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Challenges and opportunities in the arc welding of offshore steels

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Abstract: Offshore steels are required not only good strength properties but also outstanding toughness at low temperatures to ensure the safety of the structures in an extremely cold environment. The new generations of offshore steels, in the range of S420-S500 range, exhibit remarkable toughness characteristics which must be preserved as much as possible during welding. However, welding processes, can significantly reduce the toughness properties due to the welding heat input. Furthermore, it is a challenge to guarantee the impact energy level in the dendritic, mostly multi-pass weld, is the same as that in the fine-grained and micro-alloyed steel plate, which is rolled through specific rolling processes, including thermomechanical controlled process (TMCP). The welding process and its' parameters, as well as the filler material selection, play a significant role in the formation of an ideal weld and heat-affected zone (HAZ) microstructure with appropriate strength and toughness properties. The effect of microalloying elements on the formation of acicular ferrite (AF) in weld and HAZ has a determining role in terms of the toughness properties. This paper provides a detailed literature review of the characteristics, processing routes and weldability of advanced offshore steels. Gas Metal Arc Welding (GMAW) and Submerged Arc Welding (SAW) are the most frequently used technologies for offshore steels. The research results demonstrate that special attention is needed during the welding process, parameter and filler material selection to ensure the high impact safety of the welded joints under low temperatures.

Keywords: Offshore steel; S500; S420; Arc welding; Toughness; Welding parameter; Welding consumable

1. Introduction

Nowdays, in the field of structural steels the major research focus on the development of high strength steels [1], however there are several industrial areas where other aspects (e.g. toughness, ductility) are even more important than the strength level of the given steel grade. Offshore steels are typically used in applications such as oil drilling platforms, wind turbines or shipbuilding, where service conditions are harsh, and safety of the structures has an extreme importance [2-5]. Due to the unfavorable climate changes the arctic ice has drastically reduced in the past decades, however, it has opened new opportunities for the exploration of raw materials in the arctic regions. The opening of new oil fields and industrial facilities in cold climates increases the demand for steel that can withstand arctic conditions. Steel producers offer various type of steels for offshore industry including normalized (N), thermomechanically controlled rolling processed (TMCP) and quenched and tempered (Q+T) steels [6, 7]. Nonetheless, offshore steels with the highest toughness are typically manufactured by (TMCP) that leads to an extremely fine-grained microstructure. With this steel processing method good strength and toughness in the base plate are obtained, while the low content of carbon and other alloying elements, and thus low carbon equivalent, provides good weldability. TMCP steels have relatively small prior austenite grain size (PAGS), and due to accelerated cooling, a consequent fine-grained ferritic, bainitic or martensitic microstructure, or a complex mixture of these structures form [8]. However, thermal processes, such as welding, can easily deteriorate the mechanical properties by altering the microstructures and introducing harmful microstructural components in the heat-affected zone (HAZ) [8]. Deterioration of toughness in the HAZ for example is a known problem with offshore steels. Furthermore, it is a challenge to guarantee the impact energy level in the dendritic, mostly multi-pass weld, is the same as that in the fine-grained and micro-alloyed steel plate, which is rolled through specific rolling processes. The applied standards [6] have certain acceptance criteria for the toughness properties of the HAZ and the weld, which are typically required to be tested with Charpy V-notch (CVN) impact tests and with fracture toughness tests, such as crack-tip opening displacement (CTOD). In some cases, the evaluation of fracture mechanical investigations can be challenging, since common fracture toughness values are not simple to be determined on smaller specimens due to the ductile behavior of higher strength TMCP steels [9], although the reduction of test temperature may

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*Corresponding author: marcell.gaspar@uni-miskolc.hu increase the evaluation and the reliability of the results.

Present paper aims to provide an overview about the production processes and microstructure of offshore steels, highlighting the challenges and opportunities in the weldability arc welding of these steels.

