

was recently added to the accelerated cooling equipment. This tool can now be used to realise higher tensile properties by increasing the cooling capacity subsequent to TM-rolling.

Requirements:

Other main standards specifying offshore steels like API 2-W, BS 7191 or EN 10225 stay below 500 MPa Y.S. NORSOK Standard [1] defines S500 steel to have a minimum Y.S. of 500 MPa and T.S. 600-750 MPa. The tensile requirements are constant for all plate thicknesses, but the maximum being only 40 mm in the actual standard. Revision 3 of the standard is currently in preparation. The new issue will include higher thickness and modified limits for the chemical composition. For other properties and conditions NORSOK refers to steel S460 according to EN 10225 [2]. Following the classification system in accordance with EN 10027 the steel all be S500G1+M (S for structural steel, 500 for the minimum Y.S., G1 for the quality level -G2 for steels with through thickness properties-, the letter +M for the delivery condition thermomechanical rolled.

Experts from Kvaerner Oil and Gas, Aker Maritime, Statoil and Norsk Hydro were involved in designing an optimised steel. The fabricators wanted to use the same welding consumables as they successfully apply for welding existing S420 steels. Welding consumables in a higher Y.S. would require higher alloying, hence higher preheating to avoid weld metal cracking [3] and thereby penalise welding. The consumables for S420/S460 steels normally produce a weld metal with a yield strength of 560 to 640 MPa in the as welded condition. Consequently to avoid an essential undermatching the yield strength of the actual plate should not exceed 580 MPa.

However, to guarantee a yield strength range of 80 MPa through all the plate thickness is pretty puzzling for the plate mill, as will be explained shortly. For a steel composition and constant rolling parameters thicker plates result in lower tensile properties, because thicker plates cool more slowly and, thereby, the phase transformation and grain refinement is influenced. To produce constant tensile properties for different plate thickness, the normal decrease must be compensated by adapting stepwise chemical composition, and rolling parameters and heat treatment. The closer the tolerances for the tensile properties the more sophisticated this "fine tuning" must be. On the example of S420 deliveries (Huldra and Snorre B project) such a stepwise optimisation is illustrated for the T.S., see Figure 2 [4]. An excellent reproducibility of the processes in steelmaking and plate rolling are further prerequisites to keep the required 80 MPa tolerance in the industrial production.

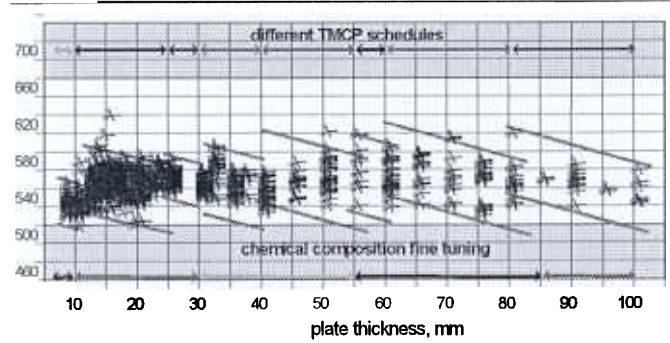


Figure 2 : Tensile strength of S420M deliveries and applied adjustment of the chemical composition and rolling conditions for different thickness ranges.

S500 concept :

Different alloy concepts were investigated by rolling trials and by weld thermal simulation testing with particular focus on HAZ toughness. Special etching techniques [5] were used to measure retained austenite in the HAZ microstructure until the best candidate compositions were selected (Table 1). Carbon content was kept low for reasons of weldability, manganese on the other hand was chosen at the upper limit to increase tensile properties. Micro alloys were added to control recrystallisation in TMCP rolling and to increase tensile properties by precipitation hardening. On the other hand, micro alloys have to be limited in order not to affect the toughness in the HAZ. Nickel was kept below 0.70% to limit alloying cost and to satisfy the range prescribed for S460M (EN10225). Silicon is low to ease decomposition of local brittle zones and to improve brittle fracture resistance in the HAZ. A decent Molybdenum addition is only necessary for the thicker plates. After accelerated cooling the Mo-alloyed steel was tempered to homogenise the properties in the plate.

