STRENX™ PERFORMANCE STEEL

Welding of Strenx

advanced high strength steels

SSAB

Introduction

For many years, fusion welding has been employed for the welding of Strenx and Domex Advanced High Strength Steels. Compared with the fusion welding of mild steels, the process does not differ significantly. However, in order to maximize the benefits of these high strength steels, the welding process must still be controlled in a suitable manner. The following pages offer useful information about welding with Strenx and Domex from SSAB. The advice and information here can help you to achieve optimal welding results, which allow you to experience the full potential of your choice in Strenx or Domex from SSAB.

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Strenx and Domex are the names of our hot-rolled steels from SSAB. These steels are supplied in the thickness range 2–16 mm, and due to their exceptional formability in a cold state, they are also known as cold-forming steels. Strenx and Domex steels are characterized by high yield strength, excellent formability and good weldability. These qualities make them optimal for use in the transportation industry (trailers, trucks, tippers, automotive, trains and cranes).

Strenx and Domex steels are available in the yield strength levels shown in figure 1. Their mechanical properties and chemical composition can be seen in tables 1 and 2.

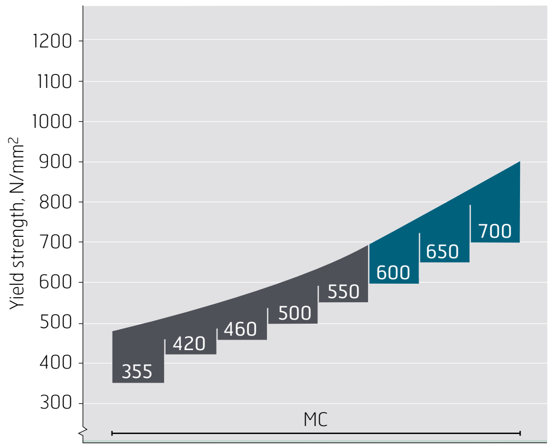


FIGURE 1 Strength of Strenx and Domex

TABLE 1 Mechanical properties of Strenx and Domex.

