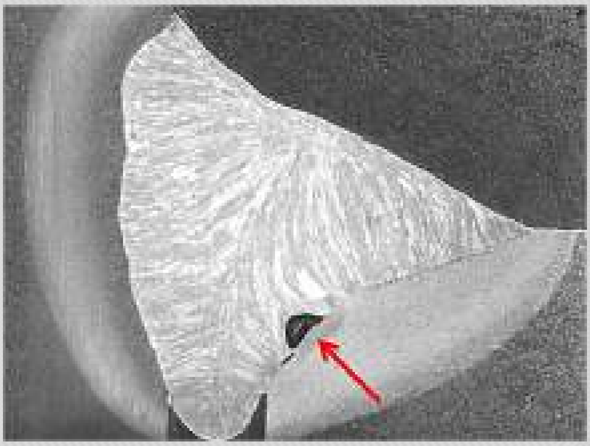
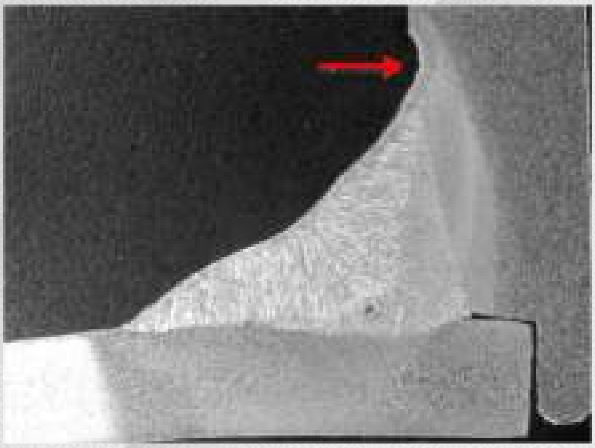
Welding Defects in Steel Material





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Weld Joint Discontinuities

- **Misalignment** (hi-lo)
- **Undercut**
- **Underfill**
- **Concavity or Convexity**
- **Excessive reinforcement**
- **Improper reinforcement**
- **Overlap**
- **Burn-through**
- **Incomplete or Insufficient Penetration**
- **Incomplete Fusion**
- **Surface irregularity**
  - Overlap
- **Arc Strikes**
- **Inclusions**
  - Slag
  - Wagontracks
  - Tungsten
- **Spatter**
- **Arc Craters**
- **Cracks**
  - Longitudinal
  - Transverse
  - Crater
  - Throat
  - Toe
  - Root
  - Under-bead and Heat-affected zone
  - Hot
  - Cold or delayed
- **Base Metal Discontinuities**
  - Laminations and Delaminations
  - Lamellar tearing
  - Laps and Seams
- **Porosity**
  - Uniformly Scattered
  - Cluster
  - Linear
  - Piping
- **HAZ microstructure alteration**
- **Size or dimensions**

Weld Process Related

- Undercut
  - Groove melted in basemetal adjacent to weld edge and left unfilled
- Slag Inclusion
  - Nonmetallic solid entrapped in weld
- Porosity
  - Gas cavity trapped during solidification
- Overlap
  - Weld metal protrusion beyond toe, face or root
- Tungsten inclusion
  - Tungsten electrode particles entrapped in weld
- Melt-through
  - Condition where arc melts through weld root
- Spatter
  - Metal particles expelled during welding that do not become part of the weld.
- Backing piece left in place
  - Failure to remove backing
- Shrinkage voids
  - Cavities formed by shrinkage at solidification
- Oxide Inclusions
  - Un-melted surface oxide particles
- Lack of fusion (LOF)
  - Less than complete fusion
- Lack of Penetration
  - Less than the specified penetration
- Craters
  - Depressions at the termination of the weld bead
- Arc strikes
  - Localized re-melted or heat affected metal resulting from an errant arc
- Under fill
  - A depression of the weld below the intended profile

Metallurgical Discontinuities

- Cracks
  - Fracture type discontinuities characterized by a sharp tip and a high length to depth ratio
- Fissures
  - Small crack-like discontinuities with only slight separation of the fracture surfaces
- Fisheye
  - Discontinuity found on the fracture surface of a steel weld consisting of a small pore surrounded by a bright round area
- Segregation
  - non-uniform distribution or concentration of impurities or alloying elements during solidification
- Lamellar tearing
  - Cracking that occurs in the basemetal or heat affected zone of restrained weld joints

There are numerous welding processes including arc welding, electron beam welding, friction welding, laser welding, and resistance welding. This article will concentrate on arc welding, which is the most common technique used to join most steels. Factors affecting weld quality will be discussed and how to avoid common weld defects will be presented.

Arc welding requires striking a low-voltage, high-current arc between an electrode and the base metal. The intense heat generated with this arc melts the base metal and allows the joining of two components. The characteristic of the metal that is being welded and the joint type (i.e. groove, fillet, etc.) dictates the welding parameters and the procedure that needs to be followed to obtain a sound weld joint.

Typical Arc Welding Processes

Shielded metal arc welding (SMAW), which is also known as stick welding, is the most widely used process. The arc is struck between the metal to be welded and a flux coated consumable electrode. The fluxes are mostly made from mineral components and cover the hot weld deposit and protect it from the environment. The solidified glassy product (slag) should be removed by chipping or with a wire brush after welding.

Gas metal arc welding (GMAW) is also referred to as metal inert-gas (MIG) welding. This process uses an uncoated continuous wire and the weld area is shielded from contamination by the gas that is fed through the welding torch.

The mode of metal transfer (spray, globular, short-circuiting, pulsed-arc) is varied by adjusting the amperage, and the shielding gases used depending on the welding position and the type of joint.

In Flux-cored arc welding (FCAW) the shielding gases and slag are provided by the decomposing flux that is contained within the electrode. Auxiliary shielding is also used in certain instances where deeper penetration is needed.

Gas tungsten arc welding (GTAW) is also known as tungsten inert-gas (TIG). This process uses a non-consumable electrode. The shielding gas is again fed through the welding torch. Welding may be accomplished without the addition of filler metal, which is especially advantageous for thin walled parts.

Shielding gases

The primary purpose of the shielding gas is to protect the molten weld metal from contamination and high temperature oxidation by the surrounding atmosphere. Although plain inert gases such as argon and helium may not be suitable for all applications, mixtures with reactive gases (i.e. oxygen, nitrogen, hydrogen and carbon dioxide) in controlled quantities will produce stable and relatively spatter-free metal transfer.

A mixture of argon and oxygen or argon and carbon dioxide is usually preferred for ferrous metals. The high-density arc that is created by argon permits the energy to go into the base metal as heat, resulting in a narrow bead width with deep penetration.

Helium has higher thermal conductivity and arc voltage than argon, which causes it to produce broader weld beads.

Because helium is a very light gas, higher flow rates must be used for effective shielding. This characteristic is beneficial in overhead welding.

Carbon dioxide is widely used for steels. Higher welding speed, better joint penetration and sound deposits with good mechanical properties can be achieved. Carbon dioxide is not an inert gas and breaks down into carbon monoxide and free oxygen under the heat of the arc. The oxygen superheats the weld metal transferring across the arc.

Weld quality

Factors that can affect the quality of a welded component include the following:

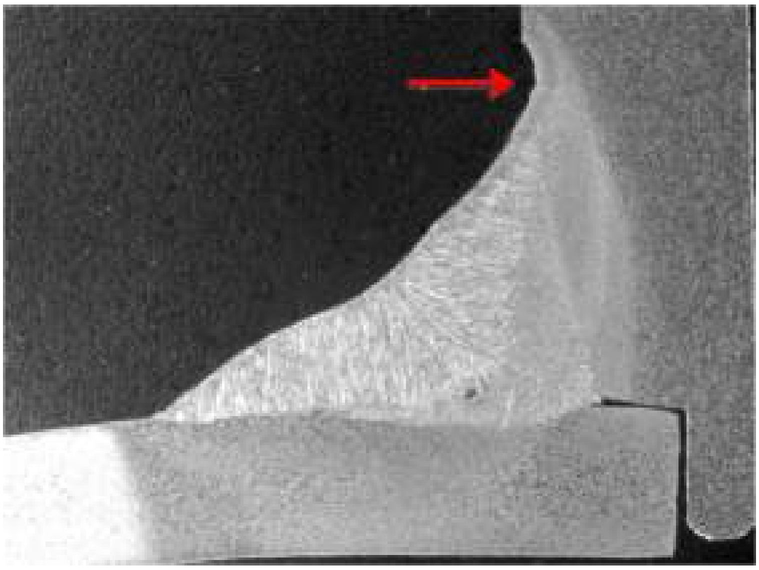
1. Design of the weld joint
2. Selection of the proper welding process
3. Qualification of the welding process (by testing)
4. Proper preparation of the joint prior to welding
5. Utilization of certified welders
6. In-process monitoring of the welding to ensure quality

Arc welding defects

Most welds contain defects (porosity, cracks, slag inclusions, etc.). The question is to determine if they are significant considering the application. Typically, the applicable codes or standards specify the maximum allowable limits of these types of defects in a weld based on the application. Sometimes discontinuities that may not affect mechanical properties may reduce corrosion performance. The properties of the heat-affected zone (HAZ) are one of the significant factors to consider when evaluating the soundness of the weld joint. The HAZ may be considered as a discontinuity because of the metallurgical alterations as a result of the welding heat, which causes very rapid heating and cooling rates. Grain growth, phase transformations (such as brittle untempered martensite that can form depending on the cooling rate and the chemical composition of the base material), formation of precipitates or overaging (loss of strength in precipitation-hardened alloys) all have a drastic effect on the properties of the HAZ. It is possible to improve the weld zone properties by controlling the cooling rate. This may be accomplished by slowing the cooling rate down either by increasing the heat input or using preheat.

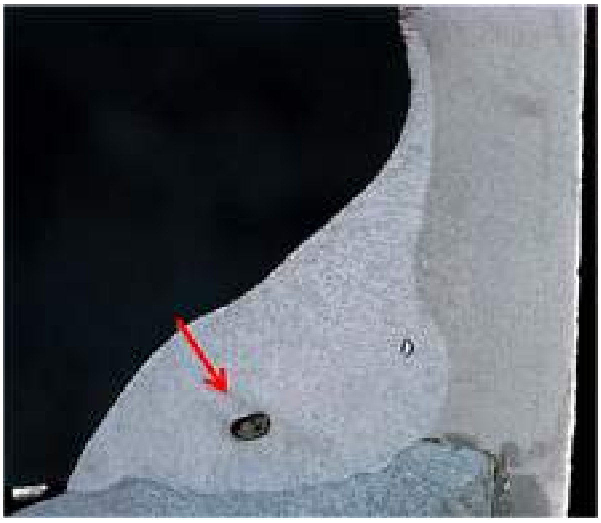
Porosity: Porosity is used to describe cavities or pores caused in the weld during solidification. Gas pockets are formed in the weld metal when they are entrapped during solidification. Molten steel readily absorbs hydrogen, carbon monoxide and other gases to which it is exposed. Since these are not soluble in solid metal, they are expelled as the metal solidifies. Standard shielded arc electrodes with organic coating such as E6010 produce an atmosphere around the arc that contains hydrogen, a notable contributor to porosity. When using such electrodes, welding should be done slowly to allow the gases time to escape since too high of a travel speed causes rapid solidification of the weld metal leading to porosity. Weld joint cleanliness is also crucial in avoiding porosity since moisture, oil, paint, or rust on the base metal may also cause porosity by introducing oxygen or hydrogen into the weld metal. Employing some minimum preheat temperature is often useful to remove condensation. It is also necessary to maintain the fluxes and the coated electrodes dry to avoid moisture pick-up. They are typically kept in an oven at approximately 250ºF, or if the hermetic seal is broken on the containers then the consumables (e.g. welding rods) should be baked at higher temperatures to drive off the moisture and restore the low hydrogen characteristics. Common causes and remedies of porosity are listed below along with a macrograph of a fillet weld containing porosity.

Porosity: gas pockets or voids that are found in welds	
Possible Causes	**Possible Remedies**
Excessive hydrogen, nitrogen or oxygen in welding atmosphere	Use low hydrogen welding process, filler metals high in deoxidizers, increase shielding gas flow
High solidification rate	Use preheat or increase heat input
Dirty base metal	Clean joint faces and adjacent surfaces
Dirty filler wire	Use clean wire and store fillers in a clean area
Improper arc length, welding current or electrode manipulation	Modify welding parameters and techniques
Inadequate gas coverage	Check for proper gas coverage Use a wind screen (when outdoors)
Galvanized Steel	Use E7010 electrode and manipulate the arc heat to volatilize the galvanizing (zinc) ahead of the molten weld pool
Excessive moisture in electrode covering or on joint surfaces	Use recommended procedures for baking and storing electrodes
High sulfur base metal	Use electrodes with basic slagging reactions

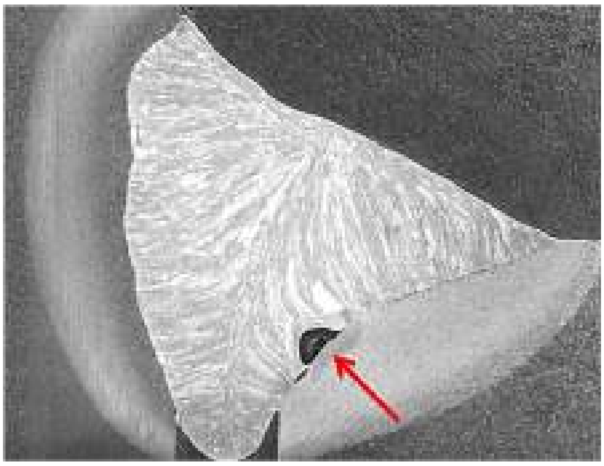


Incomplete fusion/penetration: Although these terms are sometimes used interchangeably, lack of fusion occurs when the weld and base metal fail to adequately fuse together. It can also be encountered between weld passes. It may be caused by not raising the temperature of the base metal or previously applied weld metal to the melting point or failure to remove the slag or mill scale. Lack of penetration is typically due to inadequate heat input for the particular joint that is being welded and is usually seen at the sidewalls or at the root of the weld joint. The shielding gas can also influence the penetration; typically helium is added for nonferrous metals and carbon dioxide is added for ferrous metals (to argon) to increase penetration. They are internal discontinuities that are difficult to detect. These defects are usually caused by incorrect welding parameters, such as too low of a welding current, insufficient preheat, too fast of a welding speed, incorrect joint preparation, short arc length or insufficient electrode size.

This type of defect can only be repaired by grinding or gouging out the area and re-welding. The first macrograph below shows a butt weld with excessive reinforcement and incomplete penetration. The second macrograph shows lack of penetration to the root of a weld joint, and the third macrograph illustrates lack of fusion to the vertical member of a fillet weld.

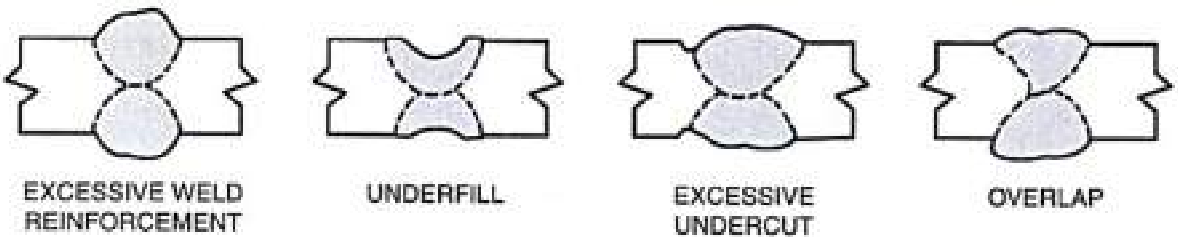


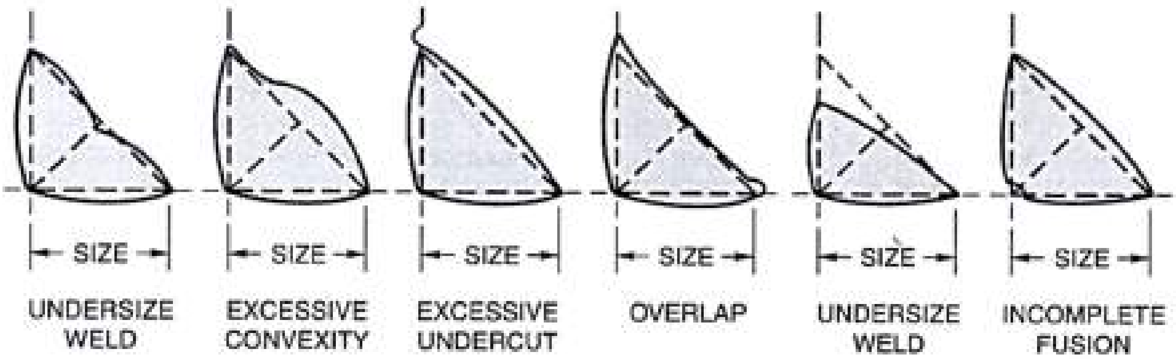
Undercut occurs when a groove that is formed adjacent to the weld as a result of the melting of the base metal remains unfilled. The causes are usually associated with incorrect electrode angles, incorrect weaving technique, and excessive current and/or travel speed. Undercut can be avoided by using proper welding technique and parameters. It can be repaired by welding up the resultant groove with a smaller electrode. An example is shown in the macrograph below (at the toe of the fillet weld).



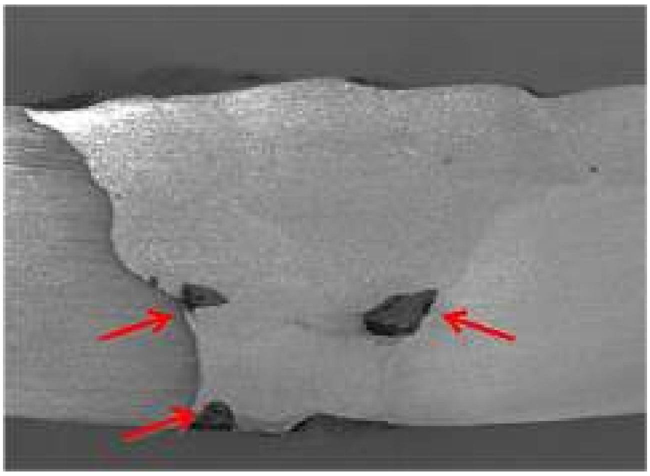
Weld profile: Geometric imperfections such as the profile of a finished weld may have a considerable effect on the performance under dynamic loading conditions. Overlap, excessive reinforcement or misalignment are indications of poor workmanship and can provide stress concentration points where fatigue cracks can initiate. Underfill is a depression on the weld face extending below the surface of the base metal. Misalignment is generally caused by a fitup problem. Overlap is the protrusion of unfused weld metal beyond the weld toe or weld root. Since overlap forms a mechanical notch it should be repaired by grinding off excess weld metal and smoothly blending the surface to the base metal. Excessively concave or convex welds can be repaired either by filling with further weld metal or grinding back to remove it.

Typical unacceptable butt and fillet weld profiles are shown below.

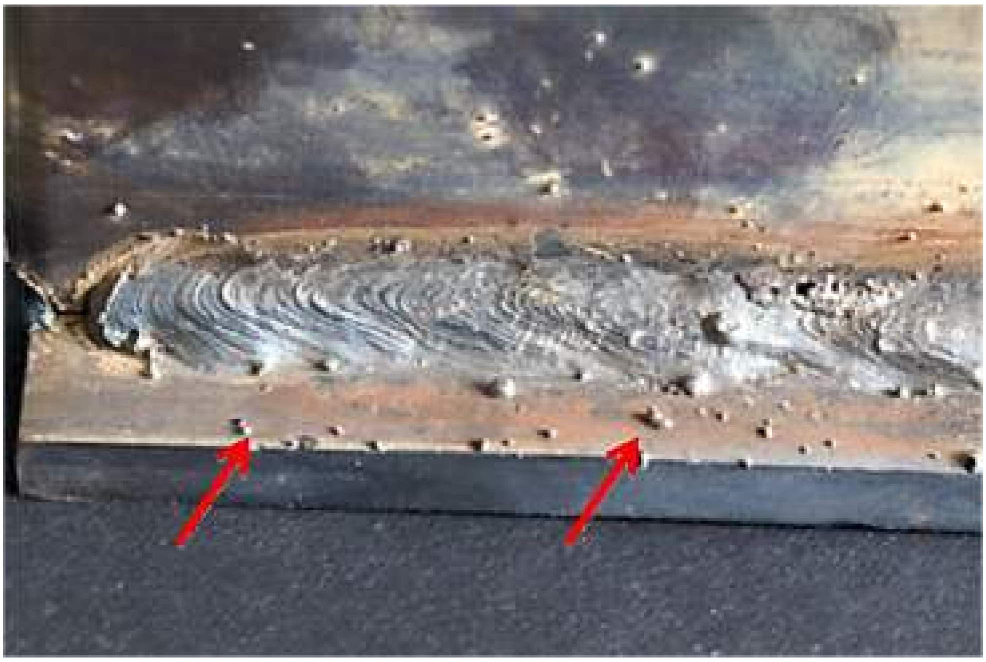




Arc strikes. They are caused by the unintentional melting of the base metal outside the weld deposit area by the welding arc. It can create localized hard or soft spots, cracking or undercut. Another welder-induced defect is weld spatter. Weld spatter is metal drops expelled from the weld that stick to surrounding surfaces. It usually occurs when excessive welding current, long arc or welding voltage is used. Below photographs show arc strikes and weld spatter near fillet welds.



Tungsten inclusions. In the TIG process, the touching of the electrode to the weld metal may cause transfer of the tungsten particles into the weld metal. These inclusions are detected by x-ray and show up as bright particles since they are much denser than the steel. An example is shown below where the x-ray revealed the tungsten inclusions.

