The International Journal Of Engineering And Science (IJES)
|| Volume || 3 || Issue || 5 || Pages || 62-69 || 2014 ||
ISSN (e): 2319 – 1813 ISSN (p): 2319 – 1805

Weldability Of Thermo-Mechanically Rolled Steels Used In Oil And Gas Offshore Structures

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--ABSTRACT--
A major consideration in the construction of offshore structures is the ability to produce sound weld. The harsh conditions of offshore environments impose additional demands on the weldability and weld quality. This paper proposes possible solutions to achieve high quality welds that are almost or totally free from weld defects. The objective of the study is to determine how to control the alloying element content of structural steels within lower and upper limits to ensure the desired hardenability of the steel. The use of a cooling rate suitable for production of the desired hardenability is fundamental to favorable outcomes. The study analyses the effect of chemical composition and cooling time of the welded structure on weld quality and susceptibility to cracking. Such knowledge will enable control of the alloying elements and the cooling rate such that a weld heat affected zone (HAZ) with a suitable microstructure and minimal or no weld defects can be obtained, ensuring a high quality weld for steels with high strength and toughness. A carefully controlled alloying element can enable the use of welding process with high heat input, which can result in increased productivity.

KEYWORDS : *Alloying elements, Cooling rate, Heat input, Weldability, Weld defects*

Date of Submission: 2 May 2014 Date of Publication: 20 May 2014

I. INTRODUCTION

Rising demand for oil and gas coupled with depletion of easily exploitable reserves has made it necessary for oil and gas industries to explore hitherto-unexploited offshore environments. Although such offshore environments possess huge potential, the energy industry faces considerable challenges posed by the difficult and harsh conditions of the marine environment. A major problem confronting construction of offshore structures is the ability to produce a sound weld that can withstand the harsh environmental conditions. This paper reviews the performance of typical offshore steels with improved weldability. Thermo-mechanically rolled steels with reduced carbon content down to 0.08% makes it possible to achieve good weldability, toughness and strength for high strength steels used in offshore applications. Importantly, optimal welding procedures should be strictly followed. The fabrication process is important in achieving a sound weld that is free of weld defects such as hydrogen induced cracking, lamellar tearing and solidification cracking.

II. STRUCTURAL STEELS AND THEIR CHEMICAL COMPOSITION

The various types of structural steels are classified according to the European standard EN 10020 based on their chemical composition and application characteristics. These classes include carbon-manganese steels, high-strength low-alloy (HSLA) steels, and high-strength quenched and tempered alloy steels. HSLA steels are a recent development where the aim has been to increase the strength of steels by the addition of chemical elements such as in Table 1 below. Thermo-mechanically rolled HSLA steels for offshore applications have improved weldability and toughness [1]. To alter the characteristics of a particular steel with the aim of achieving a desired result for welded joints, the alloying elements of these steels have to be controlled. Table 1 shows the effect of alloying elements in steels. In addition to the various alloying elements listed below, traces of other elements, such as phosphorus and sulfur, can be found as impurities. The lower the presence of these impurities, the better the quality of the weld that can be achieved. Such impurities can reduce the toughness and ductility of the base material. The maximum limit of phosphorus and sulfur in steels should be 0.02% to achieve a better weld quality [2].

Table 1. Alloying element of steel and their effect [2].

