

Weld Defects

Weld defects can occur in all weld situations for every type of steel. This TechSupport focuses on the most frequent defects encountered when welding high strength steels

Introduction to weld defects

The absolute majority of steel produced today will be welded. This is also the case for high strength steels. Therefore, welding knowledge is essential for customers of SSAB Oxelösund.

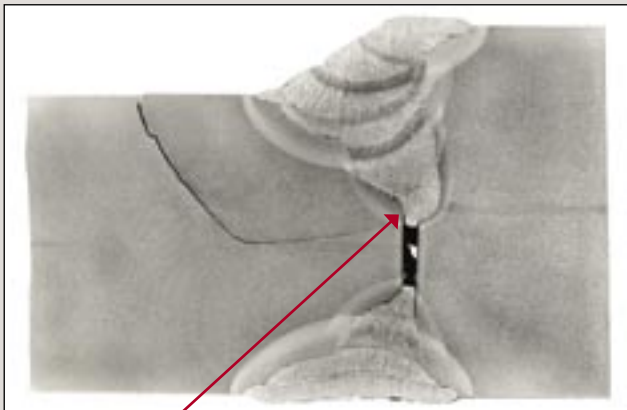
All steels from SSAB Oxelösund can be welded using common welding methods and the steels themselves are characterized by high weldability. By following the welding recommendations put forth by SSAB Oxelösund one can obtain welded joints with good mechanical properties. Cracks and other types of weld defects can be avoided.

Welding recommendations related to SSAB Oxelösund's specific steel grades can be found at www.ssabox.com.

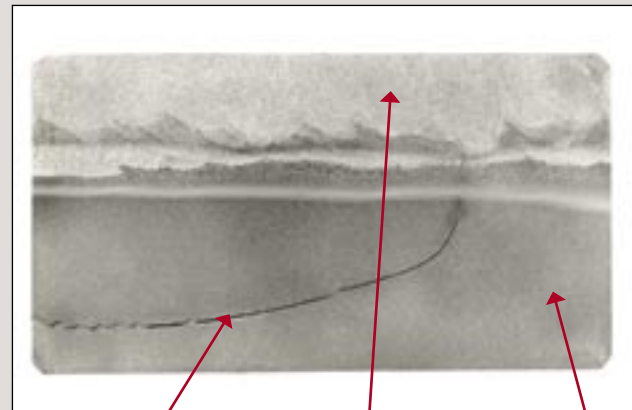
The purpose of this TechSupport is to:

- Explain different types of weld defects that can occur when welding high strength steels.
- Propose measures to avoid specific weld defects.
- Show the acceptance levels for different weld defects according to standard EN ISO 5817:2004. The most stringent requirements are according to weld class B followed by weld classes C and D.

Hydrogen cracks



Crack initiation



Hydrogen crack

Weld metal

Parent metal

View: Welded joint seen from above.

Description of hydrogen cracks

Hydrogen cracks are a serious weld defect. They are a delayed type of crack that often forms after welding at temperatures below 200°C. They can develop hours after welding. Hydrogen cracks are normally formed in the HAZ of the parent metal. The cracks can then propagate to the unaffected parent metal. These types of cracks are surface breaking in most cases even though underbead cracks exist. Hydrogen cracks that are initiated in the HAZ can be very long.

Hydrogen cracks can also form in the weld metal. In these cases they are oriented transverse to the welded joint. These types of cracks are less frequent than cracks formed in the HAZ.

Hydrogen cracks form when three conditions occur at the same time:

1) *A brittle structure in the welded joint.* A high carbon equivalent increases the risk for a brittle structure in the welded joint. There are different methods to calculate the carbon equivalent in steels. The carbon equivalents according to CE(IIW) and CET are two internationally recognized methods (chemical analysis in weight %):

CE (IIW): $C + (Cr + Mo + V)/5 + Mn/6 + (Ni + Cu)/15$

CET: $C + (Mo + Mn)/10 + (Cr + Cu)/20 + Ni/40$

The general tendency is that the higher the strength a parent metal/ weld metal has, the higher the carbon equivalent is.

2) A relatively high amount of hydrogen. The risk for cracks increases with high levels of hydrogen in the welded joint.

3) High levels of tensile stress in the welded joint.

Detection

Control of hydrogen cracks in the welded joint can take place after an interval of ~16-48 h after welding depending on standard or other regulation. Hydrogen cracks that reach the surface can be identified by all non destructive test methods.

Underbead cracks are identified by radiographic or ultrasonic examination.

Ways to eliminate hydrogen cracks

- Follow the preheating recommendations for the parent metal and the welding consumable. The preheat recommendations for the welding consumable can be considered if the carbon equivalent, according to CET, is higher for the consumable than the parent metal. The carbon equivalent is normally lower for the welding consumable than the plates for yield strengths ≤ 700 MPa. For even higher strengths the consumables might have a higher carbon equivalent than the parent metal. Preheat the tack welds like an ordinary weld. The minimum length of a tack weld should be 50 mm.
- Keep the welded joint clean from contaminations like water and oil.
- Use welding consumables with low hydrogen content. The recommended hydrogen content in the consumable is ≤ 5 ml H/100g of weld metal.
- Use welding consumables with yield strengths according to the recommendations from SSAB Oxelösund.
- Use the recommended levels of heat input according to SSAB Oxelösund.

Hydrogen cracks (continue...)

- Apply weld sequences that do not produce very high tensile stresses in the welded joint. Examples are as follows:

Appropriate measures

- 1) Avoid starts and stops in the corners of welded joints according to fig 1.

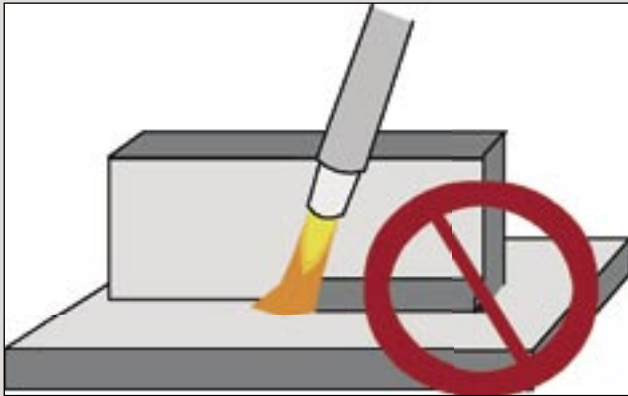
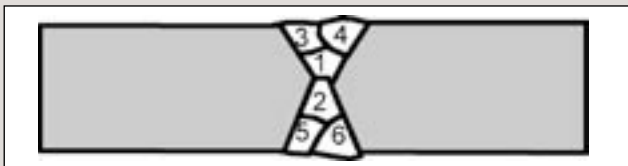


Fig 1: Start sequence for welding

- 2) Eliminate wide gaps in the joint. Gaps should preferably be less than 3 mm wide.

