MAG welding of high strength special-purpose structural steel with Flux cored wires

Dr.-Ing. E. Engindeniz

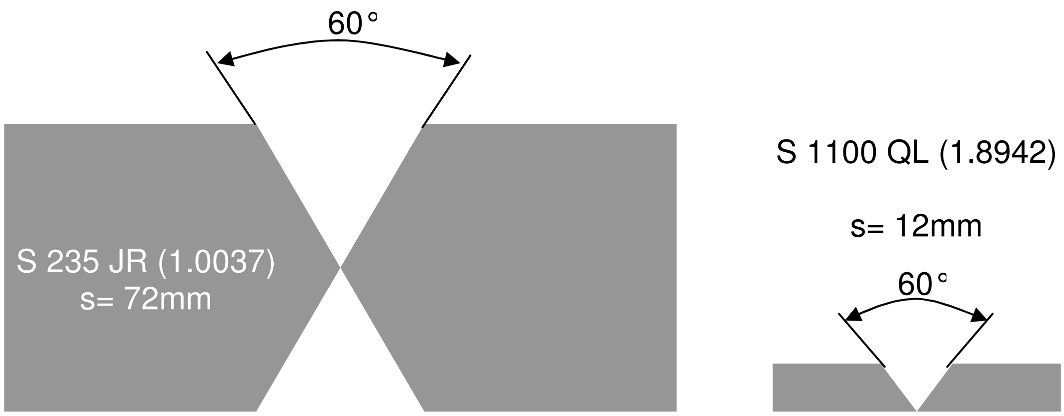
DRAHTZUG STEIN

1. Introduction

In order to meet the increasingly demanding requirements on steel regarding its strength, especially for the construction of mobile cranes, pressure vessels, utility vehicles, turbines, underwater vehicles etc., over the past 30 years, steel producers have been pushing research to such an extent that construction steels of 1100 N/mm^2 are now available and have been in use for 5 years. When developing the new steels the customers' wishes regarding good weldability, high toughness and operational safety were of course taken into account. These are prerequisites for the economically successful use of high strength steel.
This report first discusses cost savings and describes the high-strength steels that are currently available and then treats the associated welding engineering aspects. In the last part the latest developments in the field of filler materials for flux-cored electrodes and their processing methods are pointed out.

2. Economic evaluation of high strength steel use

By choosing high strength steel in the constructive design of components, the sheet thickness is tremendously reduced while the functionality of the construction remains unchanged. The best example for this are applications in the mobile crane and utility vehicle construction where a lower net weight saves energy costs and reduces transport distances. Besides, the efficiency of the vehicles can be improved as a higher load capacity can be achieved if the net weight remains the same.
This is similar in the field of submarine construction where significantly higher diving depths can be realized at a comparable design weight.
Thanks to the reduced thickness of the sheets, material purchasing costs both for base material and for consumables are lower. Since the lower sheet thickness also reduces welding times, costs for labor and machinery can be saved.
A comparison of the costs for S 1100 QL (1.8942) and S 235 JR (1.0037, formerly St 37-2) can be seen in figure 1 in the case of a single V butt weld and a double V butt weld. The results clearly show that the costs saved are approximately proportional to the yield points and amount to about 80%.



S 235 JR	description	S 1100 QL
183	yield point [N/mm^2]	1100
72	sheet thickness [mm]	12
6	ratio of thickness	1
11.527	seam weight [kg/m]	0.726
40	labor costs [€/h]	40
320	electricity [A]	220
6.5	weight of electrode melted in unit time [kg/h]	4
80	operating time [%]	80
SG 2	type of wire ∅ 1.2mm	**STEIN-MEGAFIL 1100 M**
0.8	price of wire [€/kg]	6.5
95	output [%]	90
0.01	gas price [€/l]	0.01
15	gas flow rate [l/min]	15
118.87	production costs [€/m]	23.26
5.11	**cost ratio**	**1**

figure 1: comparison of welding costs for S 1100 QL and S 235 JR

3. Weldable high strength special-purpose structural steels

Table 1 lists the steel grades of class 690 N/mm^2 < $R_{p0,2}$ < 1100 N/mm^2 from three producers. All grades are water-quenched fine-grained steels, which are mainly used for mobile crane, utility vehicle and vessel construction and mechanical engineering. The likewise water-quenched fine-grained steels shown in table 2 are mainly used for the construction of underwater vehicles.

