

HOT-ROLLED STEEL PLATES AND COILS

Welding and thermal cutting of Raex[®] wear-resistant steels

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• **o Introduction**

Raex is a special steel with excellent resistance to wear and surface pressure which offers high strength and good engineering properties. Steel grades Raex 300, Raex 400, Raex 450 and Raex 500 have been developed for structures that improve energy efficiency and make use of innovative design. In its typical applications, Raex is exposed to the abrasive wear of soil, rocks, concrete and/or other materials. By choosing Raex, you can manufacture durable products that are lighter than ever. Ruukki's Raex steel is available as heavy plates, cut lengths, pipe products, and ready-to-install parts.

Applications for Raex wear-resistant steels

- Crushers, buckets and lip plates
- Platforms and base structures
- Materials and waste handling machinery, tanks and conveyors
- Silos, hoppers, screens and mixers
- Special containers
- Wearing parts and cutting blades

The excellent wear resistance of Raex steels is based on steel alloying and the hardened delivery condition. High alloying, hardness and strength make the welding and thermal cutting of wear-resistant steels more demanding than the processing of ordinary structural steel. Welding design of wear-resistant steel has two main objectives. Firstly, cold cracks need to be prevented in advance. This requirement is emphasised when welding thick plates. Secondly, the mechanical properties of the welded joint need to be optimal. In addition to these two objectives concerning the parent metal, demanding welding operations must satisfy work-specific demands, such as quality level. Things to avoid in thermal cutting include cracks on the cut surface and excessive softening of the cut area.

This technical brochure provides practical welding instructions for the Raex 400, Raex 450 and Raex 500 grades and specifies their special features with regard to thermal cutting. A correct working temperature and heat input, as well as careful preparation, play the key role in welding. The groove surfaces to be welded need to be dry and clean. The content of hydrogen dissolved in the weld metal must be kept especially low, because we are dealing with extremely high-strength steel. Low hydrogen content is achieved with correct welding parameters and by using proper welding consumables. The data sheet provides welding consumable recommendations for gas-shielded arc welding, manual metal arc welding, and submerged arc welding. All stages of welding and thermal cutting, from design to finishing, must be performed with care in order to achieve the best possible result.

● **1 Wear-resistant Raex steels**

Raex is a high-strength steel with excellent resistance to abrasive wear and high surface pressure. With Raex you can extend the lifespan of machinery, equipment and manufacturing processes and save costs. The selection includes steel grades Raex 300, Raex 400, Raex 450 and Raex 500. The average hardness of the steels is 300/400/450/500 HBW, respectively, figure 1.

Figure 1
Wear-resistant steels Raex 300, Raex 400, Raex 450 and Raex 500

Hardness and tensile strength. An ordinary S355 structural steel as a reference steel.

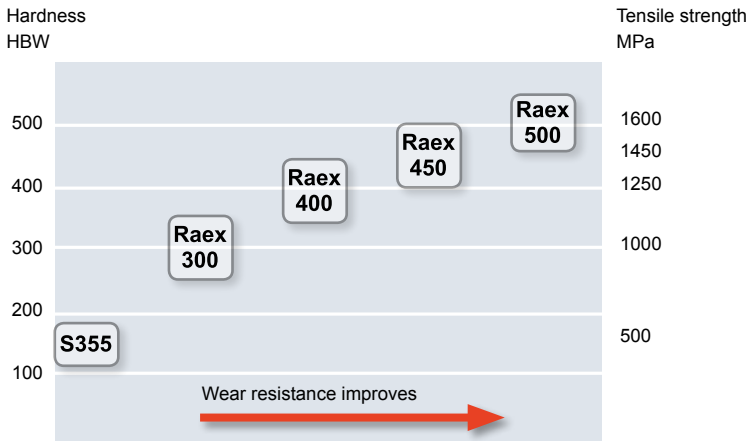
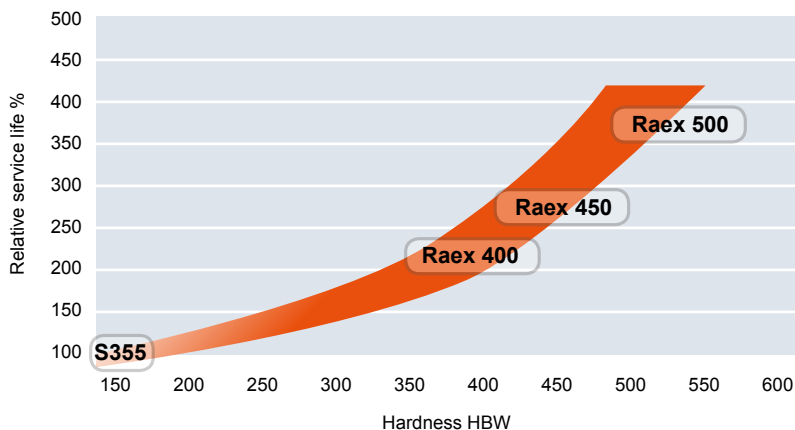


Figure 1 shows nominal hardness as well as the typical hardness distribution for each grade and the average tensile strength. The dimensions of Raex steels as cut length and plate products, as well as their properties, can be found on Ruukki's website.

The resistance of steel against general abrasive wear and tear improves as the hardness increases. Figure 2 shows the relative service life of Raex 400, Raex 450 and Raex 500 steels in an abrasion test. However, it must be remembered that the wearing of a material is always case-specific and depends on several different factors.

Figure 2
Raex 400, Raex 450 and Raex 500. Abrasion test.

The relative lengthening of service life as the steel hardness increases. The service life of ordinary S355 structural steel has been modified into the reference value 100%.



• 2 Weldability of wear-resistant steel

The high strength and hardness of wear-resistant steel is achieved by alloying and quenching. A correct hardenability is achieved with suitable alloying. Due to high alloying, the welding of wear-resistant steel is more demanding than that of ordinary structural steel. In the welding of wear-resistant steel, special attention must be paid to two objectives:

- Prevention of cold cracks in welded joints
- Achieving optimal properties in welded joints.

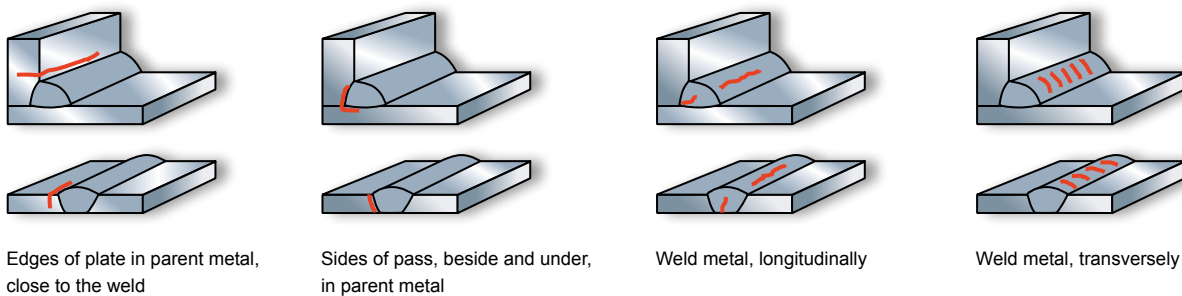
2.1 Susceptibility to cold cracking

The most common factor impeding the weldability of wear-resistant steels is cold cracking. Cold cracks are usually formed when the weld cools down to about +150°C or below, hence the term “cold crack”. Alternatively, cold cracking is known as hydrogen cracking or delayed cracking. The detrimental effect of hydrogen may manifest itself as cracking only after several days from welding. When planning NDT testing of the welded structure, the delay in the emergence of cold cracks must be taken into account.