Examples 3-5 shows suitable measures but these are not as important as example 1 and example 2.

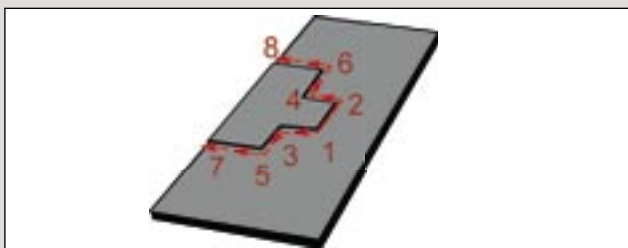
- 3) Perform alternating weld passes around the centre of



gravity of the construction according to fig 2.

Fig 2: Suggestion of weld plan

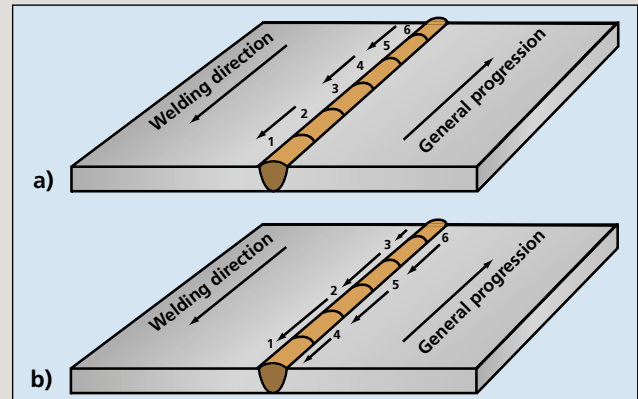
- 4) Weld from sections with the highest restraint towards sections with lower degrees of restraint



according to fig 3.

Fig 3: Suggestion of weld sequences

- 5) Back-step welding techniques can be used like the two examples below. This procedure is most effective



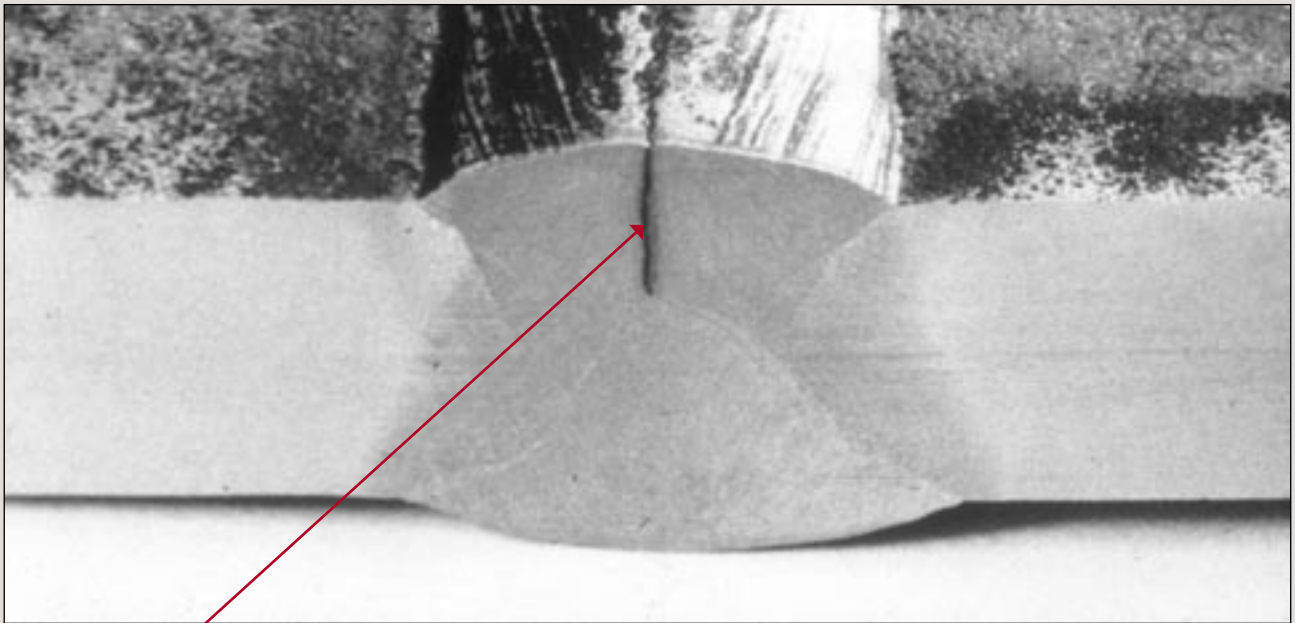
for long welds according to fig 4

Fig 4: Back step welding.

- The level of preheating can be reduced by using austenitic consumables of type AWS E(R) 307 or AWS E(R) 309. These types of consumables can be used for all steels from SSAB Oxelösund.

Acceptance criteria According to EN ISO 5817:2004
Hydrogen cracks are not accepted for any weld class.

Solidification cracks (Hot cracks)



Solidification crack.

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Description of solidification cracks

Solidification cracks are a serious type of weld defect that occurs in the weld metal. They typically form along the weld metal in the centre line of a weld pass. Solidification cracks often reach the surface of the welded joint but they can also be embedded in the weld metal. The length of these solidification cracks can be long. One meter long cracks are not unusual.

Detection

Solidification cracks that reach the surface can be detected by all non destructive methods and by micro examination.

Cracks that are embedded in the welded joint can be detected by radiographic or ultrasonic examination. Ultrasonic examination often detects solidification cracks easier than radiographic examination.

Ways to eliminate solidification cracks

- Make sure that the joint is clean before welding. Contaminates promote solidification cracking.
- Reduce the heat input, preferably using weld parameters other than increasing the weld speed.
- Use weld parameters that create a weld surface that is not concave according to fig 5. This can be achieved by using ample wire feed.

- Very deep weld passes can cause solidification cracks. A weld pass with a width/depth ratio ≈ 1 is preferable according to fig 6.
- Keep the size of the gap at a suitable level. A very large gap can promote solidification cracks. However, a narrow gap can cause lack of root fusion.

