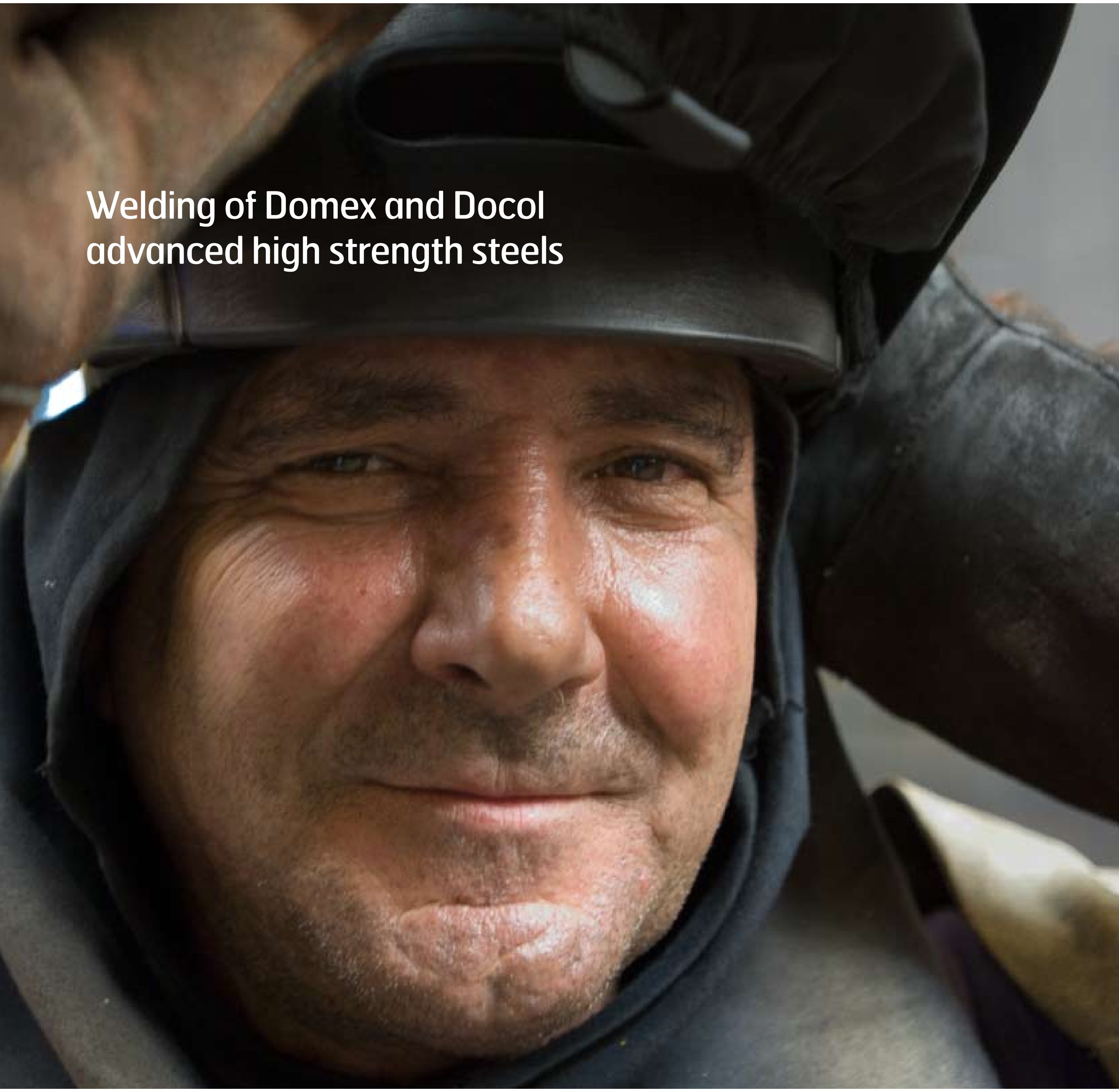
DOMEX®
HIGH STRENGTH STEEL

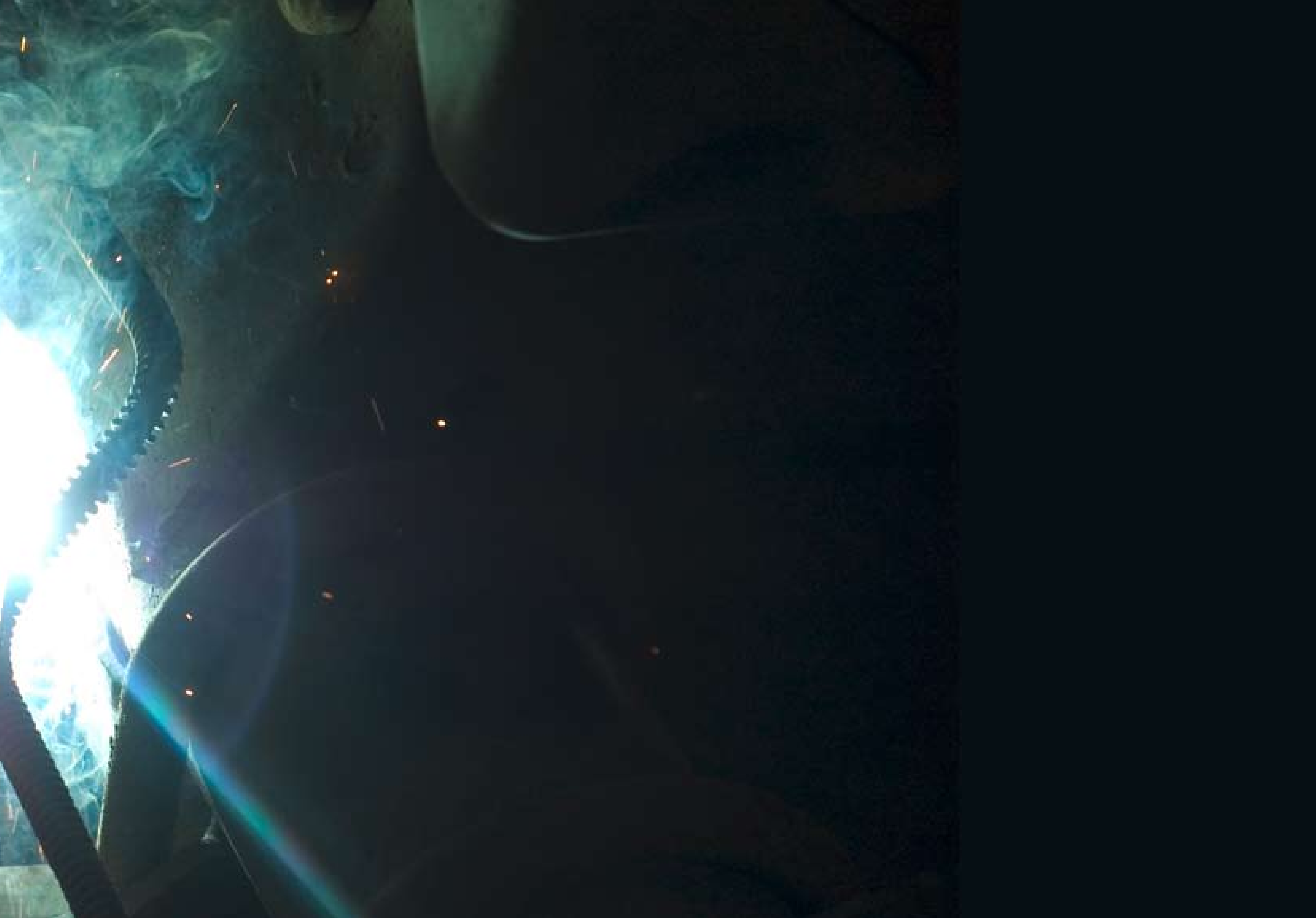
Welding of Domex and Docol advanced high strength steels



SSAB

Introduction

Fusion welding of Domex advanced high strength steels (AHSS) has been employed for many years and does not differ significantly from fusion welding of mild steels. In order to reap the benefits of these high strength steels, the welding process must be controlled in a suitable manner.



