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EDITION NUMBER 1

WELDING HANDBOOK

A GUIDE TO BETTER WELDING OF HARDOX AND WELDOX



SSAB

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2.0 Introduction

The absolute majority of Hardox® wear plate steel and Weldox® high strength steels are subjected to welding. Therefore, in order to utilize the full potential of welded structures, knowledge of welding technology related to these steel grades is essential.

The principal areas of welding technology are material technology, industrial engineering, and the mechanics of materials. The objective of the welding handbook from SSAB is to describe and provide recommendations for a wide range of weldability aspects within these fields. Especially emphasized, are the mechanical properties and the material technology of welded structures in Hardox and Weldox.

When welding technology is considered from the early stages of product development through the completion of the manufacturing process, substantial benefits can be gained. Well-planned engineering can optimize the performance of welded structures in both technical and economical terms.

This handbook can be read from start to finish or individual chapters can be referred to regarding specific topics. The majority of the chapters address theories, recommendations and suitable procedures within a certain field. However, the last three chapters are informational. These chapters relate to the properties of the Hardox and Weldox grades without addressing specific welding recommendations.

These three chapters are:

- Microstructures in the heat affected zone (HAZ) and the unaffected parent metal
- Hardening mechanisms in the heat-affected zone and the unaffected parent metal
- The influence of alloys and contaminants on the Hardox and Weldox grades

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2.1 The Hardox and Weldox grades

Starting with the steel processing at SSAB, the complete range of Hardox and Weldox grades are designed for favorable weldability. The selection of the chemical alloy content together with the extremely low levels of contaminants for each individual steel grade contributes to these conditions. In addition, the steel processing at SSAB is developed in a manner that supports beneficial properties in the joints of these steel grades.

Each Hardox and Weldox grade has a datasheet stating its unique mechanical properties. These documents list the maximum chemical content for each element in the steel. The alloy composition varies for different plate thicknesses within each steel grade. The reason being that each plate thickness behaves differently during the production process and the alloy composition for a given plate thickness is adjusted in order to optimize its properties. The typical outcome is that the level of alloys and contaminants in each plate thickness, for all Hardox and Weldox grades, is lower than the stated maximum values.

A common factor shared by all Weldox and Hardox steels is that they can be welded to all other weldable steels using any conventional welding process.

The Hardox grades

Hardox grades are wear resistant steels with high hardness as well as high strength. The complete range of Hardox grades with corresponding hardness values are illustrated in fig. 2.1.



Fig. 2.1: The stated hardness values for the Hardox grades. Hardox HiTuf and Hardox 400-Hardox 600 have guaranteed hardness values while Hardox Extreme has typical values.

The fundamental mechanical property of wear resistant steel is a high hardness value in the unaffected parent metal. Other mechanical properties for this kind of steel are important but normally not as crucial as the hardness value. Therefore, Hardox grades are developed with a guaranteed hardness range, with the exception of Hardox Extreme, which is stated with typical values. Typical, yield strength and impact toughness are stated for certain Hardox grades. All Hardox grades are weldable. The welding technology of the Hardox grades share commonalities with the Weldox grades. However, the requirements for the mechanical properties in joints of Hardox are normally less extensive than those of Weldox.

Minimizing the risk of hydrogen cracks in joints is important for both Hardox and Weldox. In general, as the hardness and strength of the steel increases, so does the susceptibility to hydrogen cracks. Accordingly, the most stringent demands are placed on the Hardox grades with the highest

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hardness values. SSAB addresses this issue in the general welding recommendations. By following these recommendations, the risks for hydrogen cracks are minimized.

The Weldox grades

Weldox high strength steels achieve a combination of very high strength and toughness. The minimum yield strength for the different Weldox grades is illustrated in fig. 2.2.

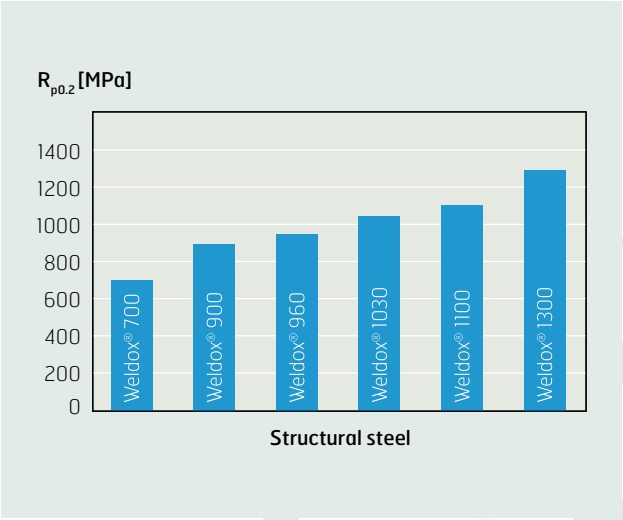


Fig. 2.2: The Weldox grades can be ordered with the displayed minimum yield strengths.

Weldox grades can be ordered based on specific impact toughness requirements. Most commonly, Weldox grades are ordered with impact toughness requirements of a minimum 27 J measured at -40°C. The actual mechanical properties for Weldox steel plates will typically exceed the guaranteed minimum yield strength, tensile strength and, especially, the impact toughness.

The typical impact toughness of the joint for all Weldox grades can also have a value of at least 27 J measured at -40°C and, in many cases, they are considerably higher.

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3.0 The thermal cycle of a welding performance

The welding process subjects a joint to a localized thermal heat treatment wherein the joint attains mechanical properties and microstructures that are different compared to that of the unaffected parent metal.

Welding properties are of vital concern for SSAB during the development of the Hardox and Weldox grades. As a result, these steels can achieve favorable properties in the joint.

The principal purpose of this chapter is to describe which parameters affect the thermal heat treatment in the joint.

3.1 The heat input

The heat input from a welding method depends on the applied current, voltage and speed and it describes the delivered energy/ length of the joint.

During welding there is loss of energy in the arc. The thermal efficiency factor (k) expresses that part of the heat input that is transferred to the joint during the welding process. This parameter depends on the welding process being used and the specific welding conditions. Approximate values for different welding methods are according to table 3.1.

Thermal efficiency	k [dimensionless]
MMA	0.8
MAG, all types	0.8
SAW	1.0
TIG	0.6

Table 3.1: The thermal efficiency factors for different welding methods.

The heat input that is transmitted to the joint can be calculated according to the following formula.

$$Q = \frac{k \times U \times I \times 60}{v \times 1000}$$

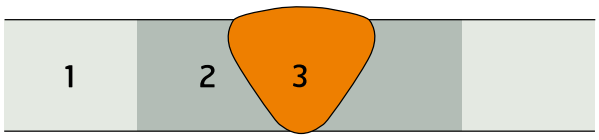
Q = Heat input [kJ/mm]
U = Voltage [V]
I = Current [A]
v = Welding speed [mm/min]
k = Thermal efficiency [dimensionless]

Recommended heat inputs for welding the Weldox and the Hardox grades are found in chapter 5.

3.2 The heat-affected zone

The complete part of the parent metal that is influenced by the thermal cycle of the welding procedure is called the heat-affected zone (HAZ). The other main areas in the joint are the unaffected parent metal and the weld metal, see fig. 3.1.

Fig. 3.1: The principal parts of the joint



1. Unaffected parent metal
2. Heat affected zone, HAZ
3. Weld metal

The characteristics of the thermal heat treatment from welding are of crucial importance for the mechanical properties and microstructures in the HAZ. Its outcome depends primarily on:

- The position in the joint
- The level of heat input
- The plate thicknesses in the joint
- The type of joint
- The preheat temperature, when applicable

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As an example, the thermal cycles during a welding performance, at different locations in a joint, are illustrated in fig. 3.2.

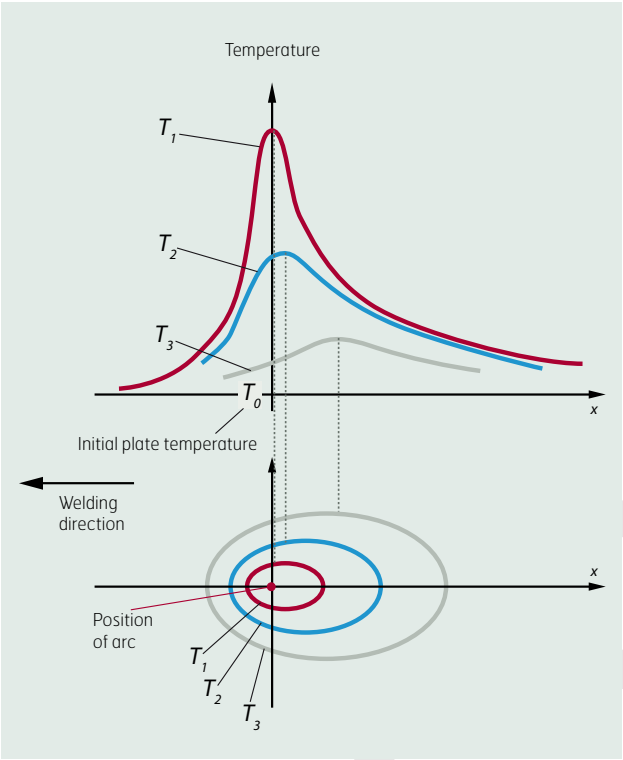


Fig. 3.2: The heating / cooling rate and the peak temperature decrease with increased distance to the arc.

3.3 Description of the thermal cycle

The thermal cycle of welding can be defined by the cooling time in the HAZ between 800°C and 500°C. This parameter is called the $t_{8/5}$ value, and it is illustrated in fig. 3.3:

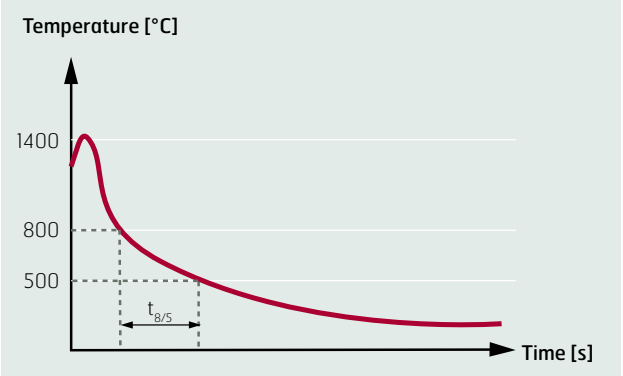


Fig. 3.3: Schematic diagram for a thermal heat treatment in the part of the HAZ situated closest to the weld metal.

There is no need to calculate the $t_{8/5}$ value but it facilitates a good understanding of the thermal treatment in the joint due to the welding process. Another name for $t_{8/5}$ is $t_{8/5}$ and the definition is the same for both symbols.

When the $t_{8/5}$ value is determined, it is most often calculated but it can also be measured. However, studies have shown that measuring $t_{8/5}$ can be difficult due to sources of errors in the measurement techniques. SSAB recommends that the $t_{8/5}$ value is only calculated.

Evaluations of the $t_{8/5}$ value show that it is mostly constant throughout different parts of a joint as long as the peak temperature in the joint reaches above 900°C during the welding process.

The mechanical properties of toughness, static strength and hardness in the HAZ are affected by the thermal cycle of the welding process. In many cases, when welding Weldox grades, the impact toughness in the HAZ is an important parameter to consider. The minimum impact toughness value is normally reached in the part of the HAZ located closest to the weld metal where the peak temperature has reached levels between ~1500°C down to ~1100°C. This zone is called the coarse grained HAZ (CGHAZ).

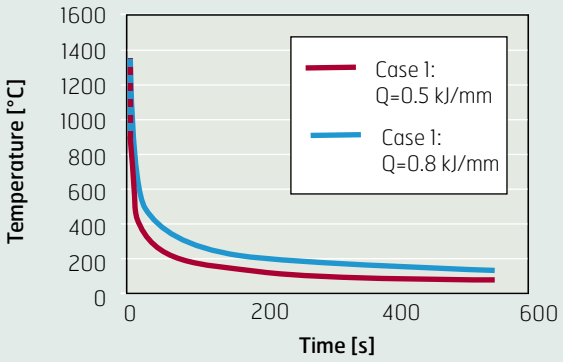
If the $t_{8/5}$ value for a certain welding situation is not calculated, appropriate $t_{8/5}$ values are automatically attained if all other welding recommendations are followed for the Weldox grades. Recommended $t_{8/5}$ values for these steel grades are presented in chapter 5.

SSAB does not specify suitable $t_{8/5}$ intervals for welding of the Hardox grades since the mechanical properties in the joints of these steel grades are normally not as emphasized as for the Weldox grades.

The following example illustrates the effect on the thermal cycle when welding a joint with different parameters. In this case, a single-V butt weld with a plate thickness of 5 mm is welded using two different heat inputs, according to fig. 3.4.

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Case 1)	Case 2)
Type of joint: single-V butt joint	Type of joint: single-V butt joint
Pt*: 5 mm	Pt*: 5 mm
Q: 0.5 kJ/mm	Q: 0.8 kJ/mm
Welding method: MAG	Welding method: MAG
$t_{8/5}$: 7 s	$t_{8/5}$: 20 s
Preheat temp: 20°C	Preheat temp: 20°C

*Plate thicknesses throughout the joint.

Fig. 3.4: Thermal cycles in the coarse grained zone of a butt joint welded with two different heat inputs.

3.4 The calculation of the $t_{8/5}$ value

The use of the software WeldCalc, from SSAB, facilitates easy determination of the $t_{8/5}$ value for a given welding situation. If the $t_{8/5}$ value is calculated manually, the procedure will take more effort. The procedure according to the European Norm 1011-2 is now described.

Two different principal situations call for the calculation of the $t_{8/5}$ value. The first is for joints with small plate thicknesses. During this situation, the heat flow in the joint from the welding performance is mainly perpendicular to the plate thickness and along the joint. This type of heat distribution is called two-dimensional heat flow, see fig. 3.5. In this case, each weld pass corresponds to a large fraction of the plate thickness of the joint.

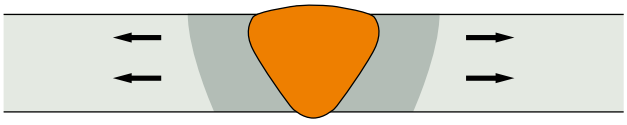


Fig. 3.5: Two-dimensional heat flow.

During two-dimensional heat flow the $t_{8/5}$ value increases by:

- Increasing heat input
- A rise in the preheat temperature
- Decreasing plate thickness

The second situation, known as three-dimensional heat flow, occurs when each weld pass represents a small part of the plate thicknesses in the joint. During this situation, heat flow is added to the thickness direction of the parent metal, compared with the situation of two-dimensional heatflow. Three-dimensional heatflow is illustrated in fig. 3.6.

In this case, the $t_{8/5}$ value increases with a rise in the:

- Heat input
- Preheat temperature

During three-dimensional heat flow, the $t_{8/5}$ value is independent of changes in the plate thickness of the joint.

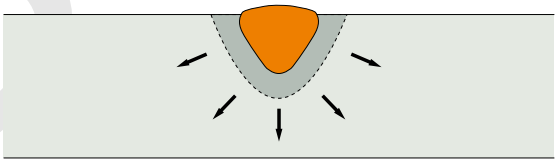
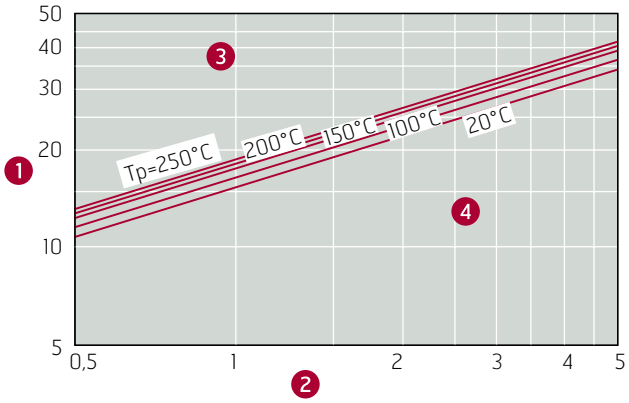


Fig. 3.6: Three-dimensional heat flow.

Fig. 3.7 illustrates the determination of whether a joint is subjected to two- or three-dimensional heat flow.



Key:

1 Plate thickness [mm]
2 Heat input [kJ/mm]
3 Three-dimensional heat flow
4 Two-dimensional heat flow
Tp = Preheat temperature [°C]

Fig. 3.7: Assessment of type of heat flow in the joint.

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The calculation of the $t_{8/5}$ value is made by:

1) Decide if the joint is subjected to two- or three-dimensional heat flow, according to fig. 3.7.
2) The heat flow in the joint is influenced by the geometry of the joint. Shape factors for different types of joints are according to table 3.2. Decide the shape factor for the joint where the unit F_2 is used for two-dimensional heat flow and the shape factor F_3 is determined for joints with three-dimensional heat flow.
3) The $t_{8/5}$ value are determined according to the diagrams or formulas for two- and three-dimensional heat flow, presented in the following context.

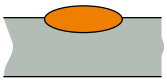
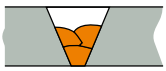
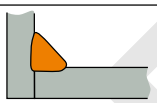
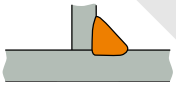
Form of weld		Shape factor F_2 two-dimensional heat flow	Shape factor F_3 three-dimensional heat flow
Run on plate		1	1
Between runs in butt welds		0.9	0.9
Single run fillet weld on a corner-joint		0.9 to 0.67	0.67
Single run fillet weld on a T-joint		0.45 to 0.67	0.67

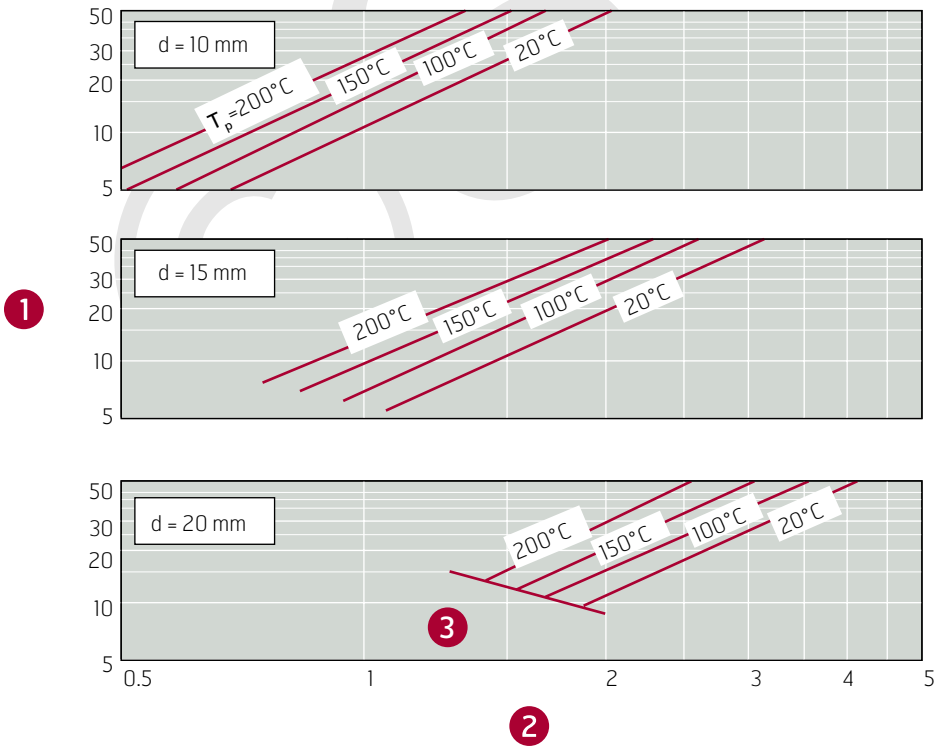
Table 3.2: Shape factors for different joint geometries.

The $t_{8/5}$ value during two-dimensional heat flow

Alt. 1:

Diagrams for three plate thicknesses (d) of a run on plate weld are specified in fig. 3.8.

The $t_{8/5}$ value for the welding situation is calculated by multiplying the shape factor F_2, determined in step 2, with the $t_{8/5}$ value for the run on plate weld.



1 Cooling time $t_{8/5}$ [s]
2 Heat Input [kJ/mm]
3 Three-dimensional heat flow
Tp =Preheat temperature [°C]

Fig. 3.8: Cooling times for run on plate joints during two dimensional heat flow.

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Alt 2:

Formula 3.1 can be used for all types of plate thicknesses subjected to two-dimensional heat flow:

$$t_{8/5} = (4300 - 4.3\,T_0) \times 10^5 \times \frac{Q^2}{d^2} \times \left(\left(\frac{1}{500 - T_0} \right)^2 - \left(\frac{1}{800 - T_0} \right)^2 \right) \times F_2$$

Formula 3.1

d:	Plate thickness [mm]
Q:	Heat input [kJ/mm]
T_0:	Initial plate temperature [°C]. If preheating is performed, this temperature is stated.
F_2:	Shape factor, se table 3.8

Alt 2:

Calculation of the $t_{8/5}$ value can be made according to formula 3.2:

$$t_{8/5} = (6700 - 5 \times T_0) \times Q \times \left(\frac{1}{500 - T_0} - \frac{1}{800 - T_0} \right) \times F_3$$

Formula 3.2

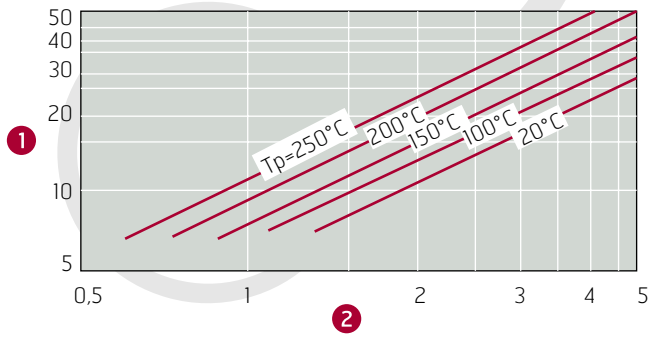
d:	Plate thickness [mm]
Q:	Heat input [kJ/mm]
T_0:	Initial plate temperature [°C]. If preheating is performed, this temperature is stated.
F_3:	Shape factor, se table 3.8

The $t_{8/5}$ value during three-dimensional heat flow

The $t_{8/5}$ value can be concluded according to the figure below for all types of plate thicknesses during three dimensional heat flow.

Alt 1:

Figures for run on plate welds are specified in fig. 3.9.



1 Cooling time $t_{8/5}$ [s]
2 Heat input [kJ/mm]
Tp = Preheat temperature [°C]

Fig. 3.9: Cooling times for run on plate joints of different plate thicknesses during three dimensional heat flow.

The $t_{8/5}$ value for the welding situation is calculated by multiplying the $t_{8/5}$ value for the run on plate weld with the shape factor F_3 that was determined during step 2.

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4.0 Hydrogen cracks

Each type of steel has its own unique characteristics regarding its resistance to different kinds of weld discontinuities in joints. Hydrogen cracks can form in different kinds of steels but they are emphasized in high strength steels including the Hardox and Weldox grades. The risk for this type of crack in joints of Hardox and Weldox grades is minimized by following the welding recommendations put forth by SSAB.

Another name for a hydrogen crack is a cold crack. As both names indicate, this type of crack is influenced by hydrogen and is formed at relatively low temperatures. Hydrogen cracks can be initiated in the HAZ and in the weld metal.

4.1 Description of crack appearance

A hydrogen crack is a delayed crack that normally forms after the welding process when the temperature in the joint drops below +200°C. A crack can initiate and develop hours after welding is finalized. Detection of potential cracks is normally made 16-48 hours after the completion of welding. The actual time depends on standard requirements or a separate agreement.

Three conditions must be present at the same time in order for hydrogen cracks to form:

1) A relatively high content of alloy elements in the steel and/or in the consumable

2) A rather high quantity of hydrogen in the joint

3) High levels of tensile stresses in the joint.

These three factors interact with each other. For example, if the hydrogen content is increased in the joint for a specific welding situation, the cracks are able to form at lower tensile stresses. Different models exist on how these three parameters interact with each other. However, no exact proven mechanism for the initiation of hydrogen cracks exists.

Hydrogen cracks can be surface breaking or exist as enclosed cracks in the joint. Examples of small hydrogen cracks are shown in fig. 4.1.

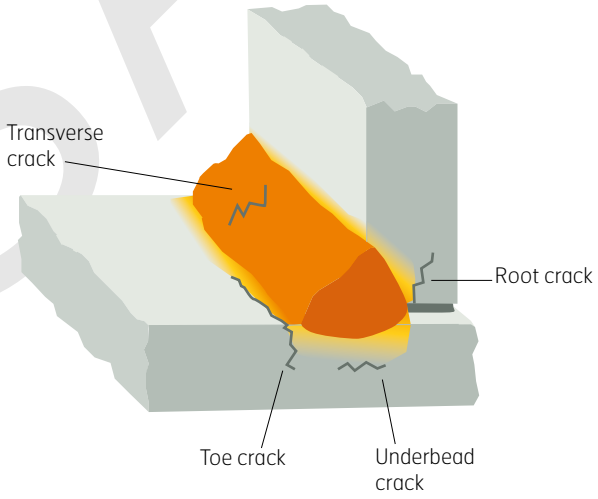


Fig. 4.1: Examples of where hydrogen cracks can form in a joint.

If a hydrogen crack is formed, it can propagate perpendicularly to the direction of the main stress that is present in the joint. A crack that is initiated in the HAZ will normally grow into the unaffected parent metal; an example is illustrated in fig. 4.2.

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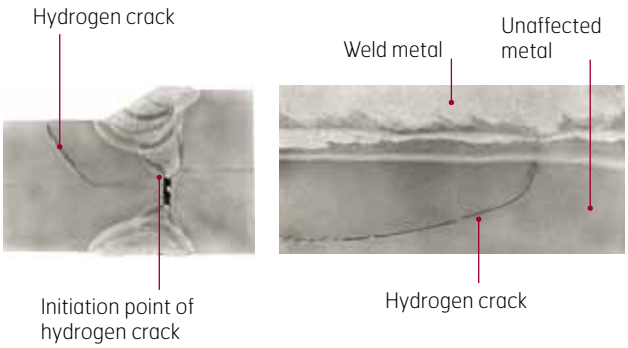


Fig. 4.2: A surface breaking hydrogen crack seen transverse to, and above the joint. The extension of these cracks can be relatively long. A length of up to several dm is not unusual, and surface breaking cracks can often be identified visually.

In general, cracks located in the weld metal are related to welding with high strength consumables. If cracks of this kind occur, the crack propagation is typically restricted to the weld metal. Their orientation is most commonly perpendicular to the direction of the joint. The cracks are usually small and narrow and they can either be embedded or surface breaking. Their presence can be hard to find with non-destructive methods due to their small size.

4.2 The influence of alloy elements in the steel

The Hardox and Weldox grades are high strength steels with relatively low levels of alloys. However, the amounts of alloy elements that are added to a specific steel are crucial to achieving the required mechanical properties in the parent metal. The alloy content, in general terms, rises with larger plate thicknesses for each steel grade. This is because higher levels of alloy elements are, in general terms, required in order to achieve the desired mechanical properties.

Certain alloys can promote the formation of hydrogen cracks. As these elements increase in content level, so does the sensitivity of the steel, making more welding restrictions necessary in order to minimize the risk of hydrogen cracks.

The recommendations for the prevention of hydrogen cracks in the Hardox and Weldox grades are based on careful evaluations performed by SSAB.

The purpose of these studies is to attain optimized recommendations with regard to the individual characteristics of each Hardox and Weldox grade.

As a compliment to the recommendations from SSAB, other general models can be used for the assessment of hydrogen cracks in different types of high strength steels. The established models describe the resistance to hydrogen cracks for a certain plate according to its carbon equivalent, which is calculated from the chemical content of the plate. A lower carbon equivalent value corresponds to a higher resistance to hydrogen cracks.

Several models for the carbon equivalent exist and each formula is derived from studies based on specific steels. The most common international carbon equivalents are according to the CET and CEV models. SSAB prefers the CET formula for the Hardox and Weldox grades because this carbon equivalent is especially designed to suit high strength steels. The CEV formula is also valid for high strength steels; however, its carbon equivalent focuses on unalloyed and low-alloyed steels with lower strengths than the Hardox and Weldox grades. Formulas for the calculation of the CET and CEV value are defined below. A synonymous name for CEV is CE. When a carbon equivalent value is calculated, the alloy content stated on the inspection certificate of the plate is to be used. All alloy elements are stated by their weight percentage in the formulas presented below.

$$CET = C + (Mn+Mo)/10 + (Cr+Cu)20 + Ni/40 \quad [\%] \quad \text{Formula 4.1}$$

$$CEV = C + (Cr+Mo+V)/5 + Mn/6 + (Ni+Cu)/15 \quad [\%] \quad \text{Formula 4.2}$$

Calculating a carbon equivalent is a mean for determining if – and to what level – preheating is needed in order to avoid hydrogen cracks. The methods for determining the preheat temperature in this context are the CET method and the CEV method which refers to the respective carbon equivalents. These two methods are described in the European Standard EN1011-2.

SSAB has special recommendations for preventing hydrogen cracks because the other methods typically

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result in measures that are too conservative for the Hardox and Weldox grades. It is very likely that this is because the methods based on carbon equivalents are more generally adapted in order to suit a wide range of steels. The minimum required preheat recommendations from SSAB are derived from evaluations with TEKKEN tests. The basis for this methodology is well recognized within welding technology.

4.3 The influence of alloy elements in unalloyed and low-alloyed consumables

The objective of adding alloys to the consumables is to attain favorable properties in the weld metal and to achieve beneficial properties during welding.

The resistance towards hydrogen cracks in the weld metal can be expressed by the carbon equivalent according to the CET method, see formula 3.2 chapter 3. The CEV method is not applicable for consumables.

When the carbon equivalent of the welded steels has a CET value that is equal to or greater than 1.03*CET value for the consumable, the minimum preheat temperature is set by the requirements for the steels. Unalloyed and low-alloyed consumables with a yield strength of less than 700 MPa in the all weld metal normally have a carbon equivalent that fulfils this criterion.

The Weldox grades can be welded with high strength consumables that have a yield strength of 700 MPa and above. The CET value for the steels in these cases are often below 1.03*CET value for the consumables. During this situation, the preheat temperature is adapted to fulfill the requirements for the steels as well as for the consumable being used.

4.4 Hydrogen content in the joint

During arc welding, the joint is always exposed to some level of hydrogen and the weld metal receives a larger amount of hydrogen in comparison to the surrounding parent metal.

Sources of hydrogen are related to:

- The characteristics of the consumable, and how it is handled.
- Welding environment issues.
- The hydrogen content in the steel itself and in its shop primer, when applied.

Hydrogen pickup is feasible because the heated, molten weld metal largely dissolves the hydrogen. The solubility of the hydrogen decreases as the temperature drops when the weld metal is in a solid state. The dissolved hydrogen diffuses, via the HAZ, to both the unaffected parent metal and the surrounding air. If just a fraction too much of the diffusible hydrogen remains in the HAZ or the weld metal, there will be a risk for hydrogen cracks in these locations.

A crucial issue is, therefore, to keep the hydrogen level in the joint sufficiently low. Requested maximum levels of hydrogen at these locations can be obtained by following the recommendations put forth by SSAB.

Hydrogen levels in unalloyed and low-alloyed consumables

The hydrogen in the weld metal that diffuses to its surroundings is called the diffusible hydrogen content. The part of the hydrogen that is dissolved by the weld metal is called the residual hydrogen content. Consumables for the Hardox and Weldox grades are recommended to have a diffusible hydrogen level that corresponds to ≤ 5ml H_2/100 g of weld metal.

The implicit meaning of hydrogen content refers to the diffusible amount of hydrogen for the given consumable. Further information regarding hydrogen content in different types of consumables is described in chapter 6.

The storage and handling of the consumables should be in accordance to the manufacturer in order to avoid excessive hydrogen pickup. The most stringent requirements regarding the handling of consumables

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normally apply to consumables for MMA welding and for the flux used in SAW.

Welding environment issues

Contaminates present in the weld area can often contain hydrogen. Consequently, it is important to keep the joint clean prior to and during welding. Substances like water, oil and grease should be removed from the joint before welding. Also, make sure that the welding equipment is working properly so that it does not add additional hydrogen to the joint. Welding in a humate climate can also cause hydrogen pick-up. At these situations, a preventive measure is mentioned in chapter 4.5.

Hydrogen presence in the steel and its primer

Steels themselves contain hydrogen to some extent. The Hardox and Weldox grades are manufactured in a manner that results in very low levels of hydrogen in the plates.

When the shop primer is left on the joint, it contributes to a slightly increased fraction of hydrogen in this section joint. However, the hydrogen from the primer is at such a low level that it does not influence the recommendations from SSAB for the prevention of hydrogen cracks.

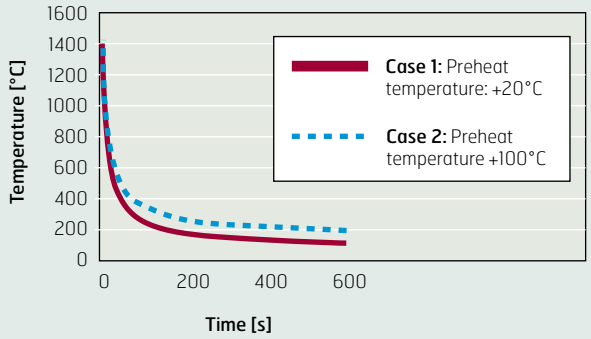
4.5 Preheat temperatures during welding of the Hardox and Weldox grades

Preheating is necessary in some situations to remove hydrogen from the joint and minimize the risk for hydrogen cracks.

The hydrogen content is, as mentioned before, higher in the weld metal than in the parent metal. Preheating facilitates a more rapid migration of the diffusible hydrogen from the weld metal, via the HAZ, to the unaffected parent metal as well as the air surrounding the joint. The direction of the hydrogen diffusion is determined by the differences of hydrogen concentration in the joint compared to that in the unaffected parent metal and the surrounding air. There is a natural driving force to equalize these concentration differences of hydrogen heat. Heat in form of preheating accelerates this process.

The rate at which hydrogen diffuses from the weld metal in a solid state and from the HAZ rises with increased temperatures.

An important function of preheating is to slow down the cooling time significantly between 400°C and 200°C. This effect is exemplified in the following two cases presented in fig. 4.3. The welding conditions, including the type of joint being welded, are the same in both cases, with the exception that preheating is only performed in case 2.



	Case 1	Case 2
Type of joint	Single-V butt joint	Single-V butt joint
Pt*	5 mm	5 mm
Q	0,8 kJ/mm	0,8 kJ/mm
Welding process	MAG	MAG
$t_{8/5}$	16 s	23 s
Preheat temperature	20°C	100°C

*Plate thicknesses throughout the joint.

Fig. 4.3: The thermal cycles in the joint due to welding with and without preheating. The location in the HAZ is situated closest to the weld metal.

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Preheat levels for the Hardox and Weldox grades

The minimum recommended preheat temperatures for the Hardox and Weldox grades are according to fig. 4.5. Unless otherwise stated, these values are applicable to welding with unalloyed and low-alloyed consumables.

The conditions for application are that:

- The recommendations are based on the single plate thickness of the joint, which is the largest plate thickness in the joint, see fig. 4.4.
- All preheat temperatures in the diagram are valid for welding with heat inputs of 1.7 kJ/mm or higher.
- The CET value for the steel is equal or above 1.03*CET value for the consumable. For other situations with unalloyed or low-alloyed consumables, apply a minimum preheat temperature that fulfils the requests from the included steels in the joint as well as for the consumable being used.
- When different steel grades are welded together, the plate with the most stringent requirements regarding preheat levels determines the minimum and maximum preheat temperature.

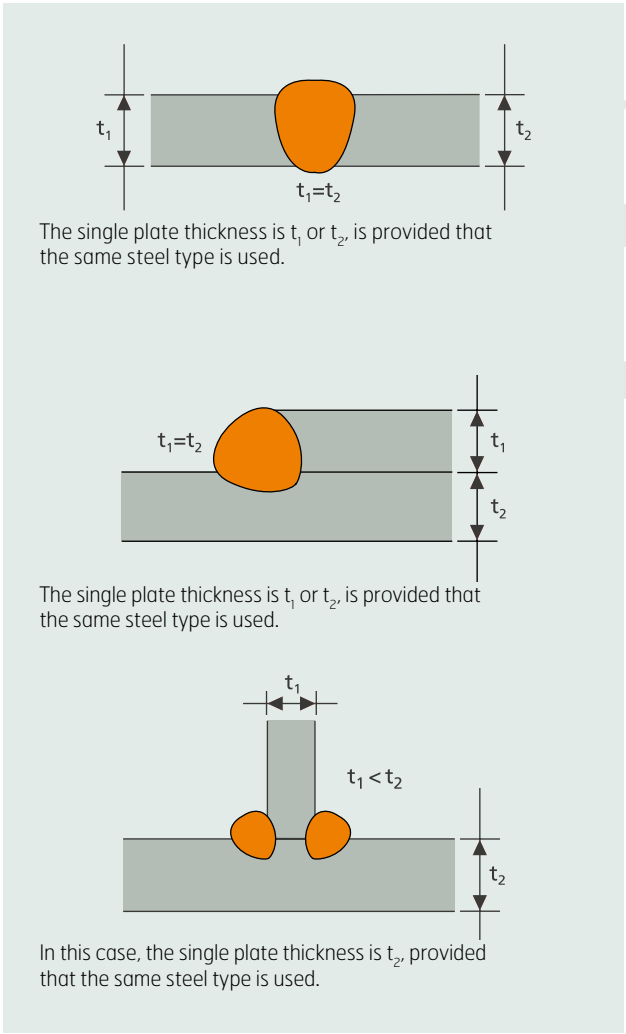


Fig. 4.4: Definition of the single plate thickness.