<table>
<tr><th></th><th>C Max %</th><th>Si Max %</th><th>Mn Max %</th><th>P Max %</th><th>S Max %</th><th>Cr Max %</th><th>Mo Max %</th><th>Ni Max %</th><th>Nb+V Max %</th><th>Cu Max %</th><th>Ti Max %</th><th>R_m N/mm^2</th><th>$R_{p0,2}$ N/mm^2</th><th>A_5 %</th></tr>
<tr><td>N-A-XTRA 70</td><td>0.2</td><td>0.8</td><td>1.6</td><td>0.02</td><td>0.01</td><td>1.5</td><td>0.6</td><td>- -</td><td>- -</td><td>n.d</td><td>- -</td><td>770 940</td><td>690</td><td>14</td></tr>
<tr><td>XABO 890</td><td rowspan="2">0.18</td><td rowspan="2">0.5</td><td rowspan="2">1.6</td><td rowspan="2">0.02</td><td rowspan="2">0.01</td><td rowspan="2">0.8</td><td rowspan="2">0.6</td><td rowspan="2">2.0</td><td rowspan="2">0.1</td><td rowspan="2">n.d</td><td rowspan="2">- -</td><td>940 1100</td><td>890</td><td>11</td></tr>
<tr><td>XABO 960</td><td>980 1150</td><td>960</td><td>10</td></tr>
<tr><td>XABO 1100</td><td>0.2</td><td>0.5</td><td>1.7</td><td>0.02</td><td>0.005</td><td>1.5</td><td>0.7</td><td>2.5</td><td>0.12</td><td>n.d</td><td>- -</td><td>1200 1500</td><td>1100</td><td>8</td></tr>
<tr><td>WELDOX 700</td><td>0.2</td><td>0.6</td><td>1.6</td><td>0.02</td><td>0.01</td><td>0.7</td><td>0.7</td><td>2.0</td><td>0.13</td><td>0.3</td><td>0.04</td><td>780 930</td><td>700</td><td>14</td></tr>
<tr><td>WELDOX 900</td><td rowspan="2">0.2</td><td rowspan="2">0.5</td><td rowspan="2">1.6</td><td rowspan="2">0.02</td><td rowspan="2">0.01</td><td rowspan="2">0.7</td><td rowspan="2">0.7</td><td rowspan="2">2.0</td><td rowspan="2">0.1</td><td rowspan="2">0.3</td><td rowspan="2">0.04</td><td>940 1100</td><td>900</td><td>12</td></tr>
<tr><td>WELDOX 960</td><td>980 1150</td><td>960</td><td>12</td></tr>
<tr><td>WELDOX 1100</td><td>0.21</td><td>0.5</td><td>1.4</td><td>0.02</td><td>0.01</td><td>0.8</td><td>0.7</td><td>3.0</td><td>0.12</td><td>0.3</td><td>0.02</td><td>1250 1550</td><td>1100</td><td>10</td></tr>
<tr><td>DILLIMAX 690</td><td>0.18</td><td>0.5</td><td>1.6</td><td>0.02</td><td>0.01</td><td>1.5</td><td>0.6</td><td>1.5</td><td>0.1</td><td>- -</td><td>+</td><td>770 940</td><td>690</td><td>14</td></tr>
<tr><td>DILLIMAX 890</td><td>0.2</td><td>0.5</td><td>1.6</td><td>0.02</td><td>0.01</td><td>0.8</td><td>0.7</td><td>1.2</td><td>0.1</td><td>- -</td><td>+</td><td>940 1100</td><td>890</td><td>12</td></tr>
<tr><td>DILLIMAX 965</td><td>0.2</td><td>0.5</td><td>1.2</td><td>0.02</td><td>0.01</td><td>0.8</td><td>0.7</td><td>2.0</td><td>0.1</td><td>- -</td><td>+</td><td>980 1150</td><td>960</td><td>12</td></tr>
<tr><td>DILLIMAX 1100</td><td>0.18</td><td>0.5</td><td>1.3</td><td>0.015</td><td>0.01</td><td>1.5</td><td>0.8</td><td>2.5</td><td>0.1</td><td>- -</td><td>0.1</td><td>1200 1500</td><td>1100</td><td>10</td></tr>
</table>

table 1: ladle analyses of the water-quenched, high strength fine-grained steels

As can be seen from the chemical ladle analysis of equivalent classes there are almost no differences in the main alloy formation. In the tables the maximum content according to the manufacturer was given for all elements. Therefore, actual analyses might produce different results. Generally, the content of trace elements and impurities such as P, S, H, N, O must be minimized in all steel grades. For this purpose steel producers use the technologies of secondary metallurgy and vacuum degassing. It can be assumed that the actual values for impurities of P and S resulting from product analyses only amount to half of the values given for the ladle analyses. Today, modern steel works are able to realize N contents significantly below 100ppm. The cast steels are Al-killed. The minimum Al content should be 180ppm. Al is necessary to bind the dissolved nitrogen and also prevents grain growth due the resulting Al nitrides. The content of other grain refining elements such as Nb-Ti, V, Zr amounts to a minimum of 150 ppm.

	C	Si	Mn	P	S	Cr	Mo	Ni	V	Cu	Ti
HY 80 15 NiCrMo 10 6 Thyssen / DH	0.12 0.16	0.15 0.35	0.10 0.40	0.01	0.01	1.0 1.8	0.2 0.6	2.0 3.25	0.03	0.25	0.02
HY 80 USA	0.18	0.15 0.35	0.1 0.4	0.025	0.025	1.0 1.8	0.2 0.6	2.0 3.25	n.d.	n.d.	n.d.
HY 100 16 NiCrMo 12 6 Thyssen / DH	0.12 0.20	0.15 0.35	0.1 0.4	P+S $\leq$ 0.04		1.0 1.8	0.2 0.6	2.0 3.5	0.03	0.25	0.02
HY 100 USA	0.2	0.15 0.35	0.1 0.4	0.025	0.025	1.0 1.8	0.2 0.6	2.25 3.50	n.d.	n.d.	n.d.

table 2: ladle analyses of the water-quenched, high strength fine-grained steels

The chemical analyses of the likewise water-quenched high strength special-purpose structural steels of the HY-grades in table 2 are described in more detail. The main alloy elements do not only have upper limits but also lower limits while the basis is fixed as Cr, Mo and Ni. It is remarkable that the HY range has exceptionally low Mn contents between 0.1% and 0.4%. This indicates that HY grades are alloyed with high Ni contents while the special-purpose steels shown in table 1 can be Ni-free or have a low Ni-content. The high Ni-content only causes a tough, easily formable structure if the Mn-content in the base metal is significantly below 1.0%. This limit can be raised to 1.2% without problems in weld metal structures with a Ni content of 3%.