2.1.1 Location of cold cracks

Figure 3 shows the critical areas where cold cracks appear in the weld metal, fusion line and heat affected zone.

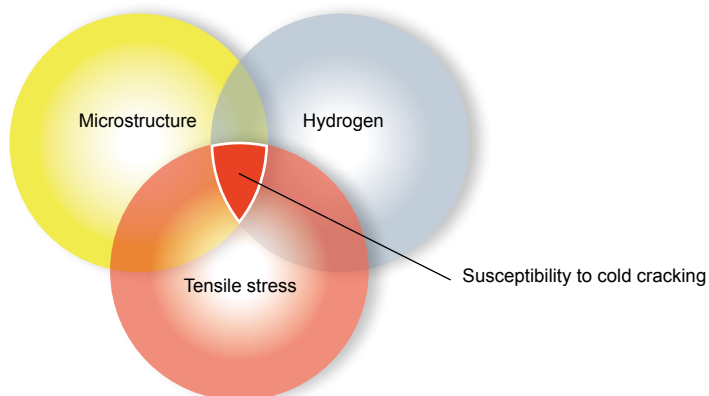
Figure 3
Places susceptible to cold cracks in welded joints of high-strength wear-resistant steels



2.1.2 Factors that cause cold cracking

Cold cracking is the detrimental combined effect of three simultaneous factors. These factors are, as shown in figure 4, 1) the microstructure of the welded joint, 2) the hydrogen content of the welded joint, and 3) the tensile stress in the welded joint.

Figure 4
The susceptibility to cold cracking of a welded joint is the detrimental combined effect of three factors



2.1.2.1 Microstructure of a welded joint

Good wear resistance is based on a martensitic microstructure in the parent metal and the weld metal, as well as in the heat-affected zone of a welded joint. If the joint cools too quickly, the martensite may become too hard and low in toughness. Such a microstructure is susceptible to cracking. The hardening capacity of steel and weld metal is represented with carbon equivalent formulae that are based on alloying. The formulae “CEV” and “CET” shown here are widely used for wear-resistant steels. The abbreviation “CE” is also used for CEV.

Carbon equivalent formulae used to represent the hardening capacity of steel and weld metal

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

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

An increase in carbon equivalent, or hardening capacity, leads to a harder microstructure.

2.1.2.2 Critical hydrogen content in a welded joint

Hydrogen is a very lightweight gas that dissolves in steel as atoms and molecules. When a steel plate is manufactured, it already contains small amounts of hydrogen. The manufacturing process of Raex steels is such that the natural hydrogen content of the steel plates remains safely small. Therefore, in welding, hydrogen that predisposes steel to cold cracking tries to penetrate the joint from outside the steel plate.

Critical hydrogen content is not a specific constant, but its value is affected especially by the microstructure of steel. Martensite, ferrite and austenite phases are present in the microstructure of wear-resistant steel, depending on the temperature and treatment state. Only very small amounts of hydrogen dissolves in a martensitic and ferritic microstructure, unlike an austenitic microstructure that can hold considerably more.

During welding, most hydrogen gas is dissolved in steel at high temperatures in which the microstructure of steel is austenitic. When the welded joint cools, the microstructure of steel becomes ferritic or martensitic. In these microstructures only a small amount of hydrogen is dissolved, and the safe space required for the physical placement of hydrogen atoms is restricted. Therefore hydrogen atoms that get trapped in the microstructure of the welded joint may cause local internal tension and crack formation, known as cold cracking.

2.1.2.3 Strength and stress level of a welded joint

Welding as well as other plate processing produce stresses in the joint. The strength and residual stress of a welded joint is determined mainly by the strength of the weld metal. Residual stress depends on the strength of the filler metal and on the rigidity of the structure and the thickness of the steel sheet. At the highest, the stress in the welded joint equals the yield point of the steel. High stress increases susceptibility to cold cracking.

2.1.2.4 Combined effect of three factors

The microstructure, hydrogen content and stress in a welded joint are interdependent in the emergence of cold cracks. For example, if the stress level of a joint increases with the same welding procedure, even lower hydrogen content leads to cold cracking. Similarly, a higher strength and more fragile microstructure are prone to cracking at lower hydrogen contents. In fighting cold cracking, the combined effect of these three factors needs to be predicted, and welding needs to be planned accordingly.

2.2 Optimal properties of a welded joint

The properties required of wear-resistant steel are not as extensive as those set for structural steels. The same goes for welded joints and structures made of wear-resistant steel. Despite this fact, when planning the welding of wear-resistant steels, the joint should be assessed in relation to the properties in table 1.

Table 1.
Optimal combination of properties in welded joints of wear-resistant steels

Combination of properties
Hardness
Wear resistance
Strength
Impact toughness

When designing wear-resistant structures, welds should be positioned, as far as possible, in places that are not subjected to the heaviest loading. If especially good wear resistance is required of a welded joint, high-strength welding consumables with suitable alloying must be used. In structures where numerical values of impact toughness are required of welded joints, values that match those of the parent metal can be achieved with tough welding consumables and correct welding parameters.

The properties in table 1 are interdependent. Increasing hardness and strength, for example, has a decreasing effect on impact toughness. Optimal properties in the weld area are ensured with the correct welding parameters and the recommended working temperature. No numerical values are usually given for the properties of welded joints of wear-resistant steels, apart from hardness, and possibly strength. Neither of these properties are usually tested.

● **3 Welding parameters and their effect on the properties of a welded joint**

During welding, steel undergoes a strong thermal effect. The temperature of the joint rises quickly from the working temperature to the temperature of liquid steel, above +1500°C. The heat input of welding and the cooling rate of the joint are the main variables with which the welding procedure is controlled.

3.1 The most important welding parameters

The heat energy used in welding is indicated with the concepts heat input (Q) and arc energy (E). The relationship between heat input and welding energy is represented by the welding procedure specific coefficient of thermal efficiency “k”. At its highest, k=1, in which case the thermal efficiency is 100% and all the arc energy is used for heat input. The most important welding parameters and variables are given in figure 5. The typical thermal efficiency of methods used in welding wear-resistant steels is given in table 2.

