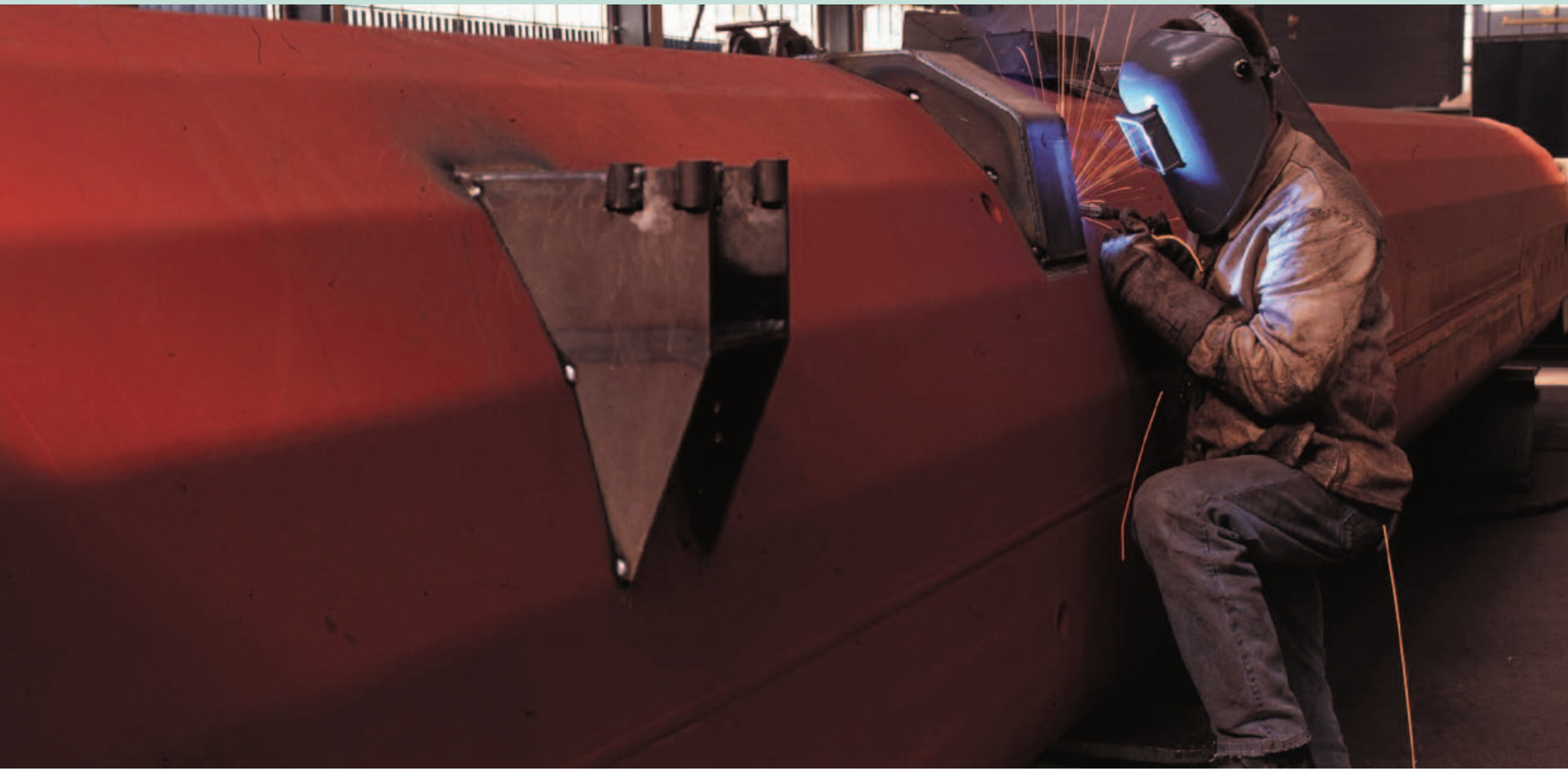
TECHSUPPORT #47

Avoidance of discontinuities in the joint



Discontinuities, including different types of cracks, can occur during welding of every type of steel including the Hardox® and Weldox® grades. The discontinuities mentioned in this TechSupport can all occur during welding of various types of steel including the Hardox and Weldox grades. However, the steel properties of the Hardox and Weldox grades do not have any particular sensitivity to these discontinuities in relation to other types of steels.

SSAB

Introduction

A discontinuity in the joint is an interruption of the physical structure of the weldment and they are of different types. Some types of discontinuities can be called defects but the meaning of these two terms differs to some extent. A defect, on the other hand, is a discontinuity that causes the weldment to be unable to meet the specified requirements of the structure. Consequently, a defect needs to be removed and corrected in a welded component while there are discontinuities that can be allowed in the structure. This means that a certain kind of discontinuity is a defect in certain structures and in others not.

THIS TECHSUPPORT FOCUSES ON:

- A short explanation of different types of discontinuities and how they occur.

- Suitable measures to avoid each kind of discontinuity. The mentioned measures are examples of preventive assessments that can be made.

- Descriptions of the acceptance criteria for specific discontinuities according to the standard ISO 5817.

The standard ISO 5817 is a well-established international publication. In this publication, the feature of the joint is divided into three different quality levels. Level B has the most stringent requirements regarding the accepted levels of discontinuities. Level C has a somewhat milder requirements and level D has the least requirements in this respect.