S/No	Alloying element	Min.(%)	Max.(%)	Effect of the alloying element
1	Carbon	0.03	0.20	It increases the strength of the base material and consequently decreases the toughness.
2	Aluminum	0.01	0.08	It acts as a deoxidizing element. An excessive amount reduces the toughness of the base material.
3	Copper	0.1	1.5	It helps to improve the hardenability of the base material and HAZ.
4	Molybdenum	0.05	0.1	It helps to improve the hardenability of the base material and HAZ.
5	Silicon	0.6	2.0	It helps to improve the fatigue strength of steel by inhibiting dislocation motion and fatigue cracking.
6	Titanium	0.005	0.05	When titanium is combined with nitrogen, it refines the HAZ micro-structure, which consequently improves the toughness of the HAZ.
7	Nickel	0.1	3.0	It helps to improve the hardenability of the base material and HAZ. An excessive addition will result in the formation of low bainite and martensite, and consequently reduces the toughness of the HAZ.
8	Vanadium	0.01	0.10	It helps to improve the hardenability of the base material and HAZ. An excessive addition will result in the formation of low bainite and martensite, and consequently reduces the toughness of the HAZ.
9	Manganese	0.6	2.0	It increases the strength of the base metal without significant loss of toughness.
10	Boron	0	0.0020	It improves hardenability and simultaneously slows down the formation of grain boundary ferrite, which is a site for fatigue cracking.
11	Chromium	0.1	1.0	It helps to improve the hardenability of the base material and HAZ. An excessive addition will result in the formation of low bainite and martensite, and consequently reduces the toughness of the HAZ.
12	Niobium	0.005	0.06	It improves the strength and the hardenability of the base material at the same time.
13	Calcium	0.0005	0.0050	It helps remove sulfide, which is a fatigue crack source, and this helps to improve the ductility. An excessive amount decreases the toughness of the base material.
14	Nitrogen	0.002	0.008	It is combined with titanium to slow the growth of austenite grains in the HAZ. An excessive amount will lower the HAZ toughness.
15	Rear earth metalREM	0.0005	0.0050	It helps remove sulfide, which is a fatigue crack source, and this helps to improve the ductility.

III. WELDABILITY OF STRUCTURAL STEELS

The weldability of a material by DIN8528-1 is described by three variables, as shown in Fig.1 below. These variables are the materials to be welded, the influence of the manufacturing process, and the design of the material to be welded. The welding criteria in DIN8528-1 are of equal importance when considering a welding procedure [3]. Steels with good strength properties and toughness during service life are considered to be weldable. A fusion welded material with high tendency to form hard and brittle areas in the HAZ with a susceptibility of defects being formed, such as hydrogen induced cold cracks, lamellar tearing, stress relieve cracks and solidification cracks, is classified as having a poor weldability [4]. A sound weld can be achieved by good weld preparation and minimization of defects caused by the welding operator, such as lack of penetration or fusion. However, factors such as extremes in heating, cooling and stress lead to difficulties in achieving quality welds. Microstructural changes and environmental effects during welding are further problems associated with the quality of the welded joint and this can lead to joint cracking [4]. Problems associated with the weld metal HAZ can be addressed by changing the electrode and base metal, or by changing the heat input. However, such solutions incur additional cost and expenses. To calculate the weldability of a base material, the IIW has published a parameter called carbon equivalent (CE), as shown in eq. (1). In Japan, the Ito-Bessyo composition characterizing parameter (P_{cm}), shown in eq. (2), is also used. The carbon equivalent was initially used to characterize the hydrogen cracking tendency of steels but is now also used to assess the hardenability of the steel based on their alloying elements [5].

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

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

The effect of CE on weldability and procedures to improve the weldability of steel at different CE range is described below [5]:

- Steels having CE less than 0.4% have excellent weldability. However preheating is necessary to remove moisture.
- Steels with CE between 0.41% and 0.45% have good weldability. The steel should be preheated and the use of low hydrogen electrodes is advisable.

- Steels with CE between 0.46% and 0.52% have fair weldability. To achieve an improved weld quality, the steel should be preheated, use of low hydrogen electrode is required, and the interpass temperature should be controlled.
- Steels with CE greater than 0.52% have poor weldability. The procedure for achieving good quality involves preheating, the use of low hydrogen electrodes, control of the interpass temperature, and post weld heat treatment.

The carbon equivalent P_{cm} gives information about susceptibility to cold cracking. As can be seen from eq. (2) above, boron (B) creates the highest susceptibility to cold cracking. This means that the higher the coefficient of B, the more susceptible the steel is to cold cracking. To improve the fatigue strength of a weld, B has to be limited to ensure good weldability. To achieve a weld with sufficient high strength and toughness without cold cracking, each alloying element in the weld metal should be between the lower and upper limits shown in Table 1. A P_{cm} value less than 0.23% will lead to low strength of the weld metal. If the P_{cm} value is greater than 0.35%, the weld metal will have a toughness that is not sufficient to prevent cold cracking. It is therefore recommended that the P_{cm} value should be between 0.25% to 0.30%. However, having a P_{cm} within the recommended range is not enough to avoid cold cracking. The cooling time t of the weld metal to 100 ^{0}C after welding should be controlled so as to be in the range of eq. (3) shown below [6].