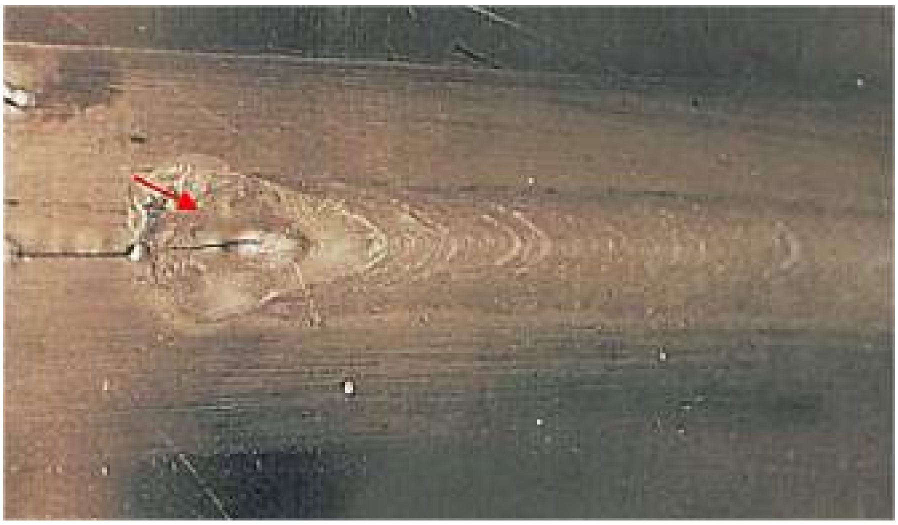


Slag inclusions. One of the main functions of the flux coating in welding is to produce a slag, which flows freely over the surface of the weld pool and protect it from oxidation. Slag is the residue of the flux coating in arc welding and is principally a deoxidation product from the reaction between the flux, air and surface oxides. However, these oxides become entrapped in the weld metal and need to be cleaned between weld passes (in multi-pass operations) using a chipping hammer or a wire brush since they do not get melted out. Slag inclusions not only reduce the cross sectional area of the weld and reduce its strength, but may also serve as imitation points for fatigue cracks. These imperfections can only be repaired by grinding down and re-welding. The macrograph below illustrates slag residue remaining in a groove weld due to inadequate cleaning between weld passes.

Discontinuity	Possible Causes	Possible Remedies
Undercut	Improper welding technique	Reduce arc length Reduce travel speed Use proper electrode angle
Incomplete Fusion	"Cold" welding Travel speed too slow/fast Improper joint detail	Increase current Use proper travel speed Improve groove angle
Incomplete Joint Penetration	"Cold" welding Travel speed too slow/fast Improper joint detail	Increase current Use proper travel speed Improve groove angle
Excessive Reinforcement	"Cold" welding Travel speed too slow	Increase current Increase travel speed
Underfill	Insufficient weld metal	Reduce travel speed Reduce arc length Use suitable electrode manipulation
Concave Root Surface (Suck-back)	Current too high Arc length too long Root face too small	Reduce current Maintain proper arc length Use proper joint fit-up

Excessive melt through (burn-through)	Excessive root opening Current too high	Reduce root opening Reduce current
Uneven Leg Size	Improper electrode angle	Use appropriate electrode work angle
Overlap	Travel speed too slow Current too low Arc length too short	Use proper travel speed, welding current and arc length
Arc Strikes	Improper welding technique	Initiate arc inside the weld joint
Slag Inclusions	Improper welding technique Excessive welding current Excessive arc length Improper cleaning between passes	Use welding technique to produce smooth weld beads to avoid pockets that can trap slag Use correct current and travel speed to avoid undercutting the sidewall Clean weld between passes
Tungsten Inclusions	Electrode dipping Contact between electrode and filler Current too high Interrupted gas shielding Too high electrode stick-out	Keep gun at a distance to avoid contact with weld puddle Hold rod slightly away from electrode tip Reduce current Maintain adequate shielding Adjust electrode extension from torch collet

Cracks. Cracks are the most serious type of weld defects that can lead to catastrophic failures in service. There are many different types of cracks. One way of categorizing them is as surface or subsurface cracks. Another way would be as hot (which occur during or immediately after the weld is deposited or cold (cracks that occur after the weld has cooled to room temperature-sometimes within hours or days). In general, weld or heat- affected zone cracks indicate that the weld or the base metal has low ductility and that there is high joint restraint. Many factors can contribute to this condition such as rapid cooling, high alloy composition, insufficient heat input, poor joint preparation, incorrect electrode type, insufficient weld size or lack of preheat. Some common causes and remedies are given in table below.



Photograph illustrating crater cracking resulting from abrupt weld termination.

Cracks: Hot and cold cracks or microfissures in the weld or the base metal	
Possible Causes	**Possible Remedies**
Cold cracks (root, toe, underbead and transverse): diffusible hydrogen, brittle structures, restraint stresses	Redry coatings and fluxes, preheat base metals
Cold crack (lamellar tear): inadequate ductility of base metal, high sulfur or inclusion content in the base metal, hydrogen in weld, high tensile stresses in the thickness direction	Use a base metal with higher ductility, lower sulfur and inclusion content, utilize low hydrogen electrodes, modify joint detail and welding process to lower stresses
Hot cracks (crater, longitudinal, center-line): too high welding current, too narrow welding groove	Use proper welding current, fill crater, use appropriate groove angle
Highly rigid joint	Preheat Relieve residual stresses mechanically Minimize shrinkage stresses using backstep sequence (a longitudinal sequence in which weld passes are made in the direction opposite to the progress of welding)
Excessive dilution (change in chemical composition of a weld deposit caused by the admixture of the base metal)	Change welding current and travel speed Weld with covered electrode negative; butter the joint faces prior to welding (buttering is depositing surfacing metal to provide metallurgically compatible weld metal to the subsequent weld passes)
Poor fit-up	Reduce root opening
Small weld bead	Increase electrode size, raise welding current, reduce travel speed
High sulfur base metal	Use filler metal low in sulfur
Excessive distortion	Change to balanced welding on both sides of joint
Crater cracking	Fill crater before extinguishing the arc
High residual stresses	Redesign weldment, change welding sequence, apply intermediate stress relief
High hardenability	Preheat, increase heat input, heat treat before cooling to room temperature

The effect of carbon equivalent.

The carbon equivalent (C.E.) may be considered as the main factor in estimating the need for preheat. Generally, the higher the carbon content of steel, the greater the tendency to form a hard and brittle HAZ. This necessitates the use of preheat and low hydrogen electrodes. Carbon, however, is not the only element that influences hardenability.

Other elements in steel also are responsible for the hardening and loss of ductility that occur with rapid cooling. One of the various empirical formulas used to determine carbon equivalent is given in the Structural Steel Welding Code (AWS D1.1) as follows:

$$\%C.E. = \%C + \%\,(Mn+Si)/6 + \%\,(Cr+Mo+V)/5 + \%\,(Ni+Cu)/15$$

The approximate recommended preheat temperatures based on C.E. are:

For up to 0.45%…………preheat is optional

0.45-0.60%………………200-400ºF

Over 0.60%……………....400-700ºF

Usually a steel that requires preheat must also be kept at this temperature between weld passes. The heat input of the welding process is adequate to maintain the required interpass temperature on most weldments. On massive components this may not be the case and torch heating between passes may be required. Since the purpose of preheating is to reduce the quench rate, the same slow cooling rate must be achieved for all passes.

Besides the widely used carbon equivalent criteria, the following factors should also be considered when determining the need for preheat/post weld heat treat: code requirements, section thickness, restraint, ambient temperature, filler metal hydrogen content and previous cracking problems. https://www.welding-advisers.com/FCA-welding-tips.html

Table 11-12 —Preheats for various metals.

Type of Steel	Preheat
Low-Carbon Steel	Room Temperature or up to 200°F (93°C)
Medium-Carbon Steel	400-500°F (205-260°C)
High-Carbon Steel	500-600°F (260-315°C)
Low-alloy Nickel Steel	
-Less than ¼' (6.4 mm) thick	Room Temperature
-More than ¼' (6.4 mm) thick	500°F (260°C)
Low-alloy Nickel-Chrome Steel	
-Carbon content below .20%	200-300°F (93-150°C)
-Carbon content .20% to .35%	600-800°F (315-425°C)
-Carbon content above .35%	900-1100°F (480-595°C)
Low-alloy Manganese Steel	400-600°F (205-315°C)
Low-alloy Chrome Steel	Up to 750°F (400°C)
Low-alloy Molybdenum Steel	
Carbon content below .150%	Room Temperature
Carbon content above .15%	400-650°F (205-345°C)
Low-alloy High Tensile Steel	150-300°F (66-150°C)
Austenitic Stainless Steel	Room Temperature
Ferritic Stainless Steel	300-350°F (150-260°C)
Martensitic Stainless Steel	400-600°F (205-315°C)

Note:

The actual preheat needed may depend on several other factors, such as the thickness of the base metal, the amount of joint restraint, and whether or not low-hydrogen types of electrodes are used. This chart is intended as general information; the specifications of the job should be checked for the specific preheat temperature used.

Weld Process Related

Metallurgical Discontinuities

Undercut

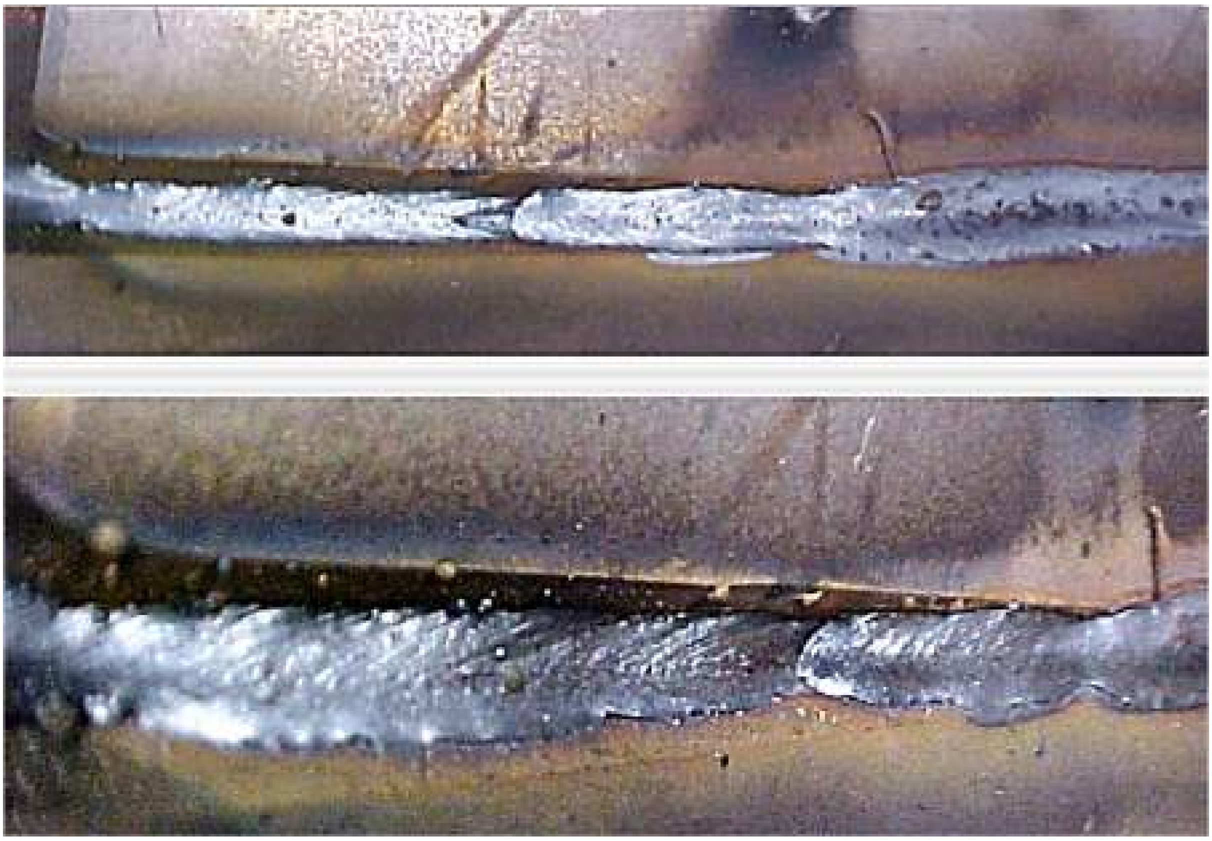
 

- Undercut typically has an allowable limit.
- Different codes and standards vary greatly in the allowable amount.
- Plate - the lesser of 1/32" or 5% (typ.)

Insufficient Fill Definition:

- The weld surface is below the adjacent surfaces of the base metal
- Cause: Improper welding techniques
- Prevention: Apply proper welding techniques for the weld type and position. Use stripper beads before the cover pass.
- Repair: Simply weld to fill. May require preparation by grinding.

Underfill

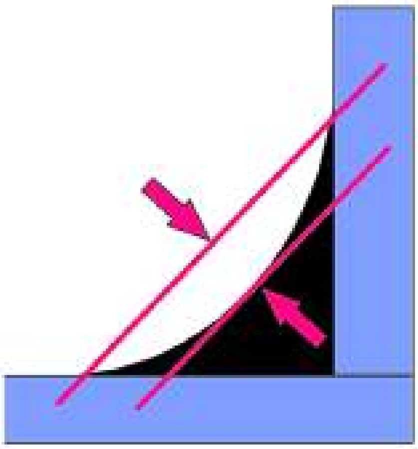


Insufficient Fill on the Root Side (suckback)

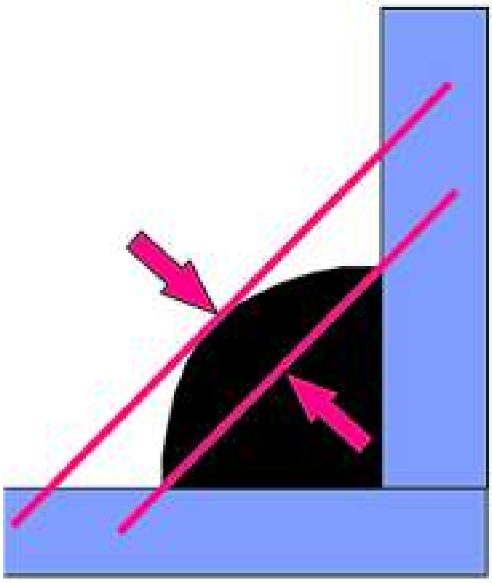
- Definition: The weld surface is below the adjacent surfaces of the base metal at the weld root.
- Cause: Typically improper joint preparation or excessive weld pool heat.
- Prevention: Correct cause. (see next slide)
  Repair: Backweld to fill. May require removal of weld section by grinding for access to the joint root.

Excessive Concavity or Convexity

- **Definition:** Concavity or convexity of a fillet weld exceeding specified limits
- **Cause:** Amperage and travel speed
- **Prevention:** Observe proper parameters and techniques.
- **Repair:** Grind off or weld on. Must blend smoothly into the base metal.



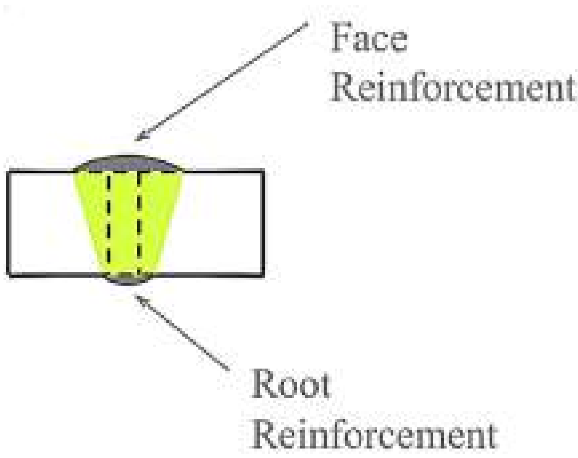
Convexity



Excessive convexity

Reinforcement

- The amount a groove weld extends beyond the surface of the plate
- Excessive
- Insufficient
- Improper contour



Excessive Reinforcement

- Definition: Specifically defined standard.
- Typically, Flush to 1/16”(pipe) or flush to 1/8”
- (plate or structural shapes).
- Cause: Travel speed too slow, amperage too low
- Prevention: Set amperage and travel speed on scrap plate.
- Repair: Remove excessive reinforcement and feather weld toes to a smooth transition to the base plate.

Excessive weld reinforcement

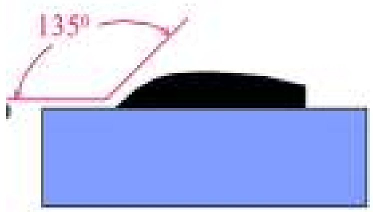
Insufficient Reinforcement

Definition: Specifically defined standard.

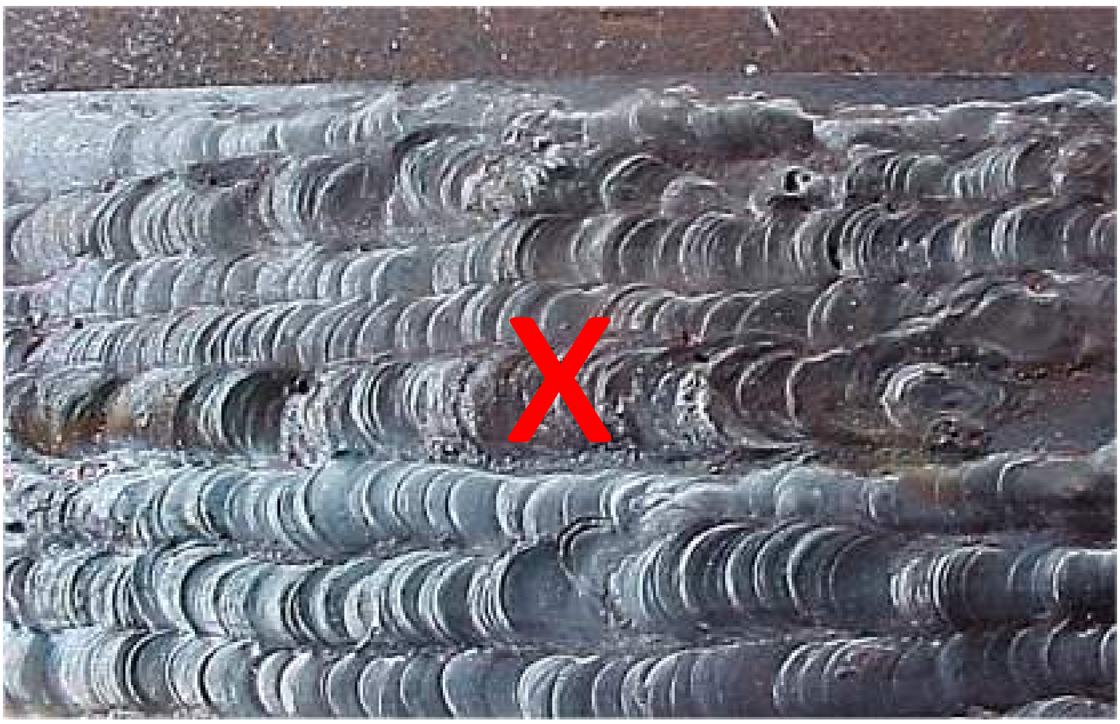
- Typically, None or up to 5% of metal thickness not to exceed 1/32" as long as the thickness is made up in the opposite reinforcement. Not applied to fillet welds.
- Cause: Open root reinforcement - Too little filler metal will cause thinning of the filler metal. In OH position, too hot or too wide will cause drooping of the open root puddle.
- Prevention: Use proper welding technique. Use backing or consumable inserts. Use back weld or backing.
- Repair: Possibly simply increase the face reinforcement.
- If back-welding is not possible, must remove and re-weld.

Improper Weld Contour

- Definition: When the weld exhibits less than a 135^0 transition angle at the weld toe.
- Cause: Poor welding technique
- Prevention: Use proper techniques. A weave or whip motion can often eliminate the problem.
- Repair: The weld face must be feathered into the base plate.



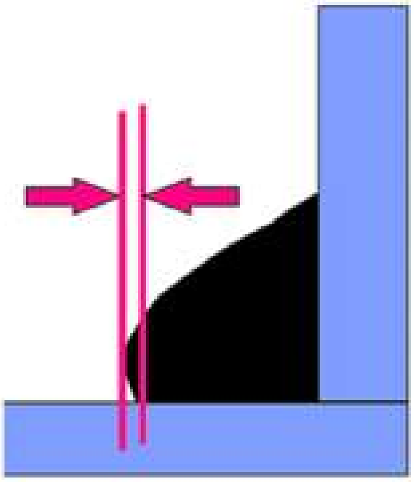
Unacceptable weld profiles



Overlap

Definition: When the face of the weld extends beyond the weld toe

- Cause: Improper welding technique. Typically, electrode angles and travel speed.
- Prevention: Overlap is a contour problem. Proper welding technique will prevent this problem.
- Repair: Overlap must be removed to blend smoothly into the base metal.
  - Be careful of deep grind marks that run transverse to the load.
  - Also be careful of fusion discontinuities hidden by grinding. Use NDT to be sure.
- Overlap is measured with a square edge such as a 6” rule. No amount of overlap is typically allowed.



Burn-through (non-standard)

- Definition: When an undesirable open hole has been completely melted through the base metal. The hole may or may not be left open with further processing.
- Cause: Excessive heat input.
- Prevention: Reduce heat input by increasing travel speed, use of a heat sink, or reduce welding parameters.
- Repair: Will be defined by standards. Filling may suffice. Otherwise, removal and re-welding may be required. Some standards may require special filler metal and/or PWHT.

Incomplete or Insufficient Penetration

- Definition: When the weld metal does not extend to the required depth into the joint root
- Cause: Low amperage, low preheat, tight root opening, fast travel speed, short arc length.
- Prevention: Correct the contributing factor(s).
- Repair: Back gouge and back weld or remove and reweld.

Incomplete & excessive penetration

Incomplete (or Lack of) Fusion

- Definition: Where weld metal does not form a cohesive bond with the base metal.
- Cause: Low amperage, steep electrode angles, fast travel speed, short arc gap, lack of preheat, electrode too small, unclean base metal, arc off seam.
- Prevention: Eliminate potential causes.
- Repair: remove and re-weld, being careful to completely remove the defective area. This is sometimes extremely difficult to find.

Incomplete fusion

Arc Strike

- Definition: A localized coalescence outside the weld zone
- Cause: Carelessness.
- Prevention: In difficult areas, adjacent areas can be protected using fire blankets.
- Repair: Where applicable, arc strikes must be sanded smooth and tested for cracks. If found, they must be remove and repaired using a qualified repair procedure and inspected as any other weld.

