MANAGEMENT OF WELDING OPERATIONS WITH HIGH STRENGTH STEELS

P. DAINELLI
(INSTITUT DE SOUDURE)

F. MALTRUD
(INSTITUT DE SOUDURE)

High strength steels find ever increasing applications for several reasons:
- Reducing the weight of structures,
- Improving equipment performance,
- Reducing costs (shipping, smaller lifting equipment, time required for welding operations...)

For steels with a yield strength up to 700 MPa, welding problems and issues are well known. However, welding operations are not always well conducted. For yield strength over 700 MPa, problems such as mismatch... are not fully predictable.

In fact, the higher the yield strength of a steel, the more important are the following two issues:
- Cold cracking risks,
- Mechanical properties of the weld joints (yield strength, tensile strength, toughness...)

Achieving both good soundness and mechanical properties of the weld joint has been assessed in a lot of studies. However achieving this level of quality on site is another matter. How can one be sure of getting a perfect control of:
- Welding heat input?
- Preheating and postheating conditions?
- Diffusible hydrogen content of welding consumables?

Traveling from site to site, the user could not be aware of that and then can work this steel grade. For example, for bridge construction, S460 could be considered as a high strength steel, whereas in crane construction S690 is commonly used. In this paper we consider that high strength steel are steels with yield strength up to 460 MPa. This standard concerns both TMCP, QT and QST (quenched and self-tempered) steels.

By analyzing the mechanical and chemical properties of these steels, the trade offer of steels and consumables manufacturers, experimental work performed by Institut de Soudure, we propose to:
- Emphasize and appreciate the singular welding properties of these steels,
- Provide information and advices to solve the potential problems and manage fabrication.

1. INTRODUCTION

Increasing yield strength of steels is the trend in welding fabrication. For the same level of performance, this evolution leads to decreasing thickness, reducing construction weight, lowering consumption of welding consumables and less welding time. Moreover, using high-performance steels enables new designs. However, these beneficial properties require stringent welding conditions. The welding operations of high strength steels are not always well managed by fabricators, and the properties of these steels are always evolving.

How can you define a high strength steel? The answer is not the same for each industrial field. For example for bridge construction, S460 could be considered as a high strength steel, whereas in crane construction S690 is commonly used. In this paper we consider that high strength steel are steels or beams with yield strength above 355 MPa. By analyzing the mechanical and chemical properties of these steels, the trade offer of steel producers and consumables manufacturers, experimental work performed by Institut de Soudure, we propose to:

- Emphasize and appreciate the singular welding properties of these steels,
- Provide information and advice to solve the potential problems and manage fabrication.

2. STANDARDS AND HIGH STRENGTH STEELS

When speaking about high strength steels, two families of steels should be distinguished. The common characteristic of each family is the process of plate production.

- Thermomechanical rolling (TMCP) process which gives S460ML, S500MC, S700MC, X100, X120 grades,
- Quenched and tempered (QT) or quenched and self-tempered (QST) process which gives S460M, S690QL, S890QL..., S1300QL grades.

TMCP steels offer good weldability but require the use of low hydrogen consumables. Moreover the weld metal is often more sensitive to cold cracking than the heat affected zone (HAZ). This high sensitivity of the weld metal lead to a very stringent management of the whole welding application. Welding quenched and tempered steels implies in most cases preheating and often postheating. Contrary to TMCP steels, quenched and tempered steels are available in thicknesses higher than 100 mm. TMCP plates or tubes are included in EN 10149, EN 10025-4 (with some QST steels for this standard), API-5L standards whereas quenched and tempered plates are concerned by EN 10025-6 standard.

The EN 10225 standard also provides technical delivery conditions for weldable structural steels for fixed offshore structures which includes steels with yield strength up to 460 MPa. This standard concerns both TMCP, QT and QST (quenched and self-tempered) plates and beams (see Table I).

