HIGH STRENGTH STEELS FOR ARCTIC CONDITIONS

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During the last years the demand of new steels for arctic conditions has constantly increased. The development goes to operational temperatures ranging from about -70°C to +30°C. At the same time there is also a need of special steels with yield strengths up to f_y = 690 MPa and high ductility at -40°C. Steel manufacturers are developing better production lines and steel qualities resulting in high strength heavy plates and seamless hollow sections. These new steels are aiming for structural solutions with high demands for fatigue and toughness. One of the important aspects using high strength steels is their weldability. Exemplarily on basis of the new Vallourec steel grade for seamless quenched and tempered hollow sections with a strength level 690 MPa up to wall thickness of 40 mm, which is based on a micro-alloyed low carbon concept, the welding concept will be presented. It will be shown that the welding procedures and the welding consumables together with the new high strength steels match the high requirements even for arctic structural applications under extreme conditions.

Keywords: High strength steel; arctic conditions; seamless hollow sections; high toughness.

1 Introduction

High strength steels with yield strengths up to 700 MPa are widely used in onshore applications, mechanical engineering, mobile cranes, amusement rides and all kind of machinery. But also offshore structures as in Jack-up rigs and Wind Turbine Installation Vessel (WTIV) high strength steels are used since many years, whereby the main applications are legs, spud cans, racks, pinions and jib or boom of cranes. The advantages are thinner sections, less weight, less welding costs. In case of fatigue and thinner sections a lower wall-thickness reduction factor can be taken into account.

For many years the design was done for temperatures down to -30 °C, which is fully sufficient for most applications. New challenges and developments are aiming for more severe applications in arctic regions with special toughness requirements at very low temperatures of -50 °C and below. The offshore classification societies like DNVGL, ABS and others recently included -60 °C in their recommendations and defined specifications for the mechanical and chemical properties for these extreme temperatures. For onshore applications the new pre-standard prEN 10210 defines requirements for seamless hollow sections for test temperatures of -50 °C.

At the same time the steel manufactures developed their products to very thick steel plates and new hot rolled seamless hollow sections fulfilling these challenging requirements. In the following some information about these new steels, their properties and the adequate requirements are given.

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The most important factor for these new arctic steels is the combination of high strength and high toughness properties under very low temperatures. Next to that, excellent weldability is required and a prerequisite in terms of processing and handling. With respect to a time and cost-effective production, high-productivity welding procedures have to be available for these steels. All features are crucial factors to guarantee safe construction and operation, especially for offshore units to meet the severe challenges in these exploration fields (Herion, 2018).

2 Modern High-Strength Steels

Steels are classified according to their yield strength. Depending on the fabrication process and the thickness plates with yield strength up to 1100 MPa and more are available. In mobile cranes for example even steel grades with yield strength 1300 MPa are going to be used. Seamless hot rolled circular hollow sections are produced with yield strengths up to 960 MPa and are used in the booms of mobile cranes also. In offshore oil and gas steel grades do not exceed 700 MPa normally.

Widely used especially in the linepipe and shipbuilding industry are thermo-mechanical rolled steels (M), also known as TM steels, because of their low carbon equivalent (CEV) and their good weldability compared to normalized steels. From economical point of view it is interesting to know that M steels need a lower pre-heating temperature for welding compared to normalized steels (N).

Regarding the steel grades of M steels there is a direct relation between yield strengths and plate thickness. Increasing both raises the risk of lamellar fracture and concern to brittle fracture is given.

To avoid this, the rolling process changes from thermo-mechanically rolled to quenched and tempered (Q) rolled steels, also known as QT steels. This process allows producing higher thicknesses and higher yield strength at the same time and leads to sufficient ductilities. Using this process for thicker plates a higher content of alloying elements is needed, which also leads to higher carbon equivalents (CEV). This is the reason why for these steels it is necessary to take special care during welding.

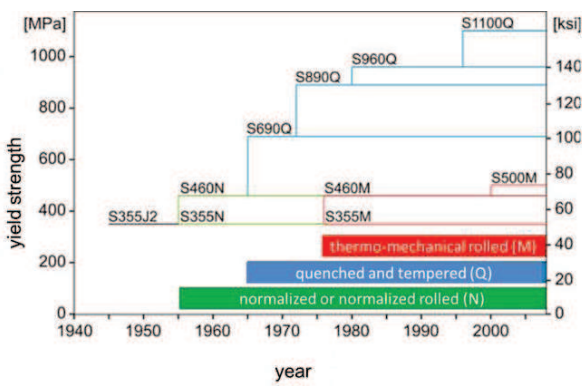

Figure 1. Historical development of rolling processes and high strength steels.