Thickness	C	Mn	Ni	Mo	Nb+V+Ti	CE _{FW}	Pcm
30 mm	0.08	1.55	0.50	-	0.02	0.39	0.18
70 mm	0.06	1.55	0.60	0.15	0.02	0.42	0.18
S460M3 EN 10225	≤ 0.14	≤ 1.6	≤ 0.70	≤ 0.25	≤ 0.11	≤ 0.43	≤ 0.22

Table 1 : Chemical composition, carbon equivalents in %

A 30 mm thick plate and a 70 mm thick plate were rolled for the qualification tests. **Table 2** shows the parent material tensile and impact properties. The target tensile properties were hit exactly and the fine grained microstructure consisting of ferrite, pearlite and some lower bainite resulted in excellent toughness.

	Req	30 mm as del.	30 mm 580°C / 4h	70 mm as del.	70 mm 580°C / 4h
Re [MPa]	500 (-580)	552	552	556	537
Rm [MPa]	600 - 750	634	629	632	615
A ₅ [%]	≥ 17	24.5	24.3	24.9	24.9
R _e /R _m	≤ 0.90	0.87	0.88	0.88	0.87
CVN @ -40 °C Subsurface					
average J	60	269		309	246
individual J	42	265		305	241
^{1/2} t	t > 40 mm				
average J	60			318	308
individual J	42			315	300

Table 2 : Mechanical properties, requirements and measured values.

Effect of post weld heat treatment and strain ageing on parent material:

To take care for possible changes of the properties during processing the effect of post weld heat treatment (PWHT) and cold forming was assessed. PWHT was carried out at 580°C with a holding time of 4 hours which should represent maximum conditions. As indicated in **Table 2** the plates did not suffer from such a heat treatment. Tensile properties were almost unchanged and the toughness was rather improved.

Hot forming is not allowed for TMCP plates, because the initial properties can not be regained by a simple heat treatment performed after the hot forming. If plates are formed into pipes or tubulars this operation is either done cold or at temperatures of PWHT. The influence of cold straining and ageing on toughness was measured by impact testing on specimens extracted from subsurface position, because in bending the maximum strain is obtained at the plate surfaces. The material was pre-strained before the impact specimens were readily machined. Different levels of strain were used representing different ratios of wall thickness to pipe diameter. A possible ageing in service was simulated by a heat treatment for 2 hours at 250 °C. To characterise the shift of the impact transition curve the energy level of 50 J was selected. The transition temperatures for the different test conditions are summarised in **Figure 3**.

The toughness requirements were still met after 10 % deformation. The strained and strain aged condition can be compared against 5 % deformation. The two plates behave differently. No effect of ageing was evident for the 70 mm plate, whilst ageing caused a shift of 15 °C for the 30 mm

plate. The embrittlement of the 30 mm plate is probably due a higher amount of diffusible carbon, that is able to interact with the dislocations. Contrary to the 30 mm plate, the 70 mm plate had been tempered after rolling, so that its carbon was precipitated more completely and in stable precipitations, like Mo-carbides. Due to the low level of free carbon, the 70 mm material was then insensitive to ageing and the transition temperatures for the strained and strain aged conditions was identical. I must emphasise, however, that both plates revealed excellent toughness at -40 °C after 10 % strain and ageing, so that the observed difference is rather of metallurgical interest than of practical relevance. The increase of yield strength and yield to tensile ratio was not particularly investigated, it should be like earlier findings on S450M steel [6].

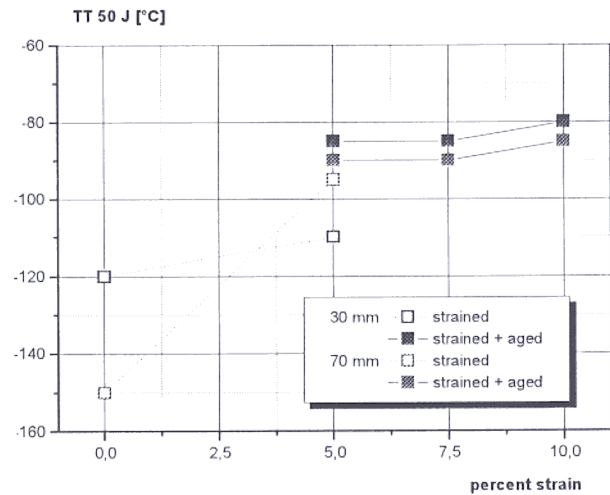


Figure 3: Influence of straining and ageing on the impact transition temperature 50 J, subsurface location, transverse to rolling direction, data reference Schütz [7]

WELDABILITY

An important weldability programme was carried out on both the 30 mm and the 70 mm thick plate. Hardenability, cold cracking sensitivity, preheat temperature and toughness of the HAZ were investigated for various welding conditions.