2. Offshore steels and their characteristics

2.1. Processing routes and grades

The general and well-known production routes (normalizing, TMCP, Q+T) of structural steels are generally used for offshore steels, however these steels need to fulfill special weldability and toughness requirements compared to other applications. The EN 10225-1 standard [6] specifies requirements for weldable structural steels, in the form of plates, to be used in the fabrication of fixed offshore structures. Minimum yield strengths up to 690 MPa are specified together with impact properties at temperatures down to –40 °C. The chemical compositions and mechanical properties of eleven offshore steels are summarized in Table 1 and 2. Among the listed steels one falls into the group of normalized steels, four are TMCP and six are Q+T steels. In their marking O indicates the offshore application. Although the standard does not distinguish the impact energy requirement for these grades, it can be assumed that medium strength TMCP steels have the highest toughness. Based on the material certificates steel plants generally safely overachieve these impact energy requirements. Steel producers have recently highlighted that there is an increasing demand for high strength steels in marine and offshore applications [7]. Nowadays, offshore high strength steels are even available between 620-1300 MPa yield strength and 27-69 J guaranteed impact energy at -40 °C [7]. These grades are generally produced by Q+T. In medium strength categories between 355 and 500 MPa yield strength the offshore steels are mostly produced by TMCP.

Table 1 Chemical compositions (maximum values) of offshore steels based on EN 10225-1 (max. values unless otherwise indicated).

Grade	C	Si	Mn	P	S	Cr	Ni	Mo	N	Al	Cu	Nb	Ti	V	Nb+V	Nb+V+ Ti
S355NLO	0.14	0.55	1.00 1.65	0.020	0.010	0.25	0.70	0.08	0.010	0.015 0.055	0.30	0.050	0.025	0.060	0.06	0.08
S355MLO	0.14	0.55	1.00 1.65	0.020	0.010	0.25	0.70	0.08	0.010	0.015 0.055	0.30	0.050	0.025	0.060	0.06	0.08
S420MLO	0.14	0.55	1.65	0.020	0.010	0.25	0.70	0.25	0.010	0.015 0.055	0.30	0.050	0.025	0.080	0.09	0.11
S460MLO	0.14	0.55	1.70	0.020	0.010	0.25	0.70	0.25	0.010	0.015 0.055	0.30	0.050	0.025	0.080	0.12	0.13
S500MLO	0.14	0.55	2.00	0.020	0.010	0.30	1.00	0.25	0.010	0.015 0.055	0.35	0.050	0.025	0.080	0.12	0.13
S420QLO	0.14	0.55	1.65	0.020	0.010	0.25	0.70	0.25	0.010	0.015 0.055	0.30	0.050	0.025	0.080	0.09	0.11
S460QLO	0.14	0.55	1.70	0.020	0.010	0.25	0.70	0.25	0.010	0.015 0.055	0.30	0.050	0.025	0.080	0.12	0.13
S500QLO	0.14	0.55	1.70	0.020	0.010	0.30	1.00	0.25	0.010	0.015 0.055	0.40	0.050	0.025	0.080	0.12	0.13
S550QLO	0.16	0.55	1.70	0.015	0.005	0.40	1.00	0.60	0.008	0.015 0.10	0.40	0.050	0.025	0.080	0.12	0.13
S620QLO	0.20	0.55	1.70	0.015	0.005	1.00	2.00	0.60	0.008	0.015 0.10	0.40	0.050	0.025	0.080	0.12	0.13
S690QLO	0.20	0.55	1.70	0.015	0.005	1.00	2.00	0.60	0.008	0.015 0.10	0.40	0.050	0.025	0.080	0.12	0.13

Table 2 Carbon equivalents and mechanical properties of offshore steels based on EN 10225-1.

