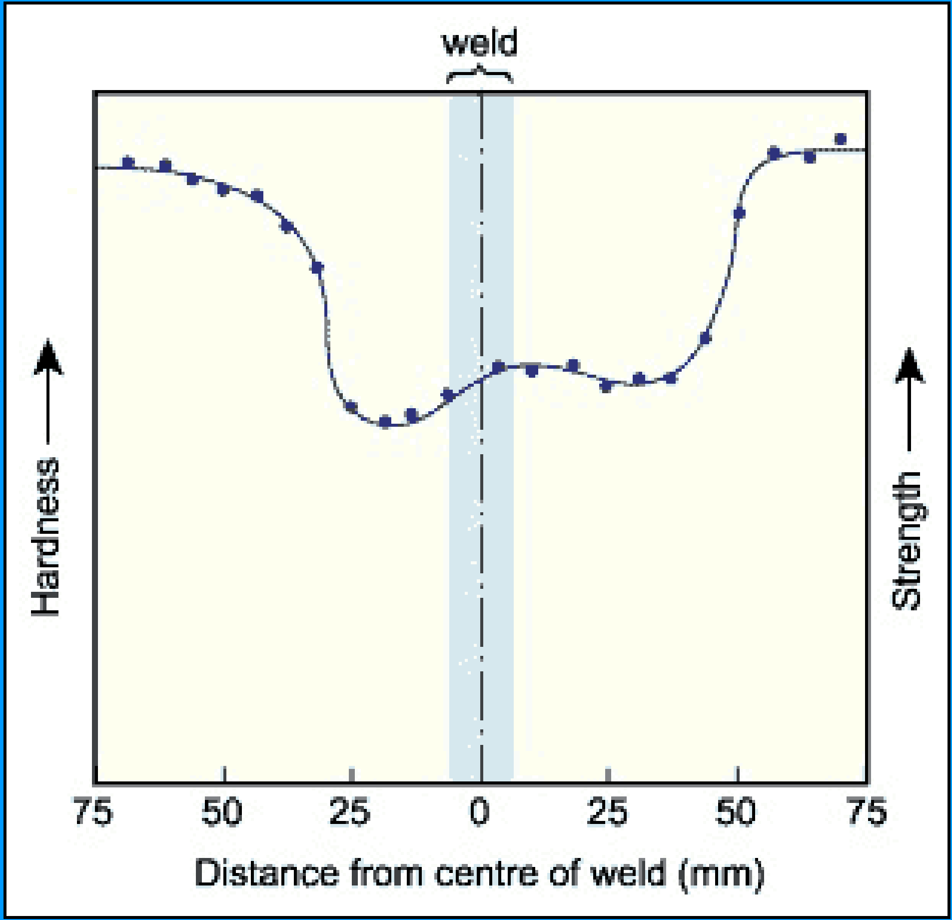


Fig.4. Variation in tensile strength across a weld

Mechanical testing - Tensile testing, Part 1

Inadequate control of the material properties by the supplier, or incompetent joining procedures and operatives are, however, equally crucial to the supply of a product that is safe in use. An example of this dual role of mechanical testing is the tensile test that may be used either to determine the yield strength of a steel for use in design calculations or to ensure that the steel complies with a material specification's strength requirements.

Fig.1. Typical tensile testing machine

Mechanical testing - Tensile testing, Part 1

The test is made by gripping the ends of a suitably prepared standardised test piece in a tensile test machine and then applying a continually increasing uni-axial load until such time as failure occurs.

Specimens are said to be *proportional* when the *gauge length*, L_0, is related to the original cross sectional area, A_0, expressed as $L_0 = k A^{1/2}_0$. The constant k is 5.65 in EN specifications and 5 in the ASME codes. These give gauge lengths of approximately 5x specimen diameter and 4x specimen diameter respectively

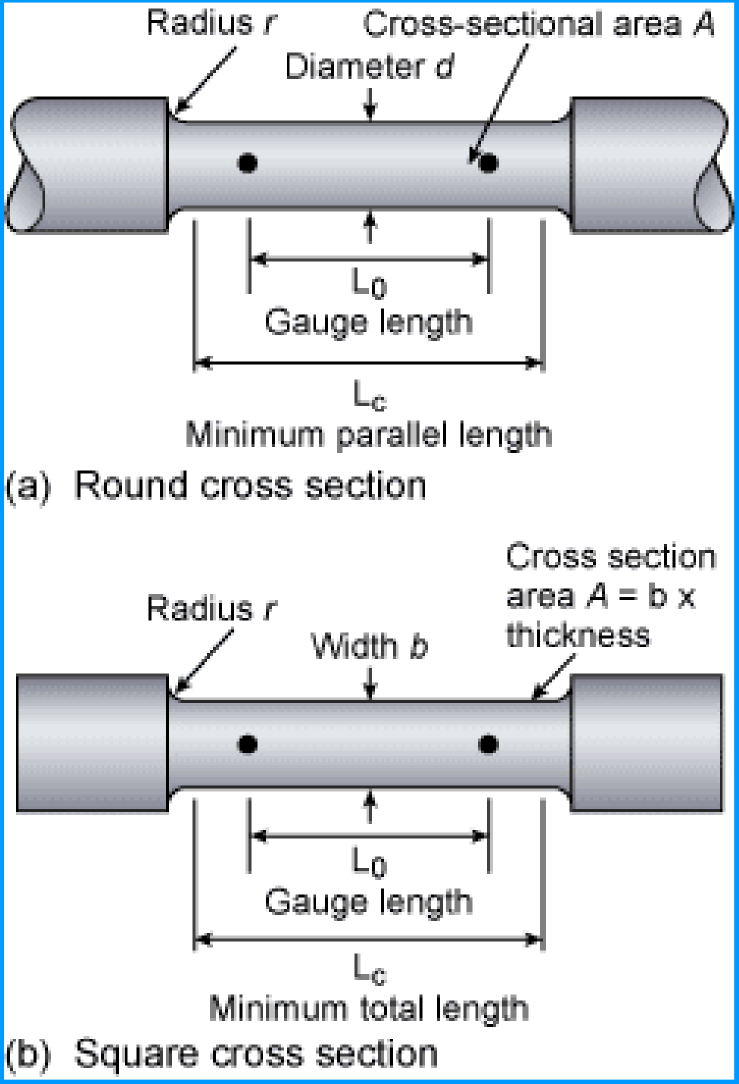


Fig.2. Standard shape tensile specimens

Mechanical testing - Tensile testing, Part 1

Both the load (stress) and the test piece extension (strain) are measured and from this data an *engineering stress/strain curve* is constructed, *Fig.3*.

