3 Welding Imperfections and Materials Inspection

3.1 Definitions see BS EN ISO 6520-1

Imperfection Any deviation from the ideal weld.
Defect An unacceptable imperfection.

Classification of imperfections according to BS EN ISO 6520-1:

This standard classifies the geometric imperfections in case of fusion welding, dividing them into six groups:

1 Cracks.
2 Cavities.
3 Solid inclusions.
4 Lack of fusion and penetration.
5 Imperfect shape and dimensions.
6 Miscellaneous imperfections.

It is important that an imperfection is correctly identified so the cause can be identified and actions taken to prevent further occurrence.

3.2 Cracks

Definition
An imperfection produced by a local rupture in the solid state, which may arise from the effect of cooling or stresses. Cracks are more significant than other types of imperfection as their geometry produces a very large stress concentration at the crack tip, making them more likely to cause fracture.

Types of crack:
- Longitudinal.
- Transverse.
- Radiating (cracks radiating from a common point).
- Crater.
- Branching (group of connected cracks originating from a common crack).

These cracks can be situated in the:
- Weld metal.
- HAZ.
- Parent metal.

Exception: Crater cracks are found only in the weld metal.

Depending on their nature, these cracks can be:

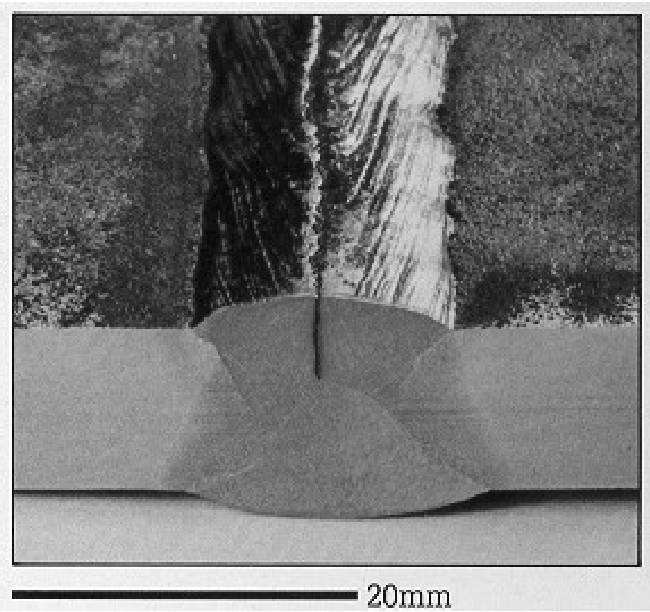
- Hot (ie solidification or liquation cracks).
- Precipitation induced (ie reheat cracks present in creep resisting steels).
- Cold (ie hydrogen induced cracks).
- Lamellar tearing.

3.2.1 Hot cracks

Depending on their location and mode of occurrence, hot cracks can be:

- Solidification cracks: Occur in the weld metal (usually along the centreline of the weld) as a result of the solidification process.
- Liquation cracks: Occur in the coarse grain HAZ, in the near vicinity of the fusion line as a result of heating the material to an elevated temperature, high enough to produce liquation of the low melting point constituents placed on grain boundaries.

3.2.2 Solidification cracks

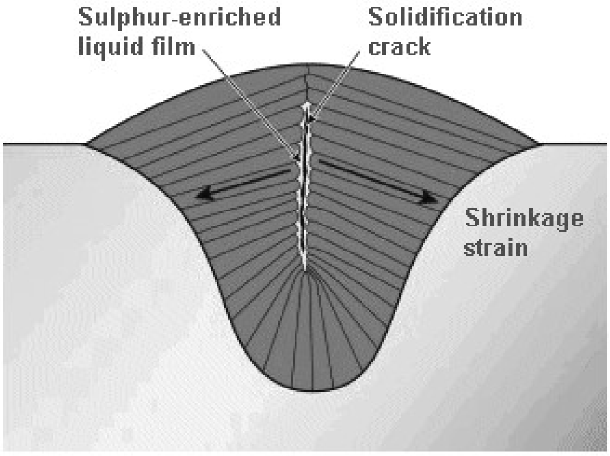


Generally, solidification cracking can occur when:

- Weld metal has a high carbon or impurity (sulphur, etc) content.
- The depth-to-width ratio of the solidifying weld bead is large (deep and narrow).
- Disruption of the heat flow condition occurs, eg stop/start condition.

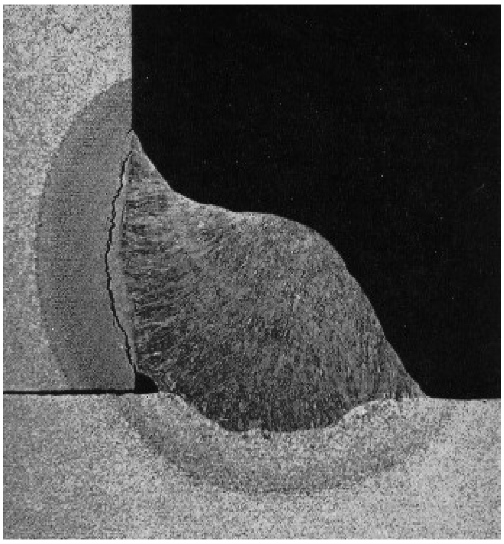
The cracks can be wide and open to the surface like shrinkage voids or sub-surface and possibly narrow.

Solidification cracking is most likely to occur in compositions and result in a wide freezing temperature range. In steels this is commonly created by a higher than normal content of carbon and impurity elements such as sulphur and phosphorus. These elements segregate during solidification, so that intergranular liquid films remain after the bulk of the weld has solidified. The thermal shrinkage of the cooling weld bead can cause these to rupture and form a crack.

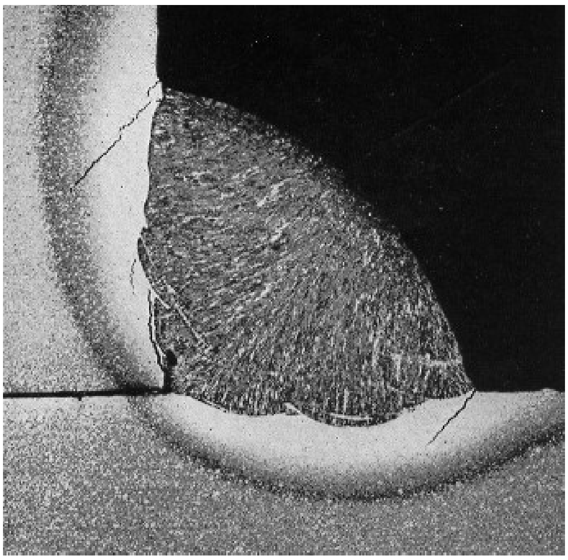


It is important that the welding fabricator does not weld on or near metal surfaces covered with scale or contaminated with oil or grease. Scale can have a high sulphur content and oil and grease can supply both carbon and sulphur. Contamination with low melting point metals such as copper, tin, lead and zinc should also be avoided.

Hydrogen induced cracks



Root (underbead) crack

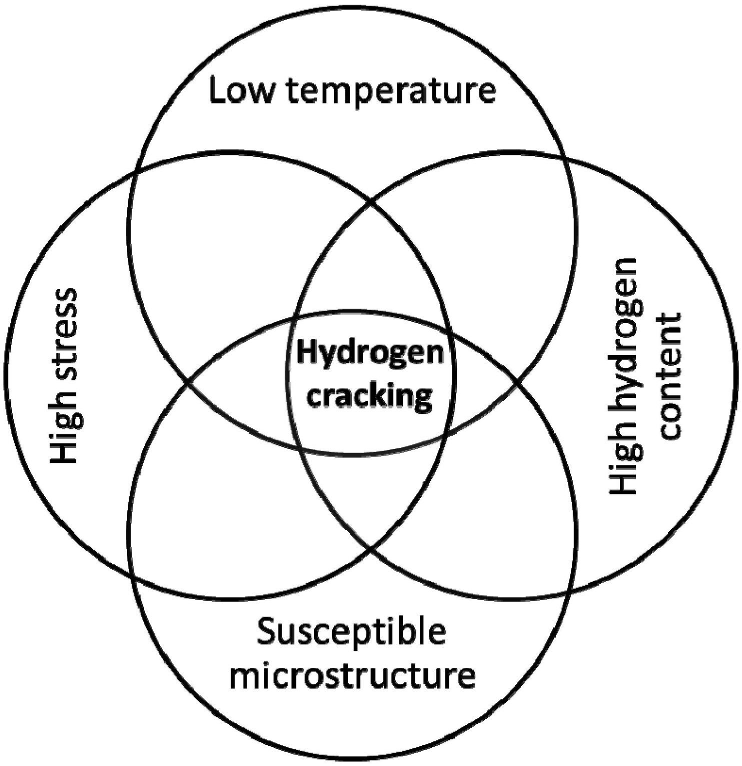


Toe crack

Hydrogen induced cracking occurs primarily in the grain-coarsened region of the HAZ and is also known as cold, delayed or underbead/toe cracking. Underbead cracking lies parallel to the fusion boundary and its path is usually a combination of inter and transgranular cracking. The direction of the principal residual tensile stress can, for toe cracks, cause the crack path to grow progressively away from the fusion boundary towards a region of lower sensitivity to hydrogen cracking. When this happens, the crack growth rate decreases and eventually arrests.