(3) $$T \text{ (seconds)} \geq \exp(7{,}0 \times P_w + 4{,}66)$$

(4) $$P_w \text{ (weld crack susceptibility index)} = P_{cm} + HD/60$$

HD is hydrogen content. If the HD is not greater than 4ml/100g, the cold cracking susceptibility will be low. However, the HD varies for different welding process and conditions. The use of submerged arc welding (SAW) helps to absorb moisture with the flux and thereby picks up hydrogen that may enter the weld metal [6].

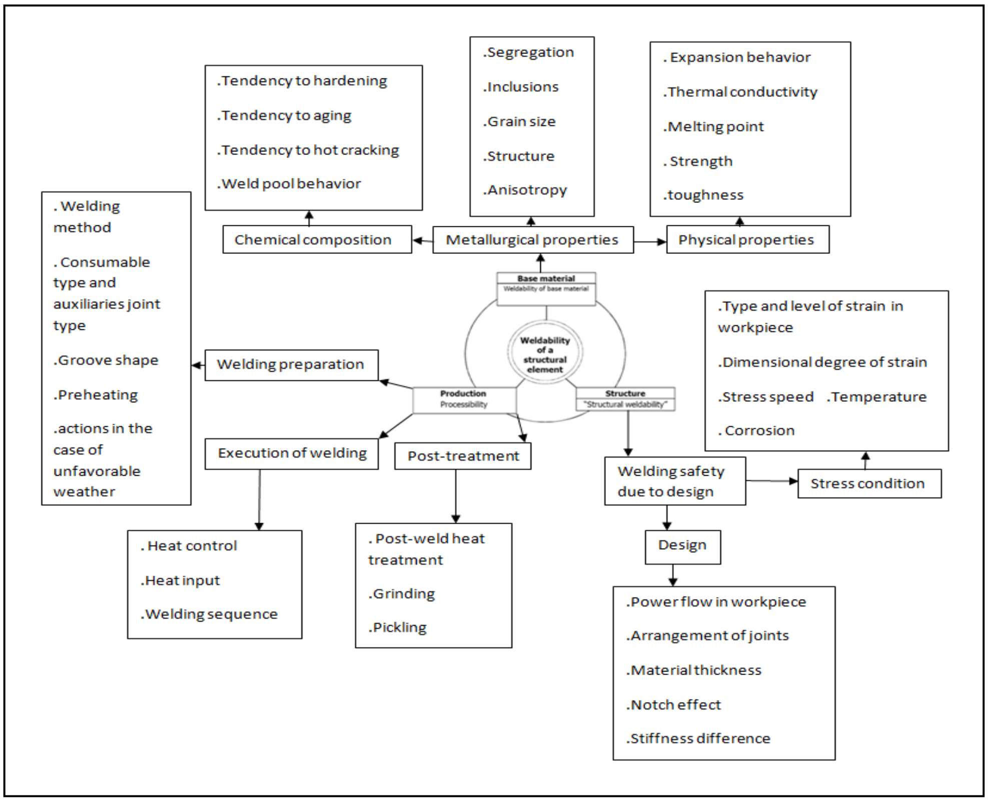


Figure 1. Weldability components adapted from DIN8528:1973 [3].

HARDENABILITY: The property of steels can be harden to a certain depth during quenching is known as hardenability. This property of steel is directly related to the strength of the steel, toughness and fatigue strength. Changes in hardenability of steel are achieved by quenching the steel from the austenizing temperature. Hardenability is dependent on the composition of the steel, and therefore alloy selection is very important in achieving the desired strength. Austenite grain size and the composition of the steel are functions of hardenability. The grain size is important in determining the cooling rate, and alloying elements that decrease ferrite and pearlite reactions increase hardenability. The hardenability of steel can be measured with the Jominy end quench test. The end quench curve is of vital importance in the alloy selection of steel [7]. Hardenability measurement helps in selection of an optimum steel and processing method that enhances welding quality