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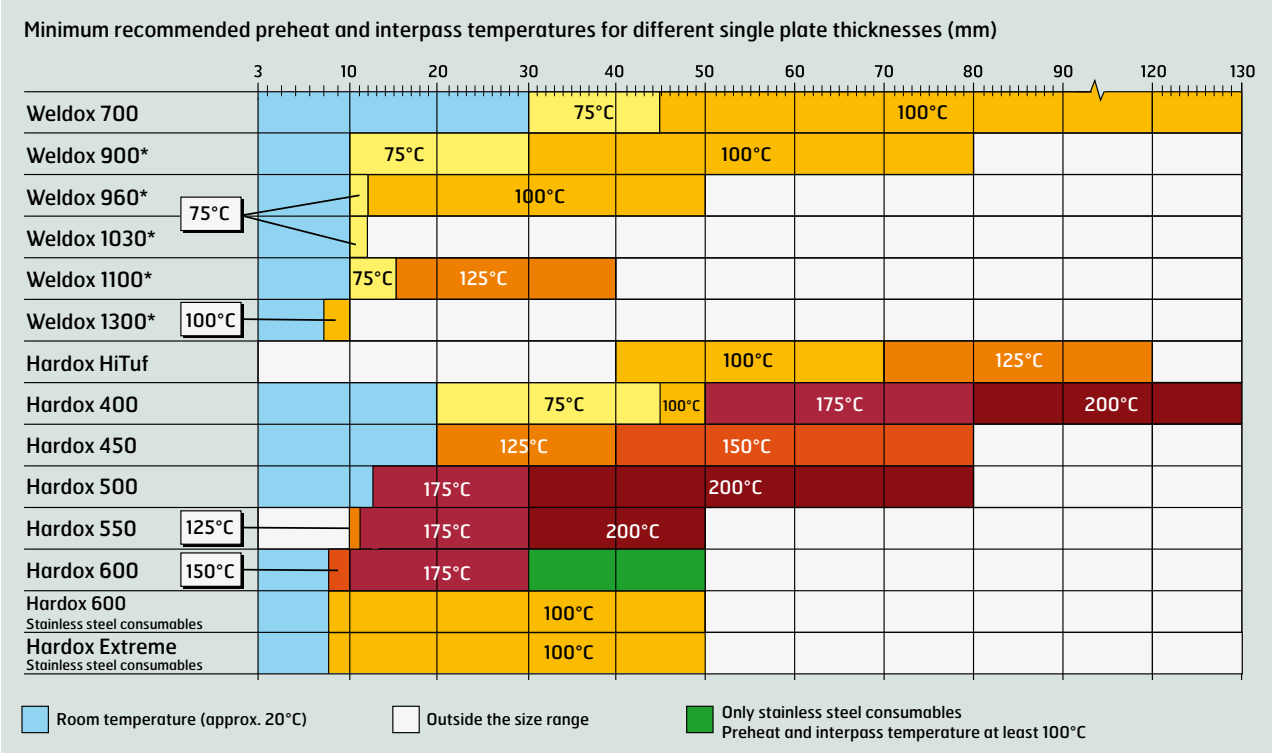


Fig. 4.5: Recommended preheat levels for Hardox and Weldox grades.

The maximum preheat levels are specified in order to achieve beneficial mechanical properties in the joint, according to table 4.1.

Due to the continuous development of the Hardox and Weldox grades, the preheat temperatures may be adjusted over time. Updated information is found in the latest versions of this Welding handbook or the Welding brochure at www.ssab.com.

Maximum recommended interpass temperature

Weldox 700**	300°C
Weldox 900**	300°C
Weldox 960**	300°C
Weldox 1030	200°C
Weldox 1100	200°C
Weldox 1300	200°C
Hardox HiTuf**	300°C
Hardox 400	225°C
Hardox 450	225°C
Hardox 500	225°C
Hardox 550	225°C
Hardox 600	225°C
Hardox Extreme	100°C

** Interpass temperatures of up to approx. 400°C can be used in certain situations. In such cases, use WeldCalc.

Table 4.1: Recommended maximum preheat levels for Hardox and Weldox grades.

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The minimum preheat temperature for welding with all types of recommended consumables is raised by 25°C, compared to fig. 4.5, for each of the following situations.

- When welding is performed with heat inputs in the interval of 1.0-1.6 kJ/mm.
- For joints with very high levels of restraint.
- For temperatures of below +5°C in the surrounding air and/or in the plates.
- When welding is performed in a very humid climate.

Contact SSAB if the latter recommendations lead to a preheat temperature above the maximum allowable level.

Preheat temperatures for welding with heat inputs < 1.0 kJ/mm can be calculated by, for example, using the software WeldCalc, developed by SSAB, or adopting a relevant standard for this measure.

Preheat requirements for low-alloyed, high strength consumables

When necessary, the minimum preheat temperatures for low-alloyed, high strength consumables can be calculated or estimated according to one of the following procedures:

- Calculate the minimum preheat temperature according to the CET method, which is described in the European Standard EN 1011-2. The minimum preheat temperature for the consumable in this standard is based on the CET value according to formula 4.2 increased by 0.03 percentage units. Example: If the calculated CET value for the consumable is 0.40 % according to formula 4.2 the minimum preheat temperature for the consumable is based on a CET value of 0.43%. The chemical content of the consumable can be attained from the datasheet for the consumable.
- SSAB has general estimates for minimum preheat temperatures for consumables with Rp0,2≥700 MPa according to table 4.2.

Single plate thickness in the joint [mm]	Min. preheat temperature [°C]
≤ 10,0	125
10,1 – 20,0	140
20,1-40,0	175
>40,0	190

Table 4.2: Estimated preheat levels for high strength consumables. SSAB does not take formal responsibility of these temperatures since they depend of the individual characteristics of the consumable being used.

The microstructure of high strength weld metal includes martensite. When the preheat temperature is too high, the desired mechanical properties of the weld metal can degenerate due to changes in the microstructure. If the manufacturer of the consumable does not state a the maximum preheat temperature, SSAB has a general estimated maximum preheat temperature of 210°C for these types of consumables.

4.6 Stainless steel consumables

A very high resistance to hydrogen cracks can be attained by welding the Hardox and Weldox grades with stainless austenitic consumables AWS 307 or AWS 309.

In these cases, the weld metal will include an austenitic microstructure that dissolves hydrogen to a larger extent than unalloyed and low-alloyed consumables. When the hydrogen in the weld metal is dissolved, the result is a high resistance towards hydrogen cracks both in the weld metal and in the HAZ.

This high resistance to hydrogen cracks means that preheat temperatures, that is a temperature above room temperature (approximately +20°C), in the joint as well as in the surrounding air, can be avoided for all of the Hardox and Weldox grades with the exception of Hardox 600 and Hardox Extreme.

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The two latter steel grades require both stainless austenitic consumables and the use of preheating during welding of certain plate thicknesses, in accordance with the section titled 4.9 Preheat levels for the Hardox and Weldox grades.

AWS 307 consumables are preferred, if possible, since they have a higher resistance to hot cracks than AWS 309.

4.7 The preheat performance

The use of preheating elements, shown in fig. 4.6 is often the best method for preheating since it facilitates uniform heating of the area in and around the joint. An alternative method is to heat the area with a gas torch. However, extra care must be taken with the latter method since it tends to give a more unevenly distributed preheat temperature in the joint.

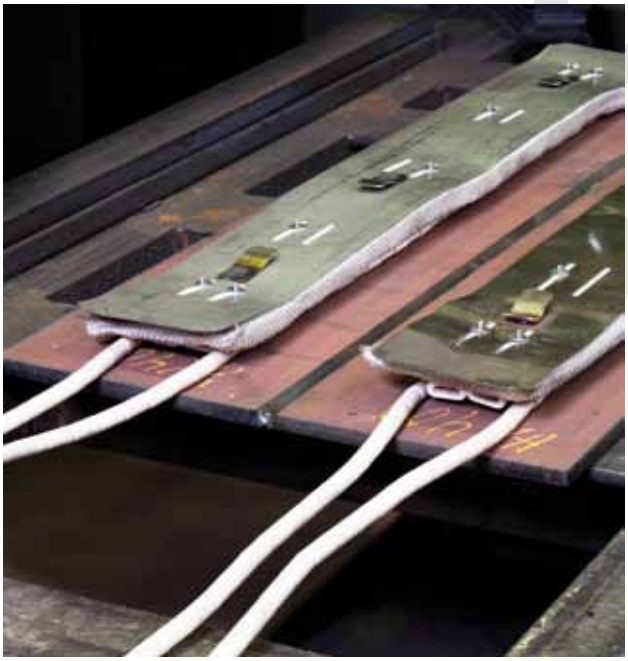


Fig. 4.6: Preheating elements.

Preheating is performed on each side of the joint, covering an area of at least 100 mm from the center of the joint. The preheat temperature is assessed 75 mm from the midpoint of the joint, illustrated in fig. 4.7, in order to achieve an even heat distribution throughout the plate thicknesses. The measurement of preheat temperature can be carried out after a soaking period of at least 2 min/25 mm of the single plate thickness.

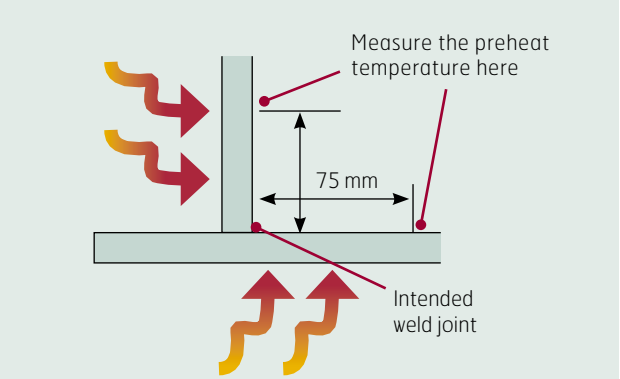


Fig. 4.7: Measure the temperature of the thickest plate in the joint. If the plate is 25 mm thick, measure the temperature 2 minutes after heating. If the plate is 12.5 mm thick, measure the temperature after 1 minute, etc. The interpass temperature can be measured in the weld metal or in the immediately adjacent parent metal.

4.8 Interpass temperatures

The requirements for the interpass temperature of multi-pass joints is the same as for the preheat temperature. The interpass temperature is measured in the weld metal or the immediately adjacent parent metal. The previous welding sequence may, in this case, produce an elevated temperature that fulfils the preheat requirements. If so, the next weld pass can be made directly after the temperature measurement.

When additional preheating is needed between weld sequences, it is carried out in the same way as for preheating prior to the first weld pass.

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4.9 Post-weld heat treatment

A post-weld heat treatment of the joint can be performed in order to increase the resistance to hydrogen cracks further. However, it is not required, and the recommendations from SSAB regarding preheat temperatures are based on cooling the joint in air without any type of post-weld heat treatment. If this operation must be carried out, contact SSAB for information regarding the particular situation.

4.10 Practical recommendations for removal of hydrogen from of the joint

It can be advantageous to make the weld passes directly one after the other when welding multi-pass joints that require preheating. This allows higher productivity since the heat generated from the previous weld pass can be utilized to reduce – or eliminate – the need for further preheating.

An even higher resistance to hydrogen cracks can easily be attained if the joint is allowed to cool slowly after welding. A longer cooling time facilitates further hydrogen diffusion from the joint. This can be achieved by, for example, placing a fireproof thermal isolation blanket over the joint after the completion of the welding performance.

4.11 Tensile stresses in the HAZ and the weld metal

The tensile residual stresses brought about by welding are usually high, making them an important factor in minimizing the risk of hydrogen cracks in the joint. These stresses arise from the thermal heat treatment during welding.

In order to get a schematic picture of the residual stresses caused by the thermal heat treatment, we can look at an example that illustrates the formation of residual stresses longitudinal to the joint. In this case, a butt weld is welded with a single pass technique.

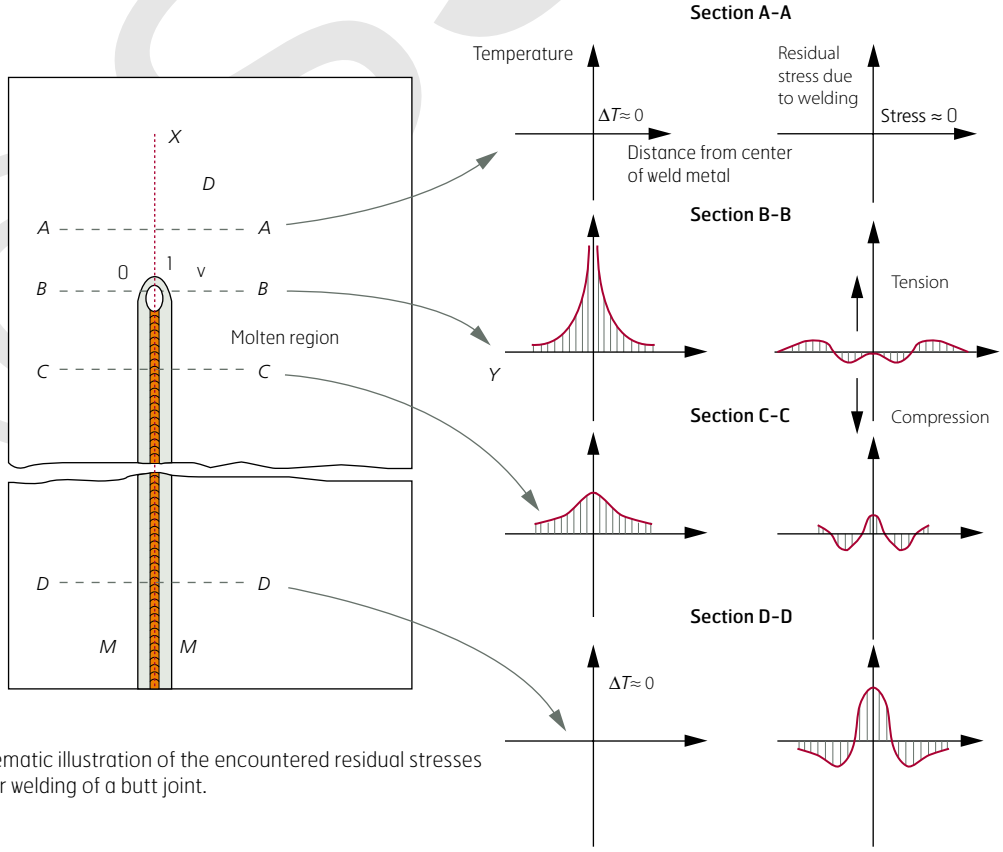


Fig. 4.8: A schematic illustration of the encountered residual stresses during and after welding of a butt joint.

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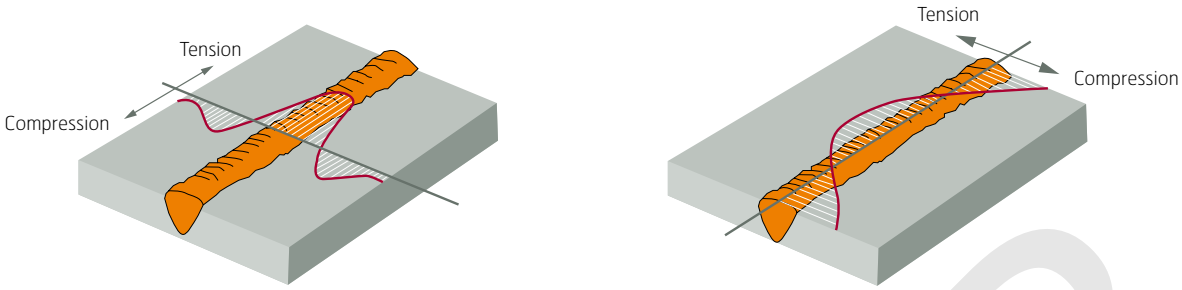


Fig. 4.9: Residual stresses in and around a butt joint, viewed longitudinal and transverse to the direction of the joint.

The weld metal is first heated to a molten state by the welding process in section B-B in fig. 4.8. The parent metals adjacent to the weld pass in this section expand as the temperature increases. The strength of the weld metal at this temperature is negligible and it is not as strong as the surrounding parent metal. This causes the weld metal to be plastically deformed by the parent metals. Due to the high temperatures, the stresses in the weld metal and its surroundings are very low at this stage.

During the cooling cycle of the welding process, when the weld metal transforms from a liquefied state to a solid state, it has a natural tendency to shrink. However, the surrounding parent metals in the joint counteract this movement. The strength of the weld metal increases gradually as its temperature decreases. As a result, there are interactions between the weld metal and the parent metals, causing very high residual tensile stresses in the weld metal and the weld metal creates compressive residual stresses in the parent metals – on both sides of the weld metal – which is illustrated in fig. 4.9.

Residual stresses are also formed transverse to the direction of the joint and in the through thickness direction of the joint. A criterion for the residual stresses in the joint is that their levels are maximized to the local yield strength in the joint. The outcome of the residual stresses transverse to the joint is illustrated in fig. 4.9.

As the level of restraint for a joint is raised, the more it will promote increased levels of residual stresses in the welded structure. However, the residual stress level is always maximized to the local yield strength in the joint.

Even though residual stresses occur during welding, the risk for hydrogen cracks is minimized, in all structures produced with the Hardox and Weldox grades, if the recommendations from SSAB are followed.

The exact measure of the levels and distributions of residual stresses for a joint are seldom analyzed in detail. They are complex and depend on the appearance of the joint and how the welding performance is carried out. A more detailed evaluation of the residual stresses for a particular joint can be preformed with, for instance, a computerized FEM (fenite element method) study.

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4.12 Measures that reduce the residual stresses in joints during welding

There are many measures that can be taken in order to reduce the levels of residual stresses in the joint. The measures discussed in this context are those that are recommended in order to minimize the risk for hydrogen cracks.

- Large root gaps facilitate stress concentrations. SSAB recommends that the size of the root gap in joints made in the Hardox and Weldox grades should be a maximum of 3 mm in order to reduce stress concentrations, see fig. 4.10.

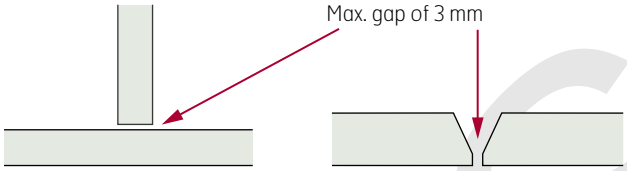


Fig. 4.10: Allowable gap sizes in joints.

- The residual stresses from a welding procedure can be lowered if start and stop sequences are not placed directly in the corners. If possible, SSAB recommends that start and stop sequences are made 50 mm-100 mm away from a corner of a joint, see fig. 4.11.

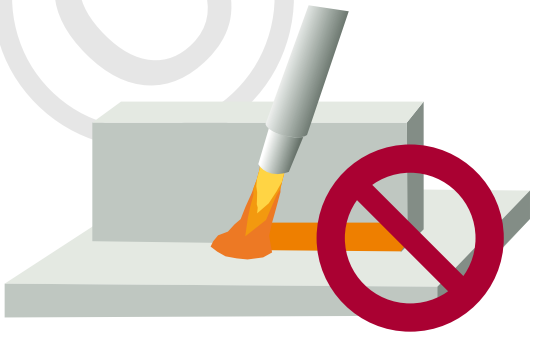


Fig. 4.11: Avoid start and stop sequences in corners when possible.

- Tack welds and root passes are more sensitive to hydrogen cracking than other passes. This is because there are often very high residual stresses at these locations. It is, therefore, essential that special attention is paid to our recommendations for these types of welds. When tack welding is performed, it is recommended that each individual tack is at least 50 mm long in order to reduce the stresses in the joint.

4.13 Recommendations for consumables for welding of the Hardox grades

- Joints made in the Hardox grades are welded using consumables with yield strengths of up to approximately 500 MPa. This requirement can be fulfilled when welding with unalloyed, low alloyed and stainless consumables. The reason for this limitation is that it further limits the residual stresses since they can not exceed the local yield strength in the joint. The Weldox grades can, however, be welded using consumables with yield strengths higher than 500 MPa since the measures for minimizing the risk for hydrogen cracks is, to some extent, less compared to the case for the Hardox grades.

4.14 A suitable measure for welding a multi-pass joint in the Weldox grades

- The first few weld passes in a multi-pass joint normally have a higher sensitivity towards hydrogen cracks than the remaining passes. When welding joints in Weldox 700-Weldox 1300, it is particularly beneficial to weld with consumables of different strengths. Tack welds and the first passes can be welded with low strength consumables and then high strength consumables can be used for the remainder of the passes. This technique increases the resistance to hydrogen cracks since the residual stresses are lowered for the welding passes that are most prone to hydrogen cracks, see fig. 4.12. Note that this kind of measure in not mandatory but it results in an extra high resistance to hydrogen cracks.

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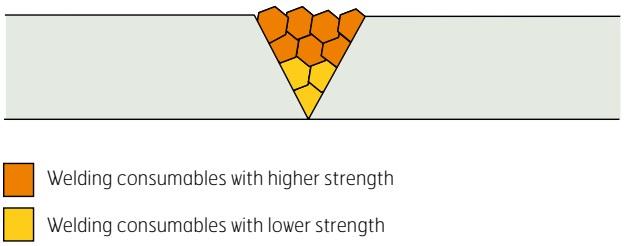


Fig. 4.12: A multi pass joint welded with consumables of different strengths.

4.15 Critical size and acceptance levels of hydrogen cracks

Hydrogen cracks can be accepted to a certain extent in some structures. In these cases, the critical crack size and acceptance levels can be calculated according to standard regulations. In other structures, hydrogen cracks are not allowed to be present. When the international standard EN ISO 5817 is followed, hydrogen cracks in a structure are not accepted in any weld class. The normal recommendation from SSAB is to remove all hydrogen cracks since assessment of potential hydrogen cracks is not evaluated for most welded structures.

4.16 Summary of measures to minimize the risk for hydrogen cracks in joints

In this chapter, the different issues regarding the nature of hydrogen cracks and how to minimize their risk are discussed.

A compilation of these measures is found below:

- Keep the hydrogen level in the joint sufficiently low. Recommended measures in this respect are to:
  - Use consumables with low diffusible hydrogen contents of up to 5 ml H_2/100g of weld metal.
  - Keep the joint clean from contaminations like water, grease and oil.
  - Follow the preheat recommendations described in the section: Preheat levels for the Weldox and Hardox grades in this chapter
  - Store opened packages of consumables according to the directions from the manufacturer.
- Avoid excessive levels of residual stresses in the joint. Recommended measures in this respect are to:
  - Use consumables with the appropriate yield strengths according to the recommendations from SSAB.
  - Do not use a welding procedure that produces unnecessarily high residual stresses in the joint. *Suitable measures are:*
    - To keep the gap size in the joint to a maximum of 3mm.
    - To perform start and stop welding sequences at least 50 mm-100 mm away from corners, if possible.
    - That the minimum length of a tack weld in the joint shall be 50 mm each.
    - That it is particularly beneficial to weld with consumables of different strengths in order to avoid hydrogen cracks in multi-pass joints in the Weldox grades. Tack welds and the first passes are welded with low strength consumables and high strength consumables are then used for the remainder of the passes.

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5.0 Properties of the heat-affected zone

As mentioned earlier in chapter 3, the heat-affected zone (HAZ) in the joint has mechanical properties and microstructures that are different from the unaffected parent metal. The mechanical properties that are affected are toughness, strength and hardness.

The requirements and characteristics of the mechanical properties in the joint are mostly emphasized for the Weldox grades because they are high strength construction steels. The properties in the HAZ of these steels are designed to attain a high standard of well-defined mechanical properties. Occasionally, structures welded with the Weldox grades are also required to meet extraordinarily high demands regarding the mechanical properties in the joint. On these occasions, the properties in the HAZ can be further improved by optimizing the welding performance beyond the normal welding recommendations.

The Hardox grades are also developed to achieve favorable properties in the HAZ. However, these properties are adapted to suit structures subjected to wear where the exact levels of toughness and strength in the joint are typically of less importance than those in the Weldox grades.

This chapter will discuss the issues related to the properties of the HAZ in the Hardox and Weldox grades and how to attain advantageous properties in this area. More information regarding the individual properties for each of the microstructures mentioned are found in chapter 21.

5.1 The different parts of the HAZ

The welding thermal cycle affects different parts of the HAZ in different ways. Depending on the distance from the weld metal, each part of the HAZ is subjected to a unique heat treatment. This creates different microstructures and mechanical properties within the HAZ. As a consequence, the HAZ can be divided into four different principal zones, with each zone sharing similar properties. They are the coarse grain zone, the normalized zone, the partially transformed zone and the annealed zone, which are illustrated for a butt joint in fig. 5.1.

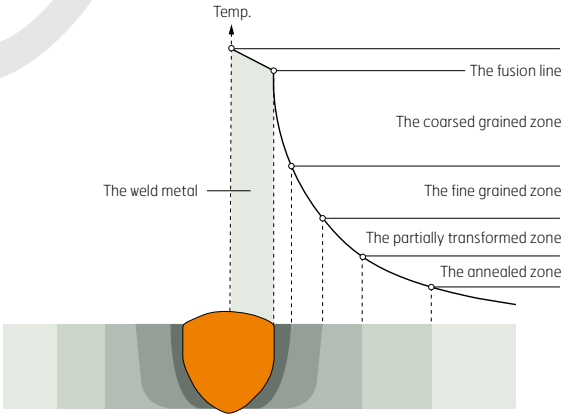


Fig. 5.1: The different parts of the HAZ.

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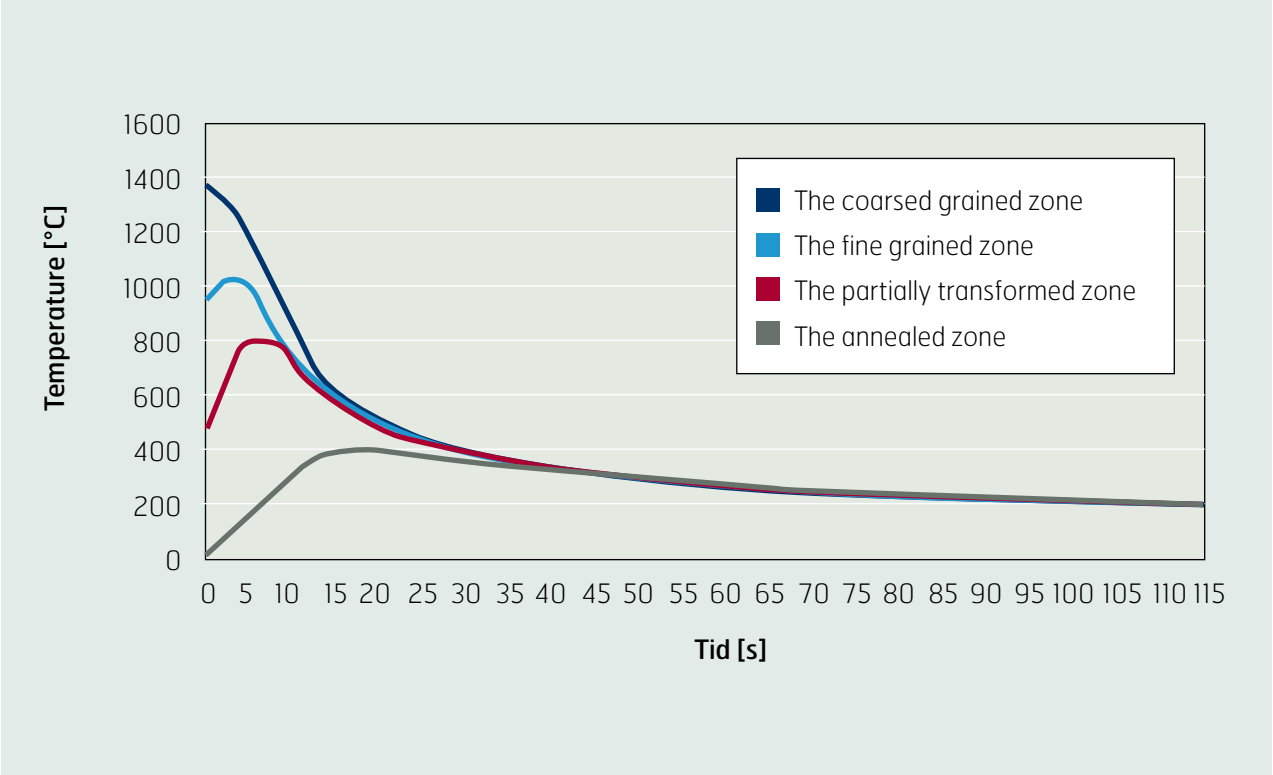


Fig. 5.2: The thermal cycles during welding of a 6 mm butt joint with a Weldox/ Hardox grade. The welding parameter in this case is: $t_{8/5}$:10 s.

Thermal cycles for the different zones in the HAZ are shown in fig. 5.2 for welding of a butt joint.

There are general characteristics for the thermal heat treatments in each zone of the HAZ that apply to all welding performances. One is that the heating and cooling rate decreases as the distance from the weld metal increases. Another being that the peak temperature, within each zone of the HAZ, increases with a smaller perpendicular distance to the weld metal.

The exact outcome of the thermal cycles in each part the HAZ depends on the location in the HAZ, the joint geometry, the welding parameters applied and the temperatures of the plates in the joint prior to welding.

The coarse grained zone

The coarse grain zone of the HAZ (CGHAZ) is the section located closest to the weld metal. During welding, the peak temperatures within this area reach approximately 1500°C down to about 1100°C.

The size of the grains grows substantially when the thermal cycle reaches temperatures of approximately 1100°C and above. The grains remain enlarged after cooling to ambient temperature. The individual sizes of the grains vary where the largest grains are present in the area with the highest peak temperature, in other words the section closest to the weld metal. The grain sizes in the CGHAZ are often around 5-15 times the grain sizes of the unaffected parent metal at ambient temperature. Their ability to grow depends on the chemical composition of the steel. Reduced heat input in a joint leads to a narrower coarse grained zone with smaller grains.

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The period of time during welding when the CGHAZ reaches temperatures between 1500°C -1100°C is relatively short, which causes this zone to be narrow in relation to other parts of the HAZ. The microstructure in the HAZ at maximum temperatures is austenite. During the cooling process, when room temperature is reached, the microstructure typically transforms to one, or a combination, of martensite or bainite. Generally, with an enlargement of grains comes a reduction in toughness in the parent metal as well as the HAZ. As a consequence, the coarse grain zone normally has the lowest toughness in the HAZ.

The fine grained zone

The fine grained zone is subjected to maximum temperatures in the range of 1100°C and 900°C during welding. This leads to small grain sizes in this section after the welding performance, which contributes to beneficial toughness values in the joint. The microstructure is considered as austenite at the peak temperature. At ambient temperature, the microstructure transforms to one, or a combination, of martensite or bainite. Another name for this zone is the normalized HAZ.

The partially transformed zone

The welding thermal cycle leads to a peak temperature between ~900°C and 700°C in this zone. During the peak temperature, the microstructures consist of austenite, tempered martensit and in some cases bainite. After cooling to room temperature, this zone typically includes one or more of the microstructures tempered martensite, martensite and bainite. The grain sizes remain relatively small during and after the welding performance. Their sizes at ambient temperatures are typically somewhat larger than in the fine grained HAZ.

This part of the HAZ is also called the intercritical HAZ. The toughness in this zone can be relatively low.

The annealed zone

The annealed zone is the outer part of the HAZ where the temperature has peaked below approximately 700°C. At these temperatures, there is not a change in the microstructure or grain size during welding even though carbide precipitations of small, hard particles can take place. The typical microstructures at room temperature are tempered martensite, bainite or a combination of the two. The toughness in this section can be somewhat low.

5.2 The width of the HAZ

The width of each of the four regions in the HAZ depends on the heat input and the preheat level for a specific welding procedure, which is illustrated for a butt joint in fig. 5.3.

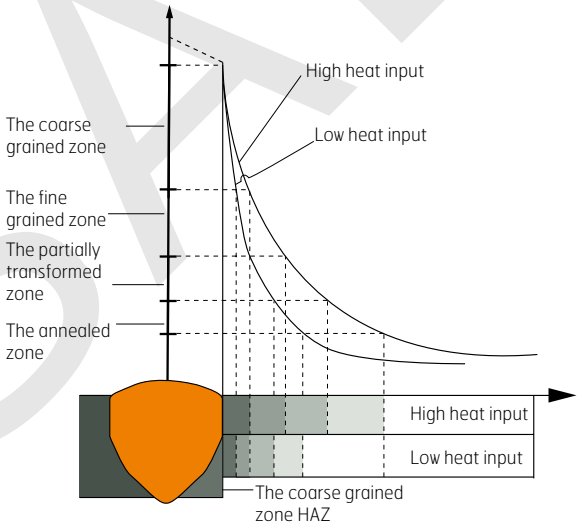


Fig. 5.3: The extension of the HAZ at different heat inputs.

The hardness values in joints of Hardox and Weldox

The hardness values in the HAZ for quenched/quenched and tempered steels have unique characteristics.

In the Hardox and Weldox grades, the peak hardness in the HAZ is located immediately adjacent to the weld metal. With further distance from the weld metal, the hardness value decreases down to its minimum level. The hardness values then gradually increase in the HAZ until they reach the values of the unaffected parent metal.

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The area in the HAZ with the lowest hardness is called the soft zone. SSAB defines the soft zone as the width of the HAZ where the hardness values are up to 90% of the unaffected parent metal.

The hardness properties in the HAZ follow two general patterns. One relates to Weldox 1030-1300 and the Hardox grades except Hardox HiTuf and the other is valid for Weldox 700-960 and Hardox HiTuf.

Hardness properties in the HAZ for Weldox 700-960 and Hardox HiTuf

The parent metals of Weldox 700-960 and Hardox HiTuf are quenched and tempered steels that are subjected to tempering at temperatures in the range of 550°C-700°C during manufacturing.

The hardness levels in the HAZ are only significantly changed for the sections where the peak temperature during welding has exceeded the maximum tempering temperature. Consequently, the soft zone in the HAZ is narrow for these steel grades, which is illustrated in fig. 5.4.

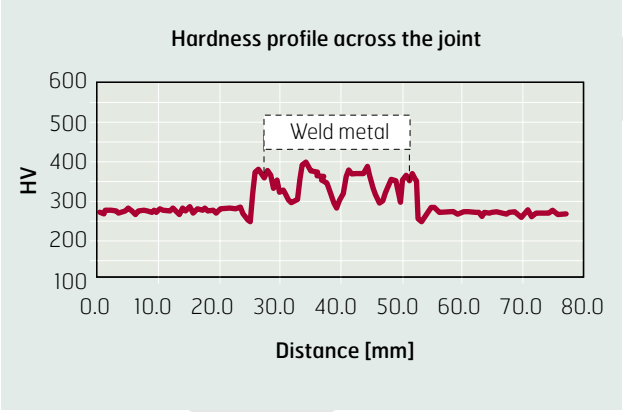


Fig. 5.4: Hardness profile for single-V butt joint of Weldox 700 welded with MAG. The plate thickness is 25 mm throughout the joint. The heat input (Q) is 0.9 kJ/mm and the $t_{8/5}$ value is 5 s in this case.

Hardness properties in the HAZ for Weldox 1030-1300 and all Hardox grades except Hardox HiTuf. Weldox 1030-1300 and all Hardox grades except Hardox HiTuf are produced as either quenched or quenched and tempered steels. When tempering is carried out, the peak temperature reaches approximately 250°C.

As for Weldox 700-960, the welding process notably influences the hardness values in the areas of the HAZ that are exposed to peak temperatures above the tempering temperature. The width of the soft zone becomes comparatively wide for these steels, according to fig. 5.5. The quenched steels have a similar appearance in the HAZ.

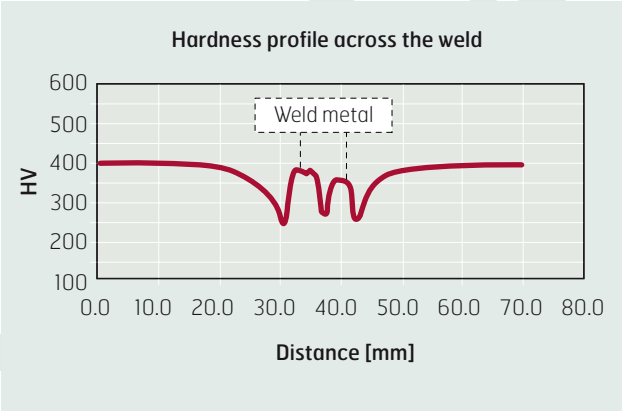


Fig. 5.5: Hardness profile for a MAG welded single-V butt joint in Weldox 1030. Plate thickness throughout the joint: 9 mm, Heat input :0.6 kJ/mm, $t_{8/5}$ value: 6 s.

The effect of heat input with regard to the hardness values in the HAZ

The width of the soft zone will, to some extent, decrease with reduced heat inputs. This is true of all Hardox and Weldox grades. The fig. 5.6 illustrates this effect for a butt joint in Hardox 400.

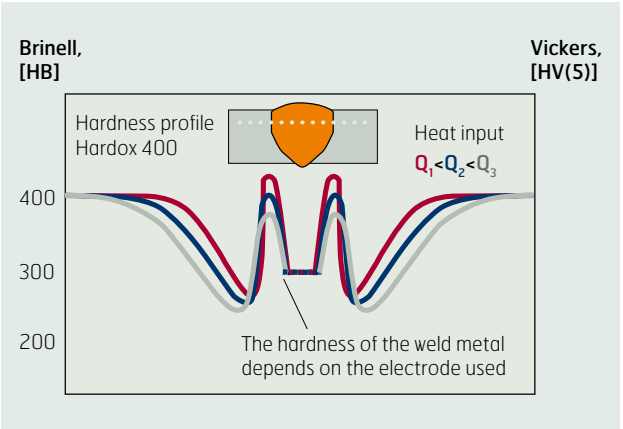


Fig. 5.6: Schematic hardness profile values transverse to a joint of Hardox 400 welded with different heat inputs.

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Effects of the chemical composition in the steel

The level of alloy elements in the Weldox and Hardox grades influences the character of the soft zone. Each individual alloy element contributes to a different extent. Generally, the soft zone narrows as the carbon equivalent of the steel increases.

Welding with a single-pass sequence compared to a multi-pass sequence

Welding a joint with more than one pass subjects the HAZ to different types of heat treatments since the weld passes are superimposed on to one another. As a result, the microstructures in the HAZ can change after each weld pass and combinations of microstructures from the different weld sequences can occur. A location in the HAZ, for example, can be characterized as a tempered coarse grained zone. However, the Hardox and Weldox grades are designed to attain the beneficial properties in joints, accounted for in this welding handbook, for both single-pass and multi-pass techniques.

5.3 Recommended levels of heat input and $t_{8/5}$ values

The heat input will affect the mechanical properties in the joint. SSAB has stated suitable levels of heat inputs for welding of the Hardox and Weldox grades. The basis for the stated recommendations regarding heat input, stated in fig. 5.7, for the Weldox and Hardox grades are that:

- The typical minimum impact toughness in the HAZ should be at least 27 J measured at -40°C for each Weldox grade.
- The strength in the joints of Weldox grades shall be on a very high level. Further information about typical strength in joints is found in TechSupport no. 60.
- The recommendations for the heat input are based on welding with the minimum preheat temperatures stated in chapter 4.
- The recommendations regarding heat input are valid for the conventional welding processes MAG, MMA, SAW and TIG. If other welding methods are to be used, contact SSAB for assistance regarding suitable heat inputs.

Due to the less stringent requirements for joints in the Hardox grades, the recommended values for the heat input are approximate.

During multi-pass welding, the interpass temperatures in the joint occasionally can be higher than the minimum preheat temperature. When this situation occurs, one can either let the joint cool to the minimum preheat temperature before welding the next pass or perform the subsequent pass at temperatures higher than the minimum preheat temperature. Welding with preheat temperatures that are above the minimum requirements means that the maximum heat input is reduced. Fig. 5.8 illustrates the recommended heat inputs for the Weldox grades at two different preheat temperatures.

Recommended heat inputs for other preheat temperatures can be determined conveniently by using the WeldCalc software developed and supplied by SSAB.

In the recommendations presented in fig. 5.7-fig. 5.8, the heat inputs correspond to $t_{8/5}$ values according to table 5.1 for the Weldox grades.

Steel grade	Recommended $t_{8/5}$ intervals*
Weldox 700	5-25 s
Weldox 900	5-20 s
Weldox 960 - Weldox 1300	5-15 s

* Valid for a typical min. impact toughness of 27 J at -40°C in the HAZ.

Table 5.1: Recommended $t_{8/5}$ intervals.

There are no $t_{8/5}$ recommendations for the Hardox grades because they have fewer restrictions regarding toughness and strength in the unaffected parent metal.