Inclusions

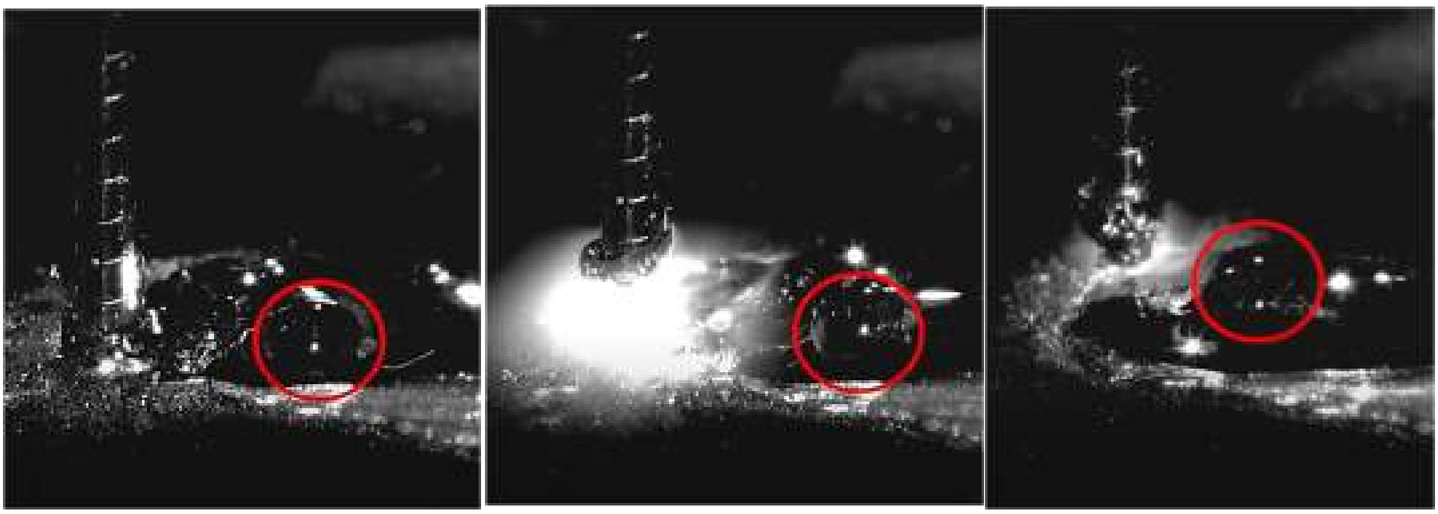
- Slag
- Wagon-tracks
- Tungsten

Slag Inclusion

- Definition: Slag entrapped within the weld
- Cause: Low amperage, improper technique, trying to weld in an area that is too tight. Slow travel in Vertical Down
- Prevention: Increase amperage or preheat, grind out tight areas to gain access to bottom of joint.
- Repair: Remove by grinding. Reweld. (https://weldguru.com/slag-inclusion/)

How Is Slag Different From Welding Flux.

- Flux is a combination of compounds that enters the molten weld pool with the filler metal.
- As it melts, it reacts with Oxygen/Nitrogen in the surrounding atmosphere to create its respective Oxides/Nitrides. This prevents these gases from oxidizing the base metal(s).
- Some of it dissolves into the weld pool and undergoes similar reactions with impurities inside the base metal.
- These non-metallic products from these chemical reactions are collectively known as slag.
- Slag rises to the top of the pool because of its low density. Upon reaching the weldment's surface, it solidifies to create a layer of protection between the molten metal and air, blocking further reactions between the two.
- This way flux, which eventually becomes slag, shields the weld pool from the air and rids it of internal impurities.
- To sum it up, flux is an essential input that keeps the weldment pure from non-metallic impurities. Slag is a waste product that must be removed from the joint after the welding is finished.   Welding Defect - Watch How Slag Inclusion Happens!



https://www.youtube.com/watch?v=us66qtKRODY&ab_channel=CavitarLtd

Wagon Tracks (non-standard)

- Definition: Slang term for a groove left at the toe of a root pass which becomes filled with slag and is trapped in the weld.
- Cause: The contour of the root pass is too high, or the weld toe is not bonded to the base metal
- Prevention: Use proper technique to deposit the weld root.
- Repair: Best repaired before applying the hot pass. Carefully grind the root pass face flat. be careful not togouge other areas on the weldment.

Whiskers

- Typically GMAW, can be GTAW
- Unconsumed weld-wire passes or pushes through weld joint and is caught in root penetration
  - Unsightly
  - Inhibits material flow in piping
  - Can break off in pipes and damage equipment downline
  - Considered inclusions

Spatter

- Definition: Small particles (droplet) of weld metal expelled from the welding operation which adhere to the base metal surface.
- Cause: Long arc length, severe electrode angles, high amperages.
- Prevention: Correct the cause. Base metal can be protected with coverings or hi-temp paints.
- Repair: Remove by grinding or sanding.
- Sometimes must be tested as if it were a weld.

Arc Craters

- Definition: A depression left at the termination of the weld where the weld pool is left unfilled.
- Cause: Improper weld termination techniques
- Prevention: Improve technique or use equipment function
- Repair: If no cracks exist, simply fill in the crater.
- Generally welding from beyond the crater back into the crater.

Cracks

- Longitudinal
- Transverse
- Crater
- Throat
- Toe
- Root
- Underbead and Heat-affected zone
- Hot
- Cold or delayed

Longitudinal Crack

- Definition: A crack running in the direction of the weld axis. May be found in the weld or base metal.
- Cause: Preheat or fast cooling problem. Also caused by shrinkage stresses in high constraint areas.
- Prevention: Weld toward areas of less constraint.
- Also preheat to even out the cooling rates.
- Repair: Remove and reweld

Toe Crack

- Definition: A crack in the base metal beginning at the toe of the weld
- Cause: Transverse shrinkage stresses. Indicates a HAZ brittleness problem.
- Prevention: Increase preheat if possible, or use a more ductile filler material.

Throat Crack

- Definition: A longitudinal crack located in the weld throat area.
- Cause: Transverse Stresses, probably from shrinkage. Indicates inadequate filler metal selection or welding procedure. May be due to crater crack propagation.
- Prevention: Correct initial cause. Increasing preheat may prevent it. be sure not to leave a crater. Use a more ductile filler material.
- Repair: Remove and reweld using appropriate procedure. Be sure to correct initial problem first.

WELDING DEFECTS!! Porosity, Arc Strikes, Undercut

https://www.youtube.com/watch?v=82LQ2cMoE5c&ab_channel=Weld.com

Crater Crack

- Definition: A crack, generally in the shape of an “X” which is found in a crater. Crater cracks are hot cracks.
- Cause: The center of the weld pool becomes solid before the outside of the weld pool, pulling the center apart during cooling
- Prevention: Use crater fill, fill the crater at weld termination and/or preheat to even out the cooling of the puddle.

Transverse Crack

- Definition: A crack running into or inside a weld, transverse to the weld axis direction.
- Cause: Weld metal hardness problem.

Root Crack

- Definition: A crack in the weld at the weld root.
- Cause: Transverse shrinkage stresses. Same as a throat crack.
- Prevention: Same as a throat crack.

Underbead Crack

- Definition: A crack in the un-melted parent metal of the HAZ.
- Cause: Hydrogen embrittlement
- Prevention: Use Lo/Hi electrodes and/or preheat
- Repair: (only found using NDT). Remove and reweld.

Hot Crack

- Definition: A crack in the weld that occurs during solidification.
- Cause: Micro stresses from weld metal shrinkage pulling apart weld metal as it cools from liquid to solid temp.

Cold Crack

- Definition: A crack that occurs after the metal has completely solidified
- Cause: Shrinkage, Highly restrained welds, Discontinuities
- Prevention: Preheat, weld toward areas of less constraint, use a more ductile weld metal Repair: Remove and reweld, correct problem first, preheat may be necessary.

All these errors are listed here in order because they are explained in detail in my other works so as not to repeat myself.

Repairs to Cracks

Determine the cause

- A crack during application of a welding process is an indicator of a bigger PROCESS PROBLEM
- Correct the problem
- Take precautions to prevent reoccurrence
- Generally required to repair using a smaller electrode.

Base Metal Discontinuities

- Laminations and De-laminations
- Lamellar tearing
- Laps and Seams

Laminations

- Base Metal Discontinuity
- Typical of rolled plate and strip
- May require repair prior to welding
- Formed during the milling process
- De-lamination - a lamination opened under stress

Laps and Seams

- A mill-induced discontinuity resulting from a lump of metal being squeezed over into the surface of the material.
- If beyond acceptable limits, must be removed and repaired or discarded.

Porosity

- Single Pore
- Uniformly Scattered
- Cluster
- Linear
- Piping

Single Pore

Separated by at least their own diameter along the axis of the weld.

Uniformly Scattered Porosity

- Typically judged by diameter and proximity to a start or stop
- Often caused by low amperage or short arc gap or an unshielded weld start.

Cluster Porosity

Typically viewed as a single large discontinuity.

Linear Porosity

being linear greatly affects the severity of this discontinuity.

Piping Porosity

Generally has special allowable limits.

Porosity

- Preheat will help eliminate
- May need an electrode with more deoxidizers
- Use run-on/run-off taps
- Restart on top of previous weld and grind off lump

Hammer marks

- Stress risers
- Unsightly
- Unnecessary

Heat-affected zone microstructure alteration

- Metallurgical change in HAZ - may include
  - grain refinement
  - grain growth
  - hardened areas
  - softened areas
  - precipitate suseptable areas.

Defect vs. Discontinuity

- Discontinuity - if it renders the part unusable, it is a defect.
- Defect - it is outside the allowable limit, it renders the part unusable.
- Design must recognize - things don't have to be perfect, just within acceptable tolerance.
- Perfection is time consuming and costly.

Repair techniques

May involve:

- **different process**
- **different procedure**
- **different preheat/PWHT**
- **different electrode**
- **smaller electrode**

Repairs

Only repair defects.

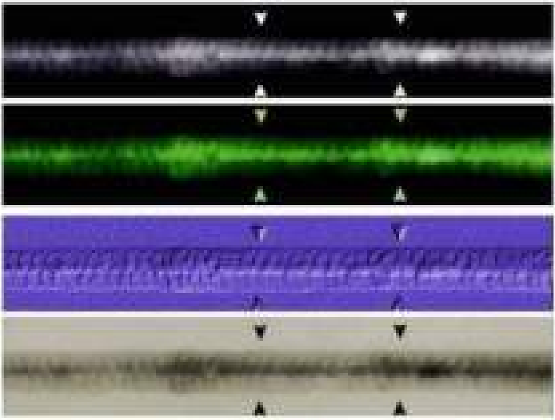
• Discontinuities are, by definition, acceptable.

• Discontinuity pair is unnecessary and not cost effective.

Longitudinal Root Crack:

A fracture in the weld metal at the edge of the root pass.

Radiographic Image
Feathery, twisting lines of darker density along the edge of the image of the root pass. The "twisting" feature helps to distinguish the root crack from incomplete root penetration.

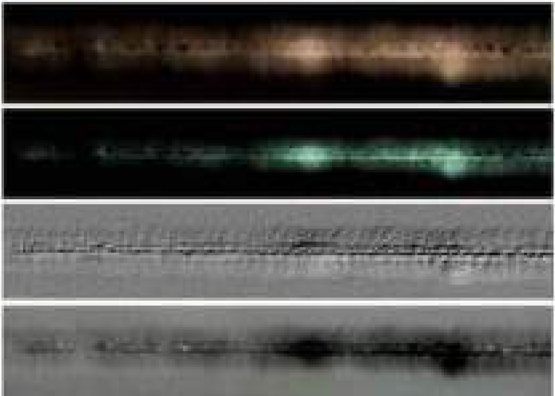


Longitudinal Root Crack

Root Pass Aligned Porosity:

Rounded & elongated voids in the bottom of the weld aligned along the weld centerline.

Radiographic Image:
Rounded & elongated darker density spots, that may be connected, in a straight line in the center of the width of the weld image.

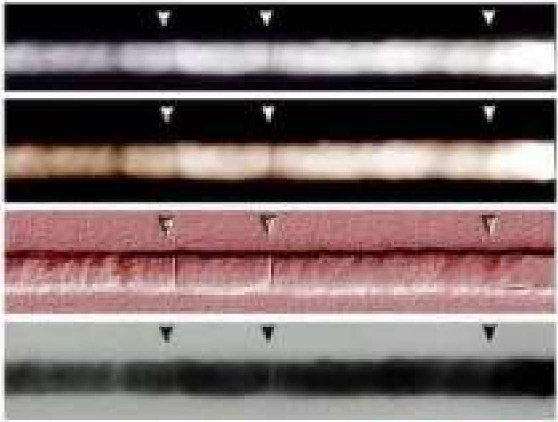


Root Pass Aligned Porosity

Transverse Crack:

A fracture in the weld running across the weld.

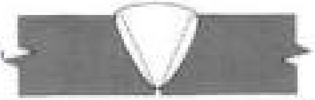
Radiographic Image
Feathery, twisting line of darker density running across the width of the weld image.



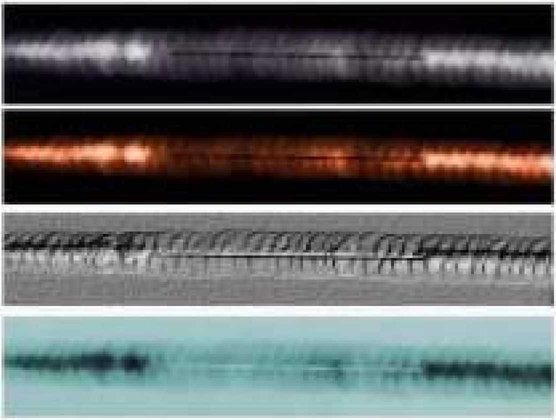
Transverse Crack

Incomplete or Lack of Penetration (LOP):

The edges if the pieces have not been welded together, usually at the bottom of single V-groove welds.

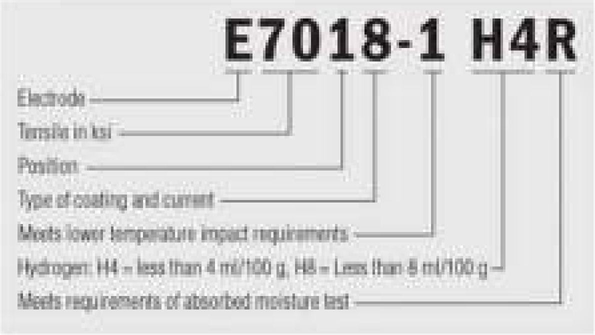


Radiographic Image
A darker density band, with very straight parallel edges, in the center of the width of the weld image.



Incomplete or Lack of Penetration (LOP)

How AWS Classifies Mild Steel Covered Electrodes, SMAW Process



Position

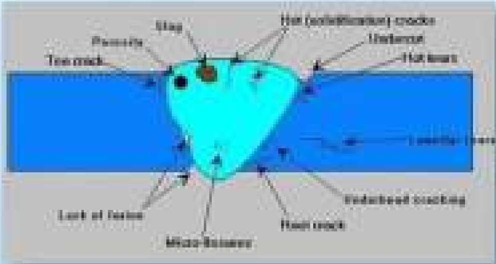
1 Flat, Horizontal, Vertical, Overhead

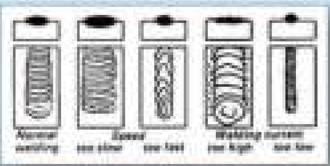
2 Flat and Horizontal only

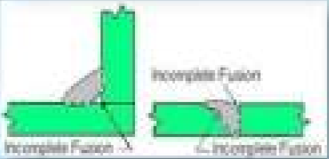
Types of Coating & Current

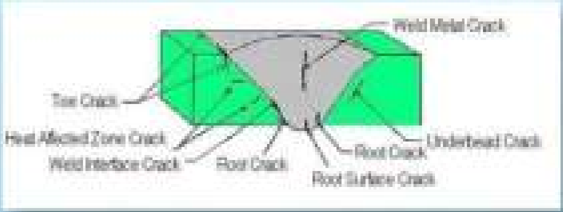
AWS	DIGIT	TYPE OF COATING	WELDING CURRENT
6010	**0**	cellulose sodium	DCEP
6011	**1**	cellulose potassium	AC or DCEP
6022	**2**	titania sodium	AC or DCEN
6013	**3**	titania potassium	AC or DCEP or DCEN
7014	**4**	iron powder titania	AC or DCEP or DCEN
7018	**8**	iron powder low hydrogen	AC or DCEP

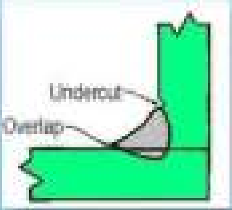
Weld Defects



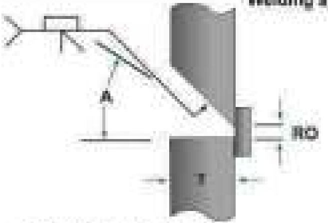






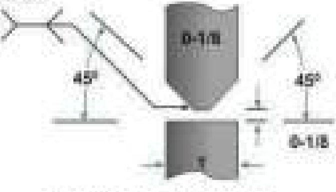


Welding symbols



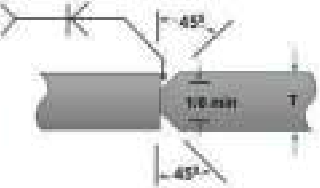
1) Single-Bevel-Groove Weld.
2) Complete Penetration - Welded One Side On Backing Strip.
3) T Unlimited.
4) May Be Used For Horizontal Joints.

RO	A	Positions
3/16	30°	Flat, Vertical & Overhead
1/4	45°	Vertical & Overhead
3/8	30°	Flat Only

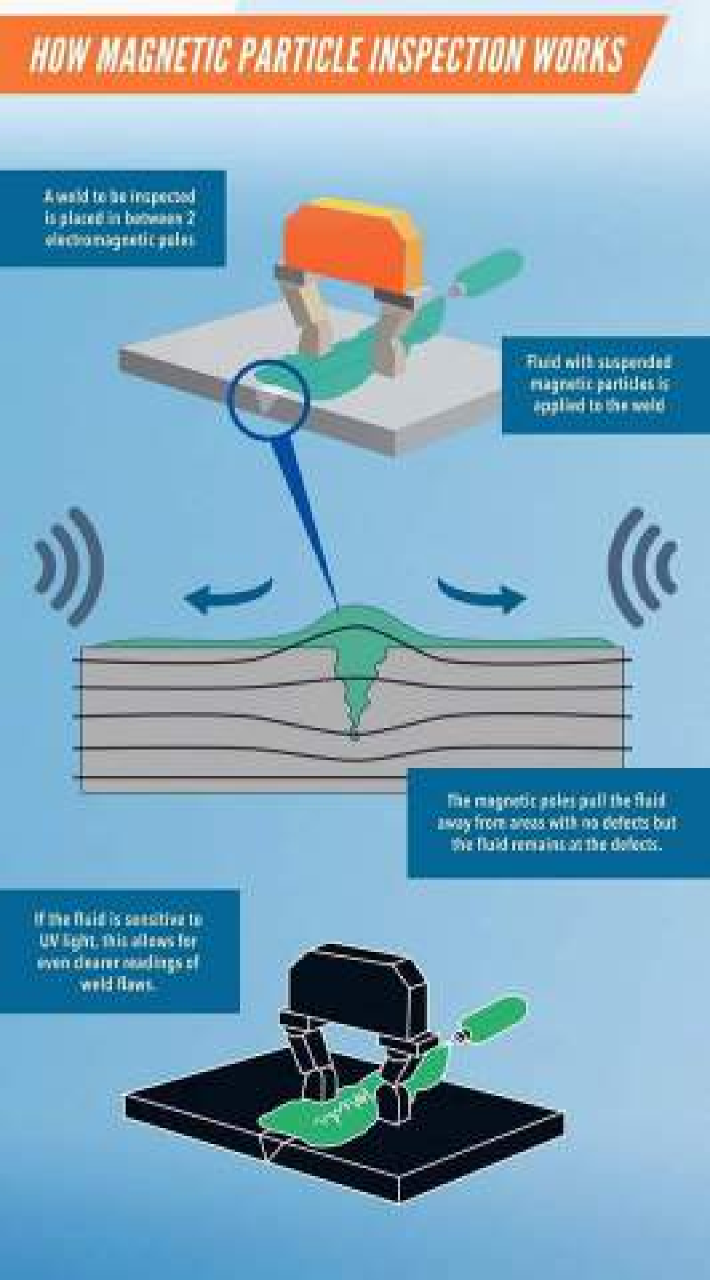


1) Double-Bevel-Groove Weld.
2) Complete Penetration - Welded Both Sides.
3) Minimum T = 3/8".
4) Root of First Weld Should Be Chipped or Gouged Out.
5) May Be Used For Horizontal Joints.

1) Single-Bevel-Groove Weld.
2) Partial Penetration - Welded One Side.
3) Minimum T = 1/4".



1) Double-Bevel-Groove Weld.
2) Partial Penetration - Welded Both Sides.
3) Minimum T = 3/8".


HOW MAGNETIC PARTICLE INSPECTION WORKS
A weld to be inspected is placed in between 2 electromagnetic poles
Fluid with suspended magnetic particles is applied to the weld
The magnetic poles pull the fluid away from areas with no defects but the fluid remains at the defects.
If the fluid is sensitive to UV light, this allows for even clearer readings of weld flaws.

Bester 215 MP Lincoln Electric

Suggested settings for welding with Bester 215MP

	STEEL																	
	DC+												DC-					
	SOLID												CORED					
	100% CO2						80%ARGON 20%CO2						NA					
Diameter	0.6mm		0.8mm		1.0mm		0.6mm		0.8mm		1.0mm		0.8mm		0.9mm		1.1mm	
1.6mm	16.5V	6.0	16.0V	3.3	16.5V	3.3	15.3V	6.4	15.0V	3.3	15.2V	3.8	15.0V	3.8	15.0V	2.5	16.0V	2.0
	16.5V	64A	16.0V	62A	16.5V	65A	15.3V	65A	15.0V	65A	15.2V	66A	15.0V	63A	15.0V	65A	16.0V	130A
3.0mm	21.0V	14.0	19.5V	7.4	19.0V	5.8	20.0V	14.0	18.5V	7.3	17.8V	5.3	17.5V	8.0	17.1V	5.0	17.0V	2.8
	21.0V	105A	19.5V	125A	19.0V	125A	20.0V	113A	18.5V	125A	17.8V	125A	17.5V	125A	17.1V	128A	17.0V	160A
4.0mm	N/A	N/A	21.5V	9.5	22.0V	6.7	N/A	N/A	19.0V	8.8	18.5V	6.5	19.0V	10.0	19.0V	6.4	19.0V	3.0
	N/A	N/A	21.5V	146A	22.0V	145A	N/A	N/A	19.0V	146A	18.5V	145A	19.0V	145A	19.0V	145A	19.0V	180A
5.0mm	N/A	N/A	23.0V	10.3	23.0V	7.6	N/A	N/A	20.5V	10.2	22.5V	7.5	20.2V	11.8	20.0V	7.8	19.0V	3.3
	N/A	N/A	23.0V	168A	23.0V	[illegible]	[illegible]	N/A	20.5V	180A	22.5V	200A	20.2V	156A	20.0V	165A	19.0V	200A

BS EN ISO 15653:2010

BSI Standards Publication

Metallic materials — Method of test for the determination of quasistatic fracture toughness of welds

raising standards worldwide™

National foreword

This British Standard is the UK implementation of EN ISO 15653:2010. It supersedes BS 7448-2:1997 which is withdrawn.