Figure 5
Heat input in welding and welding energy and other welding variables

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

- Q = k x E
- Q = Heat input, i.e. quantity of heat transferred during welding to the weld per unit of length (kJ/mm)
- E = Arc energy, i.e. energy conveyed by the welding procedure per unit of length (kJ/mm)
- k = Thermal efficiency, i.e. relationship between heat input (Q) and arc energy (E)
- U = Voltage (V)
- I = Current (A)
- v = Welding speed (mm/min)

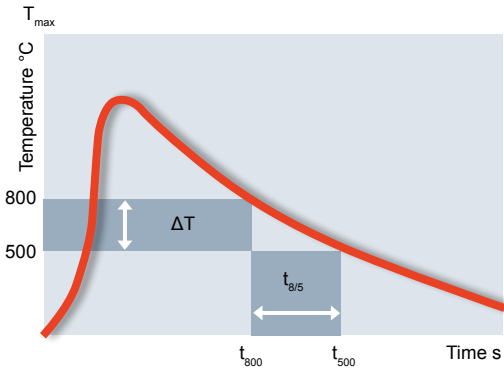
Table 2.
Typical thermal efficiency for different welding method

Welding method	Thermal efficiency, k
Gas-shielded arc welding, MAG methods	0.8
Manual metal arc welding	0.8
Submerged arc welding	1.0
Plasma arc welding and TIG welding	0.6

3.2 Effect of welding parameters on the properties of a welded joint

Heat input and the cooling rate of a joint are directly related. With high heat input the joint cools slowly, and with low heat input, it cools quickly. For the microstructure of the heat-affected zone (HAZ) of a welded joint, the most crucial thing is the cooling time from +800°C to +500°C, i.e. $t_{8/5}$, figure 6. The factors that affect the cooling rate of a welded joint are given in table 3.

Figure 6
Temperature of a welding procedure vs. time as a diagram



$\Delta T = 800^{\circ}\text{C} - 500^{\circ}\text{C}$

$t_{8/5}$ = cooling time from +800°C to +500°C

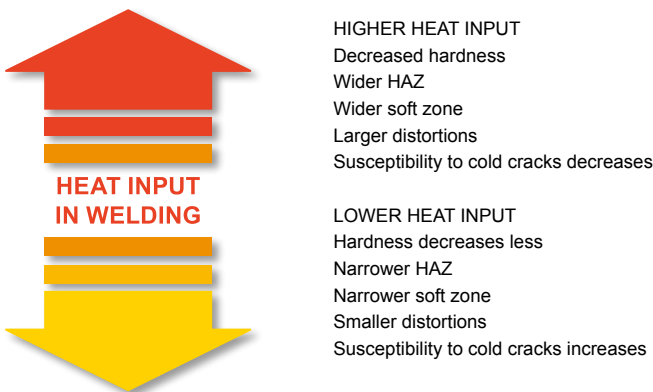
Table 3.
Factors that affect the cooling rate of a welded joint

Welding energy
Plate thickness / thicknesses
Joint form
Type of joint preparation
Working temperature
Welding sequence

The effects of higher and lower heat input on the welding of hardened wear-resistant steels are shown in figure 7. High heat input indicates a long $t_{8/5}$ time, while low heat input indicates a short $t_{8/5}$ time.

Figure 7
High-strength and hard hardened wear-resistant steels

The effects of higher and lower heat input on welding



In arc welding the higher heat input requirement is based on the improvement of welding efficiency. Higher heat input in the welding of thin wear-resistant plates is restricted by its negative effect on steel hardness.

● 4 Welding consumables and how to select them

The selection of welding consumables for Raex steels:

- 1) Undermatching ferritic, yield strength max. about 500 MPa
- 2) High-strength ferritic, yield strength max. about 700 MPa
- 3) Undermatching austenitic, yield strength max. about 500 MPa
- 4) Intended for hard facing, hardness about 300–600 HBW.

Undermatching ferritic welding consumables (1) are used for the welding of ordinary S355 structural steel. They are by far the most widely used welding consumables for wear-resistant steels, and they are recommended for all hardness classes. On the other hand, high-strength ferritic welding consumables (2) are used for the welding of high-strength S690 quenched and tempered steel. They can be used, if a higher strength weld or a harder surface, not achievable with undermatching welding consumables, is required. Undermatching austenitic welding consumables (3) are originally intended for welding of austenitic stainless steels. They are a safe choice especially for the hardest wear-resistant steels and thick plates as well as for repair welding. Welding consumables intended for hard facing (4) can be used for capping runs, when the surface of the weld must be especially wear-resistant. Welding consumables intended for hard facing are virtually uniform in strength with tempered wear-resistant steels. They are used in special cases.

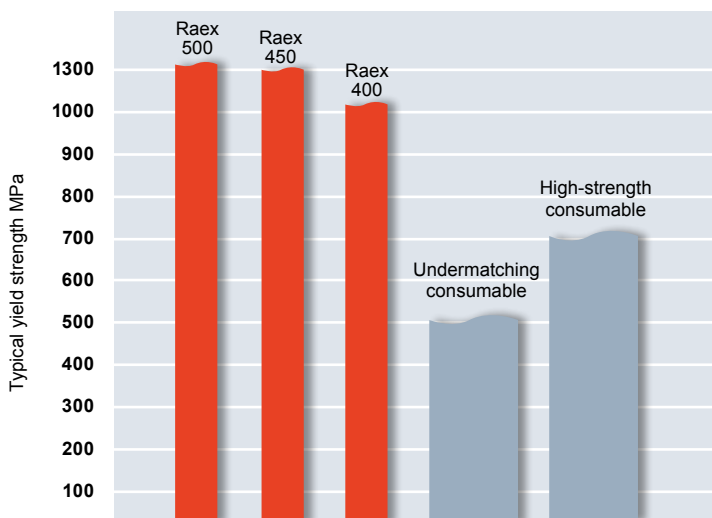
4.1 Ferritic welding consumables

The hydrogen content of ferritic welding consumables has a strong impact on the susceptibility to cold cracking. In the high-strength weld metal of wear-resistant steel the susceptibility to cold cracking may be higher than in the HAZ of the parent metal. Ferritic welding consumables must therefore be low in hydrogen. The most recommended are welding consumables which have a hydrogen content $HD \leq 5$ ml/100 g (hydrogen content class H5). Usable ferritic welding consumables are divided into undermatching and high-strength welding consumables based on their strength class, figure 8.

Figure 8

Yield strength of Raex steels and yield strength of pure weld metal in ferritic welding consumables

The yield strength of a welded joint is between that of a high-strength wear-resistant steel and pure weld metal.



4.1.1 Undermatching i.e. soft ferritic welding consumables

A welding consumable is defined as undermatching, if the pure weld metal produced by it is essentially softer than steel. The yield strength of pure weld metal produced by undermatching filler metal is about 500 MPa and its toughness is good. Undermatching filler metal is recommended for the welding of wear-resistant steels because of its many advantages, table 4.