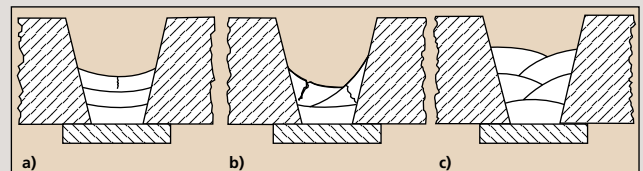


Fig. 5 Effect of weld shape in multi pass welds: a & b) Concave with tendency to crack.

c) Slightly convex weld beads

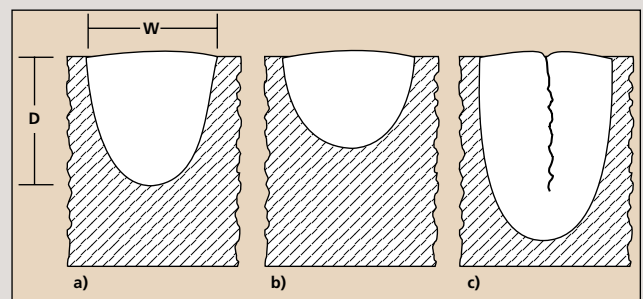


Fig. 6 Effect of weld shape on cracking tendency:

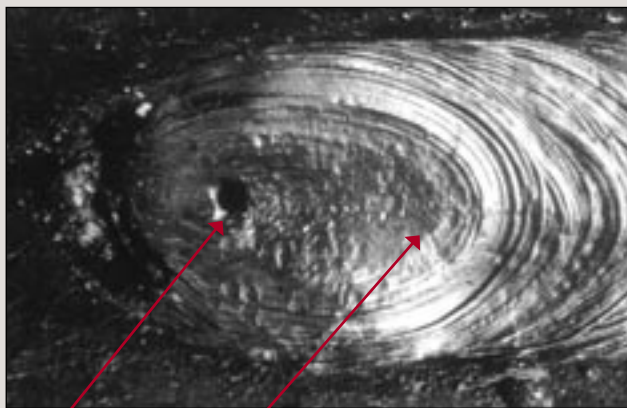
a) $W/D = 1$, sound weld b) $W/D = 1.4$, sound weld

c) $W/D = 0.7$, weld tends to crack

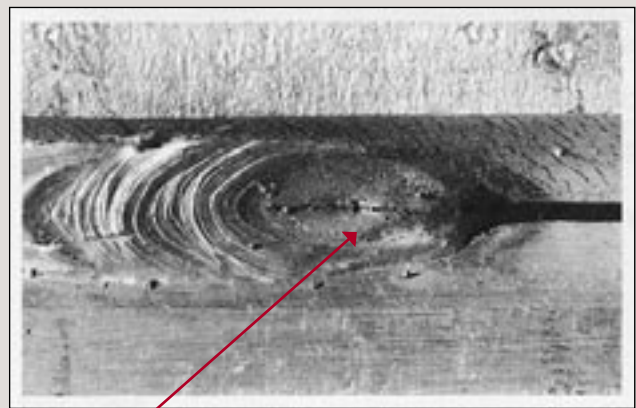
Acceptance criteria according to EN ISO 5817:2004

Solidification cracks are not accepted in any weld class.

Crater pipes and crater cracks



Pore Crater pipe Reproduced by permission, TWI Ltd.



Crater crack Reproduced by permission, KIMAB

Description of Pipes and crater cracks

Crater pipes and crater cracks are closely related to each other. Surface breaking pores often occur at the same time.

Crater pipes typically form at the end section of a weld sequence when the weld pool shrinks during solidification from the liquid state according to fig 7.

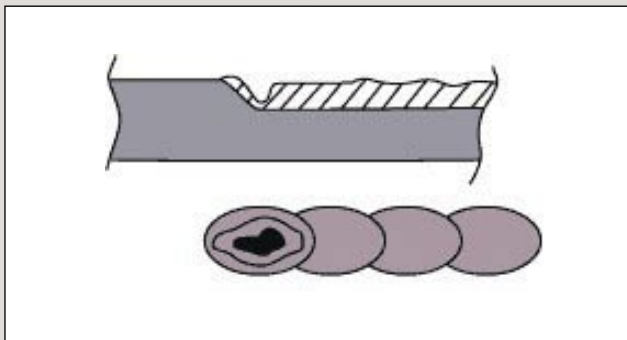


Fig 7: Crater pipe Reproduced by permission, TWI Ltd.

Crater pipes always reach the surface. However, this defect can be embedded if additional weld passes are performed.

Once a crater pipe occurs, a crater crack is easily formed in the pipe. The propagation of crater cracks are, in many cases, through the center line of the weld pass. Crater cracks are of the same nature as solidification cracks.

Detection

Crater pipes: Crater pipes are normally observed visually. Internal pipes can be detected by ultrasonic or radiographic examination.

Crater cracks: Detection of surface breaking cracks can be made with all non destructive methods. Internal cracks in the welded joint can be detected by ultrasonic or radiographic examination.

Ways to eliminate crater pipes and crater cracks

- Do not use overly high heat input. A very high heat input creates a large weld pool which will promote the formation of crater pipes.
- At the end of a weld sequence reverse your weld direction for a short distance (~10 mm–20 mm) in order to avoid a crater pipe.
- When using mechanized weld processes, gradually decrease the current level at the end of a weld sequence (slope down sequence).
- The end sequence of a weld can be placed outside the welded joint by using stop plates.

Crater pipes and crater cracks (continue...)

Acceptance criteria according to EN ISO 5817:2004

Abbreviations in fig 8-9 and table 1-2:

h: Width of lack of fusion

t: Plate thickness

Crater pipes:

Surface imperfections:

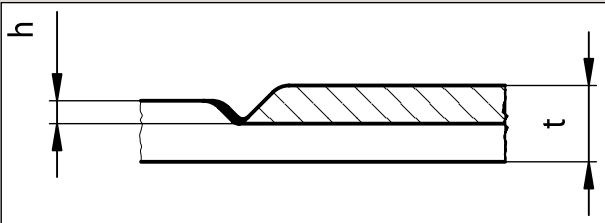


Fig 8: Surface imperfections

Table 1: Acceptance criteria for surface breaking crater pipes

Quality level D	Quality level C	Quality level B
$h \leq 0,2 \cdot t$, but max 2 mm	$h \leq 0,1 \cdot t$, but max 1 mm	Not permitted

Internal imperfections:

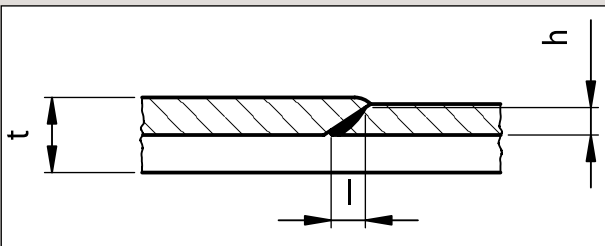


Fig 9: Internal imperfections

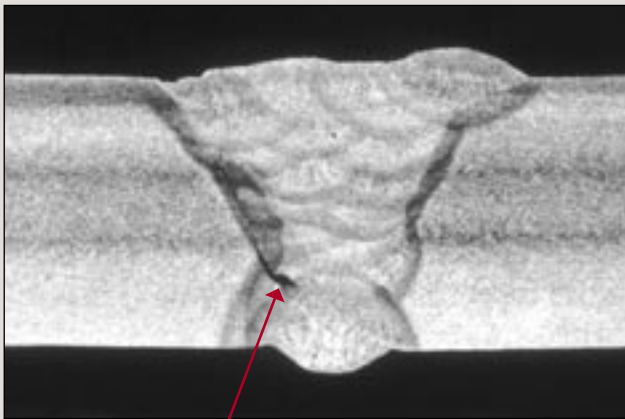
Table 2: Acceptance criteria for internal crater pipes

Quality level D	Quality level C	Quality level B
$h \leq 0,2 \cdot t$, but max 2 mm	Not permitted	Not permitted

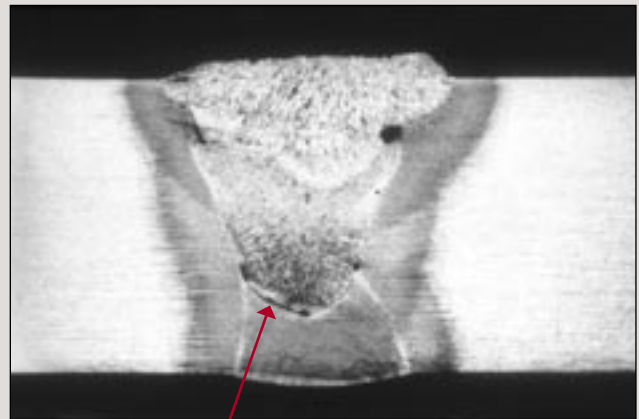
Crater cracks

Crater cracks are not accepted in any weld class.

Lack of fusion



Lack fusion between the weld metal and the parent metal.
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Lack of fusion between weld passes.
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Description of lack of fusion

Lack of fusion is a severe weld defect. This discontinuity can be located inside the weld metal or reach the surface of the welded joint. Lack of fusion can occur between parent metal and weld metal and also between different weld passes. This defect is located along the welded joint.

Lack of fusion defects that reach the surface are considered more severe than those embedded in the weld metal.

Detection

Lack of fusion defects that reach the surface can be observed by all non destructive methods and by micro examination.

Internal lack of fusion can be hard to detect because it is a narrow weld defect, but ultrasonic testing, radiographic testing and micro examination can be used. Ultrasonic examination is often considered an easier method of detection.

Ways to eliminate lack of fusion

- Use the correct weld speed in order to get enough penetration. Normally a lower weld speed reduces the risk for lack of fusion.
- Increase the weld angle (α) for butt welds according to fig 10. An angle (α) of 60-70° is often a good choice for V butt welds.
- Use a torch angle that melts both sides of the welded joint.
- Increase the current.
- FCAW has a higher resistance towards lack of fusion than MAG.
- For multi pass welds, the shape of the top section of a weld pass is preferably slightly concave. Note that a very concave top section can cause hot cracks.
- Active components such as CO_2 and O_2 in the shielding gas of MAG /FCAW can reduce the risk of lack of fusion.

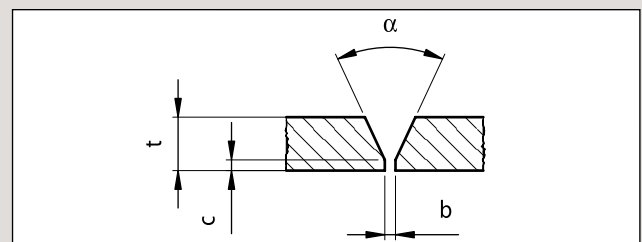


Fig. 10

b: Gap

c: Thickness of root face

t: Nominal plate thickness

α : Angle

Lack of fusion (continue...)

Acceptance criteria according to EN ISO 5817:2004

Surface Imperfections (all types of welded joints):

These defects are normally not permitted in any quality level. Exception is made for small imperfections that can only be detected by micro examination. This latter discontinuity is only accepted in quality levels B and C. No maximum size of the defect is mentioned. The magnification at the micro examination is not specified.

Limitations for internal imperfections are according to table 3, fig 11 and 12:

Type of joint	Quality level D	Quality level C	Quality level B
Butt joint	$h \leq 0,4*s$, but max 4 mm Short imperfections* permitted, but not breaking of the surfaces.	Not permitted	Not permitted
Fillet welds (including T-joints)	$h^* \leq 0,4*a$, but max 4 mm Short imperfections* permitted, but not breaking of the surfaces.	Not permitted	Not permitted

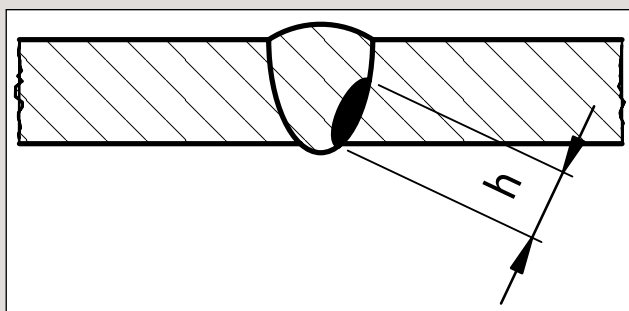
Table 3: Acceptance criteria for butt and fillet welds

* Short imperfections are: one or more imperfections of total length not greater than 25 mm in any 100 mm length of the weld or a maximum of 25% of the weld length for a weld shorter than 100 mm, the range with most imperfections being applicable.