Grade	CEV	R_{eH}	R_m	R_{eH} /R_m max	A	CVN	
		[MPa]	[MPa]	[-]	[%]	°C	J
S355NLO	0.43	355	470-630	0.87	22	-40	50
S355MLO	0.39	355	470-630	0.93	22	-40	60
S420MLO	0.42	420	500-660	0.93	19	-40	60
S460MLO	0.43	460	520-700	0.93	17	-40	60
S500MLO	0.47	500	560-740	0.95	15	-40	60
S420QLO	0.42	420	500-660	0.93	19	-40	60
S460QLO	0.43	460	520-700	0.93	17	-40	60
S500QLO	0.44	500	560-740	0.93	15	-40	60
S550QLO	0.47	550	590-750	0.93	15	-40	60
S620QLO	0.65	620	720-890	-	14	-40	60
S690QLO	0.65	690	770-940	-	14	-40	60

In the following part we will focus mostly on the properties and weldability of TMCP offshore steels since these grades have the wider application potential in disadvantageous environmental circumstances.

2.2. Microstructural characteristics and alloying elements

Medium strength offshore steels have generally a low-carbon, fine-grained, bainitic, partially ferritic microstructure with outstanding toughness properties at negative temperature range [2-4, 10-11]. Nowadays, it is not really a difficult objective for the steel producers to reach outstanding mechanical properties of these steels, however; it is rather a challenge how to develop an offshore steel which can preserve its toughness characteristics in the HAZ. In offshore structures mostly thicker plates are used welded with multipass welding when the combinations of complex HAZ subzones form as it is seen in Figure 1.

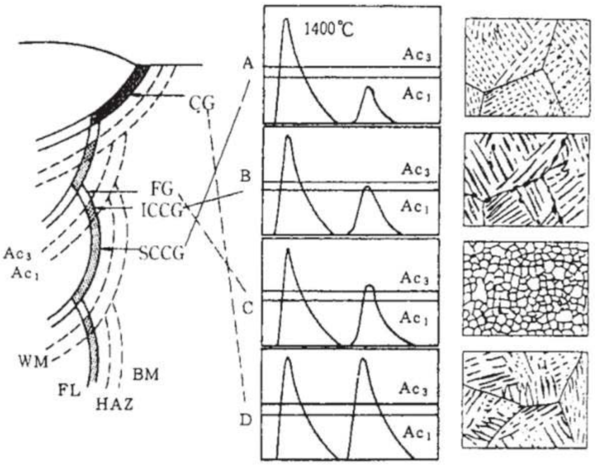

Figure 1 Structure of multipass welded joint and its HAZ [13].

Light optical microscopy (LOM) has previously been used to characterize and quantify conventional steels microstructure; however, bainitic microstructures, typical of these offshore grades, are complex and difficult to characterize accurately by LOM, particularly in multi-pass high-strength steel submerged arc weldments, which possess complicated thermal histories. More advanced techniques, such as electron backscatter diffraction (EBSD), can eliminate some of the ambiguity present in LOM characterization. EBSD allows for the utilization of features such as image quality (IQ) and inverse pole figures [12].

In terms of the toughness properties of welded joints from offshore steels the presence of acicular ferrite (AF) in the welded joint is crucial. In welded joints, ferrite plates growing in many radial directions on small-sized non-metallic inclusions, as crystallization nuclei, can contribute to the improvement of toughness properties due to their heterogeneous structure. Therefore, numerous research deals with the effect of microalloying elements and so inclusions on the formation of acicular ferrite. The schematic representation of acicular ferrite is illustrated in Figure 2 [11].

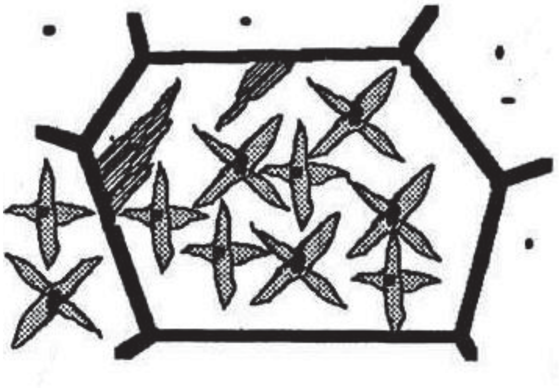

Figure 2 Schematic representation of acicular ferrite (AF) [11].