What is striking is the tolerances of both EN 10149 and 10025-6 regarding carbon equivalent and chemical composition. These tolerances may have a big impact in fabrication if purchase specifications are only depending on standards. A batch switch can lead to severe defects in welded components. For the welding engineer these standards are too permissive to enable a safe fabrication. The large chemical definition of each grade enables steel producers to adapt their fabrication to improve one specific property of the steel or to reduce the cost price in function of raw material prices. The final user could not be aware of that and then can work one day to another with two different steels in terms of metallurgy.

Even if the EN 10225 standard concerns only yield strengths up to 460 MPa, the frame defined by this...
standard should be recognised as safer towards fabrication. Moreover this standard allows some options to verify steel properties towards fabrication processes (welding, cold forming…).

### 3. DIFFERENT METALLURGY APPROACHES

For example, on high grade pipeline steels, Anne-Sophie Bilat describes several approaches for elaboration of X100 grades (Figure 1) [1].

Approach A, which uses high carbon content, increases the risk of crack development and provides poor weldability. Approach B uses high cooling rates and low cooling stop temperature could lead to some fraction of martensite providing poor toughness. Welding operations could yield to super-tempered zones in HAZ. Low carbon content in approach B decreases steel production productivity and makes uniform mechanical properties in plate more difficult to achieve. Approach C is an intermediate approach between A and B.

#### 3.1 METALLURGICAL APPROACHES ON TMCP STEELS

These steels provide high mechanical properties because of grain refinement, work hardening effect and fine carbides precipitation. The microstructure of these steels is often a mixed structure of ferrite with pearlite occurrence or ferrite and lower-bainite.

#### 3.2 METALLURGICAL APPROACHES ON QT STEELS

These steels provide high mechanical properties because of quenching and tempering operations. These heat treatments give structures of tempered martensite and some amounts of lower bainite. The chemical compositions of these steels has evolved over the years, described in a basic way in Table 2. Others factors influence the chemical composition:

- Price of raw material (adding Ni aims to reach excellent toughness in base material and HAZ, but is quite expensive),
- Range of thicknesses (increasing thickness leads to enhance the hardenability of the steel in order to achieve homogenous properties through the whole thickness),
- Technical capacity of steel producers (in terms of rolling and quenching conditions …).

Standards allow a large range of chemical compositions for high strength steels. Procurement of high strength steels must be followed very carefully to avoid problems in fabrication. The ideal case would be to select a steel manufacturer and to collaborate with him to define welding conditions for the whole fabrication range. Each fabrication process change must be evaluated in terms of weldability and properties of welded joint.

### Table 1

<table>
<thead>
<tr>
<th>Grade considered</th>
<th>EN 10149</th>
<th>EN 10025-4</th>
<th>EN 10025-6</th>
<th>EN 10225</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness range</td>
<td>S700MC</td>
<td>S460M</td>
<td>S960QL</td>
<td>S460M</td>
</tr>
<tr>
<td>Higher yield strength</td>
<td>700 MPa</td>
<td>460 MPa</td>
<td>960 MPa</td>
<td>460 MPa</td>
</tr>
<tr>
<td>Process of steel production</td>
<td>TMCP</td>
<td>TMCP or QST</td>
<td>QT</td>
<td>TMCP, QT and QST</td>
</tr>
</tbody>
</table>

### Table 2

<table>
<thead>
<tr>
<th>Chemical composition evolution</th>
<th>Potential issues</th>
</tr>
</thead>
<tbody>
<tr>
<td>C, Mn, Mo, Cr</td>
<td>High carbon equivalent</td>
</tr>
<tr>
<td>C - Ni, Mo, Cr</td>
<td>High carbon equivalent - risk of reheat cracking</td>
</tr>
<tr>
<td>Cu (HSLA steels)</td>
<td>Risk of reheat cracking</td>
</tr>
<tr>
<td>Nb, Ti, V, B micro-alloying</td>
<td>Risk of poor HAZ toughness</td>
</tr>
<tr>
<td>Complex approaches: micro-alloying elements, limited Cr, Mo</td>
<td>Improved compromised</td>
</tr>
</tbody>
</table>
4. HIGH STRENGTH STEELS WELDING ISSUES

Typical problems that can occur when welding high strength steels are:

- Cold cracking in the HAZ, longitudinal or transversal cold cracking in weld metal,
- Poor ductility or toughness, lost of strength of welds.