The UK participation in its preparation was entrusted by Technical Committee ISE/101, Test methods for metals, to Subcommittee ISE/101/4, Toughness testing.

A list of organizations represented on this committee can be obtained on request to its secretary.

This publication does not purport to include all the necessary provisions of a contract. Users are responsible for its correct application.

ISBN 978 0 580 71613 3

ICS 25.160.40

Compliance with a British Standard cannot confer immunity from legal obligations.

This British Standard was published under the authority of the Standards Policy and Strategy Committee on 31 July 2010.

Amendments and Corrigenda issued since publication

Date	Text affected

EUROPEAN STANDARD

NORME EUROPÉENNE

EUROPÄISCHE NORM

EN ISO 15653

April 2010

ICS 25.160.40

English Version

Metallic materials - Method of test for the determination of quasistatic fracture toughness of welds (ISO 15653:2010)

Matériaux métalliques - Méthode d'essai pour la détermination de la ténacité quasi statique à la rupture des soudures (ISO 15653:2010)

Metallische Werkstoffe - Prüfverfahren zur Bestimmung der quasistatischen Bruchzähigkeit von Schweißverbindungen (ISO 15653:2010)

This European Standard was approved by CEN on 23 January 2010.

CEN members are bound to comply with the CEN/CENELEC Internal Regulations which stipulate the conditions for giving this European Standard the status of a national standard without any alteration. Up-to-date lists and bibliographical references concerning such national standards may be obtained on application to the CEN Management Centre or to any CEN member.

This European Standard exists in three official versions (English, French, German). A version in any other language made by translation under the responsibility of a CEN member into its own language and notified to the CEN Management Centre has the same status as the official versions.

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Management Centre: Avenue Marnix 17, B-1000 Brussels

Ref. No. EN ISO 15653:2010: E

Foreword

This document (EN ISO 15653:2010) has been prepared by Technical Committee ISO/TC 164 "Mechanical testing of metals" in collaboration with Technical Committee CEN/TC 121 “Welding” the secretariat of which is held by DIN.

This European Standard shall be given the status of a national standard, either by publication of an identical text or by endorsement, at the latest by October 2010, and conflicting national standards shall be withdrawn at the latest by October 2010.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. CEN [and/or CENELEC] shall not be held responsible for identifying any or all such patent rights.

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Endorsement notice

The text of ISO 15653:2010 has been approved by CEN as a EN ISO 15653:2010 without any modification.

INTERNATIONAL STANDARD

ISO 15653

First edition
2010-04-15

Metallic materials — Method of test for the determination of quasistatic fracture toughness of welds

Matériaux métalliques — Méthode d'essai pour la détermination de la ténacité quasi statique à la rupture des soudures

Reference number
ISO 15653:2010(E)

Contents

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

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ISO 15653 was prepared by Technical Committee ISO/TC 164, *Mechanical testing of metals*, Subcommittee SC 4, *Toughness testing — Fracture (F), Pendulum (P), Tear (T).*

Metallic materials — Method of test for the determination of quasistatic fracture toughness of welds

1 Scope

This International Standard specifies methods for determining fracture toughness in terms of K (stress intensity factor), δ (crack tip opening displacement, CTOD) and J (experimental equivalent of the J-integral) for welds in metallic materials.

This International Standard is complementary to ISO 12135, which covers all aspects of fracture toughness testing of parent metal and which needs to be used in conjunction with this document. This International Standard describes methods for determining point values of fracture toughness. It should not be considered a way of obtaining a valid R-curve (resistance-to-crack-extension curve). However, the specimen preparation methods described in this International Standard could be usefully employed when determining R-curves for welds. The methods use fatigue precracked specimens which have been notched, after welding, in a specific target area in the weld. Methods are described to evaluate the suitability of a weld for notch placement within the target area, which is either within the weld metal or within the weld heat-affected zone (HAZ), and then, where appropriate, to evaluate the effectiveness of the fatigue crack in sampling these areas.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 3785, *Metallic materials — Designation of test specimen axes in relation to product texture*

ISO 12135, *Metallic materials — Unified method of test for the determination of quasistatic fracture toughness*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 12135 and the following apply.

3.1
stretch zone width
SZW
increase in crack length associated with crack tip blunting — i.e. prior to the onset of unstable crack extension, pop-in (see 3.3) or slow stable crack extension — and occurring in the same plane as the fatigue precrack

3.2
target area
intended fatigue crack tip position within the weld metal or HAZ

NOTE See 3.7 and 3.9.

3.3
pop-in
an abrupt discontinuity in the force versus displacement record, featured as a sudden increase in displacement and, generally, a sudden decrease in force, subsequent to which displacement and force increase to above their values at pop-in

3.4
local compression
controlled compression applied to specimens in the thickness direction on the unnotched ligament prior to fatigue cracking using hardened steel platens

NOTE See Annex C.

3.5
welding
an operation in which two or more parts are united by means of heat, friction, pressure or all three of these, in such a way that there is continuity in the nature of the metal between these parts

NOTE Filler metal, the melting temperature of which is of the same order as that of the parent metal, may or may not be used.

3.6
weld
union of pieces of metal made by welding

3.7
weld metal
all metal melted during the making of a weld and retained in the weld

3.8
parent metal
base metal
metal to be joined by welding

3.9
heat-affected zone
HAZ
zone in the parent metal that is metallurgically affected by the heat of welding

3.10
fusion line
FL
junction between the weld metal and the parent metal heat-affected zone

3.11
weld positional
WP
target position for the fatigue crack tip, defined with respect to a reference line

NOTE See Figure A.1 for examples.

3.12
specific microstructure
SM
target microstructure for the fatigue crack tip

NOTE See Figure A.2 for examples.

3.13
specimen blank
specimen prepared from weld metal plus parent metal prior to notching

3.14
postweld heat treatment
heat treatment applied after welding for the purpose of reducing residual stresses or modifying weld properties

4 Symbols and units

For the purposes of this document, the symbols and units given in Table 1 apply in addition to those in ISO 12135.

Table 1 — Symbols and units

Symbol	Unit	Designation
d_1, d_2	mm	Lengths of microstructural features associated with pop-in.
h	mm	Effective weld width, defined as shortest distance between fatigue crack tip and weld fusion line within the central 75 % of the thickness (see Figures 13 and 14).
HV10		Vickers hardness using 10 kg force.
N		Normal to welding direction.
P		Parallel to welding direction.
Q		Weld thickness direction.
$R_{p0,2b}$	MPa	0,2 % offset yield strength of parent metal at the temperature of the fracture test.
$R_{p0,2w}$	MPa	0,2 % offset yield strength of weld metal at the temperature of the fracture test.
R_{mb}	MPa	Tensile strength of parent metal at the temperature of the fracture test.
R_{mw}	MPa	Tensile strength of weld metal at the temperature of the fracture test.
s_1	mm	Distance between crack tip and target area measured in the crack plane (see Figure 12).
s_2	mm	Distance between crack tip and target area measured perpendicular to the crack plane (see Figure 12).
V, V_1, V_2	mm	Crack mouth opening displacement.
X		Direction parallel to primary grain flow of parent metal.
Y		Direction transverse to primary grain flow and to thickness of parent metal.
Z		Direction through thickness of parent metal.
Δa_{pop}	mm	Maximum length of brittle crack extension (beyond SZW) (see 3.1) associated with pop-in.
λ	mm	Length of specific microstructure measured in pre-test or post-test metallography (see Figure B.2).

5 Principle

This International Standard specifies procedures for the determination of fracture toughness on notched-plus-fatigue-cracked specimens taken from welds. It pertains to situations where the crack tip is

a) located in relation to a weld feature of interest, referred to as “weld positional” (WP);

b) specifically located within a microstructure of interest, referred to as “specific microstructure” (SM).

Metallographic examination of the weld is used to confirm that the target weld feature and/or microstructure is indeed present at the crack tip and in sufficient quantity for testing.

Specimen geometry and notch orientation are chosen, and a fatigue crack then extended from the specimen's notch tip into the target weld feature or microstructure by applying a controlled alternating force to the specimen. The purpose of the test is to determine weld fracture toughness in the absence of significant welding stresses. To achieve this and to produce a straight-fronted fatigue crack, modifications to the fatigue precracking procedure may be required. These modifications are usually necessary when testing as-welded or partially stress-relieved welds.

The fracture toughness test is performed and evaluated in accordance with ISO 12135, but subject to additional requirements of this test method regarding post-test analysis (see 12.1, 12.2 and 12.3) and qualification (see 12.4).

Post-test metallography is often required to make certain that the crack tip was located in the target weld feature and/or microstructure and to determine the significance of pop-ins.

The sequence of operations is summarized in Figure 1.

6 Choice of specimen design, specimen orientation and notch location

6.1 Classification of target area for notching

A specimen selected for weld positional (WP) testing is intended to test a defined weld region with respect to a reference position (e.g. the weld metal centreline).

A specimen selected for specific microstructure (SM) testing is intended to sample a specific microstructure along the whole or part of the crack front length within the central 75 % of the specimen thickness.

NOTE Some examples of WP and SM notch locations are given in Annex A.

WP weld metal centreline notch locations sampling predominantly grain-refined regions may give misleading (overly high) values of fracture toughness for misaligned two-pass and parallel multi-pass welds. For these welds, it is recommended that the SM notch locations shown in Figures A.2 iv) and A.2 v), respectively, be used.

6.2 Specimen design

Specimen design shall be of compact or single-edge-notched bend configuration as defined in ISO 12135 and may be plain-sided or side-grooved. Bend specimens notched into the plate thickness (see Figures 2, 3 and 4, parent metal specimens XY and YX and weld metal specimens NP and PN) are referred to as through-thickness notched specimens, whilst those notched into the planar surface of the plate (see Figures 2, 3 and 4, parent metal specimens XZ and YZ and weld metal specimens NQ and PQ) are referred to as surface-notched specimens.

NOTE Tolerances on weld specimen dimensions are less stringent than those for testing parent metal (see 8.1).

Test specimens shall have the dimension B or W (see Figure 5) equal to the full thickness of the parent metal adjacent to the weld to be tested (excluding weld overfill).

Testing of sub-sized (i.e. B or $W <$ full thickness in directions Q for weld and Z for parent metal in Figures 2, 3 and 4) and/or side-grooved specimens is permitted, but shall be properly identified as such in the test report. Results from sub-sized and/or side-grooved specimens may differ from those from full-thickness specimens owing to size effects and/or different microstructural regions being tested.

6.3 Specimen and crack plane orientation

Specimen and crack plane orientation relative to the weld and parent metal working directions shall be defined using the identification system described in Figures 2, 3 and 4.

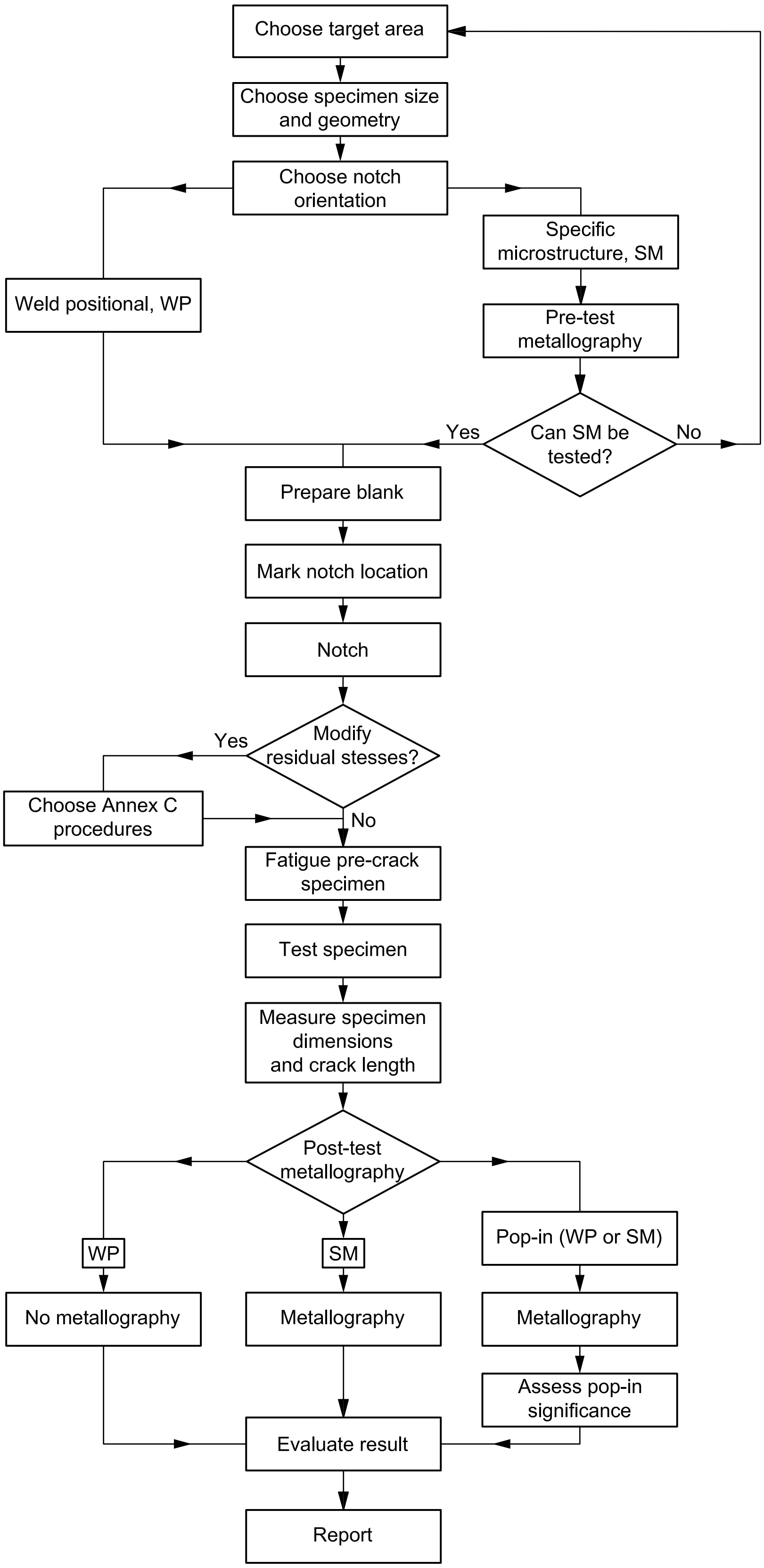
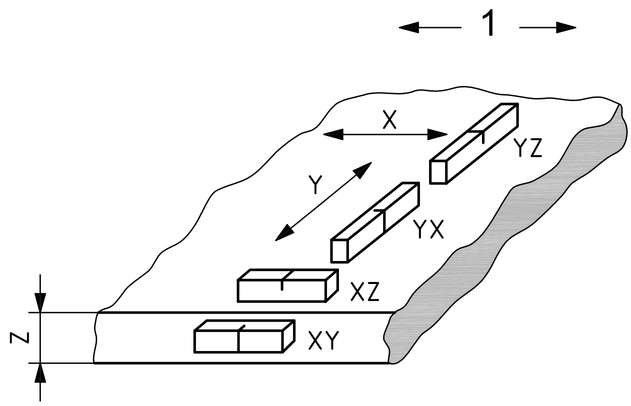
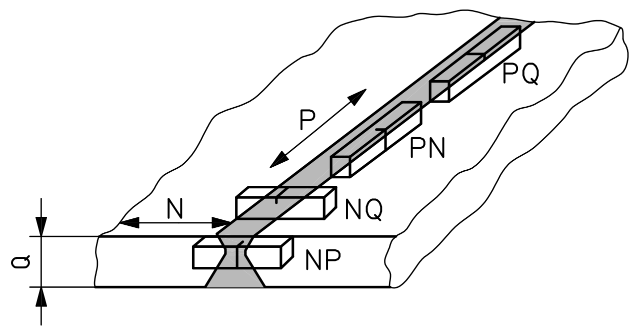


Figure 1 — Flow chart for testing



a) Parent metal



b) Weld metal

Key

1 rolling direction

N = normal to weld direction

P = parallel to weld direction

Q = weld thickness direction

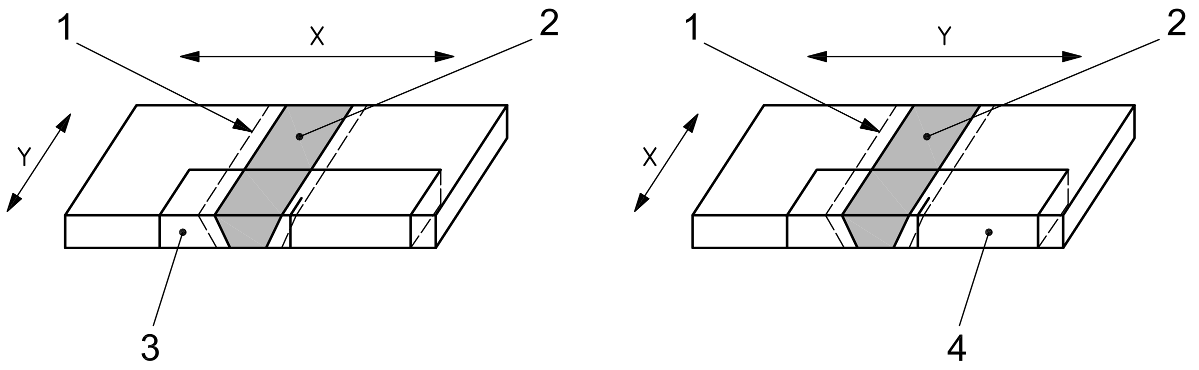
First letter in designation: the direction normal to the crack plane.

Second letter in designation: the expected direction of crack propagation.

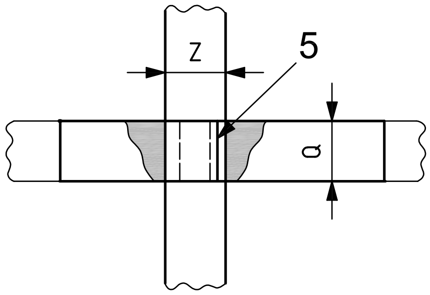
See ISO 3785 for the definitions of X, Y and Z.

Specimen orientations NP and PN shall be referred to as through-thickness notched, whilst specimen orientations NQ and PQ shall be referred to as surface-notched.

Figure 2 — Crack plane orientation code for fracture toughness specimens of parent metal and weld metal



a) Typical butt weld



b) Cruciform joint

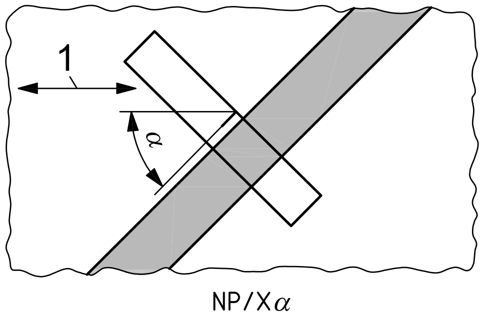
Key

1 HAZ
2 weld
3 weld specimen orientation NP/XY
4 weld specimen orientation NP/YX
5 through-crack NP/ZX or NP/ZY

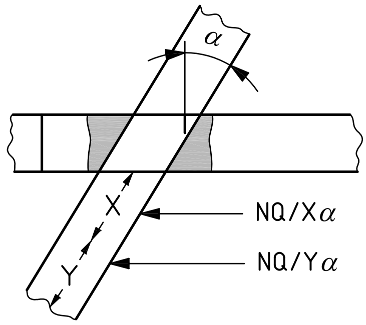
X = rolling direction
Q = weld thickness direction

For tests of the HAZ, where the rolling direction of the parent metal may affect resistance to crack extension, the weld and parent metal orientations may be combined to give both the weld direction and the parent metal rolling direction as shown in this figure and Figure 4.

Figure 3 — Crack plane orientation code for fracture toughness specimens for testing the HAZ of a typical butt weld and cruciform joint



a) Typical butt weld



b) Angled cruciform joint

Key

1 rolling direction

For tests of the HAZ, where the rolling direction of the parent metal may affect resistance to crack extension, the weld and parent metal orientations may be combined to give both the weld direction and the parent metal rolling direction as shown in this figure and Figure 3.

Figure 4 — Crack plane orientation code for fracture toughness specimens for testing the HAZ at an angle, α, to the parent metal rolling direction for a typical butt weld and angled cruciform joint

7 Pre-machining metallography

7.1 Microstructural assessment of macrosections

When the notch target area is defined as SM, either separate macrosections or the ends of the welds shall be prepared with the plane of the section perpendicular to the welding direction. These transverse weld sections shall bound the length of weld to be tested to ensure that the target microstructure is present at the expected crack tip position and in sufficient quantity for testing. The macrosections shall be polished, etched and examined at a magnification suitable to identify the target area prior to specimen manufacture. Where separate macrosections are prepared, their positions along the weld shall be recorded.

Examination of the macrosections shall be used to establish that

a) in a through-thickness notched specimen, the intended crack tip is likely to reside in the target area within the central 75 % of the thickness;

b) in a surface-notched specimen, the intended crack tip is no more than 0,5 mm from the target area.

If the desired microstructure is not present, there is insufficient quantity to test, or the crack tip position tolerances cannot be achieved, the weld shall be rejected as unsuitable for testing to the SM criteria. In this case, a new target area may be selected or a new weld prepared. If the bend specimen is to be employed and the specific microstructure is available in sufficient quantity to test, but the crack tip position tolerances cannot be achieved, the shallow-notched specimen testing procedures described in Annex E may be used by agreement between the parties involved.

Owing to the lower crack tip constraint associated with a shallow notch, the fracture toughness value determined from a shallow-notched specimen ($0,10 \leqslant a_o/W \leqslant 0,45$) ($a_o$ = initial crack length, W = specimen thickness) may be higher than that obtained from a standard notched specimen ($0,45 \leqslant a_o/W \leqslant 0,70$) for the same crack tip microstructure. The significance of this potential difference shall be considered when a shallow-notched specimen is to be used.

7.2 Additional requirements for heat-affected zone tests

When the target area is SM in the HAZ, microstructural examinations additional to those in 7.1 shall be conducted on the polished and etched macrosection to determine whether or not the target microstructure is within the central 75 % of the thickness and in sufficient quantity for a successful test.