Table 4.
The advantages of undermatching, i.e. soft welding consumables compared to higher-strength welding consumables

Advantages
Good welding properties
Extensive selection and good availability
Cost-effective both at purchase as well as during use
Lower stress level in the weld
A tough and ductile welding consumable tolerates stress well
Lower carbon equivalent and, respectively, lower hardenability
Lower susceptibility to cold cracking
Tolerates hydrogen better than a higher-strength welding consumable
Less need to increase working temperature than with higher-strength welding consumables

4.1.2 High-strength ferritic welding consumables

The strength level of pure weld metal in high-strength welding consumables is about 700 MPa, figure 8. By using these materials for welding it is possible to achieve weld metal strength that is closer to the strength of steel than when welding with undermatching welding consumables. Due to the rather high hardenability of high-strength welding consumables, special attention must be paid to the prevention of cold cracking. High-strength welding consumables are only recommended for special purposes. For example, if the welded joint is exposed to heavy wear and tear. A high-strength welding consumable is better suited for the welding of thin than thick plates, because a thin plate cools slowly and is less susceptible to cold cracking.

The working temperature is chosen according to the carbon equivalent value of the welding consumable, if it is higher than the carbon equivalent of the parent metal. This is the principal rule. However, the working temperature is always case-specific. If needed, it is advisable to discuss the need to increase the working temperature with the welding consumable manufacturer.

4.1.3 Recommended ferritic welding consumables

The recommended undermatching and high-strength welding consumables for the common welding processes are given in tables 5a, 5b, 5c and 5d.

Table 5a.**Raex 400/450/500. Recommended undermatching ferritic welding consumables. Examples. EN classification**

Corresponding, or nearly corresponding brands (Esab). Yield strength of pure weld metal max. about 500 MPa. The “X” in the standard can mean one or more specification markings.

MAG solid wire welding (weld metal)	MAG flux-cored welding: Metal-cored wire	MAG flux-cored welding: Rutile flux-cored wire	Submerged arc welding: Wire+ flux (weld metal)	Manual metal arc welding
EN ISO 14341: G 46 X	EN ISO 17632: T 46 X	EN ISO 16834: T 46 X	EN 756 S 46 X	EN ISO 2560: E 46 X
OK Autrod 12.64 (G 46 3 M G4Si1, G 42 2 C G4Si1)) OK AristoRod 12.63 (G 46 4 M G4Si1, G 42 2 C G4Si1))	PZ6102 (T 46 4 M M 2 H5)	OK Tubrod 15.14 (T 46 2 P M 2 H5, T 46 2 P C 2 H5)	OK Autrod 12.32+ OK Flux 10.71 (S 46 4 AB S3Si)	OK 55.00 (E 46 5 B 32 H5)
EN ISO 14341: G 42 X	EN ISO 16834: T 42 X		EN 756 S 38 X	EN ISO 2560: E 42 X
OK Autrod 12.51 (G 42 3 M G3Si1, G 38 2 C G3Si1)	OK Tubrod 14.12 (T 42 2 M M 1 H10, T 42 2 M C 1 H10)		OK Autrod 12.22+ OK Flux 10.71 (S 38 4 AB S2Si)	OK 48.00 (E 42 4 B 42 H5)

Table 5b.**Raex 400/450/500. Recommended undermatching ferritic welding consumables. Examples. AWS classification**

Corresponding, or nearly corresponding brands (Esab). Yield strength of pure weld metal max. about 500 MPa. The “X” in the standard can mean one or more specification markings.

MAG solid wire welding	MAG flux-cored welding: Metal-cored wire	MAG flux-cored welding: Rutile flux-cored wire	Submerged arc welding: Wire+ flux	Manual metal arc welding
AWS A5.18 ER70S-X	AWS A5.18 E70C-X	AWS A5.20 E71T-X	AWS A5.17 F7X	AWS A5.1 E7018X
OK Autrod 12.51 (ER70S-6) OK AristoRod 12.63 (ER70S-6)	OK Tubrod 14.12 (E70C-6M, E70C-6C) PZ6102 (E70C-6M H4)	OK Tubrod 15.14 (E71T-1, E71T-1M)	OK Autrod 12.22+ OK Flux 10.71 (F7A5-EM12K)	OK 48.00 (E7018) OK 55.00 (E7018-1)

Table 5c.**Raex 400/450/500. High-strength ferritic welding consumables, examples. EN classification**

Corresponding, or nearly corresponding brands (Esab). Yield strength of pure weld metal max. about 690 MPa. The “X” in the standard can mean one or more specification markings.

MAG solid wire welding (weld metal)	MAG flux-cored welding: Metal-cored wire	MAG flux-cored welding: Rutile flux-cored wire	Submerged arc welding: Wire+ flux (weld metal)	Manual metal arc welding
EN ISO 16834: G 69 X	EN ISO 12535: T 69 X	EN ISO 12535: T 69 X	EN ISO 26304: S 69 X	EN ISO 18276: E 69 X
OK AristoRod 69 (G 69 4 Mn3Ni1CrMo)	OK Tubrod 14.03 (T 69 4 Mn2NiMo M M 2 H10)	OK Tubrod 15.09 (T 69 4 Z P M 2 H5)	OK Autrod 13.43+ OK Flux 10.62 (S 69 6 FB S3Ni2,5CrMo)	OK 75.75 (E 69 4 Mn2NiCrMo B 42 H5)

Table 5d.**Raex 400/450/500. High-strength ferritic welding consumables, examples. AWS classification**

Corresponding, or nearly corresponding brands (Esab). Yield strength of pure weld metal max. about 690 MPa. The “X” in the standard can mean one or more specification markings.

MAG solid wire welding	MAG flux-cored welding: Metal-cored wire	MAG flux-cored welding: Rutile flux-cored wire	Submerged arc welding: Wire+ flux	Manual metal arc welding
AWS A5.28: ER100S-X	AWS A5.28: E110C-X	AWS A5.29: E111T1-X	AWS A5.23: F11X	AWS A5.5: E11018X
OK AristoRod 69: ER100S-G	OK Tubrod 14.03: E110C-G	OK Tubrod 15.09: E111T1-K3MJ-H4	OK Autrod 13.43+ OK Flux 10.62: F11A8-EG-G	OK 75.75: E11018-G

4.1.4 Handling of ferritic welding consumables

Ferritic welding consumables with low hydrogen content are usually basic, such as the flux used for submerged arc welding or flux cored wire, or the coating of a welding electrode. These welding consumables are hygroscopic, i.e. they readily absorb moisture, and, at the same time, hydrogen. To prevent welding consumables from getting wet, they should be stored and handled according to the manufacturer's instructions. If there is a danger that the filler metal has absorbed moisture, it should be discarded or properly dried. This is to assure a proper degree of dryness and a low hydrogen content of the weld metal. In this way the risk of cold cracking in the welded joint caused by high hydrogen content can also be prevented.

4.2 Austenitic welding consumables

An austenitic microstructure withstands hydrogen much better than a ferritic microstructure. Due to this property, austenitic welding consumables can be used for hardened steels as an alternative. Their yield strength does not exceed 500 MPa so they are clearly low-strength welding materials. Due to their softness and favourable microstructure, austenitic welding consumables have many advantages, table 6.