4.1 COLD CRACKING

As all low-alloyed steels, cold cracking can appear in the HAZ of high strength steel welds. The sensitivity to cold cracking in the HAZ is function of the metallurgy of the steel and is varying for different batches. The behaviour of the HAZ is often hidden by the higher sensitivity of weld metal. The sensitivity of the HAZ to cold cracking can be studied with implant tests. The Figure 2 presents implant test results for two HSLA steels (with Cu ageing) with the CET of 0.34 and 0.40 and two consumables of 2.53 and 0.48 ml /100 g diffusible hydrogen in deposited metal.

For high strength steel, cold cracking phenomena is more susceptible to appear in weld metal as the hardenability of weld metal must be higher than the base material. It is particularly the case for TMCP steels. The weld metal strength can not be obtained by work hardening effect and a grain refinement. Two different types of cracking phenomena must be considered for the weld metal:

- Longitudinal crack which often starts on a local geometry of the shape bead which creates a stress concentration. These cracks can appear in both single pass and multipass welds.
- Transversal crack which appears in multipass welds in high thicknesses. These cracks may initiate in the upper third part of the weld where the residual stress and hydrogen concentration are high after the piece cools down to room temperature.

In most cases, longitudinal cold cracks will appear near the fusion line and pass through both weld metal and HAZ (see Figure 3a). The crack path is difficult to predict, even if some models has been developed [2]. There are a lot of interactions between parameters like local hydrogen concentration, strain distribution, microstructure…

Some standardized methods for the avoidance of cold cracks are available in the FD CEN ISO/TR 17844 [3]. All these methods predict the minimal preheat temperature to avoid cold cracking. Although these methods provide a first starting point for the welding engineer, the results are often different from one method to another and do not take in account the effect of postheating and the validity of these methods for weld metal is not well known.

That is why the scope of the methods is only to determine preliminary welding conditions which must be subsequently validated by appropriate procedure testing and qualification [3]. In addition, some specific transverse cold cracks can occur in weld metal in high strength multipass welds. This phenomena has been studied, but needs costly and long experimentation [4]. This cold crack may take the appearance of chevron (Figure 3b).

The welding strategy has also an impact on the final results. Very often the welding engineer works in term of $T_{in,cool}$ (cooling time between 800 and 500°C) to transpose one set of welding conditions (preheat temperatures and heat input) to another one (change in thickness, reduced preheat temperature). But influence of thermical cycle on cold cracking can not be described by only one value. The cooling time between 300 and 100°C has a serious influence on hydrogen diffusion. François Maltrud performed an extensive analysis of all predictive methods for both longitudinal and transversal cold cracking in weld metal [7]. No method is validated by the whole scientific community to predict which zone of the welding joint is the more sensitive to cold cracking and which welding conditions enable to weld with a high level of safety.

For the longitudinal cold cracking in weld metal, the methods which match the best with all Institut de Soudure available results are the CET method and the Hart method with slight modifications. For the transversal cold crack, all the available methods show poor fitting. A method works well for the original test set, but provides poor results on an other test set. Applying the more conservative method is a poor alternative because it leads to excessive precautions, unsuited to industrial context. Institut de Soudure current point of view is that chevron cracking seems to be a phenomena that occurs when abnormal level of diffusible hydrogen is employed. Undermatching and low hydrogen diffusible consumable offer a positive summation that enable a decrease of the minimal preheating temperature from 50 to 75°C for S690QL and S890QL grades. The only undermatching root pass decrease the tensile strength of the joint by a maximal value of 3 % [8].