Henri et al. [2] investigated low-temperature toughness properties of 500 MPa offshore steels and their simulated coarse-grained heat-affected zones (CGHAZ). It was found that both impact and fracture toughness of an S500 offshore steel with coarse titanium-based nitrides were lower and the scatter higher than in the steel with a higher quantity of calcium-based inclusions and without the coarse nitrides. Fractographic examination showed that the failure in the samples with the lowest toughness was initiated by the coarse titanium-niobium nitrides. Thus, to avoid CGHAZ brittleness under cold conditions, it is necessary to mitigate the formation of coarse nitrides by careful control of steelmaking process and continuous casting to avoid the segregation of titanium, niobium and nitrogen.

Acicular ferrite in the HAZ is generally considered beneficial regarding the toughness [3]. Three experimental steels were studied in order to find optimal conditions for the AF formation in the CGHAZ. One of the steels was Al-deoxidized, while the other two were Ti-deoxidized. The main focus was to distinguish whether the deoxidation practice affected the AF formation in the simulated CGHAZ. It was found that AF formed in the simulated CGHAZ of one of the Ti-deoxidized steels and its fraction increased with increasing cooling time. In this steel, the inclusions consisted mainly of small (1–4 µm) TiOx-MnS, and the tendency for prior austenite grain coarsening was the highest.

In another [4] study, the effects of varying fractions of AF (0–49 vol.%) were assessed in the simulated, unaltered and CGHAZ of three experimental steels. Two steels were deoxidized using Ti and one using Al. The characterization was carried out by using electron microscopy, energy-dispersive X-ray spectrometry, electron backscatter diffraction and X-ray diffraction. The fraction of AF varied with the heat input and cooling time applied in the Gleeble thermomechanical simulator. AF was present in one of the Ti-deoxidized steels with all the applied cooling times, and its fraction increased with increasing cooling time. However, in other materials, only a small fraction (13–22%) of AF was present and only when the longest cooling time was applied. The impact toughness of the simulated specimens was evaluated using instrumented Charpy V-notch testing. Contrary to the assumption, the highest impact toughness was obtained in the conventional Al-deoxidized steel with little or no AF in the microstructure, while the variants with the highest fraction of AF had the lowest impact toughness. It was concluded that the coarser microstructural and inclusion features of the steels with AF and also the fraction of AF may not have been great enough to improve the CGHAZ toughness of the steels investigated.

The transformation behaviour of C-Mn-Ti alloyed steel weld metals with different levels of nitrogen and boron contents was investigated by Ilman et al [14]. Results showed that the addition of a small amount of boron, typically 40 ppm to a C-Mn-Ti weld metal was sufficient to significantly reduce the transformation start temperature with a decrease in the amount of grain boundary ferrite and a concomitant rise in the amount of AF. Further decrease in the transformation start temperature was observed as the level of boron content was increased up to approximately 160 ppm resulting in the formation of bainitic microstructure. However, a subsequent addition of nitrogen around 240 ppm to this type of weld metal increased the transformation temperature and modified the weld microstructure marked by the presence of intragranular AF and polygonal ferrite which nucleated on multiphase inclusions principally of the ‘TiO’ type but on which has formed BN. This finding seems to suggest that BN is a potent substrate for nucleating ferrite and the amount of acicular ferrite in Ti-B-N system is controlled by the balance between BN as an energetically favourable site for AF nucleation and soluble boron which acts as a hardenability element suppressing grain boundary ferrite (GBF) formation.