4. Welding processing information

All steels listed in tables 1 and 2 are classified as susceptible to cold cracks and hydrogen-induced crack formation. Since the cold crack behavior of steels greatly influences welding processing and therefore component production costs, steel producers and research institutes have recently conducted extensive cold crack studies. Several formulas for determining the carbon equivalent have been developed in order to define the cold crack sensitivity of individual steels and weld metals. Worldwide, there are 4 ways to calculate the carbon equivalent:

1. **CET = C + (Mn + Mo)/10 + (Cr + Cu)/20 + Ni/40**

This equation was derived by multiple regression of results of cold crack tests which have been performed at Thyssen Stahl AG over the past years.

2. **CE = C + Mn/6 + (Cr + Mo + V)/5 + (Ni + Cu)/15**

The equation above was derived from hardness measurements. It is called IIW carbon equivalent.

3. **PCM = C + Si/30 + (Mn+Cu+Cr)/20 + Mo/15 + Ni/60 + V/10 + 5*B**

This equation was derived by multiple regression of Tekken test results.

4. **CEN = C + [0.75+0.25*tanh(20*(C-0.12))] * { }**

{ } = Si/24 + Mn/6 + Cu/15 + Ni/20 + (Cr+Mo+V+Nb)/5 + 5*B

Since the description of cold crack behavior by using different carbon equivalents remains unsatisfactory, Japanese researchers tried to obtain better information about cold crack behavior by means of a purely formal mathematical combination of the IIW carbon equivalent CE and the PCM formula. The effect of the tanh function is that, purely formally, the calculated values are similar to the values calculated according to the CE formula in case of carbon contents above 0.12 % and that in the case of carbon contents below 0.12 % the calculated values are similar to the values calculated according to the PCM formula.

steel grade	CET	CE	PCM	CEN
690 N/mm^2	0.33	0.58	0.27	0.42
890-1100 N/mm^2	0.37	0.62	0.31	0.55
HY 80 / HY 100	0.32	0.60	0.28	0.47

table 3: comparison of the carbon equivalents

In table 3 the carbon equivalents which were calculated using different methods and which can be regarded as characteristic for the steel grades in question are shown in comparison. Although the analyses of the HY steels might be outside of the area of validity for Mn and Ni, a rough approximation of the cold crack sensitivity is given which can nevertheless be compared to that of the steels mentioned before. The cold crack behavior of the welded joints depends on the chemical composition of the base metal and the weld metal as well as the following factors:

- sheet metal thickness
- hydrogen content of the weld metal
- preheat and interpass temperature
- heat input
- residual stress behavior of the construction

However, in this context the interaction between cold crack sensitivity and mechanical quality characteristics of the welded joint have to be taken into account. In addition to the influencing factors stated above such as sheet metal thickness, energy input per unit length, preheat and interpass temperature these also include the geometry of the weld and the welding procedure. These procedure-specific actuating variables are united to form a parameter which is characteristic for the time-temperature curve during welding, namely the cooling-off time $t_{8/5}$ [1/2]. This is the time during which the temperature of the weld seam and the heat-affected zone drops from 800℃ to 500℃. $T_{8/5}$ can be calculated for two- and three-dimensional heat dissipation as a function of η, E, To and $F_{2/3}$. In the case of three-dimensional heat dissipation wand thickness does not matter. Transition thickness depends on heat temperature and heat input.

The effect of the welding procedure is included according to:

$$T_{8/5}=(0.67-5.10^{-4}.T_o).\ \eta.E\{(1/500-T_o)-1/800-T_o)\}.F_3 \quad \text{three-dim.}$$

$$T_{8/5}=(0.043-4.3.10^{-5}.T_o).\ \eta^2.E^2/d^2.[(1/500-T_o)^2-(1/800-T_0)^2].F_2 \quad \text{two-dim.}$$

η= 0.80 for MAG/M21

η= 0.85 for MAG/CO_2

η= 0.75 for MIG/Ar, He

For the weld factors F2 and F3 table 4 below is applicable:

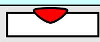
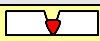
type of weld	symbol	F_2	F_3
deposited run		1	1
filler beads/ butt joint		0.9	0.9
fillet weld/ corner joint		0.9–0.67	0.67
fillet weld / T joint		0.45–0.67	0.67

table 4: influence of the weld type on $t_{8/5}$

If the material cools down too quickly, high hardness values are obtained in the heat-affected zone. If the material cools down too slowly, the required strength and toughness values of the HAZ might not be met. Experience has shown that field-tested $t_{8/5}$ values are between 6 s and 20 s depending on the type of sheet metal and the requirements.

5. Suitable flux-cored electrodes

For all tests and indications for suitability performed in the scope of the present work only seamless flux-cored electrodes were used.

5.1 Production and advantages of seamless flux-cored wires

There are a lot of filled filler metals on the market but a closer look reveals important differences. In figure 2 some examples of micrographs of common flux-cored electrodes on the market are shown.

