

Very High Strength Low Alloy Steel For High Pressure High Temperature Applications

Florian THEBAULT
Vallourec Research Center France
60 route de Leval
59 620 Aulnoye-Aymeries
France

Julien PENNEQUIN
Vallourec Research Center France
60 route de Leval
59 620 Aulnoye-Aymeries
France

John FORTAILLIER
Vallourec Oil & Gas France
54 rue Anatole France
59 620 Aulnoye-Aymeries
France

Carine LANDIER
Vallourec Oil & Gas France
12 rue de la verrerie
92 190 Meudon
France

ABSTRACT

High Pressure and High Temperature (HPHT) applications demand OCTG with increasing yield strengths, at least up to 140ksi. Due to the high total pressures, even trace amounts of H₂S lead to significant partial pressures of H₂S in wells. Consequently, the risk of SSC needs to be addressed. Typical sour conditions in such wells are pH 3.9-4.5 and 0.0035-0.03 bar of H₂S. A single steel grade has been designed so as to be suitable for a wide range of tubular products, from casing to thick accessories (up to 2.2 inch). The present paper describes the qualification approach applied to field projects using NACE TM0177 method A and D.

Key words: HPHT, SSC, OCTG, High Strength

INTRODUCTION

More and more High Pressure High Temperature (HPHT) sour wells are operated worldwide. Challenging material selection is required for such severe operating conditions.^{1,2} Very high strength materials, presenting yield strength above 896 MPa (130 ksi), are required for sustaining the pressure. Consequently, even a low amount of H₂S in the gas phase may lead to a H₂S partial pressure beyond the limit of 3.5 mbar (0.05 psi) established in NACE MR0175 / ISO 15156 standard.³ Indeed, both high yield strengths and partial pressures of H₂S contribute to a situation where the risk of Sulfide Stress Cracking (SSC) is high. The present paper is focusing on the SSC resistance of 130 ksi minimum yield strength material developed for covering such HPHT applications.

EXPERIMENTAL PROCEDURE

Materials

A single steel grade composition has been selected (Table 1). It is a AISI 4130 modified steel grade enriched in Mo, element acknowledged for enhancing the SSC resistance of low alloyed steels,⁴⁻⁶ microalloyed with Al, V and Nb. The steel composition has been selected for producing pipes hardenable up to 60 mm wall thickness and includes the latest developments on the design of sour service materials.⁷ Consequently, a single steel grade can be used for a large range of products, from casing to coupling stock or accessories. The list of pipes with dimensions variation and their respective mechanical properties is given in Table 2. The yield strength properties as determined by ASTM E8⁸ are in the range of 131 to 142 ksi.

Table 1: Typical composition of the alloy used for the test program.

C	Si	Mn	Cr	Mo	Others
0.35	0.35	0.36	1.00	1.25	Al, V, Nb

Table 2: List of pipes used for the test program with their respective dimensions and mechanical properties.

Material ID	OD x WT (mm)	YS		UTS	
		(MPa)	(ksi)	(MPa)	(ksi)
#A	339.7 x 12.95	961	139.3	1034	150.0
#B	355.6 x 20.32	945	137.0	1013	146.9
#C		934	135.5	1004	145.6
#D	244.5 x 13.84	938	136.0	999	144.9
#E	285.8 x 23.50	905	131.3	977	141.7
#F	260.4 x 21.34	940	136.3	1003	145.5
#G		944	136.9	1010	146.5
#H	317 x 33	926	134.3	983	142.6
#I		905	131.3	967	140.3
#J		918	133.1	987	143.2
#K	297.9 x 44.45	955	138.4	1025	148.7
#L	304.8 x 55.88	982	142.4	1057	153.2
#M	304.8 x 55.88	929	134.7	1018	147.6
#N	273.4 x 59.69	972	141.0	1040	150.8

Uniaxial Tensile Sulfide Stress Cracking Test (Method A)

Uniaxial tensile tests were performed at atmospheric pressure according to NACE TM0177-2016⁹ Method A. Test conditions are given in Table 3; they were defined for the purpose of material qualifications.

Salinity was obtained by addition of sodium chloride; either a given amount (5% wt.) or for reaching a given concentration of chloride up to 160 000 ppm. Consequently, chloride content varies approximately from 1 to 5. Based from recent literature data it can be expected a negligible or even a slight beneficial impact of a higher salinity on the SSC resistance of low alloyed steels. By reducing H₂S fugacity, a higher chloride content is able to increase the threshold stress intensity factor for SSC.¹⁰ Further, this observation has been supported by results showing a reduction of hydrogen permeation flux through C110 steel membrane when increasing the salt content of the sour charging solution.¹¹ SSC of low alloyed steels is mainly driven by hydrogen uptake which is not enhanced by salt content (presumably due to lower H₂S fugacity and/or adsorption competition between Cl⁻ and HS⁻).

pH and H₂S partial pressure covered a range from 3.9 to 5 and 3.5 to 30 mbar, respectively. A visual perspective of the investigated sour conditions in relation to the NACE sour service domains is given in Figure 1; they are located inside region 2 or at the boundary with region 1 or 3. However, considerations for the tested temperature are not reflected by this diagram although it has a great influence on SSC susceptibility of low alloyed steels. The effect of temperatures as low as 3°C and as high as 80°C were included in this investigation.

Table 3: Uniaxial tensile test conditions at atmospheric pressure.

Test Cond. (TC)	Environment	pH	Gas	T / °C	Applied Stress
#1	158 000 ppm Cl ⁻ + 0.40% wt. CH ₃ COONa	4.5 adjusted with HCl	1.4% H ₂ S Balance CO ₂	3°C	90% AYS
#2	5% wt. NaCl + 0.40% wt. CH ₃ COONa	4.2 adjusted with HCl	3% H ₂ S Balance CO ₂		
#3	160 000 ppm Cl ⁻ + 0.40% wt. CH ₃ COONa	3.9 adjusted with HCl	0.35% H ₂ S Balance CO ₂	4°C	
#4	5% wt. NaCl + 0.40% wt. CH ₃ COONa	4.5 adjusted with HCl	1.4% H ₂ S Balance CO ₂	24°C	
#5	5% wt. NaCl + 0.40% wt. CH ₃ COONa	5.0 adjusted with HCl	1.4% H ₂ S Balance CO ₂	80°C	
#6	100 000 ppm Cl ⁻ + 0.40% wt. CH ₃ COONa	4.5 adjusted with HCl	1.4% H ₂ S Balance CO ₂	24°C	85% SMYS
#7	5% wt. NaCl + 0.40% wt. CH ₃ COONa				

Double Cantilever Beam (DCB) Sulfide Stress Cracking Test (Method D)

DCB tests were performed at atmospheric pressure according to NACE TM0177-2016⁹ Method D. Details on test conditions are in Table 4. Acetic acid has been selected for adjusting the initial pH, instead of hydrochloric acid as specified by NACE TM0177 Solution D. The justification for this selection is supported by previous work and mainly based on two observations:¹²

- Higher acetic acid buffering reduces the occurrence of dry cracking, which helps reducing the scattering of test results;
- Higher acetic acid buffering reduces the minimum test duration for reaching the crack arrest.

In the same work,¹² it has been observed a reduction of K_{ISSC} when using acetic acid instead of hydrochloric acid for adjusting the initial pH. Test duration was 17 days, but, for the mildest test condition, a second test during 30 days was also performed for insuring the crack arrest. This extended exposure time is also supported in NACE TM0284-2016 standard for HIC test, which establishes 30 days as the recommended minimum test duration for 0.01 bar H₂S.

All specimens were fatigue pre-cracked prior exposure to the sour environment.