The measured positions and lengths of the target microstructure may optionally be presented in map form (an example is shown in Annex B). If such a map is drawn, it shall include the full macrosection thickness, showing the positions of the target microstructure. The percentage of target microstructure shall be calculated over the central 75 % of the specimen thickness.

Where surface-notched specimens are selected, the macrosection shall be used to confirm that the target microstructure is present within the range $0,45 \leqslant a_o/W \leqslant 0,70$.

If it is considered unlikely that the fatigue crack tip is placed in accordance with the SM acceptance criteria, then consideration shall be given to revising the target area, preparing a new weld or using a shallow-notched specimen as described in 7.1.

8 Machining

8.1 Tolerances on specimen dimensions

Specimen blanks shall be machined from the product so that the target area identified for testing can be successfully notched. Blanks shall be machined to the dimensional tolerances defined here prior to notching.

Compact specimens shall meet the dimensional requirements of ISO 12135. Standard bend specimens shall conform to Figure 5. Shallow-notched bend specimens (see 7.1, 7.2 and Annex E) shall likewise conform to Figure 5 except that the relative crack length shall be in the range $0,10 \leqslant a_o/W \leqslant 0,45$.

NOTE 1 The dimensional tolerances in Figure 5 for the standard single-edge-notched bend specimen are intentionally less stringent than those of ISO 12135 in order to minimize alteration of the original weld product.

Weld misalignment, weld distortion and specimen blank curvature (for blanks removed from pipe sections) shall conform to the requirements of Figure 6. The straightness requirement of 2,5 % of W on specimen blank sides applies to pipe curvatures (expressed as the ratio of pipe radius to weld thickness) $\geqslant 10$. Welded joints not meeting the specified straightness/misalignment requirements shall be straightened by local bending prior to notching. The points of straightening-force application shall be located at a minimum distance B from the region to be notched. It is essential that the region to be notched is not deformed by straightening operations. A method for straightening specimen blanks from distorted or curved sections is illustrated in Figure 7.

When it is not possible to straighten a specimen blank taken from pipe, a rectangular block of test material may be cut from the pipe and joined by welding to suitable extension pieces. The total length of the test block and extension pieces shall give a specimen of sufficient length to satisfy the curvature requirements of Figure 6. The weld joints shall be sufficiently distant so as not to affect the target microstructure.

NOTE 2 Laser and electron beam welding processes have proved useful in producing narrow joints of low distortion between the test block and the extension pieces.

When a full section thickness specimen is intended, machining shall be kept to a minimum in order to meet the tolerance requirements and the requirements for local compression (see Clause C.2).

Weld overfill shall be machined level with the original product surface.

When the metal thicknesses on each side of the weld differ by 10 % or more, the blank shall be machined down to the thickness of the thinner side. In such cases, the original and final specimen blank dimensions shall be reported.

8.2 Notch placement for through-thickness notched specimens

The procedure for through-thickness notch placement for the NP crack plane orientation is illustrated in Figure 8. Both the surface to be notched (side A) and the opposite surface (side B) are ground and etched to reveal the weld and HAZ. A reference line is scribed on each prepared surface A and B normal to the specimen axis ± 5° and along the targeted microstructure. These scribed lines are carried over onto the surfaces normal to the prepared surfaces. A new line is then constructed equidistant between the carried-over lines. This line is used to delineate the intended plane of the notch to be machined into surface A.

NOTE This procedure is designed to ensure that the final crack tip is in the targeted microstructure (especially if it is the HAZ) when the specimen axis in not perpendicular to the weld direction and $a_o/W = 0{,}5$. If $a_o/W \neq 0{,}5$, the line constructed to delineate the intended plane of the machined notch is adjusted laterally to ensure that the final crack tip is in the targeted microstructure.

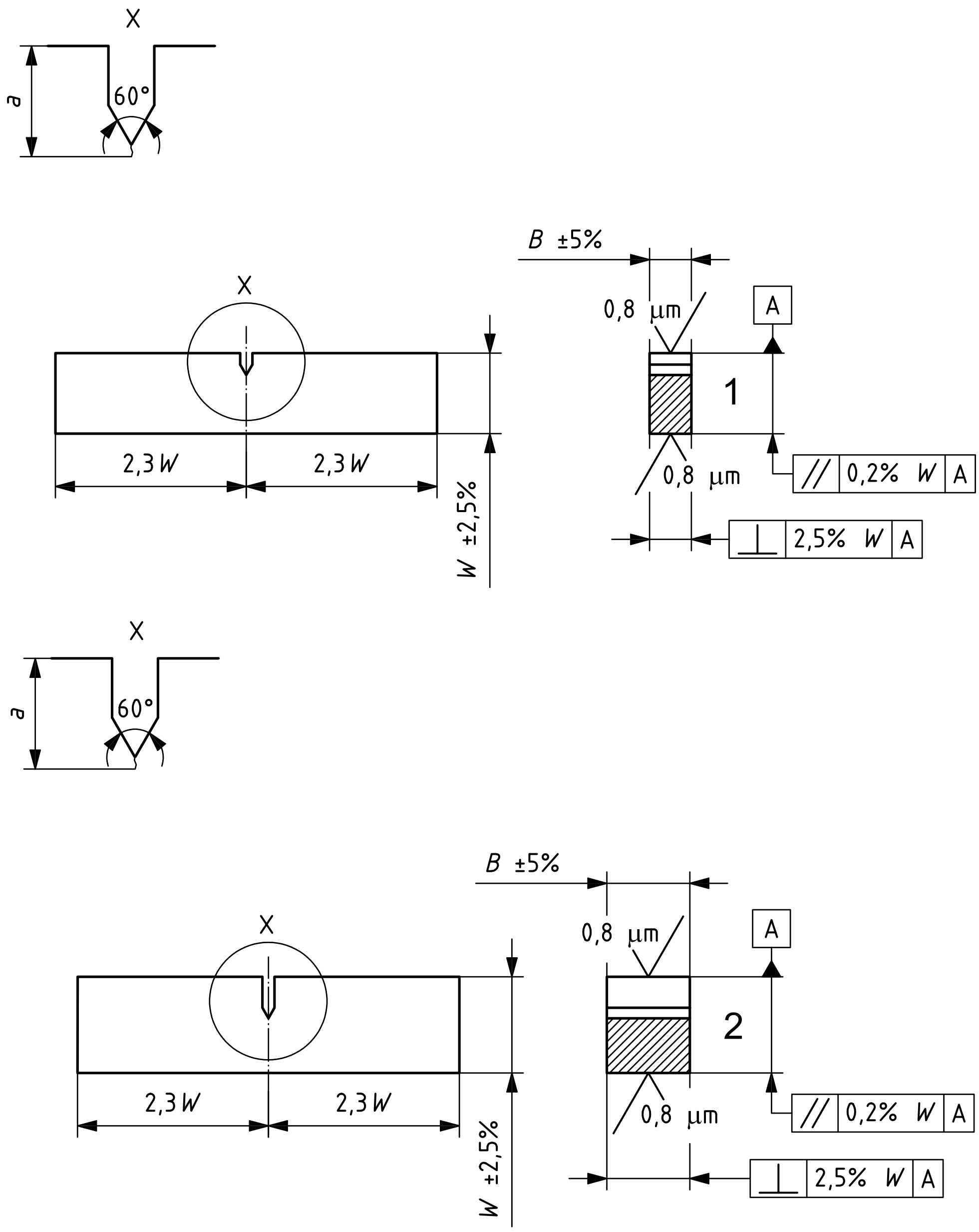
8.3 Notch placement for surface-notched specimens

The procedure for surface-notch placement for the NP crack plane orientation is illustrated in Figure 9. The side surfaces (those at right angles to the surface to be notched) are ground and etched to reveal the weld metal and HAZ. Reference lines are scribed upwards from the selected target-microstructure area to the surface to be notched. Perpendiculars emanating from the scribe lines (normal to the specimen axis ± 5°) are marked (again by scribing) on the surface to be notched. A new line is constructed equidistant between the two lines. This line is used to delineate the intended plane of the machined notch.

NOTE This procedure is designed to ensure that the final crack tip, at the specimen mid-thickness, is in the targeted microstructure when the specimen axis is not perpendicular to the weld direction.

8.4 Notch machining

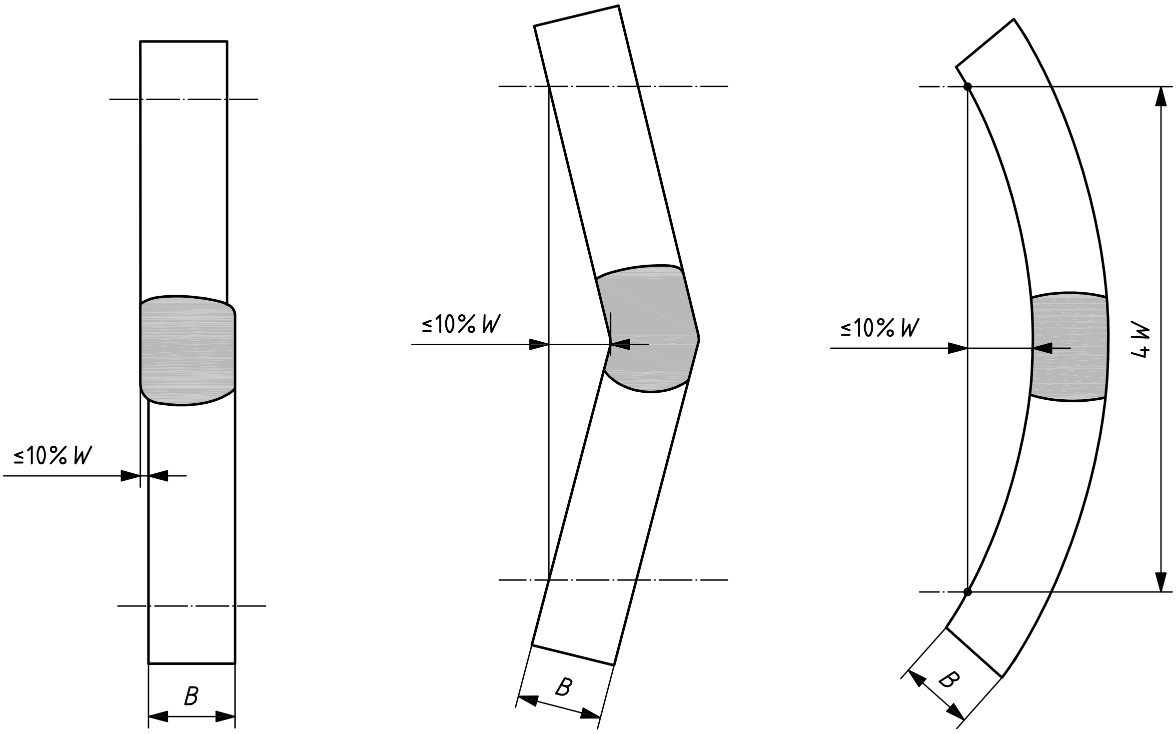
Notch machining shall follow the guidelines of ISO 12135.



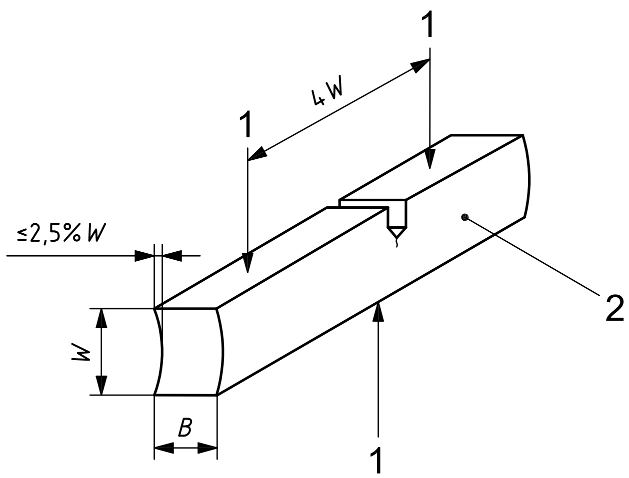
1 rectangular-section specimen
width = W
thickness = B = 0,5W
crack length = a = 0,45W to 0,7W
loading span = 4W
notch width = 0,065W_{max}
specimen straightness, see Figure 6

2 square-section specimen
width = W
thickness = B = W
crack length = a = 0,45W to 0,7W
loading span = 4W
notch width = 0,065W_{max}
specimen straightness, see Figure 6

Figure 5 — Proportional dimensions and tolerances for bend specimens



a) Misalignment **b) Misalignment and/or angular distortion** **c) Curvature**



d) Curvature

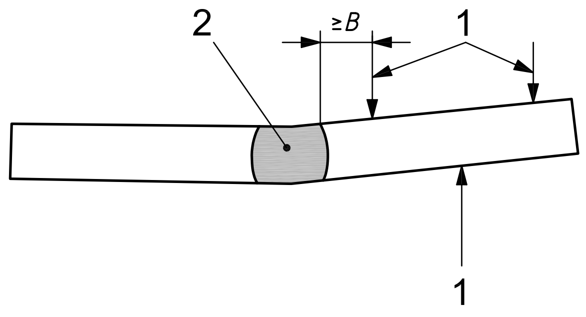
Key

1 loading points

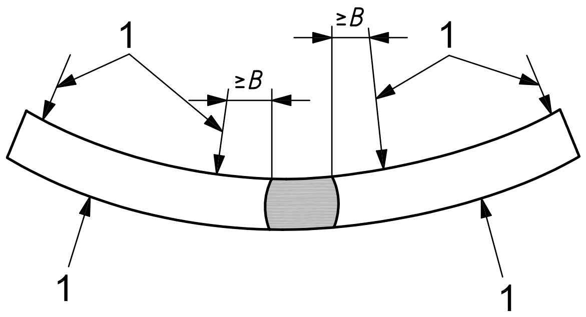
2 curved surface due to tube radius

$4W$ = span

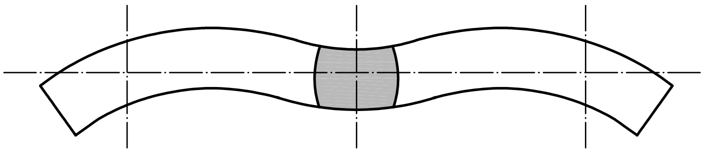
Figure 6 — Tolerances for misalignment, distortion and curvature in single-edge-notched bend specimens



a) To reduce angular distortion



b) To reduce curvature of specimen blank from pipe (each specimen arm straightened separately)



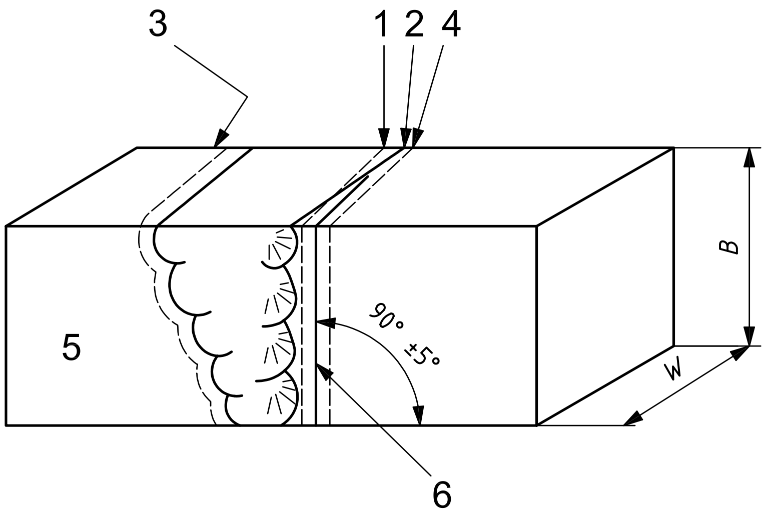
c) Resultant "gull wing" specimen blank shape

Key

1 applied straightening force

2 weld

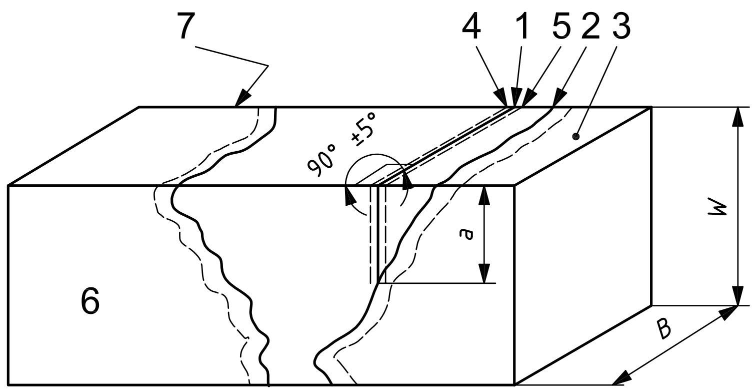
Figure 7 — Method for straightening bend specimens



Key

1 reference scribe line A
2 fusion line
3 side B (unnotched side)
4 reference scribe line B
5 side A (notched side)
6 notch

Figure 8 — Notch placement procedure using reference scribe lines in a through-thickness notched specimen (NP crack plane orientation)



Key

1 notch
2 fusion line
3 notched side
4 reference scribe line B
5 reference scribe line A
6 side A
7 side B

Figure 9 — Notch placement procedure in a surface-notched specimen (NP crack plane orientation)

9 Specimen preparation

9.1 Fatigue precracking

Fatigue precracking shall be carried out in accordance with ISO 12135. For specimens where the intended fatigue crack tip is located in weld metal, the calculation of the maximum fatigue precracking force, F_f, and the maximum fatigue stress intensity factor, K_f, shall be based on the tensile properties of the weld metal, i.e. the region in which the fatigue crack is to be located. In all other cases, the properties of the adjacent material with the lowest tensile properties shall be used.

Any post-weld or stress relief heat treatment shall be completed before fatigue precracking.

When possible, use of the shortest fatigue crack length permitted in ISO 12135 is recommended in order to minimize fatigue crack front bowing and crack deviation from the specified target area.

Problems may occur in meeting the fatigue crack front straightness requirements specified in 12.4, particularly with specimens prepared from as-welded or partially stress-relieved welds. In such instances, the procedures given in Annex C shall be considered.

NOTE 1 The magnitude and distribution of residual stresses in as-welded and partially stress-relieved specimens depend on the material, the welding procedure, the degree of restraint and the post-weld specimen preparation.

NOTE 2 Residual stresses may (or may not) contribute to uneven fatigue crack extension, and may have an effect on the resulting fracture toughness determination.

If the specimen is prepared from a stress-relieved weld, then the procedures in Annex C may not be necessary.

NOTE 3 A straight fatigue crack front may indicate a) low or b) uniform residual stresses in the vicinity of the crack tip.

If the fatigue precrack does not meet the straightness requirements of 12.4, then modifications to the fatigue precracking procedure shall be made in accordance with Annex C. When such modifications are made, the fracture toughness result shall be identified as described in 12.4.4.

9.2 Side grooving

Where side grooving is selected, it shall be conducted in accordance with the requirements of ISO 12135.

10 Test apparatus, requirements and test procedure

The apparatus, requirements and procedures for K_{Ic}, δ and J testing shall all be as prescribed in ISO 12135.

11 Post-test metallography

11.1 General

Post-test metallography shall be applied to specimens designated for SM testing in order to verify crack tip placement in the target microstructure. A section containing the fracture face shall be cut from the specimen. When the target area is the HAZ, the section shall be removed from the side of the specimen containing the weld metal. This section shall be used for the post-test analysis described in 11.2 and 11.3 to verify the microstructure at the fatigue crack tip.

Post-test sectioning is not required when the target area is WP.

In the case of brittle fracture, verification that the crack tip did indeed sample the specific microstructure does not guarantee that cleavage initiation necessarily occurred in that microstructure. Further sectioning and metallography may be necessary (when requested by the customer) to identify the microstructure at fracture initiation. The recommended sectioning procedures are the same as those described for the assessment of pop-in and are given in Annex D.

11.2 Through-thickness notched specimens

11.2.1 Sectioning

The through-thickness notched specimen shall be sectioned in a plane perpendicular to the fracture surface, behind the fatigue crack tip, at a position within 2 mm of the maximum fatigue precrack length, and shall include the fatigue crack over the central 75 % of the specimen thickness (B or B_N for side-grooved specimens) (see Figure 10, section A). The cut surface shall be examined metallographically to ensure that the fatigue crack did indeed sample the specific microstructure.

11.2.2 Assessment

The prepared metallographic surface shall be examined to ensure that the fatigue crack tip front sampled the SM and that the SM was located within the central 75 % of the specimen thickness (B or B_N). A microstructural map shall be prepared which records the positions and lengths of the specific microstructure within the central 75 % of the specimen thickness (B or B_N). An example of a specimen notched into the HAZ is shown in Annex B.

11.3 Surface-notched specimens

11.3.1 Sectioning

If the specimen fractures by cleavage, the fracture surface shall be examined at a suitable magnification to identify the initiation site, and at least one section shall be taken as close as possible to this position. If only stable crack extension has occurred, the section shall be taken at the maximum fatigue precrack length. The plane of the section shall be perpendicular to the notch/crack plane (see Figure 11).

Identification of the fracture initiation site may be done visually, but may require the aid of optical microscopy or scanning electron microscopy.

11.3.2 Assessment

The prepared metallographic surface shall be examined to ensure that the fatigue crack tip sampled the SM. If the SM lies ahead of the fatigue crack tip, the minimum separation distance, s_1, shall be measured to an accuracy of ± 0,05 mm [for NQ crack plane orientation, see Figure 12 a)]. If the specific microstructure lies to one side of the fatigue crack tip, the separation distance, s_2, shall be measured to an accuracy of ± 0,05 mm [see Figure 12 b)].