The discontinuities that are described in this TechSupport are:

- Lack of root penetration
- Lack of fusion
- Solidification cracks
- Slag formation
- Undercuts
- Crater pipes
- Porosity
- Spatter

Issues regarding hydrogen cracks are emphasized for joints in high strength steel and this matter is separately addressed in the Welding handbook chapter 4. Counteracting magnetic arc blow is a general measure that is beneficial to avoiding discontinuities. Issues regarding magnetic arc blow are separately described in TechSupport #46.

Lack of root penetration

DESCRIPTION OF LACK OF ROOT PENETRATION

Lack of root penetration means, as its name indicates, that the joint has an insufficient penetration depth between the parent metal and the weld metal. The appearance of lack of root penetration for a butt joint, which is welded from one side of the joint, is shown in figure 1. This kind of discontinuity can also be present when welding is performed from different sides of the joint, which is exemplified in figure 2.

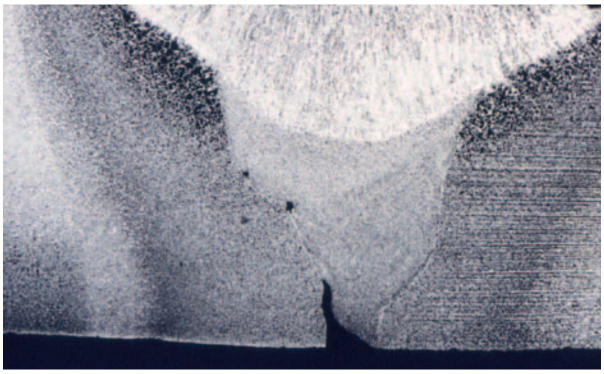


Figure.1: Lack of root fusion. (Reproduced by permission, TWI Ltd.)

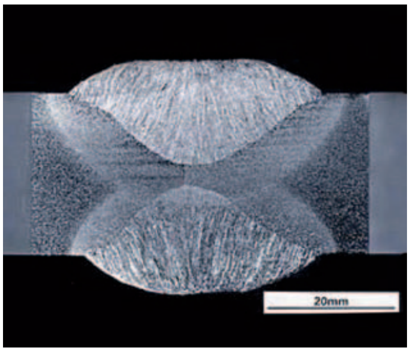


Figure 2: Lack of root fusion. (Reproduced by permission, TWI Ltd.)

FREQUENT CAUSES TO LACK OF ROOT PENETRATION AND REMEDIES TO COUNTERACT ITS PRESENCE ARE:

- A joint that is too constricted can create lack of root fusion. A proper joint configuration is characterized by: A joint preparation that is sufficiently wide to permit the torch and the consumable to operate at a position that allows for full penetration of the joint. At the same time, the volume of the joint should not be excessively large since that would support larger distortions of the welded structure and more time consuming welding operations. Adapt a gap size that is wide enough to promote a full penetration of the root pass. However, keep the gap size fit for purpose and avoid a larger than necessary gap. The recommended maximum gap size in all kinds of joints is specified to 3 mm in order to prevent hydrogen cracks, see figure 3. Suitable joint geometries depend on the welding method applied and the actual welding situation.

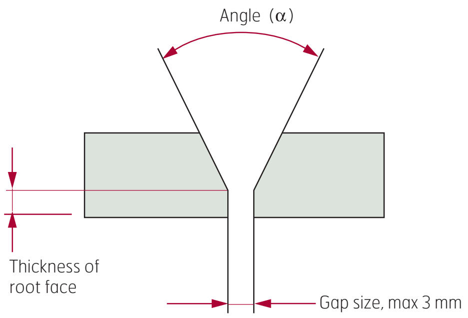


Figure 3: Drawing of a single-V butt joint.

- Contaminates in the joint and the consumable can disturb the welding performance and cause lack of root penetration. Therefore, make sure that the joint and the consumable are dry and free from contaminates such as rust, oil and grease.

- If lack of root penetration occurs, a modification of the welding parameters can change the penetration profile of the weld metal and counteract lack of fusion. Many measures can be performed in this respect. Examples are:
  - A reduction in the welding speed promotes an increased depth and width of the penetration of the weld pass. However, a welding speed that is too slow can cause a build up of molten weld metal in front of the arc. This issue can impair the weld penetration and thereby promote lack of root penetration.
  - An increased current can achieve a larger depth of the weld penetration. However, be aware that the width of the weld penetration can narrow at the same time.
  - Changing the angle and position of the torch may improve the penetration profile of the weld metal with regard to lack of root penetration.

- Applying backing support increases the resistance to lack of root penetration.

- For MMA welding: The diameter of the consumable should not be too large for the size of the joint. Instead, apply the consumable in a diameter that allows for suitable welding positions.

ACCEPTANCE CRITERIA ACCORDING TO ISO 5817

Surface breaking imperfections are not accepted in quality levels B and C in ISO 5817. Quality level D permits lack of root penetrations to a small extent.