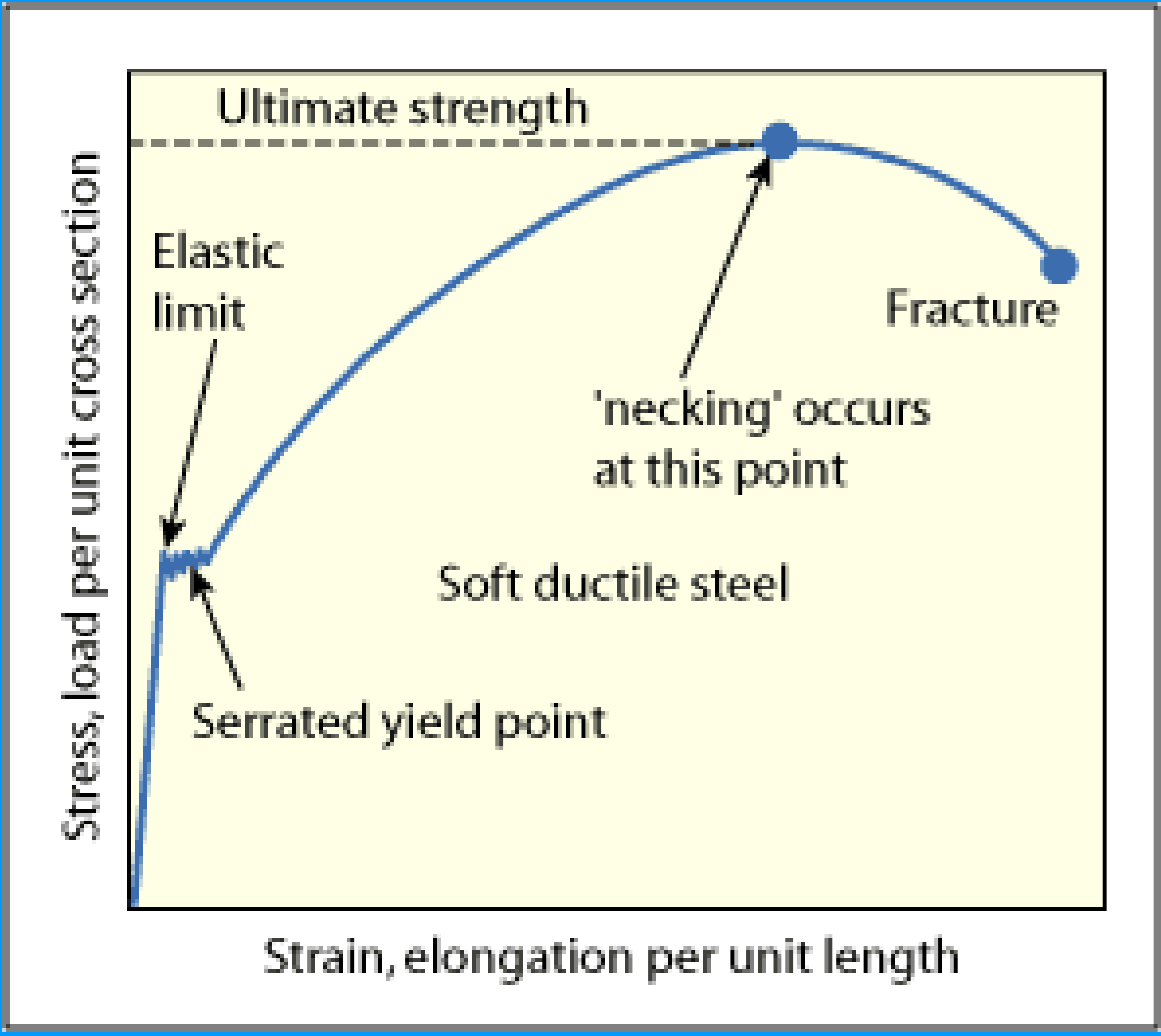


Fig.3. Stress/strain curve

Mechanical testing - Tensile testing, Part 1

From *stress/strain curve* we can determine:

- the *tensile strength*, also known as the *ultimate tensile strength*, the load at failure divided by the original cross sectional area where the ultimate tensile strength (U.T.S.), $_{max} = P_{max}/A_0$, where P_{max} = maximum load, A_0 = original cross sectional area. In EN specifications this parameter is also identified as 'R_m';

b) the *yield point* (YP), the stress at which deformation changes from elastic to plastic behaviour ie below the yield point unloading the specimen means that it returns to its original length, above the yield point permanent plastic deformation has occurred,

YP or $\sigma y = P_{yp}/A_0$ where P_{yp} = load at the yield point. In EN specifications this parameter is also identified as 'R_e';

(a) and (b) are measures of the strength of the material and (c) and (d) indicate the *ductility* or ability of the material to deform without fracture.

Mechanical testing - Tensile testing, Part 1

c) By reassembling the broken specimen we can also measure the *percentage elongation*, El% how much the test piece had stretched at failure where El% = (L_f - L_0 /L_o) x100 where Lf = gauge length at fracture and L0 = original gauge length. In EN specifications this parameter is also identified as 'A' (*Fig.4a*).

d) the *percentage reduction of area*, how much the specimen has necked or reduced in diameter at the point of failure where R of A% =(A_0 - A_f /A_0) x 100 where A_f = cross sectional area at site of the fracture. In EN specifications this parameter is also identified as 'Z', (*Fig.4b*).