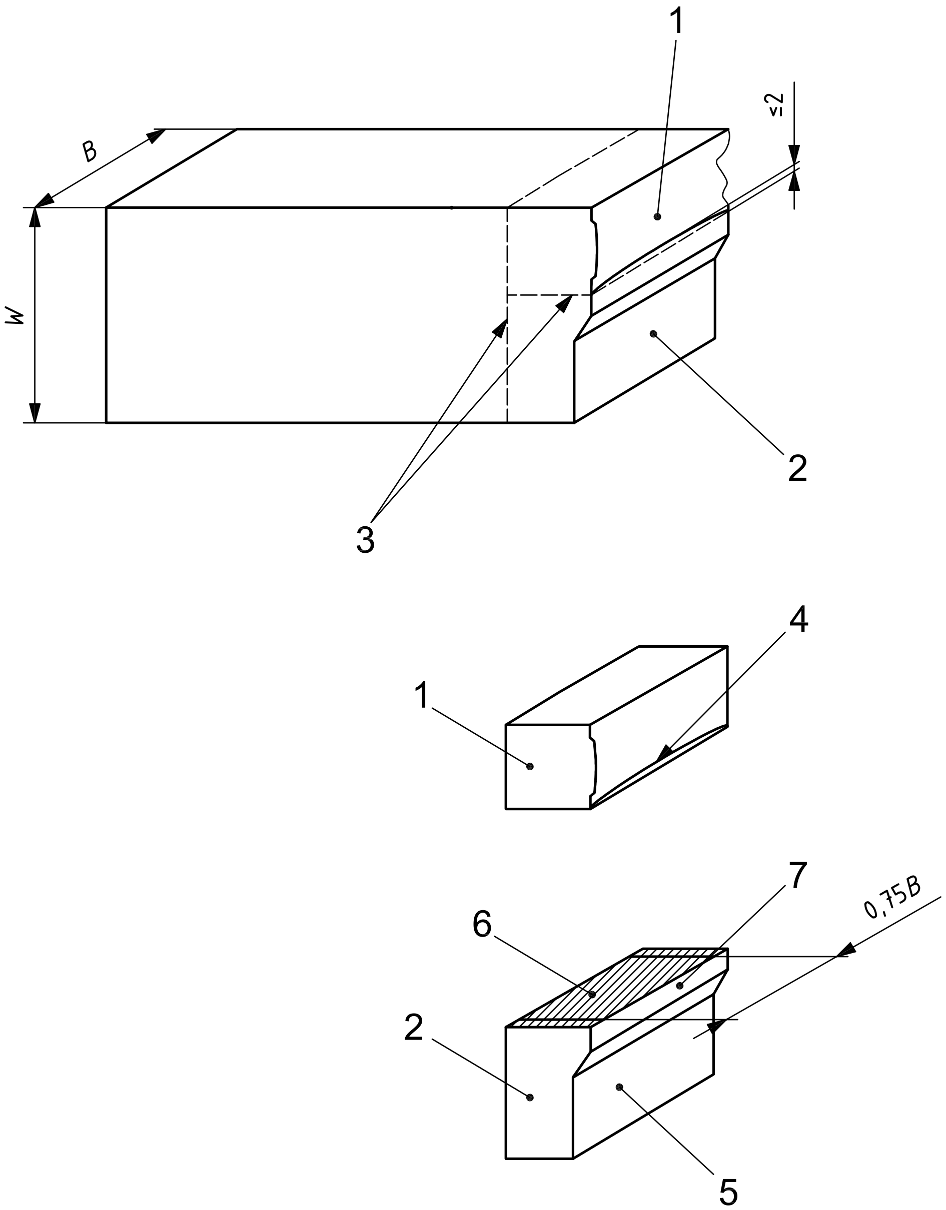
NOTE It might be necessary to section both fracture surfaces to establish these distances.

11.4 Assessment of pop-in

Pop-ins giving both force drops and displacement increases of less than 1 % shall be ignored. All other pop-ins shall be considered significant unless shown to be insignificant by the fractographic and metallographic procedures described in Annex D.

NOTE The criteria for the assessment of pop-in described in ISO 12135 are intended for testing homogeneous material and may be inappropriate for welds. Experience indicates that, for weld testing, the size of the pop-in is usually related to the length of brittle material present at the crack tip. Small changes in crack tip position can alter the size of the pop-in.

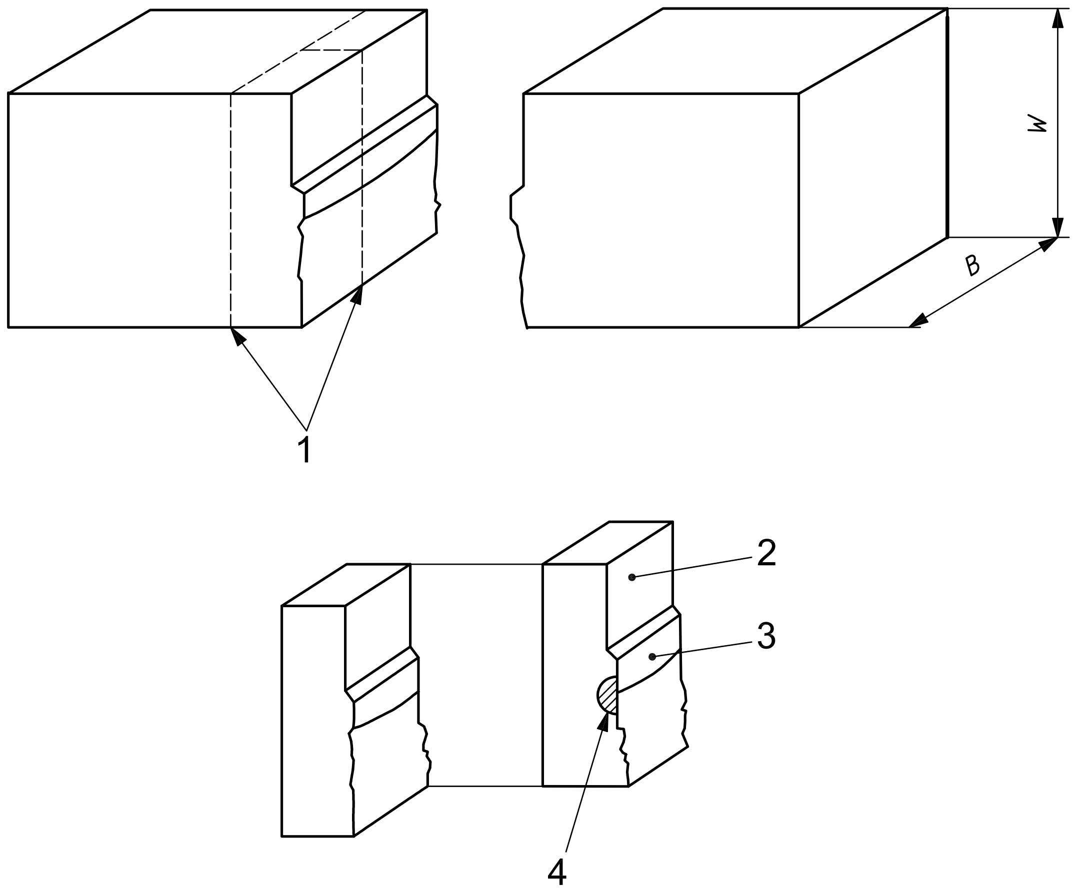
Dimensions in millimetres



Key

1 section B
2 section A
3 cuts
4 fatigue precrack tip
5 notch
6 surface to be examined (polish and etch)
7 fatigue crack

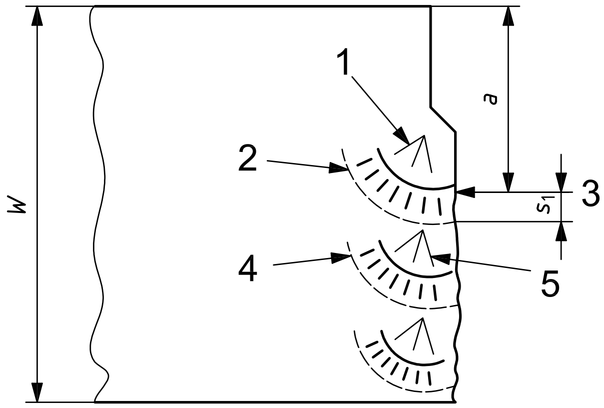
Figure 10 — Post-test sectioning procedure to identify microstructure at fatigue crack in a through-thickness notched specimen



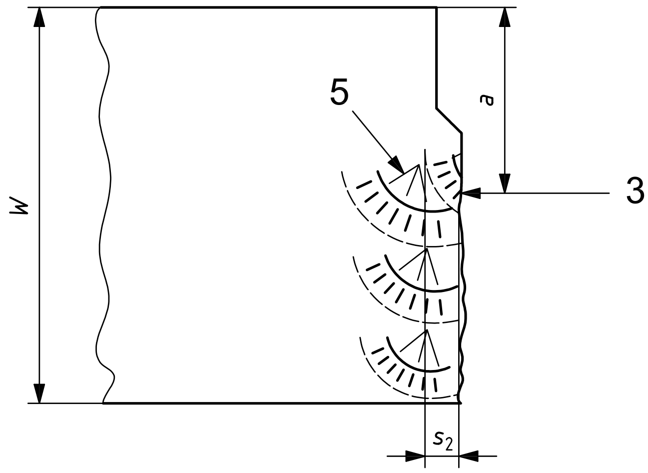
Key

1 cuts
2 notch
3 fatigue crack
4 surface to be examined (polish and etch)

Figure 11 — Post-test sectioning of a surface-notched specimen



a) Target microstructure ahead of fatigue crack tip



b) Target microstructure on one side of fatigue crack tip

Key

1 weld bead
2 reheated weld metal
3 fatigue crack tip
4 reheated weld metal
5 SM (target microstructure)

Figure 12 — Measurement of s_1 and s_2 in a surface-notched SM specimen (NQ crack plane orientation)

12 Post-test analysis

12.1 Choice of tensile properties

When the crack tip is located completely in weld metal, the pertinent tensile properties shall be those determined using an all-weld-metal tensile specimen. When located in, or partially in, the transformed HAZ, the higher of the parent metal and weld metal strengths shall apply.

NOTE Crack tip opening displacement (CTOD) in the HAZ is affected by the strength and size of the HAZ and the adjacent microstructures. Underestimates of CTOD fracture toughness will be made by using the higher of the parent metal and weld metal strengths.

For carbon and C-Mn steels, if the tensile properties of the weld metal and parent metal cannot be measured, they can be estimated (in MPa) from room temperature correlations with measured hardness (in HV10) as follows:

Parent metal [1], $R_{p0,2b} = 3{,}28\ \text{HV10} - 221$, for $160 < \text{HV10} < 495$ (1)

Weld metal, $R_{p0,2w} = 2{,}35\ \text{HV10} + 62$, for $170 < \text{HV10} < 330$ (2)

Parent metal, $R_{mb} = 3{,}3\ \text{HV10} - 8$, for $100 < \text{HV10} < 400$ (3)

Weld metal, $R_{mw} = 3{,}0\ \text{HV10} + 22{,}1$, for $170 < \text{HV10} < 330$ (4)

For ferritic steels, when tension testing below room temperature cannot be done and when the 0,2 % offset yield strength at the low temperature of the intended fracture test is not available, the low-temperature yield strength may be estimated (in MPa) from the room-temperature yield strength using the following relationship[2]:

$$R_{p0,2}\ (\text{at low temperature, } T) = R_{p0,2}\ (\text{at room temperature}) + \frac{10^5}{(491 + 1{,}8T)} - 189 \quad (5)$$

where T is the intended fracture test temperature, in °C, and is greater than –196 °C.

12.2 K_{Ic}

Interpretation of the test record to determine K_{Ic} shall be carried out in accordance with ISO 12135, but with the additional requirements of 12.1 of this International Standard concerning the appropriate choice of $R_{p0,2}$.

12.3 δ and J

Interpretation of the test record to determine δ and J from standard bend or compact specimens shall be carried out in accordance with ISO 12135, but subject to the additional requirements in 12.1. When a shallow-notched bend specimen is employed ($0{,}10 \leqslant a_o/W \leqslant 0{,}45$), interpretation of the test record to determine δ and J shall be carried out in accordance with Annex E.

12.4 Qualification requirements

12.4.1 General

All of the qualification checks listed in ISO 12135 are applicable to this International Standard, but with the following modifications.

12.4.2 Weld-width-to-crack-ligament ratio

For weld metal tests, the δ estimation procedures shall be considered qualified by this International Standard when the following requirements are met[3][4]:

a) for a crack in the centre of the weld, the ratio of the weld width (over the central 75 % of the thickness) to the crack ligament length shall be greater than 0,2, i.e. $2h/(W - a_o) > 0{,}2$ [see Figures 13 a) and 13 b) for through-thickness notched specimens and Figures 14 a) and 14 b) for surface-notched specimens];

b) for a crack offset from the weld centreline, the ratio of the effective weld width (shortest distance between the crack plane and the weld fusion boundary over the central 75 % of the specimen thickness) to the crack ligament length shall be greater than 0,1, i.e. $h/(W - a_o) > 0{,}1$ [see Figures 13 c) and 13 d) for through-thickness notched specimens and Figures 14 c) and 14 d) for surface-notched specimens];

c) for both cases a) and b) above, an additional requirement is that the ratio of the weld metal 0,2 % offset yield strength to the parent metal 0,2 % offset yield strength shall be in the range 0,50 to 1,50, i.e.

$$0{,}50 < \frac{R_{p0,2w}}{R_{p0,2b}} < 1{,}50 \qquad (6)$$

For weld metal tests, the J estimation procedures[3][4] shall be considered qualified to this International Standard when the ratio of weld metal to parent metal 0,2 % offset yield strengths is in the range 0,50 to 1,25, i.e.

$$0{,}50 < \frac{R_{p0,2w}}{R_{p0,2b}} < 1{,}25 \qquad (7)$$

For HAZ tests, the δ and J estimation procedures of ISO 12135 shall be used (see 12.1 for choice of yield strength for calculating δ). When reporting results, the 0,2 % offset yield strengths of both the parent and weld metal shall be stated.

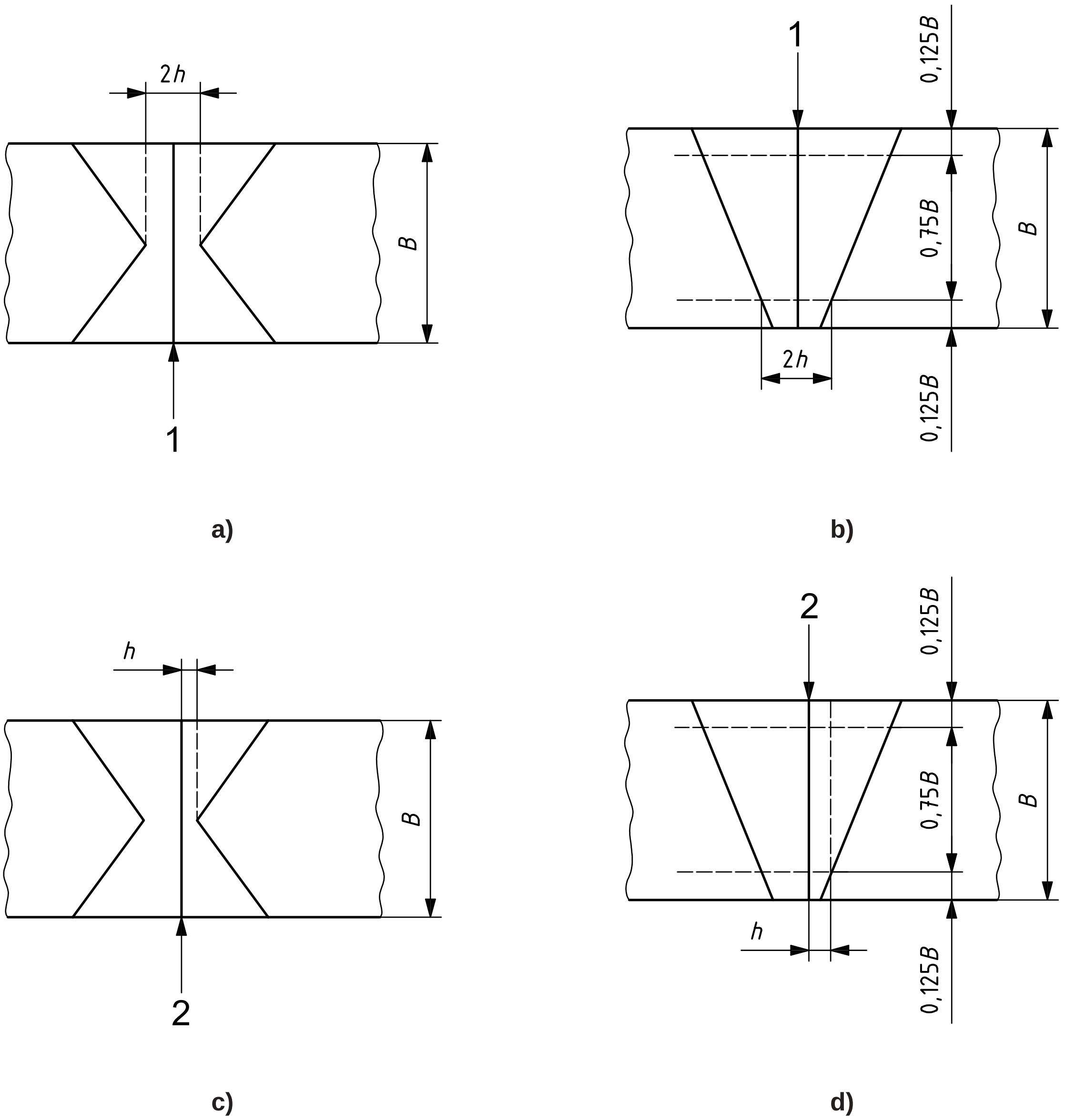
NOTE These estimation and qualification procedures may result in $\pm$ 10 % error in weld metal δ or J. Overestimates occur when $R_{p0,2w}/R_{p0,2b} > 1{,}50$ for δ, and $> 1{,}25$ for J; underestimates occur when $R_{p0,2w}/R_{p0,2b} < 0{,}50$ for δ and J [3][4]. When determining HAZ fracture toughness, the J and δ estimation procedures may result in $\pm$ 5 % and $-$ 20 % to $+$ 10 % error, respectively, for $0{,}7 < R_{p0,2w}/R_{p0,2b} < 2{,}5$[5].

12.4.3 Crack front straightness

For δ and J tests using bend specimens, the fatigue crack front straightness requirement may be broadened to 0,2 a_o; however, that for compact specimens may not be relaxed. K_{Ic} tests using either compact or bend specimens shall conform entirely to ISO 12135.

NOTE 1 Crack front straightness requirements are based on empirical evidence from bend specimens[6].

NOTE 2 In order to meet the requirements of SM and WP testing, it may not be possible to allow a relaxation of the fatigue crack front straightness requirements, and the more stringent requirements of ISO 12135 may be necessary.



Key

1 crack along weld centreline

2 crack off weld centreline

Figure 13 — Definition of h and $2h$ in through-thickness notched (NP) specimens from double- and single-sided welds

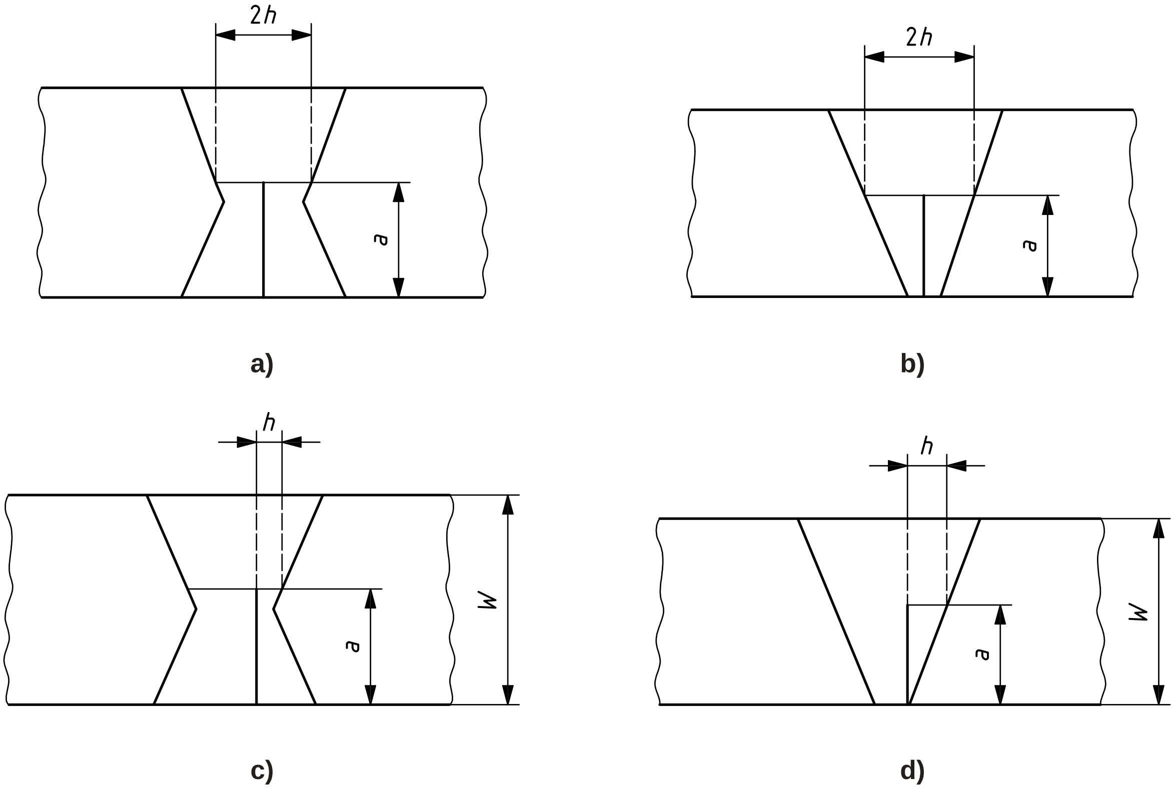


Figure 14 — Definition of h and $2h$ in surface-notched (NQ) specimens from double- and single-sided welds

12.4.4 Symbols used to identify fracture toughness values

In addition to the symbols required by ISO 12135 to identify fracture toughness values, the following shall be used:

a) K, J, δ (no superscripts) shall be used when Annex C modifications to the fatigue precracking procedure have NOT been made;

b) K^{M}, J^{M}, δ^{M} (M as superscript) shall be used to identify results from specimens when the fatigue precracking procedure HAS been modified in accordance with Annex C.

12.4.5 Through-thickness notched specimens

When post-test sectioning and metallographic examination of SM specimens in accordance with 11.2 shows that the fatigue crack front has indeed sampled both the designated target area and, where specified, the designated lengths of specific microstructure within the central 75 % of the specimen thickness (B or B_{N}), the fracture toughness result shall be considered qualified. When these requirements are not satisfied, the fracture toughness of the specific microstructure has not been determined and the test result shall be considered not qualified.

12.4.6 Surface-notched specimens

When post-test sectioning and metallographic examination of SM specimens in accordance with 11.3 shows either that the fatigue crack tip has indeed sampled the specific microstructure or that the dimension s_1 or s_2 (see 11.3.2) is $< 0{,}5$ mm, the fracture toughness result shall be considered qualified. When these requirements are not satisfied, the fracture toughness of the specific microstructure has not been determined and the test result shall be considered not qualified.