Lack of fusion

DESCRIPTION OF LACK OF FUSION

Lack of fusion occurs when there is insufficient penetration between at least one weld pass and the sidewall of the joint or between different weld passes, according to figure 4 and figure 5. Lack of fusion is similar to lack of root penetration and there are certain preventative actions that counteract both of these discontinuities. Frequent causes of lack of fusion and remedies to prevent this discontinuity:

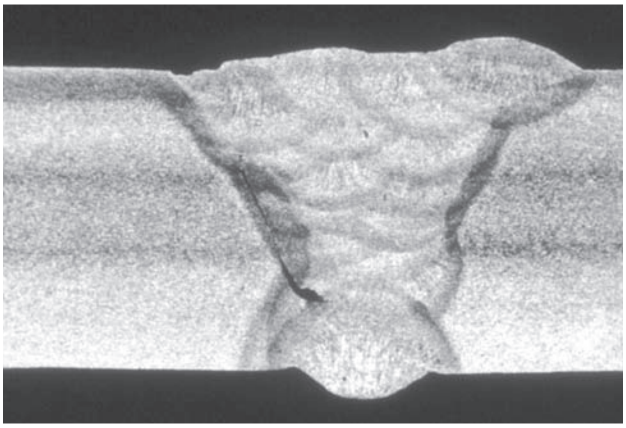


Figure 4: Lack fusion between the weld passes.
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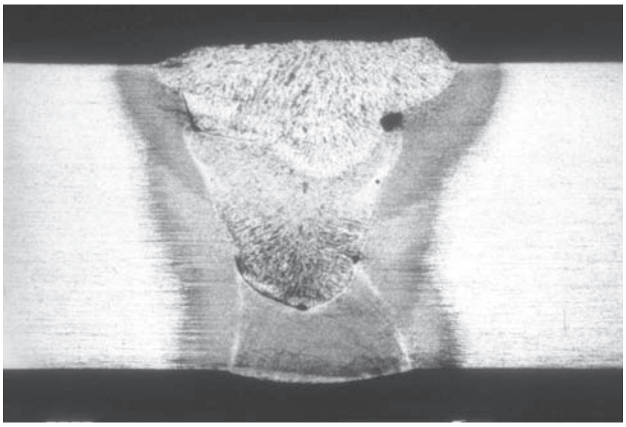

Figure 5: Lack fusion between the weld metal and the parent metal.
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FREQUENT CAUSES OF LACK OF FUSION AND REMEDIES TO PREVENT THIS DISCONTINUITY:

- Avoid a joint that is too narrow. An appropriate joint configuration will facilitate a sufficient weld fusion. It is, therefore, beneficial to take the measures that were presented for lack of root penetration, see figure 3.

- Plan the weld passes so that they are situated in locations that are suitable to one another in order to avoid lack of fusion.

- For multi-pass welds, the shape of the cap of the weld metal should not be too convex since that can counteract a complete fusion for the next weld pass to come. At the same it, it should not be too concave because that can cause solidification cracks.

- In many cases, a lower welding speed will reduce the risk for lack of fusion because it promotes a wider and larger weld penetration. However, a welding speed that is too low can lead to a build up of molten weld metal in front of the arc causing insufficient penetration.

- The angle and the position of the torch, if placed improperly in relation to the joint, could cause lack of fusion. Adjusting these two parameters may improve the penetration profile of the weld metal, thus counteracting lack of fusion.

FOR MAG WELDING:

- An increased fraction of CO_2 in Ar/CO_2 mixtures increases the size and roundness of the weld pool. These aspects can promote an enhanced resistance to lack of fusion.

- Welding with flux and metal cored wires promotes an increased width of the weld metal and provides a higher resistance to lack of fusion than welding with solid wires.

ACCEPTANCE CRITERIA ACCORDING TO ISO 5817

Lack of fusions that are surface breaking are normally not permitted in any quality level. Internal types can be present at certain sizes in quality level D but not at any time in level C and B.

Solidification cracks (Hot cracks)

DESCRIPTION OF SOLIDIFICATION CRACKS

Solidification cracks, also called hot cracks, are initiated in the weld metal. If present, they typically grow along the weld metal and are most frequently found in the centerline of a weld pass, according to figure 6. Solidification cracks can be surface breaking or embedded in the weld metal.

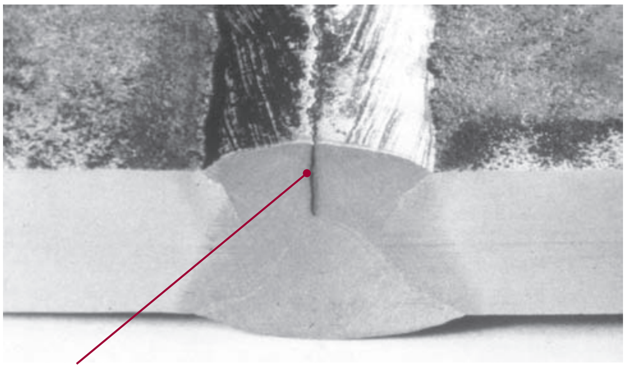

Figure 6: Solidification crack. (Reproduced by permission, TWI Ltd.)

The probability of a solidification crack occurring is influenced by:

- The chemistry of the weld metal.

- How the welding performance is carried out.

- The level of restraint in the joint.

Solidification cracks are promoted by the contaminants and the alloy content in the weld metal. Each element has its unique characteristics in this respect.