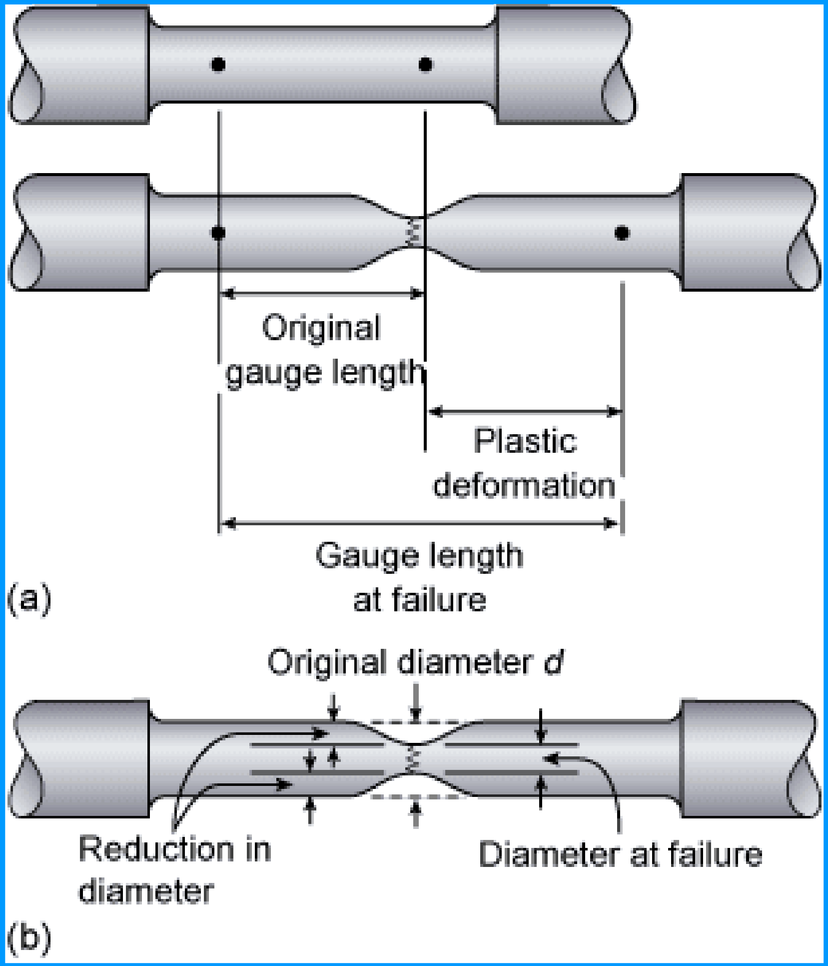


Fig.4
a) Calculation of percentage elongation
b) Calculation of percentage reduction of area

Mechanical testing - Tensile testing, Part 1

The slope of the elastic portion of the curve, essentially a straight line, will give *Young's Modulus of Elasticity*, a measure of how much a structure will elastically deform when loaded.

A low modulus means that a structure will be flexible, a high modulus a structure that will be stiff and inflexible.

The stress strain curve in Fig.3 shows a material that has a well pronounced yield point but only annealed carbon steel exhibits this sort of behaviour. Metals that are strengthened by alloying, by heat treatment or by cold working do not have a pronounced yield and some other method must be found to determine the 'yield point'.

This is done by measuring the *proof stress* (*offset yield strength* in American terminology), the stress required to produce a small specified amount of plastic deformation in the test piece.

Mechanical testing - Tensile testing, Part 1

The proof stress is measured by drawing a line parallel to the elastic portion of the stress/strain curve at a specified strain, this strain being a percentage of the original gauge length, hence *0.2% proof, 1% proof* (see *Fig.5*).

For example, 0.2% proof strength would be measured using 0.2mm of permanent deformation in a specimen with a gauge length of 100mm. Proof strength is therefore not a fixed material characteristic, such as the yield point, but will depend upon how much plastic deformation is specified. It is essential therefore when considering proof strengths that the percentage figure is always quoted. Most steel specifications use 0.2% deformation, $R_{P0.2}$ **in the EN specifications**.