CONTENTS

Domex

Domex is the brand name of hot-rolled sheet steel from SSAB Tunnplåt. Domex AHSS are supplied in the thickness range of 2–12 mm. Due to the very good formability in cold state these steels are also known as cold-forming steels.

Domex AHSS are characterized by high yield strength, excellent formability and good weldability.

Domex AHSS are very often used in the transportation industry (trailers, trucks, tippers, automotive, train and cranes).

Domex AHSS are available in the yield strength levels shown in figure 1. Mechanical properties and chemical composition could be seen from table 1 and 2.

FIGURE 1 Strength of Domex.

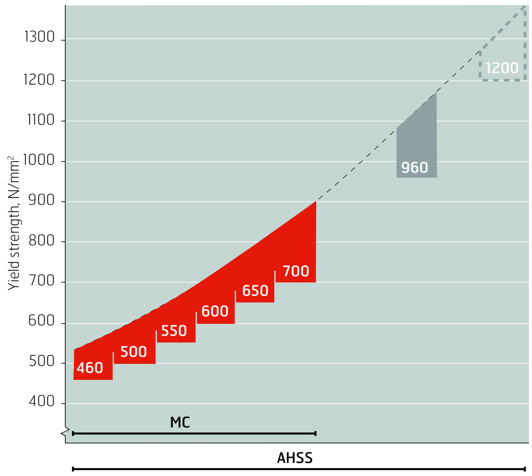


TABLE 1 Mechanical properties of Domex.

Mechanical Properties								
Steel grade	Yield strengt R_{eh} (N/mm²)	Tensile strength R_m (N/mm²)	Elongation Min. (%)		Bending radius, minimum in 90° bend.			Hardness (HBW)
	minimum	minimum	A_{80} t<3	A_5 t ≤ 3	t ≤ 3	3 < t ≤ 6	t >6	
Domex 460 MC	460	520 – 670	15	19	0.5 x t	0.7 x t	0.9 x t	
Domex 500 MC	500	550 – 700	14	18	0.6 x t	0.8 x t	1.0 x t	
Domex 550 MC	550	600 – 760	14	17	0.6 x t	1.0 x t	1.2 x t	
Domex 600 MC	600	650 – 820	13	16	0.7 x t	1.1 x t	1.4 x t	
Domex 650 MC	650*)	700 – 880	12	14	0.8 x t	1.2 x t	1.5 x t	
Domex 700 MC	700*)	750 – 950	10	12	0.8 x t	1.2 x t	1.6 x t	
Domex 960	960	≥980		8		3 x t**)		
Domex Wear 360	-	≥1200		8		3 x t		360–420

* For thickness above 8 mm the minimum yield strength may be 20 N/mm² lower

** Domex 960 and Domex Wear 360 are delivered in the thickness range 4–6 mm.

TABLE 2 Chemical composition of Domex.

Chemical composition							
Steel grade	C (%) maximum	Si (%) maximum	Mn (%) maximum	P (%) maximum	S (%) maximum	Al (%) minimum	Typical carbon equivalent (CE_{IIW}) for t = approx. 5 mm
Domex 460 MC	0.10	0.10	1.50	0.025	0.010	0.015	0.31
Domex 500 MC	0.10	0.10	1.60	0.025	0.010	0.015	0.32
Domex 550 MC	0.12	0.10	1.80	0.025	0.010	0.015	0.32
Domex 600 MC	0.12	0.10	1.90	0.025	0.010	0.015	0.34
Domex 650 MC	0.12	0.10	2.00	0.025	0.010	0.015	0.37
Domex 700 MC	0.12	0.10	2.10	0.025	0.010	0.015	0.39
Domex 960	0.15	0.50	2.10	0.020	0.010	0.015	0.44
Domex Wear 360	0.15	0.50	1.60	0.020	0.005	-	0.39

The sum of Nb, V and Ti is max. 0.22%, Mo is max 0,5%, and B is 0.005% max.

Joint preparation

All conventional methods for joint preparation could readily be used. The most common used methods are:

- Machining
- Thermal cutting

Milling and thermal cutting (gas, plasma or laser cutting) are the most common methods used for joint preparation. Joint preparation on Domex high strength steels is as easy as on mild steels. No preheating is needed for thermal cutting.

A thin oxide film is formed on the joint surface produced by thermal cutting, it is recommended to remove this film before welding.

If plasma cutting is used for joint preparation it is recommended that oxygen be used as plasma gas. The reason is that nitrogen can be absorbed at the cut surfaces of the steel, which may cause porosity in the weld metal on subsequent welding. The solution lies in oxygen being used instead as the plasma gas, or grinding down the cut surfaces by at least about 0.2 mm before welding.

If thin sheet steel parts are to be welded together, ordinary shearing is often used as joint preparation.

Welding

WELDING METHODS FOR DOMEX

All common fusion welding methods can be employed for welding Domex advanced high strength steels. Examples of welding methods that can be used are:

- MAG-welding (Metal Active Gas)
- MMA-welding (Manual Metal Arc)
- TIG-welding (Tungsten Intert Gas)
- Plasma welding
- Submerged arc welding

Other welding methods than the ones mentioned above could of course also be used

Of the methods mentioned above MAG welding is the most common used welding method in the industry today. One of the reasons for this is that MAG-welding is very easy to automate (high productivity).

HOT CRACKS AND LAMELLAR TEARING

Since Domex AHSS have a very low content of alloying elements and a low amount of inclusions there is a low risk for defects depending on the material such as hot-cracks and lamellar tearing. These defects can sometimes occur in steels with higher content of non-metallic inclusions. Good sulphide control for Domex steels enhance the properties in the thickness direction compared to steels with high content of solid inclusions, see figure 2.

When a T joint (see figure 3) is welded close to the edge of a Domex AHSS with a yield strength ≥600 N/mm² and a thickness ≥8 mm, it is important that there should be no sharp defects at the edge. Stresses that occur in the thickness direction during welding can give rise to cracking of the sheet. Since shearing can produce sharp stress raisers in the edge, it is preferable to use thermal cutting to produce an edge with a better surface quality.