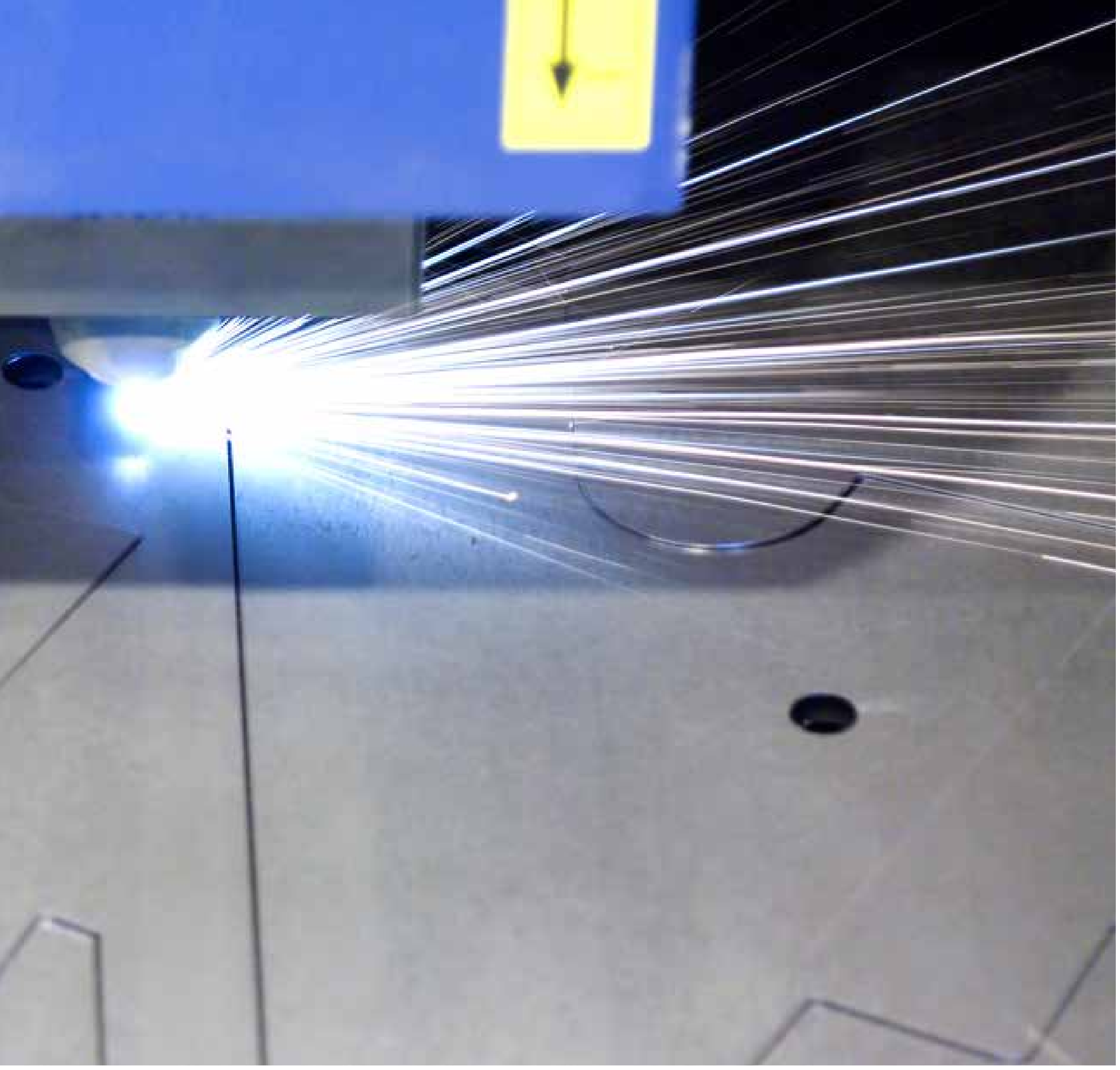
Mechanical Properties							
Steel grade	Yield strengt R_{eh} (MPa)	Tensile strength R_m (MPa)	Elongation Min. (%)		Bending radius, minimum in 90° bend.		
	minimum	minimum	A_{80} t<3	A_5 t ≤ 3	t ≤ 3	3 < t ≤ 6	t >6
Domex 355 MC	355	430–550	19	23	0.2 x t	0.3 x t	0.5 x t
Domex 420 MC	420	480–620	16	20	0.4 x t	0.5 x t	0.8 x t
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
Strenx 600 MC	600	650–820	13	16	0.7 x t	1.1 x t	1.4 x t
Strenx 650 MC	650 *	700–880	12	14	0.8 x t	1.2 x t	1.5 x t
Strenx 700 MC	700 *	750–950	10	12	0.8 x t	1.2 x t	1.6 x t
Domex 550 W	550	600		18		1.0 x t	1.5 x t
Domex 700 W	700	750		12		2.0 x t	

* For thickness above 8 mm the minimum yield strength may be 20 MPa lower.

TABLE 2 Chemical composition of Strenx and Domex.

Chemical composition								
Steel grade	C (%) maximum	Si (%) maximum	Mn (%) maximum	P (%) maximum	S (%) maximum	Al (%) minimum	CEV Typical	CET Typical
Domex 355 MC	0.10	0.03	1.50	0.025	0.010	0.015	0.26	0.18
Domex 420 MC	0.10	0.03	1.50	0.025	0.010	0.015	0.30	0.20
Domex 460 MC	0.10	0.10	1.50	0.025	0.010	0.015	0.31	0.20
Domex 500 MC	0.10	0.10	1.60	0.025	0.010	0.015	0.32	0.22
Domex 550 MC	0.12	0.10	1.80	0.025	0.010	0.015	0.32	0.16
Strenx 600 MC	0.12	0.10	1.90	0.025	0.010	0.015	0.34	0.21
Strenx 650 MC	0.12	0.10	2.00	0.025	0.010	0.015	0.37	0.23
Strenx 700 MC	0.12	0.10	2.10	0.025	0.010	0.015	0.39	0.25
Domex 550 W	0.10	0.15	1.50	0.12	0.010	0.050	0.37	0.19
Domex 700 W	0.12	0.60	2.10	0.030	0.010	0.050	0.48	0.26

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 can readily be used with these steels. However, the most common 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 is as easy to perform as it is on mild steels. No preheating is needed for thermal cutting, however, it is important to note that a thin oxide film may form 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 the plasma gas. If nitrogen is used, it can be absorbed at the cut surfaces of the steel, which may cause porosity in the weld metal. The solution lies in using oxygen as the plasma gas, or by grinding down the cut surfaces by at least an approximate 0.2 mm before welding. If thin sheet steel parts are to be welded together, ordinary shearing can be used as joint preparation.