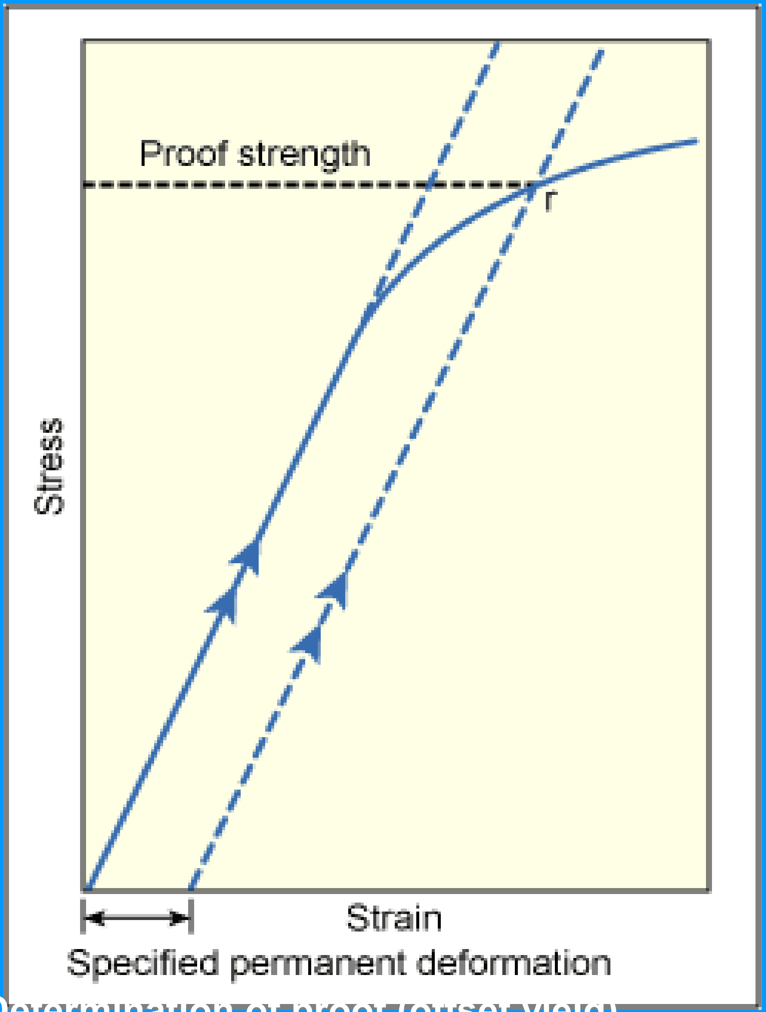


Fig.5. Determination of proof (offset yield) strength

Mechanical testing - Tensile testing, Part 2

Welding procedure approval for tensile testing.

Mechanical testing - Tensile testing, Part 2

To approve a butt welding procedure most specifications such as BS EN 288 Parts 3 and 4 and ASME IX require tensile tests to be carried out. These are generally cross joint (CJ) tensile tests of square or rectangular cross section that, as the name suggests, are oriented across the weld so that both parent metals, both heat affected zones (HAZs) and the weld metal itself are tested (*Fig.1*). The excess weld metal in the cap of the weld may be left in-situ or machined off.

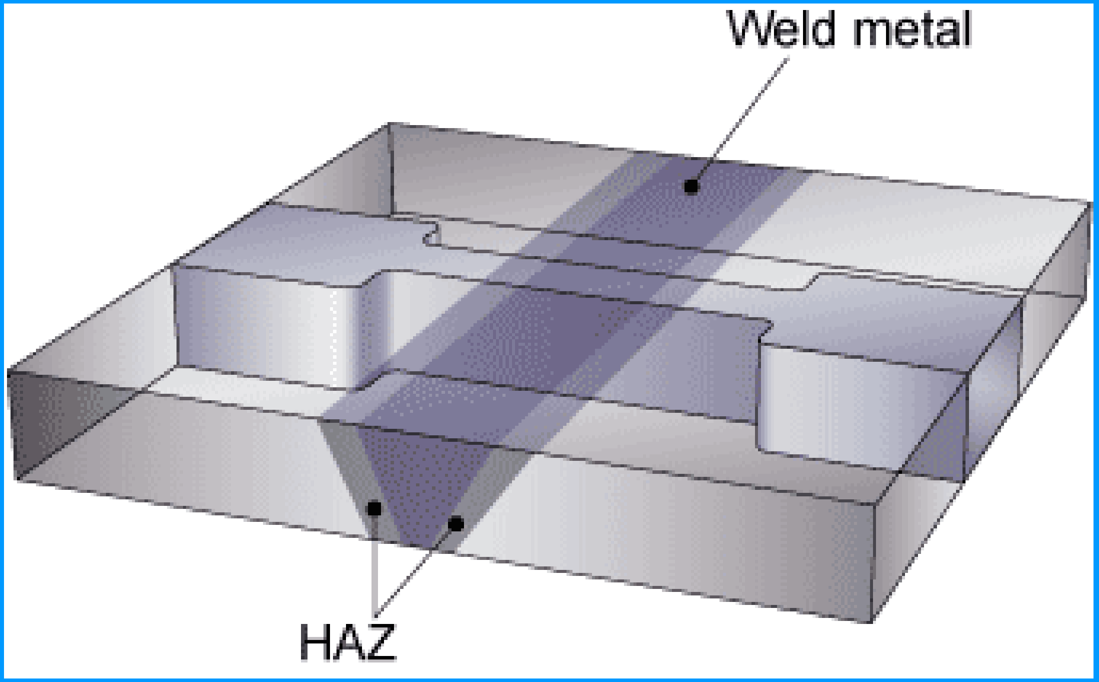


Fig.1. Square or rectangular cross joint tensile test piece

Mechanical testing - Tensile testing, Part 2

The cross joint strength is usually required to exceed the minimum specified UTS of the parent metal. In most situations the weld metal is stronger than the parent metal - it is overmatched - so that failure occurs in the parent metal or the HAZ at a stress above the specified minimum.

The tensile testing of flat plate butt welds presents few problems of specimen shape but those machined from a pipe butt joint are not flat and this curvature can affect the results. In the context of welding procedure approval testing, this is not significant since the test is used only for the determination of the UTS and the position of the fracture. For more accurate results the test piece may be wasted and may be machined flat as illustrated in *Fig.2*.