FIGURE 2 Lamellar tearing. Difference between a steel with high slag inclusions and Domex steels.

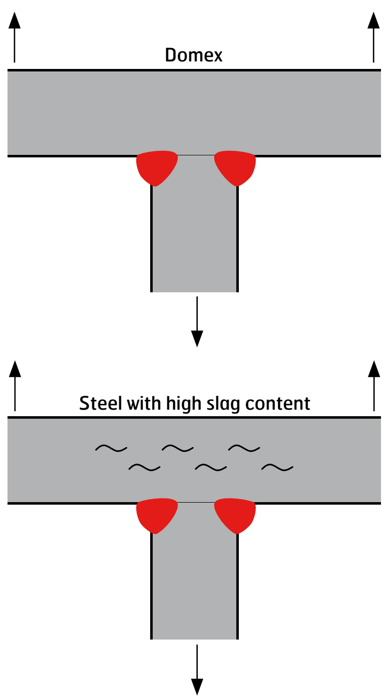
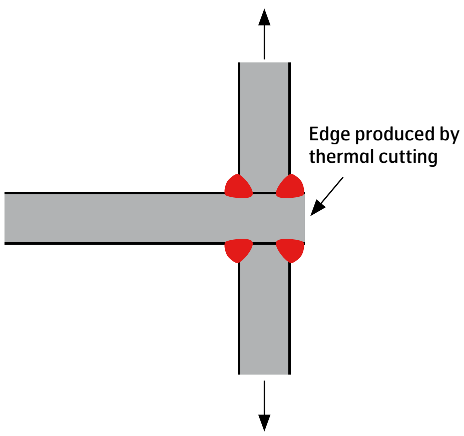


FIGURE 3 It is recommended to use thermal cut edges in T-joints with welds close to the cut edge.



HYDROGEN CRACKING

The risk of hydrogen cracking (cold cracking) to occur in Domex AHSS is very low. The reasons that there are no hydrogen cracking problems on Domex AHSS are:

- Very lean compositions of the steel and thin sheets (slow cooling), which avoids the occurrence of brittle structures.
- Very high stresses are avoided, since thin sheet joints are less stiff than joints of thick plate
- Thin sheet has lower hydrogen contents, since hydrogen can diffuse more readily from the sheet.

Carbon equivalent

The risk of hydrogen cracking during welding is linked to the amount of alloying elements in the steel. Different variants of carbon equivalent formulas are used for describing the amounts of alloying elements in conjunction with fusion welding. The most common is CE_{IIW} (IIW = International Institute of Welding).

$$CE_{IIW} = C + \frac{Mn}{6} + \frac{Cr+Mo+V}{5} + \frac{Cu+Ni}{15}$$

Figure 4 shows the relationship between the carbon equivalent CE_{IIW} and the yield strength of Domex AHSS and the standardized steels in European Standard EN 10025-2:2004. Examples of conventional steels according to EN 10025-2:2004 are:

- S235JRG2
- S275JR
- S355J2G3

These steels, according to EN 10025-2:2004 is very common and has long been used in welded structures, and are very easy to weld. There is a low risk of hydrogen cracking in thin sheets of such steels. Although the yield strength of cold-forming steels is well above that of steels to EN 10025-2:2004, the CE_{IIW} values are not much higher. In other words, this means that the risk of hydrogen cracking of Domex EHS cold-forming steels is no higher than that of the conventional weldable steels in EN 10025-2:2004.

EN 1011-2

EN 1011-2 (Recommendations for welding of metallic materials) is a standard partly used for accessing the risk for hydrogen cracks to occur in the welded joint during fusion welding. The standard specifies the working temperature needed for avoiding cold cracking. The input data used for the evaluation are the sheet thickness, type of weld (e.g. fillet weld), heat input and hydrogen content of the weld metal.

For example, according to EN 1011-2 a very high hydrogen content (>15 ml/100 g weld metal) of the weld metal and a extremely low heat input (<0,5 kJ/mm) together with a combined thickness of 30 mm for Domex 700 MC are required to promote these type of cracks to occur. If electrodes that produce low hydrogen contents (≤10 ml/100 g weld metal) are used, which is recommended by SSAB Tunnplåt for these steels, no cold cracking problems will arise. No preheating is necessary even for the thickest Domex AHSS.

It is of course important to follow the general recommendations to avoid increased risk for hydrogen cracks to occur, which are:

- Good welding circumstances is important. Keep the welded joint clear of moisture, rust, oil, etc.
- Make sure that there is no ice/white frost or condensation in the joint.
- Handle the filler metal in accordance with the supplier's recommendations.

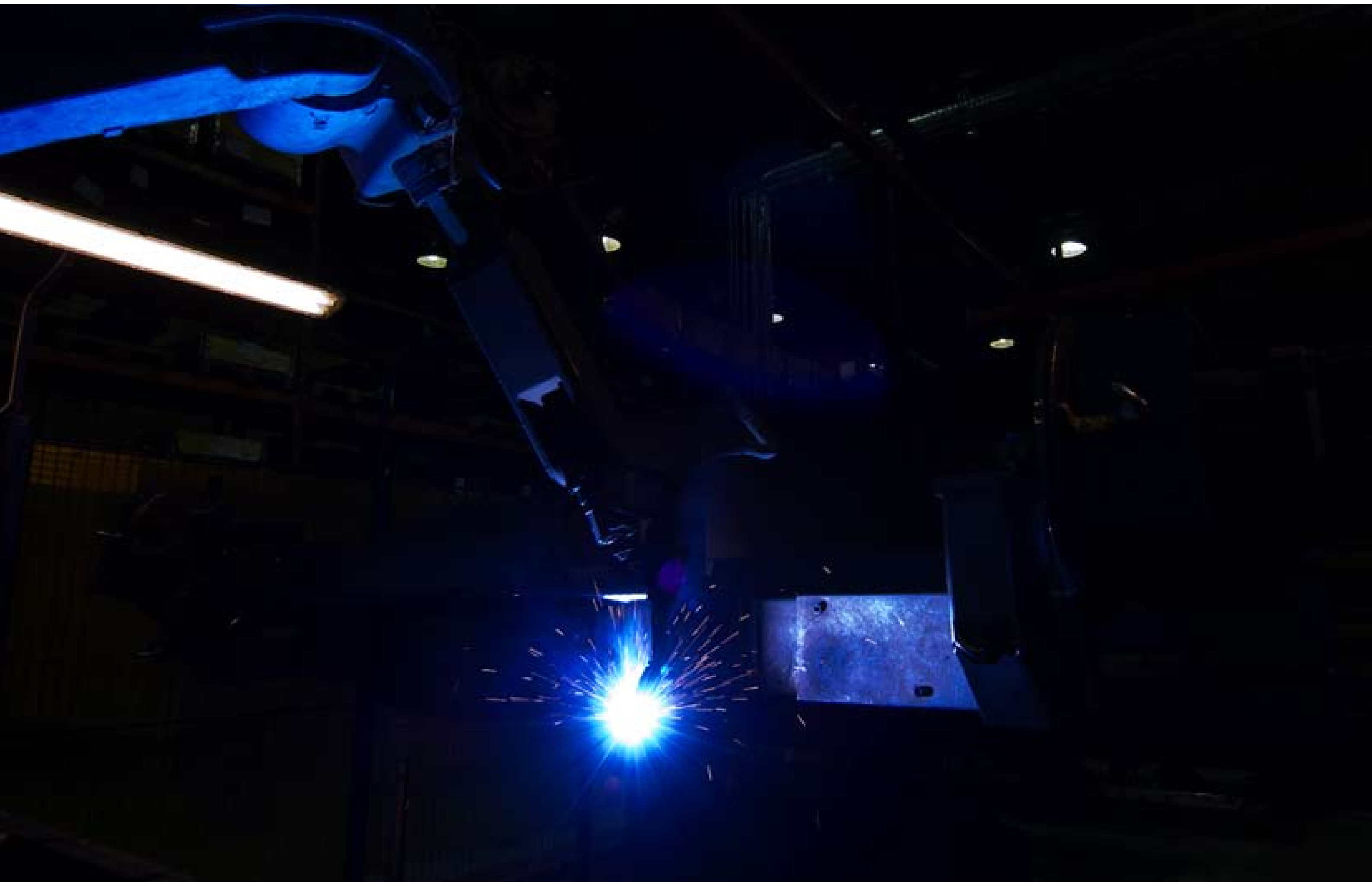
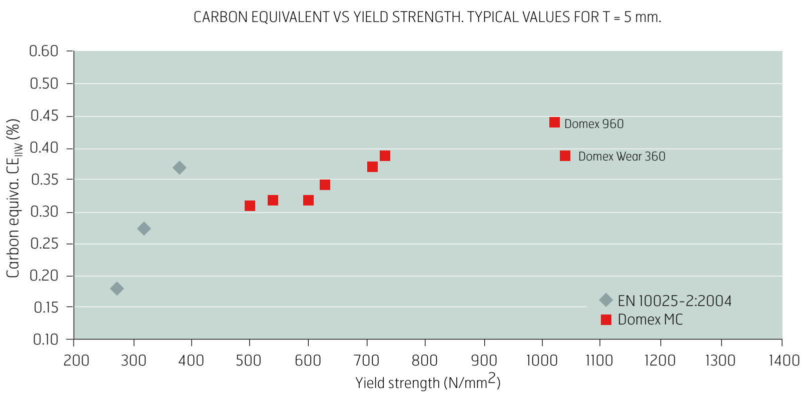