Table 6.
The advantages and properties of austenitic, stainless welding consumables in the welding of wear-resistant steels

Good welding properties
Good selection and availability
High purchase price
The stress level of the weld is low
Very tough and ductile welding consumable
Austenitic microstructure dissolves hydrogen without susceptibility to cold cracking
Usually no need to increase working temperature
Withstands welding stresses

The advantages of austenitic welding consumables are best exploited in repair welding, work site conditions and other difficult situations. They are especially well suited for back welds and root passes, and for tack welding. With austenitic welding consumables, the increase in working temperature can usually be avoided. The advantages are best displayed when welding the hardest steel grade Raex 500 in difficult conditions. The recommended austenitic welding consumables are given in tables 7a and 7b.

Table 7a.**Raex 400/450/500. Undermatching austenitic welding consumables, examples. EN classification**

Corresponding, or nearly corresponding brands (Esab). Strength class of pure weld metal max. about 500 MPa. The “X” in the standard can mean one or more specification markings.

MIG solid wire welding	MIG flux-cored welding: Metal-cored wire	MAG flux-cored welding: Rutile flux-cored wire	Submerged arc welding: Wire+ flux	Manual metal arc welding
EN 12072: G 18 8 Mn	EN 12073: T 18 8 Mn X	EN 12073: T 18 8 Mn X EN 14700: T Fe 10	EN 12072: S 18 8 Mn	EN 1600: E 18 8 MnX
OK Autrod 16.95 (G 18 8 Mn)	OK Tubrod 15.34 (T 18 8 Mn M M 2)	OK Tubrodur 14.71 (T Fe 10)	OK Autrod 16.97 (S18 8 Mn) + OK Flux 10.93	OK 67.45 (E 18 8 Mn B 4 2)

Table 7b.**Raex 400/450/500. Undermatching austenitic welding consumables, examples. AWS classification**

Corresponding, or nearly corresponding brands (Esab). Strength class of pure weld metal max. about 500 MPa. The “X” in the standard can mean one or more specification markings.

MIG solid wire welding	MAG flux-cored welding, Metal-cored wire	MAG flux-cored welding, Rutile flux-cored wire	Submerged arc welding Wire+ flux	Manual metal arc welding
AWS 5.9 ER307	AWS 5.9 EC307	AWS 5.22 EC307T-x	AWS 5.9 ER307	AWS 5.4 E307-X
OK Autrod 16.95 (ER307)	OK Tubrod 15.34	OK Tubrodur 14.71	OK Autrod 16.97+ OK Flux 10.93	OK 67.45

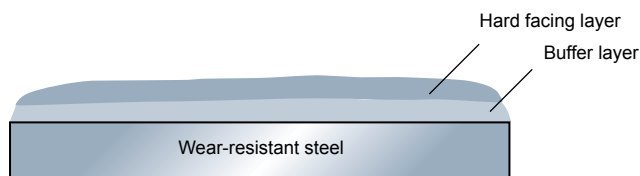
4.3 Welding consumables for hard facing

If the surface of a welded joint is to be wear-resistant, capping runs can be welded with hard facing consumables. The hardness of pure weld metal produced by hard facing electrodes is 300-400 HBW (30-45 HRC). These electrodes are usually chromium alloys (3-15% Cr).

In special applications, wear-resistant steel may be exposed to higher wear and tear than the rest of the structure. In that case, it is justifiable to weld a local hard facing layer on the surface of wear-resistant steel. The hard facing material is selected so that the weld metal is even harder than the surface of the wear-resistant steel. A hard-faced wear surface achieves its hardness (500-600 HBW) already during the cooling of the welded joint, because hard facing material hardens in air. The hardness level 500-600 HBW corresponds to the reported hardness level of 50-57 HRC. Examples of basic alloys for hard facing electrodes for the welding of wear-resistant steels:

- Hard facing electrode, alloy 0.4%C - 6%Cr-0.6%Mo
- Hard facing electrode, alloy 0.7%C - 10%Cr
- Hard facing electrode, alloy 4.5%C - 33%Cr

When hard facing materials are used, special attention must be paid to the prevention of cold cracking in the weld metal. Cold cracking can be prevented by preheating, but also by first welding a buffer layer using soft and ductile austenitic stainless weld metal, figure 9.

**Figure 9
Use of a ductile buffer layer in hard facing**

The working temperature needed for the welding of the buffer layer and the hard facing layer is determined on the basis of both the wear-resistant steel and the hard facing consumable. The selection of hard facing consumables should be discussed either with the filler metal or steel manufacturer. It must be stressed that hard facing consumables are not intended for joint welding.

● 5 Prevention of cold cracking

Keeping the level of hydrogen penetrating into the welded joint low is crucial in preventing cold cracking. In order to stay below critical hydrogen content, it is necessary to use welding methods and consumables with a low hydrogen content. In addition, Ruukki's welding instructions must be complied with. A correct working temperature and heat input in order to achieve a suitable cooling rate play a key role in welding. A sufficiently high interpass temperature must be used in multi-run welding. The need to prevent cold cracking is emphasised when the hardness of the steel and the plate thickness increase. A plate that was stored cold must warm up thoroughly, at least to room temperature (+20°C), before welding or other plate processing.

5.1 Controlling the hardening of the microstructure of a welded joint

A martensitic microstructure implies good resistance to wear. If the joint cools too quickly after welding, martensite can become detrimentally hard and low in ductility in the weld metal and/or heat affected zone of the weld. Cold cracking is prevented by restricting the hardening of the microstructure with correct welding parameters. The hardenability of steel and welding consumables appears from their carbon equivalent value.

5.2 Controlling hydrogen content in a welded joint

Keeping the hydrogen level low in the welding consumable and the heat affected zone is crucial in preventing cold cracking. It is recommended to use a low-hydrogen welding method and low-hydrogen welding consumables to achieve a hydrogen content of max. 5 ml/100 g. A low hydrogen level can be achieved with the correct welding consumables, for example, gas-shielded arc welding (MAG) with solid wire and flux-cored wire, submerged arc welding, and manual metal arc welding basic-coated rods. The manufacturers' instructions must be complied with when selecting, using and storing welding consumables.

The entry of hydrogen into the welded joint is increased by moisture on the surface of the groove, as well as dirt and contaminants such as grease or paint. To minimise cold cracking, the top of the groove must be kept completely dry and metallic clean before and during welding.

5.3 Relieving residual stress in a welded joint

Cold cracking can be efficiently prevented by relieving residual stress. The easiest way to relieve residual stress in the welded joints of Raex steels is to use undermatching ferritic or austenitic welding consumables. The stress can also be relieved with certain welding techniques. Especially when welding thin plates, the size of the weld needs to be optimised, and unnecessarily large welds are to be avoided. The temperature must be kept uniform in the different parts of the structure at all stages of welding. If needed, the structure to be welded should be supported or secured during tack welding or welding.

5.4 Practical tips for welding planning and performance

Ways to relieve residual stress and improve the strength of the welded structure are presented in table 8.