The effects of titanium content on the weld microstructure, mechanical properties, and inclusion characteristics were investigated by Seo et al [15] in the as-deposited bainitic GMA weld metals having nearly constant level of oxygen content. It was found that titanium addition enhanced the formation of AF with the maximum proportion being obtained at ~0.07 wt% Ti. The resultant change in weld microstructure with titanium content was well reflected in the Charpy impact energy showing the lowest ductile-brittle transition temperature at 0.07 wt% Ti. Detailed Transmission Electron Microscopic (TEM) and SEM analysis preformed on weld metal inclusions demonstrated that the maximum AF recorded in this weld is mainly attributable to the formation of manganese-depleted zone (MDZ) associating with the formation of nonmetallic inclusions dominant with Ti_2O_3 phase.

Results of Ilman et al [16] showed that addition of 160 ppm Al to a Ti–B–N weld metal with a low or ‘normal’ N content (designated as N) accelerated the transformation kinetics resulting in acicular ferrite as the dominant microstructure. As the amount of Al was increased to 560 ppm, the transformation was retarded as indicated by its lower transformation start temperature, hence favouring upper bainite. It is interesting to note that N could give a beneficial effect in Ti–B–N weld metals with 560 ppm Al when the amount of N was increased to an intermediate level (N1), i.e. 120 ppm, marked by an increase in the transformation start temperature with upper bainite being replaced by intragranular acicular ferrite. A reversal effect was observed as the N level was increased up to 240 ppm (N_2) where the growth of acicular ferrite had to compete with that of intragranular polygonal ferrite, and the mechanism in which AF develops in Ti–B–Al–N welds is discussed.

3. Weldability and welding technology

Offshore steels have generally low cracking sensitivity, however; these grades need to fulfill special weldability requirements compared to conventional grades to ensure the high impact safety of the welded joints under low temperatures.

3.1. Cracking sensitivity

When the weldability of a given structural steel is investigated, the first step is to analyze its position in the Graville diagram, which separates structural steels into three zones rated by their ease of weldability: zone I easily weldable, zone II weldable with care, and zone III difficult to weld [17]. The diagram highlights that with increasing carbon equivalent the weldability decreases but it also emphasizes the extremely important effect of carbon content on weldability. In Figure 3 the positions of different structural steel grades, including some offshore steels, were determined based on the information provided in the 3.1 type base material certificate of several steel producers according to EN 10204. Based on the diagram, TMCP steels, including S420M and S500M offshore steels, generally falls into the less problematic first area indicating low cold cracking sensitivity, while conventional normalized structural steels fall into the zone II, so they are expected to be welded with higher cold cracking sensitivity and precautions. As we go up to higher categories, some grades of S690QL steels can fall into the riskiest 3rd zone of Graville diagram with the highest crack sensitivity.

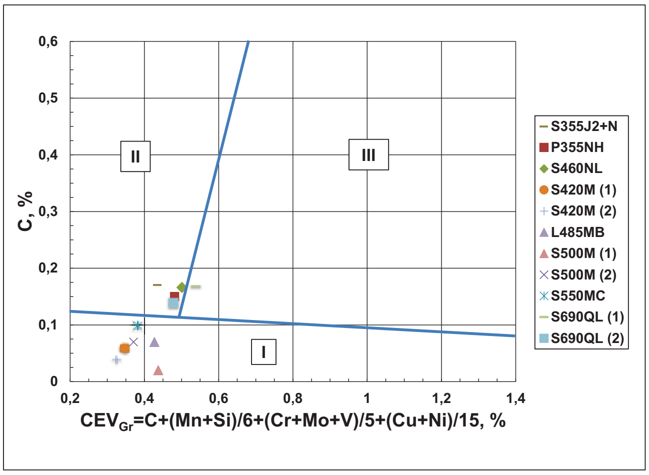

Figure 3 Structural steels including some TMCP offshore grades in the Graville diagram.