IV. CAUSES AND REMEDIES FOR CRACKING

The major challenge faced in welding is the ability to produce welded joints that are free from weld defects. The soundness of a weld is determined based on the level of defects that is present in the weld. Defects are classified into two major classes: defects formed during the welding process and defects which are present in the material as a result of the steel making process, the chemical composition and the mechanical properties of the metal. Defects which occur as a result of the welding process are grouped into external and internal weld defects. Defects resulting from the material itself are grouped into the categories of hot cracks, cold cracks and cavities within the weld metal [8]. Classification of major defects affecting the weldability of structural steels is presented in Fig. 2. Depending on the CE, different measures should be taken to avoid cracks in the weld and to achieve a sound weld. Low carbon content will lead to hardness below the critical level. High carbon content will lead to hardness above the critical level. If the carbon content is medium and the steel is slow cooled during the heat treatment, hardness will remain below the critical level. If the steel is fast cooled, hardness above the critical level ensues. Low hardness will in most cases have a low cracking tendency. Hardness above the critical level will have a high cracking tendency if there is no preheating and if there is high hydrogen content. However, if the steel is preheated and there is a low hydrogen content, a low risk of cracking can be achieved. The Fig. 3 below illustrates how to achieve improved HAZ toughness of a welded joint.

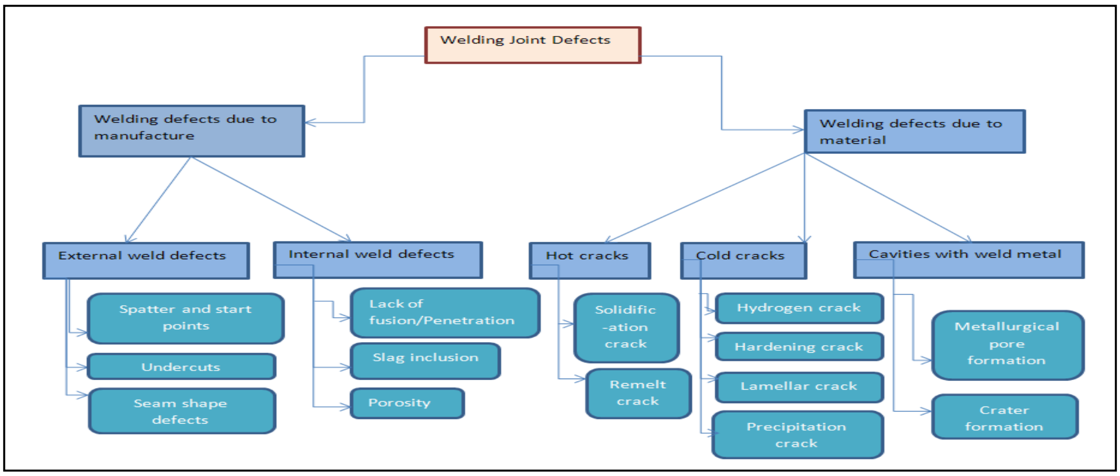


Figure 2. Weld defect classification [8].

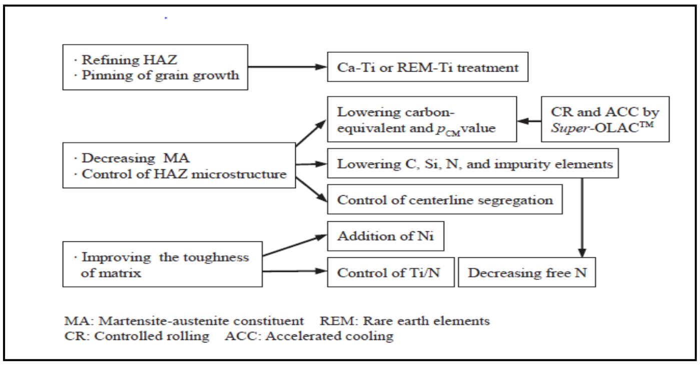


Figure 3, Improving heat affected zone (HAZ) toughness [9]

V. WELDING HEAT INPUT

The heat supplied by the welding process that affects the cooling rate and the weld metal microstructure is termed the heat input. The heat input affects the toughness of the weld metal as well as the weld bead size. An increase in the weld bead size leads to a corresponding increase in the heat input and a slower cooling rate. The heat input Q can be calculated with the formulae in eq. (5) or (6) below [10].