Abbreviations:

h: Max width of lack of fusion

s: Nominal butt weld thickness



a: Nominal throat thickness

Fig 11: Single pass butt weld

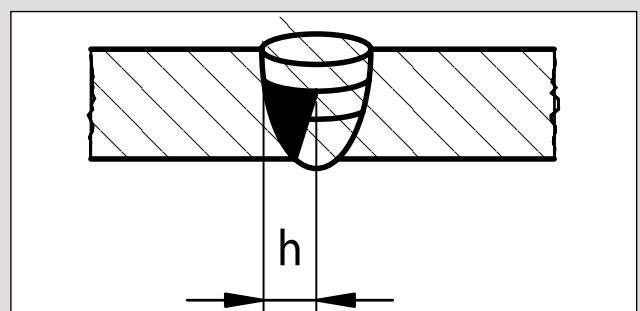
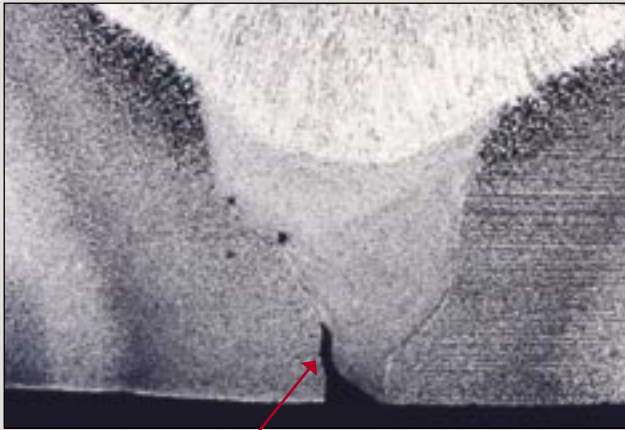
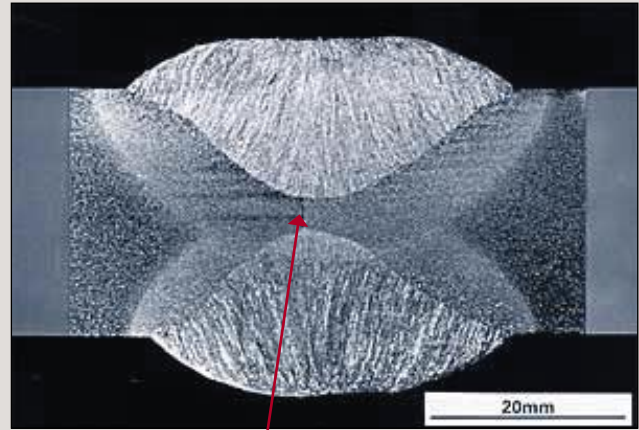


Fig 12: Multi pass butt weld

Lack of root fusion



Lack of root fusion (surface imperfection)
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Lack of root fusion (internal imperfection)
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Description of lack of root fusion

Lack of root fusion can result in a serious weld defect. This type of discontinuity can exist in the root or mid section of the welded joint. The most severe type of lack of root fusion is that which reaches the surface.

Detection

Surface lack of root fusion can be observed by all non destructive methods and by micro examination. If the weld discontinuity exists inside the welded joint, detection can be made by radiographic or ultrasonic examination. Ultrasonic examination is often considered an easier method of detection.

Ways to eliminate lack of root fusion

- Reduce the weld speed in order to assure penetration.
- Make the gap in the joint wider.
- Increase the current.
- Reduce the thickness of the root face according to fig 13.
- Keep the mismatch between the plates in the welded joint as small as possible. The mismatch of the plates is preferably taken at the top section of the joint if a butt weld is welded with different plate thicknesses.
- For joints with prepared angles, for instance V-butt welds: Increase the angle (α) according to fig 13. An angle (α) of 60-70° is often a good choice for V-butt welds.
- Use a backing bar.
- When using MMA welding, reduce the diameter of the welding consumable.
- Keep the width of the gap in the joints as constant as possible according to fig 13.

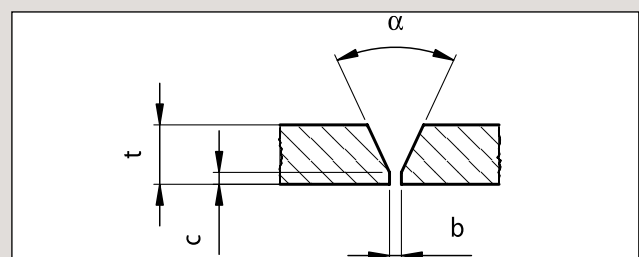


Fig 13: Drawing of a V-butt joint.

b: Gap c: Thickness of root face t: Plate thickness α : Angle

Lack of root fusion (continue...)

Acceptance criteria according to EN ISO 5817:2004

Some types of lack of root fusion are allowed according to fig 14-18 and tables 4-6. However, only short imperfections can be allowed according to fig 14-18 and tables 4-6. The definition of short imperfections is: One or more imperfections of total length not greater than 25 mm in any 100 mm length of the weld or a maximum of 25 % of the weld length for a weld shorter than 100 mm, the range with most imperfections being applicable.

Abbreviations in fig 14-18 and tables 4-6:

t: nominal plate thickness

h: height of imperfection

a: nominal throat thickness of the fillet weld

s: nominal weld thickness

Surface imperfections:

Lack of root fusion is a discontinuity that is not accepted at quality level B and C. Only small fractions of internal lack of root fusion are accepted at quality level D.

The allowed imperfection at quality level D is $h \leq 0,2 \cdot t$, but max 2 mm according to fig 14.

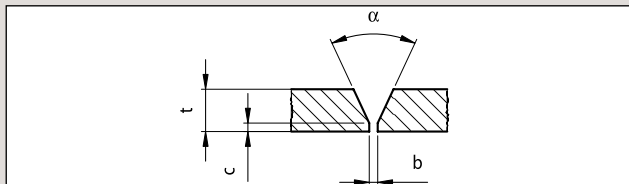


Fig 14: Drawing of butt joint

Internal imperfections:

The acceptance criteria are according to tables 4-6 and fig 15-18.

Joints with full penetration (according to fig 15)

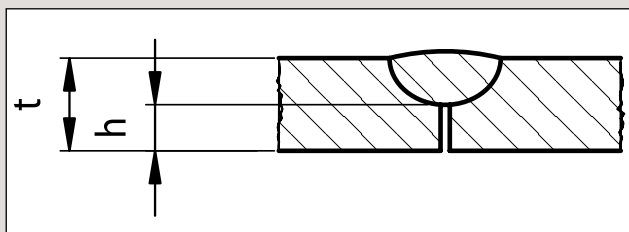


Fig 15: Joint with prescribed full penetration

Table 4: Acceptance criteria for joints with full penetration

Quality level D	Quality level C	Quality level B
$h \leq 0,2 \cdot t$, but max 2 mm	Not permitted	Not permitted

Fillet welds (according to fig 16)

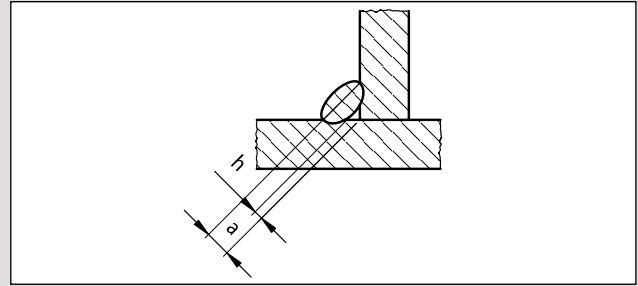


Fig 16: Fillet weld

Table 5: Acceptance criteria for fillet welds

Quality level D	Quality level C	Quality level B
$h \leq 0,2 \cdot a$, but max 2 mm	Not permitted	Not permitted