A combination of four factors is necessary to cause HAZ hydrogen cracking:

Hydrogen level	> 15ml/100g of weld metal deposited
Stress	> 0.5 of the yield stress
Temperature	< 300°C
Susceptible microstructure	> 400HV hardness

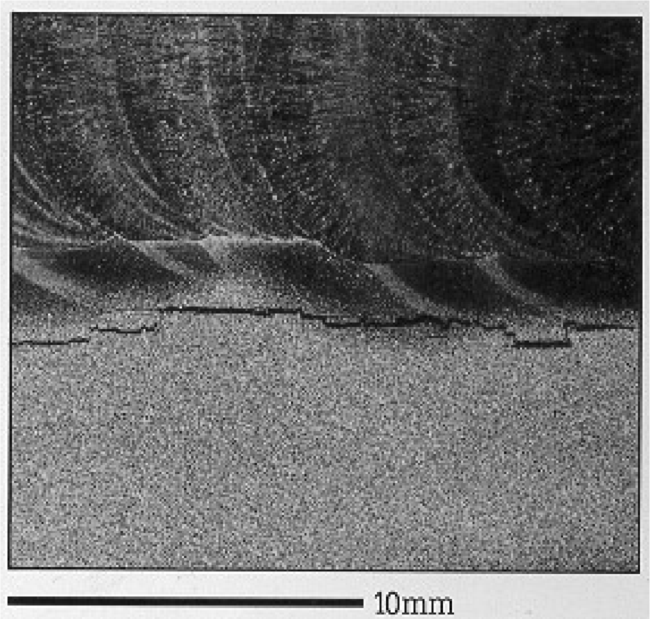


If any one factor is not satisfied, cracking is prevented, so can be avoided through control of one or more factor:

- Apply preheat (slows down the cooling rate and thus avoids the formation of susceptible microstructures).
- Maintain a specific interpass temperature (same effect as preheat).
- Postheat on completion of welding (to reduce the hydrogen content by allowing hydrogen to diffuse from the weld area).
- Apply PWHT (to reduce residual stress and eliminate susceptible microstructures).
- Reduce weld metal hydrogen by proper selection of welding process/consumable (eg use TIG welding instead of MMA, basic covered electrodes instead of cellulose ones).
- Use A multi- instead of singlerun technique (eliminate susceptible microstructures by the self-tempering effect, reduce hydrogen content by allowing hydrogen to effuse from the weld area).
- Use a temper bead or hot pass technique (same effect as above).
- Use austenitic or nickel filler (avoid susceptible microstructure formation and allow hydrogen diffusion out of critical areas).
- Use dry shielding gases (reduce hydrogen content).
- Clean rust from joint (avoid hydrogen contamination from moisture present in the rust).

- Reduce residual stress.
- Blend the weld profile (reduce stress concentration at the toes of the weld).

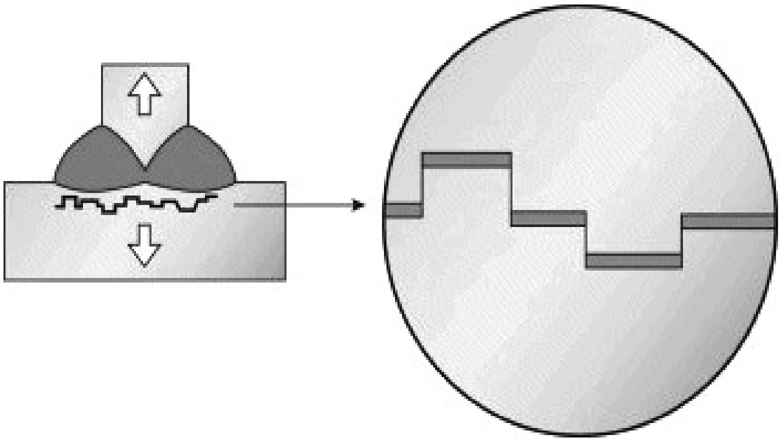
3.2.3 Lamellar tearing



Lamellar tearing occurs only in rolled steel products (primarily plates) and its main distinguishing feature is that the cracking has a terraced appearance.

Cracking occurs in joints where:

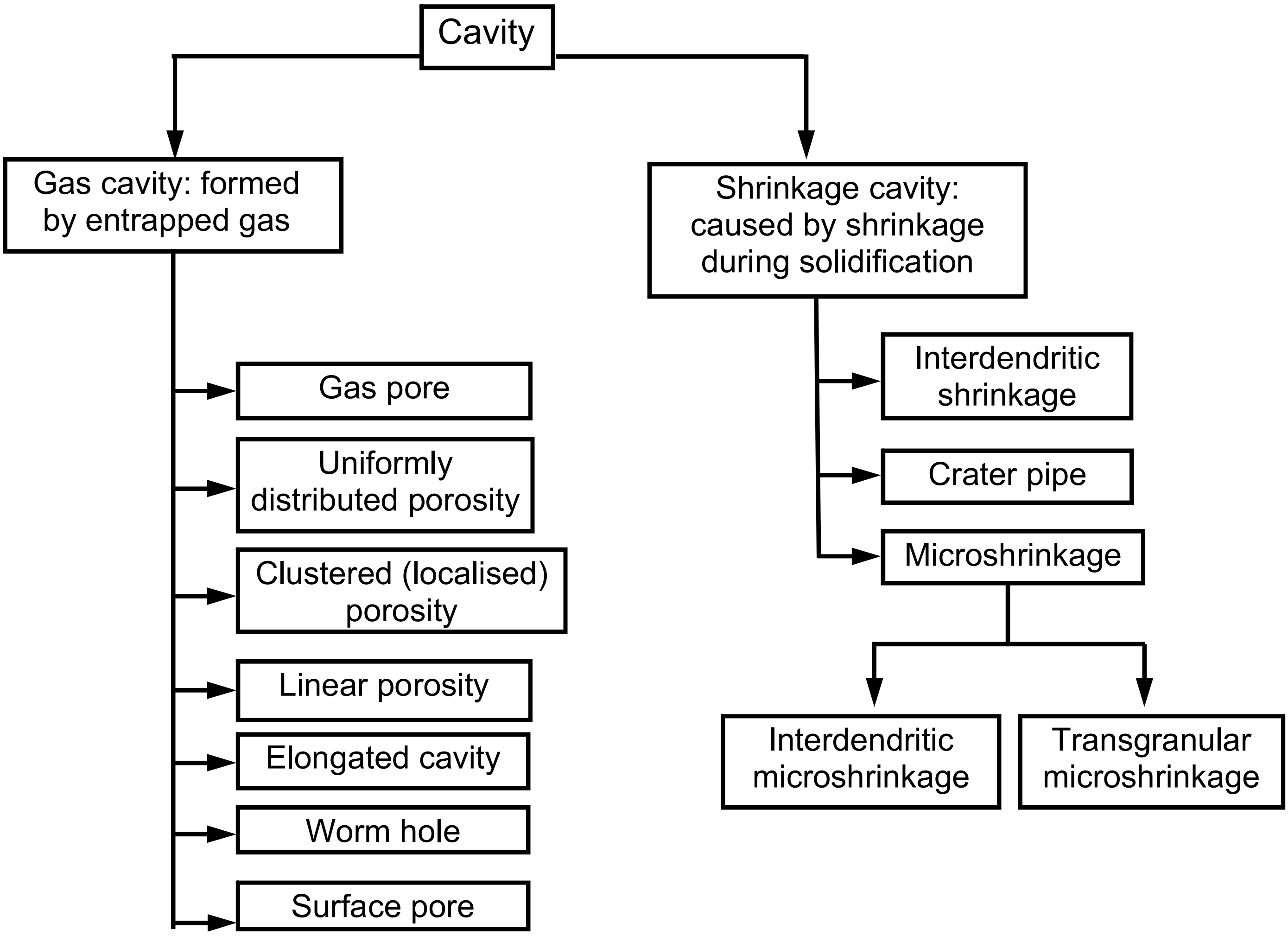
- A thermal contraction strain occurs in the through-thickness direction of steel plate.
- Non-metallic inclusions are present as very thin platelets, with their principal planes parallel to the plate surface.



Contraction strain imposed on the planar non-metallic inclusions results in progressive decohesion to form the roughly rectangular holes which are the horizontal parts of the cracking, parallel to the plate surface. With further strain the vertical parts of the cracking are produced, generally by ductile shear cracking. These two stages create the terraced appearance of these cracks.

