Journal of Achievements in Materials and Manufacturing Engineering
VOLUME 18
ISSUE 1-2
September-October
2006

Evaluation of susceptibility of high-strength steels to hydrogen delayed cracking

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Received 15.03.2006; accepted in revised form 30.04.2006

Properties

ABSTRACT

Purpose: Purpose of this paper is evaluation of susceptibility of high-strength structural steels to hydrogen delayed cracking.
Design/methodology/approach: Susceptibility to hydrogen delayed cracking of high-strength alloy steels have been made under constant load in hydrogen generating environments. Test were carried out using round notched specimens subjected to axial tensile load being equivalence to 75-96% of maximum force obtained from a tensile tests in air. Two constructional middle carbon steel – grades 26H2MF and 34HNM were tested in used (worn out) mineral engine oil at temperature of 80°C. One low carbon weldable steel grade – 14HNMBCu was investigated in sea-water under cathodic polarization at room temperature. Presence or lack of cracking within 200 hours was chosen as a measure of susceptibility to hydrogen delayed cracking. Fracture modes of failed samples were examined with the use of scanning electron microscope.
Findings: All tested steels reveal high resistance to hydrogen degradation under constant load. Hydrogen delayed cracking does not occur until the load level is as high as flow stress (yield strength).
Research limitations/implications: Further research should be taken to reveal the exact mechanism of crack initiation.
Practical implications: Tested steels could be safely utilized within elastic range of stress in hydrogen generating environments.
Originality/value: Under the critical load and hydrogen concentration notched samples premature failed and hydrogen-enhanced localised plasticity (HELP) model is a viable degradation mechanism.
Keywords: Crack resistance; High-strength steels; Hydrogen embrittlement; Hydrogen delayed cracking

1. Introduction

Most high-strength steels are thought to be susceptible to hydrogen embrittlement when they are stressed and exposed to hydrogen generating environments. The susceptibility of steels to hydrogen degradation generally increases with increasing tensile strength. Steels with tensile strength less than 700 MPa appear to be resistant to hydrogen cracking, and the structures made with such steels have been used in service without serious problems in various environments that do not contain hydrogen sulfide. Steels having a tensile strength greater than 1000 MPa are susceptible to hydrogen embrittlement, and steels with tensile strength over 1200 MPa are especially susceptible and may fail at stress much below their yield strength. This behavior is termed hydrogen delayed cracking [1,2].

A number of failures due to hydrogen have been reported, e.g. of car engines parts [3], ship engines [4], and offshore mobile drilling platforms [5,6].

Engine oils can absorb moisture and become acidic, so that hydrogen could be generated at crack tip and facilitate crack growth. Martensitic steels with a hardness greater than about 38 HRC are known to be highly susceptible to hydrogen enhanced corrosion fatigue and stress corrosion cracking even in mildly corrosive environments [3-9].

2. Materials and experimental procedure

Two constructional middle carbon steel – grades 26H2MF according to PN-75/H-84024 [10] and 34HNM according to PN-89/H-84030/04[11] were tested. Both steels were quenched and tempered. Applied tempering temperatures were: 600°C for 26H2MF steel, and 680°C for 34HNM steel. A quenched and tempered plate 12 mm in thickness made of 14HNMBCu steel grade – S690Q grade with minimum yield strength of 690 MPa according to PN-EN 10137-2 [12] was used. The chemical compositions of the tested steels are given in Table 1.

Submerged arc welded (SAW) and shielded metal arc welded (SMAW) joints were prepared for 14HNMBCu steel. Mechanical properties obtained from a tensile test for 14HNMBCu steel performed according to PN-EN 10002-1 [13] are presented in Table 2.

Hardness measured for 26H2MF and 34HNM steels were 355 HV30 and 393 HV30 respectively.

Microstructures of the steel plate and welded joints were examined with the use of the optical microscope LEICA MEF4M according to PN-EN 1321 [14]. Microstructure of the steels composed of low carbon tempered lath martensite. Microstructure of the welded joint was typical for extra high-strength low-alloy steel. Weld metal microstructure composed of acicular ferrite and bainite. Microstructure of regions of HAZ (coarse grained region, fine grained region, and intercritical region) consisted of low carbon lath martensite with various prior austenite grains size respectively.