Heat affected zone hardness

HAZ hardness was measured on cross sections prepared from bead-on-plate welds. A low heat input TIG pass corresponding to a 4-5 s cooling time $t_{8/5}$ is required by EN 10225 for which a maximum hardness of 325 HV10 is permitted. Two SAW beads resulting in $t_{8/5}$ cooling times of 10 s, respectively 20 s, were additionally tested to show the influence of cooling time on HAZ hardness. Further hardness measurements were performed on butt joints and on CTS-

specimens. The $t_{8/5}$ times were calculated for the applied welding conditions using SEW 088. The maximum bead on plate hardness values and the transition was exactly described by own formulae [8] as to be seen in Figure 4. The slightly higher carbon content of the 30 mm plate raised HAZ hardness for short cooling times. For longer cooling times the effect of molybdenum present in the 70 mm plate was stronger than the difference in carbon, so that for slower cooling the values are at the same level.

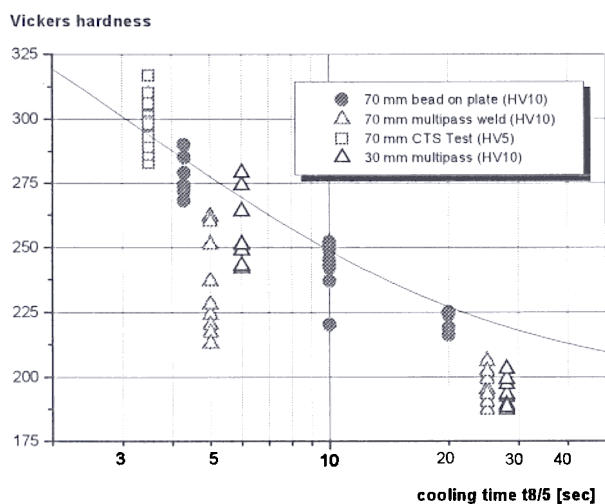


Figure 4: Measured and predicted (bead on plate) HAZ hardness versus cooling times $t_{8/5}$.

The low HAZ hardenability of S500 becomes evident in comparing the results with the requirements stated in EN 10225. For the FCAW multipass weld ($t_{8/5} \sim 5-6$ s) a maximum of 350 HV is permitted and the observed hardness is below 275 HV10 for the higher heat input ($t_{8/5} \sim 25-30$ s) hardness is limited to 325 HV10 and values were well below 250 HV.

Avoidance of HAZ cold cracking and required preheat

The risk for cold cracking of welded joints is not only depending on the chemical composition of the steel. It also increases with the hydrogen content of the weld metal, and with the level of stresses in the weld region and is affected by weld geometry and the welding conditions. Pre- and post heating may be necessary to avoid this weld defect, by lowering the cooling speed and allowing a more complete effusion of the initial hydrogen. Profound explanations of the phenomenon are given by Bailey and co-authors [9].

Low carbon content and lean alloying are the steelmaker's contribution to overcome the problem and to reduce the need to preheat. To characterise the sensitivity of a steel to cold