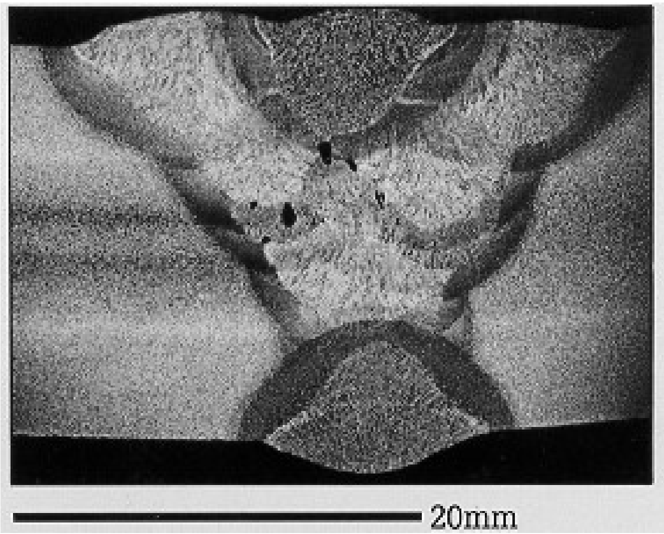
Two main options are available to control the problem in welded joints liable to lamellar tearing:

- Use a clean steel with guaranteed through-thickness properties (Z grade).
- A combination of joint design, restraint control and welding sequence to minimise the risk of cracking.



3.3 Cavities

3.3.1 Gas pore



A gas cavity of essentially spherical shape trapped within the weld metal.

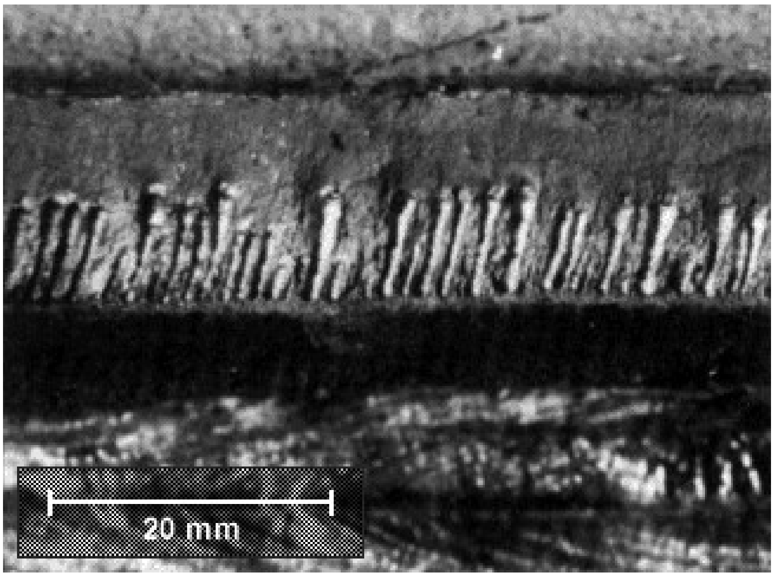
Gas cavity can be present in various forms:

- Isolated.
- Uniformly distributed porosity.
- Clustered (localised) porosity.
- Linear porosity.
- Elongated cavity.
- Surface pore.

Causes	Prevention
Damp fluxes/corroded electrode (MMA)	Use dry electrodes in good condition
Grease/hydrocarbon/water contamination of prepared surface	Clean prepared surface
Air entrapment in gas shield (MIG/MAG, TIG)	Check hose connections
Incorrect/insufficient deoxidant in electrode, filler or parent metal	Use electrode with sufficient deoxidation activity
Too great an arc voltage or length	Reduce voltage and arc length
Gas evolution from priming paints/surface treatment	Identify risk of reaction before surface treatment is applied
Too high a shielding gas flow rate results in turbulence (MIG/MAG, TIG)	Optimise gas flow rate

Comments
Porosity can be localised or finely dispersed voids throughout the weld metal.

3.3.2 Worm holes



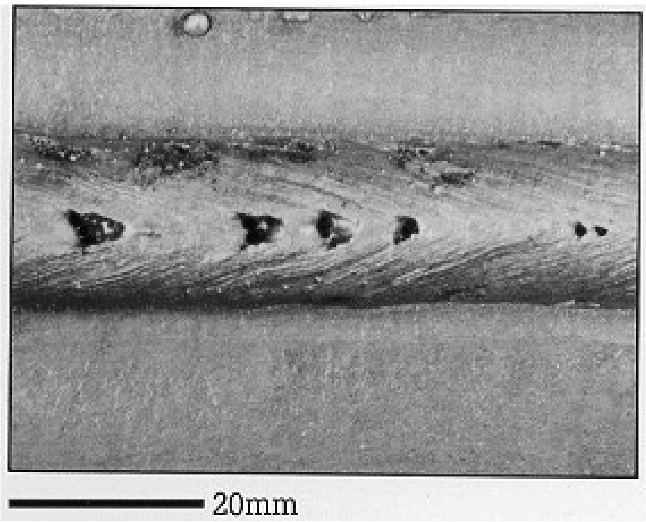
Elongated or tubular cavities formed by trapped gas during the solidification of the weld metal; can occur singly or in groups.

Causes	Prevention
Gross contamination of preparation surface	Introduce preweld cleaning procedures
Laminated work surface	Replace parent material with an unlaminated piece
Crevices in work surface due to joint geometry	Eliminate joint shapes which produce crevices

Comments

Worm holes are caused by the progressive entrapment of gas between the solidifying metal crystals (dendrites) producing characteristic elongated pores of circular cross-section. These can appear as a herringbone array on a radiograph. Some of them may break the surface of the weld.

3.3.3 Surface porosity

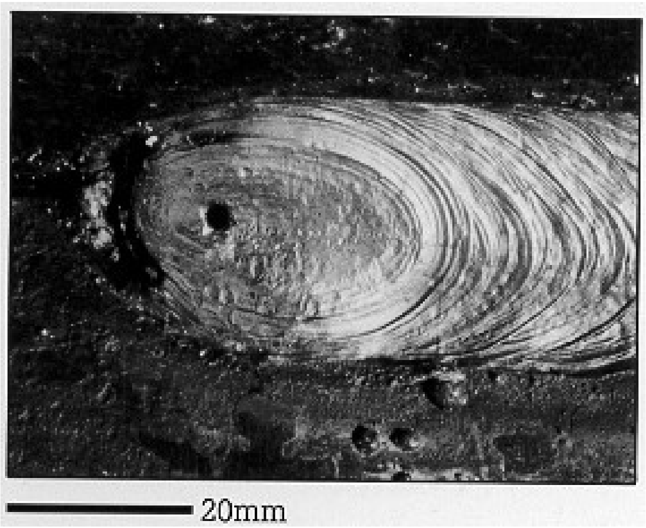


A gas pore that breaks the surface of the weld.

Causes	Prevention
Damp or contaminated surface or electrode	Clean surface and dry electrodes
Low fluxing activity (MIG/MAG)	Use a high activity flux
Excess sulphur (particularly free-cutting steels) producing sulphur dioxide	Use high manganese electrode to produce MnS. Note free-cutting steels (high sulphur) should not normally be welded
Loss of shielding gas due to long arc or high breezes (MIG/MAG)	Improve screening against draughts and reduce arc length
Too high a shielding gas flow rate which results in turbulence (MIG/MAG,TIG)	Optimise gas flow rate

The origins of surface porosity are similar to those for uniform porosity.

Crater pipe



A shrinkage cavity at the end of a weld run, usually caused by shrinkage during solidification.

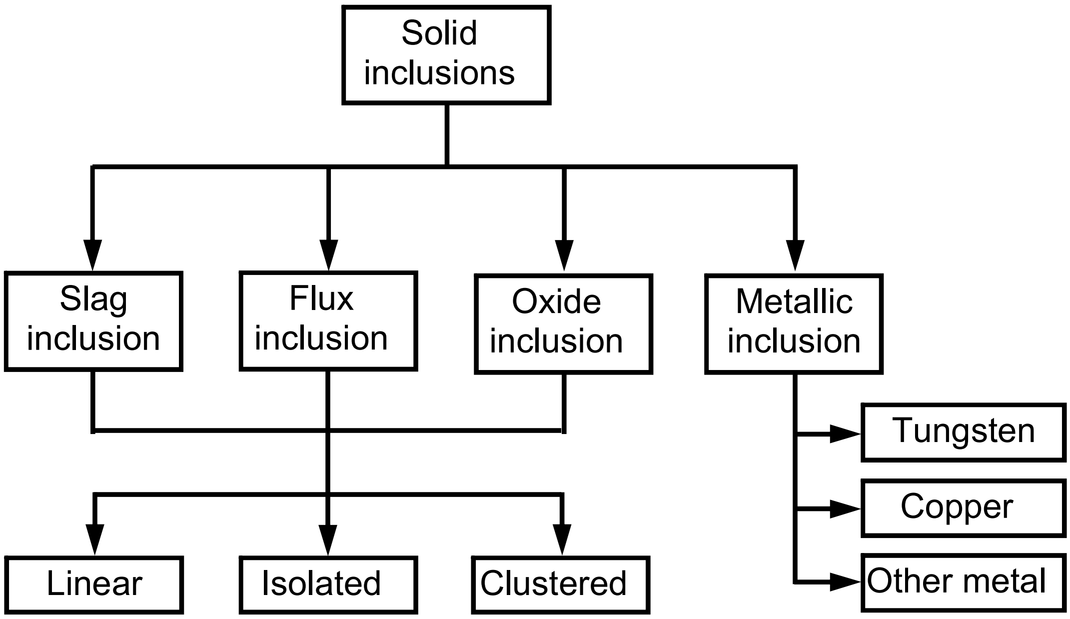
Causes	Prevention
Lack of welder skill due to using processes with too high a current	Retrain welder
Inoperative crater filler (slope out) (TIG)	Use correct crater filling techniques

Crater filling is a particular problem in TIG welding due to its low heat input. To fill the crater for this process it is necessary to reduce the weld current (slope out) in a series of descending steps until the arc is extinguished.