In order to estimate the degree of hydrogen degradation of tested steels and the welded joints, the constant load test on round notched specimens 6 mm in diameter was conducted along with PN-EN 2832 [15]. The gauge length of samples was 50 mm. The geometry of a notch is presented in Fig. 1. For samples with welded joints, welds were placed in the centre of specimens and a notch was cut in the fusion line. All specimens were cut along the transverse direction. Minimum two samples were used for each test parameters.

The constant load test was carried out with the use of a lever machine with leverage 25:1 and maximum load capacity of 20 kN. The machine was equipped with the environmental cell with platinum polarisation electrode.

Tests for steel grades 26H2MF and 34HNM were performed in used (worn out) mineral engine oil at temperature of 80°C. Tests for 14HNMBCu steel were performed at room temperature in standard artificial sea-water grade A, prepared consistent with PN-66/C-06502 16]. Tests in sea-water were conducted at open circuit potential and under cathodic polarisation with constant current densities chosen from the polarisation curves. The following cathodic currents were applied: 0.1; 1; 10 mA/cm^2 giving cathodic hydrogen charging of specimens during a test. Time to failure of specimen was recorded. When a sample did not fail within 200 hours, the test was ended and result was signed as negative (-) according to PN-EN 2832. When a sample failed premature (before 200 hours), the result was signed as positive (+). Presence or lack of delayed failure of samples was chosen as measures of hydrogen degradation – susceptibility or resistance to delayed hydrogen cracking. Applied loads were calculated as a ratio of actual force (F) to the maximum force (F_m) obtained from a tensile test. Tensile test was performed with slow strain rate 10^{-6} s^{-1} in air using the same notched samples as for a constant load test. Results of the constant load tests in hydrogen generating environments are presented in Tables 3-6.

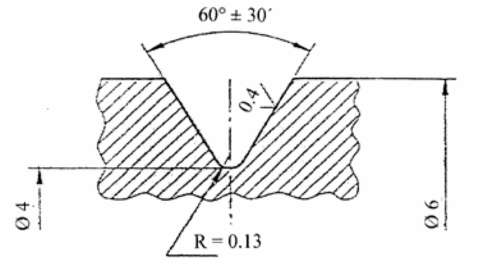

Fig. 1. The notch geometry of a specimen

Fracture surfaces of failed samples were investigated with the use of the scanning electron microscope (SEM) PHILIPS XL30 to determine mode of fracture. An example of fractographic observations is shown in Fig. 2.

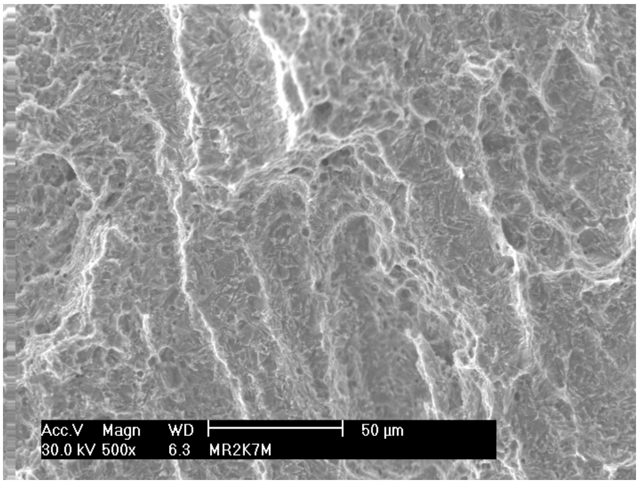

Fig. 2. SEM image of a fracture surfaces of 14HNMBCu steel after a constant load test in seawater. Relative load F/F_m = 0.96, open circuit potential

Table 1.
Chemical composition of tested steels (control analyse)

Steel	Chemical composition, wt %											
grade	C	Si	Mn	P	S	Cr	Ni	Mo	Cu	Ti	V	Al	B
26H2MF	0.30	0.45	0.43	0.007	0.001	1.61	0.16	0.72	0.15	-	0.27	-	-
34HNM	0.33	0.29	0.54	0.001	0.003	1.40	1.41	0.17	0.25	-	0.01	-	-
14HNMBCu	0.13	0.21	0.83	0.001	0.005	0.43	0.74	0.40	0.25	0.004	0.05	0.02	0.002

