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Influence of hydrogen from CP on the fracture susceptibility of 25%Cr duplex stainless steel – FE modeling of constant load testing using hydrogen influenced cohesive zone elements.

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ABSTRACT

Cohesive zone modeling of hydrogen induced stress cracking in 25% Cr duplex stainless is performed. The simulations represents constant load tensile testing of notched samples in 3.5% NaCl aqueous solution under cathodic protection. A user defined polynomial traction separation law including reduced cohesive energy with increasing hydrogen concentration is applied. FE simulations and laboratory experiments suggests that the net section stress should be kept below 580 MPa for a V-notch sample with radius 0.25mm and below 620 MPa for a U-notch sample with radius 2.0mm to avoid HISC induced fracture in 25%Cr duplex stainless steel.

KEY WORDS:

Steel; stainless; hydrogen; cracking; FE-modeling

INTRODUCTION

Hydrogen produced during cathodic protection has in recent years been found to cause cracking and failure in stainless steel subsea pipelines and fittings. Duplex stainless steel is traditionally regarded as safe due to the duplex structure of ferrite and austenite with the ductile austenite acting as a crack stopper. However, at the low corrosion protection potentials applied in the North Sea, the hydrogen production is considerable. Combined with stresses during production hydrogen induced stress cracking, HISC, is observed also in 25%Cr duplex stainless steel.

Diffusion in duplex stainless steel mainly takes place in the ferrite phase. Diffusion in the austenite phase is very slow and has an insignificant influence on the effective diffusion coefficient. However, the diffusion is still much slower than in plain ferrite steels. This is an effect of an increased diffusion length in the ferrite due to the austenite islands and trapping at the austenite phase boundaries. Aspects as the shape, size and spacing of the austenite islands will influence both diffusion length and trapping. Fine dispersed austenite islands will typically promote more tortuous diffusion paths and trapping compared to a structure consisting of coarse austenite island and larger intermediate ferrite "paths". Turnbull, Beylegaard and Hutchings (1994) reported regression equations for the effective temperature dependant diffusion coefficient, D_{eff}, based on permeation measurements for diffusion in 25%Cr duplex stainless steel. The first equation is for lattice diffusion (traps are regarded filled) the second includes the filling of traps.

$$D_{eff} = 1.3 \cdot 10^{-7} \exp\left[(-45.9\text{kJ/mol})/RT\right] \quad (\text{m}^2/\text{s}) \qquad (1)$$

$$D_{eff} = 4.3 \cdot 10^{-6} \exp\left[(-55.7\text{kJ/mol})/RT\right] \quad (\text{m}^2/\text{s}) \qquad (2)$$

R is the gas constant and T the temperature in Kelvin. The equation including reversible traps yield diffusion coefficients close to pure austenite. Zakroczymski and Owzcarek (2002) measured diffusion coefficients of trapped hydrogen close to values for austenitic steel; hence it can be argued that the austenitic phase it self seem to act as a trap.

Due to the large solubility of hydrogen in austenite the hydrogen content can be high causing only marginal reduction of the crack resistance in this phase, whereas ferrite resolves very little hydrogen and is prone to brittle cracking at low hydrogen concentrations. A typical hydrogen crack in duplex stainless steel is characterized by cleavage in {001} plane in ferrite with change of direction and stepwise zig-zag micro cracking in <111> direction when entering the austenite (Oltra and Bouillot 1994).

The effect of local stress and strain fields on the hydrogen diffusion in front of a crack tip as this is a topic of special interest related to the mechanical properties and fracture toughness. A notch or crack subjected to a plane opening stress will, in mechanical terms, be described by a local stress and strain field ahead of the notch tip. The strain field is at it's highest at the notch tip and then gradually decreases with increasing distance from the notch tip. The hydrostatic stress field reaches maximum a short distance ahead of the crack tip and the diffusible lattice hydrogen will accumulate at sites of increased hydrostatic stress due to dilatation of the lattice. One of the main challenges is to link the micromechanical and diffusion processes present in the fracture process zone, with the global behavior of the component or structure.

There are a wide range of proposed analytical and finite element models aiming to describe hydrogen assisted micromechanical behavior in front of a crack tip. In general the models are based on established elastic-plastic fracture mechanics theory. Since the hydrogen influence is active