Although, in the case of most offshore steels low cold cracking sensitivity can be predicted, it should be careful due to the applied large cross sections in welded structures. Offshore wind turbines (OWT) are a major goal of the energy strategy of Germany encompassing the increase of the installed wind power [5]. OWT components are manufactured from welded steel plates with thicknesses up to 200 mm. The underlying standards and technical recommendations for construction of OWTs encompass specifications of so-called minimum waiting time (MWT) before non-destructive testing (NDT) of the weld joints is allowed. Reason is the increased risk of time-delayed hydrogen assisted cold cracking as hydrogen diffusion is very slow due to the very thick plates. The strict consideration of those long MWT up to 48 h during the construction of OWTs leads to significant financial burden (like disproportionately high costs for installer ships as well as storage problems (onshore)). In this study [5], welded joints made of S355 ML were examined in comparison with the offshore steel grade S460 G2+M. The aim was to optimize, i.e., reduce, the MWT before NDT considering varied heat input, hydrogen concentration and using self-restraint weld tests. This would significantly reduce the manufacturing time and costs of OWT construction. To quantify the necessary delay time until hydrogen-assisted cold cracks appear, acoustic emission (AE) analysis was applied directly after welding for at least 48 h. Welding defects mainly occurred in the start and end of the welds. Scanning Electron Microscopic (SEM) tests proved the cracks found by NDT and metallographic examination to be hot cracks. These hot cracks acted as initiation sites for hydrogen-assisted cold cracking (HACC), seen by a brittle trans-granular fracture surface emanating from the hot crack. As these HACC were triggered by hot cracks in the end crater of the first pass, they possibly would not have occurred in a hot crack free weld. All relevant AE signals appeared within a timeframe of maximum 14 h after welding. That means the MWT (min. 48 hours) in the standards is perhaps too conservative. Nonetheless, further investigations are necessary to validate the experimental results from this study.

3.2. Welding technology and requirements

According to EN 10225-1 the offshore steels are typically required to be weldable using Submerged Arc Welding (SAW) and Gas Metal Arc Welding (GMAW), although other arc welding processes as self-shielded tubular cored arc welding (FCAW-S) and Shielded Metal Arc Welding (SMAW) can be also used if there is an agreement between the purchaser and the manufacturer. The Annex B of the given standard summarizes the requirements for the weldability testing and mechanical testing of butt welds. The manufacturer shall submit detailed welding procedure specification in accordance with EN ISO 15614-1 [18]. During the welding procedure tests the grades of offshore steels, listed in Table 1 and 2, can be classified into the 1st, 2nd and 3rd group of CEN ISO/TR 15608 [19].

Considering EN 10225-1 weldability tests are required in all as-welded condition of GMAW and FCAW-S joints of offshore steels (Table 1 and 2) with 0.8 ±0.2 kJ/mm welding heat input. For post-weld heat treated (PWHT) condition these tests are not required. In the case of SAW the weldability tests are required for both conditions at 3.5 ±0.2 kJ/mm welding heat input. The effect of higher 5.0 kJ/mm welding heat input should be also investigated for S355 and S420 offshore categories in as-welded and PWHT condition. The generally required minimum interpass temperature in 150 °C while the maximum is 250 °C, although other requirements can be set, if necessary. For welding heat input of 3.5 kJ/mm for S620 and S690 grades lower values can be also adopted as the discretion of the manufacturer.

The test piece thickness shall either correspond to the maximum thickness of material to be supplied. The direction of welding for plates shall be parallel to the principal direction of rolling. The width of the welded test piece shall not be less than 500 mm or 10 times the thickness, whichever is greater, to a maximum of 750 mm. In terms of the bevel details for all test welds a square-edge weld preparation shall be adopted for one side of the preparation in order to facilitate the production of a straight fusion line (FL) and HAZ normal to the rolled surface (Figure 4). The preferred weld preparation for the other side of the preparation is a single bevel having an angle of not greater than 45°. The root gap shall not exceed 10 mm.