- seamless flux-cored electrodes (STEIN-MEGAFIL® system)
- closed-form flux-cored electrodes

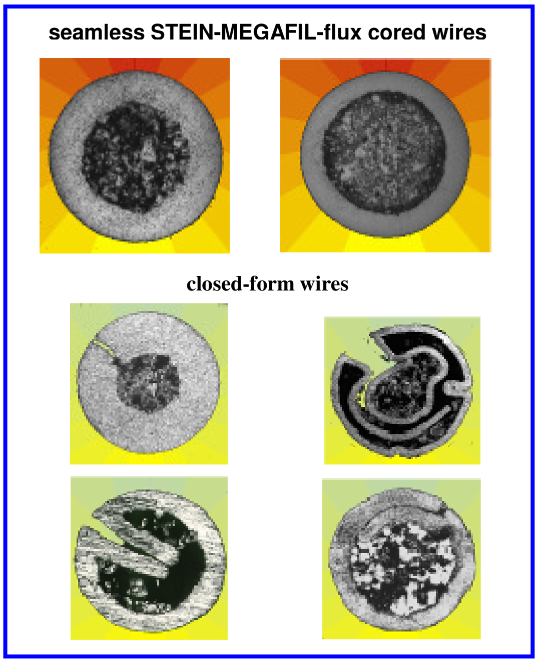


figure 2: micrographs of flux-cored wires

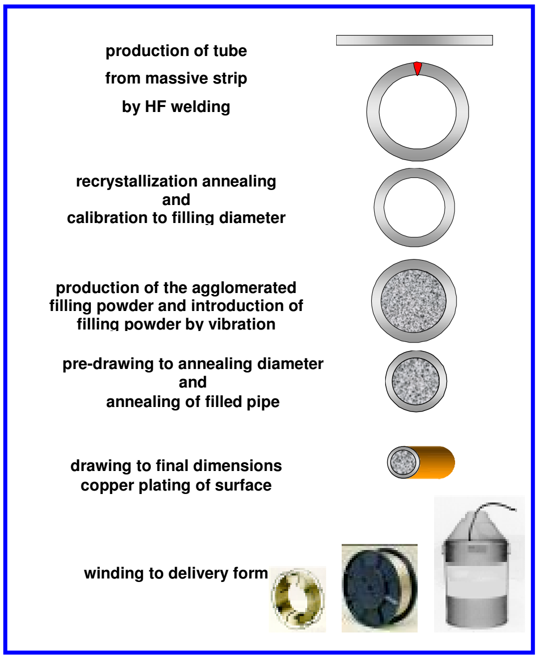


figure 3: production of STEIN-MEGAFIL flux-cored wires

The production process is shown in **figure 3**. A continuous strip of about 50 mm width and 2 mm thickness is used as primary material which is welded into tubes by high frequency welding. After recrystallization annealing the agglomerated filling powder is introduced into the tube and pre-compacted by the oscillating movements of a vibrator. Afterwards the semi-finished product is pre-drawn to the annealing diameter. While the solidified jacked is soft-annealed during this heat treatment, the hydrogen which comes from the filling powder is reduced to well below 5 ml / 100 g. Subsequently, the wire is drawn to the final dimension in several stages while being repeatedly wet-cleaned during this process and finally the wire is copper plated and polished [3].

On account of the closed wire jacket the seamless types have the following advantages compared to seamed wires:

- insensitive to moisture absorption
- baking not required even after prolonged storage
- HD values generally below 4 ml / 100 g
- copper plated surface, therefore better current transition, less wear of contact tube
- no torsion, no spin, stable wire feeding

Generally rectifiers with constant voltage characteristics are still to be regarded as the standard power sources for all gas protected flux-cored electrodes. The use of pulsing technique offers additional advantages with regard to spatter-free welds. However, it has to be ensured that the pulse frequency is between 50 Hz and 100 Hz in order to optimize the welding characteristics.

5.2 Type and alloy selection

In the face of the cold crack sensitivity of high strength fine-grained structural steels on account of hydrogen it was always thought in the past that basic flux-cored wires should be used. Optimized production conditions in flux-cored wire production have contributed to ensure an HD content below 4 ml / 100 g even for the metal powder types. This has cleared the way for metal powder flux-cored wires which offer more welding advantages.

In table 5 the individual flux-cored wires have been attributed to the high strength steel grades. It becomes apparent that the metal powder types have already become clearly dominant. It can also be seen that in the area of the class of strength of $R_{p0,2}$ 550/$R_{p0,2}$ 690, especially for submarine construction, metal powder wires are only alloyed with Ni. As Cr and Mo have been dispensed with for better welding characteristics (less spatter, better modeling characteristics in cases of welding without moving the workpiece) the strength level must be compensated by higher Ni contents.

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steel gra-	flux-cored wire	classification	C %	Si %	Mn %	P %	S %	Cr %	Mo %	Ni %	R_m N/mm^2	$R_{p0.2}$ N/mm^2	A_5 %
HY 80 550 N/mm^2	MF 741 B	E 90 T5-G	0.05	0.4	1.2	0.02	0.015	- -	0.5	1.0	650 750	560	22
	MF 741 M	E 91 T1-G											
	MF 940 M	E 91 T1-G	0.05	0.6	1.4	0.02	0.015	- -	- -	2.0	600 750	560	26
HY 100 690 N/mm^2	MF 742 B	E 110 T5-K4	0.05	0.4	1.6	0.02	0.015	0.5	0.5	2.2	780 960	690	17
	MF 742 M	E 110 T1-K4											
	MF 250 M	E 110 T1-K4	0.05	0.6	1.2	0.02	0.015	- -	- -	3.0	760 960	690	26
890 N/mm^2 960 N/mm^2	MF 745 B	E 110 T5-G	0.05	0.4	1.6	0.02	0.015	1.0	0.5	1.8	950 1100	890	14
	MF 807 B	E 110 T5-G	0.07	0.5	1.3	0.02	0.015	1.2	1.0	2.3	950 1100	890	14
	MF 807 M	E 110 T1-G											
890 N/mm^2 1100 N/mm^2	MF 1100 M	E 120 T1-G	0.07	0.5	1.5	0.02	0.015	0.8	0.8	2.7	980 1180	960	12
for tack welds	MF 240 M	E 81 T1-G	0.05	0.4	1.4	0.02	0.015	- -	- -	1.4	560 720	500	24

In the area of the highest yield points of about 960 N/mm^2 and 1100 N/mm^2 the wires MF 807 M/B and MF 1100 M can be interchanged without difficulties. The development in this field has not been completed yet. At this level of strength it is not harmful if the tensile strength of the welded seam is slightly below that of the base metal. In one case MF 1100 M was even qualified for St E 890 as well. It has to be absolutely ensured that a softer consumable is used for the root. Especially for the tack weld an absolutely crack-proof alloy with good deformation capabilities should be used as well. In practice MF 240 M has proven to be particularly suitable for this task.