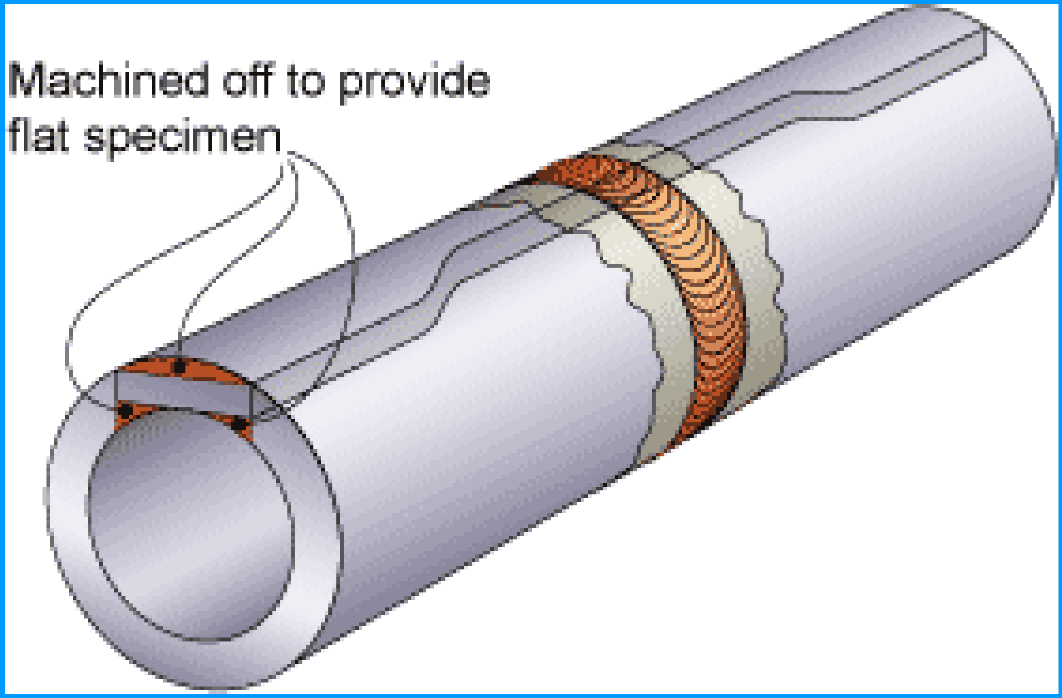


Fig.2. Flat cross joint tensile specimen machined from tube

Mechanical testing - Tensile testing, Part 2

It may be necessary to machine a number of specimens through the thickness of a weld, particularly on very thick joints where the capacity of the tensile machine is insufficient to pull a full thickness specimen, *Fig.3*.

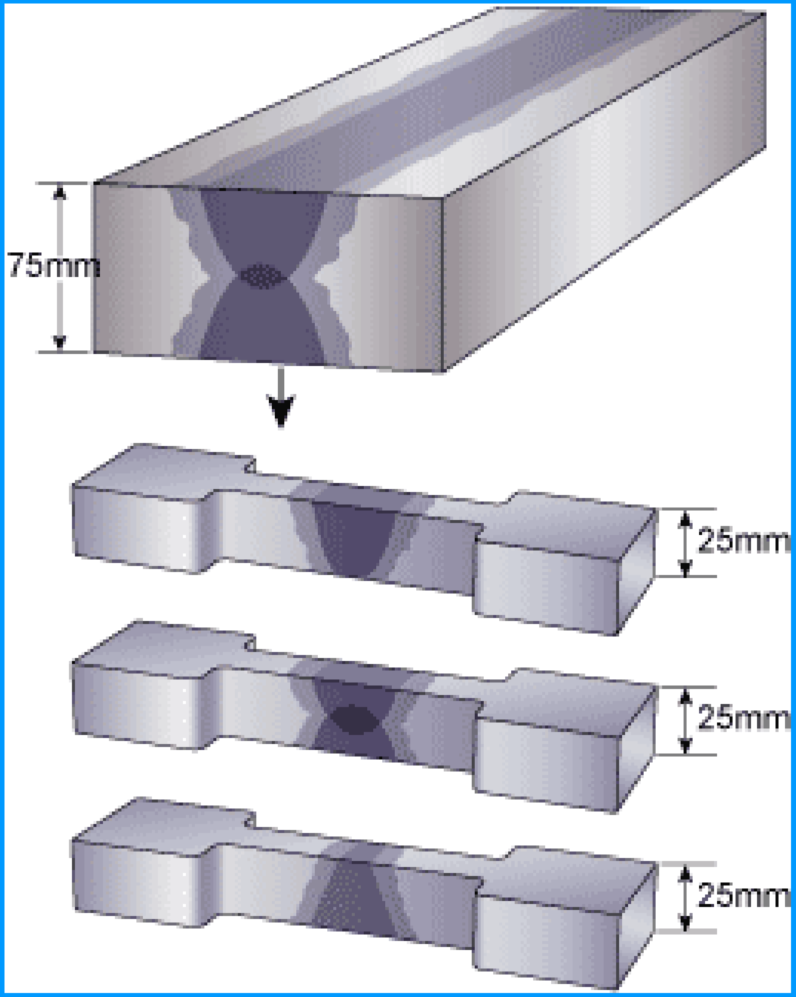


Fig.3. Multiple cross joint specimens machined from thick plate

Mechanical testing - Tensile testing, Part 2

To test a small diameter tube, a solid bar is inserted in the bore of the tube to prevent the tube collapsing when the sample is clamped into the tensile machine.

Most weld testing is carried out with CJ specimens but longitudinally oriented specimens are useful particularly where the weld metal or the HAZ is very strong but ductility is low.

In a CJ specimen the parent metal can yield and finally fail without the weld metal or the HAZ experiencing any significant amount of deformation whereas in a longitudinal test piece the load is shared more equally.

A brittle weld or HAZ will not elongate with the parent metal but will crack, with the cracks opening, but not necessarily propagating into the parent metal, as testing proceeds.

The testing described above is that required by the welding procedure approval specifications.

Since the strength of a metal falls as the temperature rises these specifications require elevated temperature tensile tests to be carried out at the maximum design temperature.

These tests are required to be carried out on the weld metal only and use a longitudinally orientated round cross section specimen from which an accurate measurement of the proof strength can be obtained.

Mechanical testing - Tensile testing, Part 2

Validity of tensile data

The samples taken are assumed to be representative of the bulk of the material but this is not always the case.

A rolled steel plate will be found to have different properties in the longitudinal, transverse and through thickness directions. Material specifications such as BS EN 10028, Flat Products in Steel for Pressure Purposes, therefore, require the tensile test to be taken transverse to the rolling direction so that the steel is tested across the 'grain' - the lower strength, lower ductility direction.

The size of a product can also influence the properties as, during heat treatment, the section thickness will affect the cooling rate with slower cooling rates, and hence softer structures, at the centre of thicker sections.

Mechanical testing - Tensile testing, Part 2

Validity of tensile data

Figure 4 shows how the tensile strength increases but ductility decreases as the testing speed is increased. The speed of the cross head of the tensile machine therefore needs to be controlled and Methods of tensile testing of metallic materials specifies a stress rate range of 6MPa per second to 60MPa per second.