All rolling processes are well-known and commonly used by all major steel producers since more than 30 years as Figure 1 demonstrates. Nevertheless, the production of heavy plates or thick walled seamless hollow sections needs the proper equipment which can handle the needed very high forces during the rolling and the exact timing and measurements during the cooling and re-heating steps. Especially for a big wall thickness very high forces are needed in the rolling stands. Only then a good deformation in the mid thickness can be achieved to get the microstructure and properties needed over the whole thickness. Together with that a lot of experience is important to bring together the perfect chemical composition and purity of the raw material and the appropriate rolling processes.

The rolling and cooling process directly influences the microstructure of the steel, which is the basis for yield strength, toughness, hardness and weldability.

3 Special steels for arctic applications

Actual developments are aiming to heavy plates and tubes with yield strength of 690 MPa and sufficient toughness properties throughout the plate cross-section at test temperatures of down to -60 °C. Developments like this are not made for very heavy offshore platforms only, what was the initial idea to develop those steels, but also it can be used in the field of onshore installations and bridges with special requirements. As these special sections are outside of the relevant ranges of the most previous standards, the relevant standards and recommendations have been adapted accordingly and help to choose the appropriate steels.

The grades and specifications given in EN 10225, DNVGL-OS-B101, ABS, API 5L and NORSOK M-120 could be used for Jack-up rigs, Wind Turbine Installation Vessel and fixed offshore structures. For fixed offshore structures the EN ISO 19902 is the most common one.

For a higher strength and microstructural transformation during the rolling process and heat treatment the elements manganese, chromium, molybdenum or nickel added. Niobium supports a fine grain microstructure and with this good strength and toughness properties. Table 1 shows the chemical analysis of the new alloy developed by Vallourec and the limits for the carbon equivalents CEIIW, Pcm and CET referred in the next chapter (Eqs. 1-3). Due to the applied low carbon concept, the presented alloy shows an optimized as well as a comparatively low carbon equivalent and exceeds the requirements of the standards mentioned.

Table 1. Chemical element limit of the investigated alloy (wt. - %)

C	Si	Mn	P	S	Cr	Cu	Nb, W, Al, N
≤ 0.09	0.10 – 0.45	≤ 1.60	≤ 0.015	≤ 0.005	≤ 0.50	≤ 1.00	alloyed
Ni	Mo				CE_{IIW}	CE_{Pcm}	CET
0.50 - 1.00	≤ 0.50				≤ 0.57	≤ 0.27	≤ 0.34

4 Weldability

Good mechanical properties after welding and weldability in general of base material in combination with high deposit rate welding parameter are essential. For an efficient and optimized fabrication, many parameters have to be taken into account, which lead to a parameter window. This welding parameter window become even narrower if the required mechanical properties are challenging for base and filler material e.g. structures for arctic application or high strength materials.

The major development goal were the improvement of mechanical properties of base material and heat affected zone directly after welding in regard to today used standard welding processes in shipyards for joints. The prediction of weldability is possible by a variety of methods, which are based on e.g. estimation of cooling conditions in conjunction with susceptibility to hardening and cold cracking.

The carbon equivalent CE provides a quantitative value to describe hardening and a tendency towards cold cracking. For the presented low alloyed steel grade in table 1, the CE can be defined as CEIIW and Pcm according to API 5 L, where the latter one is preferred for line pipe applications and with carbon content up to 0.12 wt.-%, Eqs. 1-2 (Ito and Bessyo, 1969).

$$CE_{IIW} = C + \frac{Mn}{6} + \frac{Cr+Mo+V}{5} + \frac{Ni+Cu}{15} \quad (1)$$

$$P_{cm} = C + \frac{Si}{30} + \frac{Mn+Cu+Cr}{20} + \frac{Ni}{60} + \frac{Mo}{15} + \frac{V}{10} + 5B \quad (2)$$