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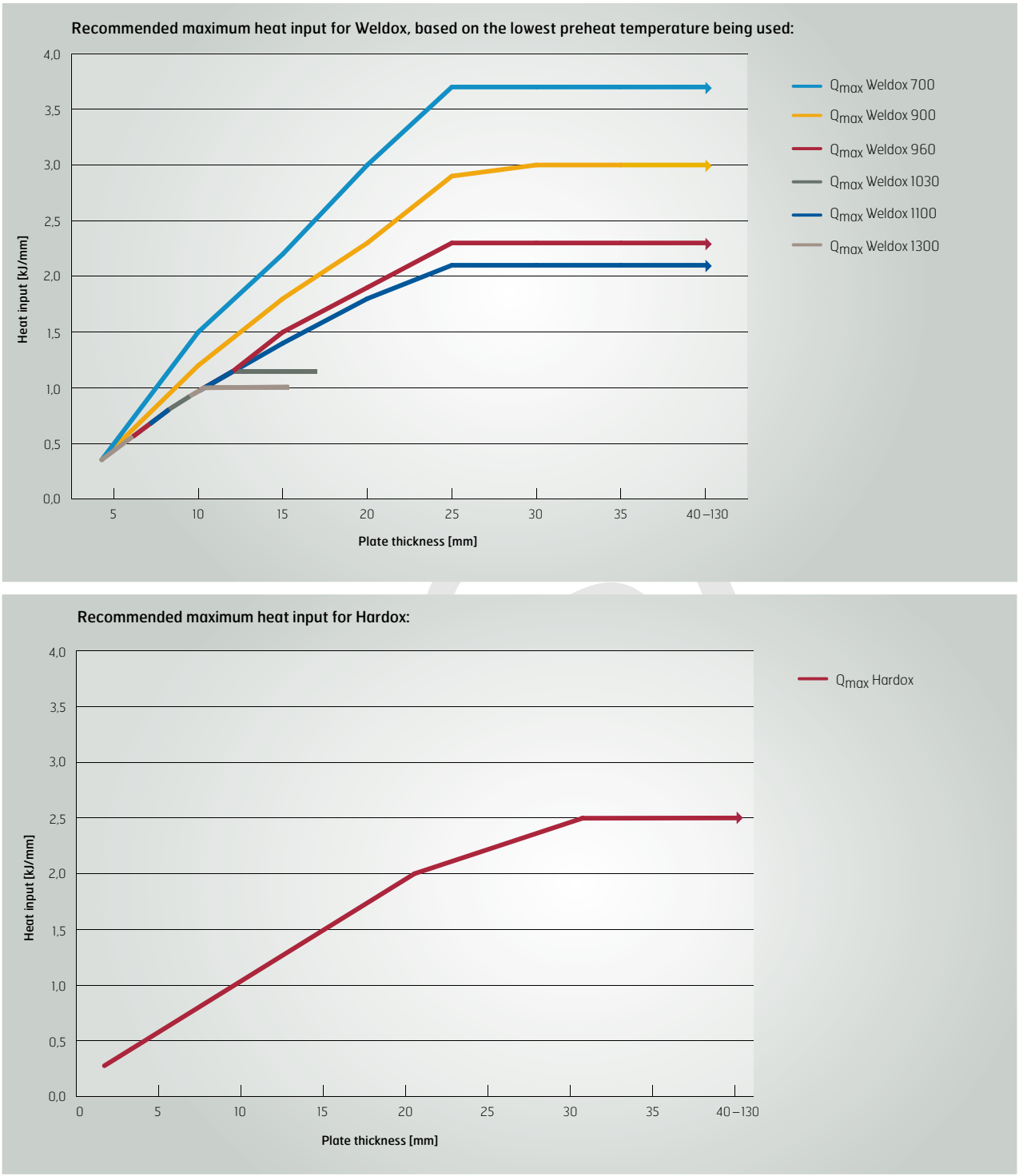
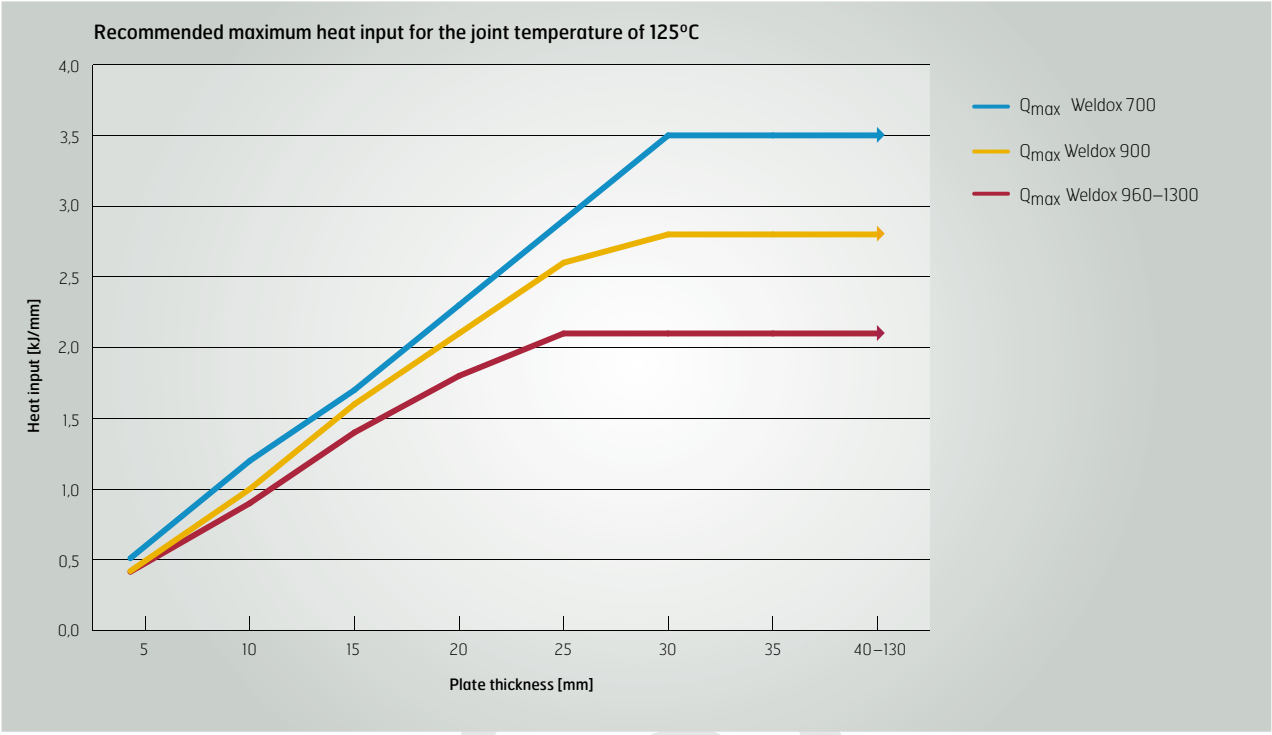


Fig. 5.7: Recommended heat inputs when a minimum preheat temperature is applied, according to chapter 4.

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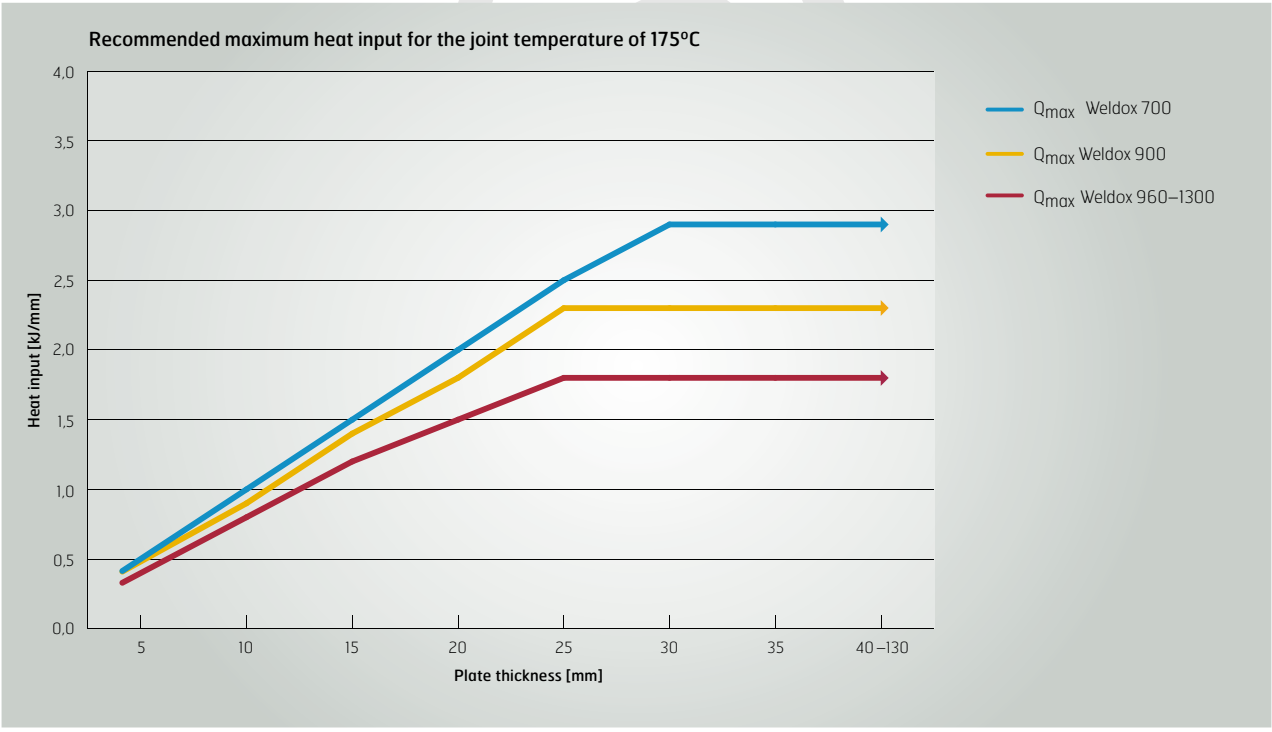


Fig. 5.8: Recommended heat inputs at preheat temperatures of 125°C and 175°C.

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5.4 Measures for additional improvements of the mechanical properties in the HAZ

Welding with heat inputs that have more restrictions than the normal recommendations supports even higher toughness values in the HAZ. By adopting an optimized heat input, with corresponding $t_{8/5}$ values in table 5.2, the typical minimum toughness in the HAZ can fulfill requirements of at least 40 J at -40°C. Applying these values can further increase the static strength in the joint.

Steel grade	Optimized $t_{8/5}$ values**
Weldox 700	5-10 s
Weldox 900	5-15 s
Weldox 960	5-15 s
Weldox 1030	5-10 s
Weldox 1100	5-10 s
Weldox 1300	5-10 s

** Valid for a typical min. impact toughness of 40 J at -40°C.

Table 5.2: Optimized $t_{8/5}$ values.

Hardness requirements for the HAZ are relatively unusual for the Weldox grades. When they do occur, it is usually for the Weldox 700 and Weldox 900 grades and they are normally related to the maximum allowed hardness values in the HAZ. This is usually done to minimize the risk of stress corrosion cracking in the HAZ, which may be relevant to structures exposed to corrosive environments. The requirements regarding maximum hardness values in the HAZ can be fulfilled in the vast majority of cases by following the recommendations for suitable heat inputs for the Hardox and Weldox grades.

There are additional techniques that can reduce the peak hardness in the HAZ, if needed.

Two different alternatives are:

1) Applying temper beads at the end of a welding performance. The microstructure at the location with the peak hardness in the HAZ has a content of martensite and /or bainite. A temper bead can anneal these microstructures and decrease the peak hardness. When applying this technique, the weld sequences in the joint are arranged so that the temper bead is placed a short distance from the HAZ according to fig. 5.9. Pay attention to the location of the temper bead. A temper bead placed too far from or too close to the HAZ might not give the desired effect.

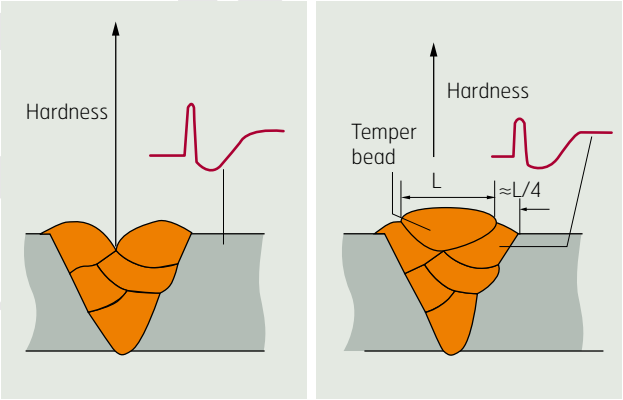


Fig. 5.9: The application of a temper bead technique.

2) A post-weld heat treatment in accordance with chapter 16 can reduce the maximum hardness values in the joint.

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6.0 The choice of consumables

The Hardox and Weldox grades are normally welded with unalloyed and low-alloyed consumables. Stainless austenitic consumables can be even more advantageous for welding of certain structures or under certain circumstances. The objective with this chapter is to describe the essential aspects when selecting these kinds of consumables.

Updated information regarding their designations in AWS standards and EN standards is found in TechSupport no. 60 at www.ssab.com. Information regarding consumables for hardfacings is described separately in chapter 20.

6.1 Unalloyed and low-alloyed consumables

The unalloyed and low-alloyed consumables that are suitable for welding the Hardox and Weldox grades have a total alloy content of up to approximately 7-8 percent by weight where the remaining parts consist of iron and a very small fraction of contaminants. Of significant importance for these consumables, is that they can combine a high static strength with favorable toughness values in the weld metal. Unalloyed and low-alloyed consumables are, in this context, grouped together since the issues for selecting these kinds of consumables are similar. The general tendency is that the low-alloyed consumables represent the consumables of highest static strength and their alloy content is typically higher in relation to unalloyed consumables.

When selecting a suitable consumable, it is crucial that the hydrogen content is sufficiently low in order to minimize the risk of hydrogen cracks in the joint.

6.2 The static strengths of the consumables

The static strength of the consumables suitable for welding the Weldox grades depends on the steel grade. Recommended values are according to fig. 6.1.

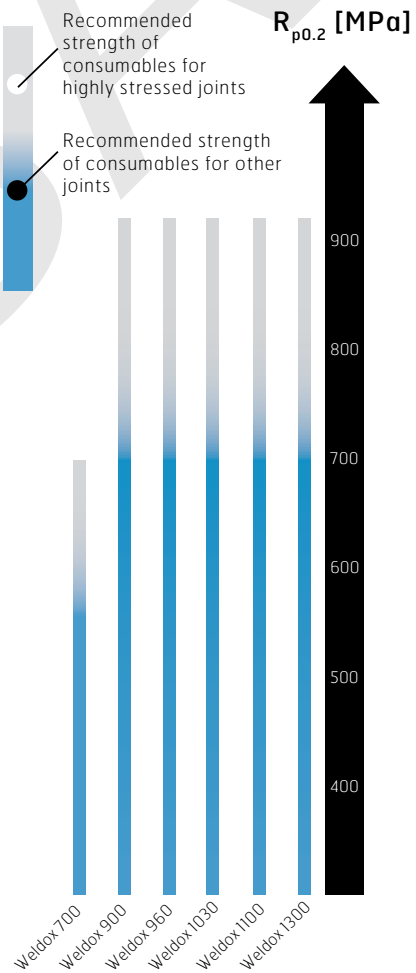


Fig. 6.1: Recommended static strengths in the all weld metal for unalloyed and low-alloyed consumables for the Hardox and Weldox grades.

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Consumables used for Weldox 960 - Weldox 1300 have lower yield strength than the unaffected parent metal. This is because consumables with a yield strength of around 930 MPa in the all weld metal represent the highest available yield strength on the market for welding of construction steels.

Using consumables with a lower maximum strength than in fig. 6.1 can benefit the Weldox grades with advantages such as increased toughness in the weld metal, lower residual stresses, and enhanced resistance to hydrogen cracks in the joint.

When welding multi-pass joints in the Weldox grades, it can be beneficial to weld the first passes with lower strength consumables and the filler passes with higher strength consumables. This will give an extra high resistance towards hydrogen cracks.

The level of static strength in joints of the Hardox grades is normally not as crucial as for joints in the Weldox grades. A more important issue with these steel grades is to reduce the risk for hydrogen cracks in the joint. Welding with consumables of relatively low yield strength supports this matter. Suitable yield strengths of consumables for welding the Hardox grades are according to fig. 6.2.

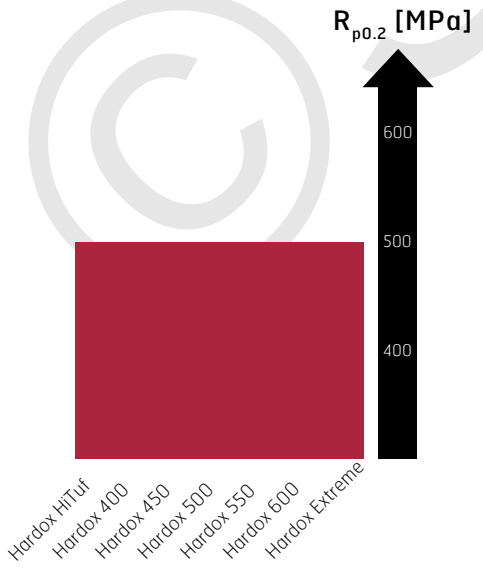


Fig. 6.2: Recommended static strengths in the all weld metal for consumables suitable for the Hardox grades.

6.3 The toughness values in the weld metal

The consumables with the appropriate strengths for welding the Hardox and Weldox grades can, in many cases, attain favorable toughness values in the all weld metal. The weld metal in joints of the Weldox grades can reach an impact toughness – with many kinds of consumables – that is typically above the toughness requirements of the unaffected parent metal.

There are seldom exact, specified toughness requirements for joints in the Hardox grades. When measured, the impact toughness values in the weld metal are normally at a level of – or above – the typical impact toughness values for these steel grades.

6.4 The maximum hydrogen content in the consumables

Hydrogen is always added to the joint during arc welding. The issue is to keep the hydrogen level low enough to minimize the risk of hydrogen cracks forming in the joint. One source of hydrogen is the consumable. Each type of consumable has individual characteristics regarding its hydrogen potential.

Sources for hydrogen in the consumables are:

- The cover for consumables for MMA welding and fluxes for SAW have minerals that bind moisture
- Drawing lubricants that are applied during manufacturing of cored wires
- Moisture from the surrounding environment

The recommendation for the Hardox and Weldox grades is to choose consumables that can achieve diffusible hydrogen contents of a maximum of 5 ml H_2/100 g of weld metal. There are consumables available for all the welding methods that can fulfill these hydrogen requirements.

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All solid wires, such as those used during MAG and TIG welding, can meet the specified hydrogen criteria.

Consumables that utilize a flux, including MAG welding with flux cored wires and SAW, have an additional source of moisture pick-up in relation to solid wires. The different fluxes are more or less prone to moisture pick-up from the environment. The hydrogen potential in fluxes used in flux cored wires and SAW depends on their chemical composition.

Fluxcored wires and fluxes for saw that include a sufficient amount of basic chemical substances can attain a sufficiently low moisture levels in the consumable. These consumables are called basic flux cored wires and basic covered consumables.

In adition there are flux cored wires for MAG welding that contain the mineral rutile (TiO_2), called rutile flux cored wires that also keep the moisture levels low in the consumable.

The cover used in consumables for MMA consists of a flux, which is kept together by a binding agent. Both the binding agent and the flux are additional sources of moisture pick-up.

For metal cored wires, there are certain name brands that can fulfill the hydrogen criteria.

The categories of consumables that can reach sufficiently low levels of hydrogen are summarized in table 6.1. This information serves as a general guide when choosing suitable consumables. It is not a guarantee that every brand will fulfill the hydrogen criteria. Information regarding the hydrogen potential for a specific consumable can be provided by the manufacturer. In addition, SSAB has specified examples of suitable brands in TechSupport no. 60.

Consumables	Type of consumable
Solid wires (MAG- and TIG welding)	All types
Flux cored wires (MAG)	Basic and rutile variants
Metal cored wires (MAG)	Certain types
Consumables for MMA-welding	Basic variants
Consumables for SAW	Basic flux/solid wire combinations

Table 6.1: Consumables that have the potential to reach sufficiently low hydrogen content for welding of Hardox and Weldox grades.

6.5 Handling of consumables

In order to achieve the intended hydrogen content, it is important that the consumables are handled in accordance with their manufacturer. Otherwise, the consumables can be subjected to excessive hydrogen pick-up from different substances in their environment.

General issues to consider in this respect are that:

- The consumables are to be stored and kept away from contaminants like dampness, oil and grease.
- Opened packages of consumables for MMA welding and fluxes for SAW often need to be stored at elevated temperatures - for example, in small furnaces specially designed for consumables - in order to avoid excessive hydrogen pick-up from the humidity in the air. Unopened packages can normally be stored at room temperature.
- Unopened and opened packages of solid wires and cored wires can normally be stored at room temperature since they have a relatively high resistance for moisture pick-up.

6.6 Preheat requirements due to the properties of the consumable

A preheat operation of the joint prior to welding is sometimes necessary in order to counteract the formation of hydrogen cracks in the joint. The necessity for a preheat operation is determined by the characteristics of the steels being welded and the properties of the consumable. Preheat requirements due to the properties of the consumable are stated in chapter 4.

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6.7 Stainless austenitic consumables

Welding the Hardox and Weldox grades with stainless austenitic consumables offers certain features. A main reason being that the weld metal in the joint will include a substantial amount of austenite in the microstructure after welding.

A joint that is welded with an appropriate stainless consumable has a very high resistance towards hydrogen cracks. This is because the austenite in the weld metal dissolves hydrogen more than the microstructures in unalloyed and low-alloyed consumables. This largely counteracts the negative effects of hydrogen in the joint.

Additionally, the austenite in the weld metal supports ductility. This typically means that the impact toughness in the weld metal of the joints exceeds the requirements for the individual Hardox and Weldox grade.

Other important benefits of welding with stainless austenitic consumables are that:

- Preheat temperatures, which means a temperature above +20°C in the joint as well as in the surrounding air, can be avoided prior to welding for all Hardox and Weldox steels, except for Hardox 600 and Hardox Extreme. The two latter steel grades require preheating, according to chapter 4.
- Stainless austenitic consumables are suitable for welding the Hardox and Weldox grades to other kinds of steels, such as:
  - Stainless steels
  - Manganese steels (Hadfield steels), which have a Mn content of approximately 13 %
  - Steels that are difficult to weld, such as spring steels
- It is preferred that the buffer layer at hardfacing is welded with stainless consumables, according to fig. 6.3. Further information on this matter is found in chapter 20.

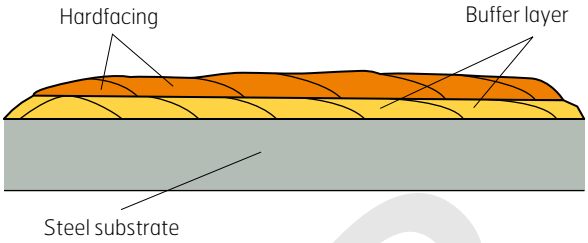


Fig. 6.3: Appliance of a buffer at hardfacing layer on a Hardox/Weldox plate

Essential drawbacks with stainless consumables are that:

- Low-alloyed consumables are feasible in higher strengths compared to stainless austenitic consumables. The yield strengths of suitable consumables are up to approximately 500 MPa in the all weld metal.
- Flame cutting in joints welded with stainless austenitic consumables is not possible. However, all other thermal cutting techniques can be applied in these weldments.
- Stainless austenitic consumables are more expensive than unalloyed and low-alloyed consumables.

The recommended stainless consumable is of type AWS 307. A second alternative is a consumable of type AWS 309, which is often used when an AWS 307 is not commercially available. However, the risk of hot cracking in the weld metal is somewhat higher for AWS 309 in relation to AWS 307.

The hydrogen potential of stainless consumables is of secondary importance due to their high resistance to hydrogen cracks. According to evaluations performed by SSAB, there are no formal restrictions regarding maximum hydrogen content for these types of consumables. However, the consumables are to be handled according to their manufacturer in order to avoid unnecessary hydrogen pick-up.

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7.0 Aspects regarding static strength in joints

The requirements regarding static strength in joints are mostly related to the Weldox grades. As a general characteristic, joints in these steel grades can achieve very high static strengths. The Hardox grades can also attain favorable strengths, even if they are not as high as the Weldox grades.

The static strength of the complete joint depends on the properties of the individual parts in the joint, which in this case, means the characteristics of the HAZ, the weld metal, the unaffected parent metal and their interactions with each other.

As accounted for in chapter 5, each part of the HAZ is subjected to a unique heat treatment from the welding performance, which causes the local mechanical properties to vary throughout the HAZ. This includes the static strength throughout the HAZ, where parts of the HAZ will typically have a lower static strength than the unaffected parent metal.

However, when the lowest strength in the joint is in the HAZ, the tensile strength transverse to the complete joint can be higher than the part of the HAZ with the lowest strength. In simplified terms, if the section with the lowest strength is narrow, the surrounding areas of higher strength interact with each other to strengthen the entire joint. This issue occurs frequently for joints in the Hardox and Weldox grades.

In many cases, joints that consist of only Weldox 700 are welded, including all weld passes, with low-alloyed consumables that have the same yield strength in the all weld metal as the unaffected parent metal. Typically, for a fully penetrated butt joint, the tensile strength transverse to the direction of the complete joint matches the tensile strength requirement for the unaffected parent metal of Weldox 700.

In structures made with Weldox 900- Weldox 1300, the joint is often welded throughout with low-alloyed consumables that have the highest accessible strengths. This means using consumables with yields strength of approximately 900 MPa in the all weld metal. In these situations, fully penetrated butt joints that include the same Weldox grade will attain tensile strengths as follows:

- Joints made with Weldox 900- Weldox 960 can in many cases typically fulfill the tensile strength requirements for the unaffected parent metal of the specific Weldox grade.
- Joints made with Weldox 1030- Weldox 1300 have a typical tensile strength that is somewhat below the specified tensile strength of the unaffected parent metal of the included Weldox grade.

Hardox grades are welded with unalloyed, low-alloyed and stainless consumables with yield strengths up to 500 MPa. A completely penetrated butt joint that includes plates of the same Hardox grade normally achieves a tensile strength, measured transverse to the joint direction, which is between the tensile strength of the unaffected parent metal and the tensile strength of the consumable being used. Updated information regarding typical static strengths in joints of Weldox grades is found in TechSupport no. 64 which is available at www.ssab.com

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7.1 Issues to consider during the tensile test

Tensile tests are normally performed for butt joints measured transverse to the direction of the joint. The most common purpose of this test is to measure the tensile strength and to determine the location of fracture after the test is performed.

The yield strength, determined as the stress level at 0.2% elongation of the tensile test specimen, of a joint is hard to evaluate accurately. The reason is that the tensile specimen is normally deformed to some extent by the welding performance. Measuring the yield strength transverse to the direction of the joint may create inaccuracies since there can be a movement perpendicular to the longitudinal movement of the specimen, see fig. 7.1. Straightening of the specimen prior to the tensile test is not normally carried out since this could affect the mechanical properties in the joint.

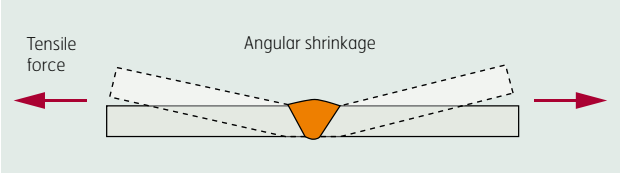


Fig. 7.1: Geometric movement of a tensile specimen subjected to a tensile test.

There may also be inaccuracies in determining the yield strength in the joint due to small sliding effects that might occur between the specimen and the contact bars of the tension testing machine. This sliding effect is supported by the high levels of forces that are often needed for joints in high strength steels. The assessment of the tensile strength in joints is less affected by this sliding effect and representative values can typically be attained even if a small amount of sliding occurs. However, it is good procedure to make sure that there is a tight grip between the tensile test specimen and the contact bars.

Results are dependent on the exact welding situation, but when Weldox grades are welded using consumables with the maximum recommended yield strength, the fracture during the tensile test typically takes place in the weld metal or the HAZ. For joints made with Hardox grades, the normal location of fractures is in the weld metal.

Elongation values that are viewed transverse to the direction of the joint are often of less importance for joints in high strength steels. This is because the local strength transverse to the joint direction varies and elongations and plastic deformations in joints tend to take place in regions of reduced strength. Consequently, the measured elongation values are often smaller compared to the measured elongation values for the unaffected parent metal. The tensile test specimens in fig. 7.2 illustrates this phenomenon.

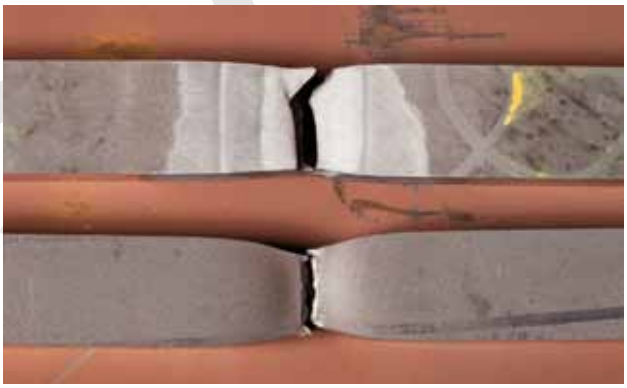


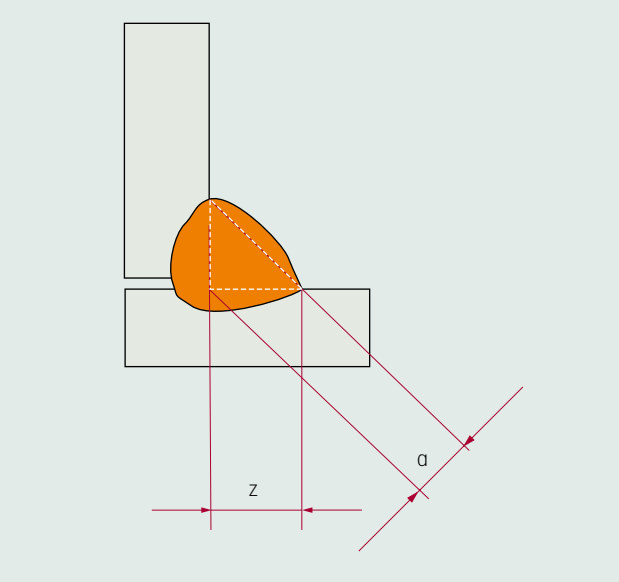
Fig. 7.2: The upper tensile test specimen includes a joint, while the lower specimen consists of unaffected parent metal.

For welded structures where there are specified requests regarding static strength, the dimensions and stresses in the joint are normally calculated during the design of the welded structure.

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For other joints than butt joints, such as fillet joints, the actual strength may be more difficult to determine in terms of static strength. In this situation, the calculation of the static strengths in the joint is often based on the throat thickness and leg length, according to fig. 7.3. However, a deep penetration of the weld metal will add strength to this type of joint. The actual strength in the joint, therefore, is even higher compared to many types of calculations.



Key

z = The leg length, which is the side of the largest isosceles triangle that can be inscribed in the section.

a = The throat thickness, which is the height of the largest isosceles triangle that can be inscribed in the section.

Fig. 7.3: Appearance of a fillet joint.

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8.0 Fatigue in welded joints

8.1 Introduction

Fatigue is a very important consideration for welded structures that are subjected to variable loads. Up to 90% of all failures in welded structures are believed to be related to fatigue. The importance is even greater when using high strength steel because the fatigue strength of a welded joint is the same, independent of the steel grade. This can lead to the misunderstanding that there is no advantage to utilizing high strength steel in structures subjected to fatigue. For structures with a low fatigue load, for example, a low number of cycles and/or a lean load spectrum, high strength steel are advantageous.

Fatigue is a process whereby a component is subject to a variable load, which is lower than the static strength of the material. The material starts to deteriorate and finally a crack is created. The final stage is a complete failure of the structure. Often, long before the failure, the component has lost its function.

The fatigue strength of welded joints is a multi-discipline subject. It involves design, dimensioning, production and quality. The general design is very important for the component's fatigue life, such as, where and which kind of welded joints are used. Getting the appropriate and/or highest fatigue strength depends on good weld quality, which in turn, depends on the welding engineer, the welder and the quality control personnel. It is also important not to add any additional welded joints, hooks, etc., after the design has been finalized.

The purpose of this chapter is to give general information regarding fatigue of welded joints, not to cover the entire field of fatigue.

8.2 Fatigue load

Fig. 8.1 shows one loading cycle with different stress definitions needed to analyze the fatigue load.

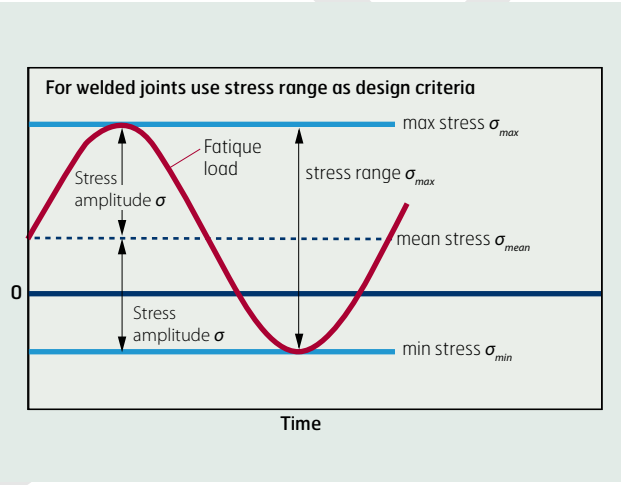


Fig. 8.1: Stress parameters for one loading cycle.

To characterize a fatigue load, two quantities are needed. For fatigue in welded joints, the stress range $\Delta\sigma$ and the stress ratio, R, are usually used.

Normally, a structure is not subjected to constant load, called constant amplitude (CA). Instead, the amplitude varies with the time, called variable amplitude (VA). Most of the fatigue strength data is tested in CA. To do the dimensioning, the given data in CA is compared with external load in VA. This is a very complex task and experience is often the key to success.

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8.3 Fatigue strength in welded joints

The main topic of this section is the fatigue strength of welded joints. The differences between what affects the fatigue strength of the base material and that of the welded joints are summarized in table 8.1.

Base material	Welded joints
Surface condition is very important	Joint geometry and weld quality determines the fatigue strength
Strong influence of mean stress	No influence of mean stress, use stress range
Strong influence of material strength	No influence of material strength

Table 8.1: Differences between fatigue strength of base material and welded joints.

Table 8.1 shows that the fatigue strength of welded joints is independent from the strength of the parent material. The fatigue strength of welded joints is also much lower than that of the parent material. The next section will explain why this is.

Usually, a fatigue failure can be divided into three stages: initiation, propagation and final failure. This means that the total number of cycles can be divided into cycles for initiation (*Ni*) and cycles for propagation (*Np*, *Ntot=Ni+Np*). A welded joint always has discontinuities such as cold laps, under cuts, and slag particles around the weld toe, see fig. 8.2. These discontinuities act like a fatigue crack that has already been initiated. For welded joints, the number of cycles to initiation is 10-30% of the total numbers of cycles, but for a polished parent material, the number of cycles to initiation is about 90%. Fatigue in the welded joint is said to be governed by propagation and in the parent material by initiation. The propagation rate is independent of the strength of the material and this is the reason why welded joints in high strength steel have the same fatigue strength as those in low strength steel.

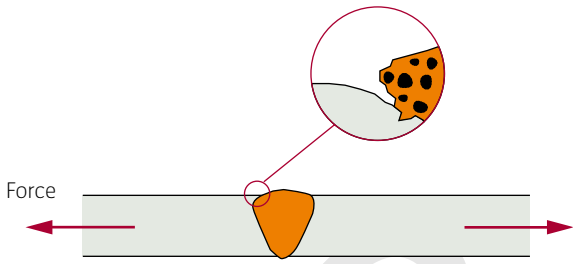


Fig. 8.2: Examples of discontinuities around the weld toe.

The area around the welded joint has stress concentrations due to the welded joint itself. Fig. 8.3 gives an idea of the difference between nominal stress and the stress concentration close to the weld. The picture shows the stress over the thickness of a plate with and without a weld. The stress concentration depends on the joint geometry and the geometry of the transition between the weld metal and the parent material. A smoother transition gives less stress concentration and higher fatigue strength consequently.

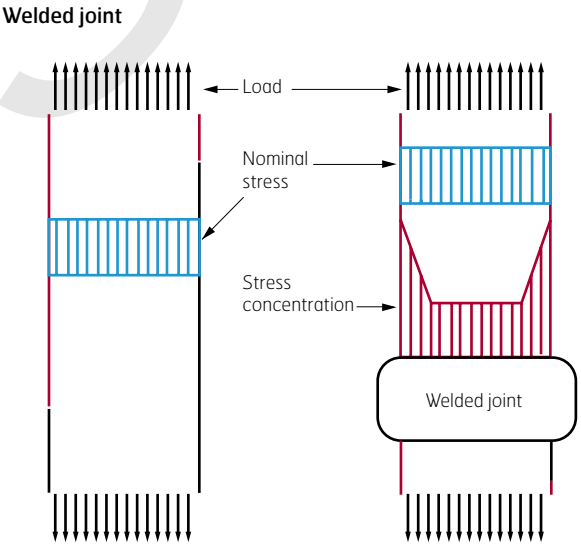


Fig. 8.3: Stress concentration close to weld over the thickness of the plate.

The last effect comes from the residual tensile stresses around the joint caused by the welding process, see chapter 4.16. These stresses can add to the stress from the external load. The welded joint is then subjected to tensile stress even if the external load is compressive.

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Fig. 8.4 shows the difference between stresses from the external load and the actual stresses acting on the welded joints. Compressive stress is not considered a contributing factor to the fatigue process.

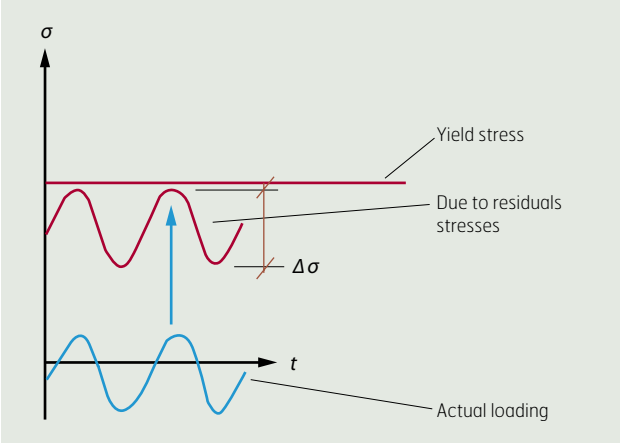


Fig. 8.4: The effect of residual stress close to the welded joint.

