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Mechanism of hydrogen enhanced-cracking of high-strength steel welded joints

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Properties

ABSTRACT

Purpose: Purpose of this paper is evaluation of susceptibility of high-strength steel welded joints to hydrogen degradation and establishing of applicable mechanism of their hydrogen-enhanced cracking.
Design/methodology/approach: High-strength quenched and tempered steel grade S690Q and its welded joints have been used. Susceptibility to hydrogen degradation of steel and welded joints has been evaluated using monotonically increasing load. Slow strain rate test (SSRT) was carried out on round smooth specimens in air, and seawater under cathodic polarization. Elongation and reduction in area were choosen as measures of susceptibility to hydrogen embrittlement. Fractographic examinations with the use of scanning electron microscope (SEM) were performed to establish suitable mechanism of hydrogen-enhanced cracking of the welded joints.
Findings: Tested high-strength steel and its welded joints are susceptible to hydrogen embrittlement when evaluated with the use of SSRT. The loss of plasticity is higher for welded joints then for the base metal.
Research limitations/implications: There is no possibility to perform direct observations of exact mechanism of hydrogen-assisted cracking so far. On the base of mechanical tests and fractographic observations it is likely to deduce which of nowadays models of hydrogen degradation and cracking is the most viable.
Practical implications: Tested steel and its welded joints could be safely utilized in marine constructions under cathodic protection provided that overprotection does not take place.
Originality/value: Hydrogen-enhanced localized plasticity (HELP) model is more applicable mechanism of hydrogen degradation than other for high-strength welded joints in seawater environment.
Keywords: Crack resistance; High-strength steel; Welded joint; Hydrogen degradation

1. Introduction

High-strength steels have been widely used in construction of large scale welded-structures. The principal advantage of these steels is good combination of strength and toughness, but also their good weldability. High-strength steels are especially suitable for application in pipelines, offshore facilities, and naval vessels and ships.

High-strength steels are produced as: quenched and tempered, direct quenched and tempered (the kind of TMCP - Thermo Mechanical Controlled Process), or precipitation hardened with copper. Especially, quenched and tempered steels are thought to be sensitive to hydrogen degradation. Significant limitation of use of extra high-strength steels could be their hydrogen degradation [1].

Hydrogen embrittlement has been the cause of failures in high-strength constructional steels used in the offshore industry [2,3]. The problem is due to absorption of hydrogen from seawater, which is promoted when cathodic protection is applied to the steel to control corrosion. It is known that hydrogen uptake is increased substantially when sulphides are generated by active sulphate reducing bacteria (SRB) in marine sediments or biofilms on the metal surface [4].

Hydrogen effect is greater near room temperature and decreases with increasing strain rate. Hydrogen degradation is more pronounced with increasing hydrogen content or charging rate and with increasing strength of steel.

Hydrogen degrades properties of steel under condition where cracking proceeds by all microstructural modes, including: ductile fracture – micro-void coalescence (MVC), quasicleavage, transgranular cleavage, and brittle intergranular fracture [5,6].

2. Mechanisms of hydrogen degradation

The numerous mechanisms have been proposed to explain LTHA phenomena, which reflect the many ways in which hydrogen was observed to interact with metals [5,7-10].

Internal Pressure Model - Precipitation of molecular hydrogen at internal defects (nonmetallic inclusions, voids) develops high internal pressure. This pressure is added to applied stress and thus lowers the apparent fracture stress. The mechanism was initially proposed by Zapffe and Sims.

Hydrogen Induced Decohesion Model - Dissolved hydrogen (lattice hydrogen) reduces the cohesive strength of the lattice, i.e. interatomic bonds and thereby promotes decohesion. Mechanism proposed by Troiano and modified by Oriani. There is absence of direct experimental measurements supporting this mechanism. There are also a number of "open issues" relating to the observational base on which the decohesion model is founded. The most important is that fractography of transgranular fracture resulting from decohesion should be cleavage fracture, whereas most observations can be classified as quasi-cleavage.

Surface Energy Model (Adsorption Model) - Adsorption of hydrogen reduces the surface energy required to form a crack propagation and thus lowering of fracture stress. This model was first proposed by Petch. There are no direct experimental observation and reliable calculations that hydrogen can reduce surface energy

Adsorption Induced Localised Slip Model - Adsorption of environmental hydrogen atoms at crack tip results in weakening of interatomic bonds facilitating dislocation injection from a crack tip and then crack growth by slip and formation of microvoids. Mechanism proposed by Lynch.

Hydrogen-Enhanced Localised Plasticity (HELP) Model - Absorption of hydrogen and its solid solution increases the ease of dislocation motion or generation, or both. Mechanism first proposed by Beachem and developed by Birnbaum et al. In many cases, the definition of hydrogen-related fracture as a "brittle fracture" is based on loss of macroscopic ductility (e.g. decrease of reduction in area and elongation). But careful fractographic examinations with high resolution technique shows, that hydrogen embrittlement of steel is associated with locally enhanced plasticity at the crack tip. Distribution of hydrogen can be highly nonuniform under an applied stress. Thus, locally the flow stress can be reduced, resulting in localised deformation that leads to highly localised failure by ductile processes, while the macroscopic deformation remains small.