Table 8.
Practical ways to relieve residual stress

Relieve residual stress already during the planning stage
Minimise rigidity differences in various parts of the structure
Optimise the size of the weld
Predict and control distortions
Use prestressing in the welding of large structures
Favour small gaps in constructions to be welded
Make good use of two-side full penetration grooves, when welding of thick plates
Grind smooth the edges and corners of a welded steel structure
Finish the welding of a fatigue critical structure by grinding smooth the connections between welds and parent metal

5.5 Welding at correct working temperature

Suitably high working temperature and sufficient heat input slow down the cooling of a welded joint to the correct rate. Thanks to these measures there will be no cold cracking.

The correct working temperature is determined on the basis of the following factors:

- Steel grade and its carbon equivalent value
- Combined plate thickness
- Heat input
- Hydrogen content of welding consumable
- Carbon equivalent value of welding consumables
- Strength level of welding consumables (undermatching / high-strength)
- Type of welding consumable (ferritic / austenitic).

The need to raise the working temperature increases with the carbon equivalent, hardness and plate thickness of the steel grade. The typical carbon equivalent values of Raex steels for each plate thickness are given in their respective data sheets. Plate-specific carbon equivalent values which can be used in the preparing of a detailed welding plan are given in material certificates.

The recommended working temperatures for Raex 400, Raex 450 and Raex 500 are shown in figure 10. The recommendations are based on standard EN 1011-2. The temperatures in figure 10 apply to welding with undermatching ferritic welding consumables with hydrogen content 5 ml/100 g or below.

Figure 10
Raex steels. Recommended working temperatures for welding when the heat input is chosen according to the recommendations in figures 11, 12 and 13.

	Plate thickness, mm				
	10	20	30	40	
Raex 400	20°C		75°C	100°C	125°C
Raex 450	20°C	50°C	75°C	125°C	150°C
Raex 500	20°C	100°C	150°C		175°C

The working temperature is usually raised by preheating. In multi-run welding the energy brought to the joint by the previous run may be sufficient to maintain the correct working temperature before the welding of the next run, so external heating is not required during welding. In multi-run welding, the working temperature recommendations apply as the minimum interpass temperature. The interpass temperature may not be lower than the working temperature recommendation and not higher than +220°C. The smaller the hydrogen content generated by the welding method, the less need there is to raise the working temperature. If welding consumables HD>5 ml/100 g need to be used, the working temperature must be raised above the values in the table. The need to raise the working temperature decreases as the heat input is increased.

Raising the working temperature is especially important in tack welding and repair welding, because a small and local weld cools quickly and hardens at a rapid rate. Starting and stopping the welding run at the corners of a structure should be avoided. Experience in the welding of hardened steels speaks for the clear advantages of preheating. Even moderate preheating to temperatures under +100°C affects weldability favourably, also for plate thicknesses that do not require preheating according to the instructions. In welding large-sized and complicated structures, as well as in especially difficult conditions, a working temperature above the tabular values but below +220°C must be used. Working temperatures or interpass temperatures higher than that should not be used, because they decrease the hardness of the weld.

• **6 Achieving an optimal combination of properties in welded joints**

Strength, hardness and resistance to wear are the things required of welded joints of wear-resistant steel. Depending on the use and the usage conditions, other requirements include impact strength and case-specific properties. Despite hardness, there are no other general numeral requirements. Optimal properties in the weld area are ensured with the correct welding parameters and the recommended working temperature.

6.1 Recommended welding parameters

The recommended welding parameters are determined with the variable $t_{8/5}$. Achieving optimal properties in a welded joint requires that the selected heat input corresponds to a cooling time $t_{8/5} = 10-20$ seconds. In practical welding work the cooling time of 10 seconds corresponds to the minimum value of heat input, and the cooling time of 20 seconds to the maximum value of heat input. A too small $t_{8/5}$ (quick cooling) increases the hardening of the HAZ and susceptibility to cold cracking. A too large $t_{8/5}$ (slow cooling) decreases the hardness, strength and impact toughness of the joint.

Figures 11, 12 and 13 show the recommended minimum and maximum values of heat input for butt joints in Raex steels. The working temperatures in figure 10 have been taken into account when determining heat input limits. The minimum heat input values in the figures can be decreased by raising the working temperature. This may be necessary e.g. in tack welding and the welding of back welds or root passes. In joint types other than butt joints, such as T joints or corner joints, the effects of the joint form factor of the joint type in question on the $t_{8/5}$ cooling time should be taken into account when selecting the heat input.

Figure 11
Raex 400. Heat input (Q) in welding. Recommended minimum and maximum values.

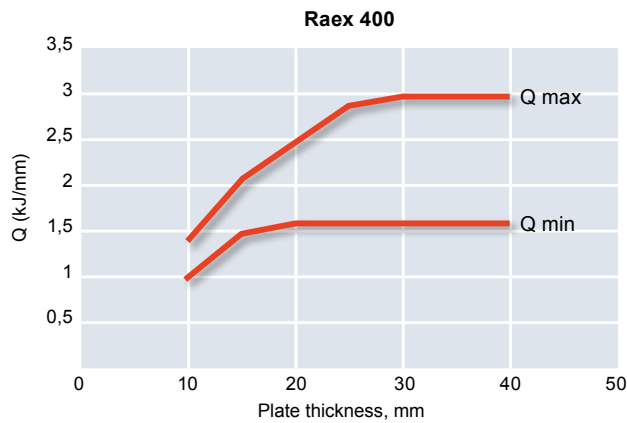


Figure 12.
Raex 450. Heat input (Q) in welding. Recommended minimum and maximum values.

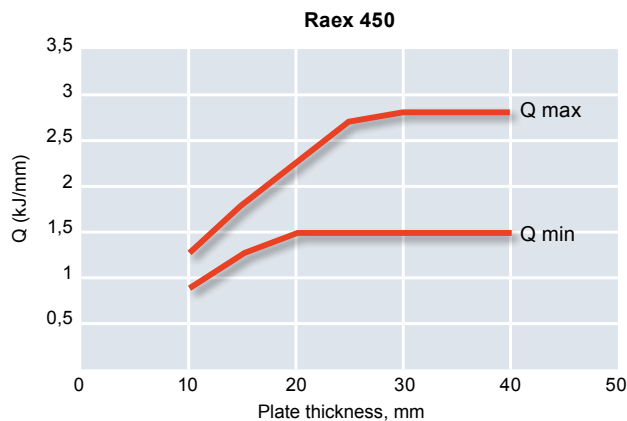
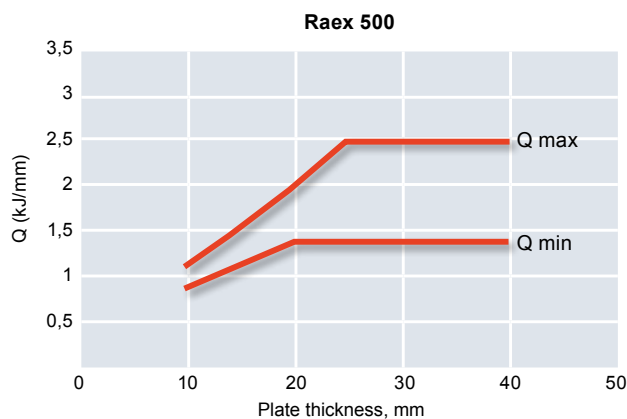


Figure 13. Raex 500.
Heat input (Q) in welding. Recommended minimum and maximum values.