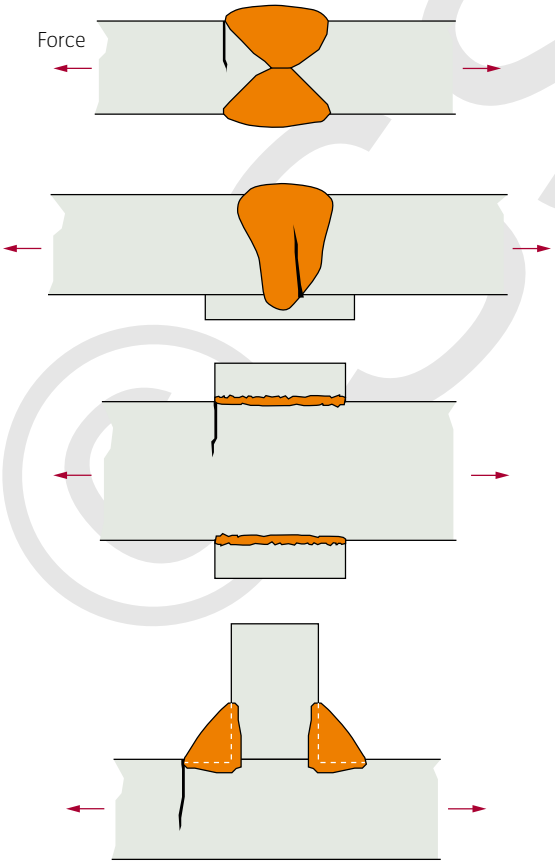


Fig. 8.5: Examples of different fatigue cracks from different welded joints.

The fatigue strength is normally presented in a SN-diagram, sometimes called a Wöhler diagram. In a SN-diagram, the logarithm of the stress range is plotted on the y-axis and the logarithm of the number of cycles to failure is plotted on the x-axis. The data comes from testing specimens at different stress levels and registering the number of cycles to failure. Below a certain stress level, the specimen will not fail at a predetermined number of cycles and these samples are called run outs. Fig. 8.6 shows an example of a SN-diagram for Weldox 700 and a butt weld in Weldox 700.

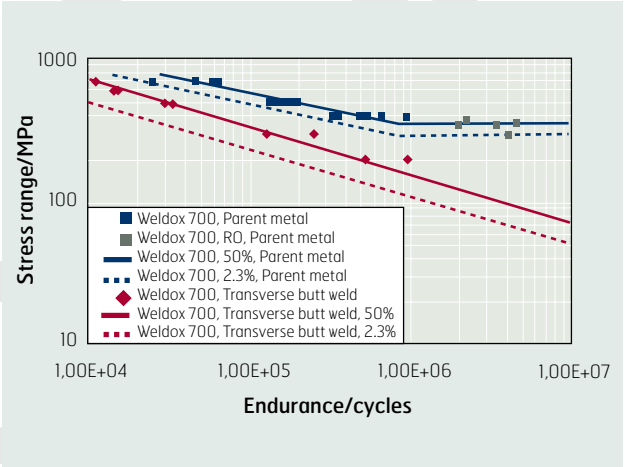


Fig. 8.6: Example of a SN-diagram of Weldox 700 and a fully penetrated butt weld.

The data points in fig. 8.6 show a scatter in the number of cycles to failure. Normally, the data points are shown by a 50% probability of failure line and the "2.3%" line, which is generally the characteristic fatigue strength (2.3% probability of failure).

The sloped line in fig. 8.6 is described by formula 8.1.

$$\Delta \sigma^m N = C \qquad \textit{Formula 8.1}$$

Where m and C are constants, N is the number of cycles to failure and $\Delta\sigma$ is the stress range. m is the inverse slope in a logarithmic-logarithmic diagram. The constant C depends mostly on the geometry, for example, the geometry and the quality of the welded joint.

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8.4 Weld quality

Weld quality is very important to the fatigue strength of the welded joint. Higher loads demand better weld quality. In ISO 5817, there are defined weld quality classes, these, however, are not related to the fatigue strength of a welded joint.

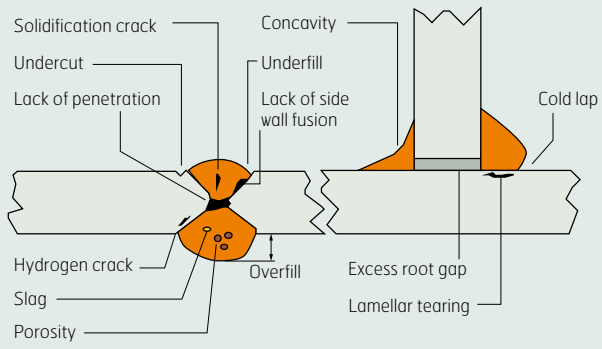


Fig. 8.7: Examples of discontinuities in a welded joint.

Generally, crack-like discontinuities are more severe than rounded discontinuities and discontinuities close to the surface are more severe as well. Solidification cracks, hydrogen cracks and lack of penetration cannot be tolerated in fatigue-loaded structures. Cold laps and under cuts should be avoided as well. Small rounded pores in the welded joints have a very small influence on the fatigue strength.

Design discontinuities like starts and stops should be placed on low stressed areas or non-loaded components. For cases when the above cannot be achieved, starts and stops should be grinded down.

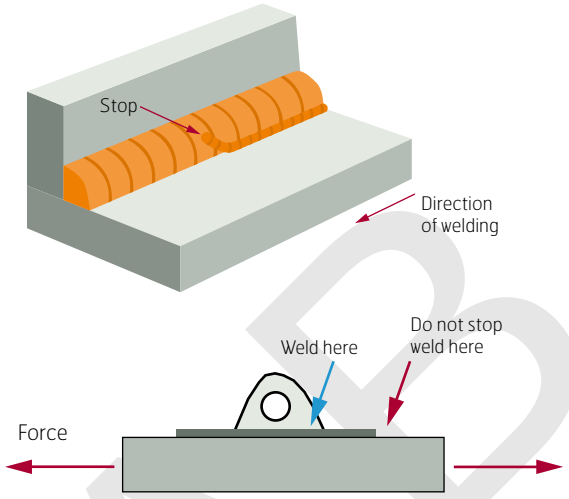


Fig. 8.8: Place starts and stops at the side of the attachment longitudinally, not at the end of the weld.

The welding process and the filler material affect the fatigue strength at the transition point between the weld metal and the parent material. They also affect the amount of discontinuities in the welded joint. The process and the filler material, therefore, should be chosen in a way that minimizes these effects. Differences in strength between the filler material and the parent material have no proven effect on the fatigue strength.

8.5 Nominal stress method

This section is a short introduction to dimension and designing of fatigue in welded joints.

The nominal stress method is based on categorizing weld geometries into joint classes. Depending on the standard of use, these joint classes are designated differently; notch class (NC) for EN 1993-1-9, $\Delta\sigma c$ in EN 13001, etc. FAT is the designation in the International Institute of Welding (IIW) "Recommendation for fatigue design of welded joints and components". Henceforth, FAT will be used to designate joint classes in general. The FAT value is defined as the characteristic fatigue strength at 2 million cycles. Modifying formula 8.1 gives:

$$\Delta\sigma = FAT \left[\frac{2 \times 10^6}{N} \right]^{\frac{1}{m}} \qquad \textit{Fomula 8.2}$$

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Formula 8.2 gives the fatigue strength up to the so-called knee point. For welded joints, m is usually 3, at knee point m changes. The knee point is defined differently depending on the standard and the value of m. Fig. 8.9 shows the fatigue strength versus the numbers of cycles for three different FAT (56, 90 and 140) for IIW "Recommendation for fatigue design of welded joints and components", in the blue lines and EN 1993-1-9 in the red lines. The knee points are marked with a red and blue vertical line.

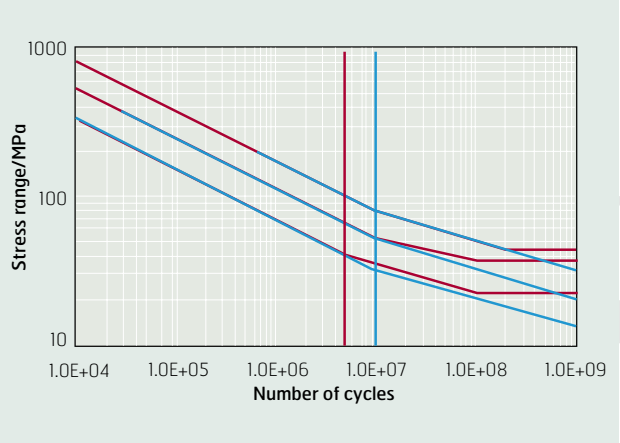


Fig. 8.9: Fatigue strength for IIW recommendation, blue lines, and EN 1993-1-9, red lines.

The load parameter being used is the stress range due to the presence of the tensile residual stresses. Fig.ure 8.10 shows an example of some FAT's from IIW "Fatigue design of welded joints and components". The fig.ure also gives information about some weld quality demands that must be fulfilled for the specific joint class. The load direction is also given in the different pictures for the joint classes.

In the joint classes, a small amount of misalignment is already considered, typically 15%. Fig. 8.10 illustrates that the amount of misalignment is less than 15% for some joints, see the requirements and remark column. For joint 213 in fig. 8.10, the misalignment is 10%. For larger misalignment, the FAT must be reduced. The linear misalignment in fig. 8.11 can act as an example.

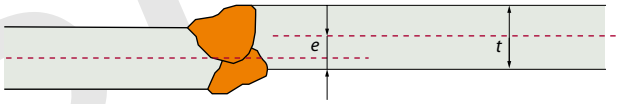


Fig. 8.11: Example of a linear misalignment. e is the linear misalignment and t is plate thickness.

No.	Structural detail	Description (St. = steel; Al. = Aluminium)	FAT St.	FAT Al.	Requirements and remarks
200	Butt welds, transverse loaded				
211	Force	Transverse loaded butt weld (X-groove or V-groove) ground flush to plate, 100% NDT	112	45	All welds ground flush to surface, grinding parallel to direction of stress. Weld run-on and run-off to be used and subsequently removed. Pate edges to be ground flush in direction of stress. Welded from both sides. Misanlignment <5% of plate thickness. Required quality cannot be inspected by NDT!
212		Transverse butt weld mad in shop in flat position NDT weld reinforcement <0.1 thickness	50	36	Weld run-on and run-off piece to be used and subsequently removed. Plate edges to be ground flush in direction of stress. Welded from both sides. Milalignment <5% of plate thickness.
213		Transverse butt weld not satisfying conditions of 212, NDT Al.: Butt weld with toe angle < 50° Butt weld with toe angle > 50°	80	 32 25	Weld run-on and run-off pieces to be used and subsequently removed. Plate edges to be ground flush in direction of stress. Welded from both sides. Misalignment <10% of plate thickness.

Fig. 8.10: Example of FAT in IIW "Recommendation for fatigue design of welded joints and components".

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The FAT is 80 MPa taken from fig. 8.10, no. 213. The corrected FAT for different thicknesses is shown in fig. 8.12. The amount of misalignment already in the FAT can also be seen in fig. 8.10, for a 10 mm plate this misalignment is 0.5 mm and for a 20 mm it is 1 mm. For a 20 mm plate with a misalignment of 4 mm, the FAT is about 58 MPa instead of 80 MPa; see the red line in fig. 8.12. This gives a reduction in lifetime of about 2.6 times. Chapter 13 explains how to minimize the misalignment.

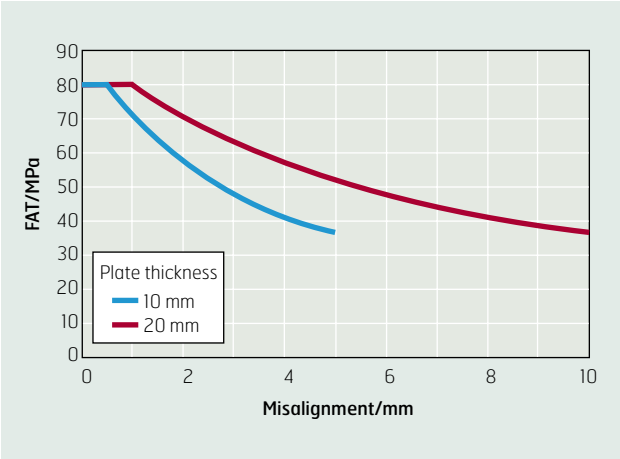


Fig. 8.12: Corrected FAT due to misalignment.

Two other fatigue assessment methods have been developed from the nominal stress method: the structural stress method Hot Spot Stress, HSS in IIW, and the effective notch stress method. One other method to access fatigue is to use linear elastic fracture mechanics, mostly used with an existing crack or at the root side. All of these methods are covered in IIW "Recommendation for fatigue design of welded joints and components".

8.6 Improvement methods

In general, improvement methods are divided in to two types: geometric and residual stress. Geometric improvement methods include burr grinding and TIG-dressing. Residual stress improvement methods include post-weld heat treatment (PWHT), hammer peening, blast peening and ultrasonic methods. It is very important to know that if improvement methods are needed, they should only be applied locally to the problem areas, see fig. 8.13, otherwise using improvement methods becomes very costly.

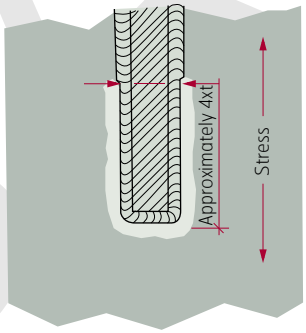


Fig. 8.13: Example of where to use improvement methods.

For an improvement method to be successful, it must be performed with the correct parameters. For more information about the process parameters and gains in fatigue strength, it is recommended to consult IIW "Recommendations on Post Weld Improvement of Steel and Aluminium Structures".

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8.7 TIG-dressing

TIG dressing is the process of melting the weld toe to smooth the transition between the welded joint and parent material. This gives a lower stress concentration, see fig. 8.14.

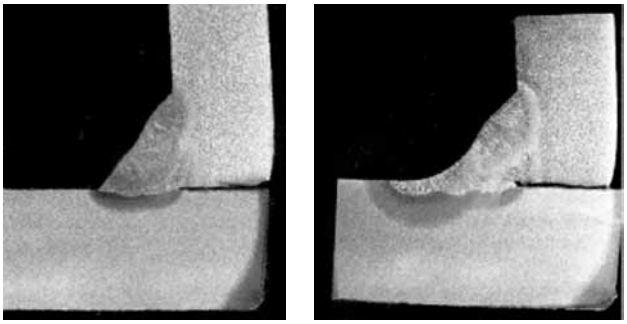


Fig. 8.14: Effects of TIG dressing.

Some inner defects (slag, etc) are also removed with TIG dressing. TIG dressing also fuses cold laps. TIG dressing is performed with normal TIG equipment. For the best results, the electrode should be grinded prior to use. Fig. 8.15 shows the proper weld parameters. The voltage is normally between 12-17 V, D.C. Steels from SSAB can be TIG-dressed without preheating.

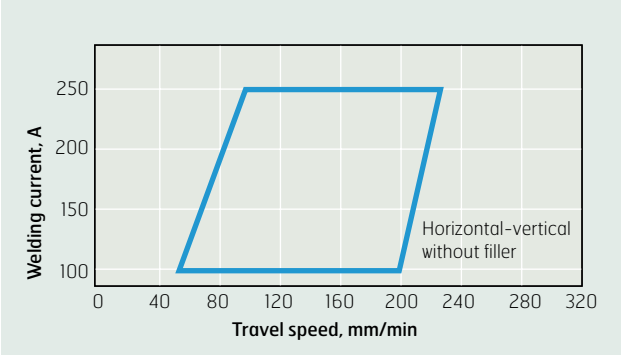


Fig. 8.15: Process window for TIG-dressing.

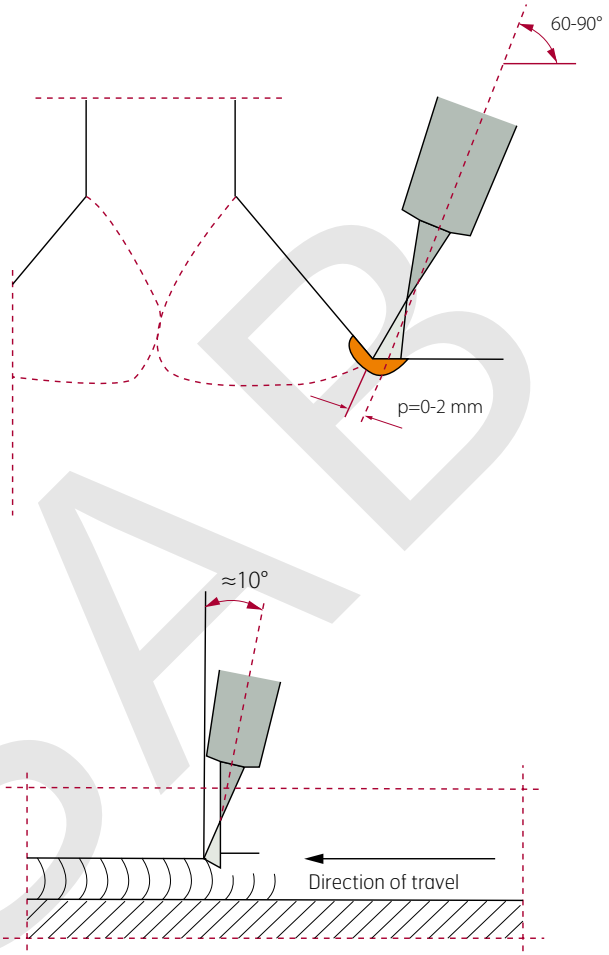


Fig. 8.16: The recommended angle of the TIG-gun.

Fig. 8.16 gives the angle of the TIG-gun. The gun should be placed 0.2-1.5 mm in front of the weld toe for optimal results, see fig. 8.16. The process should start and stop in the weld metal.

The above-mentioned recommendation gives a typical increase in FAT of 30%.

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8.8 Burr grinding

Burr grinding has almost the same effect as TIG-dressing when applied at the weld toe. With this method, the transition radius is decided by the burr. Some defects are also removed by the grinding itself. Grinding with roundels is not recommended. The diameter of the grinding tool for plates with a thickness between 10 50- mm is normally 10-25 mm. The radius of the grinding "ditch" should be at least 0.25 of the thickness of the plate. Minimum depth is 0.5 mm or to the point where all defects are removed. The maximum depth is 2 mm or 5% of the thickness for t>40 mm and 7% of the thickness for t<40 mm. The speed of the tool is 1500-40000 rpm. The angles are shown in fig. 8.17.

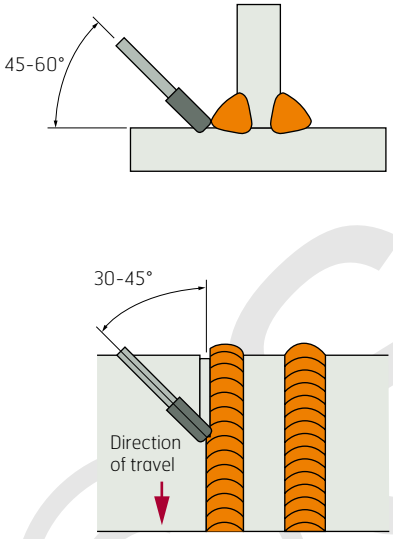


Fig. 8.17: Tool angles for burr grinding.

The above-mentioned recommendation gives a typical increase in FAT of 30%.

8.9 Hammer peening

During hammer peening, compressive residual stresses are introduced when the area around the weld toe is cold formed. These compressive residual stresses prevent the crack from initiating and growing. This method is not recommended for structures with a dominant external compressive load. The compressive load relaxes the build in compressive residual stresses. To get the full effect of this method, it is recommended to consult "IIW Recommendations on Post Weld Improvement of Steel and Aluminium Structures"

8.10 Post-weld heat treatment (PWHT)

Post-weld heat treatment has long been used to obtain higher fatigue strength in welded structures. The treatment reduces the tensile residual stresses around the welded joint, but never/rarely down to zero. For complicated welded structures, there are risks of high tensile residuals stresses being left in the structure after PWHT. Chapter 16 gives more information about PWHT.

To get an effect from this method, a part of the load must be compressive. The largest gain in stress range for PWHT is about 25% for R=-1.

8.11 Other methods

Shot peening has almost the same effect as hammer peening. To a lesser extent, the same effect could also be achieved by heavy sand blasting.

Ultrasonic methods like Ultrasonic Impact Treatment (UIT) and Ultrasonic peening are two relatively new techniques. They work along the same lines as hammer peening but have the advantage of being less noisy and giving off minimum vibration to the operator.

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9.0 Hardox and Weldox shop primers

SSAB can provide the Hardox and Weldox grades with a shop primer that provides an effective corrosion protection of each plate during storage, transportation and fabrication.

Shop primed plates in the Hardox and Weldox grades are coated with an inorganic low zinc silicate primer, which is illustrated in fig. 9.1. Depending on the thickness of the primer film applied, different corrosion protection durations are attained. Two alternatives exist. The primer can provide a protection from corrosion for either three months or six months. The thickness of the primer is approximately10-15 µm. The three-month protection represents thinner primer thicknesses and the six-month protection thicker primer thicknesses of this interval. The plates that SSAB keeps in stock are always painted with a primer thickness corresponding to a minimum of six months of corrosion protection. Additional information regarding the general properties of primed plates in Hardox and Weldox grades are found in TechSupport no. 25 at www.ssab.com. If requested, the primer is easily removed from the parts of the plate that will be subjected to cutting and/or welding by, for example, a brush or a grinding tool.

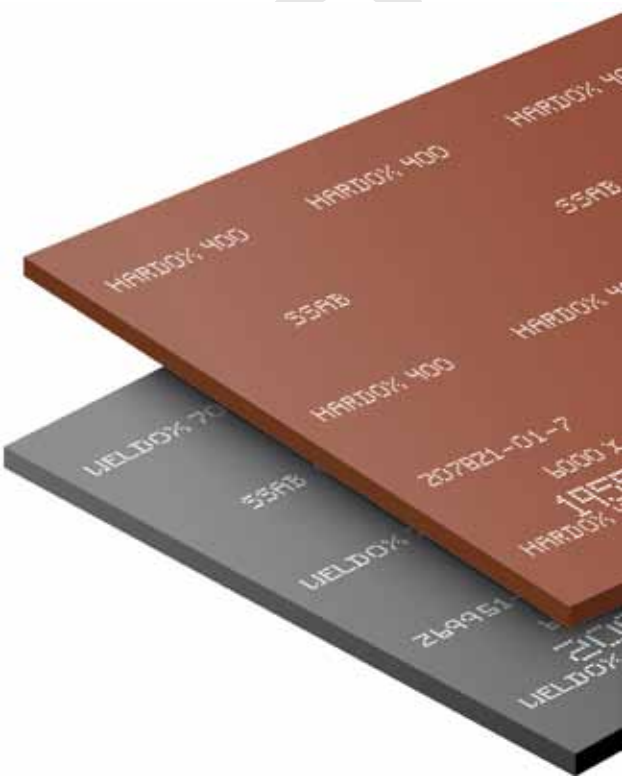


Fig. 9.1: The standard primer colors are red for Hardox and gray for Weldox.

9.1 Welding of shop primed plates

Welding can be performed with or without leaving the primer in the joint. When the primer is left on, it is possible to attain advantageous results of the general properties in the joint. It is also feasible to perform welding with the same parameters as for a joint without a primer. However, the outcome may be further improved if the primer is removed from the joint and the adjacent surroundings prior to welding.

The principal advantages with this measure are that:

- The level of porosity in the weld metal can be lowered. For stringent requirements regarding low porosity levels, SSAB proposes that the primer is removed prior to welding. In comparison, welding a joint without primer can achieve porosity levels down to zero. Evaluations of fillet welds that are welded in the horizontal position, where the primer remains in the joint, show that the porosity is typically up to some percentage of the total volume of weld metal. These results are attained for both of the primer alternatives. In general, the primer with a three-month corrosion protection supports lower porosity than the primer with a six-month corrosion protection.

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- Out of position welding, which means welding in positions other than the horizontal, is enhanced. In these situations, there may be a tendency for insufficient bonding of the molten weld metal to the joint if the primer is not removed. This can cause lack of root penetration and lack of fusion in the joint.

9.2 Thermal cutting of shop primer painted plate

Oxygen fuel cutting and plasma cutting can be performed without incident on plates with the shop primer left on. There is no need for special consideration of the cutting parameters due to the primer.

During laser cutting of primed plate surfaces the primer burns off and generates fumes that cause a disturbance of the laser beam. This reduces the effectiveness of the laser cutting process. This loss of power can be compensated by a lowered cutting speed.

How large this reduction is depends on:

- The thickness of the primer
- The plate thickness

The shop primers applied to the Weldox and Hardox grades feature comparatively small reductions of the laser cutting speed. The primer with the three-month corrosion protection causes less reduction in speed than the primer with the six-month corrosion protection.

The thinner primer represents values in the lower part of the intervals and the thicker primer in the upper part of the intervals.

- For plate thicknesses t<10mm:
  The cutting speed reduction is typically 15-40 %
- For plate thicknesses t≥10mm:
  The cutting speed reduction is typically 5-20%.

Cutting parameters other than the speed are not significantly affected due to the primer.

9.3 Health aspects

Welding and cutting of primed plates can be performed in normal ventilated workshop premises. However, there will be an increase of fumes due to the primer. Tests have shown that the shop primer itself does not have additional health risks for the welder or the operator during these conditions.

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10.0 Joint preparations

A sound welded joint requires proper joint preparation prior to and during welding. Accurately preparing the joint can counteract several types of discontinuities.

General issues to consider during joint preparation are to:

- Take measures to minimize the risk for hydrogen cracks in the cut edge and its surroundings from the cutting performance by following our recommendations for avoidance of cracks. If hydrogen cracks develop, leaving the cracks in the plate can impair the mechanical properties of the structure. Normal measures to remove these cracks include repair welding or removing the section that includes the cracks by a separate cutting operation.
- Choose a suitable joint geometry. It should be sufficiently wide to facilitate proper welding conditions and minimize the risk for discontinuities in the joint. On the other hand, a joint geometry that is too wide and large causes negative effects. The most common issues in this respect are that:
  - Additional weld passes may be required in the joint
  - The amount of weld passes may remain the same as for a narrower joint, but each weld pass may need to be executed with a reduced welding speed in order to produce the required amount of weld metal.
  - A higher degree of distortions in the structure is promoted, due to the increase of the volume of weld metal.

The choice of a suitable joint geometry depends on the specific welding process and the present welding situation.

Therefore, the proper joint geometry for a given situation is for the user to decide.

- Keep the joint preparation area clean from contaminants such as moisture, grease, rust and oil prior to each weld pass. If these substances are not removed, discontinuities may occur such as:
  - Hydrogen cracks in the joint.
  - Lack of root penetration.
  - Lack of fusion.
  - Porosity.
  - Slag inclusion.
- After thermal cutting, the joint contains an oxide layer and a carbonized layer. The total thickness of these layers is typically around 0.1 mm. These layers are removed before welding, usually by grinding.

More information regarding hydrogen cracks can be found in chapter 4, the mentioned discontinuities in chapter 14 and suitable proceedings for repair welding in chapter 17.

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11.0 Cutting of Hardox and Weldox

The Hardox and Weldox grades are designed to facilitate all thermal cutting methods, including oxy-fuel cutting, plasma cutting and laser cutting. Furthermore, cold cutting processes can also be utilized. The recommendations for the Hardox and Weldox grades are mainly associated with the thermal cutting processes. The contents of this chapter, therefore, mainly relate to issues regarding the latter processes.

The enhanced thermal cutting performance of the Hardox and Weldox grades are primarily derived from their low alloy content. Additionally, favorable properties that can be utilized for laser cutting are the narrow thickness tolerances and smooth plate surfaces of the steel.

Many of the Hardox and Weldox grades' plate thicknesses can be thermally cut using the same parameters as for ordinary unalloyed and low-alloyed steels, with yield strength up to 355 MPa, without additional consideration. However, in some cases, it is necessary to adapt parameters to minimize the risk for hydrogen cracking. Other issues that relate to the characteristics of the steel are:

- The change of the mechanical properties in the thermally affected part of the steel due to cutting. This section is called the heat-affected zone (HAZ).
- The distortions that appear due to thermal cutting. Due to the higher levels of stresses, Hardox and Weldox plates are prone to more movement during thermal cutting than ordinary steels.

The gases for the different thermal cutting methods are selected and applied in the same manner as for unalloyed and low-alloyed steels with yield strengths up to 355 MPa. There are different gas compositions and application parameters that are suitable for the thermal cutting methods. SSAB does not have any further stated recommendations in this respect for the Hardox and Weldox grades.

The cold cutting methods, shearing and punching, are limited to the Weldox grades, Hardox 400 and Hardox 450 up to 10 mm in plate thickness. Abrasive water jet (AWJ) cutting is a cold cutting method that provides advantageous mechanical properties in the HAZ of the Hardox and Weldox grades. With this method, there is no risk for hydrogen cracks. The AWJ cutting method is, however, relatively unusual so the process is described separately in the publication: Abrasive Water Jet Cutting, issued by SSAB.

11.1 Hydrogen cracks

Cutting can cause hydrogen cracks for the same reasons as welding. The risk for these cracks can be minimized if the recommendations from SSAB are followed.

If hydrogen cracks appear, it is normally within a couple of days after cutting. In the first phase, small cracks form in the center of the plate that run horizontally within the HAZ. They form just behind the cut edge and they typically appear within a couple of hours after cutting is finalized. The cracks are not visible to the naked eye at this stage.

In the second phase, which typically arises after a couple of days, the cracks propagate to the cut edge surface and build longer horizontal cracks, typically up to 5-10 cm. A third phase may take place, which normally occurs after a couple of weeks, where the crack propagation continues, changes direction, and spreads up to the plate surface. Although vertical cracks are unusual, the risk for this emergence rises with the increasing hardness and thickness of the steel. Hydrogen cracks due to cutting are illustrated in fig. 11.1. This kind of crack can be extended between or through the grains in the microstructure.

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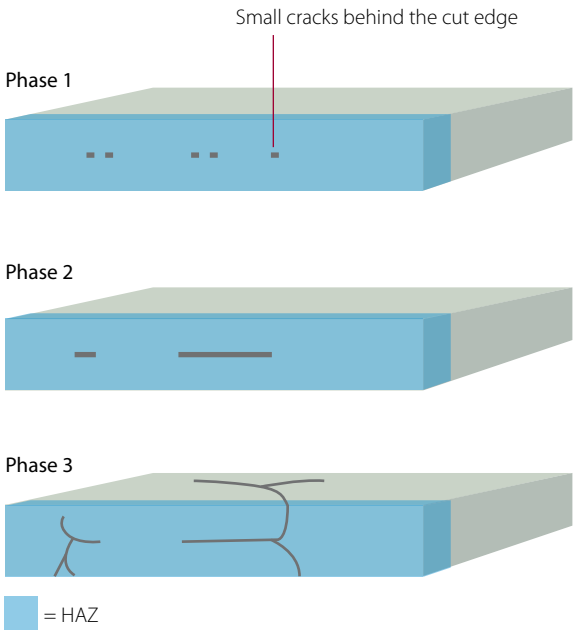


Fig. 11.1: Formation of hydrogen cracks at, and around, the cut edge.

Three conditions must be present in the steel at the same time in order for hydrogen cracks to form. They are:

- A relatively high content of alloy elements.
- A high levels of tensile stresses.
- A presence of a high hydrogen content in the joint.

These factors interact with each other; by keeping their levels suitably low, the risk for hydrogen cracks is minimized.

11.2 The influence from alloy elements in the steel

The influence of alloy elements is the same during thermal cutting as for welding. This means that higher carbon equivalent values in the steel correspond to increased sensitivity to hydrogen cracks. In general terms, the carbon equivalent rises with increased hardness and strength of the Hardox and Weldox grades. Additionally, the alloy content is typically higher for larger plate thicknesses in order for them to attain sufficient quench hardenability.

Consequently:

- There are more restrictions regarding cutting of the Hardox and Weldox grades with increasing strengths and hardness values.
- Larger plate thicknesses have more restrictions for minimizing the risk of hydrogen cracks during cutting.

Further information about the carbon equivalent is found in chapter 4.

11.3 Tensile stresses due to cutting

The cutting operation causes a non-uniform heat treatment of the cutting edge and its surroundings. For instance, the peak temperatures in the plate decrease as the distance from the cutting edge increases. This non-uniform thermal heat treatment causes the mechanical properties in the HAZ to vary.

Thermal cutting methods always induce tensile stresses in and around the area to be cut. A main cause of their emergence, according to the theory from SSAB, is now explained.

The HAZ due to cutting of the Weldox and Hardox grades can, in this context, be divided into two zones. This is illustrated for a plate of Hardox 450 that is thermally cut, according to fig. 11.2.

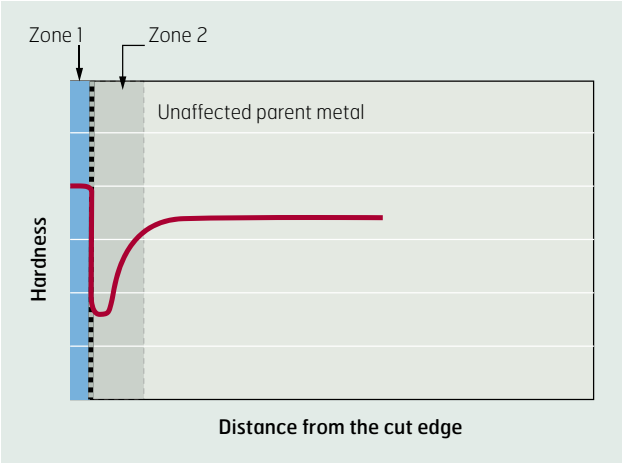


Fig. 11.2: Schematic hardness profile of the HAZ due to thermal cutting of Hardox 450.

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The outer part of the HAZ, marked as zone I in fig. 11.2, located approximately 1-2 mm from the cut edge and at a right angle to the center of the plate, has been re-quenched immediately after cutting. This zone is also heated to above 900°C during cutting and cooled rapidly as soon as the cutting torch has passed. A common factor shared by the Hardox and Weldox grades is that the hardness, as well as the strength, in this zone is higher than in other parts of the HAZ and unaffected parent metal.

Zone II, positioned between zone I and the unaffected parent material, is heated to temperatures below 900°C during cutting. The hardness values in this zone vary, depending of the steel grade and the cutting performance.

During cooling, zone I strives to expand in the thickness direction more so than zone II. As a result, residual tensile stresses are created in the thickness direction in zone II, from which hydrogen cracks can be formed. The general tendency is that these stress levels increases with larger plate thicknesses.

During oxy-fuel cutting, preheating and the reduced cutting speeds redistribute and reduce the levels of tensile stresses. Depending on the situation, one or both of these measures will be necessary when cutting the Hardox grades. However, sufficiently low levels of tensile stresses are attained by following the cutting recommendations.

Cutting geometry should be considered because it affects the level of residual stresses, which is a concern for thermal cutting methods related to Hardox 400-Hardox 600 and Hardox Extreme. Sharp cutting angles should be avoided, if possible, since they promote additional stress concentrations in and close to the area to be cut. If corners are required, a suitable cutting procedure is found in fig.11.3.

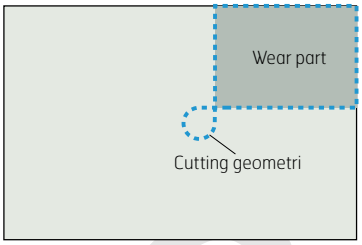


Fig. 11.3: An appropriate procedure for cutting of corners. Take into account that the cutting speed, is typically reduced at the cross section where the cutting path intersect in order to attain a stable cutting operation.

With the exception of Hardox HiTuf, all Hardox grades and Weldox 1030-Weldox 1300 should not be stored with sharp corners from cutting to avoid excessive residual stresses.

11.4 Presence of hydrogen

The presence of hydrogen how is primarily a result of the chemistry of the steel. However, the hydrogen content in the HAZ, where hydrogen cracks can form, can be reduced by applying different measures. The Weldox grades have a high enough resistance to hydrogen cracks that it is unnecessary to take additional steps to remove hydrogen from the HAZ. However, during oxy-fuel cutting, certain grades and thicknesses of the Hardox grades do require special measures to remove hydrogen from the HAZ. This is because a sufficient amount of hydrogen can migrate, by one of the following techniques, during oxy-fuel cutting in an air environment:

1. Preheating the plate.
2. Post heating of areas subjected to cutting.
3. Reduced cutting speed.
4. Combinations of preheating, post heating and reduced cutting speed together with a prolonged cooling process of the HAZ.

The only corresponding measure for underwater oxy-fuel cutting is a reduced cutting speed.

Preheating to enhance hydrogen migration from the HAZ is not required during plasma cutting and laser cutting of the Hardox and Weldox grades.

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11.5 Preheating

The most effective method for avoiding hydrogen cracking during oxy-fuel cutting is preheating the plate. However, preheating is not to be applied prior to laser or plasma cutting of Hardox and Weldox plates due to the negative effect on the quality of the cut edge.

Preheating is an effective way to enhance hydrogen migration from the HAZ to the surrounding air. The mechanism behind preheating is that the higher temperature facilitates a higher degree of hydrogen removal from the HAZ to the surrounding parent metal as well as to the air. The higher the preheat temperature is, the more it will promote hydrogen migration out of the HAZ.

Preheat temperatures for oxy-fuel cutting

The preheat recommendations for oxy-fuel cutting are specified in table 11.2. Due to the continuous development of the Hardox grades, the preheat temperatures may be adjusted over time. Updated information can be found in TechSupport no. 16 or the latest version of this Welding handbook at www.ssab.com.

Grade	Plate thickness	Minimum preheating temp. (°C)	Maximum preheat temperature (°C)
Hardox HiTuf	< 90 mm ≥ 90 mm	No preheating 100	300
Hardox 400	< 44,9 mm 45 - 59,9 mm 60 - 80 mm > 80 mm	No preheating 100 150 175	225
Hardox 450	< 39,9 mm 40 - 49,9 mm 50 - 69,9 mm 70 - 80 mm	No preheating 100 150 175	225
Hardox 500	< 25 mm 25 - 49,9 mm 50 - 59,9 mm 60 - 80 mm	No preheating 100 150 175	225
Hardox 550	10 - 19,9 mm 20 - 50 mm	No preheating 150	225
Hardox 600	12 - 50 mm	175	225
Hardox Extreme*	8 - 25 mm	100 + reduced cutting speed	100

* Due to its crack sensitivity in thermal cutting, SSAB recommends AWJ cutting for Hardox Extreme. If only oxy-fuel is available, the recommendation is to preheat Hardox Extreme to max. 100°C in air and apply the same reduced cutting speed as for Hardox 600.

Tab 11.2: Preheat temperatures for oxy-fuel cutting of the Hardox grades.

	Cutting speed (mm/min)				
Max plate thickness (mm)	Hardox 400	Hardox 450 Weldox 1100	Hardox 500	Hardox 550	Hardox 600
12	no restrictions	no restrictions	no restrictions	no restrictions	no restrictions
15	no restrictions	no restrictions	no restrictions	no restrictions	Max 300
20	no restrictions	no restrictions	no restrictions	no restrictions	Max 200
25	no restrictions	no restrictions	Max 300	Max 270	Max 180
30	no restrictions	no restrictions	Max 250	Max 230	Max 150
35	no restrictions	no restrictions	Max 230	Max 190	Max 140
40	no restrictions	Max 230	Max 200	Max 160	Max 130
45	Max 230	Max 200	Max 170	Max 140	Max 120
50	Max 210	Max 180	Max 150	Max 130	Max 110
60	Max 200	Max 170	Max 140	-	-
70	Max 190	Max 160	Max 135	-	-
80	180	150	130	-	-
>80	Only preheating apply	-	-	-	-

Table 11.1: Recommended reduced cutting speeds for oxy-fuel cutting of Hardox. The recommendations are valid for plate temperatures of min 20°C. When cutting of plates at lower temperatures, further reduction of cutting speed is necessary. The exact cutting speed is for the user to determine for the particular situation.