6. Harmful effect of hydrogen and nitrogen

Hydrogen has the smallest atoms of all gases and if it is present at high temperatures it is absorbed by the metal structure.

Depending on the steel grade and the hydrogen content in the weld metal, hydrogen may lead to cracks in the weld seam. The hydrogen-induced cracks do not necessarily occur immediately after welding. It may happen that cracks only occur up to 72 hours after welding. These cracks are always deformation-free and transcrystalline and transversal to the weld seam. Possible absorption sources and factors which favor crack formation are compiled in figure 4.

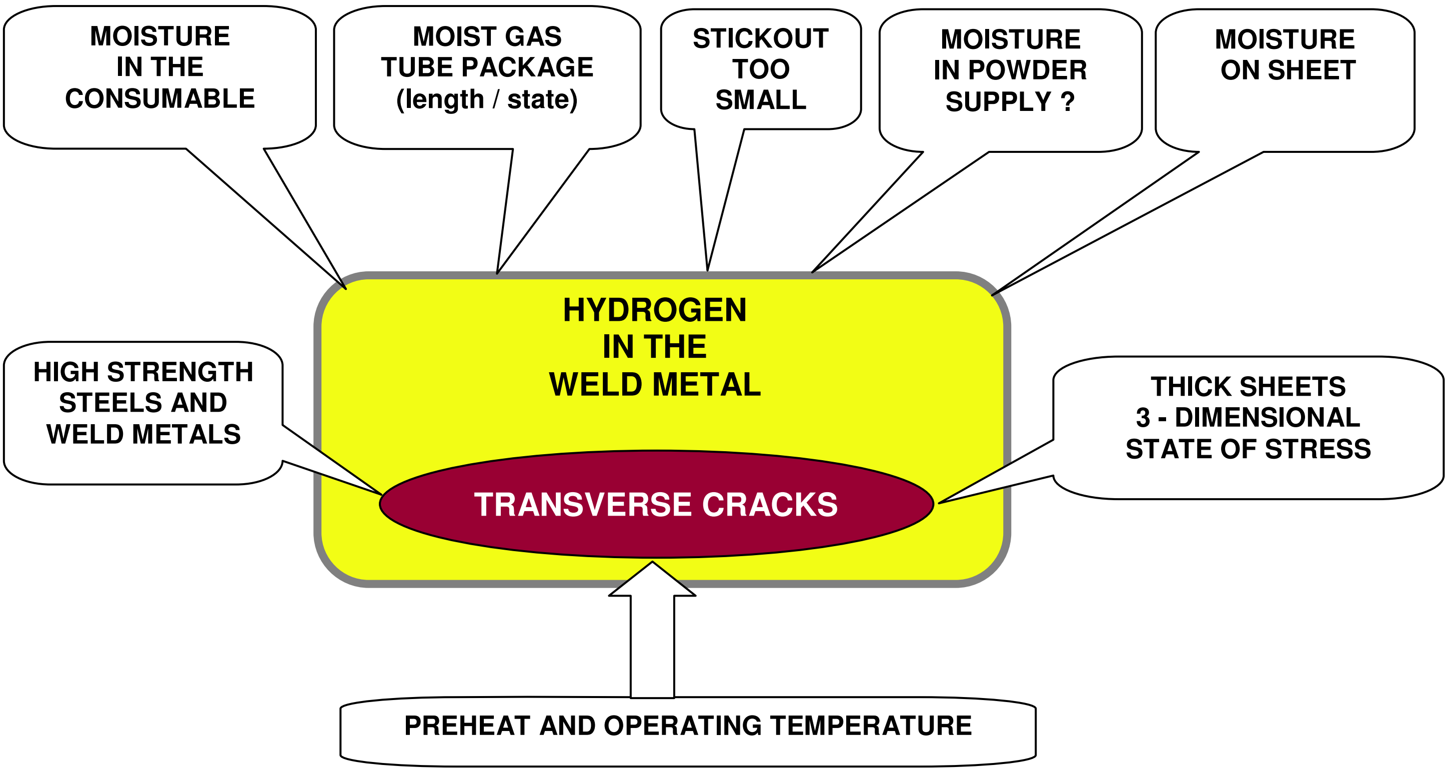


figure 4: hydrogen absorption into the weld metal and favoring factors

Amongst others the hydrogen content in the weld metal increases as stickout decreases. According to figure 5 the free wire end of wires of a 1.2mm ∅ should be more than 20 mm in order to ensure minimum H_2 content. However, studies show that the nitrogen content in weld metals increases as stickout increases. In general the following rules apply:

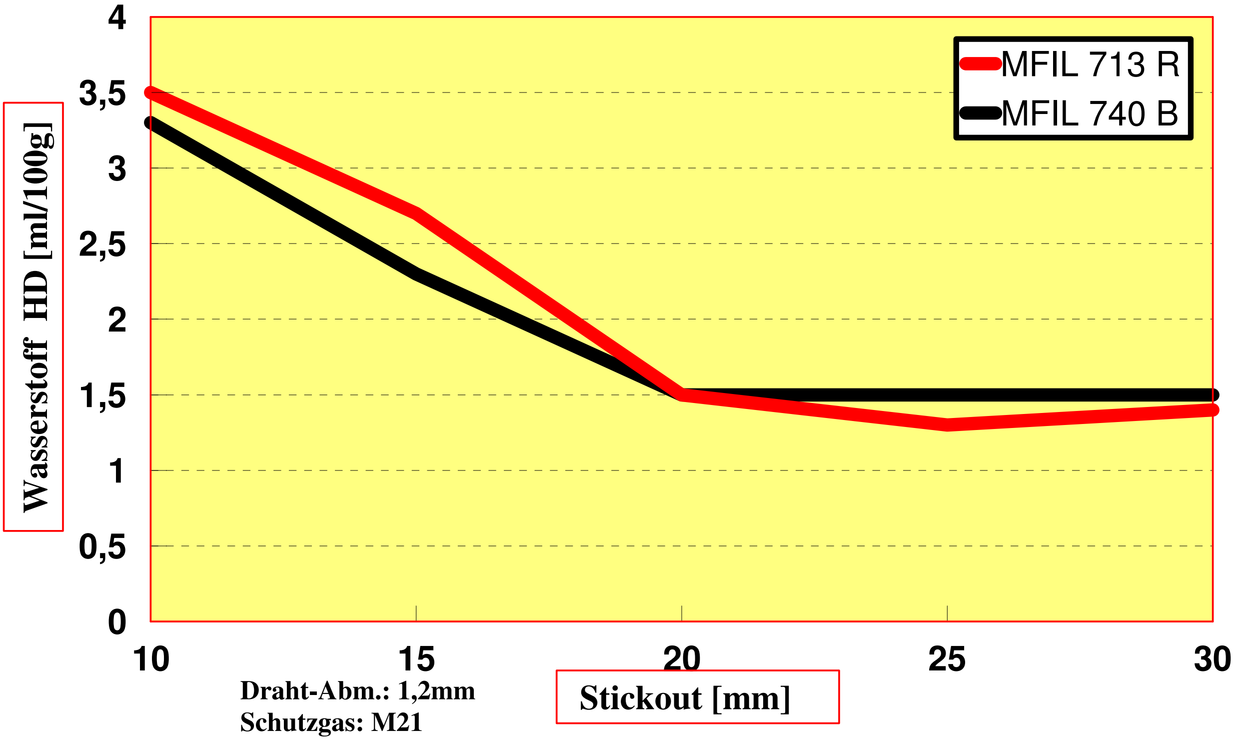


figure 5: influence of stickout on hydrogen absorption into the weld metal

- diffus. hydrogen HD in weld metal if possible below **5 ml** / **100 g** Dep. SG
- nitrogen content in weld metal if possible below **80 ppm** but not more than **100 ppm**

If the HD value is inadmissibly high, the seam might very well be sensitive to crack formation. Figure 6 shows some typical hydrogen-induced cracks in a fillet weld through all layers, transversal to the seam.

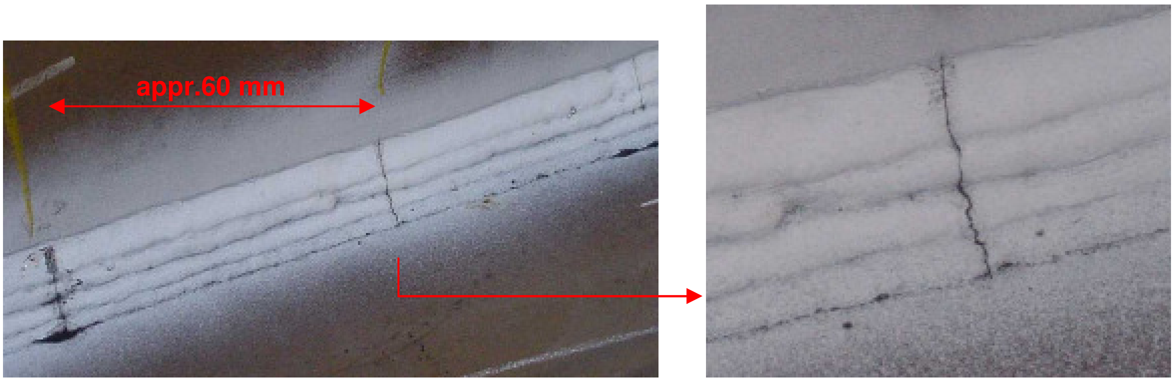


figure 6: cracks in a fillet weld cause by hydrogen

A common method to avoid such defects is the so-called low hydrogen annealing. In this process the component is heated to 250℃ for 2 hours after welding.