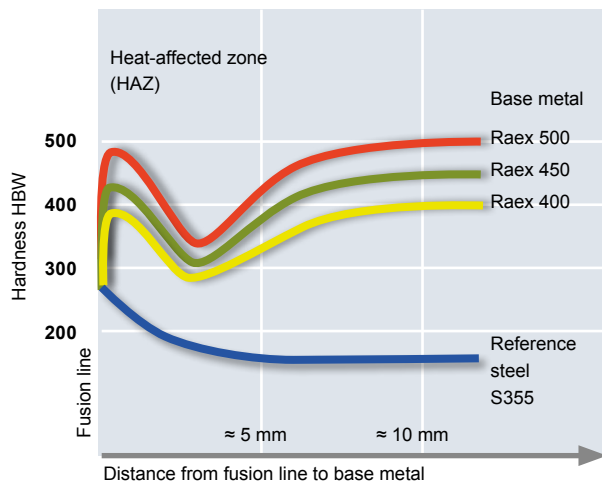
In practical welding work the cooling time of 10 seconds corresponds to the minimum value of heat input, and the cooling time of 20 seconds to the maximum value of heat input. A too small $t_{8/5}$ (quick cooling) increases the hardening of the HAZ and susceptibility to cold cracking. A too large $t_{8/5}$ (slow cooling) decreases the hardness, strength and impact toughness of the joint.

6.2 Soft zone in welded joints

The high strength and hardness of wear-resistant steel is achieved by alloying and hardening. In fusion welding the temperature of the joint reaches +1500°C or more. Consequently, soft zones are formed in the joint when welding wear-resistant steels. There is always softening in the HAZ. In addition, the weld metal usually remains softer than the hard base metal. A typical hardness profile of welded joints in Raex steels is shown in figure 14.

Figure 14
Raex steels. A typical hardness profile of the HAZ of a welded joint when using the recommended $t_{8/5}$ cooling times

Comparison with a corresponding hardness profile of a standard S355 structural steel.



General about hardness profile:

- The hardness of the HAZ in welded joints of Raex steels is typically lower than that of the base metal
- The hardness profile of thermally cut Raex steel from the cut edge towards the base metal follows the hardness profile of the HAZ with two exceptions: the maximum hardness of the cut edge is somewhat greater, and the soft zone of the cut plate narrower than in a welded joint.
- The hardness of the HAZ in ordinary S355 steel is typically greater than the hardness of the base metal; the same applies to thermally cut edges.

The hardness profile of welded joints in Raex steels:

- The hardness of the weld metal depends on heat input and the alloying of the welding consumables.
- In the HAZ, close to the fusion line, the hardness equals that of the base metal.
- The softening of the HAZ is emphasised when heat input is increased, i.e. when the cooling time ($t_{8/5}$) becomes longer.
- By decreasing heat input, the hardness is reduced less and the soft zone is narrower.

The softening tendency caused by welding must be taken into account especially with harder grades and small thicknesses. To avoid softening, thin plates should be welded at room temperature of +20°C and pre-heating is not allowed. Softening is prevented by limiting heat input and by observing the maximum work temperature/interpass temperature.

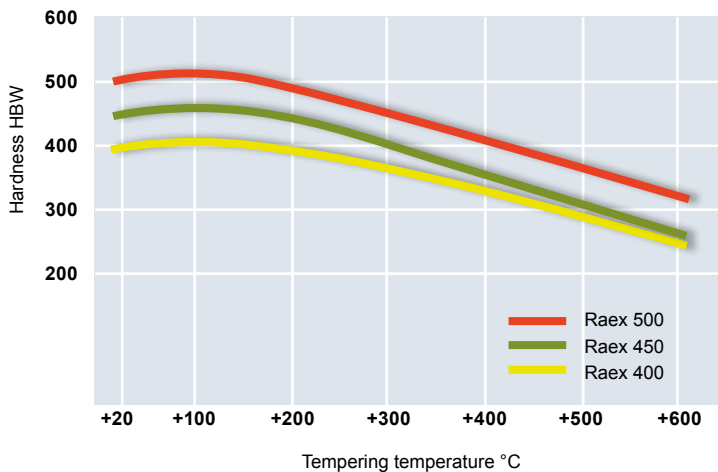
In wear-resistant steel applications a soft zone does not usually shorten the useful life of the equipment or structure. However, in applications where structural strength is required, the soft zone should be taken into account in the design. In such structures welded joints should not be placed in the most stressed locations.

● 7 Heat treatment

Hardened steels are not intended to be heat treated. Heat treatment at elevated temperatures decreases their hardness, strength and wear resistance properties. Figure 15 shows the change in the hardness of Raex steels after tempering at various temperatures. As shown in the figure, some of the hardness generated by the hardening process has disappeared in tempering.

Figure 15
Raex 400 and Raex 500. The effect of tempering temperature on hardness

The hardness values have been measured at room temperature after tempering at elevated temperatures. The holding time was 2 hours, after which the steels cooled in air to room temperature.



Heat treating in a temperature of more than about +220°C reduces the hardness. So, Raex steels cannot be stress relieved without reducing their hardness. Post weld heat treatment (PWHT) is not recommended, respectively.

In some applications, hardened steel is tempered or stress relieved by choice after welding or other machine shop operations. In this case, the mechanical properties entailed by such a heat treatment are accepted. The toughness of hardened steel can be improved by tempering - this may be the argument behind the decision of deliberate heat treatment. Stress relieving may reduce the stress formed in a steel plate during work shop fabrication.

● 8 Behaviour of steel in thermal cutting

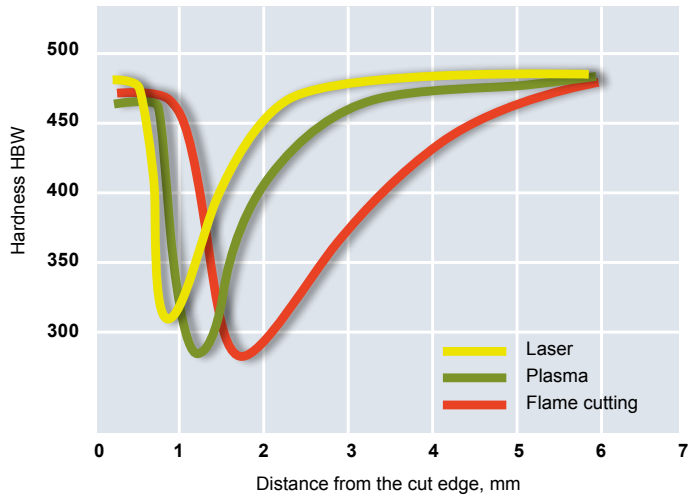
Thick plates and large objects are generally cut using thermal methods. During thermal cutting the steel surface undergoes local heat treatment to a depth of a few millimetres from the cut edge, including changes in the microstructure. Due to these changes both a hard and a soft layer are formed on the cut edge.