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Preheating methods and procedures

Depending on the situation, either part of the plate or the entire plate can be heated. Several different operations can be used for this purpose. Examples in this respect are the use of:

- Heating furnace
- Preheating lances
- Electrical mats

A heating furnace is the best way to preheat Hardox plates. This method generates even heating of the entire plate.

Preheating lances can also be applied advantageously for preheating of Hardox and Weldox plates, according to fig. 11.4. However, the lances have to be in motion in order to minimize risks for annealing of the plates. The preheat temperature of the plate is measured on the opposite side of where the preheating procedure is applied. The heating time depends on the plate's thickness and size and is often between 0.5 h-1.5 h when heating is performed from the top side of the plate. Heating from the bottom side will reduce heating time by approximately 30%.



Fig. 11.4: Appliance of preheating lances.

A suitable procedure for preheating the entire plate with electrical mats involves the following steps:

1. Place electrical mats on the floor.
2. Position the plate on the mats. Use a spacing device between the electrical mats and the plate.
3. The preheating of the plate is activated.
4. Cover the plate with insulating material.

Since it takes several hours to heat the plate to 150-200°C, a good practice can be to preheat the plate overnight and begin the cutting performance the next morning.

11.6 Post heating

Similar to preheating, post heating facilitates hydrogen migration away from the HAZ. Post heating is, however, not as effective for preventing hydrogen cracks as preheating. The use of preheating is, therefore, preferable to post heating. Temperatures and application procedures for post heating are the same as for preheating.

11.7 Reduced cutting speed

When the cutting speed is reduced, the material heats up around the cut front. As a result, it will redistribute the residual stresses, reduce their maximum levels and act as a local preheating. This method can only be applied for oxy-fuel cutting of the Hardox grades, except Hardox HiTuf. A reduced cutting speed is not normally applied for laser and plasma cutting because it has negligible influence on cut edge cracking.

Reduced cutting speed is not as reliable as preheating and should only be used as a substitute if, for instance, the workshop does not have appropriate preheating equipment. Preheating is not feasible during underwater oxy-fuel cutting. This fact, therefore, may cause less resistance to hydrogen cracks. A reduced cutting speed, in accordance with table 11.1, can be employed during both cutting in air and underwater. Future development of the Hardox grades may affect the reduced cutting speeds. Updated information can be found in TechSupport no. 16 or the latest version of this Welding handbook at www.ssab.com.

It is possible to gain even further resistance to hydrogen cracks. This procedure may be an option for the Hardox steel grades in thicknesses ≥60 mm, since they have less resistance to hydrogen cracks. It is carried out by first preheating the plate to be cut. Cutting is then executed with a reduced cutting speed and finally, the cut pieces are covered with mineral

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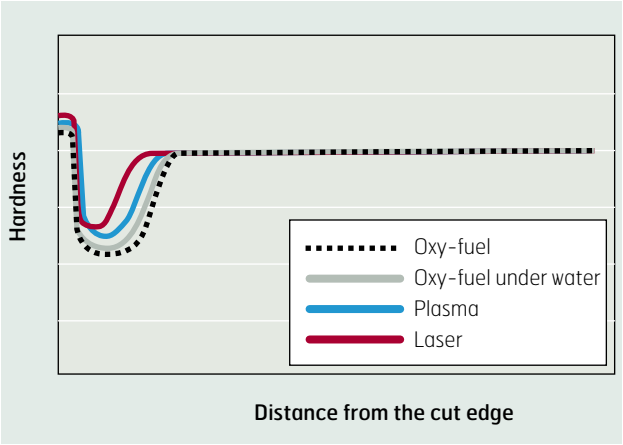


Fig. 11.5: Hardness profiles in the HAZ after thermal cutting of Hardox 400-Hardox 600, Hardox Extreme and Weldox 1030-Weldox 1300 with different cutting methods.

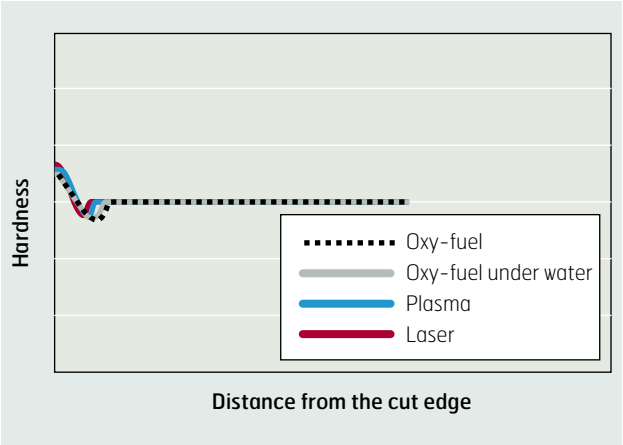


Fig. 11.6: Schematic hardness profiles in HAZ for Weldox 700-Weldox 960 and Hardox HiTuf due to cutting with thermal cutting methods.

wool or another fireproof insulating material, to prolong the cooling time. A reduced cutting speed is to be applied according to table 11.1 and preheating is to be performed in accordance to table 11.2.

11.8 The hardness properties in the HAZ

The outcome of the hardness values in the HAZ depend on:

- Whether or not the steel was tempered during manufacturing, and if so, how it was carried out.
- The specific chemical composition of the steel.
- The impact of the thermal treatment from the cutting process.

The width of the HAZ broadens with increasing thermal impact from the cutting process. A common method to determine the exact thermal impact for the different cutting processes does not exist due to the differences in process technology. However, estimates can be made. From lowest to highest, the following lists the typical heat influence from cutting a plate with a specific thickness: 1) oxy-fuel cutting 2) plasma cutting 3) laser cutting.

Regardless of the cutting method, when the cutting speed is reduced and the other parameters are kept constant, a wider HAZ will develop due to increased thermal impact on the plate. Underwater cutting cools the cutting edge and the HAZ. As a result, there is some reduction in heat impact when compared to an air environment.

Weldox 1030-Weldox 1300 and Hardox 400-Hardox 550 are tempered at relatively low temperatures, typically up to 250°C, or not at all. Schematic hardness profiles in the HAZ for these steels are illustrated in fig. 11.5.

Weldox 700-Weldox 960 and Hardox HiTuf are tempered at high temperatures up to approximately 600 °C. General hardness values in the HAZ for these steel grades are schematically illustrated in fig. 11.6.

Cutting of these steel grades promotes a narrower HAZ compared to Hardox 400-Hardox 550, holding the other cutting conditions the same. This is because the mechanical properties in the HAZ are stabilized for subsequent thermal heat treatments up to the tempering temperature.

More information regarding the hardness distribution in the HAZ for the Hardox and Weldox grades can be attained from SSAB.

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When small pieces are cut, there is an enhanced risk for annealing; this is true for all Hardox grades and Weldox 1030, Weldox 1100 and Weldox 1300. The volume of metal is insufficient to act as a heat sink for the heat supplied. The plate temperature may then increase to more than the maximum preheat temperature, stated in table 11.3, and the hardness of the entire cut piece may be reduced.

Maximum recommended interpass temperature

Weldox 700**	300°C
Weldox 900**	300°C
Weldox 960**	300°C
Weldox 1030	200°C
Weldox 1100	200°C
Weldox 1300	200°C
Hardox HiTuf**	300°C
Hardox 400	225°C
Hardox 450	225°C
Hardox 500	225°C
Hardox 550	225°C
Hardox 600	225°C
Hardox Extreme	100°C

** Interpass temperatures of up to approx. 400°C can be used in certain situations. In such cases, use WeldCalc.

Table 11.3: Recommended maximum preheat levels for Hardox and Weldox grades.

This phenomenon can primarily occur during oxy-fuel cutting because of its high thermal effect. The best way to minimize this risk for hardness loss is to perform the oxy-fuel cutting underwater to diminish the heat impact. Underwater plasma and laser cutting methods can be used for cutting small parts with only a slight risk for annealing of the entire piece.

11.9 Additional benefits to underwater cutting

Cutting plates under water is feasible for the oxy-fuel and plasma methods.

Essential benefits of underwater cutting include:

- Less distortion of cut parts. This is because the water cools the plate during cutting, which obstructs the thermal impact.
- Less smoke and dust is generated during cutting. The reduction is even greater for the plasma method in relation to oxy-fuel cutting.
- Cut parts can be handled immediately after cutting due to cooling effects of the water.

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12.0 The use of shielding gas

The main function of the shielding gas is to protect the melt from the nitrogen and the oxygen in the air during welding, thus promoting beneficial mechanical properties in the weld metal. Additionally, the shielding gas aids in:

- Facilitating a stabilized arc during welding.
- Achieving high welding productivity.
- Providing an appropriate weld penetration profile.

The chemical composition of the shielding gas is dependent on the specific welding situation. In this context, proposals of suitable shielding gas compositions and flow rates are described for the different MAG processes as well as for the TIG process. The selection and application of the shielding gas for Hardox and Weldox steels is the same as for unalloyed and low-alloyed steels in general.

12.1 MAG welding

MAG welding is performed with different kinds of consumables including solid wires, flux cored wires and metal cored wires. A typical shielding gas for MAG welding with these types of consumables is a mixture of argon (Ar) and carbon dioxide (CO_2). Another alternative is a shielding gas consisting of 100% CO_2, which can be a good option in certain situations for MAG welding with flux cored wires. The proportions of argon and carbon dioxide in Ar/CO_2 mixtures are related to the type of arc that is applied. Some mixtures are optimized for welding with a specific arc. Others can attain favorable results when welding with more than one arc type.

The two principal arc types that are feasible during MAG welding are short arc and spray arc. A pulsed arc, which can be considered as a kind of spray arc, is also possible. However, use of this kind of arc when welding high strength steels such as Weldox and Hardox is comparatively unusual.

Arc types for MAG welding

Each arc type is confined to certain intervals of the current and voltage that are applied during the welding operation. A schematic diagram for the emergence of short arc and spray arc is illustrated in fig. 12.1. Improper settings of the current and voltage can result in the formation of a globular arc that is very unstable and, therefore, undesirable.

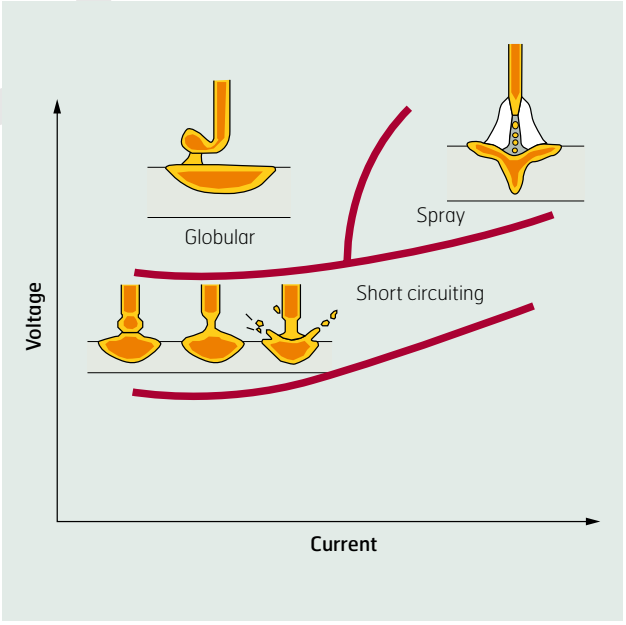


Fig. 12.1: The short arc and spray arc appearance for different levels of current and voltage settings during MAG welding with an Ar/CO_2 shielding gas mixture. Welding is typically performed with D.C.

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Short circuiting transfer

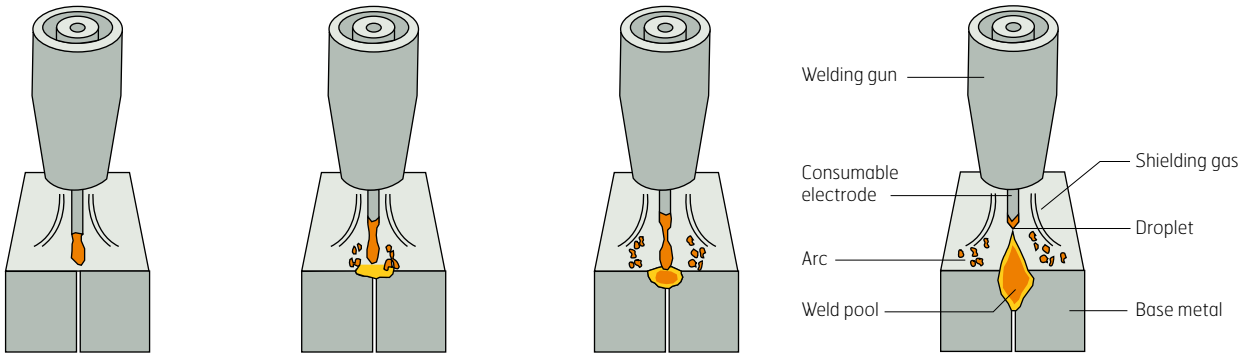


Fig. 12.2: Illustation of short arc welding.

Other welding parameters also influence the emergence of the arc types, including the chemical composition of the shielding gas, the diameter of the consumable and the stick-out length of the wire from the contact nozzle.

Short arc occurs during welding with relatively low heat inputs. This arc allows for versatile welding operations, including:

- Out of position welding, making all types of welding positions conceivable.
- Welding of joints with a wide range of plate thicknesses, including the complete thickness range of the Hardox and Weldox grades.

Some general drawbacks for short arc welding include:

- Relatively low welding productivity.
- The tendency toward an unstable arc. Therefore, special care should be taken in order to achieve suitable welding parameters. A good general measure is to apply a short arc length to promote a stabilized arc performance.
- The increased risk for lack of fusion when welding in heavy plate thicknesses, due to the low heat input.

Short arc welding is characterized by a metal transfer from the consumable, where each droplet short-circuits the arc. The droplet transfer has a low frequency of approximately 50-200 Hz.

Each droplet grows to a comparatively large size during the metal transfer and then short circuits, giving a momentarily high current. The droplet leaves the wire and the arc is struck again, see fig. 12.2. The metal transfer leaves the wire assisted by the surface energy in the melt. Short arc welding can be identified by its characteristic sparkling sound.

Spray arc welding normally has a rather high heat input which leads to higher productivity compared to short arc welding. This arc has a degree of stability that contributes to a very low level of spatter. Spray arc can be performed in the horizontal position for solid wires, flux cored wires and metal cord wires. Using rutile flux-cored wires gives the advantage of welding in positions other than the horizontal. The high heat input means that the range of suitable single plate thicknesses for this technique is limited to approximately 5 mm and above. The exception is pulsed arc welding, which can weld joints of thinner single plate thicknesses.

The metal droplet transfer has a higher frequency compared to short arc welding and the size of each metal droplet is small. In spray arc welding there are no short circuits and the droplet leaves the wire as a small droplet or a spray through the arc, according to fig. 12.3.

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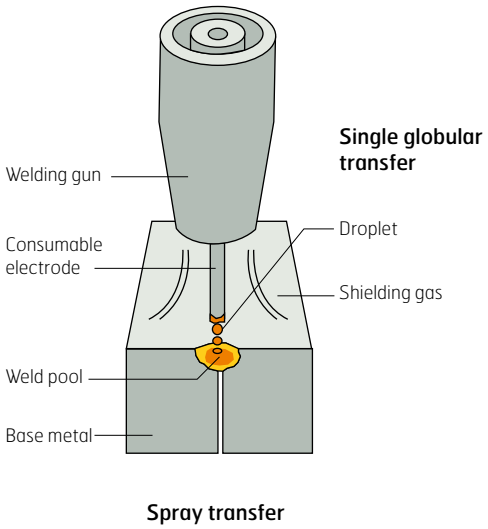


Fig. 12.3: MAG welding with a spray arc.

The sound from spray arc welding can be distinguished from short arc welding by its uniform character.

Welding with a pulsed arc technique means that a spray arc can be attained with relatively low heat inputs. This technique uses a pulsed current where the top values of the parameters are high enough for a spray arc to form while, at the same time, the mean value of the current is proportionally low. Each pulse peak of the current enables a droplet transfer, without short-circuiting, from the consumable to the melt, which is illustrated in fig. 12.4.

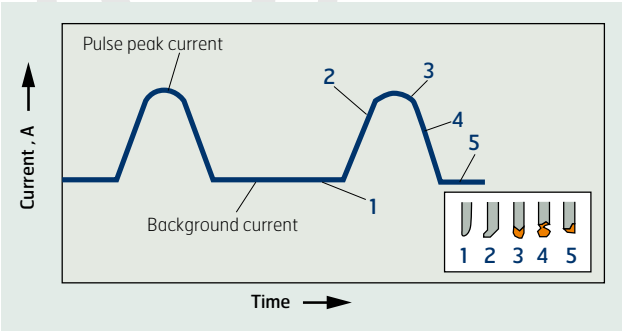


Fig. 12.4: Typical current appearance during pulsed arc welding.

The pulsed arc technique is similar to the spray arc technique with the main exceptions being:

- Thinner plate thicknesses can be welded using the pulsed arc technique since welding can be carried out with lower heat input in relation to conventional spray arc welding. Even the thinnest plate thicknesses in the Hardox and Weldox range can be welded with the pulsed arc technique.
- A disadvantage of the pulsed arc technique is lower productivity, compared to spray arc welding, and the possibility of lowered productivity compared to short arc welding.

The selection of shielding gas compositions for pulsed arc welding is the same as for spray arc welding. The issues regarding pulsed arc welding are, therefore, included in the recommendations for spray arc welding.

Because of the continuous developments in MAG welding of high strength steels, there are other, more unconventional, arc types than those mentioned in this chapter. For updated information in these matters, contact SSAB.

Shielding gases for MAG welding

When applying a gas mixture of argon and carbon dioxide in MAG welding, there are advantages as well as drawbacks associated with each chemical component. The objective is to optimize the mixture for each specific welding situation by drawing on the benefits of both chemicals while minimizing the drawbacks as much as possible.

There are alternatives to the suggested gas mixtures mentioned in this chapter. One alternative is to partly or completely replace CO_2 with oxygen. Since these mixtures have a limited usage, they are not mentioned further in this context. Additional information regarding these shielding gas mixtures can be obtained from the gas manufacturers.

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Argon

The addition of argon in the shielding gas promotes the formation of the arc during welding. An electric arc in the gap between the electrode and the work piece can be established when the atoms are ionized to ions and electrons, see fig. 12.5. Argon atoms are ionized relatively easily. Consequently, argon promotes easy arc striking.

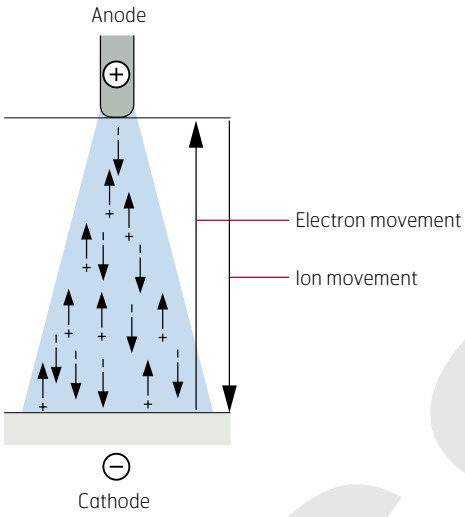


Fig. 12.5: Movement of electrons and ions in an arc. In this case, the electrode has a positive polarity and the joint has a negative polarity. The temperature in the arc reaches several thousand degrees Celsius.

Argon also enhances the formation of the spray arc transfer. However, a 100 % argon shielding gas would lead to an unstable arc so the shielding gases need to include another gas component that has the ability to stabilize the arc.

Argon promotes a narrow and intense arc that produces a deep penetration profile in the center of the weld metal, often called the argon finger, see fig. 12.6. It lowers the heat transfer capacity in the melt during welding; contributing to a narrower penetration profile for each weld pass.

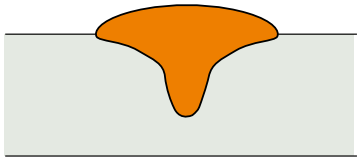


Fig. 12.6: The penetration profile promoted by a shielding gas with high argon content.

The negative effects from a relatively small and narrow penetration profile include an increased risk for lack of fusion in the joint as well as a somewhat higher susceptibility towards porosity in the weld metal.

Carbon dioxide

The carbon dioxide in the Ar/CO_2 shielding gas mixtures stabilizes the arc.

The CO_2 also contributes to a higher capacity of heat transfer to the liquefied melt, which influences the geometry of the weld metal. It helps to give the weld metal a relatively large and round shape which is illustrated in fig. 12.7. The shape and size of the weld metal provides further resistance to lack of fusion and porosity in the weld metal.

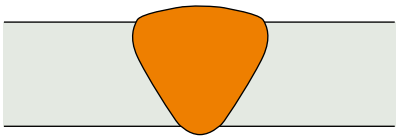


Fig. 12.7: Penetration performance of a shielding gas consisting of only CO_2.

CO_2 is normally added in relatively small amounts according to the proposals in table 12.1. If the CO_2 content in the shielding gas is too high, it will obstruct the formation of spray arc welding. The maximum CO_2 content under which spray arc welding is feasible in Ar/CO_2 mixtures is approximately ≤ 25%.

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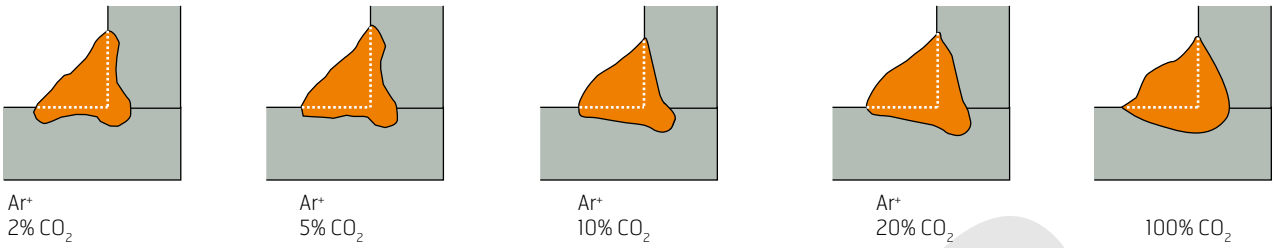


Fig. 12.8: Schematic penetration profiles when varying the composition of the shielding gas during MAG welding.

Selection of shielding gas for MAG welding

Due to the influence of the shielding gas, the final welding performance is a combination of the properties from each individual gas component. An increased fraction of a gas component leads to a greater influence of the characteristics for that specific gas. The typical penetration profiles for different gas mixtures are illustrated below in fig. 12.8. for the welding of fillet joints.

General proposals for shielding compositions are according to the table 12.1.

Welding method	Arc type	Shielding gas [weight %]
MAG, solid wire MAG, metal cored wire	Short arc	Ar + 15-25 % CO_2
MAG, solid wire MAG, metal cored wire	Spray arc	Ar + 8-25 % CO_2
MAG, flux cored wire	Short arc	Ar + 15-25 % CO_2, or pure CO_2
MAG, flux cored wire	Spray arc	Ar + 8-25 % CO_2, or pure CO_2
MAG, all types	All arc types	Ar + 15-25 CO_2
TIG		Pure Ar

Table 12.1: Suggestions of different gas mixtures for welding the Hardox and Weldox grades.

12.2 Shielding gas for TIG welding

The shielding gas mixture for TIG welding is easier to decide since there are fewer options compared to MAG welding. During TIG welding, a gas should be used to protect the weld pool, its immidiate adjecent parent metal and the tungsten electrode from oxidation. Furthermore, it should allow for a stable arc to be established. In general, SSAB proposes a shielding gas composition of pure argon for TIG welding which fulfills these requirements.

12.3 General grouping of suitable shielding gases in MAG and TIG welding of Hardox and Weldox

The shielding gases proposed in table 12.1 for MAG and TIG welding of Hardox and Weldox are well balanced in order to support a high quality welding performance. If Hardox and Weldox grades are welded to other types of steel the same gas types may be applied.

Note that shielding gases other than the ones mentioned in the table above can also be used. The consumable manufacturer can also specify a certain shielding gas composition for a specific consumable. In such a case, the recommendations for the consumable should be applied.

12.4 Gas flow during MAG and TIG welding of Hardox and Weldox

Gas flow can be optimized in order to get a well-balanced welding performance. Too little gas flow results in inadequate protection of the melt. Excessive gas flow can become turbulent thus deteriorating the gas protection. The gas flow for all welding methods based on shielding gases, as a rule of thumb, can be set by using the same number of the gas flow measured in l/min as the inner diameter of the nozzle measured in mm.

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13.0 Distortions in joints

There is a natural tendency for distortions to occur during arc welding and the Hardox and Weldox grades are no exception in this respect. Sometimes the distortions need to be corrected which means that further work and costs are encountered. However, the levels of distortions that emerge due to welding can be decreased if suitable measures are taken during the:

- Design of the structure
- Planning and execution of the welding performance

In this chapter, issues regarding the emergence of distortions and how to keep them at reasonably low levels are addressed.

13.1 Mechanisms behind the formation of distortions

Stresses that cause distortions are formed by the same factors that cause residual stresses in the joint, described in chapter 4. As such, the basis for their occurrence is a welding performance that creates a non-uniform heat treatment in and around the weldment.

Distortions can develop in the structure during cooling for up to 0.5 h-1 h after the completion of welding. The dimensional changes that occur are related to one or more of the appearences displayed in fig. 13.1.

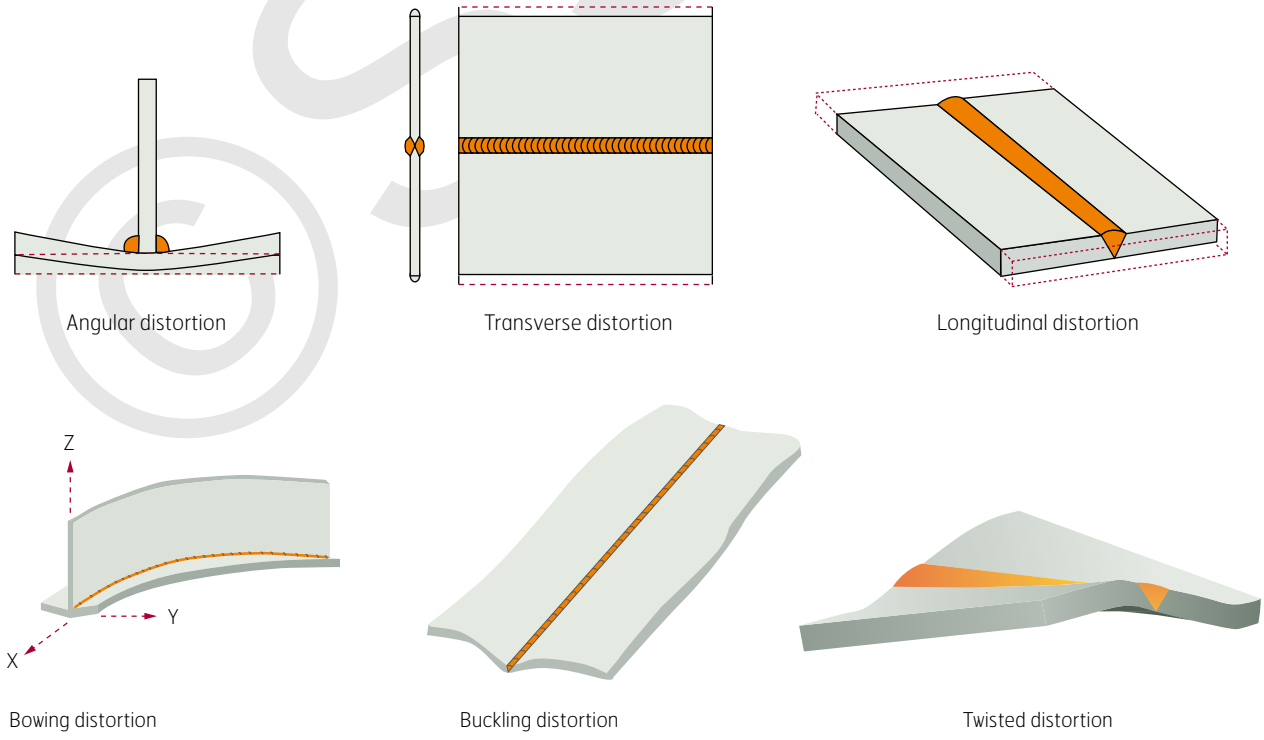


Fig. 13.1: Frequent principal directions of distortions in welded structures.

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The actual geometry and size of the distortions in a welded structure is complex and can take various forms. Their appearance depends on a combination of effects from several factors such as:

- Joint geometry
- Heat input applied
- Locations of the joints in the structure
- The planning and execution of weld sequences
- The level of restraint in the joint
- If presetting of the joint is carried out

The exact directions and levels of the distortion in a structure are normally difficult to predict before welding actually takes place. However, the following issues address general measures that can reduce distortions in a welded structure.

Appearance of the joint geometry

Reducing the volume of the joint geometry decreases the general distortion of the joint. This is because the weld metal naturally shrinks during the cooling process of welding, consequently, smaller volumes of weld metal lead to less distortion compared to larger volumes.

Example 1:

Unsymmetrical joints typically lead to angular distortions. This issue is exemplified for a single-V butt joint. In this type of joint, there is more weld metal at the upper section compared to the lower section. Since larger volumes of weld metal contract more than smaller ones during welding, an angular distortion will occur. If the groove angle is increased, then larger levels of angular distortions are further promoted, see fig. 13.2.

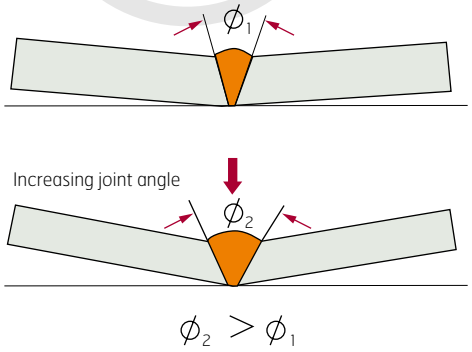


Fig. 13.2: Influence of different groove angles in single-V butt joints

Example 2:

If feasible, a balanced welding sequence that alternates between each side of the joint is favorable since this measure reduces the distortion in the joint. In this case, each weld pass counteracts distortions from the previous weld pass. A symmetrical joint supports these types of welding sequences. This issue is mainly addressed for the first weld passes, see fig. 13.3.

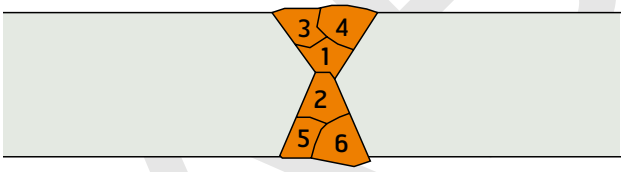


Fig. 13.3: Favorable welding sequences for a double-V joint. The number of each pass indicates the weld sequence. A double-V joint is often suitable for thicker joint sections where a number of weld passes are to be performed.

The effect of heat input

A lowered heat input can lower the distortion levels in the joint as long as the number of weld passes in the joint does not increase. The reasons are that:

- The volume of the weld metal from each weld pass decreases with a lowered heat input. The weld metal from each pass shrinks during cooling leading to less distortion because a smaller amount of weld metal deforms less than a larger amount
- Parent metals that are thermally affected around the weld metals can shrink and cause distortions. A reduced heatinput causes a narrower zone of thermally affected parent metals, which thereby supports lowered distortions.

A common way to decrease distortions using this measure is to increase the welding speed. However, if a reduction in heat input leads to additional weld passes in the joint, this technique might not be advantageous and may instead cause increased levels of distortions.

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Placement of the joint

The closer the joints are situated to the center of gravity of the structure, the lower the bowing distortions are due to welding. This is because distortions lead to more bending as the distance from the center of gravity increases, see fig. 13.4.

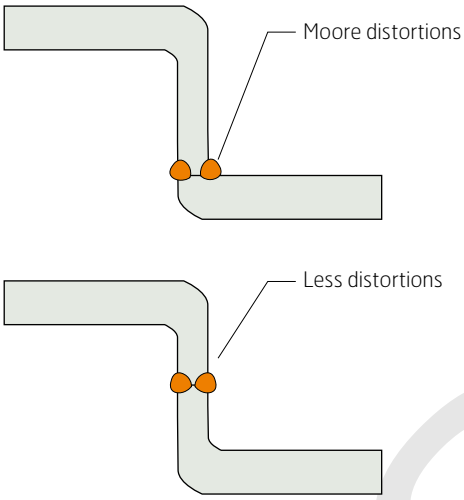


Fig. 13.4: The bottom structure supports lower levels of bowing distortions than the top structure.

Joints located symmetrically around the center of gravity lower the level of bowing distortions since the distortions from each joint counteract each other, which is illustrated in fig. 13.5. If the joints on each side of the center of gravity are welded simultaneously, the distortions are additionally reduced compared to welding the joints one at a time.

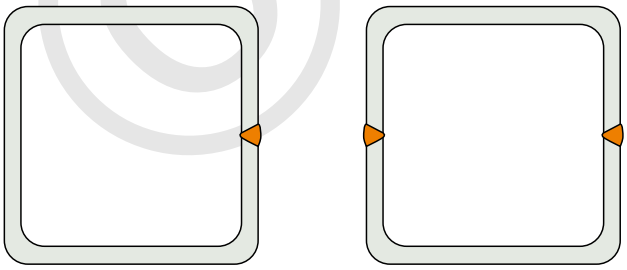


Fig. 13.5: The welded structure on the right favors lower bowing distortions than the structure on the left.

The influence of external joint restraint

A joint with a high degree of restraint will have less distortions compared to a joint with a lower degree of constriction. External restraint can be applied by using fixtures, clamps or welding tack welds, as exemplified in fig. 13.6. However, a higher level of restraint supports higher residual stresses in the welded joint.



Fig. 13.6: Utilizing clamps in a joint.

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Welding towards sections of lower constriction

Welding evaluations that are executed from areas with high levels of restraint towards areas with lower levels of restraint show decreased levels of distortions. Two suitable options in this respect are illustrated in fig. 13.7.

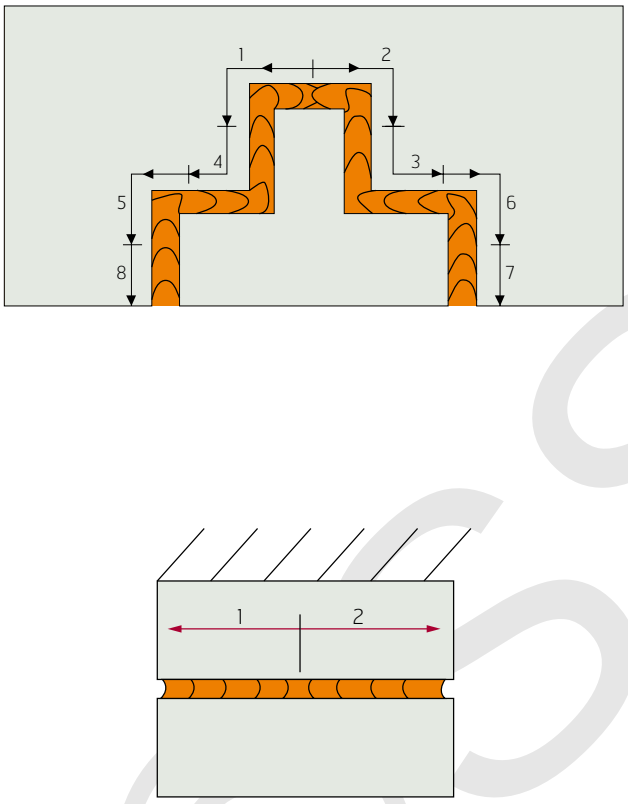


Fig. 13.7: Different examples where welding sequences are performed towards sections with lower levels of restraints.

Presetting of the joint

Presetting the plates in the structure prior to welding can compensate for the distortions to come.

One way to prevent distortions is to make welding trials with no presetting to see where the distortions occur. After each trial, the distortions are measured and the average values of the distortions are calculated. Finally, prior to production welding, the joint is preset at the average values of distortions, but in the opposite direction, see fig. 13.8.

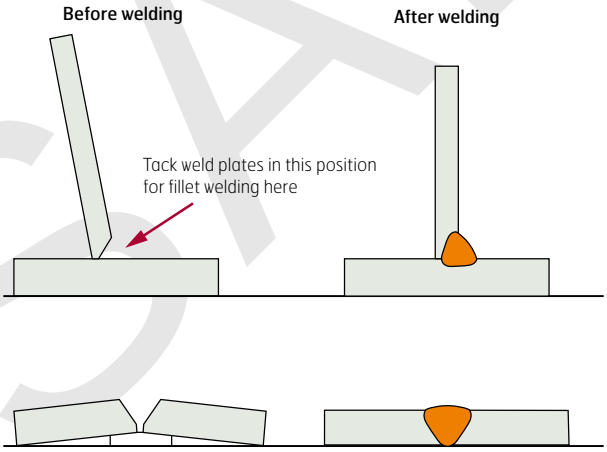


Fig. 13.8: Presetting of a fillet joint and a single-V butt joint.

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The use of back step or skip welding techniques

Experience has shown that welding the joint in smaller sections backward to the general progression may result in reduced distortions. This method is utilized in the back step and skip welding techniques, according to fig. 13.9.

In these techniques, the length of each weld sequence can be adapted in order suit the actual welding situation. As an example, if welding is performed with MMA, the length of each welding sequence can be set to the run out length for the individual consumable.

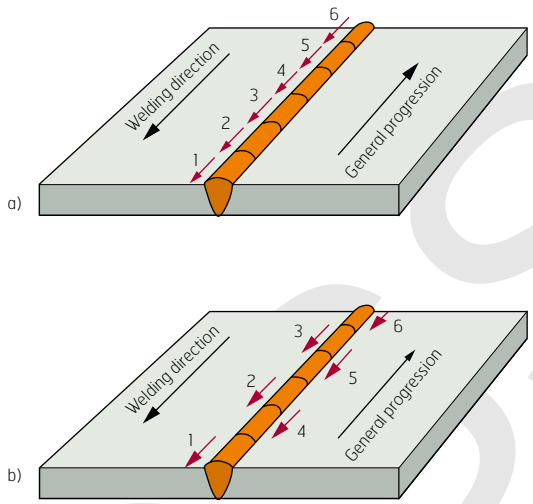


Fig. 13.9: Illustration of back step and skip welding techniques.

Software for analyses of distortions

Predictions of distortions in joints are feasible with computerized methods based on fenite element models (FEM). The software available for these purposes is continuously being developed. If this kind of calculation method is to be used, it is a good practice to first evaluate the software of interest. An assessment of the software can, for instance, be made in order to find out if sufficient results can be attained compared to actual measurements of distortions in joints.

Straightening of distortions

After welding, straightening of the structure using mechanical straightening methods is sometimes necessary.