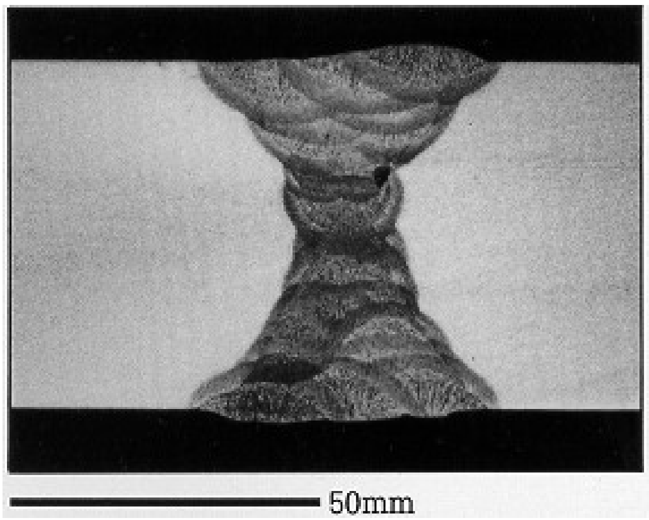
3.4 Solid inclusions

Definition

Solid foreign substances trapped in the weld metal.



3.4.1 Slag inclusions



Slag trapped during welding. The imperfection is an irregular shape so differs in appearance from a gas pore.

Causes	Prevention
Incomplete slag removal from underlying surface of multi-pass weld	Improve inter-run slag removal
Slag flooding ahead of arc	Position work to gain control of slag. Welder needs to correct electrode angle
Entrapment of slag in work surface	Dress/make work surface smooth

A fine dispersion of inclusions may be present within the weld metal, particularly if the MMA process is used. These only become a problem when large or sharp-edged inclusions are produced.

3.4.2 Flux inclusions

Flux trapped during welding. The imperfection is of an irregular shape so differs in appearance from a gas pore. Appear only in flux associated welding processes (ie MMA, SAW and FCAW).

Causes	Prevention
Unfused flux due to damaged coating	Use electrodes in good condition
Flux fails to melt and becomes trapped in the weld (SAW or FCAW)	Change the flux/wire. Adjust welding parameters ie current, voltage etc to produce satisfactory welding conditions

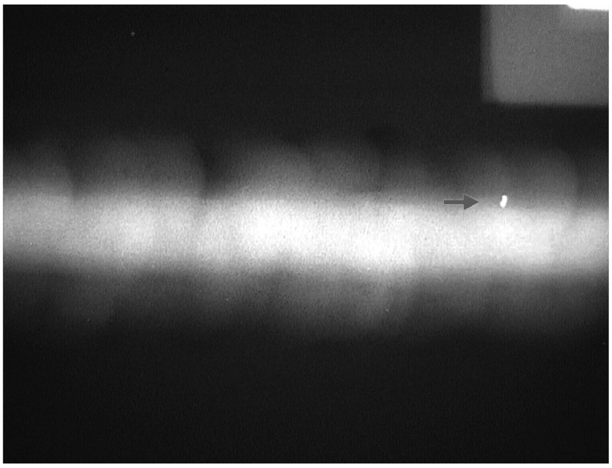
3.4.3 Oxide inclusions

Oxides trapped during welding. The imperfection is of an irregular shape so differs in appearance from a gas pore.

Cause	Prevention
Heavy millscale/rust on work surface	Grind surface prior to welding

A special type of oxide inclusion is puckering, which occurs especially in the case of aluminium alloys. Gross oxide film enfoldment can occur due to a combination of unsatisfactory protection from atmospheric contamination and turbulence in the weld pool.

3.4.4 Tungsten inclusions



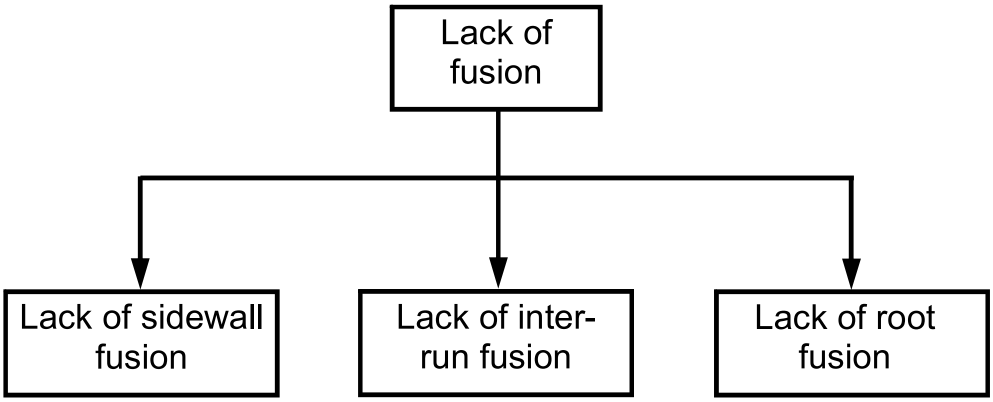
Particles of tungsten can become embedded during TIG welding. This imperfection appears as a light area on radiographs as tungsten is denser than the surrounding metal and absorbs larger amounts of X-/gamma radiation.

Causes	Prevention
Contact of electrode tip with weld pool	Keep tungsten out of weld pool; use HF start
Contact of filler metal with hot tip of electrode	Avoid contact between electrode and filler metal
Contamination of the electrode tip by spatter from the weld pool	Reduce welding current; adjust shielding gas flow rate
Exceeding the current limit for a given electrode size or type	Reduce welding current; replace electrode with a larger diameter one
Extension of electrode beyond the normal distance from the collet, resulting in overheating of the electrode	Reduce electrode extension and/or welding current
Inadequate tightening of the collet	Tighten the collet
Inadequate shielding gas flow rate or excessive draughts resulting in oxidation of the electrode tip	Adjust the shielding gas flow rate; protect the weld area; ensure that the post gas flow after stopping the arc continues for at least 5 seconds
Splits or cracks in the electrode	Change the electrode, ensure the correct size tungsten is selected for the given welding current used
Inadequate shielding gas (eg use of argon-oxygen or argon-carbon dioxide mixtures that are used for MAG welding)	Change to correct gas composition

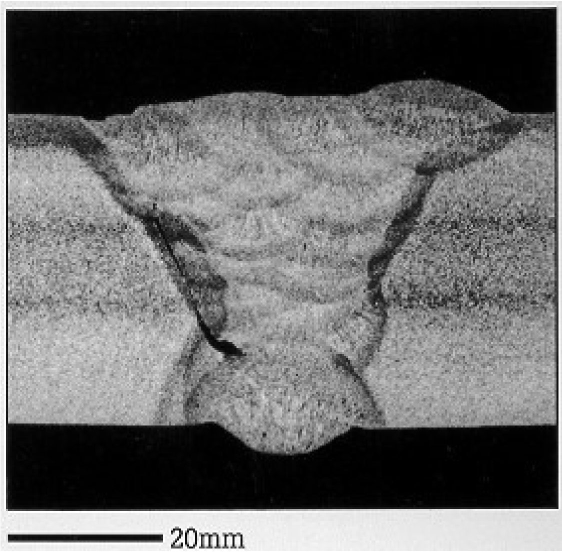
3.5 Lack of fusion and penetration

3.5.1 Lack of fusion

Lack of union between the weld metal and the parent metal or between the successive layers of weld metal.



Lack of sidewall fusion

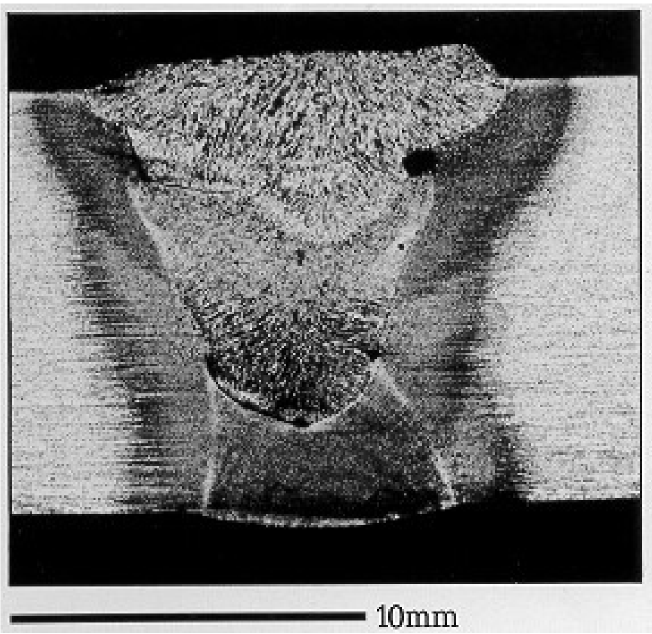


Lack of union between the weld and parent metal at one or both sides of the weld.