$$CET = C + \frac{Mn+Mo}{10} + \frac{Cu+Cr}{20} + \frac{Ni}{40} \quad (3)$$

4.1 *Welding tests*

For the weldability test of seamless hot rolled circular hollow sections (CHS) the dimensions 323.9 x 27.8 mm and 406.4 x 35.7 mm were chosen. The metal-cored arc welding process (MCAW, 138) was used for the weldability test due to its excellent mechanical properties of the weld material. The chosen welding wires are in accordance to EN ISO 18276-A (T 69 6 Mn2NiCrMo M M 1 H5) and approved for grade S690 / X100 / EQ & FQ70 / NV EO & FO690QT for toughness class F (-60 °C) according to DNVGL-OS-B101 (V Y69MS H5) and ABS (5YQ690SA H5).
All weldability tests performed with a static torch and a rotating positioning table in PA (1G) position. The weld performed perpendicular to the rolling direction. The prescribed joint design of classification society is a half V-bevel type. This joint design enables a better characterization of a straight heat affected zone (HAZ) and fusion line (FL) orthogonal to the rolling surface on the vertical side of the bevel. Due to the root configuration with a root gap and root face of 1.0 – 2.0 mm the welding without a temporary backing was possible. For the investigation of the process window for the welding process, two different heat inputs at the filler passes tested with stringer beads: low heat input with 1.1 kJ/mm, which covers a short cooling time and high heat input with 1.9 kJ/mm, which cover a longer cooling time.

The applied preheating temperature was set to 90 – 110 °C. A higher interpass temperature of 160 °C was not achieved with 1.9 kJ/mm due to the stringer bead technique in combination with the heat input of 1.9 kJ/mm.

4.2 *Results*

Visual, ultrasonic and magnetic particle testing carried out to prove that the weld is free of imperfection. Additionally, macrographs made of each weld at various positions to proof the vertical fusion line without lack of failure – no defects detected.
The main objective of the weldability test for base material is proof of mechanical properties of heat affected zone and base material in dependence on the welding process. Mechanical tests were performed in accordance to EN ISO 4136 for tensile testing, Charpy impact test in accordance to EN ISO 148-1 and EN ISO 9016, hardness measurement in accordance to EN 10225-3 and EN ISO 6507-1 and CTOD test in accordance to BS 7448-1 and EN ISO 15653. The tensile test specimen has to be in the range of minimum 770 MPa to maximum 940 MPa tensile strength according to offshore standards – specimen fulfilled the requirements.

The Charpy V-notch impact test results of the performed tests at cap location are shown in Figure 2. The impact tests performed at -60°C. Therefore, 69J average (continuous line) and min. 48J single value (dashed line) have to be achieved for base material and weld material. The lowest single value of base material was 79J at cap FL+2 of 406.4 x 35.7 mm with 1.9 kJ/mm weldment (see Figure 2). The lowest single value of weld metal was 57J, below the min average but above the allowed min. single value. The min average of 69J was achieved by weld metal generally. The requirements of offshore codes and standards DNVGL-OS-B101, ABS, EN 10225-3 fulfilled in a safe manner.

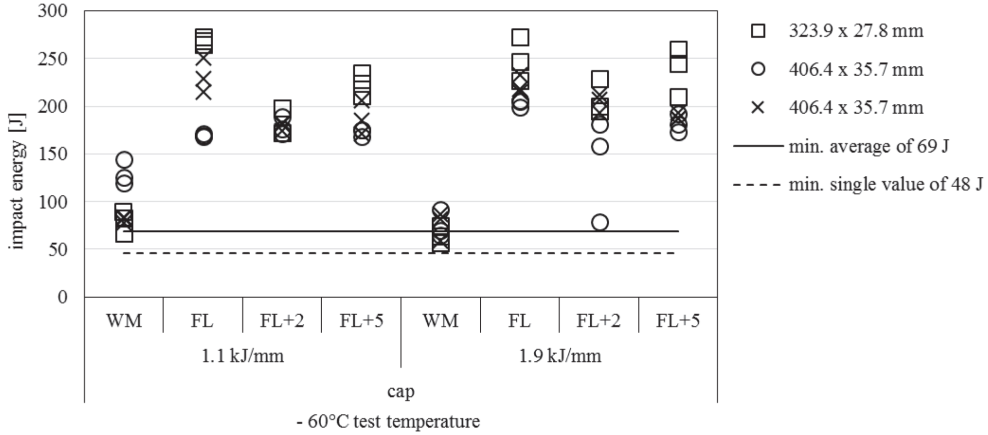

Figure 2. Macrograph of weld with 1.1 kJ/mm (left) and for 1.9 kJ/mm (right)

In addition to the Charpy V-notch impact test all welds have been tested by Vickers HV10 hardness imprints. The tests performed at cap, mid and root location. For steels with a yield strength of minimum 690 MPa are existing different requirements in dependence on the standard. The hardness limits are 400 HV10 acc. to DNVGL-CP-0243, 420 HV10 acc. to DNVGL-OS-C401 and ABS and 450 HV10 acc. to EN ISO 15614-1. In Figure 3 the average values in the cap of all weldability tests are shown – requirements by offshore standards were fulfilled by far.