(5) $$Q = \frac{k \times U \times I \times 60}{v \times 1000}$$

(6) $$Q = K \times E$$

Where U = Voltage (V); I = Current (A); v = Welding speed (mm/min); k = Thermal efficiency of the welding process and E = Arc energy (kJ/mm). The thermal efficiency for different welding processes are 0.8, 0.8, 1.0, and 0,6 for SMAW, GMAW, SAW, and GTAW respectively [14]. SAW is the most applicable welding process for thick sections, since the k factor is 1.0 and the heat input for the process can be increased [10, 11].

The recommended upper limit of heat input for the different steel delivery conditions are 3.5 kJ/mm, 5.0 kJ/mm, and 3.5 kJ/mm for normalized, thermo-mechanically rolled, and quenched and tempered steels respectively [4]. Based on the recommended heat input, the cooling time can be calculated with the formulae in eq. (7) or (8). The cooling time of a welded joint is a characteristic determinant of the properties of the welded joint. The duration of the cooling time is determined by the heat input, plate thickness, joint type, and working temperature. A short cooling time gives rise to a low transition temperature and favors weld toughness properties. A longer cooling time results in low hardness and high transition temperature, which gives rise to low weld toughness. To achieve a weld with optimum properties, the cooling time should be within the range II as shown in Fig. 4 [12].

The cooling time for two-dimensional heat conduction for thin plate is calculated with eq. (7) below [12].

(7) $$T_{8/5} = (4300 - 4.3{*}T_0){*}10^5{*}\frac{K^2{*}E^2}{d^2}{*}[(\frac{1}{500 - T_0})^2 - (\frac{1}{800 - T_0})^2]{*}F_2$$

The cooling time for three-dimensional heat conduction for thick material is calculated with eq. (8) below [20].

(8) $$T_{8/5} = (6700 - 5{*}T_0){*}K{*}E{*}[(\frac{1}{500 - T_0}) - (\frac{1}{800 - T_0})]{*}F_3$$

Where $t_{8/5}$ = Cooling time between 800 – 500 ^{0}C; T_0 = Working temperature (^{0}C); d = Workpiece material thickness (mm); F_2 = Joint type factor in two-dimensional heat conduction as shown in Table 2 below; and F_3 = Joint type factor in three-dimensional heat conduction as shown in Table 2 below.

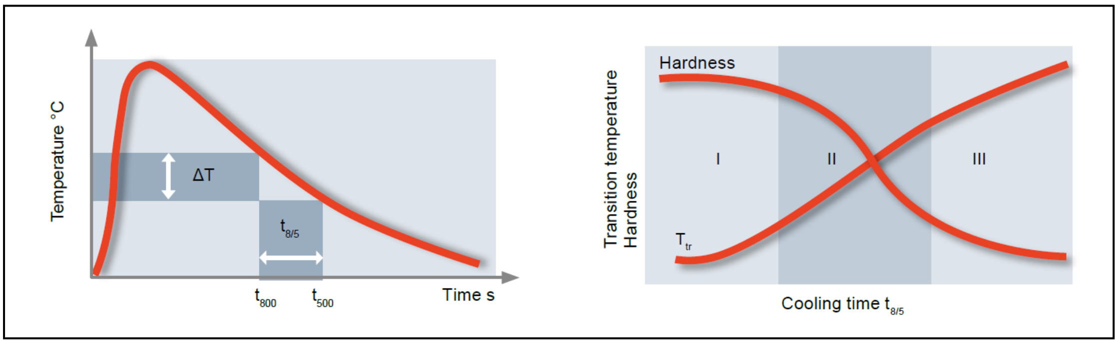
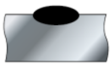
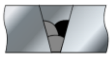
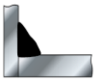
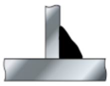


Figure 4. Cooling time $t_{8/5}$ and its impact on HAZ hardness and impact strength transition temperature [12].

Table 2. Influence of the type of joint [12].