Welding

WELDING METHODS FOR STRENX / DOMEX

All common fusion welding methods can be employed for welding. Examples of welding methods that can be used are:

- MAG-welding (Metal Active Gas), (GMAW)
- MMA-welding (Manual Metal Arc), (SMAW)
- TIG-welding (Tungsten Intert Gas), (GTAW)
- Plasma welding
- Submerged arc welding
- Laser welding

Welding methods other than those mentioned above may also be used. However, of the methods mentioned, MAG-welding is the most commonly used welding method in the industry today. One of the reasons for this is because MAG-welding is very easy to automate (high productivity).

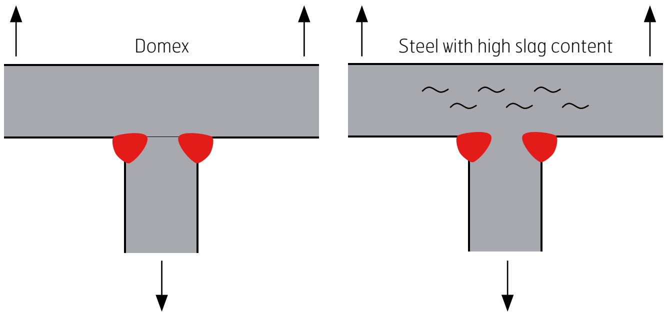


FIGURE 2 Lamellar tearing. Difference between a steel with high slag inclusions and Strenx and Domex steels.

HOT CRACKS AND LAMELLAR TEARING

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

When a T joint (see figure 3) is welded close to the edge of Strenx steel with a thickness of ≥ 8 mm, it is important that there are 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.

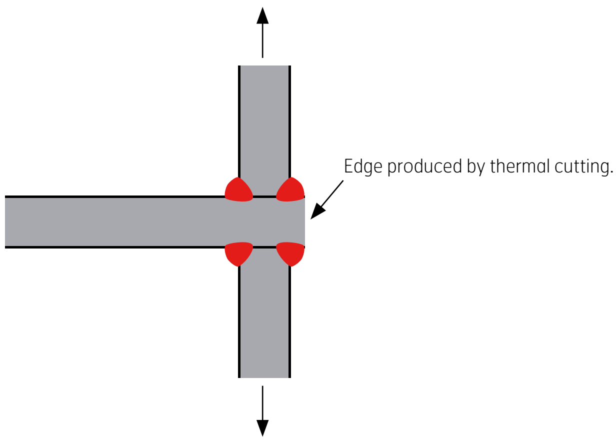


FIGURE 3 It is recommended to use thermal cut edges in T-joints with welds close to the cut edge.

HYDROGEN CRACKING

The risk of hydrogen cracking (cold cracking) occurring in Strenx and Domex is very low. The reason for this is due to:

- Very lean steel composition and thin sheets (slow cooling), which reduce the occurrence of brittle structures;
- The avoidance of high stresses, since thin sheet joints are less stiff than thick plate joints;
- 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 to describe the amount of alloying elements in conjunction with fusion welding. The two most common are CEV or CET.

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

$$CET = C + \frac{Mn + Mo}{10} + \frac{Cr + Cu}{20} + \frac{Ni}{40}$$

CARBON EQUIVALENT VS YIELD STRENGTH. TYPICAL VALUES FOR T = 5 mm.

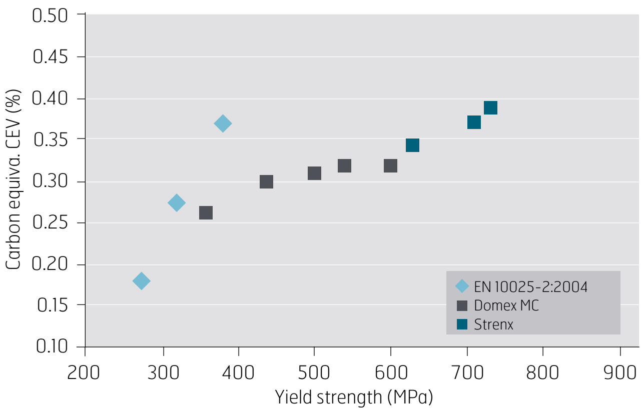


FIGURE 4 Relationship between carbon equivalent (CEV) and yield strength (MPa of Strenx and Domex compared to the conventional steels in EN 10025-2:2004 (thickness 5 mm).