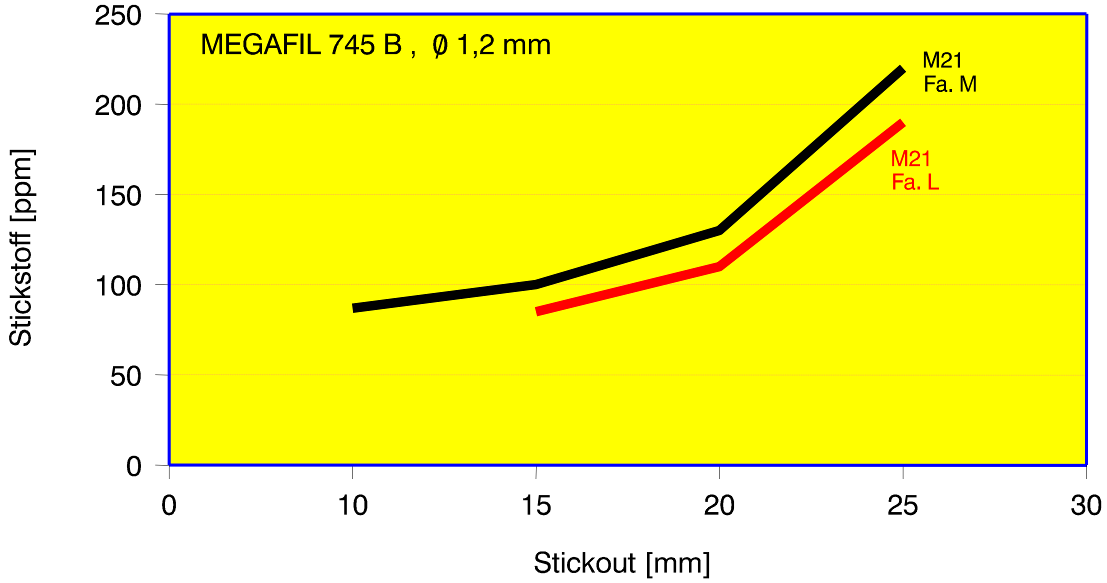


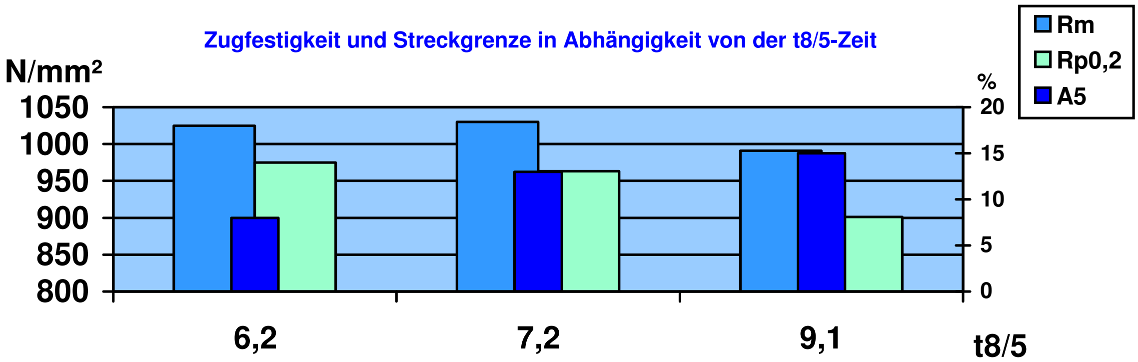
figure 7: influence of stickout on the nitrogen absorption into the weld metal

Figure 7 shows that for wires with a ∅ of 1.2 mm the stickout must not exceed 20 mm either. Otherwise a significant embrittlement of the weld metal structure due to nitrogen contents above 100 ppm has to be expected which would lead to a substantially decreased notched impact strength and the seam would lose its deformation capabilities. It must absolutely be taken into account that the nitrogen content can be different depending on each product.

Following these explanations it can be stated that a stickout of appr. 18 mm for wires of a 1.2 mm ∅ can be considered as an acceptable compromise.

7. Welding of steel quality Weldox 1100

After first practical tests several weld metal test specimens as well as joints on high strength steel WELDOX 1100 were produced. The results of the mechanical quality characteristics of the pure weld metal in dependence on $t_{8/5}$ time are shown in figure 8. The process parameters remained absolutely constant during the execution of the welds. Only different cooling down rates of 6.2 s, 7.2 s and 9.1 s were realized by changing the operating temperature. The corresponding interpass temperatures of 120°C, 160°C and 220° C are entered into the diagram as well. As expected, the best notched impact strength values can be achieved with the smallest $t_{8/5}$ time, while an acceptable level can also be obtained in the upper cooling down range, although with small reserves. The yield point of the pure weld material also reacts according to the rules of metallurgy and drops as $t_{8/5}$ time increases.



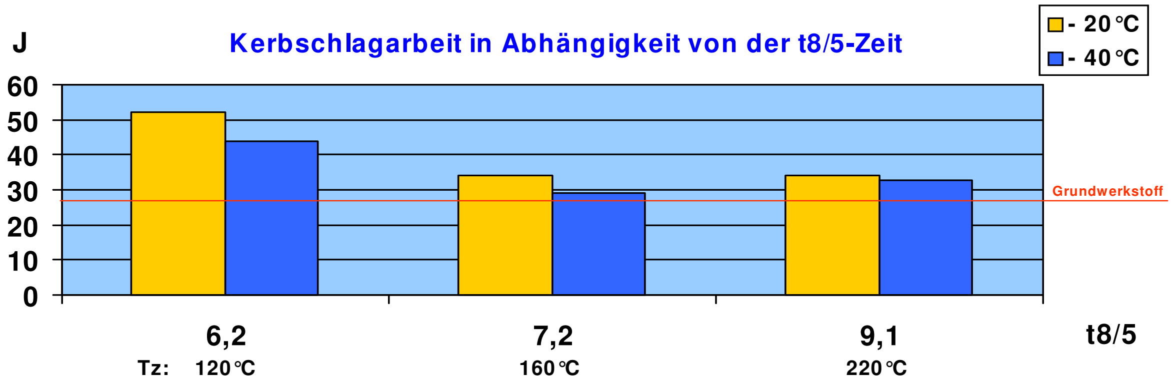
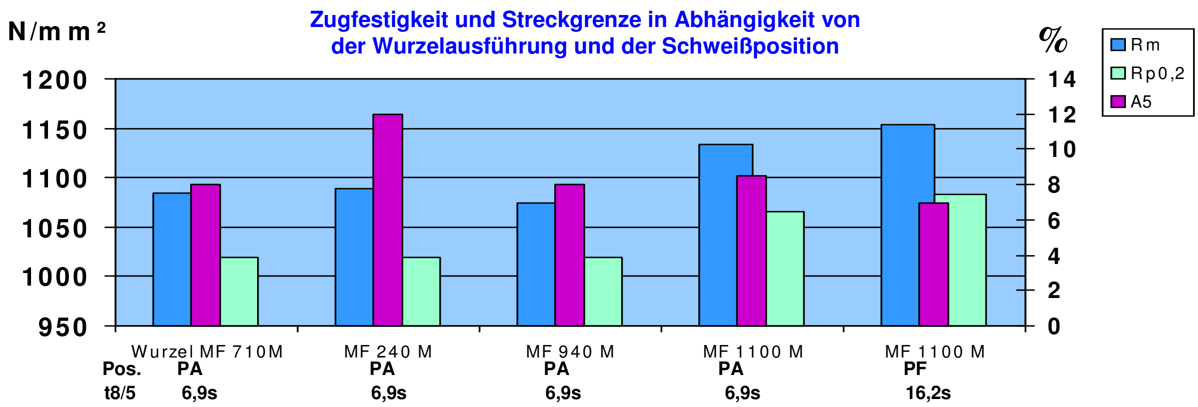