Causes	Prevention
Low heat input to weld	Increase arc voltage and/or welding current; decrease travel speed
Molten metal flooding ahead of arc	Improve electrode angle and work position; increase travel speed
Oxide or scale on weld preparation	Improve edge preparation procedure
Excessive inductance in MAG dip transfer welding	Reduce inductance, even if this increases spatter

During welding sufficient heat must be available at the edge of the weld pool to produce fusion with the parent metal.

Lack of inter-run fusion

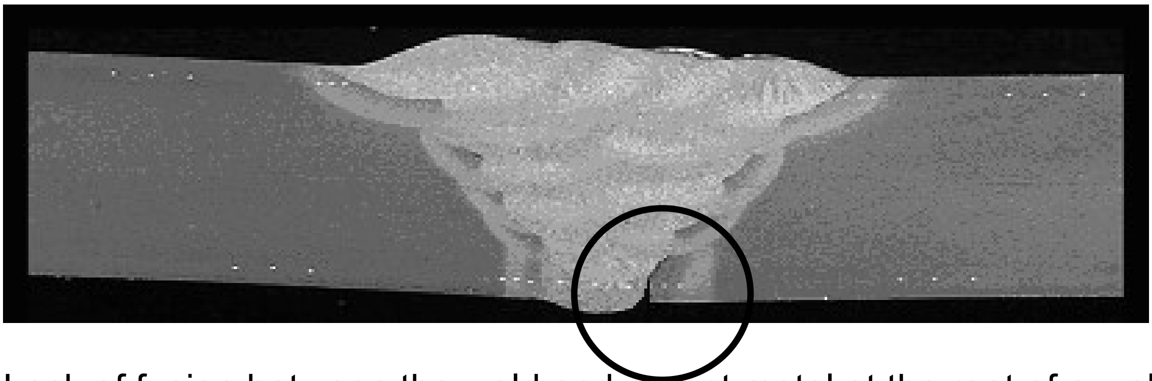


Lack of union along the fusion line, between the weld beads.

Causes	Prevention
Low arc current resulting in low fluidity of weld pool	Increase current
Too high a travel speed	Reduce travel speed
Inaccurate bead placement	Retrain welder

Lack of inter-run fusion produces crevices between the weld beads and causes local entrapment of slag.

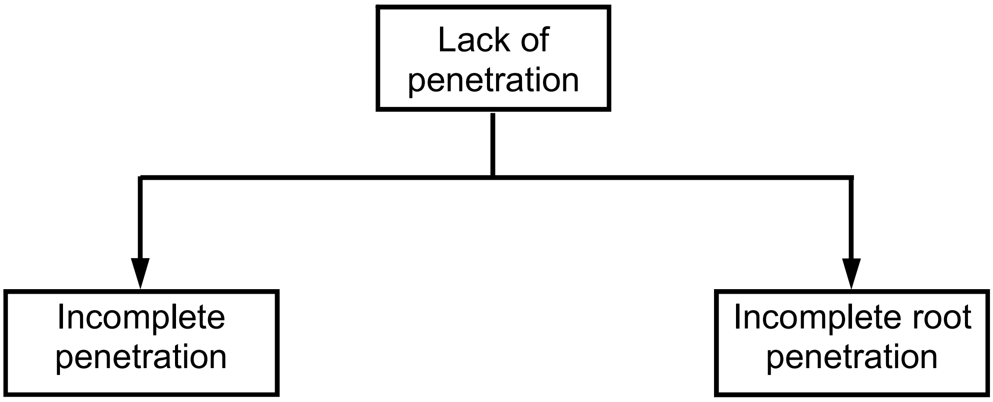
Lack of root fusion



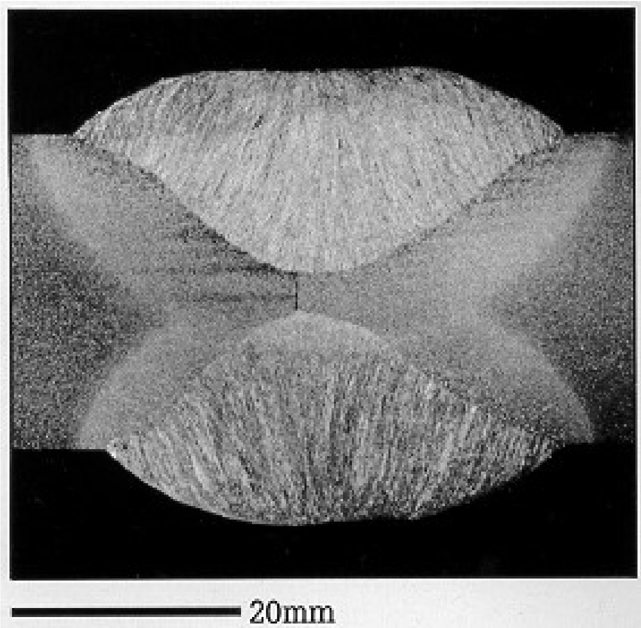
Lack of fusion between the weld and parent metal at the root of a weld.

Causes	Prevention
Low heat input	Increase welding current and/or arc voltage; decrease travel speed
Excessive inductance in MAG dip transfer welding,	Use correct induction setting for the parent metal thickness
MMA electrode too large (low current density)	Reduce electrode size
Use of vertical down welding	Switch to vertical-up procedure
Large root face	Reduce root face
Small root gap	Ensure correct root opening
Incorrect angle or electrode manipulation	Use correct electrode angle. Ensure welder is fully qualified and competent
Excessive misalignment at root	Ensure correct alignment

3.5.2 Lack of penetration



Incomplete penetration

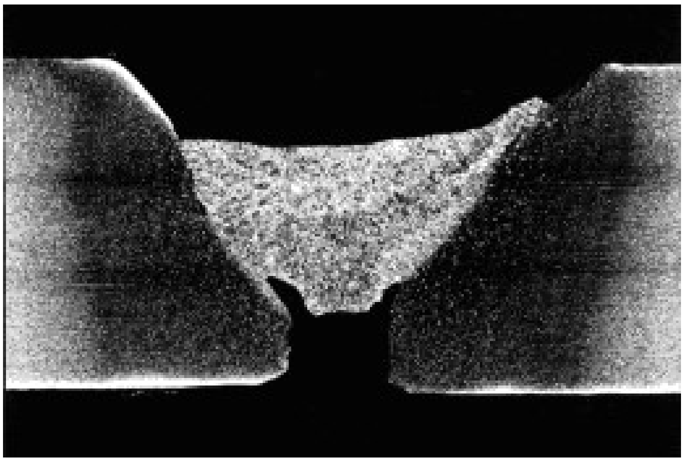


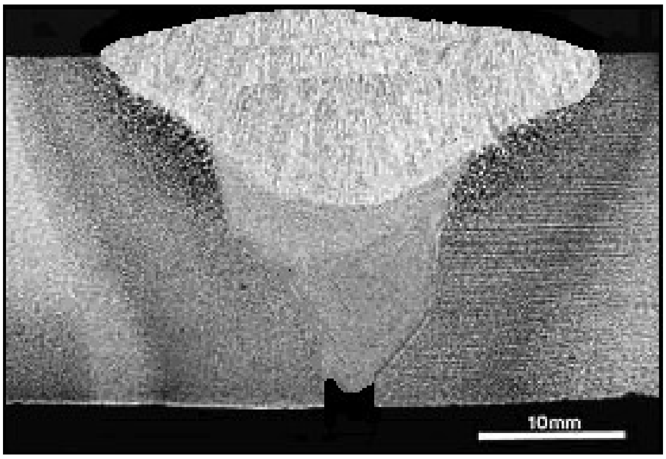
The difference between actual and nominal penetration.

Causes	Prevention
Excessively thick root face, insufficient root gap or failure to cut back to sound metal when back gouging	Improve back gouging technique and ensure the edge preparation is as per approved WPS
Low heat input	Increase welding current and/or arc voltage; decrease travel speed
Excessive inductance in MAG dip transfer welding, pool flooding ahead of arc	Improve electrical settings and possibly switch to spray arc transfer
MMA electrode too large (low current density)	Reduce electrode size
Use of vertical-down welding	Switch to vertical-up procedure

If the weld joint is not of a critical nature, ie the required strength is low and the area is not prone to fatigue cracking, it is possible to produce a partial penetration weld. In this case incomplete root penetration is considered part of this structure and not an imperfection (this would normally be determined by the design or code requirement).