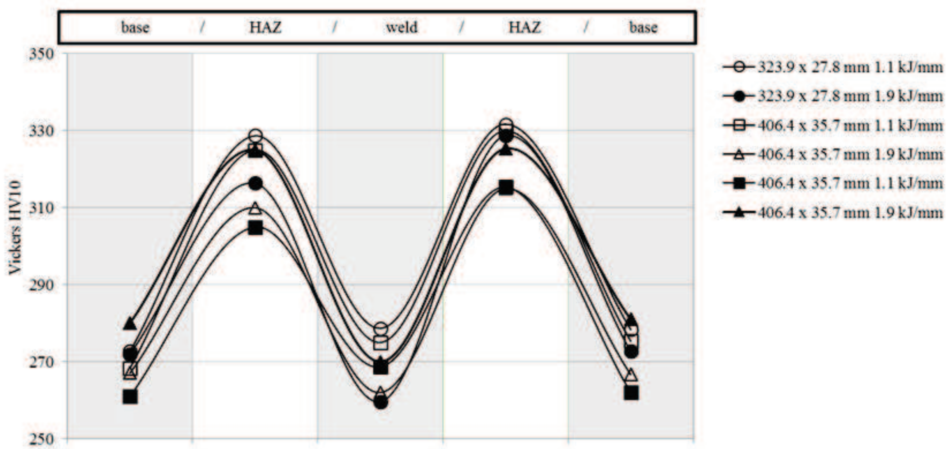

Figure 3. Hardness Vickers HV10 of low and high input weldability tests

Micrographs of one high heat weldability test shown in Figure 4. On the right side in the pictures, the very fine microstructure of heat affected zone can be seen. The dashed line marks the fusion line of weld material and base material. Next to the dashed line the coarse grain heat affected zone is visible. The prior austenite grain boundaries can be seen with individual grain diameter of up to 80 µm on the left figure at the top right corner. But this zone only extends to an area of a few hundred micrometers in width. Comparing this with the structure on the right-hand side of the respective images, the mean grain size of the micro-constituents is in the range of 5 to 20 µm, describing the bainitic sub-units. The fine-grained heat affected zones are adjacent to these areas, are showing even finer grains. The general structure consists of long lathed bainite with some martensitic fractions. In the finer structured zones of the HAZ, the dominant phase fractions are bainite, which supports the good mechanical properties of the new grade even in the welded condition.

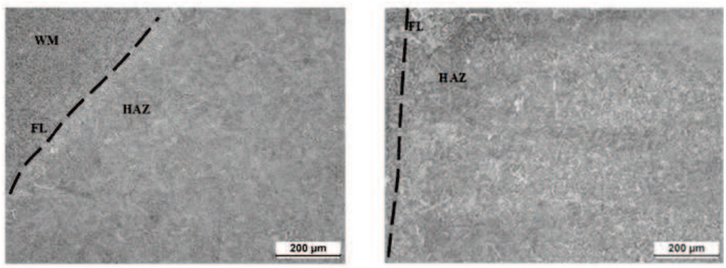

Figure 4. Macrograph of weld with 1.9 kJ/mm at root (left) and cap (right)

The CTOD tests performed on welded joints of the dimension 406.4 x 27.8 & 35.7 mm. A minimum CTOD value of 0.15 mm is defined as qualification criterion and in Figure 5 marked as dashed line. The minimum test temperature is the respective defined service temperature EN ISO 19902 of the application, which is -10°C down to -30°C normally. Due to the pipe and weld geometry the single edge-notched bend specimen (SEB) was choosen. Metallographic investigation after testing confirmed the validity of the pre-crack at coarse grained heat affected zone (CGHAZ) and crack propagation.

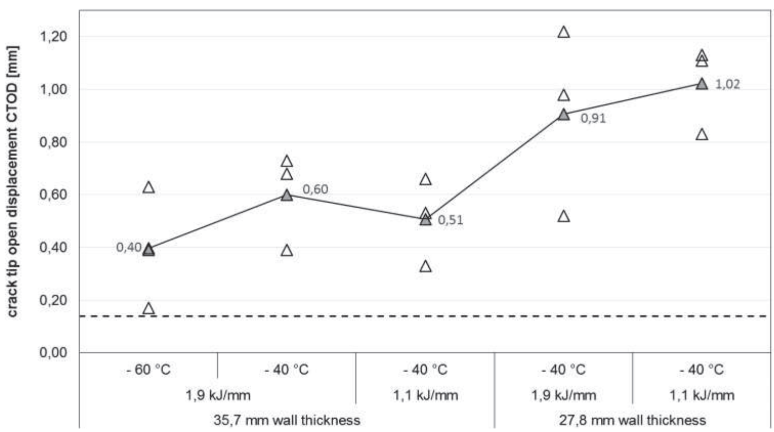

Figure 5. Macrograph of weld with 1.9 kJ/mm at root (left) and cap (right)