cracking different carbon equivalents were developed, like Pcm, CET and CE(IIW), the latter one being more suitable for steels of higher carbon content. The low carbon equivalents of the S500 steels, mentioned in Table 1, were well below the acceptance limits set for the 2W-Gr60 and S460M steels. Some tests were carried out to confirm that the steel is easily weldable. As the required preheat rises with increasing plate thickness we focussed cold cracking tests on the 70 mm plate. Amongst the different test assemblies, CTS (controlled thermal severity) and y-groove tests were used. The testing procedures were according to the recommendations of Annex G of EN 10225 and API RP2z, Chapter 4. CTS (Controlled Thermal Severity) tests represent a moderately restrained weld, y-groove specimens normally need higher preheat temperatures because of the higher residual stresses achieved in this configuration. For the test welds the electrode Tenacito 38 (AWS E 7018-G) from Oerlikon was used. This basic covered electrode produces about 4 ml hydrogen per 100 g deposit metal after being properly redried. The electrode contains approximately 1 % Ni. Welded with low heat inputs of 1.0 kJ/mm and 1.4 kJ/mm as actually applied, the weld metal was harder than parent plate and HAZ. We can therefore conclude that the weld metal tensile properties were overmatching the ones of the parent material and the weld vicinity was exposed to high stresses. Each of the test welds was cut and sectioned for metallographic examination. 6 cut faces were examined per CTS specimen and 5 faces for the y-groove specimens. The conditions and results of the cold cracking tests are indicated in Table 3.

Specimen Type	Heat input KJ/mm	Hydrogen [ml/100g]	Applied Preheat [°C]	Result
CTS	1.0	4	20	no crack
Y-groove	1.4	4	130	no crack
Y-groove	1.4	4	20	no crack

Table 3 : Conditions for the cold cracking tests on 70 mm specimens.

They can be easily summarised - no cracks were obtained for any section and any test condition. Despite the very low heat input of 1.0 kJ/mm no preheating was necessary for the CTS test. The corresponding HAZ hardness at the fusion line was in the range of 280 to 320 HV5. Also the y-groove test revealed no cracking even for welding without preheat.. API allows a preheat up to 130 °C for the y-groove test and up to 80 °C for the CTS test. Due to the absence of defects a boundary between cracking and no cracking could not be determined. The steel is therefore much easier to weld than is actually required to pass the qualification.

Impact toughness on butt welds:

A series of butt welds with 2 heat inputs were welded. As detailed in EN 10225 the test welds covered the normal heat input range of 0.7 kJ/mm and 3.5 kJ/mm. A half V preparation was used in order to produce a straight side for impact and CTOD testing of the HAZ toughness. Welding consumables were used that are typically selected for welding of S450 steel.

Mechanised FCAW was used for the low heat input, the other weld was produced with submerged arc process.

Welds were parallel to the plate rolling direction, so that the impact and CTOD specimens were orientated transverse to R.D. which generally results in lower toughness values. Prior to machining of the notch the impact bars were etched to allow a correct notch placement. Location of specimens and notch positions are again different for both specifications. EN 10225 asks for testing of the HAZ at the cap, mid thickness and root position with notching at the fusion line (FL), FL+2mm and FL+5mm. All impact tests are at -40°C with a requirement of 46 J and 32 J lowest individual impact energy, as set for S460 steel. As shown in Figure 5 all values are safe above the requirements.

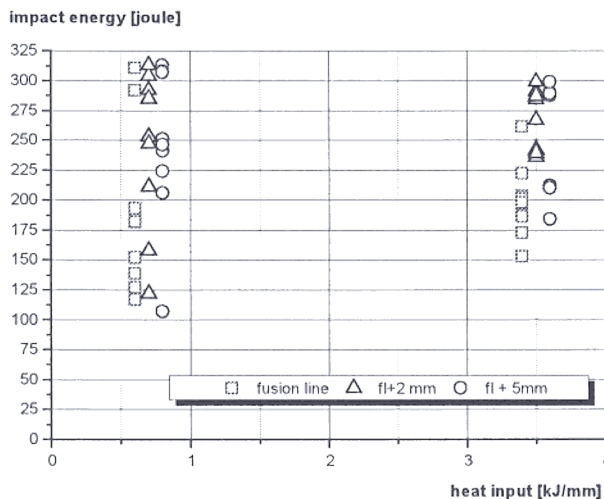


Figure 5: Single impact values for different notch positions in the HAZ, straight side of the weld, testing at -40°C.

More homogeneous mechanical properties from parent plate through HAZ to weld metal is one reason for the improved toughness, predominant however is an increasing amount of polygonal ferrite which reduces the effective grain size of the microstructure close to the fusion line.