8.1 Thermal cutting procedure

The surface part of thermally cut steel experiences a short-term heating almost to the melting point of steel. After cutting, the cut cools down quickly, unless the cooling rate is controlled. Due to the heat treatment, the thermally cut steel surface undergoes changes in the microstructure, similar to the HAZ of a welded joint. The outermost surface of the cut piece hardens. A surface that is too hard is brittle and susceptible to cold cracking. A soft zone forms under the hard surface (figure 16). The soft zone has undergone annealing. The width as well as the hardness level of both the hard surface and soft zone depend on the cutting method and cutting parameters.

Figure 16
Thermally cut hardened wear-resistant steel, plate thickness 6 mm

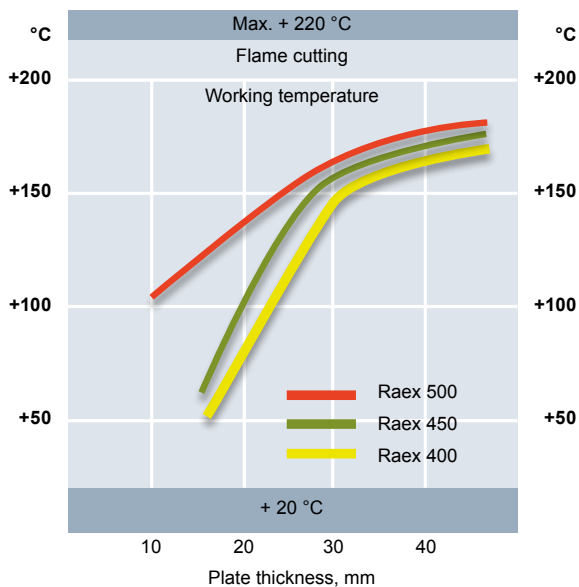
The typical hardness profile of a thermally cut surface illustrated from the cut edge towards the base metal. The shape of the hardness profile depends on the steel grade, cutting method and cutting parameters.



8.2 Controlling surface hardness by increasing the working temperature

In thermal cutting it is recommended that the hardness of the heat-treated surface is controlled so as to ensure that the surface remains undamaged. A sufficiently low maximum hardness prevents cracks from forming on the cut edge. Preheating is often used to control the hardening. The recommended working temperatures for thermal cutting are shown in figure 17.

Figure 17
Raex steels. Recommended working temperatures for flame cutting



Preheating (above room temperature) can be avoided when the thermal cutting rate is adjusted to be suitably slow and when cutting nozzles and other equipment are chosen accordingly. In order to find the best cutting method, it is advisable to contact our Technical Customer Service and the cutting equipment manufacturer.

8.3 Prevention of softening in thermal cutting

The cutting energy of large steel sections is freely transmitted to the surrounding plate, which accelerates the cooling of the cutting area and restricts the width of the soft zone. However, in the flame cutting of plates 30 mm or less in thickness, the distance between cutting lines must be at least 200 mm in order to avoid the softening of the entire plate. The cutting order can be conveniently used to control softening.

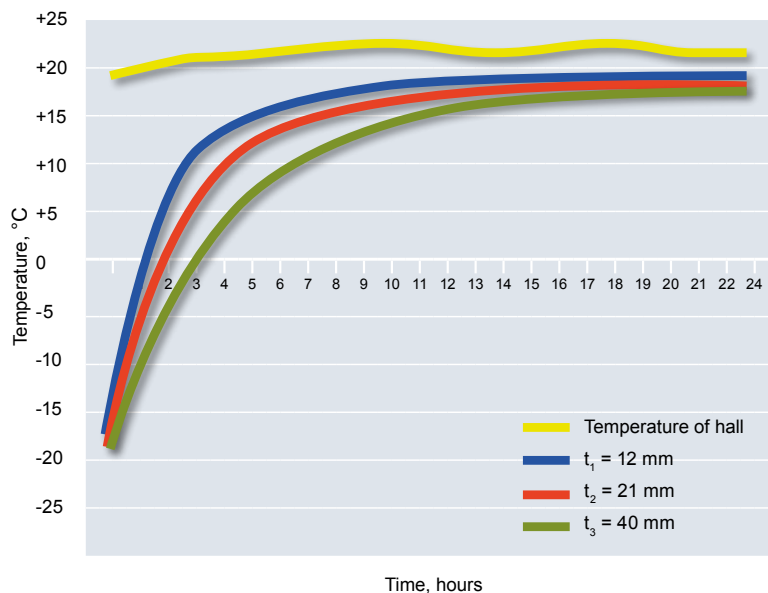
Reduced section size and plate thickness increase softening. With small sections the thermal energy generated by the cutting method and the possible preheating accumulates in the cut section, which slows the cooling process. Of all thermal cutting methods the ones that cause the least softening are laser cutting and plasma cutting of suitable thicknesses. The soft zone of laser or plasma cut steel is narrower than that of flame cut steel (figure 16). Submerged plasma cutting and flame cutting efficiently control the softening of the cut section and are therefore suitable for the cutting of sections of all sizes. To control softening, it is recommended that cold cutting methods are used, for example non-thermal waterjet cutting or abrasive waterjet cutting.

8.4 Practical tips for thermal cutting

In cold weather the effect of the temperature on the processability of a steel plate should be taken into account at the machine shop. Plates that have been stored in a cold environment should be brought in well in advance before flame cutting and welding. Figure 18 shows the time needed for warming up, when a steel plate is brought inside from a subzero temperature. The measurements were performed for plates of three different thicknesses.

Figure 18
The warm-up time of cold (-20°C) steel plates in a hall with a temperature between +20°C and +22°C.

The test was performed at Rautaruukki in Raahе in February 2011. Plate sizes 12 x 1000 x 2000, 21 x 1000 x 1600 and 40 x 1000 x 2000 mm.



The test in figure 18 gave the following warming results from -20°C to +17°C:

- about 8 hours for a 12 mm plate
- about 12 hours for a 21 mm plate
- about 17 hours for a 40 mm plate.

The surface and the centre of the plate warm up at equal rates with such a slow change. It must be emphasised that large, thick plates stacked one on the other warm even more slowly. As a basic rule, it can be concluded that a cold plate (width 2 m, length 6 m) that has been stored outside in a subzero temperature warms to room temperature in about 24 hours.

Practical tips:

- A hardened steel plate should not be taken directly from cold storage to thermal cutting.
- Before cutting, cold plates must be allowed to thoroughly warm-up to room temperature (+20°C).
- Move plates from cold storage to the machine shop on the preceding day.
- Store cold plates on wooden bearers.
- A cold 40 mm plate (-20°C) warms to room temperature (+20°C) in about 24 hours.
- When cutting thick plates, an elevated working temperature should be used according to figure 17.
- For chip removal of a thermally cut section, the surface that has hardened in flame cutting and sharp edges must be removed by grinding.

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