Incomplete root penetration



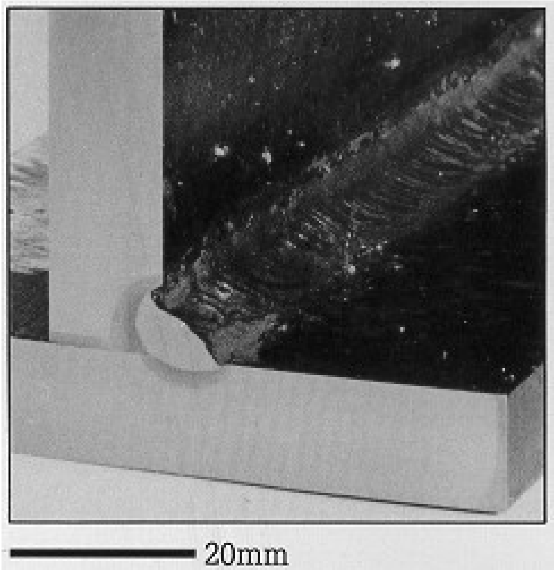


Both fusion faces of the root are not melted. When examined from the root side, you can clearly see both of the root edges unmelted.

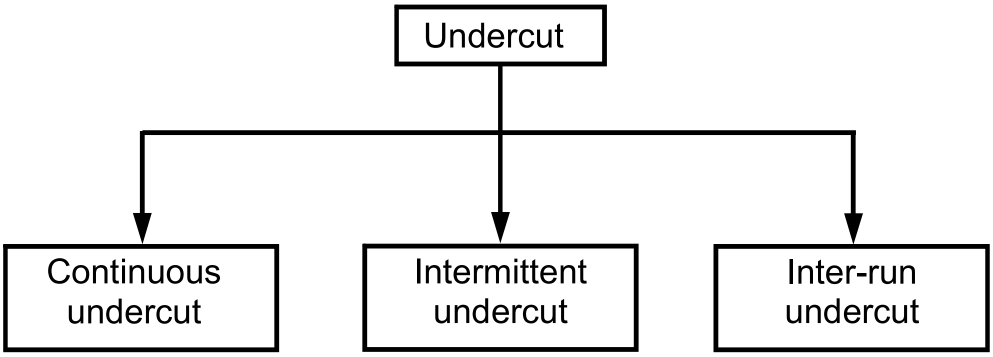
Causes and prevention
Same as for lack of root fusion.

3.6 Imperfect shape and dimensions

3.6.1 Undercut



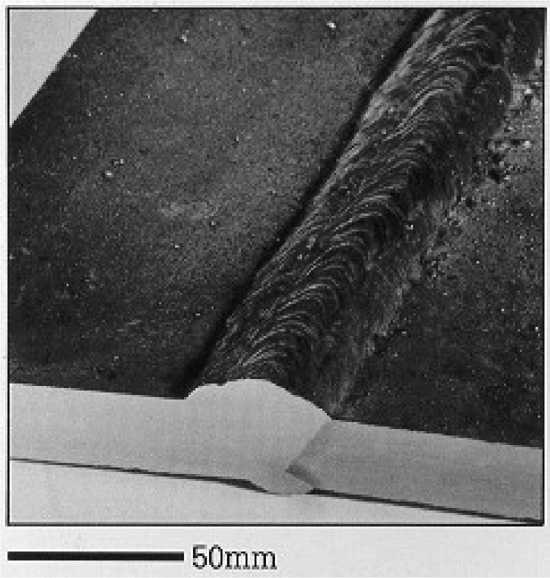
An irregular groove at the toe of a run in the parent metal or previously deposited weld metal due to welding. Characterised by its depth, length and sharpness.



Causes	Prevention
Melting of top edge due to high welding current (especially at free edge) or high travel speed	Reduce power input, especially approaching a free edge where overheating can occur
Attempting a fillet weld in horizontal vertical (PB) position with leg length >9mm	Weld in the flat position or use multi-run techniques
Excessive/incorrect weaving	Reduce weaving width or switch to multi-runs
Incorrect electrode angle	Direct arc towards thicker member
Incorrect shielding gas selection (MAG)	Ensure correct gas mixture for material type and thickness (MAG)

Care must be taken during weld repairs of undercut to control the heat input. If the bead of a repair weld is too small, the cooling rate following welding will be excessive and the parent metal may have an increased hardness and the weld susceptible to hydrogen cracking.

3.6.2 Excess weld metal

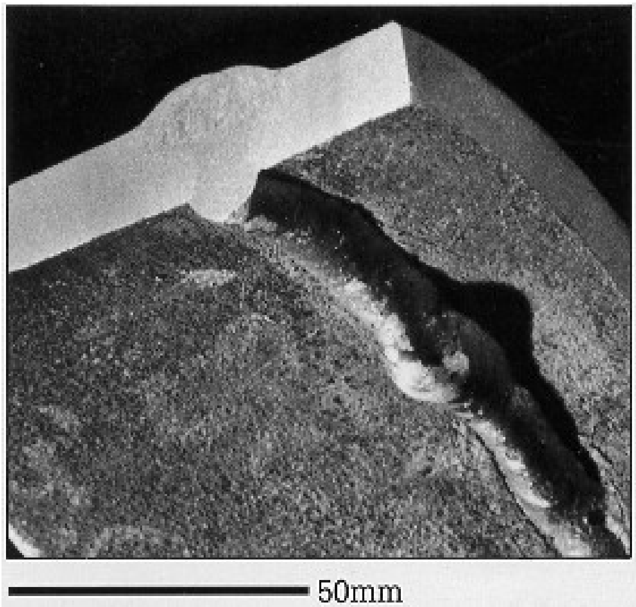


Excess weld metal is the extra metal that produces excessive convexity in fillet welds and a weld thickness greater than the parent metal plate in butt welds. It is regarded as an imperfection only when the height of the excess weld metal is greater than a specified limit.

Causes	Prevention
Excess arc energy (MAG, SAW)	Reduction of heat input
Shallow edge preparation	Deepen edge preparation
Faulty electrode manipulation or build-up sequence	Improve welder skill
Incorrect electrode size	Reduce electrode size
Too slow a travel speed	Ensure correct travel speed is used
Incorrect electrode angle	Ensure correct electrode angle is used
Wrong polarity used (electrode polarity DC-Ve (MMA, SAW)	Ensure correct polarity ie DC+Ve Note DC-Ve must be used for TIG

The term reinforcement used to designate this feature of the weld is misleading since the excess metal does not normally produce a stronger weld in a butt joint in ordinary steel. This imperfection can become a problem, as the angle of the weld toe can be sharp, leading to an increased stress concentration at the toes of the weld and fatigue cracking.

3.6.3 Excess penetration

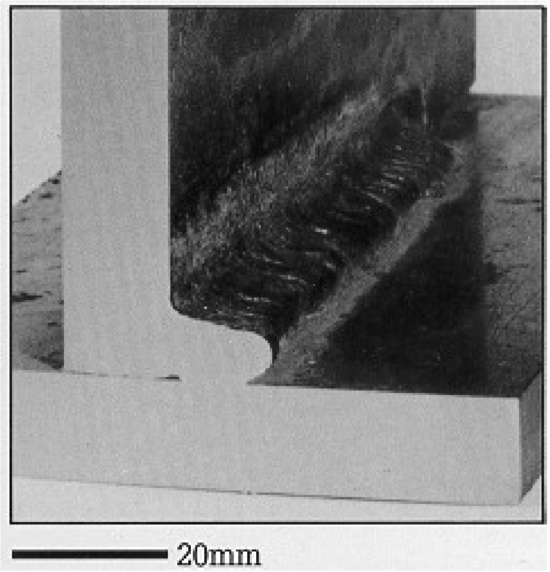


Projection of the root penetration bead beyond a specified limit, local or continuous.

Causes	Prevention
Weld heat input too high	Reduce arc voltage and/or welding current; increase welding speed
Incorrect weld preparation ie excessive root gap, thin edge preparation, lack of backing	Improve workpiece preparation
Use of electrode unsuited to welding position	Use correct electrode for position
Lack of welder skill	Retrain welder

The maintenance of a penetration bead of uniform dimensions requires a great deal of skill, particularly in pipe butt welding. This can be made more difficult if there is restricted access to the weld or a narrow preparation. Permanent or temporary backing bars can assist in the control of penetration.

3.6.4 Overlap

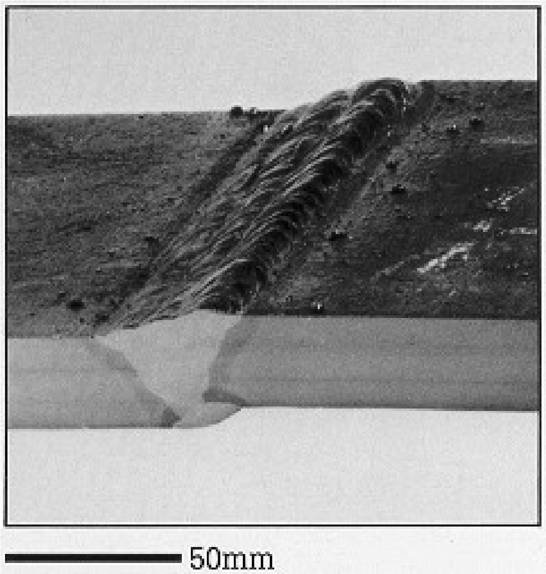


Imperfection at the toe of a weld caused by metal flowing on to the surface of the parent metal without fusing to it.