Thermal straightening methods are not normally recommended for the Hardox and Weldox grades. Weldox 700-Weldox 960 and Hardox HiTuf can, in some special cases, be straightened by thermal methods. Contact SSAB for further information on this matter.

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14.0 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 chapter 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.

Some types of discontinuities can be called defects but the meaning of these two terms differs to some extent. A discontinuity is an interruption of the physical structure of the weldment. 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 chapter 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 chapter 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 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 chapter 15.

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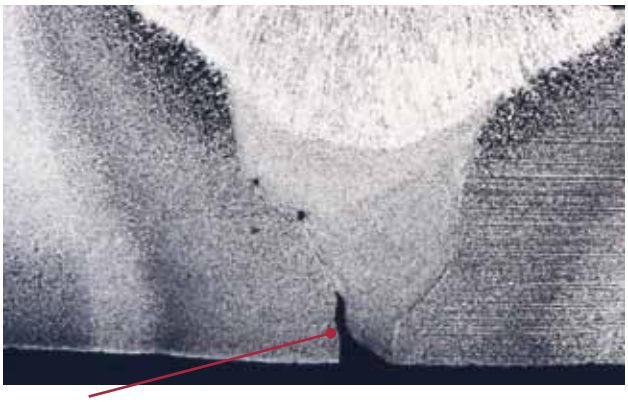


Fig. 14.1: Lack of root fusion. (Reproduced by permission, TWI Ltd.)

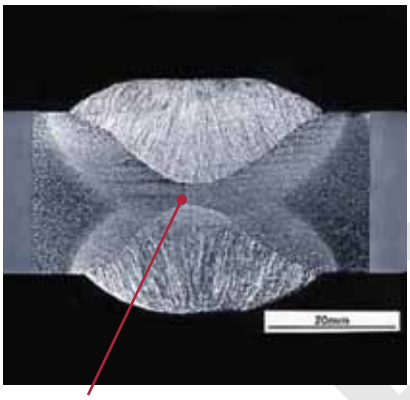


Fig. 14.2: Lack of root fusion. (Reproduced by permission, TWI Ltd.)

14.1 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 fig. 14.1. This kind of discontinuity can also be present when welding is performed from different sides of the joint, which is exemplified in fig. 14.2.

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 fig. 14.3. Suitable joint geometries depend on the welding method applied and the actual welding situation.
- 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.

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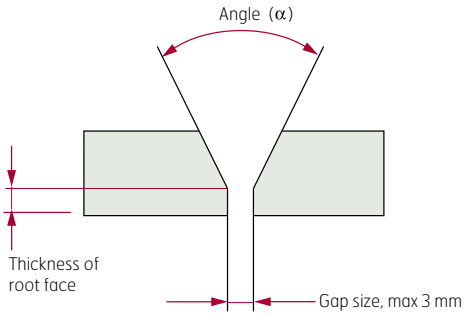


Fig. 14.3: Drawing of a single-V butt joint.

- 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.

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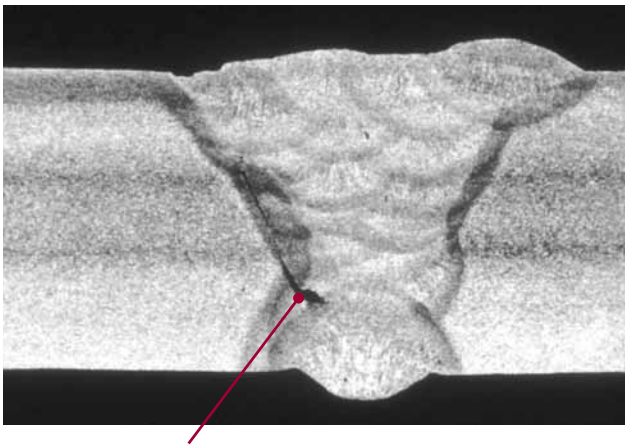


Fig. 14.4: Lack fusion between the weld passes. (Reproduced by permission, TWI Ltd.)

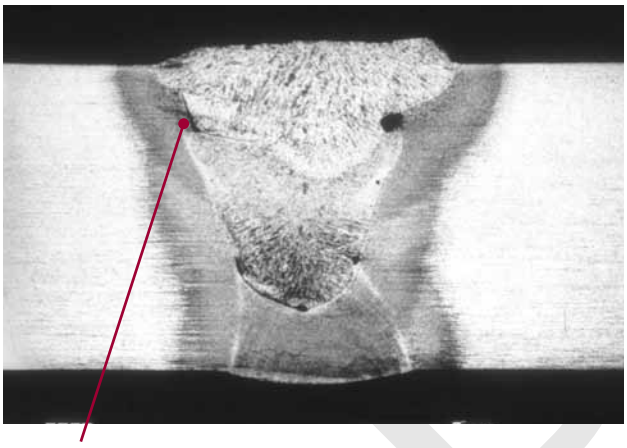


Fig. 14.5: Lack fusion between the weld metal and the parent metal. (Reproduced by permission, TWI Ltd.)

14.2 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 fig. 14.4 - fig. 14.5. 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:

- 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 fig. 14.3.
- 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 EN 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.

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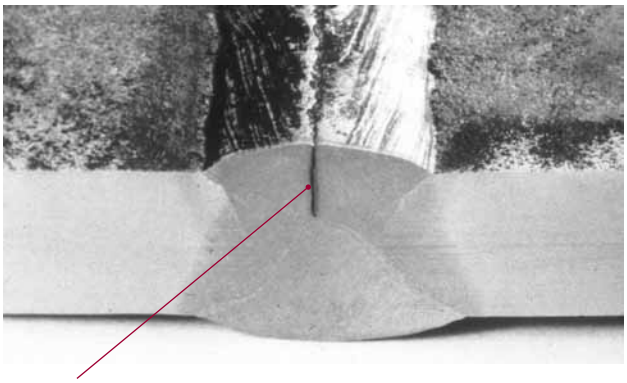


Fig. 14.6: Solidification crack.
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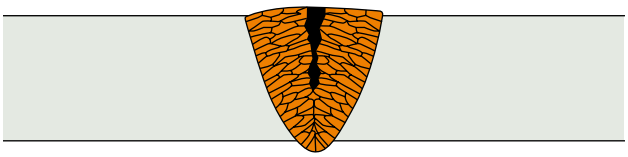


Fig. 14.7: Hot cracks can form if the weld pool is not fed with a sufficient amount of weld metal from the consumable.

14.3 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 fig. 14.6. Solidification cracks can be surface breaking or embedded in the weld metal.

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 fig. 14.7. 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.

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.

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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 fig. 14.8. This can be achieved, for example, by using a sufficiently high wire feed.

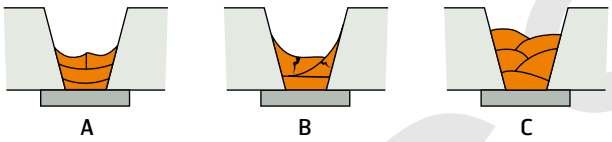


Fig. 14.8: Effect of weld shape in multi pass welds:
A and B) Concave welds with tendency to crack.
C) Slightly convex weld beads

- 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 fig. 14.10. 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.

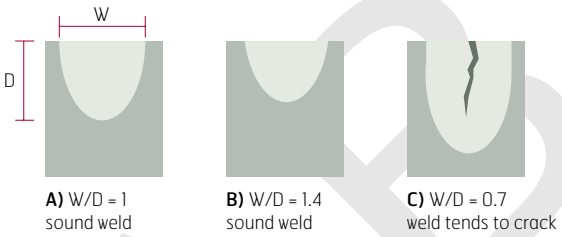


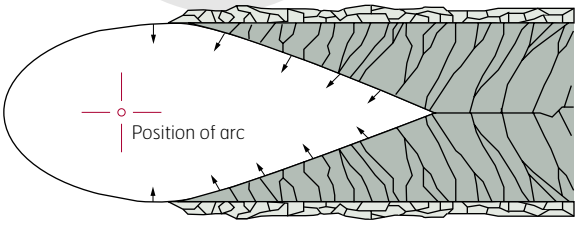
Fig. 14.10: Effect of weld shape on cracking tendency:
A) W/D = 1, sound weld
B) W/D = 1.4, sound weld
C) W/D = 0.7, weld tends to crack

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 fig. 14.9.

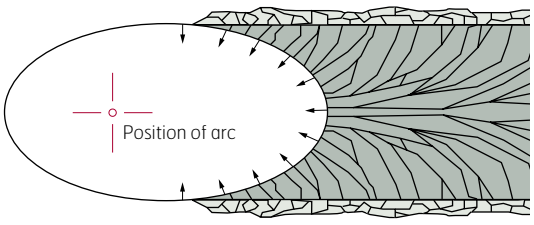
- Applying a joint with a lower level of restraint is beneficial in order to counteract solidification cracks.

Acceptance criteria according to ISO 5817

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



Schematic diagram showing competitive growth with a teardrop shaped weld pool



Schematic diagram showing competitive growth with an elliptical weld pool

Fig. 14.9: 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.

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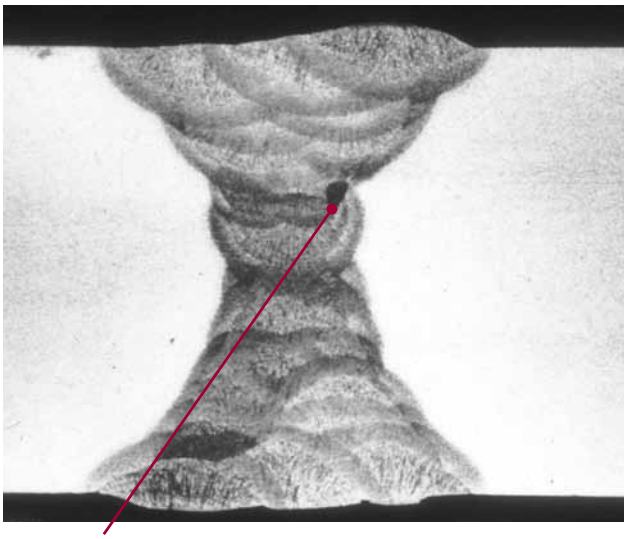


Fig. 14.11: Internal slag formation in weld metal.
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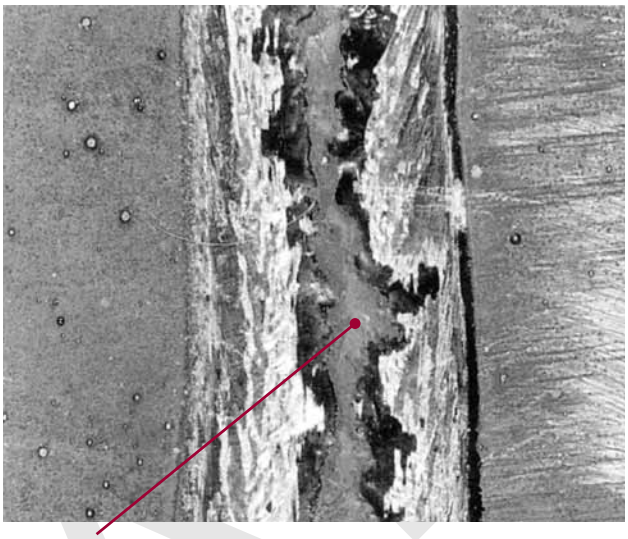


Fig. 14.12: Slag formation at the weld surface.
(Reproduced by permission, TWI Ltd.)

14.4 Slag formation

Description of slag formation

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 fig. 14.11 and fig. 14.12. Slag is less dense than weld metal so it typically floats up to the surface during welding.

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 related 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.

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Fig. 14.13: 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.

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 fig. 14.13.
- 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.

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14.5 Undercuts

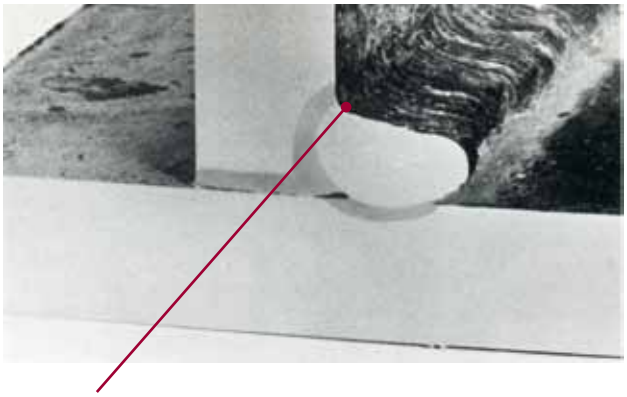


Fig. 14.14: Undercuts.
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Description of undercuts

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 fig. 14.14. If undercuts occur, they are longitudinal to the joint.

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.

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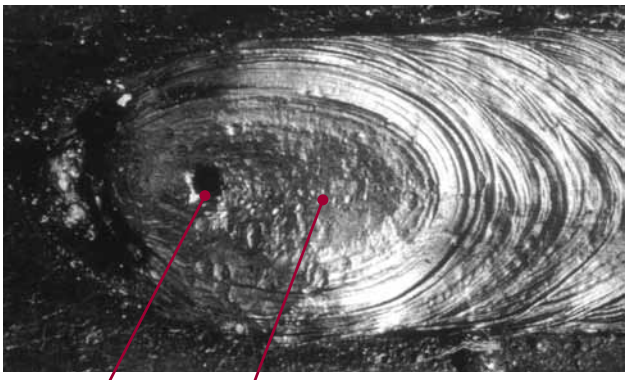


Fig. 14.15: Pore Crater pipe
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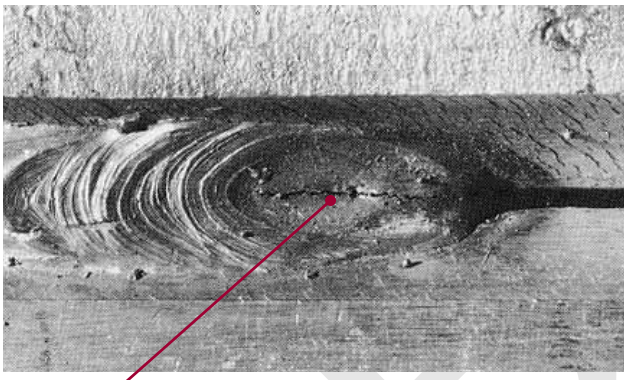


Fig. 14.16: Crater crack
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14.6 Crater pipes

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 fig. 14.15 - fig. 14.17. Crater pipes reach the surface of each weld pass.

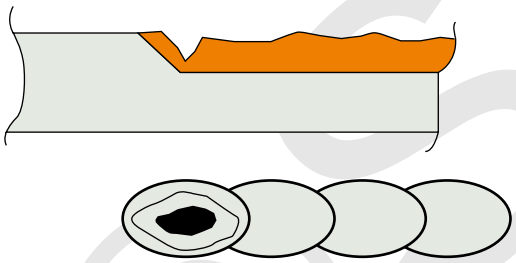


Fig. 14.17: Crater pipe.

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.

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.

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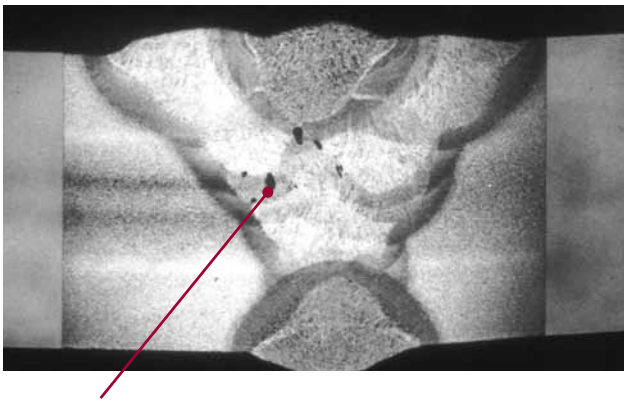


Fig. 14.18: Internal porosity in the weld metal.
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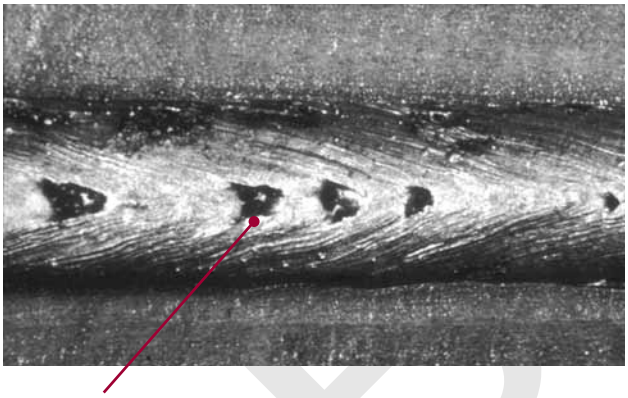


Fig. 14.19: Surface breaking porosity.
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14.7 Porosity

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 fig. 14.18, or surface breaking, see fig. 14.19. They can appear in various geometrical forms and concentrations. The principal gases that are found in embedded pores are nitrogen, oxygen and hydrogen.

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.

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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.

14.8 Spatter

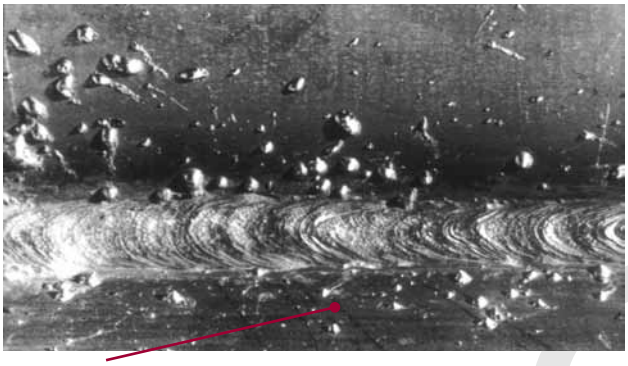


Fig. 14.20: Spatter
(Reproduced by permission, TWI Ltd.)

Description of spatter

Spatter is small metal droplets that can form in the arc during a welding performance, according to fig. 14.20. 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.

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15.0 Magnetic arc blow

Welding with an electric arc creates a magnetic field around the electrode, according to fig. 15.1. The intensity of its lines of force, also called the magnetic flux density, gradually lowers as the distance from the electrode increases. If the magnetic field is disturbed by external sources, it may cause deflection of the arc during welding. This phenomenon is called magnetic arc blow, or arc blow. It can lead to several kinds of discontinuities in the joint, including lack of root penetration, lack of fusion, undercuts and pores. It may not be possible to totally eliminate arc blow but steps can be taken in order to reduce its negative effect.

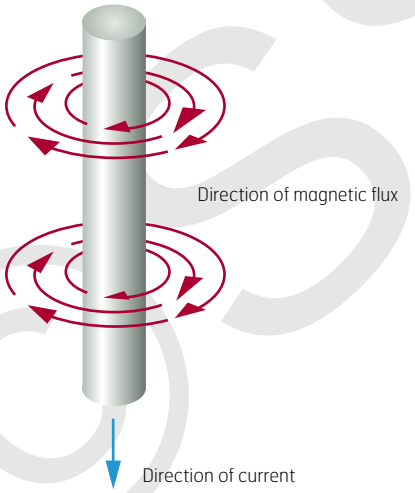


Fig. 15.1: The direction of the magnetic field in relation to the current during welding with D.C.

The deflection of the arc can be more or less stable during magnetic arc blow. The source of the interference is what influences its behavior. A deflection of forward arc blow and backward arc blow is illustrated in fig. 15.2.

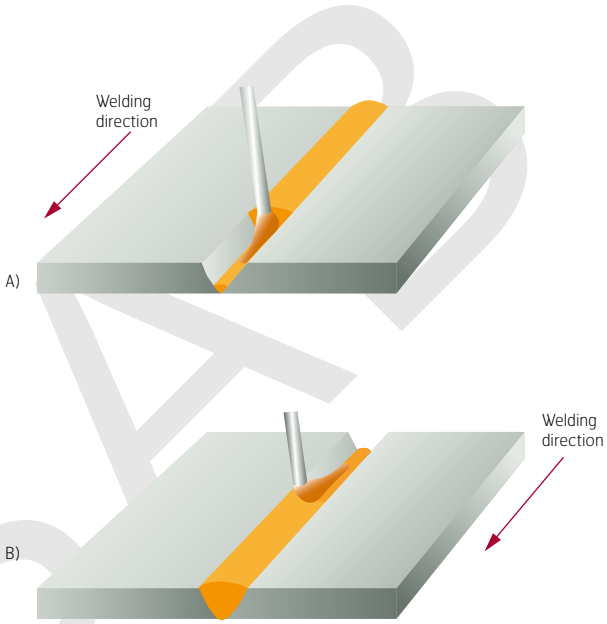


Fig. 15.2: Forward arc blow is illustrated in the upper figure A) and backward arc blow in the lower figure B).

Essential sources that can achieve, or contribute to, magnetic arc blow are:

- Residual magnetism in the steels subjected to welding.
- The appearance of the joint.
- Welding with multiple electrodes.

Residual magnetism is primarily an issue related to tack welds and root runs. After these sequences, the residual magnetism in the joint is normally low enough to reduce arc blow.

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15.1 Residual magnetism in steels

Ferromagnetic steels, including the Hardox and Weldox grades, can contain varying levels of residual magnetism. If the intensity of the lines of force is high enough, this magnetism can interfere with the magnetic field from the welding torch and cause magnetic arc blow. Common sources that enhance the magnetism of the steel include magnets used in jacking equipment or storage in a place with high levels of magnetic flux densities.

Low levels of magnetism in the joint will not influence the stability of the arc. Arc blow disturbances can occur when the magnetic flux density is approximately 40 Gauss or above.

The Hardox and the Weldox grades are high strength steels with favorable resistance to residual magnetism, even though there are instances when they can obtain magnetic flux densities of 40 Gauss or more. The sensitivity towards magnetic arc blow, caused by residual magnetism in the steel, is generally more emphasized with Hardox grades of higher hardness and higher strength Weldox grades.

15.2 The appearance of the joint

The resistance to magnetic flux depends on the characteristics of the medium through which it flows. Steel has a substantially lower resistance in this respect than air. Consequently, free ends of plates can have a lower level of magnetism than a joint including the same plates.

The level of residual magnetism can vary throughout the joint when the distances between the steels in the joint vary. For instance, in a single-V joint, the distance between the parent metals in the joint are shortest at the root section. Therefore, there is a higher level of magnetism compared to other parts of the joint where the space between the steels is greater, see fig. 15.3. The magnetic flux density, therefore, should be measured at the location of the next weld pass in order to determine the risk for magnetic arc blow. A hand held gauss meter is a typical instrument used for this purpose.

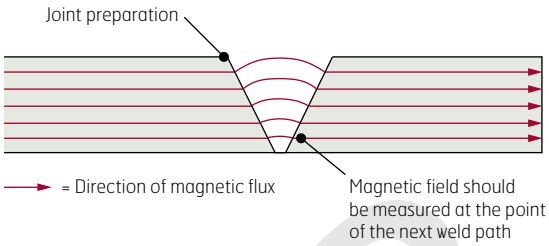


Fig. 15.3: Magnetic fields in a single-V prepared joint.

The geometry in joints of larger plate thicknesses can cause an increased risk for magnetic arc blow. Welding in this condition means that a substantial fraction of the arc can be surrounded by the parent metals at a close vicinity, especially during root passes and tack welds. Since the magnetic field flows easier through steel than air, an unsymmetrical magnetic field can be formed around the torch, which may cause arc blow.

Similarly, arc blow can occur when welding plates of different thicknesses, according to fig. 15.4. In this situation, the arc may deflect towards the thicker plate in the joint.



Fig. 15.4: Arc blow due to different plate thicknesses in the joint.

15.3 Welding with multiple arcs

Multiple electrodes normally lead to increased welding productivity in comparison to welding with a single electrode.

Welding with multiple arcs using D.C., where there is only a small distance between the electrodes, may cause arc blow since the magnetic field from each electrode can influence the performance of the adjacent arc.

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If arc blow is encountered, equal polarity between the electrodes supports inward arc deflection and unequal polarity supports outward arc deflection, according to fig. 15.5.

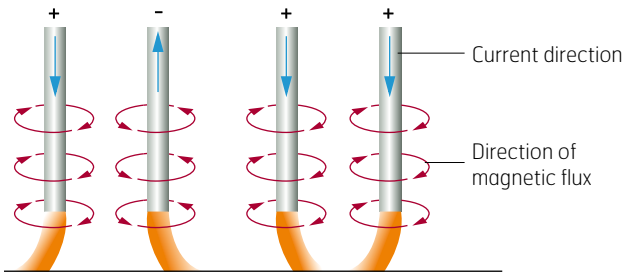


Fig. 15.5: Arc deflections during welding with two electrodes.

15.4 Measures to counteract magnetic arc blow

When magnetic arc blow is encountered or suspected, steps can be taken to attain suitable conditions for welding.

The angle of the torch

A magnetic arc blow that deflects the arc at a specific direction can be counteracted by inclining the electrode angle opposite to the direction of the arc blow, see fig. 15.6.

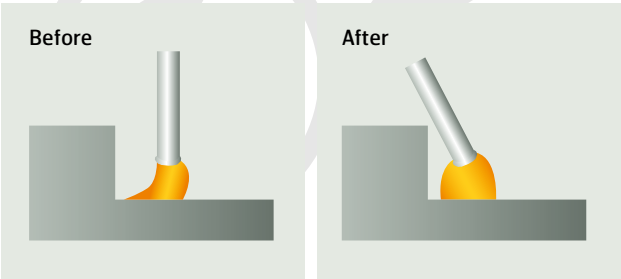


Fig. 15.6: Straightening of the arc by angling the electrode.

Welding sequences

Tack welds and root runs diminish and/or redistribute the magnetic fields in the joint.

This effect is brought on by:

- Heating of the joint due to welding.
- A redistribution of the magnetic field. This is facilitated if weld metal is present in the joint because it acts as a bridge for the magnetic flux flow.

The following two steps can be utilized to plan the welding sequences appropriately so that the level of magnetism is below 40 Gauss in sections of the joint: First, mark the locations in the joint where the local magnetism is below 40 Gauss. Then place tack welds at suitable locations along the marked areas. Long individual lengths of tack welds are preferred and their individual lengths should be set to a minimum of 50 mm each. Repeat this procedure until the magnetism is below 40 Gauss in the complete joint, after which, the rest of the welding procedures can be performed.

Welding with A.C.

Electrodes connected to A.C. are less prone to arc blow in the joint compared to those coupled with D.C.

The reasons are that:

- The direction of the magnetic field around the electrode continuously changes making it less susceptible to external sources of magnetism.
- Welding with A.C. introduces eddy currents into the joint, see fig. 15.7, which reduces the negative effect from an external magnetic field.

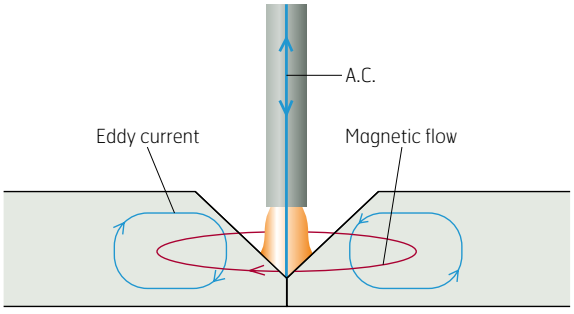


Fig. 15.7: Induction of eddy currents in the joint.

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Workpiece connections

Proper placement of the workpiece connection can diminish magnetic arc blow. This technique intro duces a magnetic field in the opposite direction to the one causing the arc blow.

The cause is that the current return from welding goes through the workpiece, which causes a magnetic field in its path. This magnetic field supports an arc deflection away from the workpiece connection, according to fig. 15.8.

If back blow of the arc is encountered, it can be counteracted by positioning the workpiece connection away from the direction of welding. If forward arc blow occurs, locate the workpiece connection towards the direction of welding. The use of more than one workpiece connection might further improve this method. The effect from the location of the workpiece connection is limited, so this measure is normally done together with other complimentary measures in order to avoid arc blow.

Welding joints of larger plate thicknesses

If arc blow is encountered due to large plate thicknesses in the joint, and the level of residual magnetism is insignificant, then widening the joint at the root section may be beneficial. One example is to change the V-prepared joint to a U-prepared joint.

Demagnetizing equipment

The steel in the joint can be demagnetized from residual magnetism. There are different types of techniques and equipment available for this purpose. The appropriate solution is situation based.

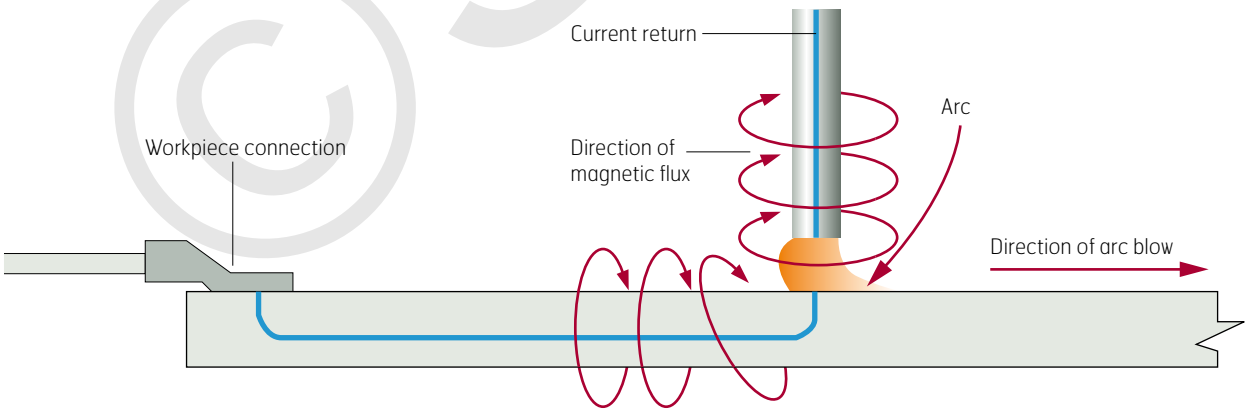


Fig. 15.8: The position of the workpiece connection supports an arc deflection in accordance to the figure.

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The selection of welding parameters

The stability of the arc depends on the welding parameters. A short arc length and low current value can stabilize the arc. If needed, a reduced diameter of the consumable further assists in reducing the current level. However, observe that a lowered current level promotes lowered welding productivity.

Measures for multiple arc welding

Arc blow encountered when using multiple electrodes can be counteracted by feeding one or more electrodes with A.C. In this case, the electrode with A.C. continuously changes the direction of its magnetic field, counteracting arc blow, according to fig. 15.9.

A beneficial technique to use during multiple arc welding is to combine the positive aspects from both A.C. and D.C. welding. The first electrode is fed by a D.C. current with positive polarity in order to attain a deeper penetration profile. The other electrode/electrodes are supported by A.C. When applying two electrodes connected to A.C., the current phase shift between them can be set to approximately 90° for a high resistance to arc blow.

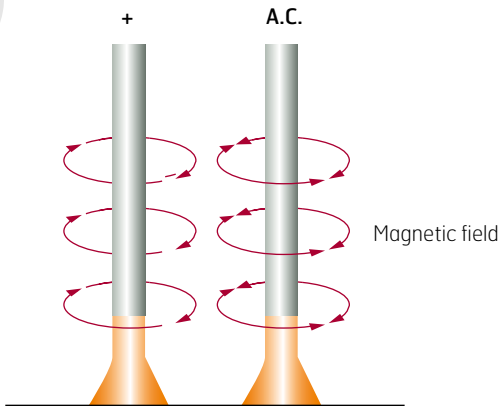


Fig. 15.9: Welding performances with two electrodes using a combination of D.C. and A.C.

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16.0 Post-weld heat treatment

Welding creates residual stresses in a structure's joint and its surrounding area. In certain types of steels, these stresses can be reduced by applying a post-weld heat treatment (PWHT).

Weldox 700-Weldox 960 and Hardox HiTuf can be subjected to PWHT. However, the treatment is rarely applied to these steel grades because, in most cases, the properties of the welded structures make it unnecessary and there are drawbacks associated with this operation.

The principal advantages of a PWHT in welded structures of Weldox 700-Weldox 960 and Hardox HiTuf are:

- Lowered levels of residual stresses can further increase the ductile behavior of the structure.
- Chip producing machining of a component is facilitated since a lower level of residual stresses promotes less distortion in the structure.
- A reduction of the residual stresses in a structure can improve its fatigue properties. More information on this matter is found in chapter 8.
- Lowered hardness values in the joint are possible. This, together with decreased levels of residual stresses, can diminish the risk for stress corrosion cracking in the joint. This issue is relevant if the structure is subjected to certain types of corrosive environments.

The drawbacks associated with the PWHT of a structure are that:

- The mechanical properties in the HAZ and other parts of the parent metals can be reduced.
- The PWHT increases the production cost substantially since a separate operation is added to the manufacturing process.
- New residual stresses can be encountered in the stucture if the PWHT is performed without following the recommendations from SSAB.

Weldox 1030-Weldox 1300 and all Hardox grades, except Hardox HiTuf, should not be exposed to a PWHT. Doing so will impair the mechanical properties in the unaffected parent metal.

The PWHT is performed by first heating the welded structure with a specified heating rate. Once the holding temperature is reached, it is maintained for a certain period of time. As a final step, the temperature is reduced with a specified cooling rate until ambient temperature is reached. This process is normally carried out in a furnace, but other techniques, such as placing electric heating mats on the welded structure, may be applied.

Recommended procedures for PWHT of structures in Weldox 700-Weldox 960 and Hardox HiTuf are according to table 16.1.

Steel grade	Holding temperature [°C]	Heating and cooling rate [°C/h]	Holding time	Suitable time at the holding temperature [h]
Weldox 700	550-580 °C	100	2 min/mm of single plate thickness*, min 1 h	1-6
Weldox 900	520-550 °C	-"-	-"-	-"-
Weldox 960	520-550 °C	-"-	-"-	-"-
Hardox HiTuf	510-530 °C	-"-	-"-	-"-

* A definition of the term single plate thickness can be found in chapter 4.

Table 16.1: Recommended parameters for PWHT of welded structures in different Hardox and Weldox grades. The holding temperatures are preferably measured on the actual structures.

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The exact changes in mechanical properties in the joint due to a PWHT depend on how the process is carried out. However, the yield strength, tensile strength, impact toughness and hardness in the joints and other parts of the parent metals will often be decreased to some extent.

The issues regarding the effect of a PWHT on the toughness properties in the joint may seem contradictory. However, toughness depends on both residual stresses and external load. External forces and residual stresses promote brittleness; welded structures are subjected to both. Small Charpy-V test specimens used for impact toughness tests, on the other hand, have lowered residual stresses when they are removed from the joint. As a result, a small test specimen subjected to a PWHT may show lowered toughness values than if it were a part of a larger structure subjected to a PWHT.

The properties in the unaffected parent metal are not significantly changed because of a PWHT.

In order to attain the desired characteristics in the welded structure, SSAB recommends that the relevant properties are evaluated for the specific situation prior to welding.

Normally, a PWHT is performed for the complete component. A PWHT can, however, be executed for separate parts of the structure. Contact SSAB for further assistance in the latter case.

16.1 Aspects regarding welding processes

Structures that are going to be post-weld heat-treated can be welded using all types of conventional welding methods including MAG welding, MMA welding, SAW and TIG welding.

16.2 Suitable consumables for welding of structures that are subjected to a PWHT

Several types of consumables are appropriate for this type of application. The basis for selecting proper consumables is according to our normal recommendations. Make sure that the consumable is suitable for use in structures subjected to a PWHT. This information can be attained from the consumable manufacturer.

A general concern for MAG welding with flux cored wires is the higher fraction of basic wires compared to rutile wires that are applicable to structures subjected to PWHT.

16.3 Other types of requirements

Contact SSAB for further advice if there are other requirements involved in the execution of the PWHT procedure that are outside of those recommendations specified in this chapter.

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17.0 Repair welding of structures

Repair welding addresses separate types of issues in relation to other welding operations. Repair welding is most commonly done to repair discontinuities from a previous welding procedure or to repair a structure due to an earlier overloading. Matters related to these two areas are described in this context.

If undesired discontinuities occur in the joint, or a fracture appears in the structure, it is essential that the situation is assessed and that, if necessary, preventative actions are taken in order to reduce the risk of reoccurrence. If unacceptable discontinuities are present; it means that the original welding performance needs to be modified. For situations where overloading occurs, appropriate actions like a reduction of load or improving the design of the structure are essential.

The assessment can, on occasion, show that the discontinuities in the joint – including potential cracks – are not critical for the function of the structure. In these cases, it may be that repair welding is unnecessary and that:

- Another operation, such as grinding off the discontinuities, is the best solution to solve the problem.
- Additional measures are not needed at all.

17.1 The planning of repair welding

If repair welding is performed, care should be taken to ensure that all requirements can be fulfilled for the structure.

Examples of frequent issues in this respect are that:

- The requirements regarding the mechanical properties in the joint shall be fulfilled.
- Distortions formed during repair welding are considered. If needed, suitable counteractive proceedings are planned for in order to reduce their levels. When straightening of the structure is – or might be – required, it is preferable that a suitable procedure is determined prior to repair welding.
- The non-destructive evaluations to be made on the welded structure are decided. This measure is preferably performed both prior to and after repair welding in order to detect potential discontinuities.
- New approvals of the structure might be required due to the repair welding.

Repair welding procedures that are performed indoors can be executed with all types of conventional welding methods. The original welding method, in these situations, may be a good choice since the production equipment is adapted for the specific structure. Outdoor welding is mostly performed using the MMA welding process since it is very versatile. Examples in this respect are that:

- The MMA equipment can often be moved with relative ease from one location to another.
- It is feasible to weld with MMA welding in all welding positions.
- The joint can attain good properties during both indoor and outdoor welding.

The shielding gas related welding methods should only be applied indoors. Outside, the shielding gas can blow away during the welding process leading to an insufficient protection of the weld pool. Outdoor welding also carries a greater risk for an increased level of hydrogen during the welding performance from substances such as moisture, rust, grease and oil. This is because factors like dampness, rust, and contaminants in the joint can be more difficult to control and eradicate during outdoor welding.

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Additional measures should be taken in order to reduce moisture pick-up during these situations:

- During outdoor welding, the recommended minimum preheat temperature is set to a minimum of 50°C above the preheat recommendations, mentioned in chapter 4, when possible, or to at least 100°C. This is because enhanced levels of preheating facilitate further hydrogen migration from the joint to its surroundings. The maximum preheat temperature is the same as for other kinds of welding performances, described in chapter 4.
- Outdoor welding is to be performed without direct exposure to rain or snow.
- During outdoor welding, it is especially important to handle the consumables in accordance with their manufacturer. Preferably, new consumable packages should be opened just prior to welding in order to avoid excessive moisture pick-up.

When planning repair welding, it is beneficial to study the instructions and results from the original welding procedure. A judgment can then be made as to whether or not certain welding parameters from these procedures can be utilized. This information can be attained from earlier welding procedure qualification records (WPQR), welding procedure specifications (WPS) and similar documents.

Welding in the horizontal position (PA) is preferable whenever possible. The principal benefits for this welding position in comparison to others are that:

- It enhances the control of the welding performance thus promoting high property qualities in the joint.
- The horizontal position permits the highest degree of welding productivity.

17.2 Realization of the weld repair

The established weld discontinuities or fractures are first removed. It is also beneficial to remove a few millimeters or more beyond the point where the flaw seems to end, since part of the flaw can be embedded in the joint and hard to find.