Butt and fillet welds with partial penetration (according to fig 17 and 18)

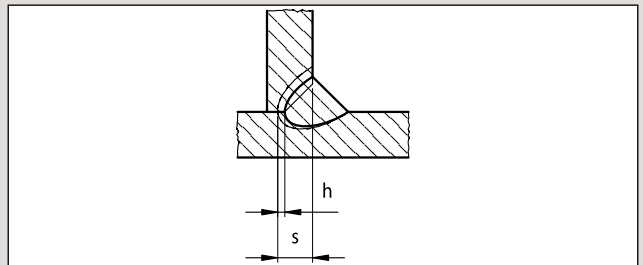


Fig 17: Butt joint with partial penetration

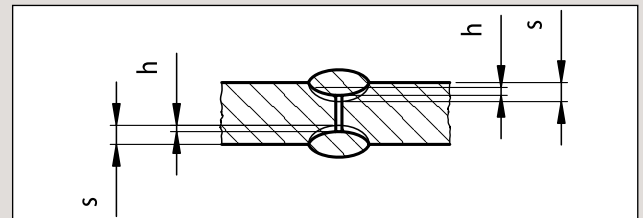
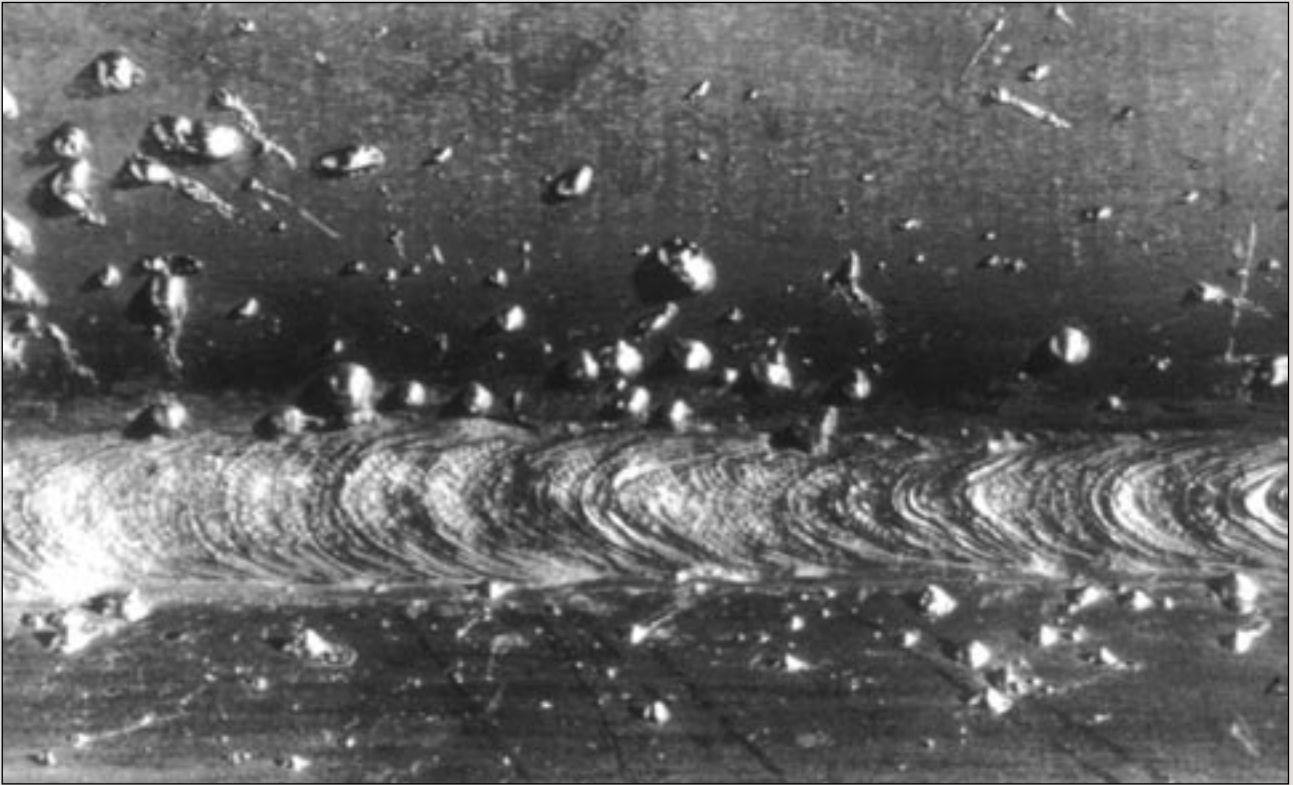


Fig 18: Fillet weld with partial penetration

Table 6: Acceptance criteria for butt and fillet weld with partial penetration

Type of joint	Quality level D	Quality level C	Quality level B
Butt joint	$h \leq 0,2 \cdot s$, but max 2 mm	$h \leq 0,1 \cdot s$, but max 1,5 mm	Not permitted
Fillet welds	$h \leq 0,2 \cdot a$, but max 2 mm	$h \leq 0,1 \cdot a$, but max 1,5 mm	Not permitted

Spatter



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Description of spatter

Spatter can form along the surface of a welded joint. It not only creates a negative visual effect on the welded joint but can also remove primer and paint, thereby creating localized corrosion.

Detection

Spatter is easily visually detected.

Ways to eliminate spatter

- Keep the welding consumables free from contaminants such as dirt and dampness.
- Long, unstable arcs can create spatter. A more stable arc can be achieved by changing the weld parameters. For example, by adjusting wire feed and voltage.
- Choose the right mixture of shielding gas. A high content of CO_2 in MAG welding and FCAW increases the amount of spatter.
- Spatter can form if the welded joint is magnetized. Minimization of magnetism is presented in TechSupport #46.
- The amount of spatter depends on the weld process. FCAW generally produces fewer spatters than MAG welding.