The origins of this type of crack emerge from the solidification process of the liquefied weld metal. The solidification begins in the outer parts of the weld metal and progresses towards its center. The weld metal shrinks during solidification, so it is essential that the weld pool is continuously supplied with a sufficient amount of consumable to compensate for the contraction. Solidification cracks can also form if there is an insufficient bonding in the last part of the solidified weld metal, see figure 7. It is, therefore, important that a sufficient amount of filler metal is fed from the consumable into the weld pool in order to compensate for the shrinkage of the weld metal.

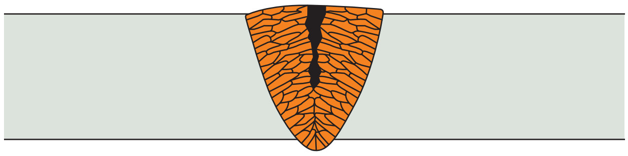

Figure 7: Hot cracks can form if the weld pool is not fed with a sufficient amount of weld metal from the consumable.

The sensitivity to solidification cracks is enhanced if the joint is subjected to high levels of restraint. This is because high levels of restraint cause a more rigid joint structure, promoting higher levels of strain in the weld metal as it contracts during solidification.

The resistance to solidification cracks is influenced by the content of alloys and contaminates in the weld metal. The reason being that the weld metal has a different ability to dissolve alloys and contaminants in the liquid state compared to the solid state. As the weld metal solidifies, the part of the weld metal that is still liquid is gradually enriched by contaminates. It is of essential importance to keep the contaminants phosphorous and, especially, sulfur at low levels since these elements will be concentrated in the last part of the weld metal to solidify. Locally enhanced levels of these substances can cause areas of low toughness and low strength in the weld metal, promoting solidification cracks. The negative effects from sulfur are further counteracted by the addition of manganese to the steel. Manganese binds with sulfur resulting in manganese-sulfide (MnS) which reduces the negative effects of the sulfur with regard to solidification cracks.

The sulfur and phosphorous content in the weld metal comes, for many types of steel, mostly from the parent metal. However, the Hardox and the Weldox grades are characterized by a very small level of these contaminants. In addition, the manganese content is relatively high for these steels.

The overall resistance to solidification cracks is, therefore, considerable and this kind of crack is comparatively unusual in joints of Hardox and Weldox.

CAUSES OF SOLIDIFICATION CRACKS AND REMEDIES TO PREVENT THIS DISCONTINUITY

- A joint that contains sulfur and other contaminates can contribute to the formation of solidification cracks. Therefore, make sure that the joint is clean, both before and during welding, in order to avoid pick-up of contaminates to the weld metal.

- An insufficient amount of consumable in the weld, pool promotes the formation of solidification cracks as the melt contracts during solidification. A pronounced concave shape in the surface of the weld metal indicates that the feeding rate of the consumable to the weld pool is too low. Instead, adopt a feeding rate that does not create a weld surface that is too concave, according to figure 8. This can be achieved, for example, by using a sufficiently high wire feed.

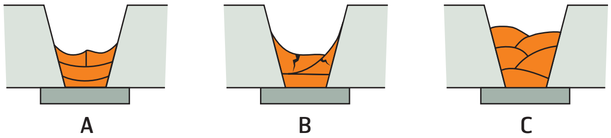

Figure 8: Effect of weld shape in multi pass welds:
A and B) Concave welds with tendency to crack.
C) Slightly convex weld beads

- The shape of the weld metal influences the solidification pattern of the weld metal. Very deep weld passes promote high levels of strain during the solidification process, which can cause solidification cracks. A weld pass with a width/depth ratio ≥ 1 is preferable, according to figure 9. An increase of the width/depth ratio of the weld metal, for instance, can be accomplished by decreasing the welding speed or reducing the current level during welding.
  One way to determine a suitable welding speed is to create an elliptically shaped weld pool. Welding with a high speed that creates a teardrop shaped weld pool is not desirable from a solidification crack point of view, see figure 10.

- Applying a joint with a lower level of restraint is beneficial in order to counteract solidification cracks.

ACCEPTANCE CRITERIA ACCORDING TO ISO 5817

Solidification cracks are not accepted in any weld class according to ISO 5817.

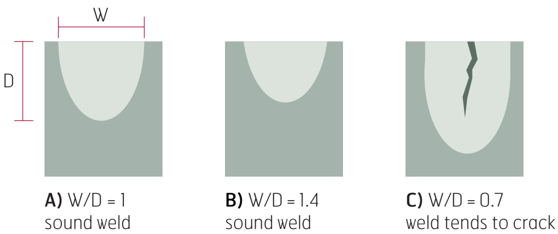

Figure 9: Effect of weld shape on cracking tendency:
A) W/D = 1, sound weld
B) W/D = 1.4, sound weld
C) W/D = 0.7, weld tends to crack

Slag formation

DESCRIPTION OF SOLIDIFICATION CRACKS

Slag is a by-product of welding. It consists of different mixtures and sizes of oxides and/or sulfides. The sizes can range from small to relatively large and they can appear in different forms, as in figure 11 and figure 12. Slag is less dense than weld metal so it typically floats up to the surface during welding.