Causes	Prevention
Poor electrode manipulation (MMA)	Retrain welder
High heat input/low travel speed causing surface flow of fillet welds	Reduce heat input or limit leg size to 9mm max leg size for single pass fillets
Incorrect positioning of weld	Change to flat position
Wrong electrode coating type resulting in too high a fluidity	Change electrode coating type to a more suitable fast freezing type which is less fluid

For a fillet weld overlap is often associated with undercut, as if the weld pool is too fluid the top of the weld will flow away to produce undercut at the top and overlap at the base. If the volume of the weld pool is too large in a fillet weld in horizontal-vertical (PB) position, weld metal will collapse due to gravity, producing both defects (undercut at the top and overlap at the base), this defect is called sagging.

3.6.5 Linear misalignment

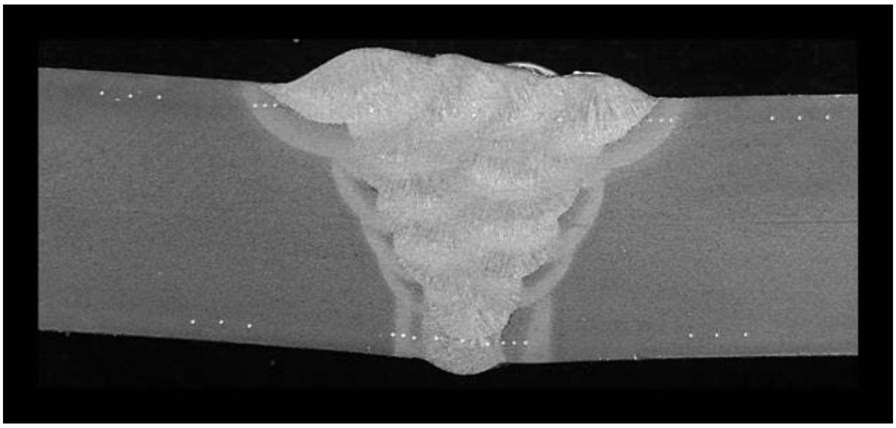


Misalignment between two welded pieces such that while their surface planes are parallel, they are not in the required same plane.

Causes	Prevention
Inaccuracies in assembly procedures or distortion from other welds	Adequate checking of alignment prior to welding coupled with the use of clamps and wedges
Excessive out of flatness in hot rolled plates or sections	Check accuracy of rolled section prior to welding

Misalignment is not a weld imperfection, but a structural preparation problem. Even a small amount of misalignment can drastically increase the local shear stress at a joint and induce bending stress.

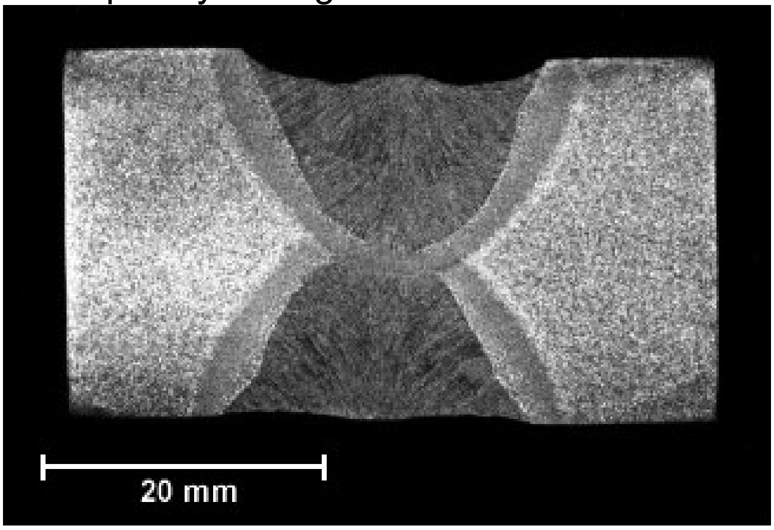
3.6.6 Angular distortion



Misalignment between two welded pieces such that their surface planes are not parallel or at the intended angle.

Causes and prevention same as for linear misalignment.

Incompletely filled groove

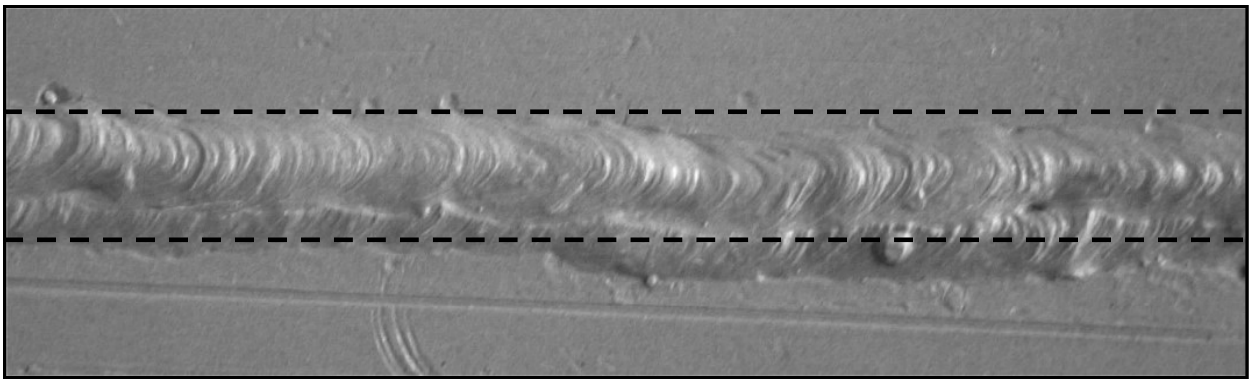


Continuous or intermittent channel in the weld surface due to insufficient deposition of weld filler metal.

Causes	Prevention
Insufficient weld metal	Increase the number of weld runs
Irregular weld bead surface	Retrain welder

This imperfection differs from undercut, as it reduces the load-bearing capacity of a weld, whereas undercut produces a sharp stress-raising notch at the edge of a weld.

3.6.7 Irregular width

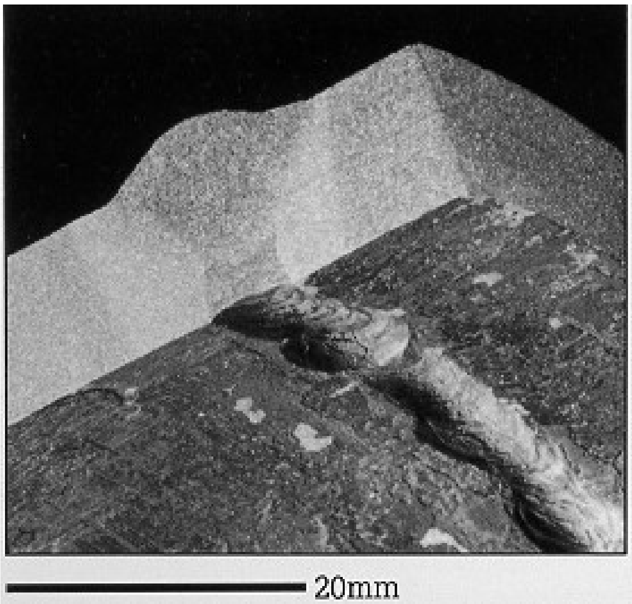


Excessive variation in width of the weld.

Causes	Prevention
Severe arc blow	Switch from DC to AC, keep arc length as short as possible
Irregular weld bead surface	Retrain welder

Although this imperfection may not affect the integrity of the completed weld, it can affect the width of HAZ and reduce the load-carrying capacity of the joint (in fine-grained structural steels) or impair corrosion resistance (in duplex stainless steels).

3.6.8 Root concavity

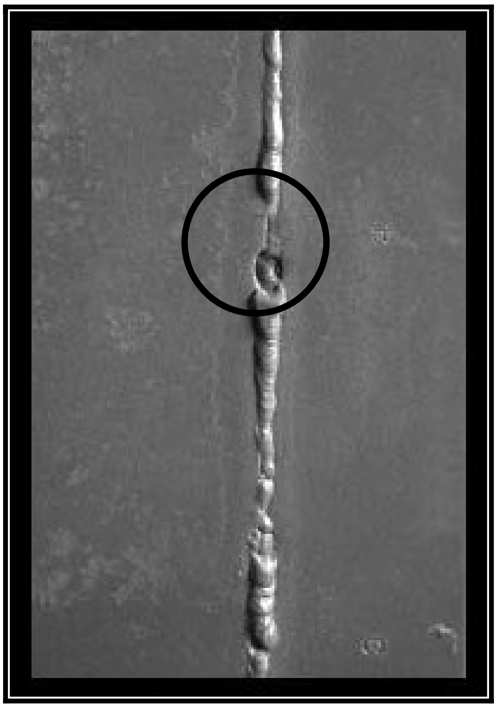


A shallow groove that occurs due to shrinkage at the root of a butt weld.

Causes	Prevention
Insufficient arc power to produce positive bead	Raise arc energy
Incorrect preparation/fit-up	Work to WPS
Excessive backing gas pressure (TIG)	Reduce gas pressure
Lack of welder skill	Retrain welder
Slag flooding in backing bar groove	Tilt work to prevent slag flooding

A backing strip can be used to control the extent of the root bead.