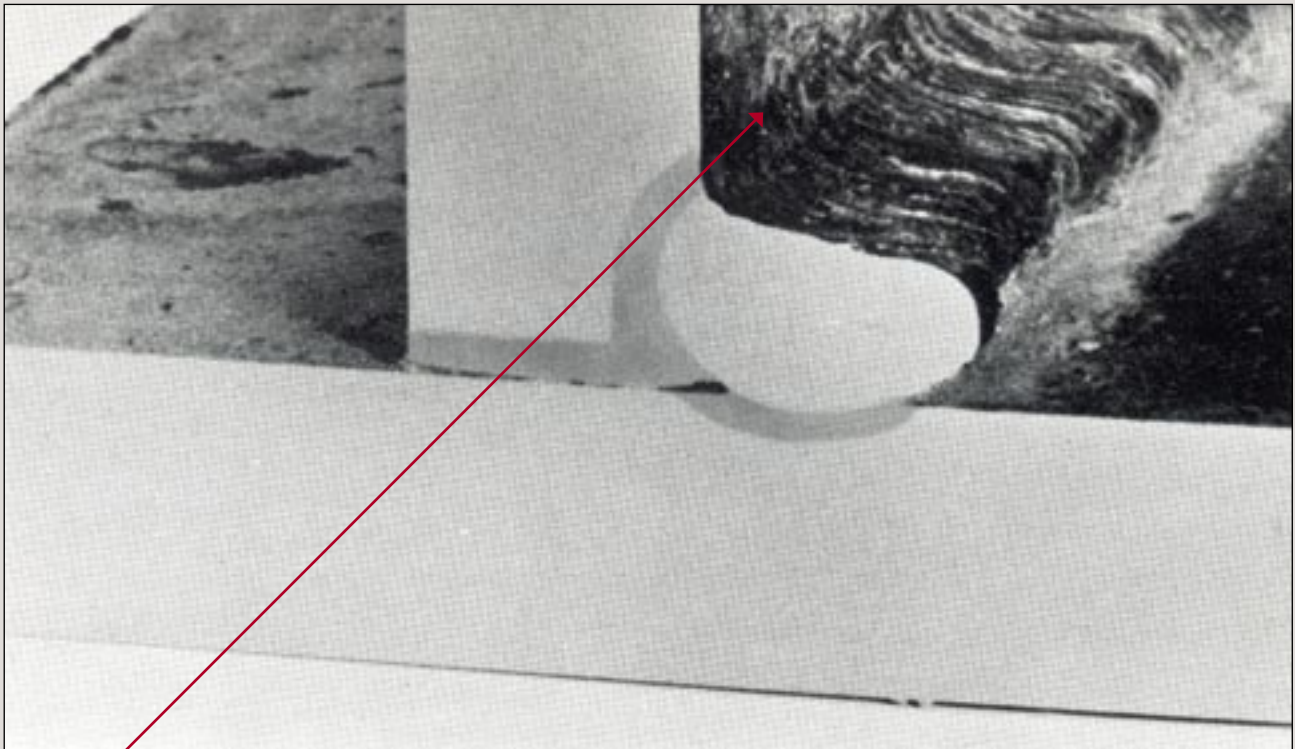
Acceptance criteria according to EN ISO 5817:2004

Spatter can be accepted in all weld classes.

No maximum limits are presented in EN ISO 5817.

The acceptance of spatter depends on the application.

Undercuts



Undercuts

Description of undercuts

Undercuts can occur in the transition area between the weld metal and the parent metal. Undercuts occur longitudinal to the welded joint and can reduce the fatigue strength in the welded joint.

Detection

Undercuts are mostly identified by visual examination. They can also be detected by radiographic and micro examination.

Ways to eliminate under cuts

- Reduce the voltage in relation to the current level.
- Decrease the weld speed.
- Place the welding torch in a right angle relative to the joint so that both sides of the welded joint are melted by the welding process.
- Eliminate existing undercuts by TIG dressing the welded joint.

Acceptance criteria according to EN ISO 5817:2004

Undercuts can be accepted in all quality levels. A smooth transition between the base metal and the weld metal is required according to fig 19 and 20.

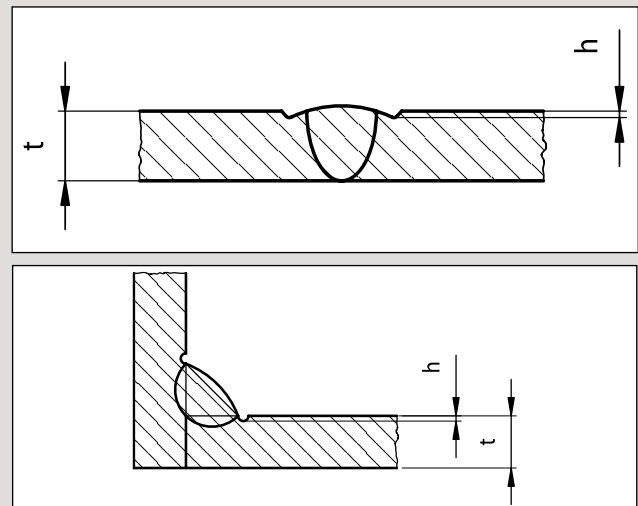


Fig 19 and 20: Undercuts, definitions

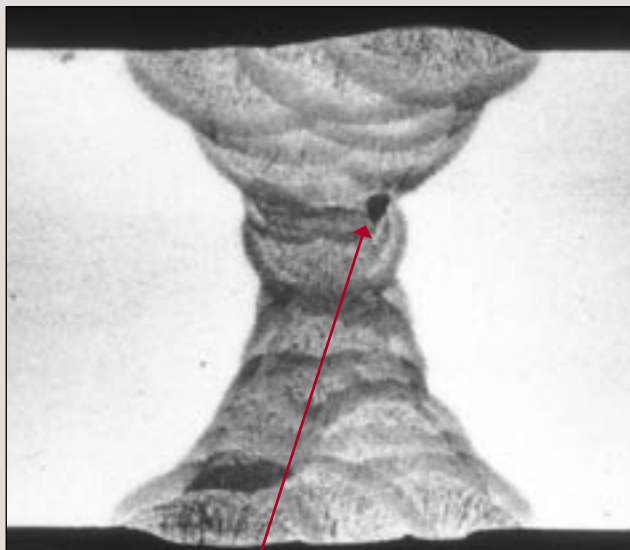
h: depth of undercut

t: Nominal plate thickness

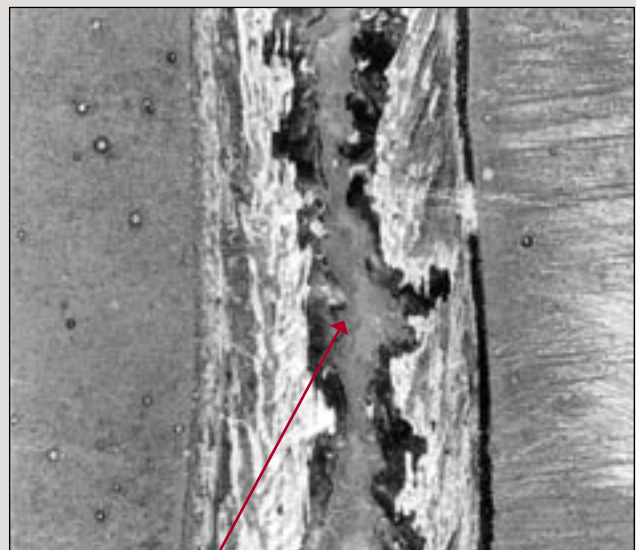
Table 7: Acceptance criteria according to EN ISO 5817 and fig 19 and 20 for all types of welded joints:

Quality level D	Quality level C	Quality level B
$h \leq 0,2 \cdot t$, but max 1 mm	$h \leq 0,1 \cdot t$, but max 0,5 mm	$h \leq 0,05 \cdot t$, but max 0,5 mm

Slag



Internal slag in weld metal Reproduced by permission, TWI Ltd.