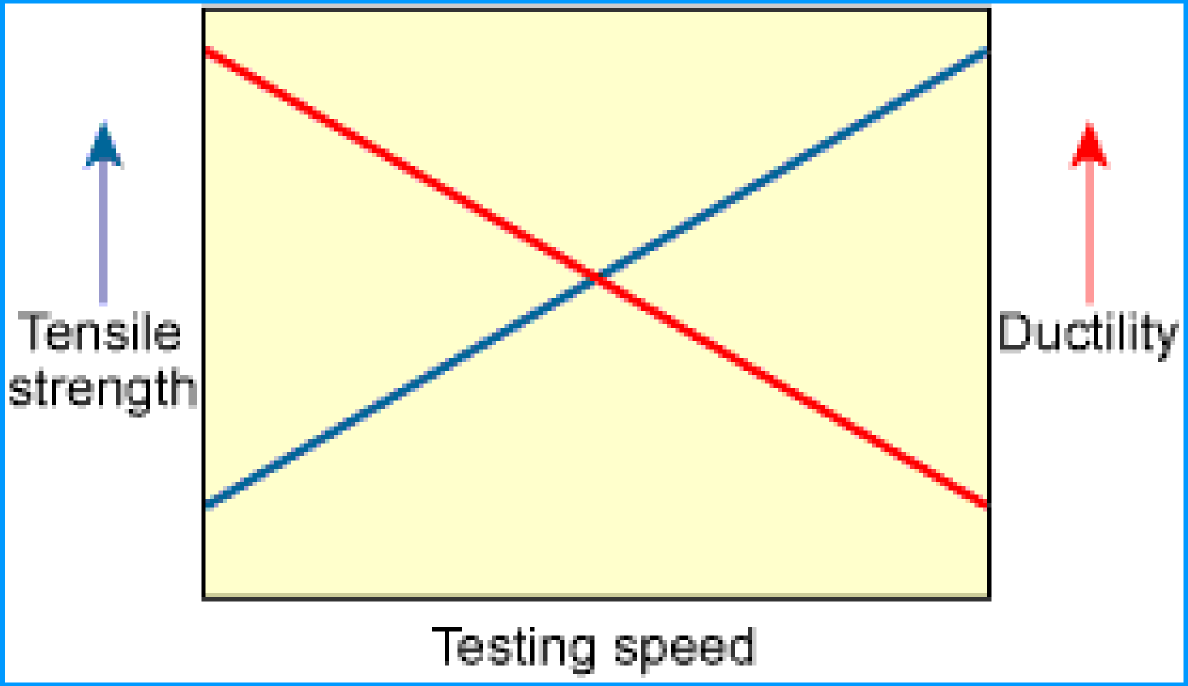


Fig.4. Effect of speed of testing on strength and ductility

Additional files

Adhesive bonding

- Adhesive bonding

Arc welding

- Fume
- MIG/MAG welding
- MMA welding
- Submerged arc welding
- TIG welding
- Underwater wet welding

Brazing & soldering

- Brazing
- Soldering

Ceramics joining

- Ceramics

Composites joining

- Composites

Cutting

- Abrasive water-jet (AWJ) cutting
- Laser cutting
- Oxy-fuel cutting
- Plasma cutting

Diffusion bonding

- Diffusion bonding

Electron beam processing

- Electron beam processing

Friction processing

- Friction extrusion
- Friction hydro pillar processing
- Friction stir welding
- Friction surfacing
- Linear friction welding
- Orbital friction welding
- Radial friction welding
- Rotary friction welding

Laser processing

- Laser welding

Mechanical fastening

- Clinching
- Mechanical fastening
- Self-piercing riveting

Microjoining

- Environmental testing
- Glob top
- Real-time microfocus X-ray inspection
- Wire bonding

Nondestructive testing

- Electromagnetic inspection
- Nondestructive testing
- Real-time microfocus X-ray inspectio
- Thermography
- Ultrasonic inspection

Plastics welding

- Plastics welding - 1
- Plastics welding - 2
- Plastics welding - 3

Resistance welding

- Flash & resistance butt welding
- High frequency welding (ERW)
- Resistance projection welding
- Resistance seam welding
- Resistance spot welding

Surface engineering

- Friction surfacing
- High velocity oxyfuel spraying
- Sol-gel
- Surface engineering & coatings

- Gouging processes
  - Thermal gouging
  - Oxygen-fuel gas flame gouging
  - Manual metal arc gouging
  - Plasma arc gouging
  - Air carbon arc gouging

Weldability

- Weldability of materials - steels
- Weldability of materials - stainless steels
- Weldability of materials - aluminium alloys
- Weldability of materials - nickel and nickel alloys
- Weldability of materials - copper and copper alloys
- Weldability of materials - titanium and titanium alloys
- Weldability of materials - cast irons

Weldability of materials

Steels

In arc welding, as the weld metal needs mechanical properties to match the parent metal, the welder must avoid forming defects in the weld. Imperfections are principally caused by:Techniques to avoid imperfections such as lack of fusion and slag inclusions, which result from poor welder techniques, are relatively well known. However, the welder should be aware that the material itself may be susceptible to formation of imperfections caused by the welding process. In the materials section of the Job Knowledge for Welders, guidelines are given on material weldability and precautions to be taken to avoid defects.

Material types

In terms of Weldability, commonly used materials can be divided into the following types:

•Steels
•Stainless steels
•Aluminium and its alloys
•Nickel and its alloys
•Copper and its alloys
•Titanium and its alloys
•Cast iron

Fusion welding processes can be used to weld most alloys of these materials, in a wide range of thickness. When imperfections are formed, they will be located in either the weld metal or the parent material immediately adjacent to the weld, called the heat affected zone (HAZ). As chemical composition of the weld metal determines the risk of imperfections, the choice of filler metal may be crucial not only in achieving adequate mechanical properties and corrosion resistance but also in producing a sound weld. However, HAZ imperfections are caused by the adverse effect of the heat generated during welding and can only be avoided by strict adherence to the welding procedure.

