Fracture Control of Hydrogen Containment Components

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3rd International Conference on Hydrogen Safety
Ajaccio, Corsica, France
September 18, 2009

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94AL85000
Pressure vessels and pipelines are important components in the hydrogen energy infrastructure.

- Current examples:
  - Cr-Mo ferritic steels
  - <45 MPa H₂ gas
  - <1 pressure cycle/day

- Current examples:
  - C-Mn ferritic steels
  - <15 MPa H₂ gas
  - static pressure

Evolving H₂ containment components will operate outside windows of current service conditions.
Fatigue crack growth aided by hydrogen embrittlement can dictate component life.

Maximum number of pressure cycles must be defined for H$_2$ components.

Barthélémy, 1st ESSHS, 2006
American Society of Mechanical Engineers (ASME) developed design method for H₂ pressure vessels

- Article KD-10 in Section VIII, Division 3 of Boiler and Pressure Vessel (BPV) code
  - “Special Requirements for Vessels in High Pressure Gaseous Hydrogen Service”
  - Mandatory for seamless vessels with H₂ pressure > 41 MPa and welded vessels with H₂ pressure > 17 MPa
  - Allows H₂ pressure up to 100 MPa
  - Design method also considered for H₂ pipelines
  - Calculate maximum number of cycles by coupling fatigue crack growth data with structural analysis
Fatigue crack growth rate must be measured in high-pressure hydrogen gas. The crack growth rate, $da/dN$, is measured in laboratory $H_2$ gas.

The relationship between crack growth rate and crack size, $a$, is given by the Paris Law:

$$da/dN = C[\Delta K]^m$$

where $C$ and $m$ are material constants.
Fatigue crack growth rates measured for Cr-Mo steel SA-372 Gr. J in 100 MPa H₂ gas

Data sets in high-pressure H₂ are rare, in part because measurements are complex.
Fatigue crack growth rate data enable determination of maximum number of pressure cycles

\[ da/dN = C[\Delta K]^m \]

\[ \Delta K = \Delta p[f(a, t, R_o, R_i)] \]
Example: crack depth vs number of cycles calculations for three component variations

Design life depends on both fatigue crack growth rate response and component features
Fatigue crack growth measurements for component design must consider *environmental similitude*

Environmental similitude affected by variables such as H\(_2\) pressure and *load-cycle frequency*.

*Walter and Chandler, Effects of Hydrogen on Behavior of Metals, 1975*
Summary

• Fatigue crack growth aided by hydrogen embrittlement can dictate service life of H₂ containment components
  - Maximum number of pressure cycles must be defined

• Maximum number of cycles calculated by coupling fatigue crack growth data with structural analysis
  - Framework established in ASME codes

• Measurements of fatigue crack growth rates in high-pressure H₂ gas in progress
  - Initial data for Cr-Mo steel SA-372 Gr. J in 100 MPa H₂
  - Must address effects of load cycle frequency and wave form on fatigue crack growth rates in H₂