Slag at weld surface Reproduced by permission, TWI Ltd.

Description of slag

Slag is a discontinuity in the weld metal that is commonly accepted in small amounts. Slag consists of oxides and/or sulphides. They can occur both inside the welded joint and at the surface of the weld.

Detection

Slag that is located at the surface is normally observed visually. Note that slag at the surface can not be identified by dye penetrant testing. Slag inside the welded joint can be observed by radiographic and ultrasonic examination.

Ways to eliminate slag

General:

- Use welding consumables that produce small amounts of surface slag.

- When using gas shielded weld methods, low fractions of CO_2 and O_2 in the shielding gas reduce the amount of slag, but bear in mind that a lower composition of CO_2 and O_2 reduces the weld penetration.

- When changing consumables during MMA welding, start the next weld sequence a short distance above the old weld sequence.

Multi pass welds:

- Remove any slag from the previous weld pass before beginning the next weld pass. Removal can be done with a brush, a slag pick or by grinding.
- Remove undercuts from the previous weld pass, by grinding or other methods.

Acceptance criteria according to EN ISO 5817:2004

Surface defects: Restrictions of surface slag are not mentioned in EN ISO 5817.

Internal imperfections: Limitations for embedded imperfections are according to table 8:

Table 8: acceptance criteria for slag inclusions.

Type of joint	Quality level D	Quality level C	Quality level B
Butt joint	$h \leq 0,4*s$, but max 4 mm $l \leq s$, but max 75 mm	$h \leq 0,3*s$, but max 3 mm $l \leq s$, but max 50 mm	$h \leq 0,2*s$, but max 2 mm $l \leq s$, but max 25 mm
Fillet welds	$h \leq 0,4*a$, but max 4 mm $l \leq a$, but max 75 mm	$h \leq 0,3*a$, but max 3 mm $l \leq a$, but max 50 mm	$h \leq 0,2*a$, but max 2 mm $l \leq a$, but max 25 mm

Abbreviations in table 8:

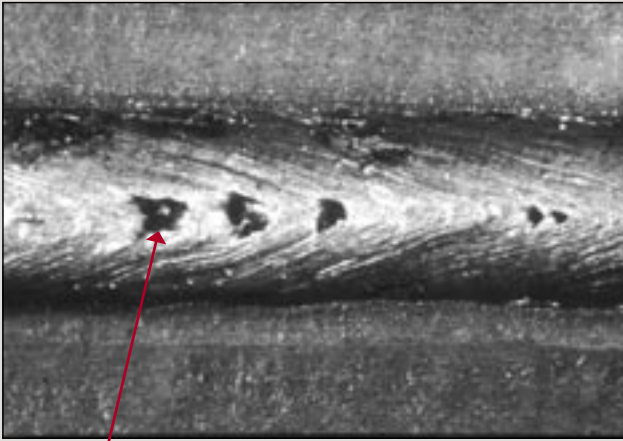
h: Max width of slag

a: Nominal throat thickness

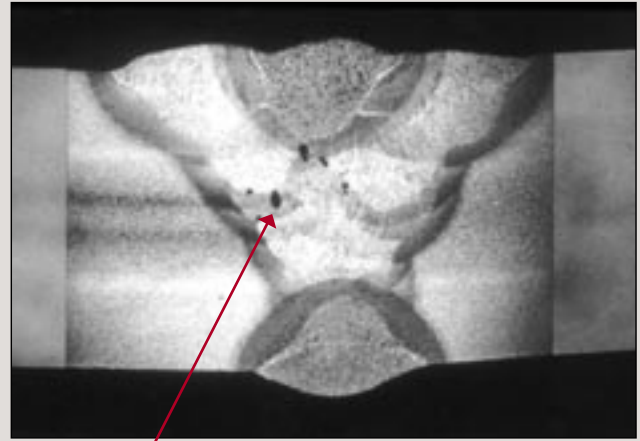
s: Nominal butt weld thickness

l: Length of imperfection in longitudinal direction of weld

Porosity



Surface breaking porosity
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Internal porosity in the weld metal
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Description of pores

Pores occur in the weld metal and are formed during the solidification of the weld pool. In the liquefied state the weld metal solves more substances than in the solidified state. The result is pore formation during solidification. Pores can be round or elongated. This imperfection can be surface breaking or embedded in the weld metal. Oxygen, Nitrogen and Hydrogen are common gases found in pores.

Pores are normally a mild weld defect. Pore occurrence can be kept low by maintaining the weld equipment and by adopting appropriate weld conditions.

Detection

Surface porosity is most often detected visually but can also be identified by dye penetrant, radiographic and ultrasonic testing. Internal pores in the weld metal are detected by ultrasonic or radiographic testing; radiographic being the easiest detection method.

Ways to eliminate pores

- Keep welding consumables and fluxes dry.
- Check that gas shielding hoses are leak proof.
- Keep the welded joint clean from contaminants such as oil and dirt.
- Use the proper amount of shielding gas. Flow rates that are either too low or too high can cause pores. As a rule of thumb, the shielding gas, measured in l/min, should be approximately the same as the inner diameter of the nozzle, measured in mm.
- Avoid welding with a long arc, especially during the start sequence of a weld.
- Welding directly on primer or painted surfaces creates more pores than if the primer or paint is removed prior to welding.
- Keep the nozzle clean from spatter.
- Do not weld in areas with a draft when using gas shielded weld methods.
- Welding consumables with relatively high levels of Mn and Si reduce the amount of pores since these substances deoxidize the weld pool.

Acceptance criteria according to EN ISO 5817:2004

Pores are accepted to a large extent in EN ISO 5817. The level of acceptance depends on size and distribution of pores along the weld metal. More information can be found in EN ISO 5817.

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