Related to Charpy V-notch impact tests one set of three tests per position should be tested at −40 °C. The samples positions and impact energy requirements generally differ from the welding procedure test of EN 15614-1 for conventional structural steels. The sample positions should be transverse to rolling direction; FL-2, FL, FL+2 and FL+5 on specimens from cap, mid-thickness and root from the straight edge (Figure 4). For S355 grades a minimum average of 36 J and a minimum individual value of 26 J is required; for S420 grades a minimum average of 42 J and a minimum individual value of 29 J, for S460 grades a minimum average of 46 J and a minimum individual value of 32 J. For S500 to S690 grades a minimum average of 46 J and a minimum individual value of 32 J.

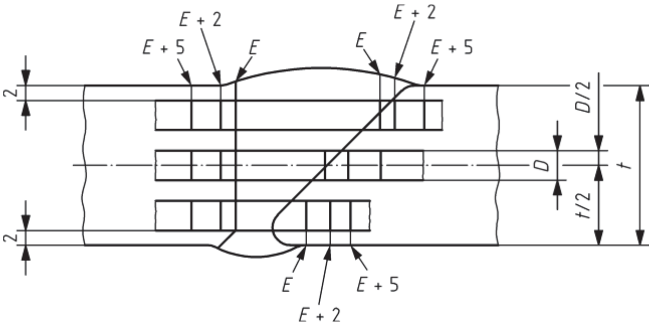

Figure 4 Location of Charpy V-notch impact test specimens.

The fracture mechanical tests including the sample location (transverse to rolling direction) should be performed also in accordance with the presence of critical HAZ subzones (CGHAZ, SCHAZ/ICHAZ boundary, weld metal) of multipass welded joints. Three tests per position should be performed at -10 °C.

Related to macro/hardness and tensile tests the requirements are systematically in accordance with the EN ISO 15614-1 and the generally referred materials testing standards. The manufacturer shall carry out CTS (Controlled thermal severity tests) tests to assess the susceptibility of the material to HACC of the HAZ.

The influence of interpass temperature on the microstructure and mechanical properties of multi-pass weld joints (up to 36-mm thickness) by submerged arc welding (SAW) was studied in [21] from the perspective of offshore engineering. Optimal mechanical properties were obtained with the interpass temperature of ~130 °C. Decreasing interpass temperature from 130 to 80 °C increases the strength and hardness at the cost of impact toughness of the weld joint due to the formation of hard phases including bainite and martensite. Increasing the interpass temperature from 130 to 250 °C promotes a larger volume fraction of coarse martensite-austenite (M-A) constituents and larger interspacing of high-angle boundaries, which, in turn, deteriorates the toughness. In addition, a large amount of M-A constituent necklacing prior austenite grains was observed in the reheated zone of all weld metals and was responsible for the low impact energy of the weld joint.

3.3. Filler materials

In terms of the applicable filler materials the high Charpy impact energy values at negative temperature is indispensable for offshore steels. Only welding consumables, which have previously demonstrated consistently high fracture mechanic values at −10 °C, shall be used [6].

In Sainio’ s work [8] two S420 grade offshore steels were subjected to multi-pass welding with varying welding parameters and consumables. The aim was to investigate how the welding parameters influence on the toughness properties of the HAZ and how different welding consumables with varying chemical compositions affect to the toughness properties of the weld metal and HAZ. The toughness of the weld metals and HAZs are investigated using instrumented CVN, and CTOD tests. Due to similarities in the microstructures and M-A fractions in the HAZs of the multi-pass regions, the changes in the welding parameters did not have significant effect on the toughness properties of the weldments. All the welding parameter combinations showed good toughness properties in dynamic impact and quasistatic loading situations. The different welding consumables (ESAB filler OK Autorod 13.27 and flux OK 10.62, Lincoln filler LNS 165 and flux P240, Bavaria filler BA-S2Ni3 and flux BF 10 MV and Nippon filler Y-204B and flux NB-250H.) produced different weld metal microstructures, ranging from fully AF to almost fully GBF with FSP (ferrite side plate). Consumables produced weldments that had good fracture toughness, however, when the weld metal microstructure was mainly AF, the fracture path deviated towards BM in CTOD test and, hence, the significance of these results is hard to evaluate without knowing what regions have been sampled. With smaller plate thicknesses the weld bead placement affects the straightness of the FL and to the sequences of the reheated regions in the WM and similarly in the HAZ of the BM. The straightness of the FL affects the placement accuracy of the CTOD or CVN specimen, which emphasizes the sampling effect. Overall, impact toughness was at relatively high level with all the welding consumables, regardless of the uncertainty about what regions have been sampled, due to the irregularity in the weld bead placement and undulating FL.