4.2 TOUGHNESS AND STRENGTH OF WELDING JOINTS

Avoidance of cold cracking requires minimal preheat temperature and heat input which can be considered as the lower welding conditions limits. However too high preheat temperatures and heat inputs lead to a severe decrease of both HAZ and weld metal toughness and also of welding joints strength.
The problem is even more complex as it depends on the metallurgy of the welding joint which implies both consumable and base material. The Figure 4 shows the effect of an increase of 50°C of the interpass temperature on a S890QL steel and Figure 5, the soften HAZ of TMCP S700MC steel with heat input of 1.2 kJ/mm with GMAW process. The thermal cycle of welding could erase the thermomechanical effect on HAZ of TMCP steels. The tensile strength of the welded joint is then lower than the effective tensile strength of the base material. However proper welding conditions provide a tensile strength of welded joint remaining higher than the minimal value specified by the standard for the base material. That is why industrial practices limit maximal $T_{\text{max,cool}}$ of 15 s. For QT steels, the thermal cycle of welding will produce a supertempering effect and/or the transformation of upper-bainite in HAZ.

In weld metal, the thermal cycle has also an influence on the strength of the weld metal. The importance of this influence depends on the chemical composition of the weld metal. The Figure 6 illustrates the impact of thermal cycle for two consumables.

As avoidance of cold cracking requires lower welding conditions limits, keeping good toughness and strength in welding joints requires upper welding conditions limits. Actually, these lower and upper limits induce a frame of welding conditions. The Figure 6 presents the two welding frames of S355K2+N and high S1100QL grades given by welding software based on CET method [10]. It is an evidence that high strength steels require more stringent restrictions on welding conditions and method to ensure these conditions are respected.

5. INDUSTRIAL WELDING PRACTICES

The industrial approaches for welding high strength steel depends on the industrial field as described in Table 3. In fact each field takes in account the general state of art for welding high strength steels, but introduces specific method and knowledge. The massive production, business and experience feedback of pipelines production leads to a lot of rules, standards, codes and specifications which provides a high level of safety required by oil and gas industry. Moreover the economic impact of this industry can influence steel and consumable producers to develop specific products. Penstock pipes for hydropower plants uses in fact very few high strength steels. Only the lower part of the penstock pipes are concerned by high strength steels. Even if the part sizes are important in terms of diameter and thickness, the amount of high strength steels used is rather small and can not easily pretend to specific requirements in terms of steel and consumables. S890QL is considered for some specific cases in order to reduce the weight of the individual shells, to increase the length of preassembled pipe segments that could be handled in the tunnel and to reduce the number of circumferential welds on site [12]. New grades are required by crane construction to reduce the weight of the arm and improve the loading capacity. High loading capacity cranes are very specific products but with a very high added-value which justifies the use of very specific steel in rather small quantities.
Very soon, it must be clarified with the steel and set the specific requirement of raw material procurement. One should select properly the right grades and mechanical characteristics of welded joints. After work for the design and warning designers of real design department and welding must perform teamwork with purchasing agents to ensure that welding procedure, traceability and storage conditions of raw material will be understood and overlocked by all operation teams. The level of inspection must be set. For high added-value equipment, best practices recommend high level of inspection. It is a major issue for all manual welding operations: one can consider one inspector per welder. Otherwise it is possible to define for each welding procedure specification a relationship between the bead width and the heat input. Alignment chart enables auto-control by welders.

For bridge constructions, S235 and S355 are always the most used grades. However some parts in highly stressed region are made of S460M, ML or even in S690QL. The S460M or ML grades enables weight reduction (which decreases erection costs) and also construction of larger bridges. Military sub-marines equipment are a very political topic. Sub-marines fabrication requires a specific demand which often involves national steel producer and army and a lot of technical development. Moreover military nuclear sub-marines must offered a very high level of safety in severe environments.

6. INSTITUT DE SOUDURE ADVICES

6.1 ENGINEERING AND DESIGN

First of all, for Institut de Soudure, engineering & design department and welding must perform teamwork for the design and warning designers of real mechanical characteristics of welded joints. After that, one should select properly the right grades and continue the teamwork with purchasing agents to set the specification of raw material procurement. Very soon, it must be clarified with the steel and consumable producers how could be modified the metallurgy of theirs products between different batches.