Corrosion Enhanced Plasticity (CEP) Model - This model takes into account the generation of vacancies due to localised anodic dissolution and hydrogen evolution by cathodic reaction at the newly depasivated crack tip. Thus, corrosion produces an enhanced localised plasticity. The activated dislocations along slip bands form pile-ups interacting with obstacles. The resulting high local stress can initiate cracking. Model was developed by Magnin et al. This model has application mainly to passive metals and alloys like stainless steels, nickel and its alloys.

Hydrogen Rich Phases Model - Formation of hydrogen rich phases – hydrides, whose mechanical properties differ from those of matrix. Cracking could proceed by the formation and cracking of brittle hydride near the crack tip. Model was generalised by Westlake. For iron it was found that no stable hydrides are formed up to hydrogen pressure of 2 GPa, so this model is not valid for steel hydrogen degradation.

3. Materials and experimental procedure

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 [11] was used. The chemical compositions of the tested steel is given in Table 1. Submerged arc welded (SAW) and shielded metal arc welded (SMAW) joints were prepared. Mechanical properties obtained from a tensile test performed according to PN-EN 10002-1 [12] are presented in Table 2.

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

In order to estimate the degree of hydrogen degradation of tested steel and its welded joints, slow strain rate test (SSRT) according to PN-EN ISO 7539-7 [13] was conducted on round smooth specimens 4 mm in diameter made according to PN-EN ISO 7539-4 [14]. The gage length was 50 mm. Welded joints were placed in the centre of the specimens. Specimens were cut along the transverse direction. Tests were performed at ambient temperature either in dry air or in standard artificial sea-water grade A prepared according to PN-66/C-06502 [15]. The applied strain rate was 10^{-6} s^{-1}. Tests in sea-water were conducted at open circuit potential and under cathodic polarisation with constant current densities, chosen from the polarisation curves obtained in artificial sea-water for base metals with the potentiostatic method. The following cathodic currents were applied: 0.1; 1; 10; 20 and 50 mA/cm^2.

Elongation and reduction in area were chosen as measures of hydrogen embrittlement. Then, relative parameters determined as the ratio of the appropriate value measured in air to that measured in artificial sea-water were calculated and presented as bar charts (Fig. 1-2).

Fracture surfaces of failed samples were investigated with the use of the scanning electron microscope (SEM) to determine mode of fracture. Examples of fractographic observations are shown in Fig. 3-4.

4. Results and discussion

Observed decrease of relative values of elongation, and reduction in area with the increase of current density exhibits a certain minimum. Further increase of current density does not cause higher degradation. The loss of elongation was as high as 10% for base metal, and 35% for welded joints. Reduction in area decreased of 40% for base metal, and 55-75% in the case of SMAW and SAW welded joints respectively.

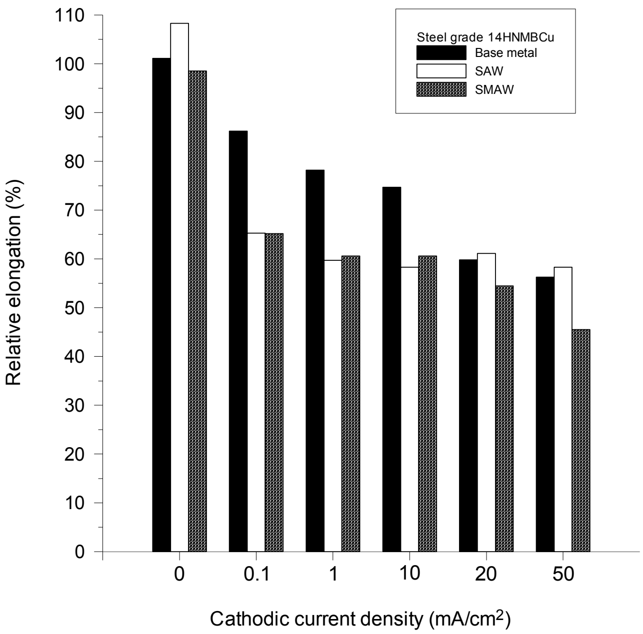

Fig. 1. Relative elongation versus cathodic current density for 14HNMBCu steel and its welded joints

Failure of samples with welded joints occurred always in weld metal, where strength was lower comparing to base metal. The reduction of ductility by hydrogen was accompanied by a change in fracture mode. For samples tested in air crack growth occurred in a ductile mode with microvoid coalescence and quasi-cleavage fracture. For samples tested in sea-water transgranular brittle mode with quasi-cleavage and cleavage fracture was observed. At higher cathodic current densities the presence of hydrogen induced microcracks and flakes appeared (Fig. 4).

Obtained results of SSRT test and fractographic observations suggest that hydrogen-enhanced localised plasticity (HELP) model is the more applicable mechanism of hydrogen degradation.