FIGURE 4 Relationship between carbon equivalent (CE_{IIW}) and yield strength (N/mm²) of Domex compared to the conventional steels in EN 10025-2:2004 (thickness 5 mm).



FILLER METALS FOR DOMEX

The filler metals recommended for Domex AHSS are listed in table 4. These filler metals are basically matched or slightly under-matched for Domex 960 and Domex Wear 360.

If the stresses acting on the weld are very high and the tensile strength of the weld is required to be equal or close to the requirements of the parent material we recommend to use matching filler metals. Under-matched filler metal can often also be used for Domex AHSS in the following typical cases:

- The weld is in a low-stress area
- For fillet welds (compensate by larger throat thickness)
- For welding to an ordinary mild steel
- If the weld reinforcement is not removed
- In most joints subjected to fatigue loads
- If lower hardness of the weld metal is desired (easier milling of weld metal)

A large number of solid wires for MAG welding of Domex AHSS are available on the market today, in yield strength in range of 460 to 900 N/mm^2. Rutile cored wires are available with yield strengths of up to 800 MPa, whereas basic flux-cored wires are available in yield strength of up to 900 N/mm^2.

If cored wires are intended to be used, rutile cored wires are recommended. Rutile cored wires are easier to weld and they normally give a much better surface appearance than basic cored wires. Basic cored wires are primarily used if the impact toughness requirements on the product are very high.

Basic electrodes are recommended for MMA welding of Domex AHSS. The risk of cold cracking (caused by hydrogen embrittlement) in the HAZ is then very low, even for the Domex AHSS with the highest yield strength (Domex 960). Preheating is not necessary.

If submerged arc welding is used for Domex AHSS it is recommended that a basic powder should be used together with a wire that provides the required mechanical properties.

The storage recommendations supplied by the filler metals manufacturer are very important to follow in order to minimize the risks of weld defects and to achieve the required mechanical properties. Electrodes that e.g. have been stored without protection in the workshop can absorb moisture from the air that can lead to high hydrogen contents of the weld metal, with increased risk for hydrogen cracking.

SSAB Tunnplåt recommends electrodes/filler metals that give maximum hydrogen content in the weld metal according to table 3.

TABLE 3 Recommended max. hydrogen content of the weld metal.

Steel grade	Maximum hydrogen content ml/100 g weld metal
Domex 460 MC	10
Domex 500 MC	10
Domex 550 MC	10
Domex 600 MC	10
Domex 650 MC	10
Domex 700 MC	10
Domex 960	5
Domex Wear 360	5

TABLE 4 Recommended filler metals for Domex.

Steel grade	MAG welding		MMA welding, coated electrode	Submerged arc welding
	Solid wire	Cored wire		
Domex 460 MC Domex 500 MC	AWS: A5. 18 ER80S-X DIN8559: SG2 EN440: G50X-xx	AWS: A5.29 E81T-X DIN 7084: T541 EN758: T50X-xx	AWS: A5.5 E9018 DIN8529: EY5543MnMoB	AWS: A5.23-F7AX-EX
Domex 550 MC Domex 600 MC	AWS: A5.28 ER100S-X	AWS: A5.29 E100T-X	AWS: A5.5 E11018 DIN8529: EY6965 Mn2NiCrMoB EN757: E69X-xx	AWS: A5.23-F 10A4-EX
Domex 650 MC	AWS: A5.28 ER100S-X AWS: A5.28 ER110S-X DINSGNiMoCr2	AWS: A5.29 E100T-X	AWS: A5.5 E11018 DIN8529: EY6965 Mn2NiCrMoB EN757: E79X-xx	AWS: A5.23-F 11AX-EX
Domex 700 MC	AWS: A5.28 ER100S-X AWS: A5.28 ER110S-X DINSGNiMoCr2	AWS: A5.29 E100T-X	AWS: A5.5 E11018 DIN8529: EY6965 Mn2NiCrMoB EN757: E79X-xx	AWS: A5.23-F 11 AX-EX
Domex 960	AWS: A5.28 ER120S-X	AWS: A5.29 E121T-X	EN757: E89XZB42H5	AWS: A5.23-F AX-EX
Domex Wear 360	AWS: A5.28 ER120S-X	AWS: A5.29 E121T-X	EN757: E89XZB42H5	AWS: A5.23-F AX-EX

Static strength of welded joints

In order to reach the required tensile strength of the welded joint, both the weld metal and the HAZ (heat affected zone) must have sufficient strength. Several factors affect the strength of the welded joint e.g. filler metal used (matching or undermatching), chemical composition, heat input, interpass temperature, etc. The strength of the weld metal (N/mm²) is mainly determined by the filler metal used whereas the strength of the HAZ more or less is determined by the cooling cycle ($\Delta t_{8/5}$).