6.2 QUALITY AND INSPECTION

The quality department must also be involved to ensure that welding procedure, traceability and storage conditions of raw material will be understood and overlocked by all operation teams. The level of inspection must be set. For high added-value equipment, best practices recommend high level of inspection. It is a major issue for all manual welding operations: one can consider one inspector per welder. Otherwise it is possible to define for each welding procedure specification a relationship between the bead width and the heat input. Alignment chart enables auto-control by welders.

6.3 PROCEDURE QUALIFICATION

Then, an extensive study must be performed to determine the welding conditions. Each key parameter should be measured and notified. For Institut de Soudure, conventional procedure qualification is not sufficient to ensure safe welding conditions. Tests have to be carried out to assess the welding conditions towards cold cracking like those described in NF EN ISO 17642-2 and 3 standards and more specific ones [13, 14]. Welder qualifications should consider toughness and tensile tests which are sensitive towards welding conditions. When hardly humidity conditions are expected, the welding procedure must cover these extreme cases. In fact on yard conditions, all possible issues must be inventoried and criterion of decision should be available to decide whether repair must be performed or not. Improvisation and late decisions can lead to cold cracks propagation to base material. Moreover the diffusible hydrogen is susceptible to vary as a function of batch treatment, real storage conditions, welding parameters… For each condition, some diffusible hydrogen specimens should be carried out to identify problems.

6.4 NON DESTRUCTIVE TECHNIQUES

The non-destructive techniques (NDT) must consider the possibility of transversal cold cracking. Determining the delay to perform NDT is not obvious. The delay that enable cold cracking detection is not clearly known as it depends on a lot of parameters. A delay of 16 h seems to be too short for specific cases. Sometimes, ultrasonic NDT needs several days to be able to identify transversal cold cracking [4, 6].

### Table 3

<table>
<thead>
<tr>
<th>Industrial Field</th>
<th>High Strength Steel grade</th>
<th>Welded joints</th>
<th>Welding processes</th>
<th>Fabrication and welding conditions</th>
<th>Specific conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipelines (offshore</td>
<td>X80</td>
<td>V groove welded from outside of tube</td>
<td>121 (longitudinal welds) 111, 141, 136 (girth welds)</td>
<td>Outside under marquee Preheating</td>
<td>Offshore applications in presence of H₂S</td>
</tr>
<tr>
<td></td>
<td>S960QL</td>
<td>V or U groove welded from inside of tube</td>
<td>121 (longitudinal welds) 111, 141, 136 (girth welds)</td>
<td>Outside and often under ground with high level of moisture Pre and postheating</td>
<td>High moisture content in Yard</td>
</tr>
<tr>
<td>Cranes</td>
<td>S1300QL (no standard for this grade)</td>
<td>Fillet welds</td>
<td>135</td>
<td>In fabrication shop Preheating and undermatching</td>
<td>Fatigue stress</td>
</tr>
<tr>
<td>Bridges</td>
<td>S890QL (higher grade authorized by Eurocode 3)</td>
<td>Fillet and V or X groove butt weld</td>
<td>121 (pre-fabrication) 111, 114</td>
<td>Prefabrication in shop, intensive inspection Outside with windy conditions Pre and postheating</td>
<td>Outside welding</td>
</tr>
<tr>
<td>Sub-marines</td>
<td>Specific grades, Ni alloyed</td>
<td>Various joints</td>
<td>111 121 136 141</td>
<td>Intensive inspection, fabrication in shop Pre and postheating</td>
<td>Nuclear environment</td>
</tr>
</tbody>
</table>
7. CONCLUSION

In conclusion a fundamental point must be raised. Whatever the method used to define the procedure qualification, the welding conditions can not be efficient if stringent procedures are not applied to ensure that key parameters remain constant during all welding operations. It includes in non extensive way, the real chemical compositions of raw material, the diffusible hydrogen during welding operations, the heat input, the real preheat and postheating conditions in the whole thickness of the welding joints.

REFERENCES