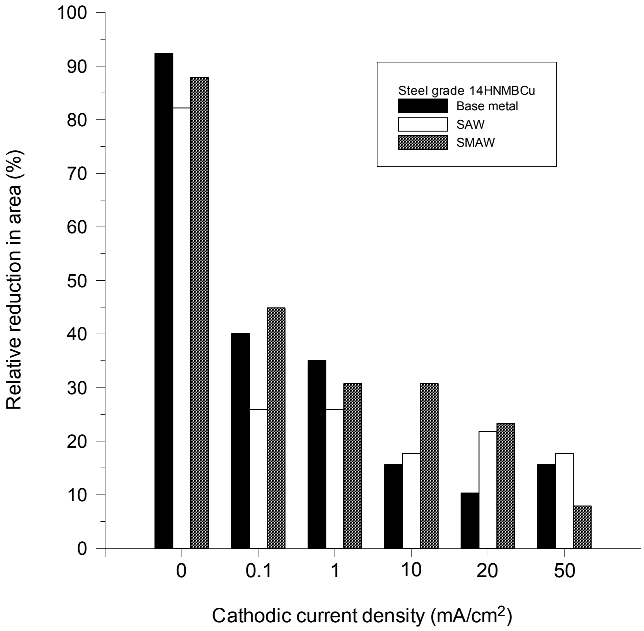

Fig. 2. Relative reduction in area versus cathodic current density for 14HNMBCu steel and its welded joints

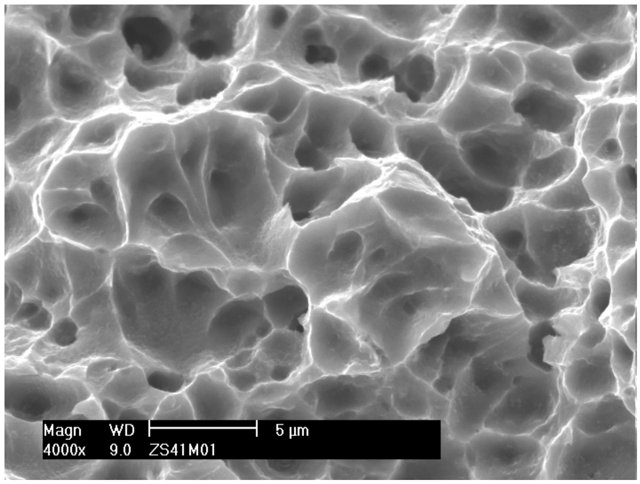

Fig. 3. SEM image of the fracture surfaces of welded joint (SMAW) of 14HNMBCu steel. SSRT test in seawater i = 0.1 mA/cm^2

Hydrogen assisted-cracking occurs at load level as high as flow stress (yield strength) of tested steel and its welded joints. Ductile and quasi-cleavage fracture modes support suggestion that hydrogen interacts with dislocations and increase their mobility, and at the same time hydrogen is transported by mobile dislocations. Hydrogen ions transported with mobile dislocations locally increasing hydrogen concentration which facilitates cracking.

Table 1.
Chemical composition of steel plate (control analyse)

Steel grade	C	Si	Mn	P	S	Cr	Ni	Mo	Cu	Ti	V	Al	B
	Chemical composition, wt %												
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 steel plate 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

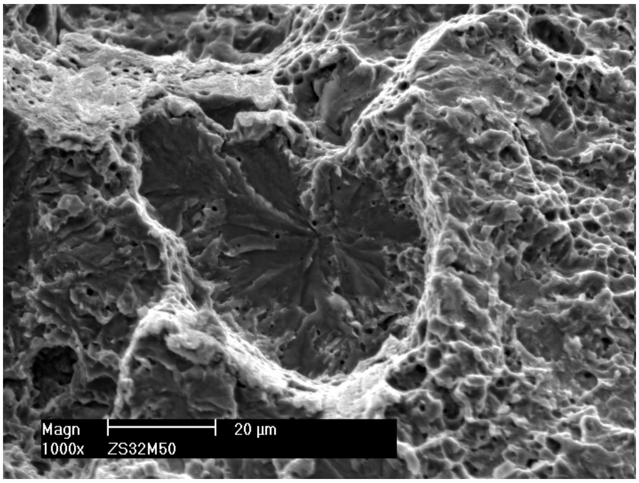

Fig. 4. SEM image of the fracture surfaces of welded joint (SAW) of 14HNMBCu steel. SSRT test in seawater i = 50 mA/cm^2

5. Conclusions

Tested high-strength steel and its welded joints are susceptible to hydrogen embrittlement when evaluated with the use of SSRT. The loss of plasticity is higher for welded joints then for the base metal.

Tested steel and its welded joints could be safely utilized in marine constructions under cathodic protection provided that overprotection does not take place.

Hydrogen-enhanced localized plasticity (HELP) model is more applicable mechanism of hydrogen degradation than other for high-strength welded joints in seawater environment.

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