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Effects of hydrogen pressure and test frequency on fatigue crack growth properties of Ni–Cr–Mo steel candidate for a storage cylinder of a 70 MPa hydrogen filling station

Arnaud Macadre [a,*], Maxim Artamonov [a,b], Saburo Matsuoka [a], Jader Furtado [a,b]

[a] Research Center for Hydrogen Industrial Use and Storage (HYDROGENIUS), Department of Mechanical Engineering Science, Kyushu University, 744 Moto-oka Nishi-ku, Fukuoka 819-0395, Japan

[b] Air Liquide R&D, Centre de Recherche Claude Delorme, 1 chemin de la Porte de Loges, Les Loges-en-Josas 78354, France

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ABSTRACT

Experiments to investigate the effect of hydrogen pressure and test frequency on the fatigue crack growth properties of a Ni–Cr–Mo steel for the storage cylinder of a 70 MPa hydrogen storage station were conducted. Compact tension specimens were cut out from the storage cylinder. The crack growth properties obtained in hydrogen gas were compared with those obtained in air. Higher hydrogen pressures and lower loading frequencies lead to faster crack growth. However, there is an upper limit to the acceleration of the fatigue crack growth rate in hydrogen gas, which can be used for the design of the hydrogen cylinder. The effect of long and large inclusions present in the steel was also verified. The observations carried out on specimen fracture surfaces showed that the low population of inclusions did not influence the fatigue crack growth rate.

1. Introduction

To construct the hydrogen society, hydrogen energy systems (fuel cell vehicles, FCVs, and stationary fuel cells, SFCs) and hydrogen energy infrastructures (hydrogen stations and pipelines) are being developed. Japan is currently conducting the Japan Hydrogen and Fuel Cell Demonstration Project (JHFC), with the first stage done from 2002 to 2005 with demonstrations of 35 MPa FCVs and 35 MPa hydrogen stations. The second stage of this project started in 2006, and should finish in 2010, with exhibitions of 70 MPa FCVs and 70 MPa hydrogen stations.

For the hydrogen storage cylinder, JIS-SCM435 steel is a candidate for a 40 MPa cylinder in the 35 MPa hydrogen station and JIS-SNCM439 steel is a candidate for 80 MPa cylinder in the 70 MPa hydrogen station [1], the hardenability of JIS-SNCM439 being superior to that of JIS-SNCM435. An example of a hydrogen filling sequence for the 40 MPa cylinder is

* Corresponding author.
E-mail address: arnaud.macadre@gmail.com (A. Macadre).

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Nomenclature

a	crack length; inner diameter of cylinder (m)
b	outer diameter of cylinder (m)
a_f	final length of crack at failure (m)
a_i	initial length of crack (m),
c	half width of a defect (μm)
C	material constant
C_H	hydrogen concentration near the crack tip (mass ppm)
$C_{H,S}$	saturated hydrogen concentration (mass ppm)
da/dN	fatigue crack growth rate (m/cycle)
$(da/dN)_{air}$	fatigue crack growth rate in air (m/cycle)
$(da/dN)_{H_2}$	fatigue crack growth rate in hydrogen gas (m/cycle)
$(da/dN)_{H_{2,upper}}$	maximum fatigue crack growth rate in hydrogen gas(m/cycle)
$d(\Delta K)/da$	decrease rate of stress intensity factor range (GPa/m)
D	hydrogen diffusion coefficient (m^2/s)
f	test frequency (Hz)
l_{max}	maximum length of a defect (μm)
m	material constant
N_f	number of cycles to failure
N_p	calculated fatigue life (calculated number of cycles to failure)
p	pressure inside the cylinder (MPa)
pH_2	hydrogen gas pressure (MPa)
R	stress ratio, ratio of minimum stress by maximum stress
S_0	area of inspection for inclusion population analysis (mm^2)
t	time (s)
T	temperature (K)
x	distance from the crack tip (m)
α	acceleration of crack growth rate in hydrogen: $(da/dN)_{H_2}/(da/dN)_{air}$
ΔK	stress intensity factor range (MPa $m^{1/2}$)
Δp_{H_2}	range of hydrogen pressure (MPa)
$\Delta\sigma$	range of stress (MPa)
$\Delta\sigma_\theta$	range of circumferential stress (MPa)
σ_{min}	minimum stress (MPa)
σ_{max}	maximum stress (MPa)
σ_{UTS}	ultimate tensile strength (MPa)
σ_θ	circumferential stress (MPa)
$\sigma_{\theta,max}$	maximum circumferential stress (MPa)
ω_ε	reversed plastic zone size in plane strain (m)

List of abbreviations

CT	compact tension specimen
FCG	fatigue crack growth
SI, SO, SCI, SCO, SLI, SLO	S: specimen, I: near inner surface of cylinder, O: near outer surface of the cylinder, C: circumferential orientation, L: longitudinal orientation

the following: first the hydrogen storage cylinders in the station are filled up to 40 MPa with a compressor. Once the cylinders are filled with 40 MPa hydrogen gas, FCVs are supplied 35 MPa hydrogen gas from the station hydrogen dispensers, using hydrogen from different storage cylinders, in three steps: up to 20 MPa (R = 0.5, pressure of the station's storage cylinder: 40 ↔ 20 MPa), up to 30 MPa (R = 0.75, pressure of the station's storage cylinder: 40 ↔ 30 MPa) and up to 35 MPa (R = 0.875, pressure of the station's storage cylinder: 40 ↔ 35 MPa). A similar sequence with a maximum hydrogen pressure of 80 MPa is used for the 80 MPa cylinder from which 70 MPa hydrogen gas will be supplied to 70 MPa FCVs. The emptying and filling process cycle will impose cyclic stress on the storage cylinder wall under hydrogen gas pressure. The goal is to have a hydrogen gas filling time at the station less than 5 min, which is equivalent to having a repeated loading at 0.003 Hz. It is also highly probable that the cycle number in service will be limited to 10^4–10^5 cycles. Therefore, it is necessary to study how different hydrogen pressures and loading frequencies at high stress ratios will affect the fatigue properties of SCM435 and SNCM439 steels.

In a previous research, Yano et al. [2] studied the influence of hydrogen on fatigue strength properties (S–N properties: stress amplitude vs. number of cycles to failure) with smooth round specimens cut out from a prototype of 80 MPa storage cylinder (Fig. 1). The longitudinal direction of the specimens was parallel to the circumferential direction of the cylinder. The