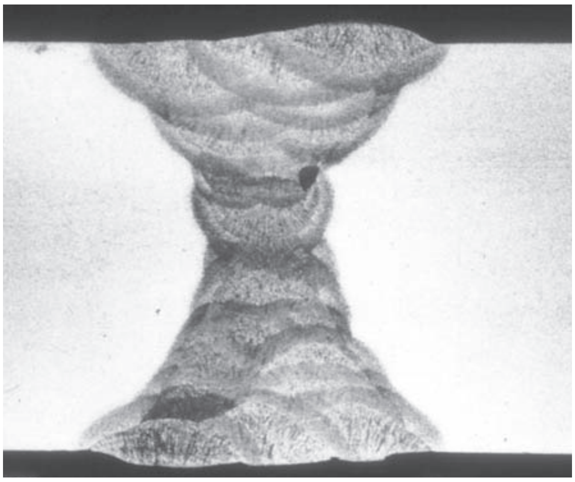

Figure 11: Internal slag formation in weld metal.
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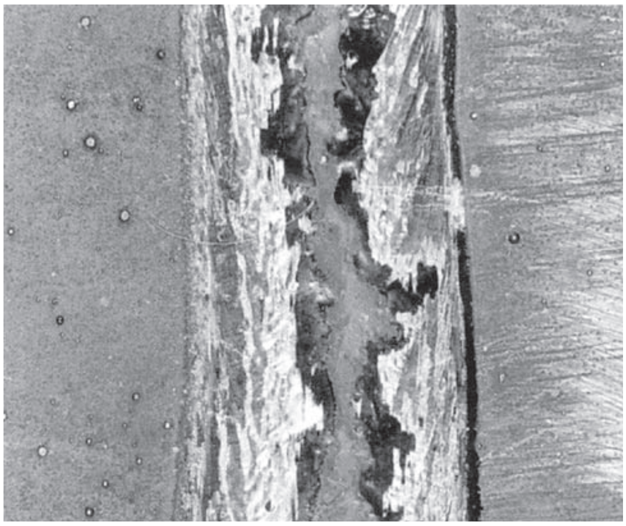

Figure 12: Slag formation at the weld surface.
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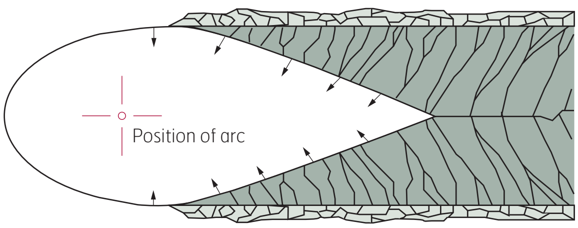
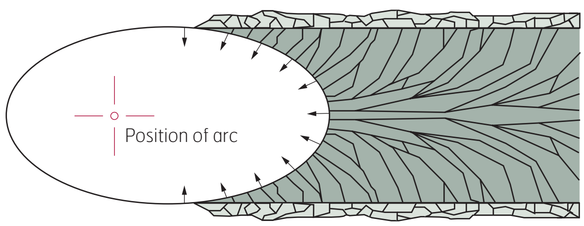


Schematic diagram showing competitive growth with a teardrop shaped weld pool



Schematic diagram showing competitive growth with an elliptical weld pool

Figure 10: The direction of the solidification process from a liquefied weld pool is in a right angle to the outer end of the liquefied weld pool.
A solidification pattern that forms in several directions will enhance the resistance to solidification cracks. A weld pool that forms like an ellipse will facilitate this matter, according to the picture to the right. In the picture to the left, welding is carried out with a higher speed that causes a tear shaped weld pool. The solidification direction is more uniform in this case, which promotes formation of solidification cracks.

The amount of slag that is formed is influenced by the welding method. When using the methods of MMA welding and SAW where a flux/coating is used, slag is always intentionally formed. Its functions include improving the mechanical properties of the weld metal, forming the shape and surface of each pass and stabilizing the arc during welding. In order to avoid slag inclusions and slag formation at the top of the last weld pass, the slag is meant to be removed after each weld pass for these welding methods.

The amount of slag for the different kinds of MAG welding varies. Flux cored wires are designed to produce slag. The elements that make up the slag can, for instance, improve the mechanical properties in the weld metal. During MAG welding with a flux-cored wire, the slag is meant to be removed between intermediate weld passes in order to avoid slag inclusions. The last weld pass/passes on the top of the weld metal may not require slag removal although it is frequently done. A reason for removing the slag from the final weld pass is that it could later come loose which, for example, could damage the paint of the welded structure.

For other types of MAG welding and TIG welding, the levels of slag are present to a lesser degree than MAG welding with flux cored wire and. The function of the slag is in these cases relates to the characteristics of the consumable. However, slag removal is preferable after each weld pass. The consumable manufacturers can provide more information regarding a specific consumable in this respect.

The most common method used to remove slag is with a slag pick during SAW and MMA welding and grinding or using a brush during MAG welding and TIG welding. Removing all traces of slag helps to avoid undesired slag inclusions between individual weld passes.

However, if slag inclusions are encountered, they are typically small fractions of the total volume of the weld metal and without sharp edges.

