3-9-2007

Use of High Strength Steel for Hydrogen Containment

X. Y. Liu
University of Pennsylvania

Jun A. Kameda
University of Pennsylvania, kamedaj@seas.upenn.edu

C. J. McMahon
University of Pennsylvania


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Abstract
The research involves experiments on model lab heats of an ultra-high-strength steel (high C, low Ni) and a high-toughness, high-strength steel (high Ni, low C) to determine the limits of toughness as a function of yield strength, grain-boundary purity, and hydrogen fugacity. In addition, the existence and mechanism of brittle intergranular cracking in ideally pure steels is being investigated.

Comments

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Use of High Strength Steel for Hydrogen Containment

X.Y. Liu, J. Kameda and C. J. McMahon Jr.

Department of Material Science and Engineering
University of Pennsylvania
Overview

The research involves experiments on model lab heats of an ultra-high-strength steel (high C, low Ni ) and a high-toughness, high-strength steel (high Ni, low C) to determine the limits of toughness as a function of yield strength, grain-boundary purity, and hydrogen fugacity.

In addition, the existence and mechanism of brittle intergranular cracking in ideally pure steels is being investigated.
Advantage of steel for tanks and transport

• Capable of high strength (low mass)
• Economical

Challenge

• Hydrogen-induced intergranular embrittlement
The mechanism

Sharp crack, Nanoscale cracking
Two kinds of steels

- Inherently High-Strength (4340)
- Inherently High-Toughness (HY130)
Ames 4340 Bending Test
850°C, 3H->200°C, 1H, O.Q.

Intergranular (IG)

Transgranular (TG)
Fracture Mode

Intergranular – Stress Driven (IG)

Transgranular – Plasticity Driven (TG)

Aim

Pressure of Hydrogen

Yield Stress
Three Controlling Parameters

- Fugacity of hydrogen
- Yield strength of the steel
- Grain-boundary purity (and microstructure?)

These parameters control the fracture mode of intergranular (IG) and transgranular (TG)
Hydrogen concentration ($C_0$) dissolved in lattice under hydrogen pressure ($P$)

\[ C_0 = 0.00185 \, P^{1/2} \exp(-3440/T) \]

$C_0 = 10^{-8}$ at.fr under $P = 1$ atm.

H concentration ahead of a crack tip under hydrostatic tensile stress ($\sigma_h$)

\[ C_H = C_0 \exp \left( \frac{\sigma_h V_m}{R \, T} \right) \]

- $\sigma_h = \frac{\sigma_{11} + \sigma_{22} + \sigma_{33}}{3} = 2.42 \, \sigma_y$
- molar volume of hydrogen in iron: $V_m = 2.1 \times 10^{-6}$ m$^3$/mole

$C_H = 10^{-6}$ at.fr under $\sigma_y = 1750$ MPa $P_{H_2} = 1$ atm
Effect of Purity of High Strength Steel

Is this possible?

\[ C_H = 0.00185 \left( P_{\text{H}_2} \right)^{1/2} \exp \left( - \frac{Q_s}{RT} \right) \exp \left( \frac{2.42 \sigma_y V_m}{RT} \right) \]
Even ideally pure grain boundaries are cracked in hydrogen at high strength levels.
Summary and Future Work

- Under low hydrogen fugacity, hydrogen induced cracking (HIC) of ultra-high strength steels grows along grain boundaries regardless of the purity.
- High-strength/high-toughness steel shows excellent resistance to HIC under low hydrogen pressure.
- To determine the limit of hydrogen fugacity that can be tolerated for high-purity/high-strength steel.
- Understanding of underlying HIC mechanism of ultra-high-purity/high-strength steel without segregated impurities and precipitates.

Acknowledgement

This research is supported by the Basic Energy Sciences office of the Department of Energy under grant No. CR-19314-429146.