Type of joint		F_2 two-dimensional heat flow	F_3 three-dimensional heat flow
Run on plate		1	1
Between runs in butt welds		0.9	0.9
Single run fillet weld on a corner-joint		0.9 to 0.67	0.67
Single run fillet weld on a T-joint		0.45 to 0.67	0.67

VI. DISCUSSION

The strength and HAZ hardness of welds are determined by the hardenability of the steels used. Alloyed steels with low carbon content will lead to low HAZ hardness because of the low carbon content. However, they will produce a wide HAZ because of high hardenability of alloyed steels. According to Maynier et al [13], carbon equivalent is an index of hardenability, and the critical cooling rate to achieve a fully martensitic structure is evaluated by hardenability. However, the formulae holds for heat treatment of steel but not for welding of steels. In determining the weldability of steels, the maximum HAZ hardness is of vital importance and formulae have been proposed that explain the relationship between steel chemical composition and welding conditions. In many of the formulae proposed, a cooling time of 800 ^{0}C and 500 ^{0}C has been adopted, which is the period of the start to the end time of the phase transformation of most ferritic steels [13]. The desire to produce sound and reliable joints has led manufacturers to use normalized offshore steels instead of conventional steels. The carbon content for such normalized offshore steels is reduced from typically 0.18 % to 0.12 % and the trace and microalloying elements are also reduced. Impurities such as oxygen, nitrogen, and sulfur are reduced, which gives a good HAZ and good base material properties, especially toughness [4]. The use of thermo-mechanically rolled steels makes it possible to reduce the carbon content to 0.08 % as a result of the grain refinement of such steels [4]. Examples of steels with carbon content of 0.08 % are S355G8+M and S460G2+M with CE of 0.35 and 0.40 respectively. The weldability of these steels is improved and the steels are suitable for offshore application because of their improved weldability and toughness. The transformation characteristics and the material properties of a steel grade can be determined from HAZ hardness measurement. The application of different heat input leads to different cooling rates. The hardness characteristics for low heat input welding, such as FCAW and laser welding, which have short cooling time, is a function of carbon content, which is important in martensite formation. However, for high heat input welding, the hardness characteristics are influenced by the alloying content, as in the case of high alloyed steels such as S460N and S690Q. However, due to the chemical composition of S460G2+M, the hardness can be kept almost 100 HV lower compared to S460N [4]. Fig. 5 below shows the comparison of hardness versus $t_{8/5}$ cooling time for different grades of offshore steels. In an attempt to avoid weld defects such as hydrogen induced cold cracking, preheating and minimum interpass temperature control are needed. However, these are expensive, difficult to control in the yard and time consuming. Steels such as S355G8+M and S460G2+M with lower carbon content have a less brittle and less hard HAZ. A preheat temperature of 70 ^{0}C is needed for each 0.01% increase in carbon content if the preheat for thermo-mechanically rolled steel having carbon content of 0.08 % is compared to normalized steel having carbon content of 0.18 % according to CET (DIN EN 1011) formulae as shown in eq. (9) below.

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

(10) $$T = 700\ CET + 160\tanh(t/35) + 62\ HD\ \exp 0.35 + (53\ CET - 32)\ Q + 330$$

CET is a carbon equivalent that is commonly used to characterize the susceptibility of steel to cold cracking. From the formulae, we can see that carbon is detrimental for cold cracking. The lower the carbon content, the less hard and less brittle is HAZ. Where T is preheating temperature. Preheating involves heating the base metal either entirely or just around the joint to a specific temperature; and t = Plate thickness (mm). A comparison of calculated preheat as a function of plate thickness for combined heat input and hydrogen level for different steel grades is shown in Fig. 6. Practical examples of thermo-mechanically rolled steel plates welded without preheating and where good weld joint quality were achieved can be seen in the S355M plate of 120 mm thickness used for the Maeslantkering storm surge barrier close to Rotterdam and S420M and S460M plates up to 50 mm welded with FCAW process. The sound weld is achievable without preheating because of the optimized chemical composition of the thermo-mechanically rolled plate and having a clean and dry surface [4].