CAUSES OF SLAG FORMATION AND REMEDIES TO PREVENT THIS DISCONTINUITY

- An unstable arc can cause excessive amounts of slag and produce a rough surface on the weld metal. An irregular surface makes slag removal more difficult. Instead, weld with parameters that endorse a stable arc, such as, welding with a shorter arc length. Results of a stable verses unstable arc are illustrated in figure 13.

- Undercuts from a weld pass can obstruct the removal of slag formations. Undercuts at intermediate weld passes can be removed by, for example, grinding.

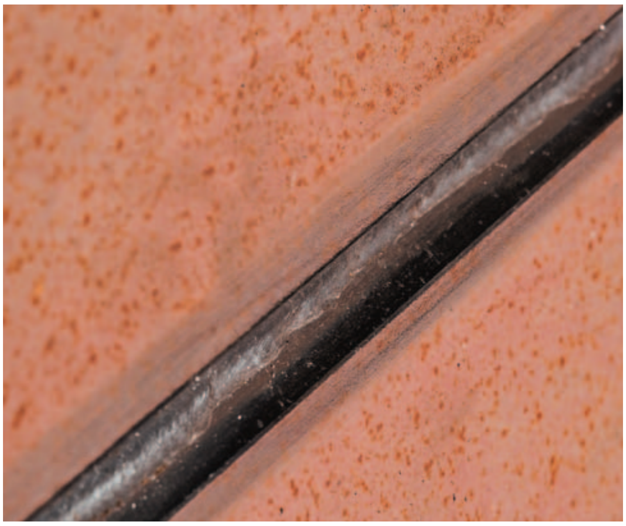
- The beginning and completion of a welding sequence may be more unstable than other parts of the welding sequence. If this is the case, the following actions may improve the situation:

  - Apply start and stop plates at the end sections of the joint, if feasible.

  - If an unstable welding condition is encountered at the end of a sequence, a suitable measure may be to grind off the end section before the next sequence is welded.

ACCEPTANCE CRITERIA ACCORDING TO ISO 5817

A certain extent of slag inclusions can be accepted at all quality levels in ISO 5817.



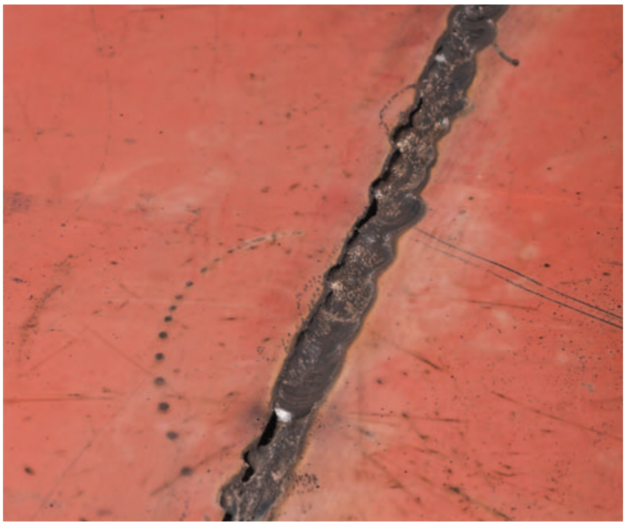


Figure 13: A smooth weld geometry facilitates easier slag removal according to the picture on the left. An unsuitable performance from an unsteady welding performance is shown in the picture to the right.

Undercuts

DESCRIPTION OF UNDERCUTS

An undercut is a groove in the joint that is located at its surface and in the transition area between the weld metal and the parent metal, according to figure 14. If undercuts occur, they are longitudinal to the joint.

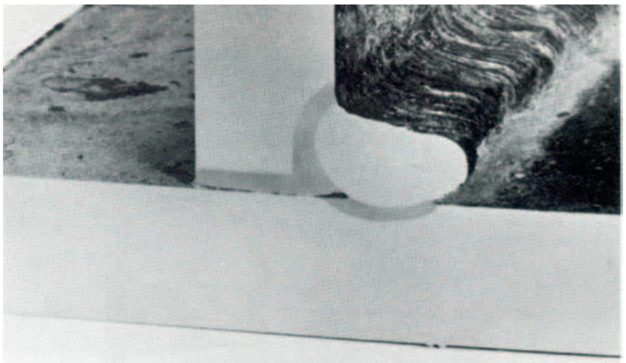


Figure 14: Undercuts. (Reproduced by permission, TWI Ltd.)

Undercuts are promoted by a high cooling rate of the weld metal during solidification. When undercuts form, the molten metal increases at the center and upper part of the weld metal leaving a lack of weld metal in the outer regions. During solidification, the top part of the weld metal is still concentrated in the center region, whereby undercuts are established.

Undercuts can also obstruct removal of slag from a previous weld pass, causing slag inclusions.

CAUSES OF UNDERCUTS AND REMEDIES TO PREVENT THIS DISCONTINUITY

- Below are measures to prolong the cooling period for the solidification of the weld metal. Following one or more of these measures can enhance the resistance to undercuts:

  - A reduction of the welding speed is an efficient way to counteract this kind of discontinue.
  - A raise of the voltage level may increase the resistance to undercuts since increased voltage promotes a wider weld pool.
    However, too much voltage can cause an excessively wide weld pool, leading to rapid solidification at the ends of the weld metal, which can promote undercuts.
  - Undercuts can form if the electrode is misplaced in the joint. Take care to position the torch in order to support the desired geometry of the weld metal.
  - An existing undercut can be removed with, for example, grinding or TIG dressing.