Arc gouging, grinding and thermal cutting are the most common methods of removal. If possible, the main part of the flawed material is separated with a highly productive process.

Arc gouging can combine a high efficiency with a high degree of flexibility. This method is, therefore, often the best choice for the primary part of the process. Remove at least 2 mm of length beyond the undesired metal, since discontinuities might be hidden in front of the arc. The experience from SSAB is that preheating – in order to avoid hydrogen cracks – is not necessary during arc gouging of the Hardox and Weldox grades. The recommendations for thermal cutting are described in chapter 11.

The next issue is to ensure that the weld area has a proper and clean joint configuration. This implies that welding can be executed in the existing condition or that further joint preparation with grinding and/or cleaning of the joint is necessary. The repair welding procedure can then be carried out according to plan.

After completing the repair welding, the earlier planned measures of non-destructive evaluations are to be taken in order to ensure that the repaired structure fulfils the required properties.

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18.0 Non-destructive evaluations

A non-destructive evaluation (NDE) of the joint and its surroundings is a way to find potential discontinuities that have occurred due to welding. Several types of methods for non-destructive evaluations exist and this chapter focuses on describing those most relevant to the Weldox and Hardox grades. These methods are visual testing, magnetic particle testing, penetrant testing and ultrasonic testing. A basis for their application is that the properties of the welded structure are not impaired by the examination.

It is recommended to conduct a non-destructive evaluation of the joint with more than one method since each method is suitable for detection of certain types of discontinuities. A basic recommendation is always to at least carry out visual testing.

Either magnetic particle testing or penetrant testing can be applied to find discontinuities that are surface breaking. These methods can detect discontinuities of various shapes, especially linear discontinuities such as cracks and lack of fusion. However, shallow discontinuities covering a relatively large area, such as undercuts and spatter, can be more difficult to identify. During magnetic particle testing, the joint is magnetized. This test can be performed on joints welded with unalloyed and low-alloyed consumables but it is not appropriate for joints welded with stainless austenitic consumables since they produce a weld metal that may not be ferromagnetic. Penetrant testing does not have any formal restrictions regarding the type of joint or the welding conditions.

By employing an ultrasonic examination of the welded joint, an inspection of potential embedded discontinuities can be performed for fully penetrated joints. Linear, rounded and elongated discontinuities can be detected with this method.

Very small discontinuities can be detected with non-destructive evaluations. However, the minimum size of a detectable discontinuity depends on factors such as:

- The shape of the discontinuity
- Characteristics of the individual NDE method
- How carefully the evaluation is carried out
- The surface conditions of the inspected area
- The thickness of the plates that are included in the joint during ultrasonic testing

Therefore, it is essential that the NDE testing is carried out in a manner, normally performed according to specified regulations, that facilitates the detection of discontinuities that cannot be accepted in the structure. For proper testing, it is essential that each NDE method is performed using trained personnel.

In the following context, the capabilities for the mentioned NDE methods are further described.

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18.1 Visual testing

Visual testing of the joint is a vital method that can detect many types of discontinuities and its simplicity makes it the most commonly used NDE method. This procedure may, in certain situations, be viewed as an obvious method and paid limited attention. However, when properly addressed and planned for, it facilitates fast and cost efficient examination of the joint.

Inspections of the joint can take place prior to, during and after the completion of welding to monitor that the desired welding conditions apply.

Furthermore, when the NDE examination also includes penetrant testing or magnetic particle testing, the visual inspection can reveal surface breaking discontinuities that are more difficult to detect with the two former methods.

An inspection of the joint, in this case, can be performed with or without a supporting instrument. The aid of an instrument is illustrated in fig. 18.1.

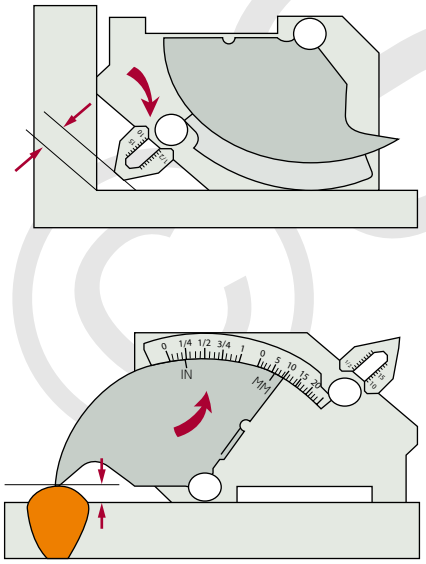


Fig. 18.1: Visual assessment of the joint performed with a weld gauge. The picture above illustrates measurement of the throat thickness and the lower picture shows measurement of the height of the excess weld metal.

18.2 Penetrant testing

The fundamental principle of penetrant testing is to use a special type of liquid and/or powder to detect potential surface breaking discontinuities in and around the joint.

Before testing, the inspection area should be cleaned to remove contaminants such as dirt, rust and grease that can cover discontinuities in the joint. The area should be cleaned by applying suitable measures for the particular contaminant such as solvents or a brush. Any paint and primer that is present in the parent metal adjacent to the weld metal should also be removed by either brushing or grinding. A liquid, called penetrant, is then applied to the joint. Its purpose is to penetrate possible discontinuities. The liquid needs to soak for a specified period, often in the range of 5-60 min. The excess liquid is then removed from the inspected area according to the instructions for the penetrant while the liquid in the discontinuity, if present, remains.

Next, a liquid or a powder developer is applied. If a discontinuity is detected, the penetrant is drawn into the developer by a reversed capillary action and a distinct marking occurs at the location of the discontinuity. The developer usually takes between 10-30 minutes, according to the specific product, to reveal discontinuities.

The character of the discontinuity can be identified to some extent even if the exact shape and depth are hard to determine. Larger discontinuities appear more quickly and have a more pronounced marking than smaller variants. The indications from linear discontinuities, cracks for example, are straighter than the more rounded types. The indication from a discontinuity is larger than its actual size.

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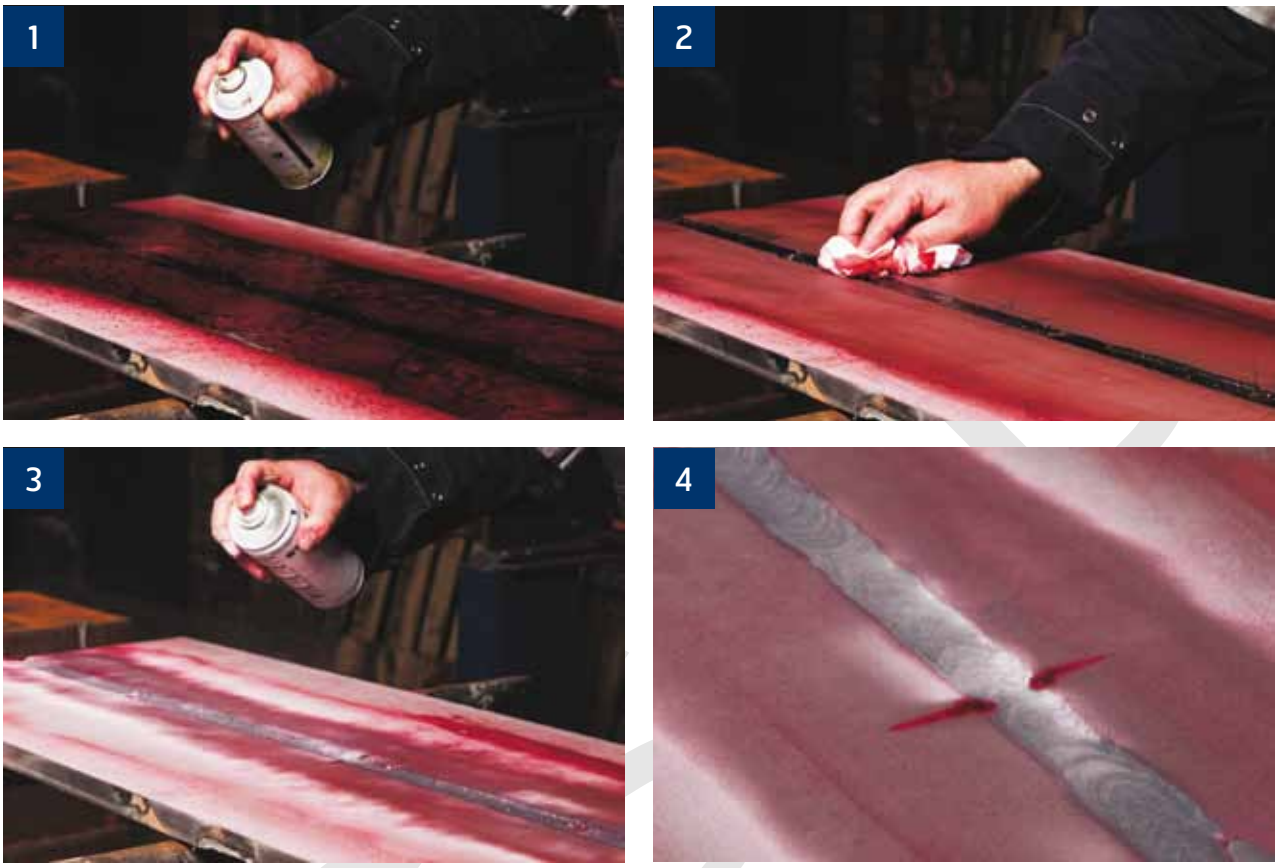


Fig. 18.2: Dye penetrant testing. **Step 1)** Appliance of penetrant. **Step 2)** Removal of excessive penetrant. **Step 3)** Appliance of developer. **Step 4)** Detection of discontinuties. In this case cracks are revealed.

As a final measure, the chemicals from the penetrant testing should be removed in accordance with the manufacturer.

The penetrant systems, including penetrants, developers and solvents, can be divided into two groups: dye penetrant or fluorescent penetrant systems. These systems are developed to provide a high contrast between the developer and the marking from a discontinuity. If a discontinuity is detected, the dye penetrant causes a mark that can be seen visually in a well lit surrounding. The discontinuity indication color is typically red with a white background from the developer. When fluorescent penetrant systems are used, the evaluation of the joint must be done using UV light to allow the discontinuity to fluoresce. In this case, a colored background from the developer is not required. This method can detect smaller discontinuities than dye penetrants since it achieves a higher contrast between the discontinuity and the background.

The different steps of dye penetrant testing are illustrated in fig. 18.2.

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18.3 Magnetic particle testing

Magnetic particle testing is a frequently used method for detecting surface breaking discontinuities in the joint. As a secondary feature, this method also allows for the detection of embedded discontinuities that lay just below the surface of the joint.

The inspection area should be clean and free from contaminants prior to inspection. These contaminants, including substances like oil, mill scale, grease, or loose or thick layers of paint should be removed using appropriate measures such as brushing or application of solvents. The cleanliness requirements are somewhat lower than for penetrant testing since magnetic particle testing can reveal discontinuities just under the surface. Therefore, the shop primer can be left on as well as a thin layer of paint, depending on the total thickness of the paint. A total thickness of paint up to 50 µm does not normally affect detection with this method. The shop primer used by SSAB has an approximate thickness of 10-15 µm.

In the subsequent phase, the joint is magnetized with external equipment that creates a magnetic flux in a certain direction. If a discontinuity is detected, the direction of the magnetic flux changes due to a flux leakage and new magnetic pools are created around the discontinuity. The direction of the magnetic flux is revealed by adding small ferromagnetic particles to the surface of the structure. These particles will orient along the magnetic flux. This means that if a discontinuity is found, the particles will form along the magnetic flux created around it.

However, if the discontinuity is situated near the direction of the magnetic flux, the disturbance will be low or absent and the discontinuity may not be revealed. The joint is, therefore, magnetized and evaluated at least two times, each time allowing the magnetic flux to be set in a different direction. After the completion of inspection, residual magnetism may be present in and adjacent to the joint. If so, the residual magnetism can be removed by a demagnetizing equipment.

The choice of magnetizing instrument depends on the requirements of the specific application. Aspects such as productivity issues and access limitations to the inspected area are to be considered when selecting a suitable instrument. Two examples are an electromagnet and a prod technique, which are illustrated in fig. 18.3 and fig. 18.4.

The magnetic particles that are applied are normally iron or iron oxide. These particles have a specific color or a coating of fluorescent material. They are applied either as a dry powder or in a mixture with liquid. Both alternatives can be used depending on the situation. A liquid solution promotes a more even distribution on the surface while the dry powder supports applications on hot surfaces.



Fig. 18.3: Magnetization of a fillet joint with an electromagnet.

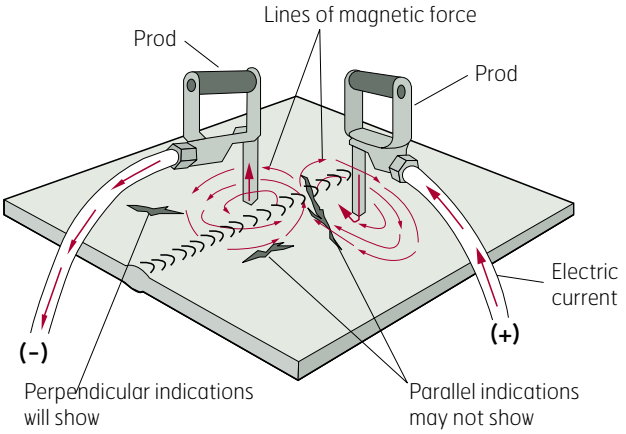


Fig. 18.4: Magnetization of a butt joint with a prod technique.

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When using non-fluorescent magnetic particles, paint is typically applied to the inspected area in order to create a higher contrast between the parent metal and the magnetic particles. An example of a detected crack is illustrated in fig. 18.5. A characteristic of magnetic particle testing is that the marked width of a detected discontinuity is larger than the actual discontinuity.



Fig. 18.5: Detection of a crack with magnetic flux inspection. The magnetic particles are black in this picture.

Identification of potential discontinuities requires good lighting conditions when using colored magnetic particles and UV light when the fluorescent type is used. The latter type can achieve a somewhat higher sensitivity than the previous type since the magnetic particles glow in this case.

After the inspection is made, excess metal particles and paint, if applicable, are removed in accordance with their instructions.

Demagnetization of the welded structure may be required if the magnetism is too high. This procedure is commonly done by applying a magnetic flux that constantly changes direction. This gradually reduces the level of magnetization in the structure. One method is to wipe the magnetized area with an A.C. yoke.

18.4 Ultrasonic testing

Ultrasonic testing is a method that can detect embedded discontinuities in joints that have plate thicknesses up to the maximum single plate thickness of the Hardox and Weldox grades. This testing method can detect small discontinuities and allows for their individual size and character to be determined. The location of the discontinuity can also be identified both horizontally and vertically.

Additional aspects to consider with ultrasonic testing are that the operator needs to be considerably skilled and the equipment requires careful and regular calibration.

Before explaining the procedure of this method, the principals of ultrasonic waves are described. In the vast majority of cases, a pulsed echo technique is used during the inspection of joints. This technique is based on distributing ultrasonic waves in a certain direction through the joint and its surroundings. These waves are not audible since the frequency is very high. During inspections of joints in the Weldox and Hardox grades, they are normally in the range of 2-4 MHz . Lower frequencies promote larger penetration depths while higher frequencies support the ability to find smaller discontinuities. The ultrasonic waves will attain a high degree of consistency when distributed in an area where there are no discontinuities.

Sonic waves that strike the interfaces between the steel structure and the surrounding air are reflected back to the steel due to the large differences in acoustic characteristics between the steel and the air. However, when ultrasonic waves strike a foreign substance in the steel, the sound waves are disturbed and reflected either more or less. When present, a discontinuity represents a substance other than the steel structure.

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During conventional inspection, ultrasonic waves are transmitted to the inspection area by a probe. The reflected echo of the ultrasonic waves can be identified by the same unit, which is illustrated in fig. 18.6, or by a separate probe.

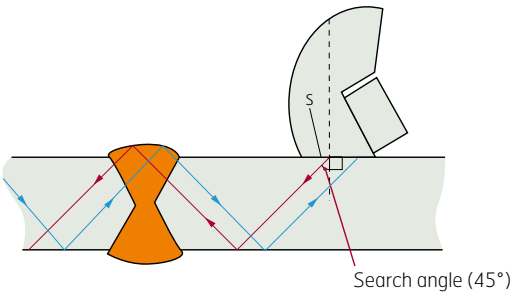


Fig. 18.6: Ultrasonic testing of a joint without discontinuities.

The response from the echo is converted to electrical signals that can then be displayed with an oscilloscope. Ultrasonic testing compares echoes from a section with no discontinuities to deviating echoes from a section with a discontinuity. Based on the outcome of the echo, the shape, size and position of a detected discontinuity can be determined.

Detection of a discontinuity is illustrated in fig. 18.7 and fig. 18.8, where a discontinuity echo is illustrated in the latter figure.

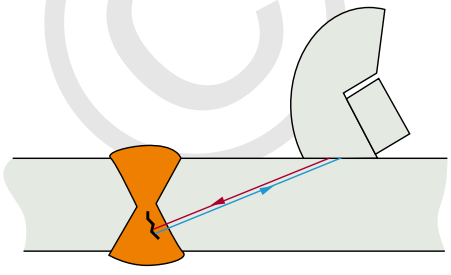


Fig. 18.7: Ultrasonic testing of a joint where a crack that is detected.

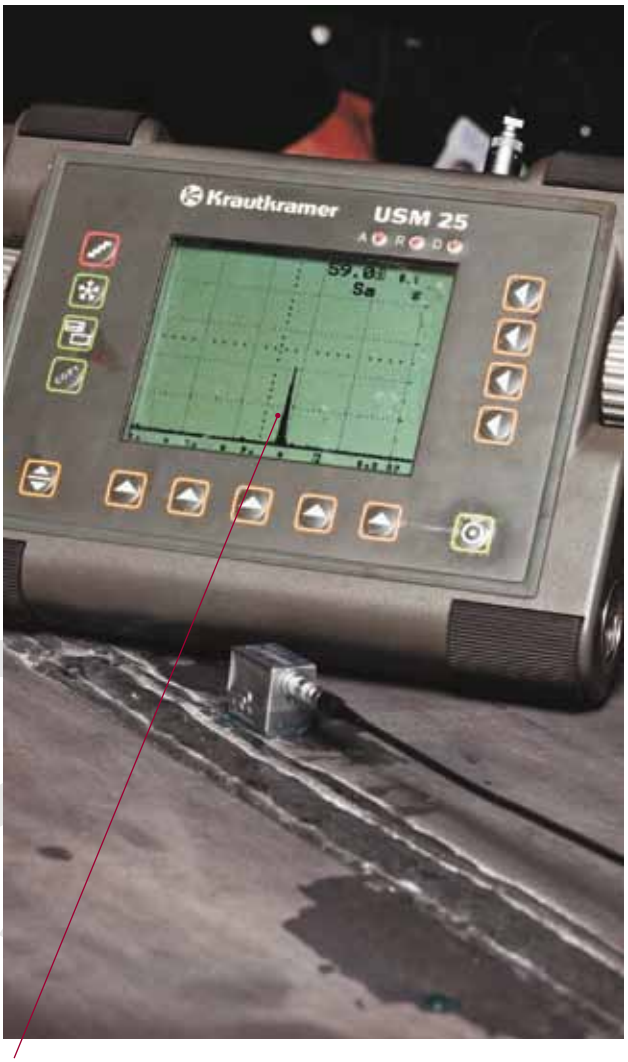


Fig. 18.8: Detection of a discontinuity with ultrasonic testing. The discontinuity echo is displayed on the screen of the oscilloscope.

The inspection of the joint starts with cleaning the area around the joint to remove any foreign substances and contaminants. This also includes removal of any outer irregularities such as spatter and slag that are present on the surface.

A couplant is then applied between the probe and the inspection area. Its function is to support the transmission of the ultrasonic waves between the probe/probes and the area to be inspected. Examples of couplants are oil, glycerin, water and silicon.

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At conventional inspections the probe is first moved transverse to the direction of the joint in order to inspect its complete cross section. This procedure is repeated along the entire joint. Detection of rounded and oval shaped discontinuities is, in general terms, relatively easy since these shapes are favorable for ultrasonic waves to strike. Linear discontinuities need more arrangement to identify. This is because the closer to a right angle the ultrasonic wave is when it strikes the discontinuity, the easier it is for an echo to be established. A complete evaluation of a joint, therefore, involves inspections with different search angles. Frequent search angles are in the range of 35°-70° as well as 90°.

The UT inspection is finalized by removing the couplant from the work piece.

A development of the conventional ultrasonic technique is the phased array technique. With this technique the probe can sweep the inspected area with different search angles continuously, according to fig. 18.9, which means that the inspection is more efficient.

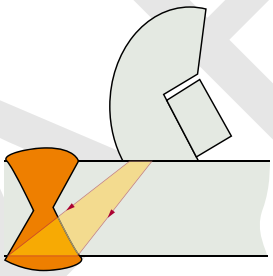


Fig. 18.9: Inspection with a phased array technique. The transmitted ultrasound is illustrated.

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19.0 Stud arc welding

Stud arc welding includes several methods where a stud is welded to a steel structure. These techniques offer benefits that include a good bond with favorable mechanical properties. The cost efficiency is also advantageous since stud arc welding can be executed with high productivity.

Essential issues that contribute to these conditions are that:

- The mechanical properties of the plate surface on the opposite side of the stud weld are unaffected. This is because the extension of the HAZ from the welding performance is small and is less than the thickness of the plate. This can increase the resistance to wear, such as abrasive wear, which is illustrated in fig. 19.1.

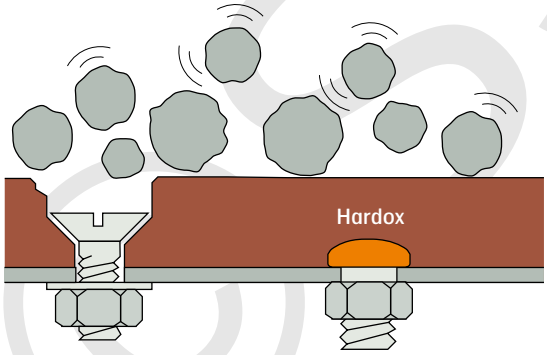


Fig. 19.1: Hardox plate with a stud weld and a bolt connection subjected to abrasive wear.

- Drilling and tapping of holes in the plate is avoided.
- The distortions in the structure due to stud welding are very low.
- The welding time per stud is very short. Often, many studs can be welded per minute.
- Stud arc welding is relatively easy to perform. This means that limited training is needed for the operator.

19.1 Stud arc welding methods

There are different types of stud arc welding methods. The type of metal, the plate thickness and the size of the stud all influence the choice of welding technique. The complete range of plate thicknesses of the
Hardox and Weldox grades are primarily suited for the arc welding processes:

- Drawn arc stud welding with ceramic ferrule.
- Drawn arc stud welding with shielding gas.
- Short cycle drawn arc welding, which is often referred to as short cycle welding. This technique can be performed with or without shielding gas. The actual arc time can be even lower compared to the already mentioned drawn arc stud welding methods.

The basic equipment for these three welding processes include a control unit, a D.C. power source, a welding gun, electrical cables and devices for the use of shielding gas, when applicable. In modern equipment, the control unit and the power source are integrated, according to fig. 19.2.

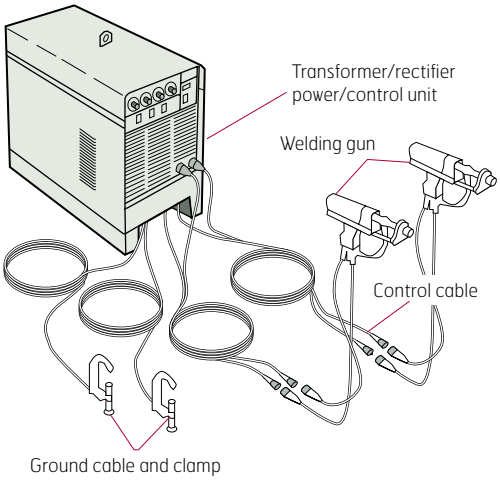


Fig. 19.2: Stud arc welding equipment for welding with a ferrule. If shielding gas is applied additional equipment is required.

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Stud arc welding of high strength steels, such as Hardox and Weldox, is performed with a negative polarity of the electrode and a positive polarity of the work piece.

The welding performance can either be hand held or executed in stationary fixed equipment in production environments.

The actual welding time for a stud is normally up to:

- 2 seconds for drawn arc stud welding with ceramic ferrule.
- 1 second for drawn arc stud welding with shielding gas.
- 0.1 second for short cycle welding.

19.2 Studs

The geometry of the stud is most commonly a solid cylindrical shape, although other shapes can be applied.

Drawn arc stud welding techniques with a ferrule or shielding gas can weld studs in the range of approximately Ø 6-30 mm. In these cases, the plate thickness needs to be at least ¼*diameter of the cylindrically shaped stud. Short cycle welding is designed for welding smaller sized studs of approximately Ø 2-12 mm. The minimum plate thickness for this method is 1/8*diameter of the cylindrically shaped stud. The suppliers of studs and stud arc welding equipment can provide the requirements for other stud dimensions and geometries.

There are studs that are especially designed for welding. Only one side of the stud can be welded to the steel structure. The weldable side has a contact tip in the center part of the cross section that facilitates a symmetrical and completely penetrated joint. When using a ferrule, the contact tip will typically include an aluminum flux. The purpose of the flux is to enhance and stabilize the arc formation during welding. When welding without a ferrule, the contact tip is normally made of the same material as the rest of the stud. The exact shape of the stud may be optimized to suit a particular stud arc welding process, see fig. 19.3. The manufacturers of studs can provide further recommendations on this matter.



Fig. 19.3: The stud to the left is suitable for the drawn arc stud welding with ceramic ferrule or shielding gas. The stud to the right has a wide flange, which makes it appropriate to short cycle welding.

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Unalloyed, low alloyed and stainless studs can be used. Unalloyed and low-alloyed studs of material group 4.8 in ISO 898-1 and stainless studs according to group A4 in the standard ISO 3506-1 have been evaluated and found suitable for welding of the Hardox and Weldox grades. Studs of other classes may be appropriate as well, but it is up to the user to evaluate their applicability.

19.3 The objective of the ferrule

When a ceramic ferrule is applied, it is placed around the stud prior to welding.

Its primary functions are to:

- Isolate and focus the heat generated from the welding process to the weld pool.
- Counteract chemical reactions between the melt and the surrounding air to promote beneficial mechanical properties in the weld metal.
- Form the cap of the weld metal.
- Prevent formation of pores in the weld metal. This is done through small vents in the lower part of the ferrule that allow gases to flow from the weld metal while at the same time prevent surrounding air from reaching the liquid melt during welding.
- Protect the welding operator from spatter while welding

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The dimensions of the ferrule are selected in order to provide a good fit between the stud and the shape of the parent metal. Different types are according to fig. 19.4. A small drawback to the use of a ferrule is that they needs to be removed after each stud weld and each ferrule can only be used once.



Fig. 19.4: A ferrule.
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19.4 The objective of the shielding gas

A shielding gas protection around the stud can be used as an alternative to a ferrule. However, this alternative is used to a lesser extent compared to welding with a ferrule.

The function of shielding gas is relatively similar to a ferrule, namely to:

- Protect the molten weld metal from reacting with the surrounding air during welding.
- Shape the cap and the penetration profile of the weld metal.
- Counteract pore formation in the weld metal.

The drawn arc methods must always be performed with a ferrule or a shielding gas protection of the weld pool. One suitable shielding gas composition for all types of studs is 82 % Ar+18 % CO_2. The gas shielding flow in both drawn arc stud welding and short cycle welding is typically set to 5-6 l/min for Ar/CO_2 mixtures.

19.5 Objectives related to short cycle welding

The short cycle method enables welding of small studs. This method is performed with a higher current and lower arc times compared to welding with the other stud arc methods mentioned. The penetration depth of the weld metal in the short cycle method is shallower in relation to the other stated methods. Welding without shielding gas will simplify the performance. Nevertheless, this alternative can lead to a larger degree of oxidation of the molten weld metal, which can cause lowered mechanical properties in the joint. Additionally, the level of spatter may increase. However, when there are mild requirements regarding the properties of the joint, this kind of short cycle process may be the best option for welding small studs.

When welding studs with diameters of 6 mm and above it is always recommended to apply a shielding gas in order to avoid pore formation in the weld metal.

19.6 The welding performance

Drawn arc stud- and short cycle welding are performed with high levels of current. The amperage is raised as the size of the stud increases. The maximum value depends on the capacity of the welding equipment. The current level can be up to approximately 2500A during the drawn arc process for studs of Ø 30 mm.

The feasible welding parameters depend on the welding equipment and the welding situation. Manufacturers of stud arc welding equipment, for instance, can provide approximate values for certain situations. These values may need to be fine tuned for the particular welding situation.

The typical penetration depth of the weld metal is usually in the range of 1-3 mm for the stud arc welding processes in this chapter.

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The principal steps in all mentioned types of stud arc welding involve:

1. Positioning of the stud and the gun.
2. Activation of the welding process. Upon contact, the stud is raised, ignites the arc and a liquid weld metal is formed. The stud serves as an electrode and is molten during welding.
3. The arc ceases after a preset period and the stud is punched down into the liquid weld metal.
4. The weld metal cools and solidifies. The welding process is finalized.

Fig. 19.5 illustrates these sequences for the different stud arc welding methods. The short cycle method in this example is performed without a ferrule or a shielding gas.

The arc voltage is based on the welding conditions and is automatically set by the welding equipment. Increased voltage values correspond to an increased lift height of the stud.

19.7 Precautions prior to welding

The studs and ferrules should be kept in a clean, dry location and in accordance with their manufacturer in order to prevent discontinuities such as hydrogen cracks in the joint.

As in other welding techniques, the surface should be free from contaminants like oil, water, rust and mill scale prior to welding in order to prevent discontinuities in the joint.

A sufficient electrical contact between the stud and the work piece is needed in order for ignition of the arc. The welding equipment normally has an indicator that signals if a satisfactory electrical contact is attained. Welding on a shop primed steel surface is sometimes feasible and at other times, it is not. If there is a lack of electrical contact, the primer can be easily removed from the location of the stud weld and the work piece connection with, for instance, a brush. Modern equipment may be

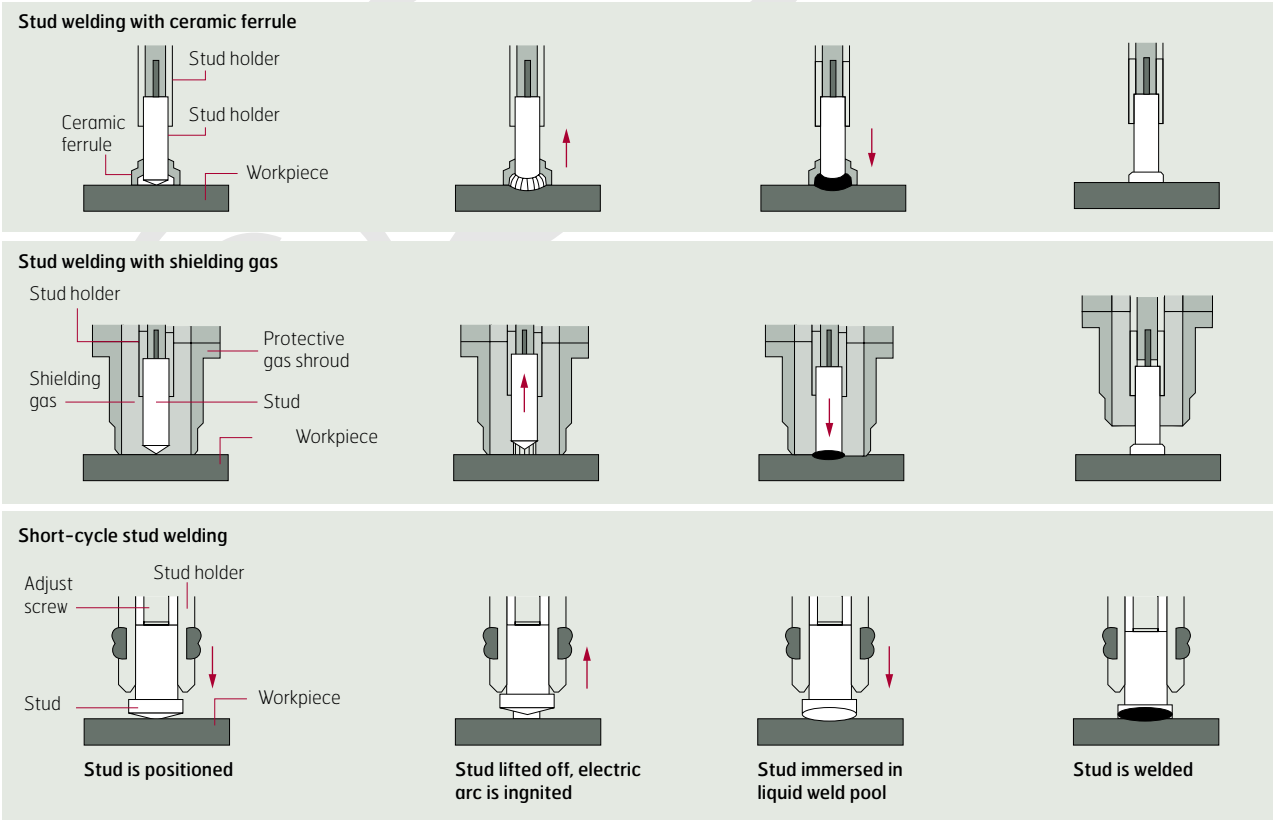


Fig. 19.5: The different welding sequences for each stud arc welding method. The short cycle method in this example is performed without shielding gas.

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equipped with a pre-current function that can remove primer and foreign substances like mill scale and mild rust prior to welding. Favorable weld quality can be attained by welding directly on primed plates, although there may be an increased tendency toward porosity in the weld metal compared to welding on a bare steel surface.

19.8 Preheating

Stud arc welding demands a lesser degree of preheating to prevent hydrogen cracks in the joint compared to the MAG, MMA, SAW and TIG methods. If hydrogen cracks appear, they are typically embedded in the HAZ. If present, a reduced torque resistance can reveal these cracks. The fractures, in these cases, are situated in the parent metal near the stud.

SSAB suggests preheat levels for the Hardox and Weldox grades based on in-house evaluations. However, these values are approximate due to the variations of parameters that are possible during welding. The stated preheat temperatures cover welding with unalloyed and low-alloyed studs from material group 4.8 in ISO 898-1 and stainless stud consumables according to group A4 in the standard ISO 3506-1. Suitable categories of studs are according to table 19.1.

Steel grade	Type of stud	Min. preheat temperature
All Weldox and Hardox grades except Hardox 550, Hardox 600 and Hardox Extreme	Unalloyed, low-alloyed and stainless studs	Room temperature
Hardox 550	Only stainless studs	100
Hardox 600, Hardox Extreme	Only stainless studs	150

Table 19.1: Appropriate stud categories.

The maximum preheat levels in order to achieve beneficial mechanical properties in the joint are specified in table 19.2.

Maximum recommended interpass temperature	
Weldox 700**	300°C
Weldox 900**	300°C
Weldox 960**	300°C
Weldox 1030	200°C
Weldox 1100	200°C
Weldox 1300	200°C
Hardox HiTuf**	300°C
Hardox 400	225°C
Hardox 450	225°C
Hardox 500	225°C
Hardox 550	225°C
Hardox 600	225°C
Hardox Extreme	100°C

Table 19.2: Maximum preheat temperatures.

The preheating process

The preheating process is the same as for other types of welding, see fig. 19.6.

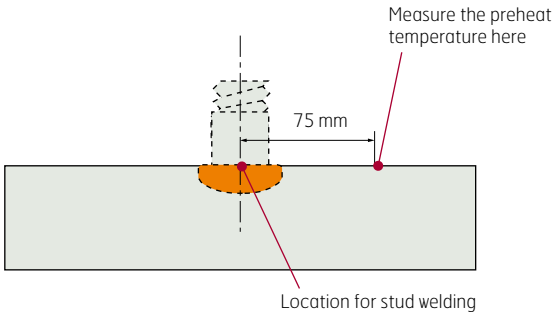


Fig. 19.6: Preheating. A holding period of at least 2 min/25 mm of the plate thickness in the joint is needed prior to welding for even heat distribution throughout the plate thickness

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19.9 Post-weld heat treatments

Post-weld heat treatment is an alternative to preheating procedures to minimize the risk for hydrogen cracks. The main advantage of a post-weld heat treatment is that, in many cases, it facilitates higher productivity compared to preheating.

If post-weld heat treatment is carried out, a feasible procedure is to:

- Heat the stud directly after welding
- When heating, make sure that the stud is heated almost completely to an orange color, see fig. 19.7. The stud is kept at the maximum temperature of approximately 15-20 s.
- Make sure that the temperature in the parent metal does not exceed the stated temperatures in table 19.2 during welding.

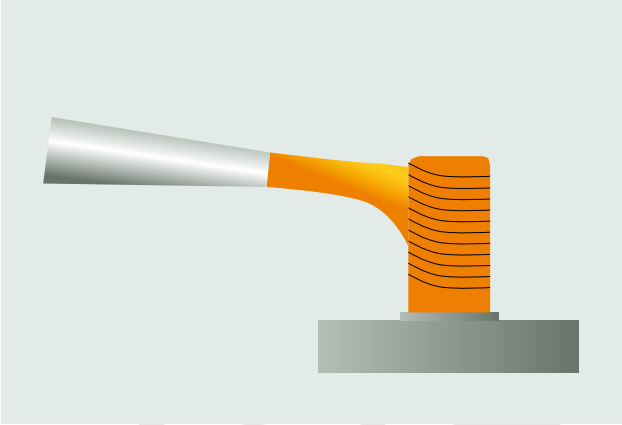


Fig. 19.7: Post-weld heat treatment.

If hydrogen cracks still occur after the post-weld heat treatment, new studs are welded and kept for gradually longer periods of time at the maximum temperature until no cracks occur.

19.10 Evaluation of properties in stud welds

It is good practice to evaluate the properties in stud welds prior to manufacturing to find a procedure that fulfils the criteria for the joint.

When assessments are made for stud welds, the evaluation methods are mostly associated with visual examination and measurements of the mechanical properties in the joint.

A geometrically sound weldment and examples of different discontinuities that can be observed visually are shown in fig. 19.8.

It is feasible to evaluate the static strength, bendability, torque resistance and hardness of stud welds. During production, a suitable measure is to check the properties in the stud welds continuously. Visual control, for example, can be made of all stud welds.