Fracture mechanics investigation :

CTOD tests were carried out on 3 welds of the 70 mm plate. Welds of the 30 mm plate were not CTOD tested. Due to the lower thickness and the higher impact toughness it can be expected that brittle fracture is unlikely and focus was on the more critical 70 mm joints. In order to cover the complete range of heat inputs welds with 0.7 kJ/mm, and 3.0 kJ/mm were CTOD tested.

CTOD testing:

Full thickness BxB specimens were used with through thickness notch with a crack length ratio of 0.5. Notch positions, fatigue precracking and evaluation of the CTOD result was performed according to BS 7448-2 [10]. The following crack locations were aimed for: weld metal next to fusion line, coarsed grained HAZ, subcritical / intercritical boundary.

Thanks to careful placement of the weld beads the welds provided a perfectly straight FL and little bulging of the individual passes, allowing to sample high amounts of the aimed microstructure. The specimens were etched before machining of the crack starter notch and the specimens with the best linearity were selected for notching at CG-HAZ. A mechanical stress relief was applied by lateral compression prior to the fatigue precracking to promote crack front straightness. All tests were carried out at -10 °C under displacement control.

Validation:

After testing the specimens were sectioned and validated using the requirements of EN 10225. High amounts of CG-HAZ microstructure were sampled, e.g. all 7 specimens from the 3.5 kJ/mm weld sampled more than 15 % CG-HAZ. The IC/SC-HAZ was much easier to hit. A minimum of 50 % of this microstructure was sampled by all the specimens. For the specimens taken from the low heat input weld the average distance between crack tip and fusion line was taken as validation criterion according to EN 10225.

CTOD-results:

Figure 6 shows all results obtained in the tests including the ones which were judged invalid after the metallographical examination. "Valid" and "invalid" tests or the distance between crack and fusion line did not show a systematic influence on the CTOD values, nor was the amount of sampled CG microstructure an essential parameter.

All results were safely above the requirement of 0.25 mm. In spite of the elevated yield strength, important thickness an excellent resistance against brittle fracture was thereby proven in the complete range of usual welding conditions.

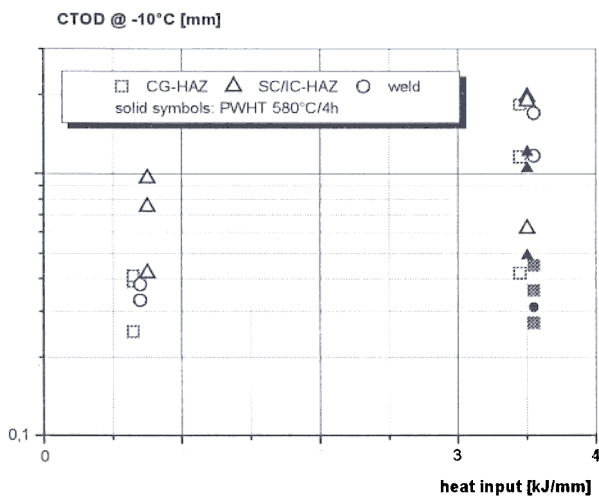


Figure 6: CTOD results on welded joints, full size BxB SENB specimens, $a/W \sim 0.5$, through thickness notch.

SUMMARY AND CONCLUSION:

A low carbon TMCP steel with minimum yield strength of 500 MPa (S500M) was developed in two plate thickness, 30 mm and 70 mm. The chemical compositions were optimised relative to each thickness. The 70 mm plate contained some molybdenum but had 0.02 % lower carbon content.

Tensile properties were exactly hitting the target, yield to tensile ratios were below 0.90 thereby assuring appropriate work hardening an excellent toughness was obtained the S500 test plates were suitable for high amounts of cold deformation the steel is suitable for PWHT.

Both steel types have proven excellent weldability, in particular:

- very low HAZ hardenability
- little cold cracking susceptibility allowing welding without preheat
- high HAZ toughness through the complete range of usual welding heat inputs
- no need for PWHT to achieve appropriate brittle fracture resistance
- particular suitability for high heat input welding

The aim to offer a S500M steel with a weldability equivalent to S420/S460 was perfectly achieved.

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