Figure 4 shows the relationship between the carbon equivalent CEV and the yield strength of Strenx and Domex and the standardized steels of the European Standard EN 10025-2:2004. Examples of conventional steels according to EN 10025-2:2004 are:

- S235JR
- S275JR
- S355J2

These steels, according to EN 10025-2:2004 are very common, have long been used in welded structures, and are very easy to weld. There is a low risk of hydrogen cracking in thin sheets of these steels. Although the yield strength of cold forming steels is well above that of steels in EN 10025-2:2004, the CEV values are not much higher. In other words, this means that the risk of hydrogen cracking of Strenx and Domex 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 occurring in the welded joint during fusion welding. The standard specifies the working temperature needed to avoid 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 an extremely low heat input (<0.5 kJ/mm), together with a combined thickness of 30 mm for Strenx 700 MC are required to promote these types of cracks to occur. If electrodes that produce low hydrogen contents (≤10 ml/100 g weld metal) are used, which is recommended by SSAB for these steels, no cold cracking problems will arise. No preheating is necessary even for the thickest dimensions of Strenx and Domex.

It is of course important to follow the general recommendations to avoid an increased risk for the occurrence of hydrogen cracks, including:

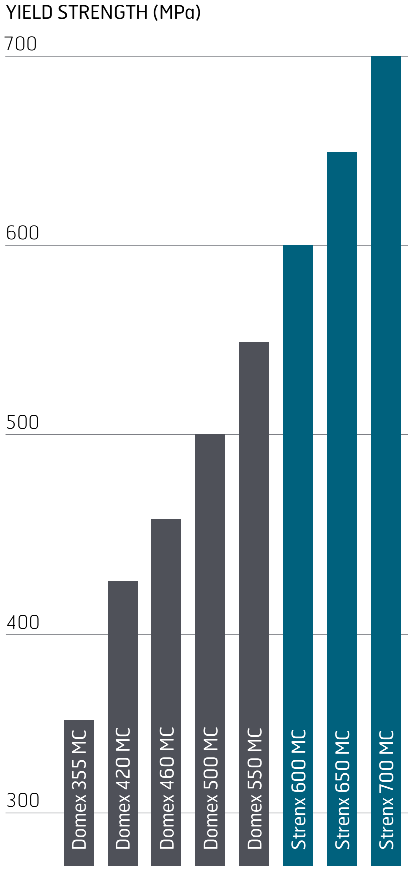
- Good welding circumstances. Keep the welded joint free from moisture, rust, oil, etc.
- Make sure that there is no ice/white frost or condensation in the joint
- Handle the filler metal in accordance with the supplier's recommendations.

FILLER METALS FOR STRENX / DOMEX

The filler metals recommended for Strenx and Domex are listed in figure 5.

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 using matching filler metals. Under-matched filler metal can often also be used for Strenx and Domex in the following typical cases:

- When 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).



MAG Welding Solid wire	MAG Welding Cored wire	MMA Welding Coated electrode	Submerged arc welding
AWS: A5.28 ER100S-X AWS: A5.28 ER110S-X EN 16834(-A) 69X	AWS: A5.29 E11XT-X EN 18276(-A) T69X	AWS: A5.5 E11018 EN757 E69X	AWS: A5.23 F11X EN 26304(-A) S69X
AWS: A5.28 ER100S-X AWS: A5.28 ER110S-X EN 16834(-A) G 62X		AWS: A5.5 E11018 EN757 E62X	AWS: A5.23 F11X EN 26304(-A) S62X
AWS: A5.28 ER100S-X AWS: A5.28 ER90S-X EN 16834(-A) G 55X	AWS: A5.29 E10XT-X AWS: A5.29 E9XT-X EN 18276(-A) T55X EN 16834(-A) T50X	AWS: A5.5 E100X EN757 E55X EN 2560 E50X	AWS A5.23 F10X EN 26304(-A) S55X EN 756 S50X AWS: A5.23 F9X
AWS: A5.28 ER80S-X EN 14341(-A) 50X EN 14341(-A) G 46X	AWS: A5.29 E8XT-X EN 16834(-A) T46X EN 16834(-A) T42X	AWS: A5.5 E80X EN 2560(-A) E46X EN 2560(-A) E42X	AWS: A5.23 F8X EN 756 S46X EN 756 S42X AWS: A5.23 F7X
AWS: A5.28 ER70S-X EN 14341(-A) G 42X		AWS: A5.5 E70X	

FIGURE 5 Recommended filler metals for Strenx and Domex.