ACCEPTANCE CRITERIA ACCORDING TO ISO 5817

Undercuts can be accepted at all quality levels of ISO 5817.

Crater pipes

DESCRIPTION OF CRATER PIPES

Crater pipes can form at the end section of a weld sequence because the weld pool shrinks during solidification, according to figure 15 – figure 17. Crater pipes reach the surface of each weld pass.

When a crater pipe occurs, there is a somewhat higher risk for a solidification crack to form in its place. When this happens, the solidification crack is also called a crater crack. The Hardox and Weldox grades have a high resistance to crater cracks – as for other kinds of solidification cracks.

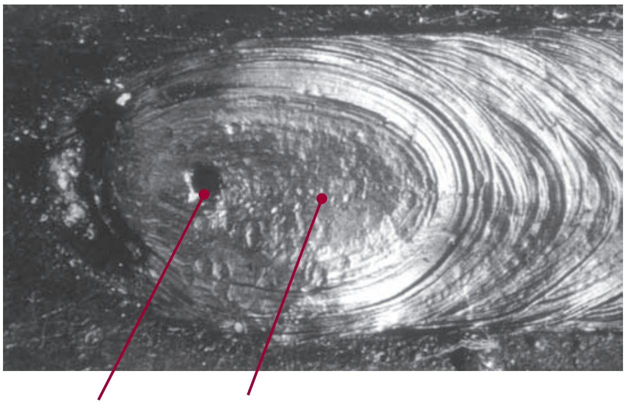


Figure 15: Pore Crater pipe
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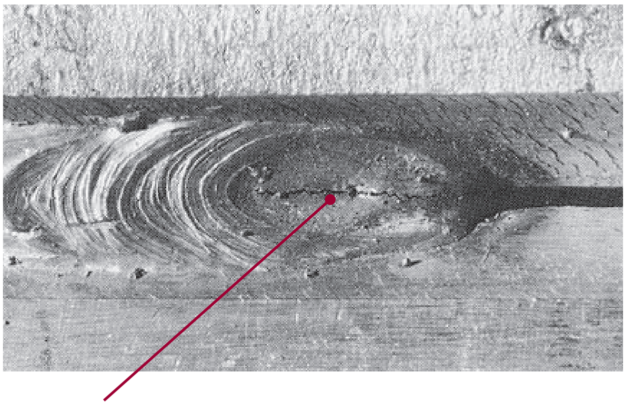

Figure 16: Crater crack
(Reproduced by permission Swerea KIMAB AB)

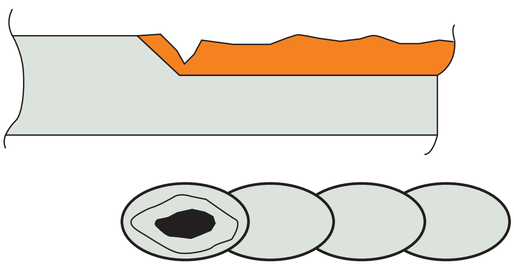

Figure 17: Crater pipe.

CAUSES OF CRATER PIPES AND REMEDIES TO PREVENT THIS DISCONTINUITY

- An insufficient amount of weld metal from the consumable can cause crater pipes. Two suitable methods for employing a sufficient feeding of the consumable in the end of a welding sequence are to:
  - Finalize a weld sequence with a reduced welding speed.
  - End the weld sequence by welding in the opposite direction for a short distance in order to fill out the crater pipe. The change of welding direction is performed without an interruption of the arc.
- Crater pipes can be avoided by using stop plates at the end of the joint.
- For MAG welding: Some types of MAG welding equipment can be set to gradually reduce amperage and voltage at the end of a welding sequence. This function facilitates a reduction of the molten weld pool, which causes less shrinkage during solidification thereby reducing the tendency for crater pipes.
- A crater pipe from a previous weld sequence can be ground off before welding the next run.

ACCEPTANCE CRITERIA ACCORDING TO ISO 5817

Crater pipes can be accepted within certain limitations in quality levels D and C but not at level B.

Porosity

DESCRIPTION OF POROSITY

Pores can occur in the weld metal and they are formed during solidification of the molten weld metal. Pores can occur in different parts of the weld metal, which means that they can be embedded in the weld metal, shown in figure 18, or surface breaking, see figure 19. They can appear in various geometrical forms and concentrations. The principal gases that are found in embedded pores are nitrogen, oxygen and hydrogen.