HEAT INPUT

The heat input in fusion welding is the amount of heat supplied to the material during welding. The following formula is generally used for calculating the heat input:

$$E = \frac{U \times I \times 60}{v \times 1000} \text{ kJ/mm}$$

Where: U = voltage (V)
I = current (A)
v = welding speed (mm/min)

If a more accurate estimate of the heat input is needed, other factors must also be taken into account, such as the welding method employed. The following formula is then used for calculating the heat input:

$Q = \eta \times E$

Where η = arc efficiency

The approximate values of η for different welding methods are as follows:

Since the first formula above is most commonly used in practice for calculating the heat input, the formula for E will be used throughout this brochure

INTERPASS TEMPERATURE

Multi-pass welding may cause the temperature in the welded joint to rise to a level that is harmful to the material, which will cause the strength to drop. This is most critical for short welds, i.e. below 500 mm, since the temperature of the material will not have time to drop before the next bead is welded. In order to limit the temperature rise so that it will not be harmful to the material, a maximum inter-pass temperature may be employed. This means that the temperature at the starting point for the next weld bead must not exceed a specified value. The maximum recommended inter-pass temperatures are as follows:

- Domex 355 MC ÷ Domex 500 MC   150 °C
- Domex 600 MC ÷ Domex 960 MC   100 °C
- Domex Wear 360   100 °C

SOFT ZONES

When Domex AHSS with yield strength above 500 N/mm² are welded, soft zones will be formed in the HAZ. These arise as a result of changes in the microstructure. The width and hardness of the soft zones are determined mainly by the sheet thickness and the heat input. A typical hardness curve for Domex 700 MC could be seen in figure 5.

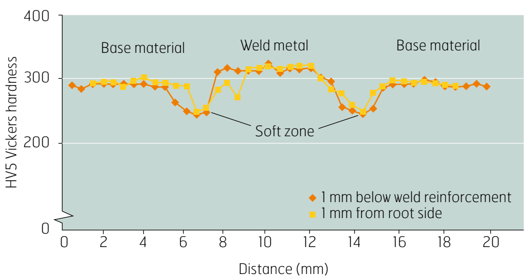
Thin sheets and high heat input (increased cooling rate ($\Delta t_{8/5}$) gives rise to a wider zone and lower strength.

TABLE 5 Arc efficiency for different welding methods.

Welding method	η
MAG	0.8
MMA	0.8
Submerged arc welding	1.0
TIG	0.6

FIGURE 5 Typical hardness curve for Domex 700 MC.

Hardness measurement in Domex 700 MC, t=6mm.

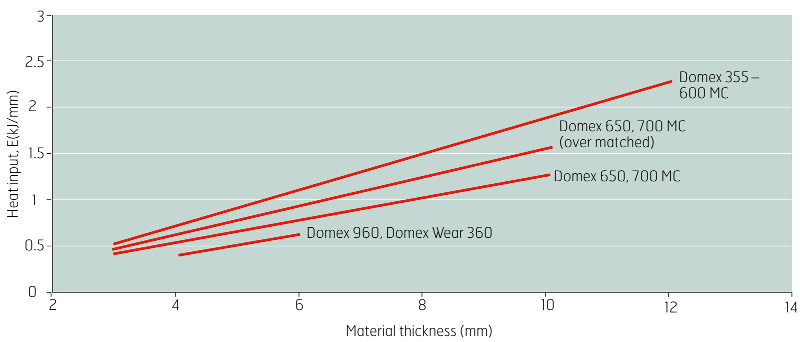


If normal heat input is used and the workpiece is not preheated when working with grades Domex 550 MC – Domex 700 MC, these soft zones normally have no influence on the strength of the weld. On tensile testing across a butt weld, for example, the increasing load will quickly give rise to a three-axis stress condition in the soft zone, which prevents further deformation in these parts of the material. Failure will thus not take place in the soft zones, but will occur in the parent metal or in the weld metal.

Due to the very high strength of Domex 960 the failure will always take place either in the weld metal or in the HAZ. However it is still possible to reach the minimum tensile strength requirement of the parent material if the maximum heat input recommended by SSAB Tunnplåt is not exceeded, see figure 6. In single pass welding or for long welds in multi pass welding the maximum permitted heat input could be raised by 10–15 %. The increase in the maximum permissible heat input for fillet welds are 40–50 %. This increase is possible because the values in the graph are based on an interpass temperature of 150 °C for Domex 460 MC – Domex 600 MC and 100 °C for Domex 650 MC – Domex 960.

FIGURE 6 Maximum recommended heat input to fulfil the minimum. Tensile strength requirement of the base material.

Max. heat input for Domex steels (butt welds) for meeting the minimum Rm requirement for the parental metal



The values in the graph are based on an interpass temperature of 150°C for Domex 460–600 MC and 100°C for Domex 650 MC up to Domex 960. If the welding operation is performed as single pass welding at ambient temperature (20°C) the maximum permitted heat input could be raised by 10–15 % for butt weld and 40–50 % for fillet welds.

RESULTS OF MECHANICAL TESTING

Some examples of mechanical properties obtained on MAG welded Domex AHSS are tabulated below. The test results relate to butt welds welded with filler metals of different matching grade. Before tensile testing the reinforcement was removed.

TABLE 6 Tensile strength and Charpy V impact toughness of welded joints in a number of steel grades in Domex.
MAG welded butt welds, removed reinforcement before testing.

Weld No	Domex Steel grade (thickness, mm)	Wire (AWS)	Pass	Heat input kJ/mm	Tensile test across		Impact test (Charpy V)			
					Rm, MPa[1)]	Fracture Location (Wm, Pm, HAZ[1)])	Direction of testing (L, T[2)])	Position[3)]	Impact energy (J/cm²)	
									−20°C	−40°C
1	Dx 460 (3	A5.18 ER7XS-X	1	0.60	595	Pm				
2	Dx 460 (6)	A5.18 ER7XS-X	1 2 3	0.58 0.61 0.62	605	Pm	L	A B C	147 208	129 156 264
3	Dx 460 (12)	A5.18 ER7XS-X	1 2 3 4	1.23 1.20 1.20 1.22	631	Wm	L	A B C	59 191 155	70 42 66
4	Dx 500(6)	A5.18 ER7XS-X	1	1.2	595	Pm	L	A B C	168 162 256	174 110 244
5	Dx 500 (12)	A5.18 ER7XS-X	1 2	1.3 1.5	636	Pm	L	A B C	61 138 275	42 46 120
6	Dx 600 (4)	A5.28 ER10XS-X	1	0.79	706	HAZ				
7	Dx 650 (6)	A5.28 ER12XS-X	1 2	0.73 0.81	810	HAZ	T	A B C		207 51 107
8	Dx 650 (8)	A5.28 ER10XS-X	1 2	0.61 1.2	774	Wm	T	A B C	176 72 89	172 46 58
9	Dx 700 (3)	A5.28 ER10XS-X	1	0.39	846	HAZ				
10	Dx 700 (6)	A5.28 ER10XS-X	1 2 3	0.61 0.41 0.42	825	Pm	L	A B C	130 66 154	112 35 145
11	Dx 700 (8)	A5.28 ER10XS-X	1 2 3	0.88 0.94 0.95	836	Pm	L	A B C	71 80 156	52 69 61
12	Dx 700 (10)	A5.28 ER10S-X	1 2 3 4	0.57 1.10 1.08 1.09	818	HAZ	L	A B C	118 104 118	74 53 47
13	Dx 960	A5.28 ER11S-X	1 2 3	0.57 0.40 0.39	1050	HAZ	L	A B C		53 40 90
14	Dx Wear 360 (4)	A5.28 ER12S-X	1	0.52	699	HAZ	L			
15	Dx Wear 360 (6)	A5.28 ER12S-X	1 2 3	0.55 0.56 0.56	800	HAZ	L	A B C	157 148 195	137 100 122