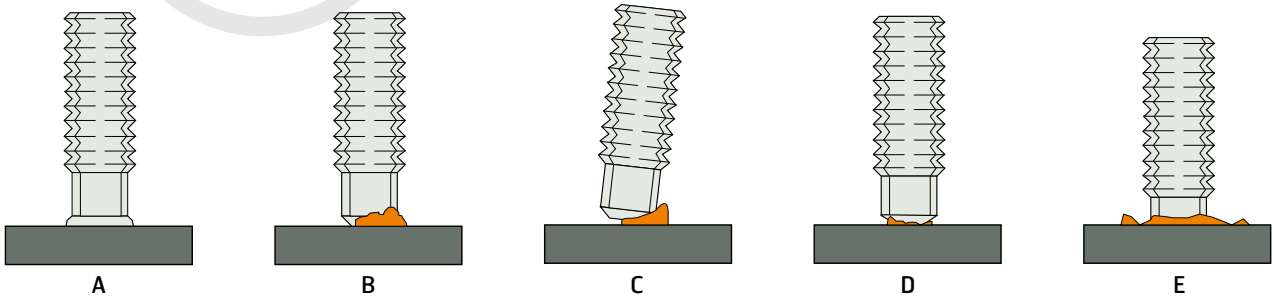


Fig. 19.8: Joints with and without visual discontinuities. **A)** A correct joint **B)** Insufficient lift at arc striking or insufficient grounding conditions **C)** Unsuitable torch angle **D)** Heat effect too low during welding **E)** Heat effect too high during welding

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20.0 Hardfacing

Hardfacing is a procedure where weld passes are welded on to the surface of the steel. The purpose of this measure is to give the structure a higher wear resistance. A picture of a steel surface subjected to hardfacing is illustrated in fig. 20.1.



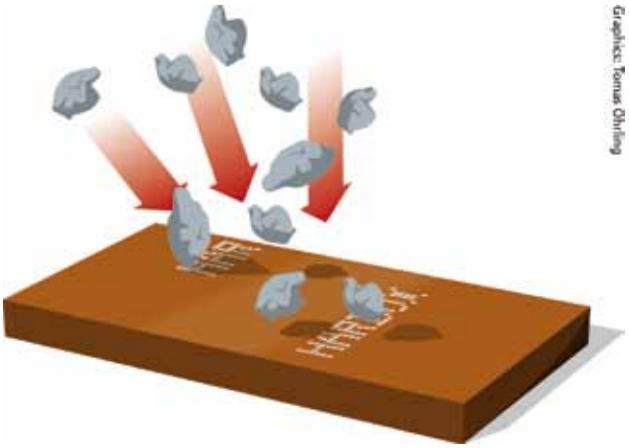
Fig. 20.1: Hardfacing of Hardox.

Hardfacing is a general measure that can be applied to structures of different steel grades. However, high strength steels such as Hardox and Weldox are not frequently subjected to hardfacing because, by design, they already have a very high resistance to wear. There are also potential drawbacks involved with hardfacing, which are discussed further on in this chapter. When hardfacing is performed, it is mostly done for the Hardox grades due to their use in high wear applications.

One instance in which a Hardox application can benefit from hardfacing is when there is localized wear on one part of the structure. In this situation, a Hardox grade with a relatively moderate hardness can be used and hardfacing can be welded on to the part of the structure that is exposed to the increased wear.

Before performing a hardfacing procedure for a Hardox or Weldox grade, the type of wear must be determined in order to choose the appropriate welding consumable. From the perspective of hardfacing technology, the different types of wear are normally related to the characteristics of the consumables for the hardfacing layer. The relevant categories of hardfacing consumables for welding of the Hardox and Weldox grades are normally divided according to the following principal wear segments:

- Impact wear occurs during impingement of solid bodies, as in the case of solid rocks striking the surface, see fig. 20.2. This kind of wear is characterized by severe pounding which tends to deform and, in some cases, break away the surface.



Graphics: Tomas Öhrling

Fig. 20.2: Impact wear.

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- Erosion wear appears when smaller particles, like sand, hit a surface at high velocity. Erosion wear can be considered as a type of impact wear.
- Abrasive wear involves abrasive sliding wear, which is characterized by a free flow of material that grinds the wear surface, according to fig. 20.3.



Fig. 20.3: Abrasive wear.

- There are also combinations of abrasion wear, impact wear and erosion wear. Impact wear and erosion wear are, in general terms, more aggressive compared to abrasive wear.

After the wear type is clarified, the hardfacing procedure can be performed. A complete hardfacing performance involves the following steps:

- Ensure that the steel surface being hardfaced has been properly cleaned.
- Weld the buffer layer, apply preheating if required.
- Weld the hardfacing layer, apply preheating if required.

The different weld layers of a hardfacing performance are illustrated in fig. 20.4.

All types of conventional welding processes can be used for both the buffer layer and the hardfacing layer. The normal welding processes for both are MMA welding, MAG welding and SAW.

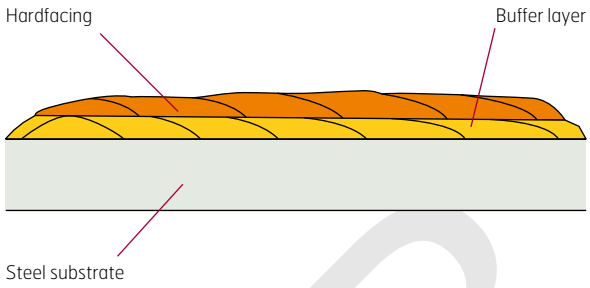


Fig. 20.4: A plate subjected to hardfacing.

20.1 Surface appearance of the steel

The steel surface should be cleaned before welding the buffer layer. Contaminants on the surface such as oil, grease, rust and water should be removed with appropriate measures prior to welding.

20.2 Characteristics of the buffer layer

The buffer layer provides a ductile weld metal between the base metal and the hardfacing layer. A ductile stainless austenitic consumable of type AWS 307 or AWS 309 is suitable. The buffer layer is normally welded with a thickness of one to two passes.

The essential benefits of applying a buffer layer are to:

- Achieve a more secure attachment between the steel substrate and the hardfacing layer. This is especially important when the structure is subjected to impact wear. Without the buffer layer, there is a greater risk for spalling of the hardfacing layers from the steel surface, according to fig. 20.5.

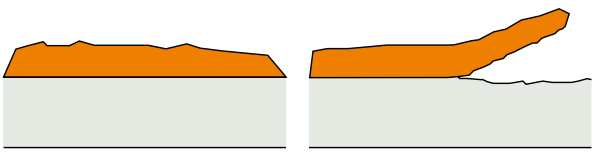


Fig. 20.5: Spalling effect of a hardfacing layer.

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- Counteract crack propagation. Cracks often occur in the hardfacing layer. A buffer layer can obstruct cracks between the hardfacing layer and the parent metal because it is ductile and it can introduce compressive stresses in the hardfacing layer.

Hardox and Weldox steels are supplied with or without primer painted surfaces. The buffer layer can be welded directly on to either surface. When the buffer layer is welded directly on to a primed plate, apply the general information regarding welding on to primer specified in chapter 9.

20.3 Characteristics of the hardfacing layer

For the Hardox and Weldox grades, martensitic and carbide rich consumables are the typical variants for the hardfacing layer.

Martensitic consumables, as the name indicates, are designed to achieve a martensitic microstructure in the weld metal. This contributes to a very high hardness of the hardfacing. Martensitic consumables typically have favorable properties for use in abrasion wear applications and can be a good alternative for preventing impact wear of solid bodies.

Carbide rich consumables exist in several variants. They all contain carbides of high hardness that are embedded in a surrounding substance called the matrix. An example of this microstructure is shown in fig. 20.6.

The characteristics and composition of the matrix depend on the specific consumable. Typically, the properties of this type of consumable provide a weld metal with favorable resistance towards abrasion and erosion wear. Carbide rich consumables with a hard matrix are preferred for structures subjected to erosion because they resist the wear caused by the small individual particles. However, this type of weld metal often has poor results in resisting impact wear of solid bodies.

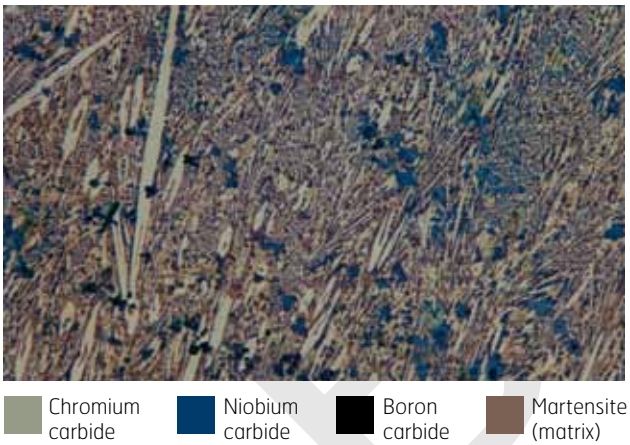


Fig. 20.6: A hardfacing layer from a carbon rich consumable. Magnification ~ x100.
(Reproduced by permission, Castolin AB)

When combinations of different types of wear are present in an application, the consumable for the hardfacing layer is selected in order to suit each wear type as closely as possible. If one wear type is dominant in relation to the others, select the consumable that provides a high resistance towards the principal wear type.

The hardfacing layer should not be too thick. Normally, the hardfacing layer has a thickness of 1 to 3 weld passes. Excessive thickness will promote spalling of the hardfacing layer. For some types of hardfacing consumables, the manufacturer specifies a certain number of weld passes in the thickness direction to attain beneficial properties in the weld metal.

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20.4 Preheat temperatures

The necessary preheat temperatures of the buffer layer and the hardfacing layer are influenced by the required preheat temperatures of both the base metal and the consumables.

Determine the required preheat temperature for both the base metal and the consumable for each welding procedure included in the hardfacing performance. Apply a preheat temperature that fulfils the demands for both. Minimum and maximum preheat temperatures for Hardox and Weldox grades are the same as for conventional types of welding, see chapter 4. The single plate thickness in this situation is the plate thickness, according to fig. 20.7.

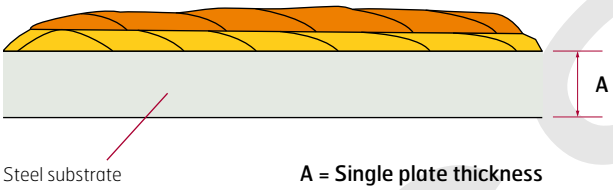


Fig. 20.7: Single plate thickness for hardfacing.

This means that preheating is not required before welding the buffer layer for all of the Hardox and Weldox grades, except for Hardox 600 and Hardox Extreme. These grades require both preheating and stainless consumables of type AWS 307 or AWS 309.

20.5 Levels of heat input

The recommended heat input for the Hardox and Weldox grades when welding the buffer layer and the hardfacing layer is the same as for other welding procedures, see chapter 5. If the consumables have separate recommendations in this respect, this should be accounted for when determining the applied heat input. Employ a heat input that fulfils the requirements for both the parent metal and the potential requirements for the specific consumable.

20.6 Recommendations regarding other welding parameters

Welding parameters related to a specific welding method, shielding gas for example, are selected and applied in the same manner as for other kinds of welding operations with the Hardox and Weldox grades.

20.7 Crack phenomena during hardfacing

Cracks can form in the area of the hardfacing. The two most relevant types of cracks related to hardfacing of high strength steels are described in this context. The first, and most common, type is a relief crack, which can occur in the hardfacing layer. The other type is an under-bead crack, which is explained in more detail since it can form in the parent metal.

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Relief cracks

Relief cracks are rather frequent occurrences in hardfacing layers. Other names for this sort of crack are transverse crack and cross crack. This kind of crack is oriented transverse to the direction of the weld metal as the two latter names indicate.

Commonly, the consumable for the hardfacing layer is designed to form relief cracks in order to lower the residual stresses in the welded area, according to fig. 20.8. This increases the resistance of the hardfacing layer to spalling from the parent metal and decreases the residual stresses in the joint caused by the hardfacing layer. The wear resistance is not substantially reduced due to this type of crack. As is earlier mentioned, the buffer layer counteracts potential crack propagation from the hardfacing layer into the parent metal.



Fig. 20.8: Transverse cracks in a hardfacing layer.

Underbead cracks

An underbead crack is a kind of hydrogen crack that can form in the parent metal during a hardfacing procedure. If underbead cracks occur, they are located in the parent metal beneath the hardfacing layers, see fig. 20.9. The risk for underbead cracks is minimized by following the welding recommendations presented in this chapter.

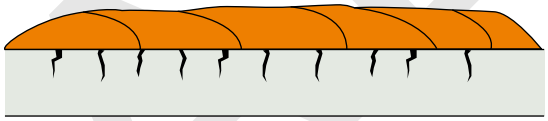


Fig. 20.9: Underbead cracks in the parent metal. The buffer layer is left out in this situation.

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21.0 Microstructures in the heat-affected zone (HAZ) and the unaffected parent metal

The microstructures in the joint and the unaffected parent metal are viewed under high magnification. The kind of microstructure that is present in the joint affects its mechanical properties. This chapter will examine the microstructures that can be present in the HAZ of the Hardox and Weldox grades. Furthermore, it will discuss the microstructures that are present in the unaffected parent metal of these steel grades in order to point out differences in the properties between the HAZ and the unaffected parent metal.

The characteristics of the microstructure in the HAZ are related to the chemistry of the steel, the outcome of the thermal cycle, and the number of passes in the joint. The microstructure in the unaffected steel, on the other hand, depends on the chemistry of the steel and how it is produced. Studies of microstructures are performed during metallographic evaluations using microscopes.

During and after the welding performance, the microstructures for both the HAZ and the unaffected parent metal of the Hardox and Weldox grades include primarily austenite, martensite, tempered martensite and bainite. Each of these structures has specific properties that are discussed in this chapter. However, there is seldom a need for the user of the Hardox and Weldox grades to map out the microstructures in a welded structure.

21.1 Austenite

Austenite is primarily present at elevated temperatures, which occurs when the Hardox and Weldox grades are heated in the solid state to temperatures of about 700°C-1500°C. An attribute of this microstructure is its toughness. In austenite, the atoms of iron (Fe) are oriented according to fig. 21.1. This atomic structure is called face centered cubic (fcc) and the black circles illustrate the atomic center for each Fe atom.

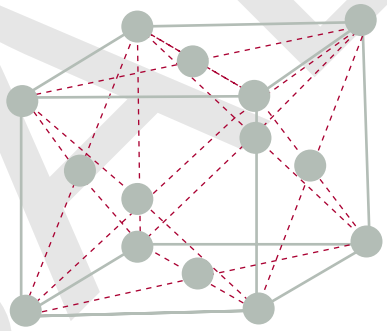


Fig. 21.1: Austenite.

Austenite in mainly found in the Weldox and Hardox grades in:

- The plate during the quenching process of production when the plate is heated to temperatures of around 900°C.
- The part of the HAZ – and at a time – where temperatures of around 700°C-1500°C are reached during welding.

In addition, there may be small portions of austenite still left in both the HAZ and the unaffected parent metal when they reach room temperature. If so, the microstructure is called retained austenite. However, this kind of microstructure is hard to detect with the common metallographic methods.

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21.2 Martensite and tempered martensite

Martensite is established in the Weldox and Hardox grades during and after the quenching process of the plates during production. Austenite must first form in order for martensite to form. The austenite develops when the hot rolled plate is heated in the furnace to temperatures of approximately 1000°C -1200°C. Martensite is then formed during the quenching process when the plate is rapidly cooled to ambient temperature.

Carbon is an alloy element that is necessary for the formation of martensite and its atomic structure is displayed in fig. 21.2.

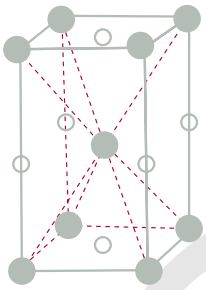


Fig. 21.2: Martensite. The black atoms illustrate the positions of the iron atoms. The white circles are possible locations for carbon atoms. The position of each iron and carbon atom represent its atomic center.

Some of the Hardox and Weldox grades are tempered after the quenching process. Updated information for a specific steel grade is found in its datasheet. The holding temperatures during tempering can be in the order of 200°C- 600°C. This type of heat treatment is primarily used as a measure to achieve the desired mechanical properties in the steel. When tempering is performed in the mid and upper region of this temperature interval, the microstructure becomes tempered martensite, which means that carbon in the martensite reacts with other chemical elements in the steel and forms carbides.

If martensite forms in the HAZ during welding, it occurs in the sections that have been heated to temperatures in the range of 700°C-1500°C. First, the austenite is formed and, if the cooling rate is rapid enough, the martensite forms at the same locations.

Tempered martensite forms in the part of the HAZ that has reached peak temperatures of approximately 150 °C -700°C during welding. In addition, martensite that is formed in the HAZ can transform in to tempered martensite due to a heat treatment from a subsequent weld pass if there is sufficient heating. The exact requirements for tempered martensite to appear depend on the carbon content of the steel.

At ambient temperatures, both martensite and tempered martensite can attain a combination of very high strength and beneficial toughness in both the unaffected parent metal and the HAZ.

21.3 Bainite

Bainite is a microstructure of high strength and hardness. The toughness can be more so or less so advantageous. The HAZ and parts of the unaffected steel in the Hardox and Weldox grades can include bainite at ambient temperature.

The formation of bainite is similar to martensite. Initial heating of the parent metal to a temperature in the range of 700°C-1500°C is necessary in order for austenite to form partly or completely. This happens during the production process of the Hardox and Weldox grades as well as during welding when parts of the HAZ reach the peak temperatures. A relatively high cooling rate is then required for the steel although it is not as rapid as when martensite is formed.

Bainite consists of ferrite and carbides. The austenitic structure dissolves carbon to a greater extent than the ferrite. During the cooling process, there is enough time for carbides to form. Bainite can be further sub-divided according to its appearance.

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The picture to the left in fig. 21.3 represents upper bainite where the iron carbides are formed between ferrite formations. A bainitic structure with a more finely distributed carbide formation that has many different orientations supports a higher toughness than a structure with larger carbide formations and fewer orientations. The bainite type to the right in fig. 21.3 is called lower bainite.

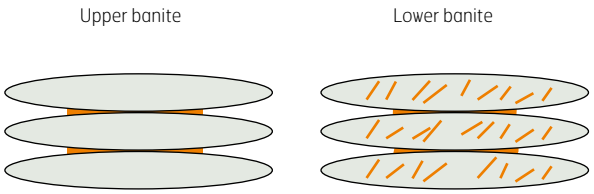


Fig. 21.3: Illustration of bainite. Gray sections represent ferrite and orange sections represent carbides.

Upper bainite is established at higher temperatures during the cooling process than lower bainite. The different types of bainite are often mixed in the microstructure. Work has been carried out to divide bainite into more subgroups. However, upper and lower bainite are the most established methods for dividing bainite into subgroups.

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22.0 Hardening mechanisms in the heat-affected zone and the unaffected parent metal

The hardening mechanisms, which occur in both the HAZ and the unaffected parent metal, have a significant role in the outcome of the mechanical properties of the Hardox and Weldox grades. The essential mechanisms addressed are grain refinement, solid solution hardening, and precipitation hardening. The occurrence of these mechanisms depends on the character of the grains in steel structures as well as the presence of dislocations. Therefore, an initial description of grains and dislocations is first presented.

In the following context, the term parent metal includes both the HAZ and the unaffected parent metal.

22.1 The grains

The structure of steel consists of small grains, including both the welded joint and the unaffected parent metal, which can be observed under magnification with a microscope.

A characteristic of an individual grain is that all the iron atoms are oriented in the same direction, which is exemplified in fig. 22.1. The area between the grains is called the grain boundary.

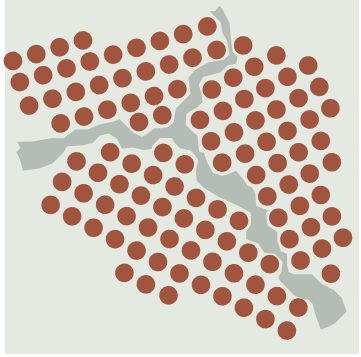


Fig. 22.1: The atomic structure, where the orientation of the iron atoms are marked with dots. The gray area illustrates the grain boundaries.

The dimensions of the grains in the unaffected parent metal vary to some extent depending on the steel grade and plate thickness. As an example, the unaffected parent metal of Weldox 1100 with a plate thickness of 10 mm has a grain size of approximately 10 µm -15 µm.

The thermal heat treatment from welding affects the sizes of the grains in the HAZ. The grain sizes throughout the HAZ vary; the largest difference is adjacent to the weld metal, see fig. 22.2. This zone is called the coarse grained zone (CGHAZ). Even though the grains in the CGHAZ are small, they are typically up to several times larger than those in the unaffected parent metal. The sizes of the grains throughout the complete HAZ depend on the characteristics of the steel and the welding performance. More information regarding characteristics of the different parts of the HAZ is found in chapter 5.

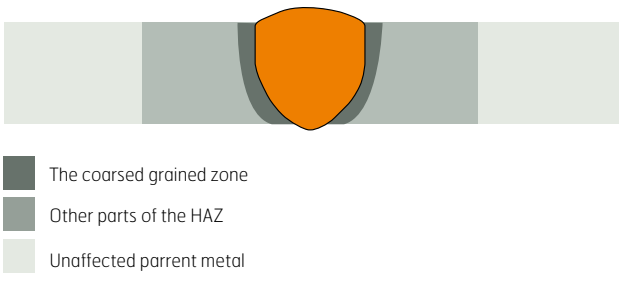


Fig. 22.2: A butt joint in the Weldox/Hardox grades.

In all types of steels and joints, each grain has line defects in its atomic structure. These defects are called dislocations.

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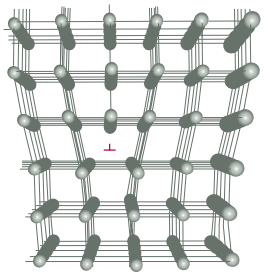


Fig. 22.3: A dislocation in a cubic structure. The dislocation represents an extra plane of atoms marked with a ⊥.

One example of their presence is illustrated in the following example, which shows an atomic structure within a grain. In order to show a dislocation schematically, this example illustrates a cubic atomic structure. Each dot represents the center part of the atom, see fig. 22.3.

When external stresses are applied to the structure, which are below its yield strength, the dislocations will not move. If the stresses are increased to the parent metal's yield strength or above, the dislocations start to move and a permanent plastic deformation of the steel structure is encountered, see fig. 22.4.

If the stresses on the structure are high enough to cause distortions above what is feasible for the parent metal, a crack is initiated that can propagate to a fracture. If this kind of fracture appears, it is of a ductile type and is oriented through the grains.

22.2 Grain refinement

The size of the individual grains in the parent metal affects the mechanical properties in the steel. A decreased grain size leads to higher yield strength, tensile strength, and increased toughness in the parent metal. The Hardox and Weldox steels are developed to attain very small grains in the unaffected parent metal.

The strength of the parent metal is enhanced by smaller grain sizes because it counteracts dislocation movement. This change in strength is caused by dislocations that move in favorable directions within a grain. When dislocations reach a grain boundary, their movement is usually obstructed since it is very likely that the favourable directions for further movement in the next grain are not the same. As a result, there is a pile-up of dislocations at the grain boundary. If the applied stress is sufficiently high, the dislocation movement can then be transferred to the next grain but, very likely, in another direction, see fig. 22.5.

Additionally, larger grains have a higher amount of dislocations than smaller grains. Fewer dislocations at a grain boundary require higher external stress levels to cause dislocation movement to the next grain. Consequently, decreased grain size increases the strength in the parent metal.

A more pronounced plastic deformation over a larger section of the steel structure is encountered when dislocation movements are transferred from grain to grain.

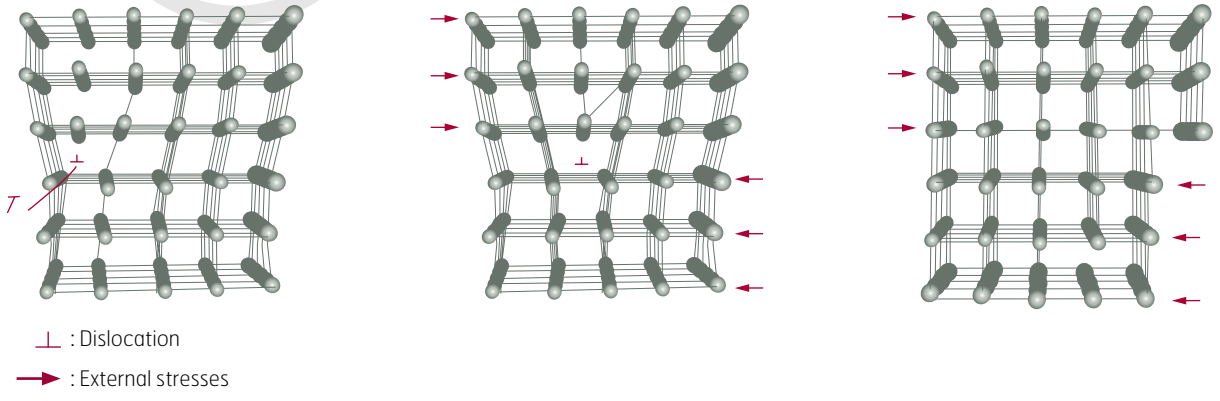


Fig. 22.4: Dislocation movement in a atomic structure.

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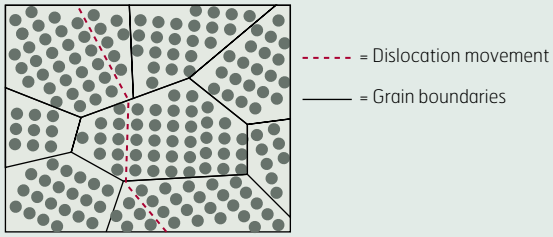


Fig. 22.5: Schematic illustration of dislocation movement in a structure, which is illustrated by the dashed red line. The gray dots show the orientation of the iron atoms in each grain.

If the stress level in the parent metal is further increased, at or above its yield strength, the stress levels finally reach such a high level that a separation between the atoms in an individual grain can take place. A crack can then form, which can develop and propagate through the grains into a trans-crystalline fracture, according to fig. 22.6.

The ability to withstand crack formation also means increased toughness in the structure. The mechanism behind this is similar to the strength mechanism. Below a certain temperature, which depends of the material, the dislocation pile-up will form a crack instead of transferring the plastic deformation to the next grain. This will lead to trans-crystalline crack propagation. A fine grained structure has a lower number of dislocations at the grain boundaries than a larger grained structure, leading to higher resistance to this kind of crack formation.

Another type of fracture is the inter-crystalline fracture, defined as a crack that propagates through the grain boundaries, which is illustrated in fig. 22.7. The grain refinement effect is, however, not as pronounced for this kind of fracture. The main fracture mechanism for sound steel structures in the Hardox and Weldox grades is a trans-crystalline fracture. However, if discontinuities, such as hydrogen cracks, or stress corrosion cracking are present, cracks can form as inter-crystalline or as a combination of trans- and inter-crystalline cracks.

As previously mentioned, the welding performance causes grain growth in the HAZ. However, alloy elements in the parent metal, including niobium, titanium, vanadium, and aluminum, can react with carbon and nitrogen in the steel and form precipitates that can lower the grain growth.

The grain growth supports reduced mechanical properties in the HAZ compared to the unaffected parent metal. However, the Weldox and the Hardox grades are characterized as high strength steels that still can attain favorable mechanical properties throughout the complete HAZ, even if the minimum toughness value in the HAZ is below that of the unaffected parent metal.

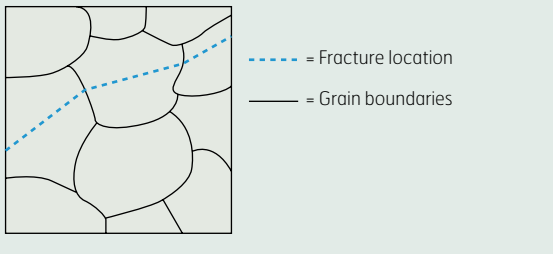


Fig. 22.6: A trans-crystalline fracture.

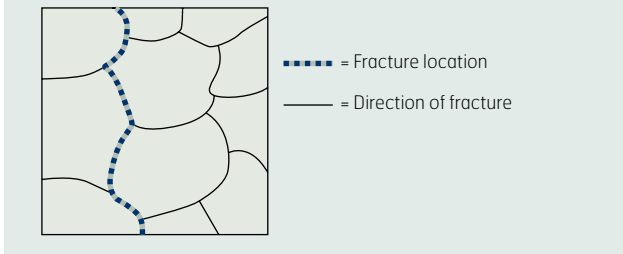


Fig. 22.7: A inter-crystalline fracture.

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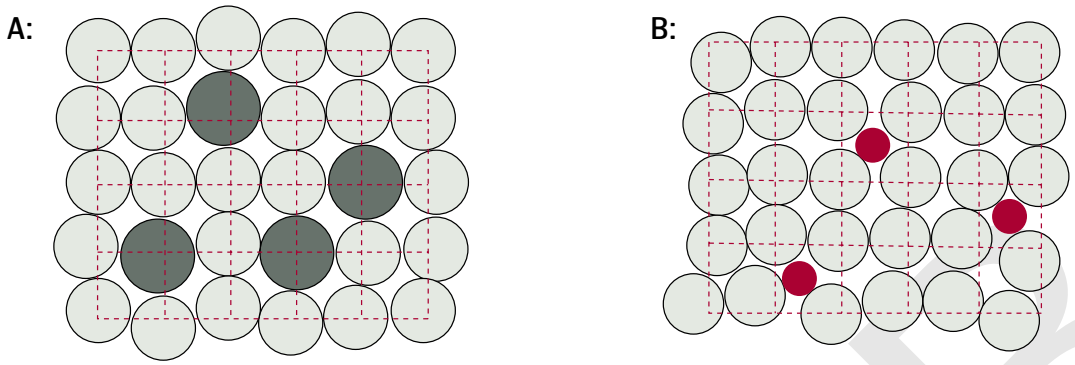


Fig. 22.8: Substitutional solution hardening displayed in A) and interstitial solution hardening is shown in B) Light gray atoms illustrate Fe atoms and dark gray and red markings shows alloy atoms.

22.3 Solid solution hardening

Solid solution hardening occurs when alloy elements are individually dissolved by the steel structure. In this situation, the atoms from the alloys will deform the main iron atomic structure. Distortion of this kind hinders the movement of dislocations in the parent metal. Consequently, the yield strength and tensile strength in the parent metal are raised while the toughness is decreased.

The reason for the increase in strength of the parent metal is that higher stress levels are needed for dislocations to move within the atomic structure. The decreased toughness is because immovable dislocations favor a less ductile fracture when the parent metal is subjected to stresses at or above the yield strength. If cracks occur due to this mechanism, they are of a trans-crystalline type.

There are two types of solid solution hardening: substitutional solution hardening and interstitial solution hardening, according to fig. 22.8. Elements with considerably smaller atom sizes than iron form interstitial solution hardening. In this situation, the alloy atoms are placed in the space between the Fe atoms.

During substitutional solution hardening, an iron atom in the atomic structure is replaced by an alloy atom. This can occur when alloy elements have an atom size that is about the same size as the iron atoms. However, the size difference between the alloy and the Fe atom is enough to deform the atomic structure.

In general, the mechanical properties in the parent metal are influenced by distortions of the atomic structure due to the presence of alloys. Elements that cause interstitial solution hardening deform the atomic structure to a greater extent than those that cause substitutional solution hardening. Therefore, interstitial solution hardening affects the mechanical properties in the steel structure more so than substitutional solution hardening. The alloys that can form solution hardening are discussed in chapter 23.

22.4 Precipitation hardening

Precipitations of particles that consist of one or more alloys and/or contaminates deform the iron atomic structure, see fig. 22.9, and this can prevent the movement of dislocations. Precipitation hardening, therefore, has a similar result to solution hardening. This means increased yield strength, tensile strength, and hardness but also decreased toughness in the parent metal. If cracks occur due to this mechanism, they are of a trans-crystalline type.

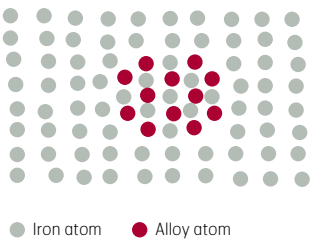


Fig. 22.9: Example of precipitation hardening .

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23.0 The influence of the alloys and contaminants on the Hardox and Weldox grades

The chemical analyses for each Hardox and Weldox grade is of essential importance for the properties in the HAZ as well as those in the unaffected parent metal. The main part of these steels consists of iron (Fe) where the alloy content is in the range of 2-4 weight %. A characteristic of the Hardox and Weldox grades is that they are refined from contaminates to a very large extent.

Each alloy element contributes to specific properties in the parent metal. There are benefits as well as drawbacks for each given alloy. The positive effect from an alloy can be furthered by increasing its level in the steel - up to a certain point. If the alloy's content is increased too much, disadvantages might occur instead.

The total chemical composition of the steel is carefully selected and evaluated in order to achieve the desired properties of each Hardox and Weldox grade. In the following text, different aspects of each alloy element and contaminant are described. The effects from the alloy elements and contaminants are frequently the same in both the HAZ and the unaffected parent metal. Common characteristics that are valid for both of these sections are referred to as the parent metal in the following text.

23.1 Carbon (C)

Carbon plays a significant role in the mechanical properties of the parent metal, especially for the non-tempered and low temperature tempered martensitic steels. It is added to the steel in order to increase the yield strength, the tensile strength and the hardness values.

Carbon contributes to the:

- Formation of different microstructures that appear in the parent metal. For instance, the ability to form martensite is strengthened by the addition of carbon.
- Mechanisms of interstitial solution hardening, precipitation hardening, and grain refinement in the parent metal.

Since parts of these mechanisms support a reduction of the toughness of the steel, it is important that the carbon content in the parent metal is well balanced. In relation to other alloy elements, carbon has a larger influence on the steel's resistance to hydrogen cracks in the joint. As the carbon level increases, so does the sensitivity towards hydrogen cracks. As a consequence, an enhanced level of carbon content in a steel means that more precautions, such as increased preheating levels, are needed in order to prevent hydrogen cracks during welding and cutting operations.

23.2 Manganese (Mn)

The addition of manganese promotes increased yield strength, tensile strength, hardness and toughness in the parent metal. Manganese improves the ability to form martensite in the parent metal and it can achieve grain refinement and substitutional solution hardening.

Manganese also counteracts the negative influence of the contaminant sulfur by reacting with it to form manganese sulfide (MnS). If manganese were not added, the sulfur content would form other sulfides, which could increase the sensitivity to solidification cracks during welding.

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23.3 Chromium (Cr) and molybdenum (Mo)

Chromium and molybdenum enhance the yield strength, tensile strength and hardness of the parent metal.

These elements support the formation of martensite in the Hardox and Weldox grades. In addition, both chromium and molybdenum contribute to substitutional solution hardening of the parent metal. Molybdenum has a stronger overall influence on the increased yield strength, tensile strength and hardness of the parent metal compared to chromium for martensitic steels that are tempered at high temperatures. For these steels, both molybdenum and chromium can form carbides that have a precipitation hardening effect on the parent metal.

23.4 Nickel (Ni)

The most important function of nickel is its ability to increase the toughness of the parent metal. There are different theories behind this fact but there is not a complete explanation as to why. One possible reason is that nickel promotes grain refinement.

Nickel can also increase the yield strength and tensile strength of the parent metal since it contributes to substitutional solution hardening and, to some extent, it supports the establishment of martensite in the parent metal.

23.5 Boron (B)

Boron is primarily added to steel because it supports the formation of martensite in the parent metal. This effect is achieved with very low fractions of the element. The level of boron is less than 50 ppm (parts per million) in the Hardox and Weldox grades.

The effect from boron can best be achieved if it does not react with nitrogen or oxygen in the steel. Before boron is added, a thorough refinement of oxygen is made in the molten steel and then titanium or aluminum is added in order to react with the nitrogen and create nitrides. These nitrides will not react with the boron.

23.6 Niobium (Nb), titanium (Ti), vanadium (V) and aluminum (Al)

Niobium, titanium, vanadium and aluminum are added in small amounts. The content is normally hundredths of a percent for each element. Each of these alloys – except aluminum – can react with either carbon and/or nitrogen and then form carbides, nitrides or carbon nitrides. However, aluminum can only form aluminum nitrides. These substances can achieve grain refinement and precipitation hardening. The precipitates that cause precipitation hardening are smaller than those that counteract grain growth.

The result of alloying the steel with these substances is an increased yield strength, tensile strength and hardness of the parent metal.

However, their influence can have an opposite effect on the toughness of the parent metal. The ability to promote grain refinement supports an increased toughness in the parent metal while the precipitation hardening effects support a decreased toughness.

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Issues regarding grain refinement

During welding performances, the parts of the HAZ that are closest to the weld metal are subjected to peak temperatures above ~1100°C. At these temperatures, considerable grain growth takes place and the grains remains enlarged throughout the welding process.

Precipitations of Nb, Ti, V and Al can reduce grain growth in the HAZ where the precipitations including Nb and Ti have the largest effect. Each kind of precipitate exists up to a certain temperature. If the temperature is increased, the precipitates dissolve in the microstructure. Grain growth is counteracted as long as the precipitations are present.

Examples of the maximum temperature for different precipitates are:

- Vanadium nitrides are present at temperatures up to ~950-1050°C
- Niobium carbides are present at temperatures up to ~1100-1250°C
- Titanium nitrides are present at temperatures up to ~1400°C

Precipitates form again during the cooling phase of welding. Once they are re-established, they can continue to reduce the growth of the grains.

The ability for these precipitates to obstruct grain growth is also used to minimize the final grain size in the steel during the production of the Hardox and Weldox grades.

Supplementary aspect of aluminum

Another purpose for adding aluminum is that it reduces the oxygen content of the melt during the metallurgical part of the steel production. Oxygen must be diminished in the melt in order to produce the Hardox and Weldox grades. Aluminum reacts with oxygen and forms slag which floats to the surface of the liquefied steel where it is removed.

23.7 Silicon (Si)

Silicon has a similar function to aluminum in the respect that it removes oxygen during steel production. Silicon reacts with oxygen and forms slag. The slag floats to the surface of the liquid steel where it is removed.

A second effect of silicon is that it adds yield strength, tensile strength and hardness to the parent metal through substitutional solution hardening of the steel.

23.8 Sulfur (S) and phosphorus (P)

Sulfur and phosphorus are contaminants in the steel. Sulfur can react with other elements and form sulfides in the parent metal, which can reduce the toughness of the steel. The addition of manganese in the Hardox and Weldox grades counteracts the negative effects of sulfur.

The level of phosphorus is to be kept as low as possible. High levels of this element would impair the toughness in the grain boundaries of the steel, which would lead to an overall reduced toughness of the parent metal.

The Hardox and Weldox grades have a very low content of both sulfide and phosphorous. As a result, these steel grades have a substantially strong resistance to the negative effects from these contaminants.

23.9 Nitrogen (N)

Nitrogen acts in different ways in the parent metal. An increase in yield strength, tensile strength and hardness of the parent metal can be attained since it contributes to precipitation hardening, interstitial solution hardening and grain refinement. However, nitrogen leads to a significant reduction in toughness in the parent metal when present at levels that are too high. Consequently, the nitrogen levels are kept low in the Hardox and Weldox grades.

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23.10 Hydrogen (H)

Hydrogen is a contaminant in the unaffected steel and the HAZ. The principal negative effect of this substance is that it can cause hydrogen cracks during welding and cutting performances of high strength steels.

The Hardox and Weldox grades contain a very small amount of hydrogen. Welding operations add additional amounts of this element to the joint. Acceptable amounts of hydrogen can be attained in the parent metal and weld metal by following the welding recommendations from SSAB.

23.11 Copper (Cu)

Copper is a residual element in the Hardox and Weldox grades that cannot be removed. However, only small fractions of copper are present in these steel grades and the effect from this element is not emphasized.

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