Table 2.
Mechanical properties (transverse direction) of the plate made of 14HNMBCu steel and its welded joints

Steel grade	Samples	Yield Strength MPa	Tensile Strength MPa	Elongation %	Reduction in Area %
14HNMBCu	Base metal	908	935	8.7	47.4
	SAW	601	631	7.2	55.5
	SMAW	599	687	6.6	61.9

Table 3.
Resistance to delayed hydrogen cracking of 26H2MF and 34HNM steels tested in used mineral engine oil at 80°C under a constant load

Steel grade	Applied relative load F/F_m			
	0,84	0,88	0,92	0,96
26H2MF	-	-	-	-
34HNM	-	-	-	-

"-" means no failure within 200 hours and resistance to delayed hydrogen cracking
"+" means premature failure and susceptibility to delayed hydrogen cracking

Table 4.
Resistance to delayed hydrogen cracking of 14HNMBCu steel under a constant load test in sea water

Cathodic current density mA/cm^2	Applied relative load F/F_m			
	0,84	0,88	0,92	0,96
open circuit potential	-	-	-	+
0,1	-	-	+	+
1	-	-	+	+
10	-	+	+	+

3. Discussion

Tables 3-6 present critical relative loads, and cathodic current densities at which delayed hydrogen cracking occurs in tested steels. As it can be seen investigated steels and the welded joints have high resistance to hydrogen degradation in hydrogen generating environments.

Table 5.
Resistance to delayed hydrogen cracking of welded joints (SAW) of 14HNMBCu steel under a constant load test in sea water

Cathodic current density mA/cm^2	Applied relative load F/F_m			
	0,84	0,88	0,92	0,96
open circuit potential	-	-	-	+
0,1	-	-	-	+
1	-	-	+	+
10	-	-	+	+

Table 6.
Resistance to delayed hydrogen cracking of welded joints (SMAW) of 14HNMBCu steel under a constant load test in sea water

Cathodic current density mA/cm^2	Applied relative load F/F_m			
	0,84	0,88	0,92	0,96
open circuit potential	-	-	-	+
0,1	-	-	+	+
1	-	+	+	+
10	-	+	+	+

Two constructional middle carbon steel 26H2MF and 34HNM tested in used mineral engine oil at 80°C are not susceptible to hydrogen delayed cracking since hydrogen concentration was below critical value in this case. Absorption of hydrogen measured in a vacuum extraction test is as follows: 1.17 wt. ppm for 26H2MF steel, and 2.78 wt. ppm for 34HNM steel.

Steel 14HNMBCu tested in seawater both at open circuit potential and cathodic polarisation has high resistance to hydrogen degradation. Additionally, high critical load at the level of 0,96 at open circuit potential shows that tested steel and its welded joints are not susceptible to pitting corrosion in seawater environment.

Submerged arc welded joint (SAW) has higher resistance to hydrogen degradation then base metal. However, shielded metal arc welded (SMAW) joint is more susceptible then base metal. Differences in resistance to hydrogen delayed cracking could be explained by variations of microstructure present in steel and welded joints. The various microstructures resulting in different mechanical properties (strength, hardness) and different susceptibility to hydrogen degradation.

Fractographic observations of failed samples revealed mixed fracture mode composed of ductile and quasicleavage fracture.

Obtained results of constant load test and fractographic observations suggest that hydrogen-enhanced localised plasticity (HELP) model is the more applicable mechanism of hydrogen degradation. Hydrogen delayed cracking occurs at load level as high as flow stress (yield strength) of tested steel and its welded joints. Ductile and quasicleavage fracture modes support suggestion that hydrogen interacts with dislocations and increase their mobility, and at the same time hydrogen is transported by mobile dislocations.

4. Conclusions

Constructional middle carbon steel 26H2MF and 34HNM tested in used mineral engine oil at 80°C are not susceptible to hydrogen delayed cracking.

High-strength low-carbon steel 14HNMBCu and its welded joints have high resistance to hydrogen delayed cracking in seawater environment

Under the critical load and cathodic current density notched samples of 14HNMBCu steel premature failed and hydrogen-enhanced localised plasticity (HELP) model is a viable degradation mechanism.

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