1) Failure position, Wm = weld metal, Pm = parent material, HAZ = heat affected zone
2) L = longitudinal, T = transversal
3) A = weld metal, B = fusion line, C = Fusion line + 1 mm

Impact toughness of welded joint

In order to avoid brittle fracture in welded structures, it is important that the parent metal, weld metal and HAZ have good impact toughness.

The impact toughness of the weld metal is determined principally by the microstructure of the weld metal. The microstructure, in turn, is dependent on the filler metal, parent metal (due to dilution) and heat input. It is therefore important to use a filler metal that meets the requirements. From experience of welding cold-forming steels, the impact toughness of the weld metal is often appreciably better than the value specified in the catalogues of filler metal suppliers. To achieve good impact toughness of the weld metal, it is also recommended that welding should be carried out at low heat input, which is also beneficial to several other properties, see below.

Lower heat input ensures:

- Improved toughness of the weld metal
- Improved toughness of the HAZ
- Increased strength of the welded joint

The HAZ nearest to the weld metal is the coarse-grained zone that has the lowest toughness, see figure 7. By welding with several passes and low heat input, the extent of the coarse-grained zone can be confined. The impact toughness of the HAZ can thus be maintained at a satisfactory level when welding Domex steels.

In order to meet the minimum impact toughness requirements of the welded joint it is recommended that a suitable number of passes be welded for a specified thickness, see figure 8.

FIGURE 7 Coarse-grained zone of HAZ.

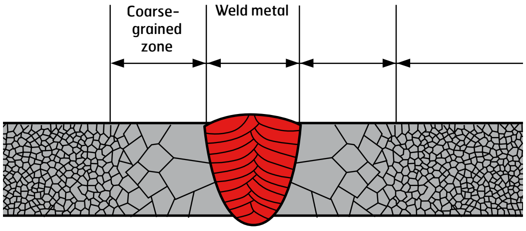
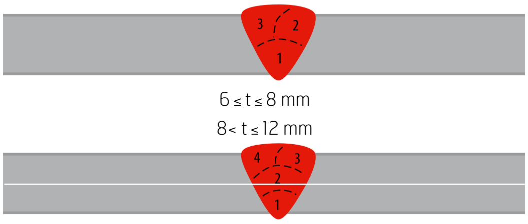


FIGURE 8 Recommended number of passes to fulfil the minimum impact toughness requirement of the welded joint.



Stress relief annealing

For Domex AHSS, stress relief annealing is not necessary for lowering the hardness or improving the toughness. The hardness need not be reduced, since the steel compositions are so lean that no hardness peaks occur after welding. The impact toughness in the as-welded condition is good, and no subsequent heat treatment is therefore necessary for impact toughness reasons. Stress relief annealing of Domex AHSS is justified only if the internal weld stresses are to be relieved or if the steel is welded to another steel that requires stress relief annealing. However, various production standards may sometimes specify stress relief annealing.

If the stress relief annealing is used on Domex 460–700 MC, the following procedure is recommended:

- Max. heating rate of 100°C/h
- Soaking time: 2 min/mm of plate thickness (minimum of 30 min)

Soaking temperature:

- Domex 460 MC – Domex 700 MC: 530°C – 580°C. Max. cooling rate: 100°C/h

Domex 960 and Domex Wear 360 must not be exposed to stress relief annealing.

If the structure is produced in accordance with a production standard that requires stress relief annealing, the instructions in the standard take precedence over the SSAB Tunnplåt recommendations.

Hot straightening

Structures may be deformed in various welding operations. A straightening operation may be necessary for restoring the structure to its original dimensional properties, for which cold straightening is recommended. More complex or heavier structures may require hot straightening. High-temperature hot straightening may lower the strength, and the temperature should therefore be restricted. If hot straightening of a welded joint is to be carried out, the maximum temperature should be restricted to the value specified in table 7.

TABLE 7 Maximum recommended hot straightening temperatures

Steel grade	Recommended maximum temperature for hot straightening of parent metal	Recommended maximum temperature for stress relief annealing and hot straigh-tening of welded joints
Domex 460 MC – 700 MC	650 °C	580 °C
Domex 960	300 °C	Not permitted

Docol

MATERIAL

The Docol advanced high strength steels (AHSS) dealt with in this welding brochure are Docol 1000 DP, Docol 1200 M and Docol Wear 450. These three steels are cold rolled steels with high tensile strength. The thickness range for these steels is between 0.5–2.1 mm. In relation to the high tensile strength, the amount of alloying elements in these steels is low and this is a benefit for the weldability.

Docol 1000 DP is a dual phase steel with a good combination of strength, formability and weldability. Typical for a Docol dual phase steel is the microstructure, which consists of a ferritic matrix containing a hard martensitic second phase. Ferrite, which is soft, contributes to the good formability and martensite to the high strength of the material. Docol 1200 M is a fully martensitic steel. Typical for a Docol M steel is the very high strength. The formability is not as good as for dual phase steels but this steel is most suitable for bending, roll forming, simple press operations and tube making. Mechanical properties and chemical compositions are shown in Tables 8–9 for Docol 1000 DP and Docol 1200 M.

Docol Wear 450 is a cold rolled continuously annealed quenched and tempered steel with excellent wear resistance. Docol Wear steels can be used for components subjected to abrasive wear by hard particles such as stones, sand and grain. Typical chemical composition and hardness values of Docol Wear 450 are shown in Table 9–10.

Heating of these Docol AHSS should be avoided but if heating is necessary for some reason the maximum temperature should be limited to 300°C for Docol 1000 DP and 200°C for Docol 1200 M and Docol Wear 450. Heating higher than these temperatures will give a reduction in tensile strength of the materials.

TABLE 8 Mechanical properties of Docol 1000 DP and Docol 1200 M.

Steel grade	Yield strength (N/mm^2) minimum	Tensile strength (N/mm^2) minimum	Elongation A80 (%) minimum	Bending radius 90° bend minimum
Docol 1000 DP	700	1000	7	2.0 x t
Docol 1200 M	950	1200	3	3.0 x t

TABLE 9 Chemical composition for Docol 1000 DP, Docol 1200 M and Docol Wear 450 (typical values).