3.3. Post-weld treatment techniques

The post-weld treatment techniques in structural steels can be classified into weld geometry improvement methods and residual stress methods. The modification of weld geometry can lead to improved fatigue resistance of the welded joints. The geometry can be modified by machining methods (e.g. grinding), remelting methods (e.g. TIG/Plasma/Laser dressing) and special welding techniques (e.g. weld profile control). The residual stress methods can be divided to mechanical (e.g. peening, overloading) and thermal technologies (e.g. stress relieving).

In offshore steel structures due to the generally larger cross sections PWHT is often required in order to reduce residual stresses and to increase the weld and HAZ toughness. Furthermore, it can be advantageous in terms of HACC, although the most of offshore steels have low cold cracking sensitivity (Figure 3). According to EN 10225-1 in the case of S355NLO, S355MLO, S420MLO, S460MLO and S500MLO grades after welding, test welds which are to be tested in the PWHT condition shall be post-weld heat treated at either (580 ± 20) °C or at another temperature to be agreed by the purchaser and the manufacturer. They shall be subjected to a soaking period of either not less than 1 h per 25 mm thickness of plate or 4 h, whichever is the greater. Heating and cooling rates shall be in accordance with the following: The rate of heating shall not exceed (5 500/t) °C/h or 55 °C/h, whichever is the greater, where t is the plate thickness in mm. Test welds shall be cooled to a temperature of 400 °C at a rate not exceeding (6 875/t) °C/h or 55 °C/h, whichever is the greater. Below 400 °C, plates may be cooled in still air. For the Q+T offshore steel grades, where applicable, PWHT shall be within the temperature range 550 °C to 620 °C, with a maximum temperature of 25 °C below the tempering range on the test certificate, for either 1 h per 25 mm thickness of plate or 4 h, whichever is the greater. Heating and cooling rates shall be in accordance with normalized and thermomechanically rolled grades.

When considered necessary, dehydrogenation of as-welded test pieces shall be carried out by a low temperature heat treatment, prior to fracture mechanic testing. The use of any dehydrogenation treatment shall be declared with the test results. Heat treatment conditions of 150 °C for 48 h are recommended, and the exact parameters shall be notified with the fracture.

4. Conclusions

Based on the performed review the following conclusions can be drawn regarding the welding and weldability of offshore steels.

1. Nowadays, offshore steels are produced by normalizing (N), thermomechanically controlled process (TMCP) and quenching and tempering (Q+T), although TMCP steels of the medium strength range have the higher toughness due to their low carbon bainitic-ferritic microstructure.
2. New generations of TMCP offshore steels have low cold cracking sensitivity, therefore the Non-Destructive Testing (NDT) requirements for the minimum waiting time (MWT) might be modified in the future after further investigations.
3. The circumstances of the formation of acicular ferrite (AF) and the role of microalloying elements (Ti, Al, N, B) in its formation is determining in terms of the weld and heat-affected zone (HAZ) toughness.
4. Submerged Arc Welding (SAW) and Gas Metal Arc Welding (GMAW) are the most frequently used joining methods for offshore steels. Special requirements for Charpy V-notch impact (CVN) testing and fracture mechanical tests should be followed in order to guarantee an acceptable toughness level is the weld and HAZ.
5. Special attention is needed during the welding process, parameter and filler material selection to ensure the high impact safety of the welded joints under low temperatures.

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