A large number of solid wires for MAG-welding of Strenx and Domex are available on the market, in yield strengths ranging from 355 to 700 MPa.

If cored wires are intended to be used, rutile cored wires are recommended. Rutile cored wires are easier to weld and they normally provide 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 Strenx and Domex. The risk of cold cracking (caused by hydrogen embrittlement) in the HAZ (heat affected zone) is then very low, even for Strenx and Domex with the highest yield strength. Preheating is not necessary.

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

It is very important to follow the storage recommendations supplied by the filler metal manufacturer in order to minimize the risks of weld defects and to achieve the required mechanical properties. Electrodes that, for example, have been stored without protection in the workshop, can absorb moisture from the air, which can lead to high hydrogen contents in the weld metal, with increased risk for hydrogen cracking. SSAB 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 355 MC	30
Domex 420 MC	30
Domex 460 MC	10
Domex 500 MC	10
Domex 550 MC	10
Strenx 600 MC	10
Strenx 650 MC	10
Strenx 700 MC	10
Domex 550 W	10
Domex 700 W	10

Static strength of welded joints

In order to reach the required tensile strength of the welded joint, both the weld metal and the HAZ must have sufficient strength. Several factors affect the strength of the welded joint e.g. filler metal used (matched or under-matched), chemical composition, heat input, interpass temperature etc. The strength of the weld metal (MPa) is mainly determined by the filler metal used whereas the strength of the HAZ is more or less determined by the cooling cycle ($\Delta t8/5$).

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:

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

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

Since the energy input to the material is of most interest, all energy inputs given in this brochure will be Q (i.e. taking the arc efficiency factor into account).

$$Q = k \cdot E$$

Where: k = arc efficiency

The approximate values of k for different welding methods are as follows, see table 4.

TABLE 4 Arc efficiency for different welding methods.

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

By using the SSAB software WeldCalc, one can easily calculate the heat input for the specific joint type, taken into account the material and weld method.

INTERPASS TEMPERATURE

Multipass welding may cause the temperature in the welded joint to rise to a level that is harmful to the material, which in turn causes 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 interpass 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 interpass temperatures are as follows:

- Domex 355 MC – Domex 550 MC 150°C
- Strenx 600 MC – Strenx 700 MC 100°C

SOFT ZONES

When Strenx and Domex with yield strength above 500 MPa is 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 primarily by the sheet thickness and the heat input. A typical hardness curve for Strenx 700 MC can be seen in figure 6. Thin sheets and high heat input (increased cooling rate (Δ t8/5) give rise to a wider zone and lower strength.

If normal heat inputs, see figure 7, is used when working with grades 550 MC– Strenx 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.

It is possible to reach the minimum tensile strength requirement of the parent material if the maximum heat input recommended by SSAB is not exceeded, see figure 7. In single-pass welding or for long welds in multipass welding, the maximum permitted heat input could be raised by 10–15%.

The increase in the maximum permissible heat input for fillet welds is 40–50%. This increase is possible because the values in the graph are based on an interpass temperature of 150°C for Domex 355 MC – Domex 550 MC, and 100°C for Strenx 600 MC – Strenx 700.

RESULTS OF MECHANICAL TESTING

Some examples of mechanical properties obtained on MAG-welded Domex 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, see table 5.