4.3 *Comparison of hardness regime at HAZ*

As seen in Figure 3 the bainite alloying concept has a very low hardness regime at HAZ after welding without post weld heat treatment (PWHT). In Table 2 below the carbon content and carbon equivalents listed for different alloying concepts, which were used in 1979, 1990, 1996 and today. The weldability tests of the today used alloying concept and Super Oceanfit® 100 WeldFIT performed with the same welding parameter as described in chapter 4.1. Therefore, a good comparability is given between the state of the art of the today used concept and the new development. In Figure 6 a comparison of today and past used martensitic alloying concepts in comparison with the new developed bainite alloying concept shown. The graphs represent the mean values.

Table 2. Carbon content and carbon equivalent development of 1979 until today

	1979	1990	1996	today	Super Oceanfit® 100 WeldFIT
C in %	0,17	0,20	0,15	0,15	0,07
CEV	1,00	0,73	0,58	0,54	*(0,54)*
P_{cm}	*(0,42)*	*(0,37)*	*(0,29)*	*(0,29)*	0,25
CET	0,49	0,45	0,36	0,35	0,32
heat input in kJ/mm	1,5	1,5	0,8	1,9	1,9

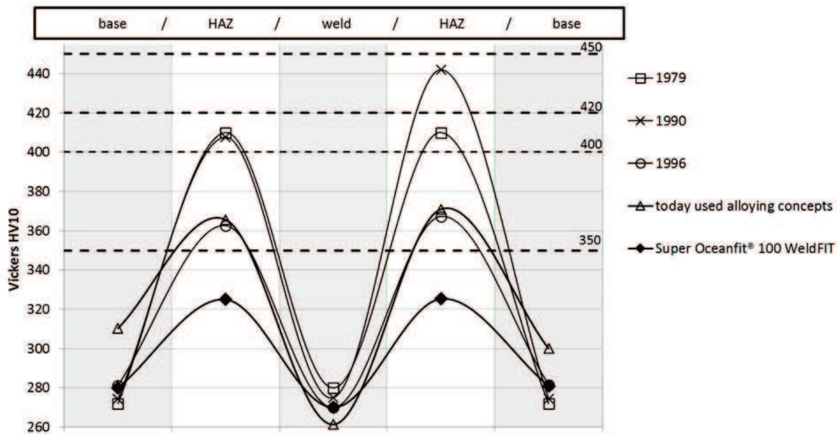

Figure 6. Comparison of Vickers HV10 hardness

The dashed line 450, 420 and 400 are the hardness requirements HV10 of the offshore standards for high strength steel with minimum yield strength of 690 MPa. Additionally, a dashed line 350 is added for the hardness requirements HV10 for steel with minimum yield strength of 360 MPa in accordance to the offshore standards. There the huge difference in the hardness regime in the HAZ of today used martensitic (~370 HV10) and the new developed bainite (~325 HV10) steel can be seen. That mean, that the new developed steel provides a high level of safety in critical environments and provides a wider range of welding parameter compared to today used alloying concepts. The hardness has a significant impact on cold and hydrogen introduced cracking of the weldment.

5 Conclusions

This paper deals with the production of modern high strength steels for special conditions. Today heavy plates with thickness over 200 mm and performing yield strength of 690 MPa are available. Sufficient toughness properties throughout the plate cross-section are available, which can be realized for arctic conditions also. But not only plates also structural seamless hollow sections were developed for this special purpose.

The new innovative and approved alloy for seamless quenched and tempered circular hollow sections in grade X100 / S690 up to wall thickness of 40 mm from Vallourec presented in this paper aims for the increasing demand for steel pipes with high strength and high toughness. A homogeneous fine microstructure and high fracture mechanic result facilitate a safe installation and operation in challenging frontier environments.

The very high toughness even at temperatures of -60 °C and below make these steels particularly suitable for structural applications under arctic conditions but also for fatigue loaded structures in cranes and bridges.

The new steels fulfill the sharp requirements of the offshore classification companies, e.g. API 5L, DNVGL-OS-B101 and ABS as well as the technical specifications of EN 10225-3 by far. This achievement tends to a higher process reliability and further welding process optimization in regard to productivity.

As long as there are no onshore specifications for these modern new steels available it is recommended to use the rules of these companies, which confirm in their certificates the accordance with the relevant offshore rules and standards.

For all aspects of processing the various steels the producers give hints and recommendations which help the fabricators to develop own optimized fabrication procedures. In any case a close contact is suggested before ordering to be sure to get the defined requirements fulfilled.

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