13 Test report

The test report shall be in accordance with ISO 12135, but with the following additional information:

a) whether weld positional (WP) or specific microstructure (SM) notching was used;

b) the crack plane orientation in accordance with Figures 2, 3 and 4;

c) the original thicknesses of the weld and parent metal adjacent to the weld;

d) the pre-test metallography results of macrosection examination (if appropriate);

e) the tensile properties of the weld and parent metal and the method used to derive the values;

f) the effective weld width, h, as appropriate;

g) the method used to achieve a straight fatigue crack front and inclusion of a superscript in the result symbol in accordance with 12.4.4, if appropriate;

h) the assessment of pop-in significance (if appropriate) in accordance with Annex D;

i) whether the result can be considered qualified with respect to crack sampling of the designated target area;

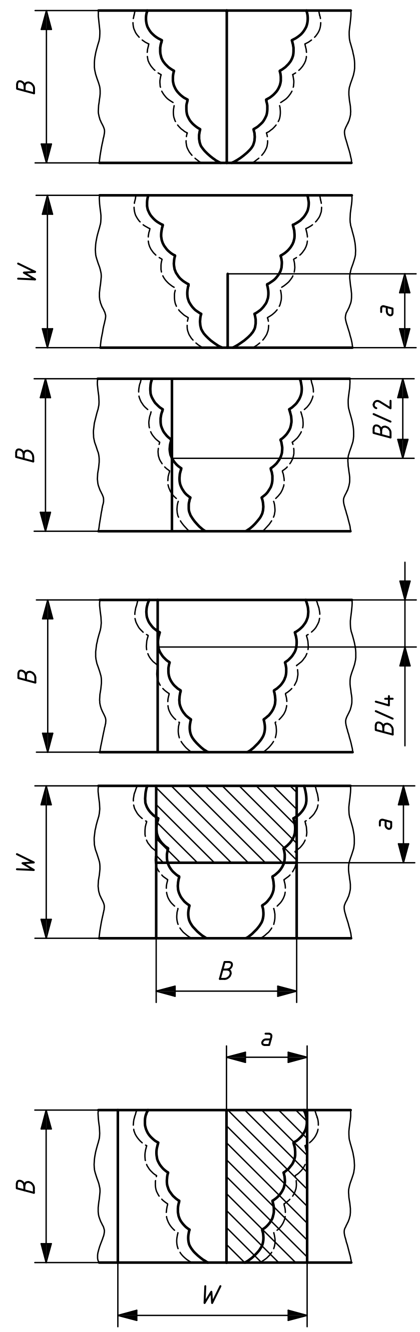
j) the distance s_1 or s_2, as appropriate, for SM notching;

k) whether a shallow-notched bend specimen was used in accordance with Annex E and, if so, the value of a_0/W.

Annex A
(informative)

Examples of notch locations

This annex gives examples of typical locations used when testing weld metal and HAZ with through-thickness and surface-notched bend specimens. Figure A.1 shows weld positional (WP) notch locations, whilst Figure A.2 shows specific microstructure (SM) notch locations.



	Orientation	Geometry	Notch location
i)	NP	$B \times B$ or $B \times 2B$	Weld metal centreline
ii)	NQ	$B \times B$	Weld metal centreline from weld root
iii)	NP	$B \times B$ or $B \times 2B$	HAZ with notch intersecting fusion line at mid-thickness
iv)	NP	$B \times B$ or $B \times 2B$	HAZ with notch intersecting fusion line at quarter-thickness
v)	PQ	$B \times B$	Transverse to weld
vi)	PN	$B \times B$	Transverse to weld, on weld centreline

Figure A.1 — Examples of weld positional (WP) notch locations

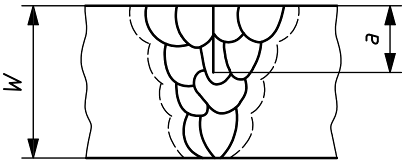
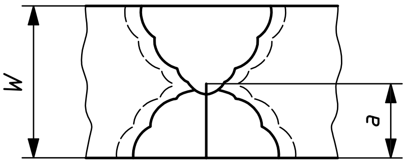
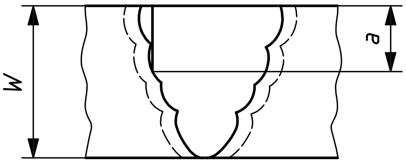
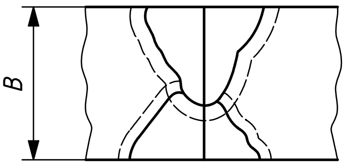
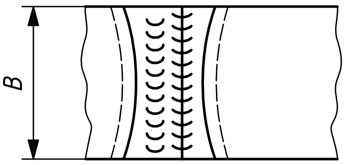
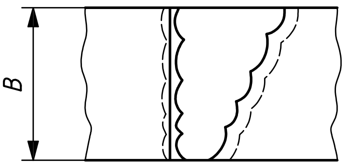
		Orientation	Cross-section proportions (thickness × width	Notch location
i)		NP	$B \times B$	Columnar weld metal on weld centreline
ii)		NQ	$B \times B$	Weld root or second side welded
iii)		NQ	$B \times B$	Grain-coarsened HAZ adjacent to columnar weld metal
iv)		NP	$B \times B$ or $B \times 2B$	Maximum volume of as-deposited columnar weld metal
v)		NP	$B \times B$ or $B \times 2B$	Maximum volume of columnar weld metal
vi)		NP	$B \times B$ or $B \times 2B$	Crack front to sample a specific region within the HAZ

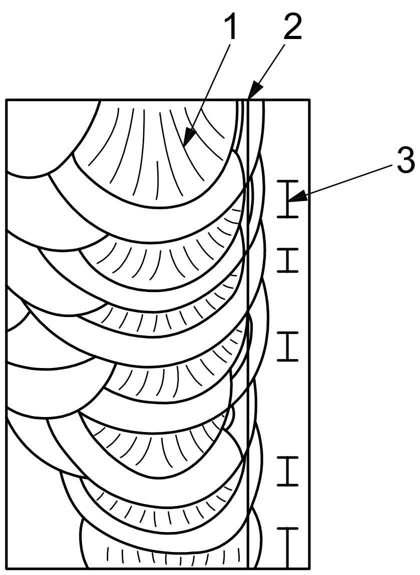
Figure A.2 — Examples of specific microstructure (SM) notch locations

Annex B
(informative)

Examples of pre-test and post-test metallography

Pre-test metallography of an etched macrosection is necessary when SM testing is specified for the HAZ. Figures B.1 and B.2 give examples of the method of quantifying the amount of HAZ microstructure, in this case the HAZ adjacent to columnar weld metal. Figure B.2 shows how to prepare a map of the target microstructure identified in the macrosection (Figure B.1) within the central 75 % of the specimen thickness. The individual lengths of SM (λ) along a line representing the idealized notch are summed to give the percentage SM present.

When SM testing is specified, post-test metallography is necessary to confirm that the target microstructure was present close to the fatigue crack tip, for example, and to confirm the mapping shown in Figure B.2 for section A in Figure 10.



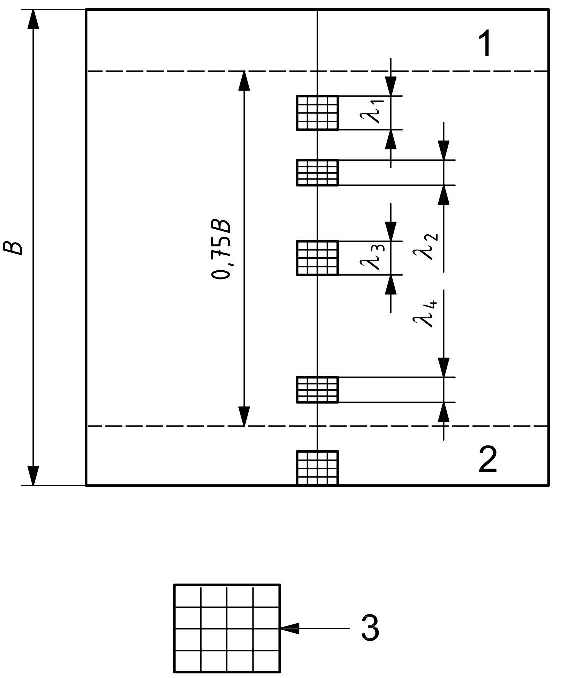
Key

1 columnar weld metal

2 idealized notch line

3 HAZ adjacent to columnar weld metal

Figure B.1 — HAZ adjacent to columnar weld metal for idealized notch line on macrosection



Key

1 cap
2 root
3 target HAZ

$$\text{Percentage of specific microstructure (over middle 75 \% of thickness)} = \frac{\sum_{\lambda_1}^{\lambda_n} \lambda}{0{,}75B} \times 100$$

Figure B.2 — Microstructural map of HAZ adjacent to columnar weld metal

Annex C
(normative)

Residual-stress modification and precracking technique

C.1 General

One of the following techniques, specified in Clauses C.2 and C.3, shall normally be used for testing as-welded or partially stress-relieved specimens. By agreement, alternative procedures may be employed if they are documented and validated. The technique used shall be indicated when reporting the test results.

NOTE 1 These techniques are normally unnecessary for welds that have been stress-relieved by post-weld heat treatment.

NOTE 2 In as-welded or partially stress-relieved specimens, residual welding stresses will be present. However, the magnitude and distribution of these stresses may be different from those present in the weld from which the specimens were taken. Residual stresses can result in unacceptable fatigue crack front shapes and, moreover, can affect the determination of the fracture toughness. Experience has shown that local compression conducted prior to fatigue precracking will reduce residual stresses to low and uniform levels[7][8], thus minimizing these effects. An alternative technique which can produce acceptably straight fatigue cracks, especially in thick-section welds where local compression is impractical, is the stepwise high R-ratio fatigue cracking method [9]. However, significant residual stresses may remain in the ligament ahead of the fatigue crack ($W - a_o$), and this may affect the fracture toughness [10].

NOTE 3 Local compression can affect fracture toughness in some materials and under certain testing conditions, but it is difficult to predict which materials are likely to be susceptible. However, experience indicates that it is preferable to accept this risk rather than obtain a result from a specimen with an unacceptable fatigue crack shape.

C.2 Local compression

Local compression[7][8] is applied across 88 % to 92 % of the ligament ($W - a$) in front of the machined notch prior to fatigue precracking and side grooving. The compression shall encompass the notch tip and be applied through hardened-steel platens to produce a total plastic strain of up to 1 % of the specimen thickness (see Notes 1 and 2). Guidance on the forces that need to be applied to rectangular-section specimens is given in Figure C.1. Depending on the thickness, B, local compression may be applied from one side only or a compression of up to 0,5 % of B may be applied simultaneously on each side of the specimen (see Figure C.1).

Multiple applications of lower compression forces may be employed. In such cases, no dimension of the contact area of the platens shall be less than 0,5B (see Figure C.1). In addition, the final deformation shall be made nearest to the notch tip.

A number of force applications may be necessary to achieve the required plastic deformation, which shall be measured to ± 0,025 mm or ± 0,1 % of B, whichever is larger.

For specimens that have been locally compressed, the dimension B used for the calculation of the fatigue force and stress intensity factor shall be B in the region of the notch measured after local compression.

NOTE 1 Local machining of the ligament to be compressed on both sides of the specimen may be necessary to ensure a smooth bearing surface for the platen and to achieve uniform deformation.

Any bulging of the back face of the ligament leading to distortion in three-point bend specimens at the loading point shall be removed by machining.

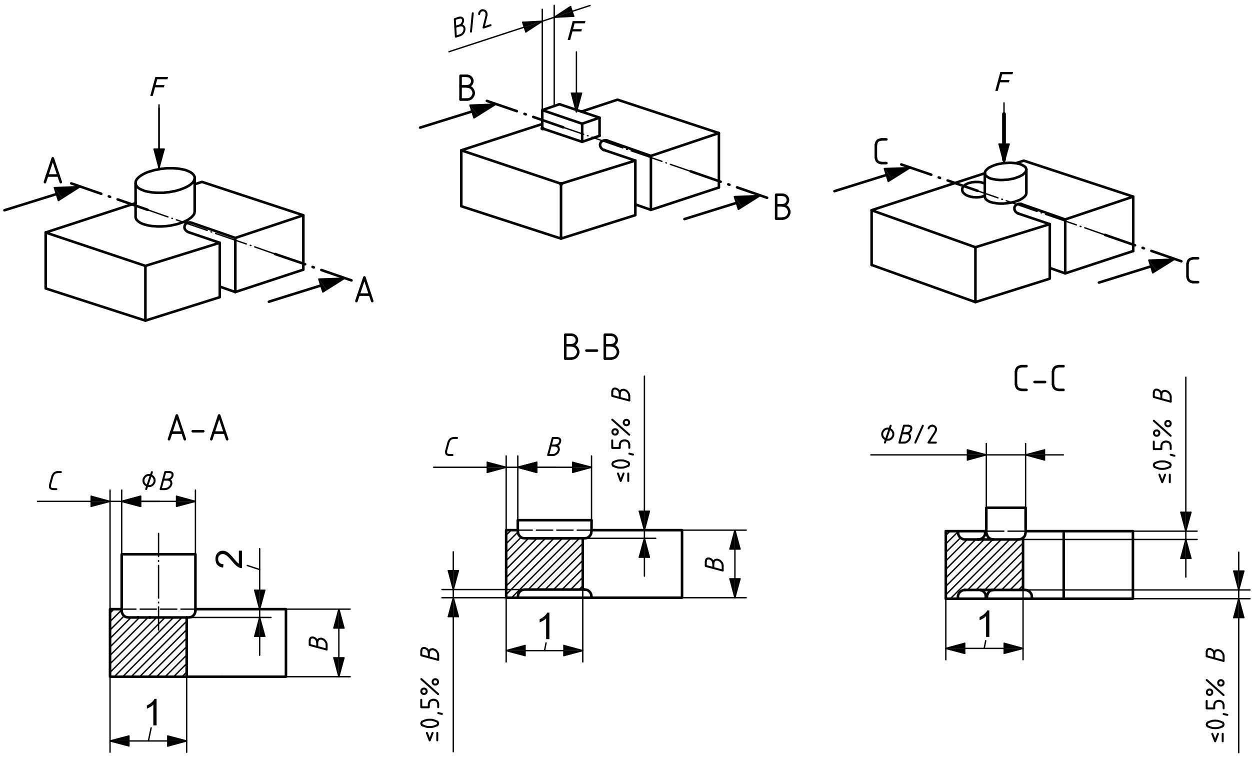
NOTE 2 Experience indicates that a total deformation equal to 1 % of B may be too much for some welds and materials, and straighter crack fronts may be obtained with less. Trials may be necessary to establish the optimum conditions.

NOTE 3 Whichever technique is chosen and where there is little experience with the technique/material combination, it is advisable that the test programme include spare specimens to confirm that the chosen procedure results in acceptably straight fatigue precracks.

C.3 Stepwise high R-ratio

In the stepwise high R-ratio technique[9], fatigue precracking consists of two steps, each at a different fatigue stress ratio, R. For the first step, the stress ratio $R = 0,1$ is used (i.e. the conventional R value for precracking) until the fatigue precrack has grown to a length of about 1 mm. In the second step, R is increased to 0,7 and the fatigue precrack grown to the desired length. The same K_f (maximum value of K) is used in both steps.

NOTE Use of $R > 0,1$ is inconsistent with the fatigue precracking requirements in ISO 12135. Experimental work indicates that fracture toughness may be increased if $R > 0,1$[8][11].



Section A-A

$F = 1,4B^2R_{p0,2}$

Section B-B

$F = 0,8B^2R_{p0,2}$

Section C-C

$F = 0,3B^2R_{p0,2}$

Key

1 W minus machined notch length

2 1 % of B (or 0,5 % of B on each side)

$R_{p0,2}$ is the lower of the values for the parent metal and the weld metal

$C = 8$ % to 12 % of $(W - a)$

Figure C.1 — Alternative local compression treatments

Annex D
(normative)

Assessment of pop-in

D.1 General

This procedure shall be used to assess the acceptability of pop-ins classified as significant in accordance with 11.4.

If the pop-in is assessed as significant in accordance with ISO 12135, post-test fractography and metallography are not required, and the pop-in is considered significant. However, if the pop-in is assessed as not significant in accordance with ISO 12135, the actual significance with respect to this International Standard can be determined from the fractographic and metallographic assessment procedures described in Clauses D.2 to D.5.

All pop-ins shall be considered significant unless the force drop and displacement increase are less than 1 % or it can be demonstrated otherwise by metallographic examination. Values of δ and J measured at the first pop-in event shall be designated δ_{pop} and J_{pop}, respectively.

D.2 Fractography

Both fracture faces shall be examined for evidence of an arrested brittle crack extension, generally in the plane of the fatigue crack, and the maximum crack extension, Δa_{pop}, excluding the SZW, shall be measured (see Figure D.1). Where no evidence of such an arrested brittle crack can be found, the significance of the pop-in shall be assessed in accordance with ISO 12135.

Pop-in can be caused by an arrested crack running perpendicular to the plane of the fatigue precrack. This is sometimes referred to as a “split”. The fracture toughness at pop-in caused by a split shall be reported, but might not characterize the fracture toughness of the material for the intended crack orientation. A different specimen and crack plane orientation might be necessary to characterize the fracture toughness of the material in the plane of the split[12][13]. Assessment of the structural significance of a split is outside the scope of this International Standard.

D.3 Sectioning and metallography

One or both fracture surfaces containing an arrested brittle crack extension shall be examined by optical and/or scanning electron microscopy to identify the primary fracture initiation site. When the crack tip is located in the HAZ, the fracture surface adjacent to the weld shall be examined. After marking the initiation position, a metallographic section shall be taken through the initiation point in a plane perpendicular to the fatigue crack plane as illustrated in Figure D.2 for a through-thickness notched specimen and Figure D.3 for a surface-notched specimen. The sections shall be polished and etched in accordance with usual metallographic practice for microstructural examinations.

D.4 Assessment

The metallographic section taken from a through-thickness notched specimen (see Figure D.4) shall be examined and the length, d_1, of the specific microstructure parallel to the crack front at initiation shall be measured. The lengths of similar microstructures present in the section within the central 75 % of B (or B_N in the case of side-grooved specimens), but not intersected by the crack front, shall be measured and the maximum individual length, d_2, recorded (see Figure D.4). If the section is beyond the fatigue crack tip, a further section behind the fatigue crack tip may be necessary to measure d_2.

The metallographic section taken from a surface-notched specimen (see Figure D.5) shall be examined and the total length, d_1, of the microstructural region in which the pop-in initiated shall be measured. This length d_1 shall only include the microstructural region ahead of the fatigue crack tip (see Figure D.5). More than one section may be taken to assess the dimension d_1.

D.5 Pop-in significance

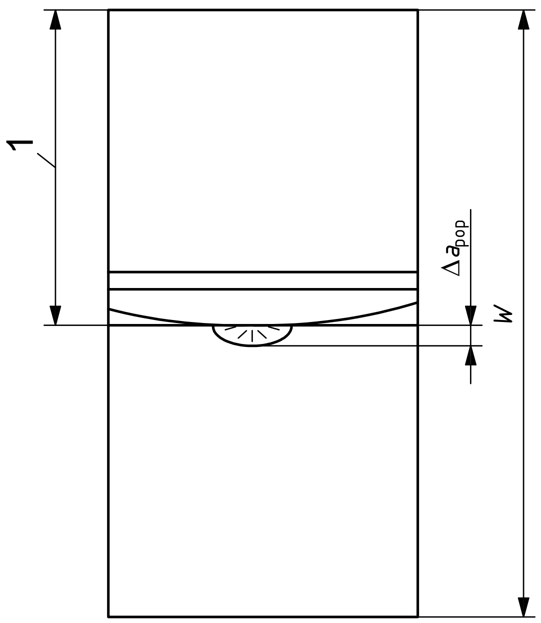
Following metallographic examination, a pop-in shall be considered not significant if

a) for a through-thickness notched specimen: P, calculated in accordance with ISO 12135, is less than 5 % and $d_1 > d_2$;

or

b) for a surface-notched specimen: P is less than 5 % and $\Delta a_{pop} < d_1$.

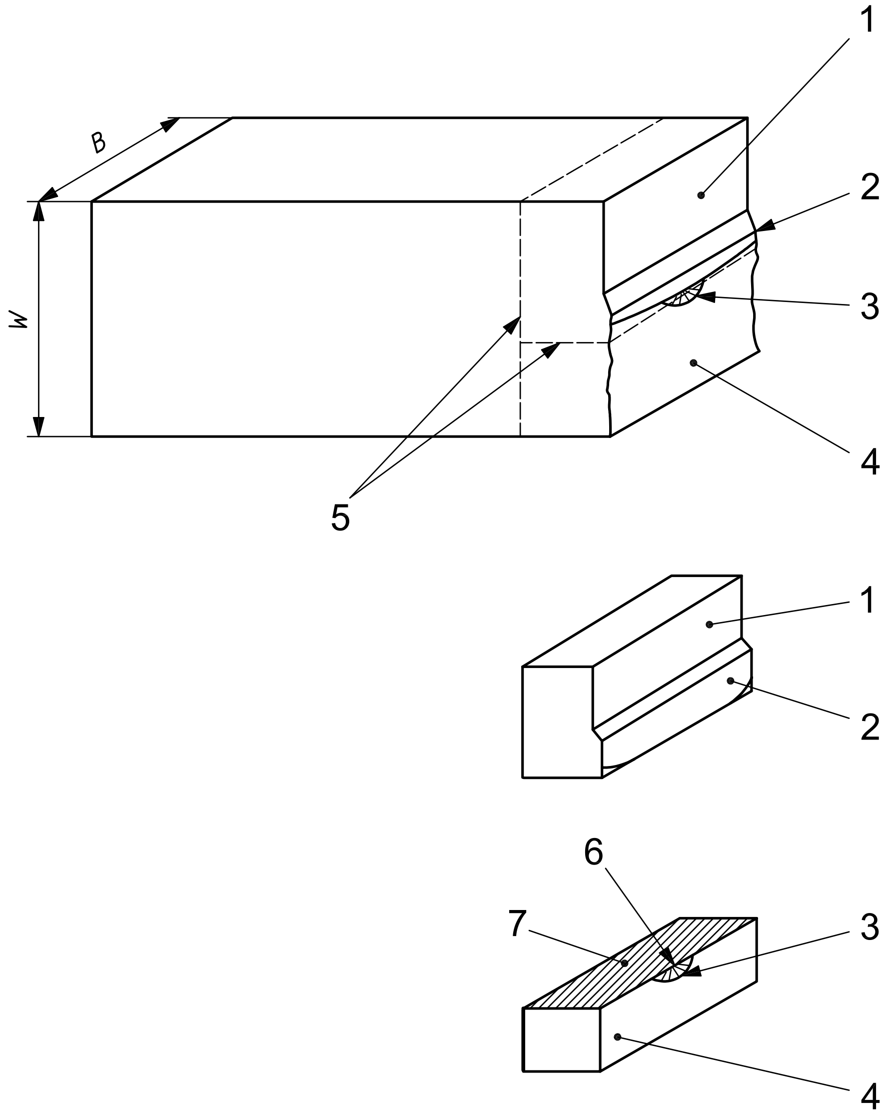
The pop-in shall be considered significant when $d_2 > d_1$ or $d_1 < \Delta a_{pop}$ because a larger pop-in may have occurred if more of the brittle microstructure had been sampled or had been present ahead of the crack tip. Further tests may be necessary to confirm or reject this possibility. A flow chart illustrating the assessment of pop-in is shown in Figure D.6.



