

SSC limits of TMCP line pipes

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ABSTRACT

Large diameter TMCP (Thermo-Mechanically Controlled Process) pipelines have recently shown detrimental local variations in mechanical properties. Additionally, industry experience demonstrated that API⁽¹⁾ 5L / ISO⁽²⁾ 3183 and NACE MR 0175 / ISO 15156 compliant TMCP linepipe presented increased ID surface hardness, commonly known as hardspots or hard layers. These surface anomalies are difficult to detect as standard QA/QC included in API/ISO standards do not cover this matter sufficiently. In cases where hard spots are present (e.g. as it has been observed on API 5L X60, X65 grades) this may lead to rapid SSC failures in severe sour service environments. Thus, the European Pipeline Research Group (EPRG)⁽³⁾ launched at the end of 2017 a research program to define the SSC (Sulfide Stress Cracking) limits of TMCP pipes, to do a literature survey on Non-Destructive Techniques (NDT) able to detect surface hardness anomalies, and finally to reproduce hard layers through a “lab scale TMCP rolling” and point out the potential root cause of surface hardening. The current paper highlights work in progress with a specific focus on SSC limits of both API 5L X52 and X65 grades suitable for sour service and for natural gas applications in compliance with NACE MR0175/ISO 15156 - SSC Region 3 requirements. Threshold stress is determined using NACE TM0316 four-point bend testing in environments ranging from 1 to 17 bar of partial pressure of H₂S. Results are discussed with respect to the through wall hardness of materials and recommendations are then proposed to be considered in general for sour service line pipe projects.

Key words: sulfide stress cracking, SSC, hydrogen induced cracking, HIC, blistering, Thermo-Mechanically Controlled Process, TMCP, linepipe, hardness

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BACKGROUND

The manufacturing and field experience of high strength low alloy (HSLA) steel plates produced by Thermo-Mechanical Controlled Process (TMCP) are well defined in industry standards e.g. American Petroleum Institute (API) and literature. The TMCP method consists of a well-prescript rolling pass schedule followed by accelerated cooling that leads to a fine-grain microstructure with the desired mechanical properties of the produced plates. From a metallurgical point of view, TMCP utilizes the complex interrelationship between (micro) alloying elements, precipitation, recrystallization and phase transformation during rolling and accelerated cooling to systematically adjust the microstructure and crystallographic texture.

Over the past several years, there were many technical challenges for linepipe steels made by TMCP. These included a need for more homogeneous microstructure and properties, improved weldability, a low yield to ultimate tensile strength ratio with safe design and a high level of toughness. This was in line with a demand for linepipe resistant to harsh environments in the Middle East and cold areas such as Siberia. By further research and development, the steel manufacturers were able to attain a good combination of required strength and toughness properties by optimizing technologies such as micro-alloying and TMCP.

Micro-alloying elements such as niobium, vanadium and titanium can enhance the mechanical properties of steels. Solutes may then precipitate in the form of carbides or nitrides. Fine dispersion of particles can retard grain boundary motion by a pinning effect, which promotes the stability of a fine microstructure.¹ Moreover, these alloying elements may also elevate the recrystallization stop temperature.

Other typical alloying elements such as nickel, chromium, molybdenum and copper are needed to further adjust the required mechanical properties. Beyond high strength and elongation values, low-temperature toughness may be improved by grain refinement and reducing the carbon content; the latter being particularly helpful in enhancing weldability. HIC susceptibility can be improved by reducing impurity concentrations through the control of non-metallic inclusions in the steel.

Generally, the microstructures of linepipe steels can be divided into the following fundamental phases:^{2,3,4,5,6}

- ferritic – pearlitic steels,
- bainitic steels,
- multi-phase steels.

Where H₂S containing effluent is a concern, the steels particularly need to resist Hydrogen Induced Cracking (HIC) and Sulfide Stress Cracking (SSC). Further issues arise because significant changes occur in mechanical properties after pipe-forming, such as the change of yield strength and a decrease on impact toughness due to work hardening.^{7,8} Dedicated requirements through specifications and detailed analysis are thus defined to ensure integrity during service.