figure 18: characteristics of the weld metal, generated by using STEIN-MEGAFIL® 1100 M ø 1.2 mm

It can be assumed that the lower limit of 900 N/mm^2 is a deciding criterion for many applications without representing the risk of a crack in the weld. It is positive that the magical limit of 950 or 960 is exceeded in less than 7.2 seconds. For welds with under matching constraints the use of 960 quality would pose no problems.

This is underlined in figure 9 with the results of the welds. Here the influences of the root execution and the welding position on the mechanical quality characteristics were examined on five welds. The interpass temperature for all welds was 180°C. For sheets with a thickness of s = 12 mm this corresponds to a $t_{8/5}$ time of 6.9 sec. in the PA position, 16.2 sec. in the vertical-up PF position. The root was executed in this order with MEGAFIL® 710 M without nickel and with STEIN-MEGAFIL® 240 M or 940 M containing nickel. For the last two samples STEIN-MEGAFIL® 1100 M was used for the root. It can be stated that the yield point was above 1,000 N/mm^2 in all cases. Although the effect of the softer root wire can be easily seen, it has no influence on the notch bar impact value. What is exceptional however is the fact that the breaking elongation level is generally low. The reason for this is the tension bar itself, namely as flat test piece, which does not represent the real values when the joint is tested, as is generally known. It has to be stated that all test samples cracked in the weld seam. The notch bar impact values are in the usual range of about 40 J at – 20 °C or – 40 °C and their behavior corresponds exactly to the alloy type which does not show a steep front compared to low alloyed, normal mild structural steels [4].



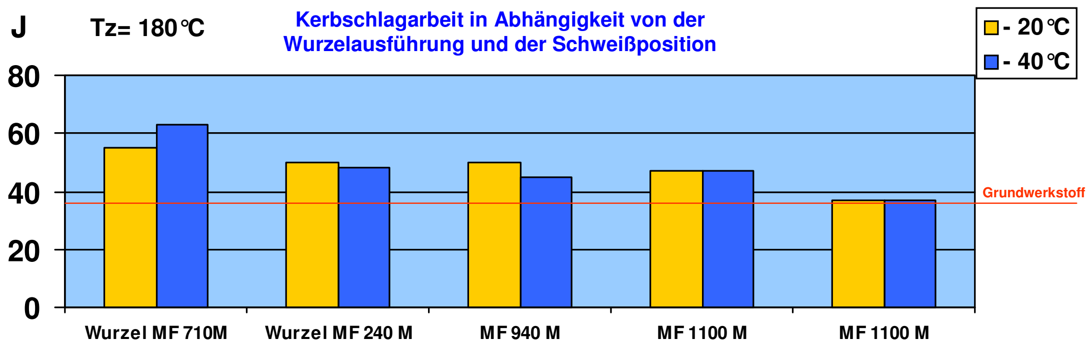


figure 9: mechanical quality characteristics of the welds, generated using STEIN-MEGAFIL® 1100 M ø 1.2 mm, GW: WELDOX 1100, s=12mm

Based on this state of information the TÜV performance test has already been performed.

8 Summary

The processing of high strength fine-grained structural steels requires special precautionary measures in order to realize crack-free joints with sufficient strength and roughness characteristics. The result of decades of research and development in steel production on the one hand and processing on the other hand have led to a concept in which the most important contributing factors and parameters as well as their interactions have been collected and defined. They include:

- carbon equivalent
- cooling down time $t_{8/5}$ two- and three-dimensional
- heat input, energy input per unit length
- cold crack behavior, hydrogen content
- chemical composition
- steel grade, sheet thickness
- preheat and interpass temperature
- residual stress behavior of the construction
- mechanical quality characteristics
- seam geometry
- welding procedures and filler metals

Although specifications regarding some of the parameters above are necessary, it will be problematic to meet these requirements under practice conditions. Amongst others based on many years of experience of a mobile crane producer the report shows that by using some pragmatic and fairly simple methods the complex theory can be reduced to an extent which a qualified welding company must not be afraid of. This is particularly supported by the use of shielding gas flux-cored wires which are even available for S 1100 SL with permits.

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