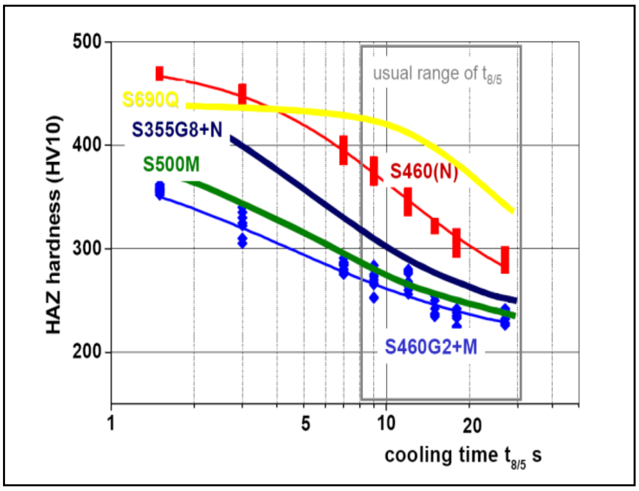


Figure 5. Bead on plate HAZ hardness for various steels As a function of weld cooling time measured in the as-Welded condition [4].

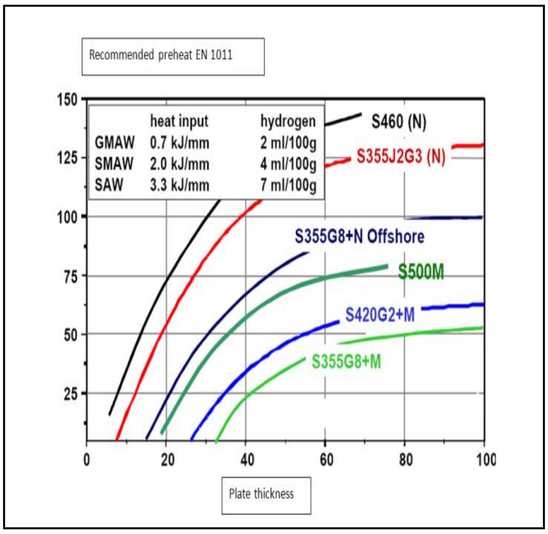


Figure 6. Calculated preheat temperature as a Function of plate thickness [4].

Offshore steels are required to have high toughness in the HAZ. Low sulfur content and absence of large inclusions is essential for toughness in the HAZ. Traditional S355 steels with high sulfur content are not able to guarantee 27 J impact strength. However, S355N steel with low sulfur content can achieve 50 J at – 40 ^{0}C while the lower sulfur and carbon content in S355M means impact strength can reach 200 J at – 40 ^{0}C, as shown in Fig. 7.

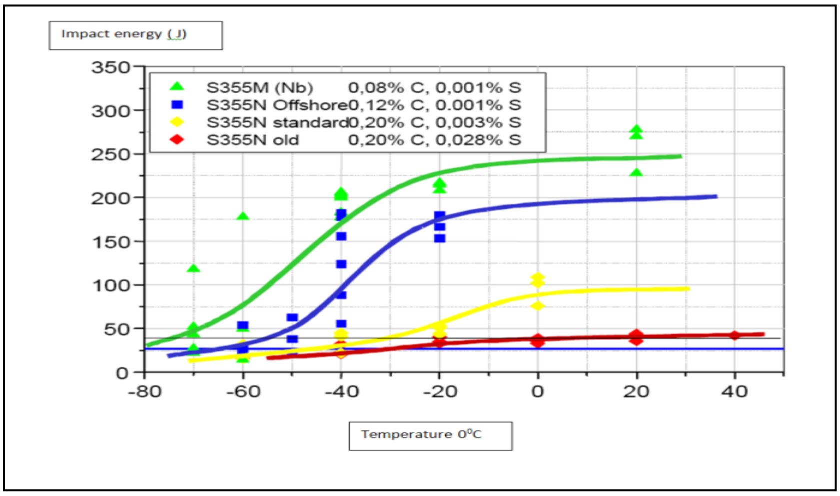


Figure 7. Impact toughness in HAZ of 3.5 kJ/mm SMAW of 20 mm thick plates of 355 Mpa [4].

VII. CONCLUSION

In this review paper, various procedures have been studied for improving the weldability of steels. Steels for offshore applications can be easily welded and the desired mechanical properties can be achieved. The ability to control the chemical composition of steel is vital in improving the weldability as hardenability of these steels plays a vital role. High strength steels with reduced carbon content are achievable for offshore structures. The findings show that boron and nickel play a very important role in weldability. Low hydrogen content enhance the weldability of steel. Importantly, the cooling rate and heat input of the welded joint are key in achieving a sound weld.

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