Key

1 a or $(a + \Delta a)$

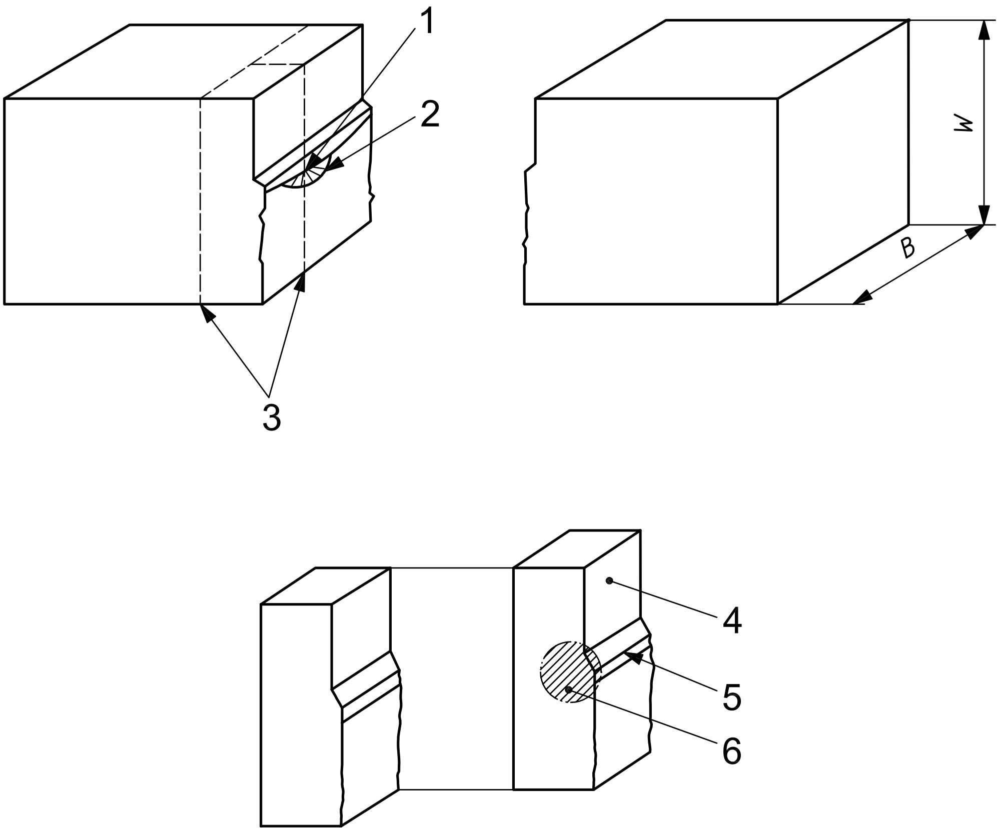
Figure D.1 — Measurement of Δa_{pop}



Key

1 section A
2 fatigue crack
3 arrested brittle crack
4 section B
5 cuts
6 initiation
7 surface to be examined (polish and etch) (see Figure D.4)

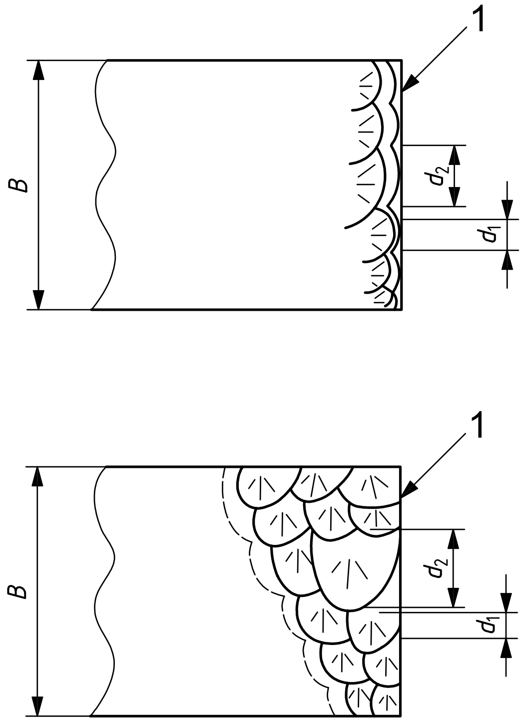
Figure D.2 — Post-test sectioning procedure for identifying fracture initiation microstructure in a through-thickness notched specimen



Key

1 initiation
2 arrested brittle crack
3 cuts
4 notch
5 fatigue crack
6 surface to be examined (polish and etch) (see Figure D.5)

Figure D.3 — Post-test sectioning for identifying fracture initiation microstructure in a surface-notched specimen



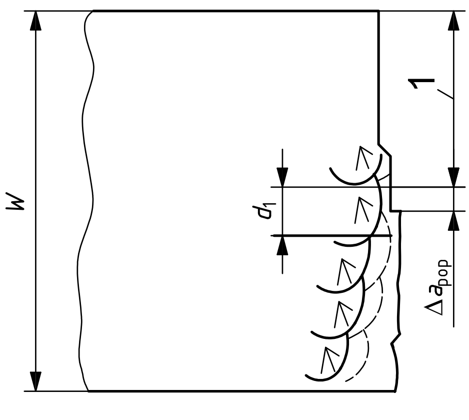
Key

1 fatigue crack

d_1 length of HAZ (upper diagram) or weld metal (lower diagram) sampled by the fatigue crack in the region of fracture initiation

d_2 maximum length of similar HAZ (upper diagram) or similar weld metal (lower diagram) within the central 75 % of B

Figure D.4 — Measurement of d_1 (along crack front) and d_2 (not along crack front) microstructure in section taken from a through-thickness notched specimen (section B in Figure D.2)



Key

1 a or ($a + \Delta a$)

Figure D.5 — Measurement of microstructure d_1 and Δa_{pop} in section taken from a surface-notched specimen (see Figure D.3) (example given for HAZ)

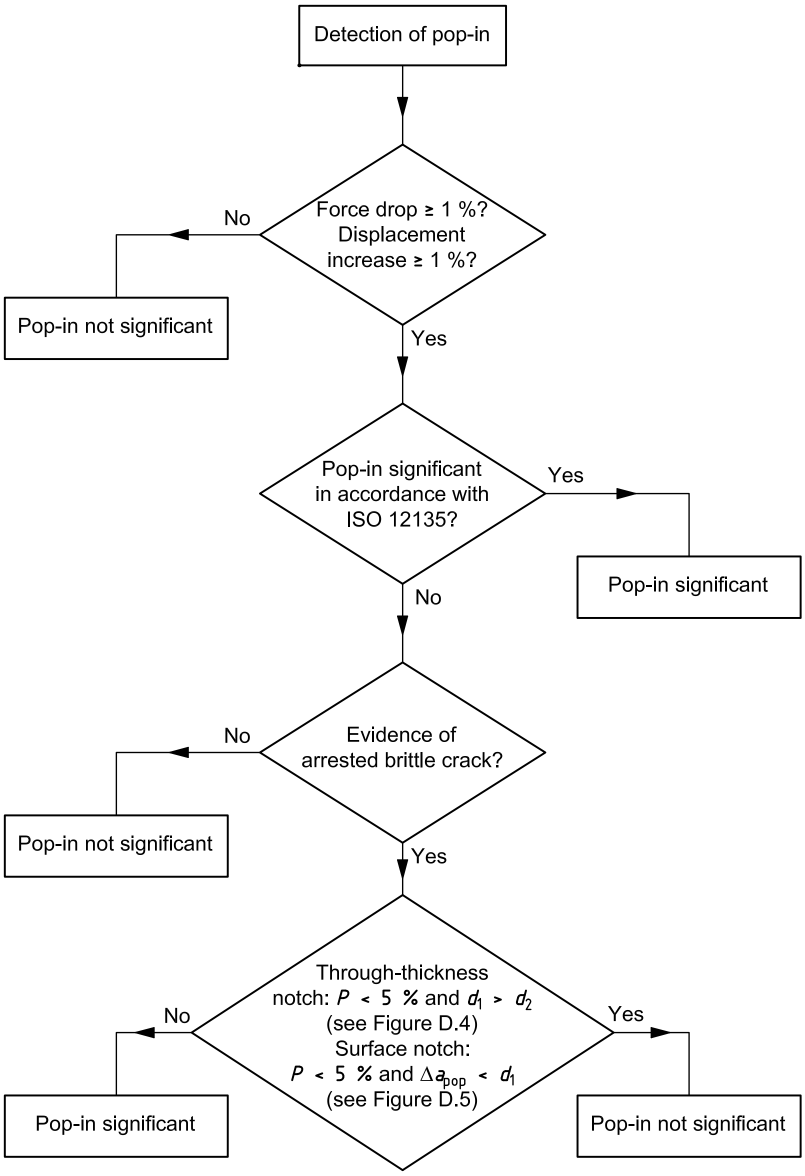


Figure D.6 — Flow chart for assessment of pop-in

Annex E
(informative)

Shallow-notched specimen testing

E.1 General

When the specific microstructure can only be tested using a shallow-notched bend specimen ($0,1 \leqslant a_o/W \leqslant 0,45$), the procedure described in this annex may be used by agreement between the interested parties. The specimen preparation and assessment procedures are the same as those described in the main body of this International Standard, except as modified by Clauses E.2 and E.3 below.

NOTE The nature of welds is such that the specific microstructure may only be present near the surface, which would preclude testing with standard specimens. Use of a shallow-notched bend specimen enables such microstructures to be tested. However, owing to the lower crack tip constraint associated with the shallow-notched specimen, the fracture toughness indication from such a specimen may be higher than that which would have been obtained from a standard notched specimen (i.e. $0,45 \leqslant a_o/W \leqslant 0,70$) for the same crack tip microstructure. This may or may not be significant with respect to the final application, but needs to be recognized by the parties involved.

E.2 Specimen preparation and instrumentation

The bend specimen configuration shall conform to 8.1 and Figure 5, except that the crack length shall be in the range $0,1 \leqslant a_o/W \leqslant 0,45$. The specimen knife edges may be integral, as described in ISO 12135, or attached, as shown in Figure E.1. The crack mouth opening displacement, V, is measured directly by means of a clip-in displacement gauge bearing on integral knife edges. When the knife edges are not integral, but attached instead, the attached knife edges shall be of a configuration such as to support dual clip-in gauges, the outputs of which are used to estimate the crack mouth opening displacement as though it were measured by means of integral knife edges.

NOTE The fatigue crack front straightness requirement of 12.4.3 may be difficult to achieve in a specimen with a_o/W approaching 0,1. However, use of local compression, described in Clause C.2, has been found to be useful in achieving straight fatigue crack front shapes.

E.3 Determination of J and δ

The determinations of J and δ follow the procedures of ISO 12135, except that the calculations are different.

The stress intensity factor relationship for three-point bend specimens is

$$K_o = \left(\frac{S}{W}\right)\frac{F}{\left(B \times B_N \times W\right)^{0,5}} \times g_1\left(a_o/W\right) \quad \text{(E.1)}$$

where

K_o corresponds to K_c, K_u, K_{uc} or K_m calculated for values of force F_c, F_u, F_{uc} and F_m, respectively, which are defined in ISO 12135;

S is the support roller span;

$g_1(a_o/W)$ is the dimensionless stress intensity factor coefficient, specific values of which are tabulated in ISO 12135.

J_o is calculated for the three-point bend specimen[3][4][5][14] from the equation

$$J_o = \frac{K_o^2\left(1-\nu^2\right)}{E} + \frac{\eta_c A_o}{\left(B \times B_N\right)^{0,5}\left(W - a_o\right)} \tag{E.2}$$

where

A_o is the area of the plastic component under the force, F, versus crack mouth opening displacement, V, curve such that

J_c corresponds to J_o, calculated using values of K_c, and F_c and A_c at V_c,

J_u corresponds to J_o, calculated using values of K_u, and F_u and A_u at V_u,

J_{uc} corresponds to J_o, calculated using values of K_{uc}, and F_{uc} and A_{uc} at V_{uc},

J_m corresponds to J_o, calculated using values of K_m, and F_m and J_m at V_m;

and

$$\eta_c = 3{,}667 - 2{,}199\left(\frac{a_o}{W}\right) + 0{,}437\left(\frac{a_o}{W}\right)^2 \tag{E.3}$$

Where attachable knife edges are employed, V is estimated from the outputs of the dual clip gauges, using the following relationship:

$$V = V_1 - z_1\left(\frac{V_2 - V_1}{z_2 - z_1}\right) - 2x\cos\left\{\arcsin^{-1}\left[\frac{1}{2}\left(\frac{V_2 - V_1}{z_2 - z_1}\right)\right]\right\} + 2x \tag{E.4}$$

where

V_1 and V_2 are crack mouth opening displacements measured with clip gauges mounted at distances z_1 and z_2, respectively, above the notched surface (see Figure E.1);

x is the distance indicated in Figure E.1.

δ_o is calculated by substituting J_o from Equation (E.2) into Equation (E.5). If the specimen is notched in the parent metal or the weld metal, Equations (E.5) and (E.6) are used. Equations (E.7) to (E.16) are appropriate to a specimen notched in the HAZ[5][15].

$$\delta_o = \frac{J_o}{m\left(\frac{R_{p0,2b} + R_{mb}}{2}\right)} \tag{E.5}$$

$$m = A_0 - A_1\left(\frac{R_{p0,2b}}{R_{mb}}\right) + A_2\left(\frac{R_{p0,2b}}{R_{mb}}\right)^2 - A_3\left(\frac{R_{p0,2b}}{R_{mb}}\right)^3 \tag{E.6}$$

where

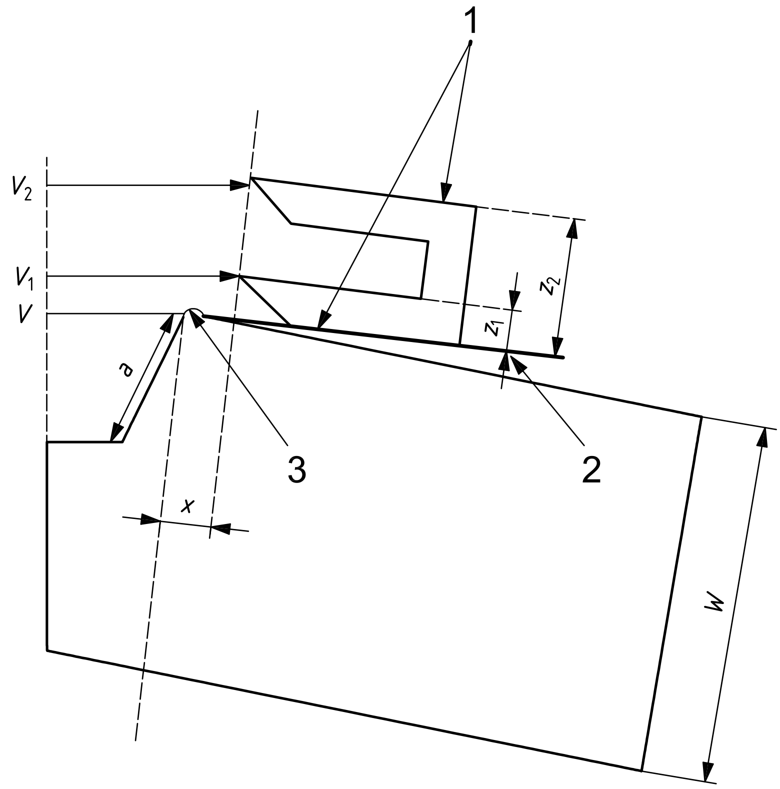
$A_0 = 3{,}18 - 0{,}22(a_o/W)$;

$A_1 = 4{,}32 - 2{,}23(a_o/W)$;

$A_2 = 4{,}44 - 2{,}29(a_o/W)$;

$A_3 = 2{,}05 - 1{,}06(a_o/W)$.

For a specimen notched in the weld metal, replace $R_{p0,2b}$ and R_{mb} in Equations (E.5) and (E.6) by $R_{p0,2w}$ and R_{mw}, respectively.



Key

1 knife edges

2 shim

3 micro TIG or laser weld

NOTE 1 The knife edges are attached to a steel shim which is welded to the notch lip using a micro TIG or laser fillet weld.

NOTE 2 Knife edge heights z_1 and z_2 include the height of the steel shim.

Figure E.1 — Design and location of knife edges for dual clip gauges used to estimate crack mouth opening displacement, V

For a specimen notched in the HAZ:

$$\delta_o = \frac{J}{m\sigma_{nom}} \tag{E.7}$$

$$m = -0{,}111 + 0{,}817(a_o/W) + 1{,}36R_{nom} \tag{E.8}$$

$$R_{nom} = \frac{(R_{mb} + R_{mw})}{(R_{p0,2b} + R_{p0,2w})} \tag{E.9}$$

$$\sigma_{nom} = \lambda_u R_{p0,2w} + (1 - \lambda_u) R_{p0,2b} \quad \text{for } M < 1 \tag{E.10}$$

$$\sigma_{nom} = R_{p0,2} \quad \text{for } M = 1 \tag{E.11}$$

$$\sigma_{nom} = \lambda_o R_{p0,2w} + (1 - \lambda_o) R_{p0,2b} \quad \text{for } M > 1 \tag{E.12}$$

$$M = \frac{R_{p0,2w}}{R_{p0,2b}} \tag{E.13}$$

$$\lambda_o = 0,5 \exp\left[-\left(1 + 0,01 n^2\right)\left(M - 1\right)\right] \tag{E.14}$$

$$\lambda_u = 1 - 0,5 \exp\left[-\left(1 + 0,01 n^2\right)\left(\frac{1}{M} - 1\right)\right] \tag{E.15}$$

$$n = \frac{41,34}{\left[1,464 + 82,68\left(R_{nom} - 1\right)\right]^{0,5} - 1,210} \tag{E.16}$$

NOTE Numerical analyses have shown that these J and δ procedures result in less than 10 % error for $0,1 < a_o/W < 0,5$ when estimating weld metal fracture toughness for $0,75 < M < 1,50$ and $h/(W - a_o) > 0,1$[3][4] and when estimating HAZ fracture toughness for $0,70 < M < 2,50$ and $0,5 < h/B < 1,25$[5][15].

Bibliography

[1] HART, P.H.M., Yield strength from hardness data, *TWI Research Bulletin*, Vol. 16, No. 6, June 1975, p. 76

[2] IRWIN, G.R., Linear fracture mechanics, fracture transition and fracture control, *Engineering Fracture Mechanics*, Vol. 1, No. 2, 1968, pp. 241-257

[3] PISARSKI, H.G., WANG, Y.Y., KIRK, M., and GORDON, J.R., *The effect of strength mismatch on CTOD and J estimation procedures for weld metal fracture toughness determination*, Offshore Mechanics and Arctic Engineering (OMAE '95) Conference, Copenhagen, Danemark, ASME, Vol. 3, 1995, pp. 77-85

[4] PISARSKI, H.G., WANG, Y.Y., KIRK, M., and GORDON, J.R., *The effect of strength mismatch on CTOD and J estimation procedures for weld fracture toughness measurement*, IIW Sub-Commission X-F "Weld Mismatch Effect", GKSS, Geesthacht, Germany, 24-15 April 1995

[5] WANG, Y.Y., *Development of fracture assessment and testing procedures for HAZ cracks — Progress report — Development of J and CTOD correlation equations*, EWI Report 06224-CPG/1/97, December 1997

[6] HADLEY, I., and DAWES, M.G., Fracture toughness testing of weld metal — Results of a European round-robin, *Fatigue Fract. Engng. Mater. Struct.*, Vol. 19, No. 8, 1996, pp. 963-973

[7] DAWES, M.G., Fatigue precracking weldment fracture mechanics specimens, *Metal Construction and British Welding Journal*, February 1971, pp. 61-65

[8] TOWERS, O.L., and DAWES, M.G., Welding Institute research on the fatigue precracking of fracture toughness specimens, in ASTM STP 856, *Elastic-Plastic Fracture Test Methods: The User's Experience*, 1985, pp. 23-26

[9] KOÇAK, M., SEIFERT, K., YAO, S., and LAMPE, H., *Comparison of fatigue precracking methods for fracture toughness testing of weldments*, Proc. Int. Conf. Welding 90 — Technology, Material, Fracture, GKSS, Geesthacht, Germany, October 1990, IITT-International, France, pp. 307-318

[10] REEMSNYDER, H.S., PISARSKI, H.G., and DAWES, M.G., Residual stresses and fatigue precracking techniques for weldment fracture toughness specimens, *Journal of Testing and Evaluation, JTEVA*, Vol. 20, No. 6, November 1991, pp. 416-423

[11] STEFFAN, A.A., *On the effect of* R-ratio *and* K_{fmax} *on fracture toughness measurement, fatigue crack propagation and fatigue closure*, Dissertation, Southern Methodist University, Texas, USA, December 1987

[12] WIESNER, C.S., and PISARSKI, H.G., Significance of pop-ins during initiation fracture toughness tests, *3R International*, Vol. 35, October/November 1996, pp. 638-643

[13] PISARSKI, H.G., HAMMOND, R., and WATT, K., *Significance of splits and pop-ins observed during fracture toughness testing of pipeline steel*, Proceedings of IPC 2008, 7th International Pipeline Conference, Calgary, Alberta, Canada, 2008, ASME, Paper IPC 2008-64676

[14] KIRK, M.T., and DODDS, R.H., *J* and CTOD estimation equations for shallow cracks in single edge notch bend specimens, *Journal of Testing and Evaluation, JTEVA*, Vol. 21, No. 4, July 1993, pp. 228-238

[15] WANG, Y.Y., *Fracture Mechanics Analysis of HAZ and Interfacial Cracks*, CRP summary, EWI report MR9819, November 1998

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