Steel grade	C (%)	Si (%)	Mn (%)	P (%)	S (%)	Al (%)	Nb (%)	Ti (%)	CE[1] (%)
Docol 1000 DP	0.15	0.50	1.50	0.010	0.002	0.040	0.015	-	0.40
Docol 1200M	0.11	0.20	1.60	0.010	0.002	0.040	0.015	0.025	0.38
Docol Wear 450	0.17	0.20	1.20	0.010	0.002	0.040	0.015	0.025	0.38

1) Carbon equivalent $CE = C + Mn/6 + (Cr + Mo + V)/5 + (Cu + Ni)/15$

TABLE 10 Hardness (typical values) of Docol Wear 450.

Steel grade	Hardness		
	Brinell (HB)	Rockwell (HRC)	Vickers (HV)
Docol Wear 450	440	43	456

Joint types and joint preparation

In Figure 9 different joint types are shown for Docol AHSS. The most common joint types of these are butt joint, lap joint and T-joint. For butt-welding of Docol AHSS, square butt joints without any special joint preparation are normally used. Shearing, punching, milling or thermal cutting can be used for the preparation of the sheet. The requirements on the edges are not very strict for ordinary fusion welding. Also for lap joints and T-joints the demands on the edges are moderate.

WELDING

General

Gas metal arc welding (GMAW) of these Docol AHSS has shown that the weldability is good. Due to the low carbon equivalent value and low level of phosphor and sulphur in combination with a clean steel surface, the risk for material related weld defects is very small. The strength of the welded joint increases with increasing steel strength. The weld strength is however slightly lower than the base metal strength.

Methods of welding and filler metals

The most common method used for fusion welding of the Docol AHSS steels is gas metal arc welding (GMAW). Another name for this method of welding is MAG (metal active gas) or in some countries also called MIG. As shielding gas a mixed gas of argon (Ar) and carbon dioxide (CO_2) is recommended (M21). All kind of GMAW can be used e.g. manual, automatic and with robot. Other methods sometimes used for fusion welding of these Docol AHSS are tungsten inert welding (TIG), manual metal arc welding (MMA), plasma welding (PAW) and laser welding. The following text is concentrated only to GMAW.

Filler metals recommended for GMAW of the three Docol AHSS are shown in Table 11. Only solid wires are mentioned in Table 11, since the use of cored wires for welding of cold rolled sheet steel is still less common. However, cored wires can also very well be used.

Only welding wires of very high tensile strength are included in Table 11. However, if the welds are placed in low stress areas, welding wires of lower tensile strength can also be used.

Results from tensile testing of welded joints with different tensile strength of filler metals are shown in section “Results of testing Docol AHSS”.

Heat input and general welding recommendations

The risk for material related weld defects such as cold cracks and hot cracks is very low for the Docol AHSS. The main reason for that is the low carbon equivalent value and low levels of phosphor, sulphur and niobium in these steels. In order to avoid corrosion damage the sheet steel is normally coated with a thin oil film. However this oil film is so thin that it does not give any porosity problems in conjunction with GMAW. The oil is gasified and quickly disappears during welding. However, if the sheet is stored in an environment where dirt may accumulate on the surface of the sheet, some precautions have to be taken. In order to avoid weld-

FIGURE 9 Examples of different joint types for gas metal arc welding of Docol.

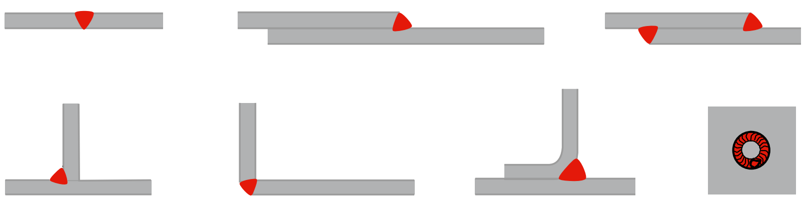


TABLE 11 Filler metals recommended for GMAW of Docol 1000 DP, Docol 1200 M and Docol Wear 450.

Steel grade	Gas metal arc welding Solid wire
Docol 1000 DP	AWS A5.28 ER 100S-G, AWS A5.28 ER 11XS-X, AWS A5.28 ER 12XS-X, DIN SGNiMoCr2
Docol 1200 M	AWS A5.28 ER11 XS-X, AWS A5.28 ER 12 XS-X, DIN SGNiMoCr2
Docol Wear 450	AWS A5.28 ER 11XS-X, AWS A5.28 ER 12 XS-X, DIN SGNiMoCr2

ing defects in this case, some form of cleaning of the sheet may then be necessary before welding.

Welding of thin sheet steel makes strict demands on the welding parameters used. To avoid burning-through and distortions of the sheet it is important to use a low heat input. The heat input is defined as the supplied heat to the material per unit length of weld. The following formula can be used for calculation of the heat input:

$$E = \frac{U \times I \times 60}{v \times 1000} \text{ kJ/mm}$$

Where: U = voltage (V)
I = current (A)
v = welding speed (mm/min)

Another benefit with a low heat input is also a higher tensile strength of the welded joint.

Preheating shall not be used for these Docol AHSS. The reason is that preheating will reduce the strength and hardness of the Docol AHSS.

Forehand welding is normally used for GMAW of lap welds and fillet welds. Forehand welding gives a smoother transition between the weld metal and the parent metal. Side penetration is also somewhat greater, which gives a greater tolerance range for positioning of the gun across the weld.

Welding distortions

Welding distortions is a very important issue when GMAW of thin sheets is used. In some cases the resulting distortions are so great that it is impossible to use welding as a joining method. To minimize the distortions it is important to use a welding plan and use a certain welding sequence. The recommendations for thin Docol steels are as follows:

- Minimize the weld reinforcement and throat thickness by using a low heat input
- If possible use a low strength filler metal
- Use back step welding if possible

To avoid distortions it is important to use a low heat input to achieve a small reinforcement and throat thickness. The reason is that a small fused area will decrease the shrinkage forces.

The distortions will be lower if a low strength filler metal is used. Before choosing a filler metal with a lower strength check that this is acceptable from the viewpoint of other demands made on the structure.

The method with back step welding is shown in Figure 10.

Another recommendation to reduce the distortions is to weld near a bent area. In this way the area close to the weld will be stiffer and can resist distortions better.

RESULTS OF TESTING DOCOL

The tensile strength of the welds for Docol AHSS increases with increasing base metal strength (see Figure 11). For the steels with high tensile strength, as for example Docol 1000 DP, Docol 1200 M and Docol Wear 450, the tensile strength of the welds are somewhat lower than the base metal strength. The reason for this is small soft zones in the heat-affected zone (HAZ) due to the applied heat during welding. Tensile testing shows that the fracture is located to this soft zone. In Figure 4 the hardness curve for a gas metal arc welded Docol 1000 DP steel illustrates these soft zones in the outer part of HAZ.

In Table 12 some more results from tensile testing of welded joints of Docol 1000 DP and Docol 1200 M are shown. The results in this

FIGURE 10 Example of back step welding to reduce distortions of the sheet.