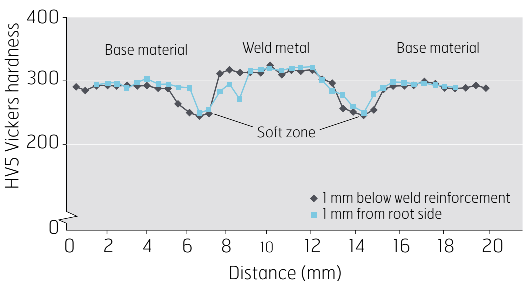
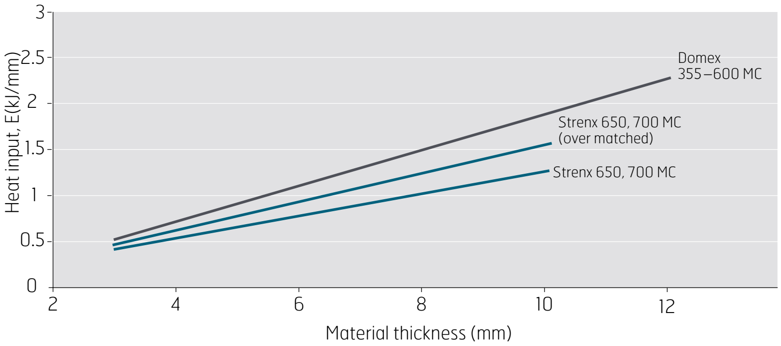


FIGURE 6 Typical hardness curve for Strenx 700 MC.
Hardness measurement in Strenx 700 MC, t=6mm.



The values in the graph are based on an interpass temperature of 150°C for Domex 355–550 MC and 100° C for Strenx 600 MC up to Strenx 700 MC. 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.

FIGURE 7 Maximum recommended heat input to fulfil the minimum. Tensile strength requirement of the base material.

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

TABLE 5 Tensile strength and Charpy V impact toughness of welded joints in a number of steel grades in Strenx and Domex. MAG welded butt welds, removed reinforcement before testing.

Weld No	Strenx and Domex Steel grade (thickness, mm)	Wire (AWS)	Pass	Heat input kJ/mm, Q	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	355(6)	A5.18ER7XS-X	1	0.70	476	Pm	L	A B	133 270	99 256
2	355(12)	A5.18ER7XS-X	1 2 3	0.85 0.86 0.87	505	Pm	L	A B	70 231	46 103
3	460 (3)	A5.18 ER7XS-X	1	0.48	595	Pm				
4	460 (6)	A5.18 ER7XS-X	1 2 3	0.46 0.49 0.50	605	Pm	L	A B	147	129 264
5	460 (12)	A5.18 ER7XS-X	1 2 3 4	0.98 0.96 0.96 0.98	631	Wm	L	A B	59 155	70 66
6	500(6)	A5.18 ER7XS-X	1	0.96	595	Pm	L	A B	168 256	174 244
7	500 (12)	A5.18 ER7XS-X	1 2	1.00 1.20	636	Pm	L	A B	61 275	42 120
8	Sx 600 (4)	A5.28 ER10XS-X	1	0.63	706	HAZ				
9	Sx 650 (6)	A5.28 ER12XS-X	1 2	0.58 0.65	810	HAZ	T	A B		207 107
10	Sx 650 (8)	A5.28 ER10XS-X	1 2	0.49 0.96	774	Wm	T	A B	176 89	172 58
11	Sx 700 (3)	A5.18ER7XS-X	1	0.26	778	Wm				
12	Sx 700 (6)	A5.18ER7XS-X	1 2 3	0.41 0.37 0.37	780	Wm	L	A B	160 130	138 88
13	Sx 700 (3)	A5.28 ER10XS-X	1	0.31	846	HAZ				
14	Sx 700 (6)	A5.28 ER10XS-X	1 2 3	0.49 0.33 0.34	825	Pm	L	A B	130 154	112 145
15	Sx 700 (8)	A5.28 ER10XS-X	1 2 3	0.70 0.75 0.76	836	Pm	L	A B	71 156	52 61
16	Sx 700 (10)	A5.28 ER10S-X	1 2 3 4	0.46 0.88 0.86 0.87	818	HAZ	L	A B	118 118	74 47

1) Failure position, Wm = weld metal, Pm = parent material, HAZ = heat affected zone
2) L = longitudinal, T = transversal (to rolling direction)
3) A = weld metal, B = 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 catalogs 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.

Low 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 8. 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.

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 9.

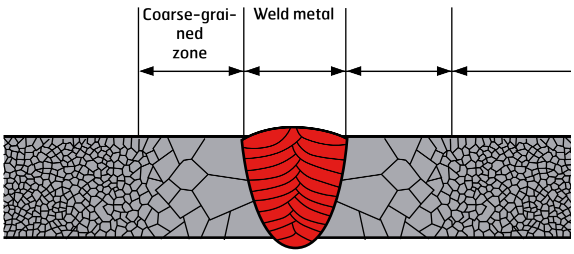


FIGURE 8 Coarse-grained zone of HAZ.