This part of the materials section of Job Knowledge for Welders considers the weldability of carbon-manganese (C-Mn) steels and low alloy steels.

Weldability of steel groups

European Standard EN 287 identifies a number of steels groups which have similar metallurgical and welding characteristics. The main risks in welding these groups are:

Group W 01 low carbon unalloyed (carbon-manganese) steels and/or low alloyed steels

For thin section, unalloyed materials, these materials are normally readily weldable. However, when welding thicker section material with a flux process (MMA), there is a risk of HAZ cracking which will needs low hydrogen electrodes. The more highly alloyed materials also require preheat, or a low hydrogen welding process, to avoid HAZ cracking .

Group W 02 chromium-molybdenum (CrMo) and/or chromium-molybdenum-vanadium (CrMoV) creep resisting steel

Thin section material may be welded without preheat but using a gas shielded process (TIG and MIG); for thicker section material, and when using a flux process, preheat with low hydrogen electrodes (MMA) is needed to avoid HAZ and weld metal cracking. Post-weld heat treatment is used to improve HAZ toughness.

Group W 03 fine-grained structural steels and nickel steels (2% to 5%)

The weldability is similar to Group W 02 in that preheat is required for welding thick section material with flux processes.

Group W 04 ferritic or martensitic stainless steel, with chromium (12% to 20%)

When using filler to produce matching weld metal strength, preheat is needed to avoid HAZ cracking. Post-weld heat treatment is essential to restore HAZ toughness.

An austenitic stainless steel filler can be used where it is not possible to apply a preheat and post-weld treatment

Stainless steel

Stainless steels are chosen because of their enhanced corrosion resistance, high temperature oxidation resistance or their strength. The various types of stainless steel are identified and guidance given on welding processes and techniques which can be employed in fabricating stainless steel components without impairing the corrosion, oxidation and mechanical properties of the material or introducing defects into the weld.

Material types

The unique properties of the stainless steels are derived from the addition of alloying elements, principally chromium and nickel, to steel. Typically, more than 10% chromium is required to produce a stainless iron. The four grades of stainless steel have been classified according to their material properties and welding requirements:

- Austenitic
- Ferritic
- Martensitic
- Austenitic-ferritic (duplex)

The alloy groups are designated largely according to their microstructure. The first three consist of a single phase but the fourth group contains both ferrite and austenite in the microstructure.

As nickel (plus carbon, manganese and nitrogen) promotes austenite and chromium (plus silicon, molybdenum and niobium) encourages ferrite formation, the structure of welds in commercially available stainless steels can be largely predicted on the basis of their chemical composition. The predicted weld metal structure is shown in the Schaeffler diagram in which austenite and ferrite promoting elements are plotted in terms of the nickel and chromium equivalents.

Because of the different microstructures, the alloy groups have both different welding characteristics and susceptibility to defects.

Austenitic stainless steel

Austenitic stainless steels typically have a composition within the range 16-26% chromium (Cr) and 8-22% nickel (Ni). A commonly used alloy for welded fabrications is Type 304 which contains approximately 18%Cr and 10%Ni. These alloys can be readily welded using any of the arc welding processes (TIG, MIG, MMA and SA). As they are non-hardenable on cooling, they exhibit good toughness and there is no need for pre- or post-weld heat treatment.

Avoiding weld imperfections

Although austenitic stainless steel is readily welded, weld metal and HAZ cracking can occur. Weld metal solidification cracking is more likely in fully austenitic structures which are more crack sensitive than those containing a small amount of ferrite. The beneficial effect of ferrite has been attributed largely to its capacity to dissolve harmful impurities which would otherwise form low melting point segregates and interdendritic cracks.

As the presence of 5-10% ferrite in the microstructure is extremely beneficial, the choice of filler material composition is crucial in suppressing the risk of cracking. An indication of the ferrite-austenite balance for different compositions is provided by the Schaeffler diagram. For example, when welding Type 304 stainless steel, a Type 308 filler material which has a slightly different alloy content, is used.

Ferritic stainless steel

Ferritic stainless steels have a Cr content typically within the range 11-28%. Commonly used alloys include the 430 grade, having 16-18% Cr and 407 grade having 10-12% Cr. As these alloys can be considered to be predominantly single phase and non-hardenable, they can be readily fusion welded. However, a coarse grained HAZ will have poor toughness.

Avoiding weld imperfections

The main problem when welding this type of stainless steel is poor HAZ toughness. Excessive grain coarsening can lead to cracking in highly restrained joints and thick section material. When welding thin section material, (less than 6mm) no special precautions are necessary.

In thicker material, it is necessary to employ a low heat input to minimise the width of the grain coarsened zone and an austenitic filler to produce a tougher weld metal. Although preheating will not reduce the grain size, it will reduce the HAZ cooling rate, maintain the weld metal above the ductile-brittle transition temperature and may reduce residual stresses. Preheat temperature should be within the range 50-250 deg.C depending on material composition.

Martensitic stainless steel

The most common martensitic alloys e.g. type 410, have a moderate chromium content, 12-18% Cr, with low Ni but more importantly have a relatively high carbon content. The principal difference compared with welding the austenitic and ferritic grades of stainless steel is the potentially hard HAZ martensitic structure and the matching composition weld metal. The material can be successfully welded providing precautions are taken to avoid cracking in the HAZ, especially in thick section components and highly restrained joints.

Avoiding weld imperfections

High hardness in the HAZ makes this type of stainless steel very prone to hydrogen cracking. The risk of cracking generally increases with the carbon content. Precautions which must be taken to minimise the risk, include:

- using low hydrogen process (TIG or MIG) and ensure the flux or flux coated consumable are dried (MMA and SAW) according to the manufacturer's instructions;
- preheating to around 200 to 300 deg.C. Actual temperature will depend on welding procedure, chemical composition (especially Cr and C content), section thickness and the amount of hydrogen entering the weld metal;
- maintaining the recommended minimum interpass temperature.
- carrying out post-weld heat treatment, e.g. at 650-750 deg.C. The time and temperature will be determined by chemical composition.