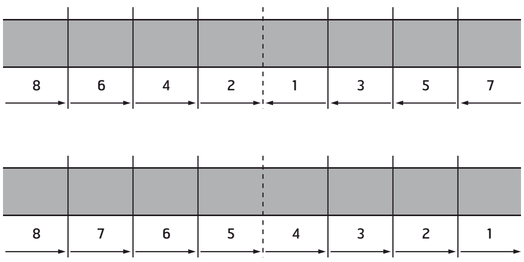


FIGURE 11 Strength of welds for Docol 1000 DP, Docol 1200 M and Docol Wear 450 (GMAW, butt welds, high tensile strength filler metal AWS A5.28 ER 110S-G, mixed shielding gas of Ar and CO_2).

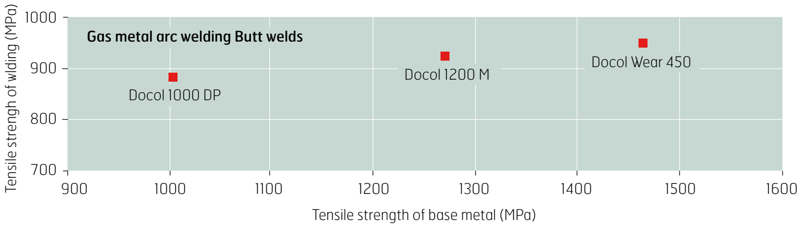


Table show that the strength of the butt welds increases with decreasing heat input (e.g. Docol 1200 M, sheet thickness 2.0 mm). The reason is that a reduction of the heat input will give less softening of the material.

Another conclusion from the results in Table 12 is that the strength of a lap joint is lower than the strength of a butt joint. The lap joint in these cases is a single sided welded lap joint. The reduction in strength for the lap joint is due to the unsymmetrical loading and the extra bending moment associated with this type of loading for the lap joint. This extra bending moment increases the stress near the weld toe.

Regarding strength and lap joints it should be mentioned that if a thin sheet is lap welded to a much thicker sheet (e.g. a sheet thickness greater than 3 mm) the corresponding strength in this case is considerably higher (see Table 12). The reason is that the thicker sheet is so stiff that no bending of the thin sheet occurs.

The strength of a welded joint (both butt joints and lap joints) is somewhat higher for a high strength filler metal in comparison with a soft filler metal (see Table 12). However the difference is not so great (approximately 20–30 MPa) so in many cases soft filler metals can probably also be used.

Docol Wear 450 is a steel subjected to abrasive wear. It is beneficial with a welded joint of high hardness and therefore a high strength filler metal is recommended in this case. A typical hardness curve across the welded joint is shown in Figure 13. Due to the applied heat from the welding there are soft zones in the HAZ. If the welded joint is located to an area of low abrasive wear and low stresses also a soft filler metal can be used.

TABLE 12 Results from testing of welds of Docol 1000 DP and Docol 1200 M (same steel grade/sheet thickness in both sheets).

Steel grade	Thickness (mm)	Joint type	Filler metal1[1), 2)]	Heat input E (kJ/mm)	Tensile strength of weld (MPa)	Fracture location [4)]
Docol 1000 DP	2.0	Butt weld	High strength	0.17	813	HAZ
Docol 1000 DP	1.2	Butt weld	High strength	0.09	882	HAZ
Docol 1000 DP	1.2	Butt weld	Low strength	0.09	864	HAZ
Docol 1000 DP	1.2	Lap weld	High strength	0.10	805	HAZ
Docol 1000 DP	1.2	Lap weld	Low strength	0.09	775	WM
Docol 1200 M	2.0	Butt weld	High strength	0.14	925	HAZ
Docol 1200 M	2.0	Butt weld	High strength	0.21	859	HAZ
Docol 1200 M	2.0	Butt weld	Low strength	0.15	893	HAZ
Docol 1200 M	1.5	Butt weld	High strength	0.12	856	HAZ
Docol 1200 M	1.5	Lap weld	High strength	0.15	740	HAZ
Docol 1200 M	1.5	Lap weld	Low strength	0.16	707	HAZ
Docol 1200 M[3)]	1.5	Lap weld	High strength	0.23	930	HAZ

1) High strength filler metal. AWS A5.28 ER 110S-G.
2) Low strength filler metal. AWS A5.18 ER 70S-6.
3) Top sheet: Docol 1200 M 1.5 mm. Bottom sheet: Domex 700 MC 4.0 mm.
4) HAZ=heat affected zone, WM=weld metal.

FIGURE 12 Hardness curve across weld for a gas metal arc welded Docol 1000 DP (sheet thickness 1.2 mm, butt weld, heat input 0.09 kJ/mm, high strength filler AWS A5.28 ER 110S-G, mixed shielding gas of Ar and CO_2).

Docol 1000 DP, Wire: OK Autrod 13.31

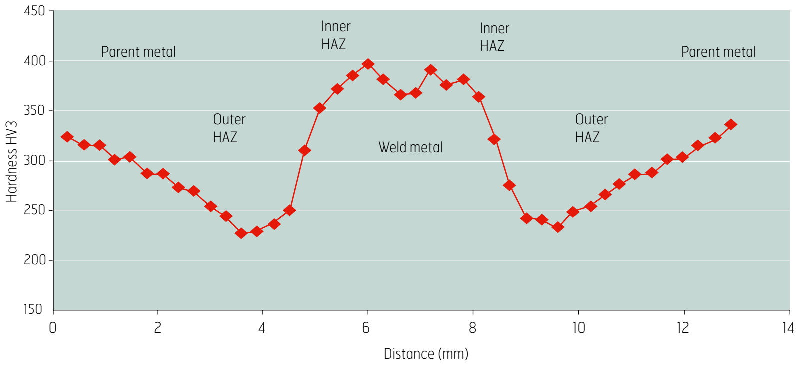
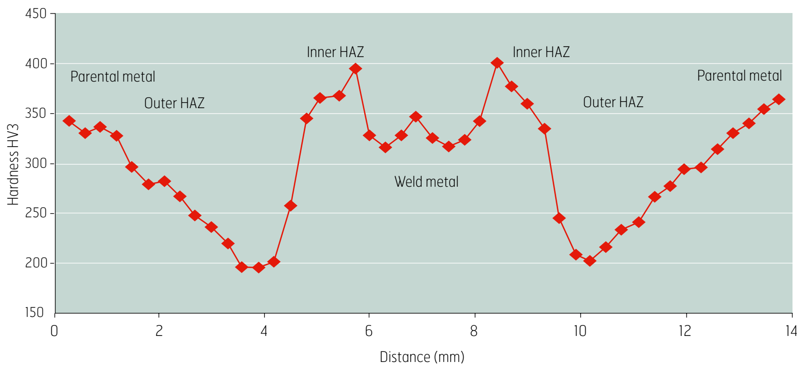


FIGURE 13 Hardness curve across weld for a gas metal arc welded Docol Wear 450 (sheet thickness 1.0 mm, butt weld, heat input 0.09 kJ/mm, high strength filler Rm=890 MPa.

Docol wear 450



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