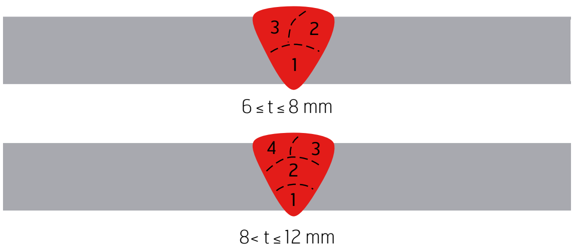


FIGURE 9 Recommended number of passes to fulfil the minimum impact toughness requirement of the welded joint.

Recommendations in order to minimize distortion

The amount of distortion during/after the welding operation is very much related to the plate thickness and welding procedure. Distortion becomes more obvious in thinner gauges where heavy deformation or even burn thru can cause problem and compromise the whole structure.

In order to minimize the amount of distortion after the welding operation:

- Weld with as low heat input as possible
- Minimize the cross sectional area, see figure 10
- Prebend, clamp or angle the parts before welding in order to compensate for the shrinking
- Avoid irregular gaps in the root
- Symmetrical welds, see figure 11
- Minimize reinforcements and optimize the throat thickness of the fillet welds
- Weld from rigid areas to loose ends
- Optimize the welding sequence
- Decrease the distance in-between the tack welds
- Use back step welding technique, see figure 12

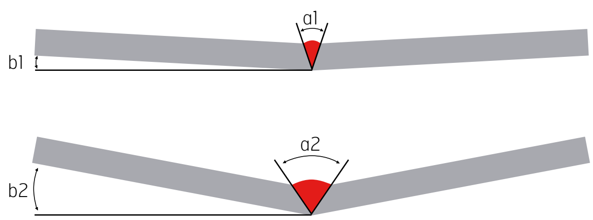


FIGURE 10 Cross section of the weld and how it influences the angle deviation

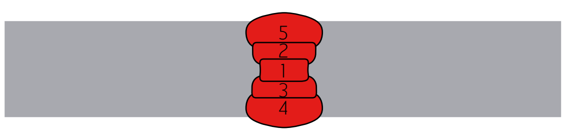


FIGURE 11 Use a symmetrical weld sequence

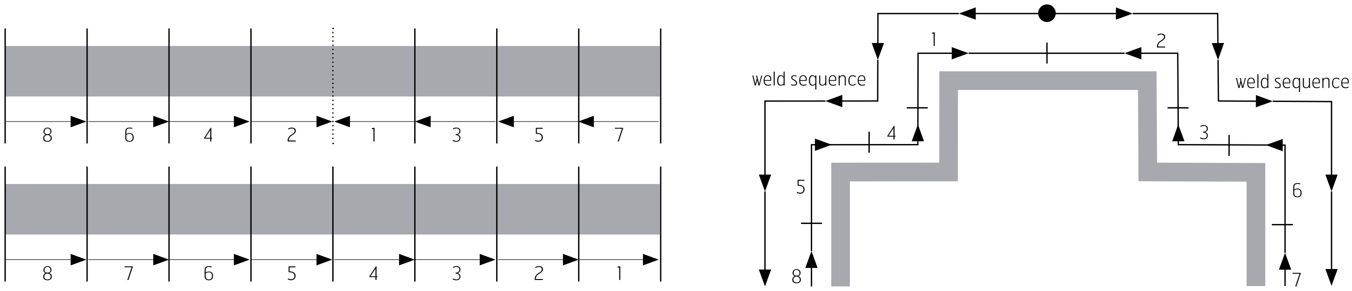


FIGURE 12 Example of back step welding technique

Stress relief annealing

For Strenx and Domex, stress relief annealing is not necessary for lowering its hardness or improving its toughness, since the steel composition 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 Strenx and Domex is only justified if the internal weld stresses are to be relieved, or if the steel is welded to 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 355 MC–550 MC and Strenx 600 MC–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 355 MC–Domex 550 MC: 530° C–580° C.
  Strenx 600 MC–Strenx 700 MC: 530° C–580° C.
  Max. cooling rate: 100° C/h.

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 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 6.

TABLE 6 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 straightening of welded joints
Domex 355 MC – 550 MC	650 °C	580 °C
Strenx 600 MC – 700 MC	650 °C	580 °C

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