Thin section, low carbon material, typically less than 3mm, can often be welded without preheat, providing that a low hydrogen process is used, the joints have low restraint and attention is paid to cleaning the joint area. Thicker section and higher carbon (> O.1%) material will probably need preheat and post-weld heat treatment. The post-weld heat treatment should be carried out immediately after welding not only to temper (toughen) the structure but also to enable the hydrogen to diffuse away from the weld metal and HAZ.

Duplex stainless steels

Duplex stainless steels have a two phase structure of almost equal proportions of austenite and ferrite. The composition of the most common duplex steels lies within the range 22-26% Cr, 4-7% Ni and 0-3% Mo normally with a small amount of nitrogen (0.1-0.3%) to stabilise the austenite. Modern duplex steels are readily weldable but the procedure, especially maintaining the heat input range, must be strictly followed to obtain the correct weld metal structure.

Avoiding weld imperfections

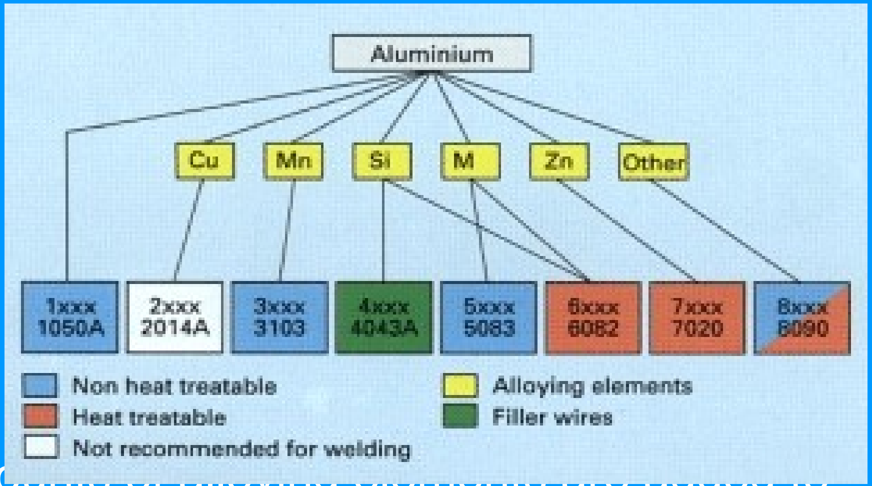
Although most welding processes can be used, low heat input welding procedures are usually avoided. Preheat is not normally required and the maximum interpass temperature must be controlled. Choice of filler is important as it is designed to produce a weld metal structure with a ferrite-austenite balance to match the parent metal. To compensate for nitrogen loss, the filler may be overalloyed with nitrogen or the shielding gas itself may contain a small amount of nitrogen.

Weldability of materials

Aluminium alloys

Aluminium and its alloys are used in fabrications because of their low weight, good corrosion resistance and weldability. Although normally low strength, some of the more complex alloys can have mechanical properties equivalent to steels. The various types of aluminium alloy are identified and guidance is given on fabricating components without impairing corrosion and mechanical properties of the material or introducing imperfections into the weld.

Material types



As pure aluminium is relatively soft, small amounts of alloying elements are added to produce a range of mechanical properties. The alloys are grouped according to the principal alloying elements, Specific commercial alloys have a four-digit designation according to the international specifications for wrought alloys or the ISO alpha - numeric system.

The alloys can be further classified according to the means by which the alloying elements develop mechanical properties, non-heat-treatable or heat-treatable alloys.

Non-heat-treatable alloys
Material strength depends on the effect of work hardening and solid solution hardening of alloy elements such as magnesium, and manganese; the alloying elements are mainly found in the 1xxx, 3xxx and 5xxx series of alloys. When welded, these alloys may lose the effects of work hardening which results in softening of the HAZ adjacent to the weld.
Heat-treatable alloys
Material hardness and strength depend on alloy composition and heat treatment (solution heat treatment and quenching followed by either natural or artificial ageing produces a fine dispersion of the alloying constituents). Principal alloying elements are found in the 2xxx, 6xxx, 7xxx and 8xxx series. Fusion welding redistributes the hardening constituents in the HAZ which locally reduces material strength.
Most of the wrought grades in the 1xxx, 3xxx, 5xxx, 6xxx and medium strength 7xxx (e.g. 7020) series can be fusion welded using TIG, MIG and oxyfuel processes. The 5xxx series alloys, in particular, have excellent weldability. High strength alloys (e.g. 7010 and 7050) and most of the 2xxx series are not recommended for fusion welding because they are prone to liquation and solidification cracking.

Filler alloys
Filler metal composition is determined by:

- weldability of the parent metal
- minimum mechanical properties of the weld metal
- corrosion resistance
- anodic coating requirements

Nominally matching filler metals are often employed for non-heat-treatable alloys. However, for alloy-lean materials and heat-treatable alloys, non-matching fillers are used to prevent solidification cracking.

The choice of filler metal composition for the various weldable alloys is specified in BS 3019 Pt 1 for TIG and BS 3571 Pt 1 for MIG welding; recommended filler metal compositions for the more commonly used alloys are given in the Table.

Designation	ISO	Classification	Filler	Application
1080A	A1998	NHT	1080A	Chemical plant
3103	A1-Mn1	NHT	4043A	Buildings, heat exchangers
4043A	A1-Si5	-	-	Filler wire/rod
5083	A1-Mg4.5Mn	NHT	5556A	Ships, rail wagons, bridges
5251	Al-Mg2	NHT	5356	Road vehicles, marine
5356	Al-Mg5	-	-	Filler wire/rod
5556A	AlMg5Mn	-	-	Filler wire/rod
6061	Al-Mg1SiCn	HT	4043A/5356	Structural, pipes
7020	Al-Zn,4.5Mg1Mn	HT	5556A	Structural, transport
HT = Heat Treatment NHT = Non heat treatable				