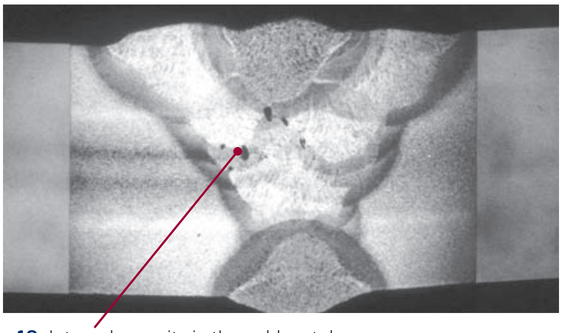

Figure 18: Internal porosity in the weld metal.
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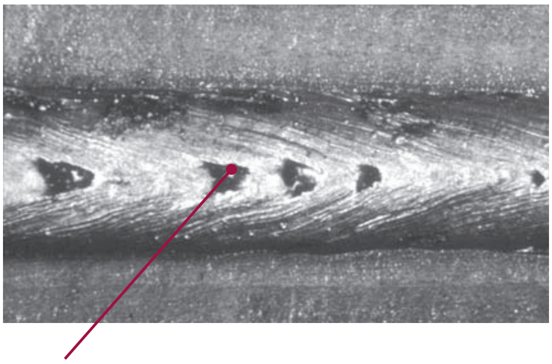

Figure 19: Surface breaking porosity.
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Pores are commonly caused by the gases that are introduced during welding. These gases are introduced into the liquid weld pool since the molten weld metal dissolves them, however, when the weld metal solidifies, their solubility decreases. As a result, pores are formed in the weld metal. Some remain completely trapped in the weld metal while others escape from the joint through the weld metal that is still liquefied. Surface breaking pores appear when pores become trapped just as they reach the surface of the weld metal.

CAUSES OF POROSITY AND REMEDIES TO PREVENT THIS DISCONTINUITY

- Keep the joint clean from contaminants such as water, snow and rust.
- Keep the consumables dry and store them in accordance with their manufacturer.
- Substances in the shop primer used on the Hardox and Weldox plates may cause small fractions of pores when welding is performed directly on the primed surface. For the best results, remove the primer from the joint prior to welding. However, the low levels of pores that can be caused by the primer are accepted in most types of regulations.
- Paints other than the shop primer may also include substances that cause unacceptable levels of porosity. The recommendation is, therefore, to remove these kinds of paints from the joint prior to welding.
- A lowered welding speed may counteract pore formation. This measure increases the size of the weld pool allowing more time for the pores to bubble up to the surface of the weld pool and disappear from the joint.
- For shielding gas related welding methods:
  - Regularly check that the gas shielding equipment is fit for purpose to avoid the surrounding air from getting into the shielding gas.
  - Use the proper amount of shielding gas. Flow rates that are 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.

- Keep the nozzle of the torch clean from spatter, as it could otherwise disturb the gas flow.
- Do not weld in a draft. This can cause the shielding gas to blow away casing an insufficient protection of the melt.
- It is beneficial to weld with a short arc length, especially during the start sequence of a weld, to improve the gas shield of the weld metal.

ACCEPTANCE CRITERIA ACCORDING TO ISO 5817

Pores are accepted to a certain extent in the different quality levels in ISO 5817. The level of acceptance depends on the size and distribution of pores along the weld metal. Information that is more specific can be found in ISO 5817.

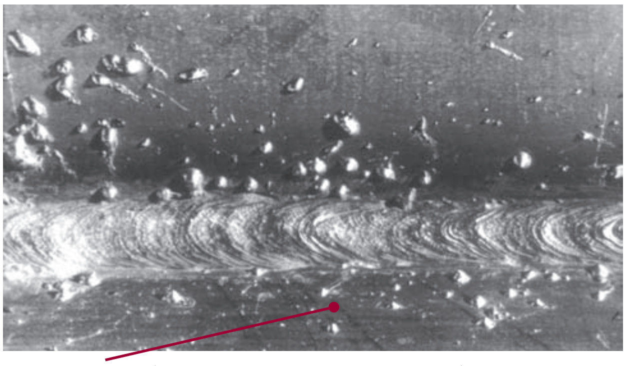

Figure 20: Spatter (Reproduced by permission, TWI Ltd.)

Spatter

DESCRIPTION OF SPATTER

Spatter is small metal droplets that can form in the arc during a welding performance, according to figure 20. They are spread in and around the joint when they occur. The spatter is located on the surface of the joint. This sort of imperfection is mostly an issue for MAG and MMA welding.

CAUSES OF SPATTER AND REMEDIES TO PREVENT THIS DISCONTINUITY

- Pollutants that are present in the welding process can cause spatter. Therefore, keep the consumables and the joint free from contaminants such as dirt, rust and dampness.
- A long arc length promotes an unstable arc that can lead to spatter. A shorter arc length will endorse a more stable arc and an enhanced resistance to spatter.
- The initial part of a welding sequence can be unstable which can lead to spatter. The use of start plates can counteract this effect.
- Some types of consumables have a higher resistance to spatter than others. Make sure to choose a consumable fit for purpose.

ISSUES RELATED TO MAG WELDING:

- Choose the right mixture of shielding gas. A relatively low content of CO_2 decreases the amount of spatter. The use of the suggested shielding gas compositions from SSAB can achieve low amounts of spatter.
- Spray arc and pulsed arc welding have a higher resistance to spatter in comparison to short arc welding.

ACCEPTANCE CRITERIA ACCORDING TO ISO 5817

Spatter can be accepted in all weld classes in ISO 5817 and no maximum limits are presented in this standard. The degree of acceptance depends on the requirements for the application.

SSAB is a global leader in value added, high strength steel. SSAB offers products developed in close cooperation with its customers to reach a stronger, lighter and more sustainable world.

SSAB employs over 8 700 people in over 45 countries around the world and operates production facilities in Sweden and the US. SSAB is listed on the NASDAQ OMX Nordic Exchange, Stockholm.

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