RECENT INCIDENTS AND INDUSTRY EXPERIENCE

As discussed above, TMCP leads to considerable economic advantages such as reduced alloying element content and faster rolling and heat treatment process with respect to phase transformation points as well as enhanced weldability. Therefore, TMCP has been accepted in API 5L / ISO 3183⁹ without additional requirements for severe sour service as compared to QT manufactured pipes from which limits of use have been derived.

For sour service applications, pipes manufactured from plates rolled by TMCP have demonstrated their suitability for a very long time by their distinctive feature to comply with sometimes conflicting requirements, particularly when the pipeline is used for natural gas transportation with Drop Weight Tear Testing (DWTT).

More recently, this TMCP process resulted in detrimental local variations of mechanical properties and recent industry issues (among them¹⁰) showed that API and NACE compliant linepipe made via TMCP manufacturing process may have hidden hardness variations on pipe ID, so-called sensitized hard spots or hard layers. These anomalies are very difficult to detect as both standard QA/QC do not deal with this matter and current API 5L / ISO 3183⁹ standard does not address this problem.

In case hardened layers are present (as it has been observed on X60 and X65 grades) this may lead to rapid SSC failures in severe sour environments; typically, SSC Region 3 as per NACE MR0175/ISO 15156¹¹ diagram that defines regions of environmental severity with respect to SSC of carbon and low alloy steels.

Hardened areas on pipe surfaces are known to be initiation points for sulfide stress cracking (SSC) in sour service applications. Due to that relevant standards, limit hardness of sour service pipes is acceptable up to 248 Vickers, which is generally proven during procedure qualification and during production by hardness tests on cross sections. Recently, randomly distributed hardened areas were found on inner pipe surfaces in which SSC developed during operation.

The extent of these hardened layers could be very small (shallow) with respect to length, width and especially to thickness. Thus, the focus on this current research program is first to investigate possible hard layers on base material (distant to the weld). The program is divided into three main topics:

- SSC resistance of TMCP line pipes: SSC environmental limits.
- SSC resistance of TMCP line pipes: NDT to detect and measure hardened surface areas.
- SSC resistance of TMCP line pipes: Possible mechanisms resulting in hard layer formation¹².

Thus, the current paper presents the SSC results achieved on regularly manufactured line pipe steels through TMCP and further discusses the corresponding SSC limits.

SSC LIMITS OF LINE PIPE STEELS

The materials selection process in H₂S service should reflect the overall philosophy regarding design life, cost profile, inspection and maintenance philosophy, safety and environmental profile,

failure risk evaluations and other specific project requirements. Materials selection should be optimized and provide acceptable safety and reliability.

Sulfide Stress Cracking (SSC) findings have been recently experienced on TMCP line pipes within the industry. The objective of this program is thus to investigate the SSC resistance of various TMCP line pipe grades within and outside of the industry recommended hardness limits.

The target of the study was NACE MR0175/ISO 15156¹¹ pH-P_{H₂S} diagram Region 3, i.e. at partial pressures of H₂S between 1 and 17 bar while there are uncertainties in the diagram above 10 bar H₂S with respect to steel's performance.

Both API 5L/ISO 3183⁹ X52 and X65 grades (suitable for sour service and for natural gas applications) have been selected with a hardness below 250 HV, i.e. acceptable for the current NACE MR0175/ISO 15156¹¹ Sour Service Region 3 diagram.

The X52 pipe is 1000 mm x 720 mm OD x 20.6 mm WT and the X65 pipe is 980 mm x 510 mm OD x 38.1 mm WT (see Figure 1).



X52



X65

Figure 1: X52 and X65 line pipe rings received from industry

The tensile properties of the materials have been checked in order to know the accurate yield strength. Table 1 below shows the data for the two pipes. Both materials are close to the mid-range of the grade as per API 5L/ISO 3183 standard⁹. A set of three uniaxial specimens were extracted from both sample grades and the test resulted in average YS of X52 was 421 MPa (61 ksi) for the X 52 grade and average YS of 544 MPa (79 ksi) for X65.