3.6.9 Burn-through



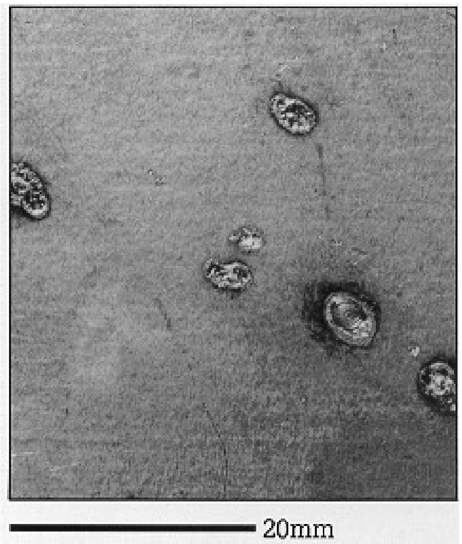
A collapse of the weld pool resulting in a hole in the weld.

Causes	Prevention
Insufficient travel speed	Increase the travel speed
Excessive welding current	Reduce welding current
Lack of welder skill	Retrain welder
Excessive grinding of root face	More care taken, retrain welder
Excessive root gap	Ensure correct fit-up

This is a gross imperfection which occurs due to lack of welder skill. It can be repaired by bridging the gap formed into the joint, but requires a great deal of attention.

3.7 Miscellaneous imperfections

3.7.1 Stray arc

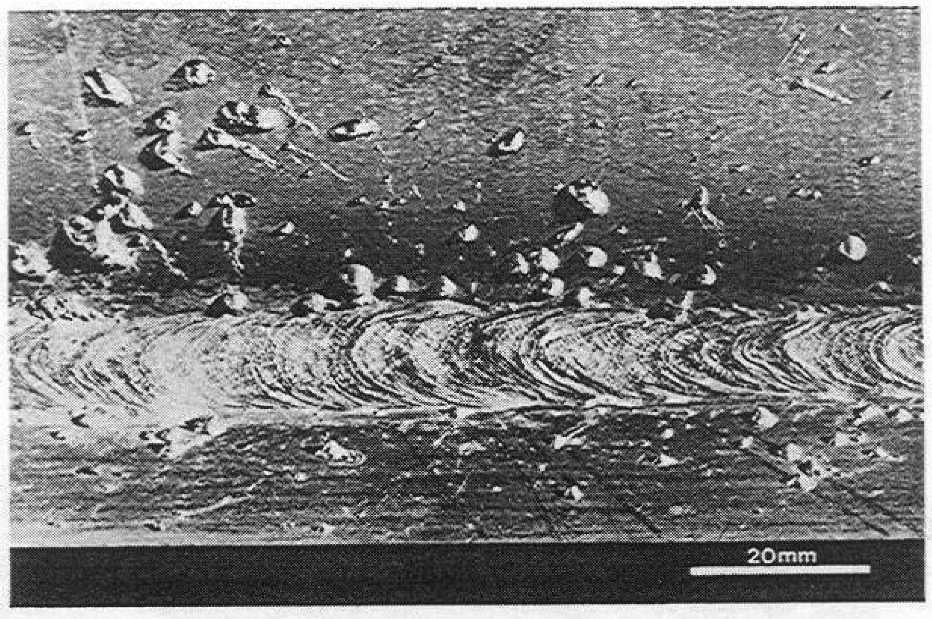


Local damage to the surface of the parent metal adjacent to the weld, resulting from arcing or striking the arc outside the weld groove. This results in random areas of fused metal where the electrode, holder or current return clamp have accidentally touched the work.

Causes	Prevention
Poor access to the work	Improve access (modify assembly sequence)
Missing insulation on electrode holder or torch	Institute a regular inspection scheme for electrode holders and torches
Failure to provide an insulated resting place for the electrode holder or torch when not in use	Provide an insulated resting place
Loose current return clamp	Regularly maintain current return clamps
Adjusting wire feed (MAG welding) without isolating welding current	Retrain welder

An arc strike can produce a hard HAZ, which may contain cracks, which can lead to serious cracking in service. It is better to remove an arc strike by grinding than weld repair.

3.7.2 Spatter



Globules of weld or filler metal expelled during welding and adhering to the surface of parent metal or solidified weld metal.

Causes	Prevention
High arc current	Reduce arc current
Long arc length	Reduce arc length
Magnetic arc blow	Reduce arc length or switch to AC power
Incorrect settings for GMAW process	Modify electrical settings (but be careful to maintain full fusion!)
Damp electrodes	Use dry electrodes
Wrong selection of shielding gas (100%CO_2)	Increase argon content if possible, however if too high may lead to lack of penetration

Spatter in itself is a cosmetic imperfection and does not affect the integrity of the weld. However as it is usually caused by an excessive welding current, it is a sign that the welding conditions are not ideal and so there are usually other associated problems within the structure ie high heat input. Some spatter is always produced by open arc consumable electrode welding processes. Anti-spatter compounds can be used on the parent metal to reduce sticking and the spatter can then be scraped off.

3.7.3 Torn surface

Description

Surface damage due to the removal by fracture of temporary welded attachments. The area should be ground off, subjected to a dye penetrant or magnetic particle examination then restored to its original shape by welding using a qualified procedure. Some applications do not allow the presence of any overlay weld on the surface of the parent material.

3.7.4 Additional imperfections

Grinding mark

Local damage due to grinding.

Chipping mark

Local damage due to the use of a chisel or other tools.

Underflushing

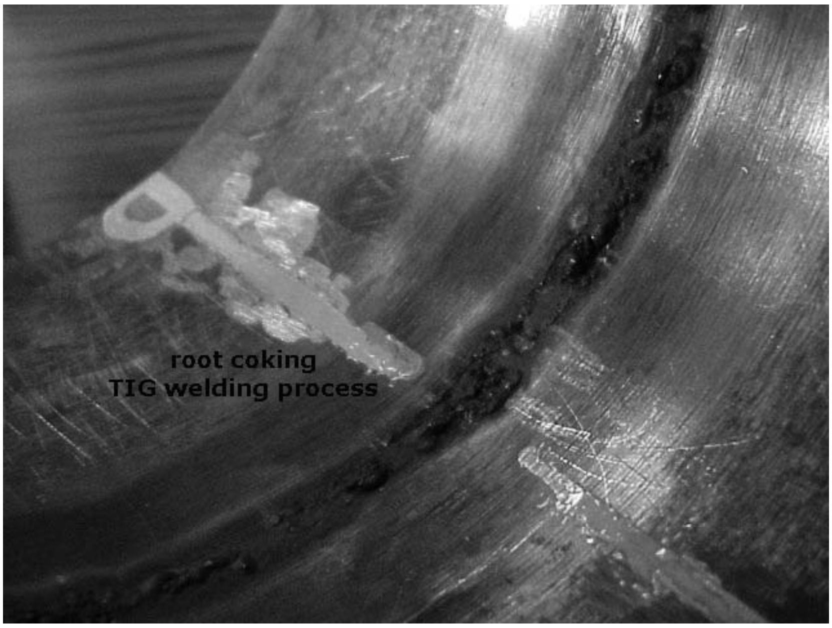
Lack of thickness of the workpiece due to excessive grinding.

Misalignment of opposite runs

Difference between the centrelines of two runs made from opposite sides of the joint.

Temper colour (visible oxide film)

Lightly oxidised surface in the weld zone, usually occurs in stainless steels.



3.8 Acceptance standards

Weld imperfections can seriously reduce the integrity of a welded structure. Prior to service of a welded joint, it is necessary to locate them using NDE techniques, assess their significance and take action to avoid their reoccurrence.

The acceptance of a certain size and type of defect for a given structure is normally expressed as the defect acceptance standard, usually incorporated in application standards or specifications.

All normal weld imperfection acceptance standards totally reject cracks, in exceptional circumstances and subject to the agreement of all parties, cracks may remain if it can be demonstrated beyond doubt that they will not lead to failure. This can be difficult to establish and usually involves fracture mechanics measurements and calculations.

It is important to note that the levels of acceptability vary between different applications and in most cases vary between different standards for the same application. Consequently, when inspecting different jobs it is important to use the applicable standard or specification quoted in the contract.

Once unacceptable weld imperfections have been found they have to be removed. If the weld imperfection is at the surface, the first consideration is whether it is of a type which is normally shallow enough to be repaired by superficial dressing. Superficial implies that after removal of the defect the remaining material thickness is sufficient not to require the addition of further weld metal.

If the defect is too deep it must be removed and new weld metal added to ensure a minimum design throat thickness.

Replacing removed metal or weld repair (as in filling an excavation or re-making a weld joint) has to be done in accordance with an approved procedure. The rigour with which this procedure is qualified depends on the application standard for the job. In some cases it will be acceptable to use a procedure qualified for making new joints whether filling an excavation or making a complete joint. If the level of reassurance required is higher, the qualification will have to be made using an exact simulation of a welded joint, which is excavated then refilled using a specified method. In either case, qualification inspection and testing will be required in accordance with the application standard.