As for any set of three samples, the specimens were taken from locations at 60°, 180° and 300° with respect to the seam weld and adjacent to the bore/ID.

Table 1
Tensile properties of X52 and X65 line pipe materials

Material	YS [MPa]	UTS [MPa]	%El	%RA
X52 60°	422	504	26.0	80
X52 180°	422	503	26.0	81
X52 300°	418	501	27.0	80
Average X52	421			
X65 60°	543	601	23.5	82
X65 120°	551	613	21.5	81
X65 300°	538	601	22.5	82
Average X65	544			

The SSC tests were carried out on the base metal according to NACE TM0316 standard¹³, including applied stress through strain gauge and oxygen control requirements.

For each of the tests, three longitudinal specimens were machined adjacent to the bore surface. The specimens were machined to 115 mm in length x 15 mm in width x 5 mm in thickness and a minimum of 2 mm was removed from the bore surface. The test face (adjacent to bore) and side faces were polished up to 600 SiC grit finish, with the orientation of the grinding in the longitudinal direction.

The threshold stress was first characterized on the two materials. Base case applied stress on machined FPB specimens was 90% AYS and in case of failure, the threshold stress was determined by decreasing the applied stress to 70%, and finally to 50% AYS.

The test environment initial pH was fixed to 3.5 while different partial pressures of H₂S were tested; namely 1, 3, 5, 7, 13 and 17 bar of H₂S. All tests were performed in autoclaves with an addition of 1 bar CO₂ in order to make the lab test environment more realistic with respect to production environments. In addition, the materials were tested in accordance to NACE Standard TM0177¹⁴ Sol. A at 1 bar H₂S (glass cell test set up under atmospheric pressure). NaCl was fixed at 50 g/l with 4 g/l of NaAc as per NACE TM0177¹⁴ and the pH was adjusted to the target value with HCl or NaOH addition.

Table 2 and 3 show the SSC test matrix and the associated SSC test results of X52 material. All the FPB specimens passed the test with no failure. Evidence of blistering and subsurface HIC have nevertheless been observed on specimens tested at partial pressure of H₂S of 7 bar and beyond.

Table 4 and 5 show the SSC test matrix and the associated SSC test results of X65 material. While tested at 90% AYS, testing at 1 bar H₂S at atmospheric pressure and 1 bar H₂S + 1 bar CO₂ in the autoclave passed with no failure nor secondary cracking including HIC and/or blistering. Testing at 5 bar H₂S and beyond led to cracking of the material with either full fracture and/or blistering and subsurface HIC.

Additional testing at 70% AYS led to failure of the specimens at 5 bar H₂S and surprisingly not beyond. Nevertheless, blisters and subsurface HIC were observed on some of the specimens.

Finally, testing at 50% of AYS did not lead to cracking regardless of H₂S partial pressure even for specimens exhibiting evidence of blisters and subsurface HIC.

Table 2
SSC test results on X52 line pipe material

Test type	Material grade	Job ref	Specimen ref (1, 2, 3)	Stress	P _{H2S}	P _{CO2}	P _{total}	SSC Results		
				(%AYS)	(bara)	(bara)	(bara)	Specimen 1	Specimen 2	Specimen 3
NACE TM0177-Sol A	X52	M703056	686,687,688	90	1	0	1	No SSC	No SSC	No SSC
Autoclave 1 bara H2S	X52	M703057	689,690,691	90	1	1	2	No SSC	No SSC	No SSC
Autoclave 7 bara H2S	X52	M703058	692,693,694	90	7	1	8	No SSC	No SSC	No SSC
Autoclave 13 bara H2S	X52	M703059	695,696,697	90	13	1	14	No SSC	No SSC	No SSC
Autoclave 17 bara H2S	X52	M703060	698,699,700	90	17	1	18	No SSC	No SSC	No SSC