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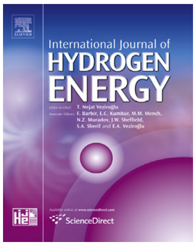

Effect of inside diameter on design fatigue life of stationary hydrogen storage vessel based on fracture mechanics

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ABSTRACT

Design fatigue life of stationary hydrogen storage vessel constructed of the practical materials of low alloy steels was analyzed based on fracture mechanics in hydrogen and air of 45, 85 and 105 MPa using cylindrical model with inside diameter (Di) of 150, 250 and 350 mm. Design fatigue life of five typical model materials was also analyzed to discuss the effect of Di on the design fatigue life by hydrogen-induced crack growth of the vessel. K_{IC} of all the practical materials qualified the leak before burst. Design fatigue life generally increased slightly with increasing Di in air, while design fatigue life by K_{IH} was much shorter than that in air. Hydrogen influence on design fatigue life increased with increasing Di due to that K_I at initial crack increased with increasing Di. The design fatigue life data of the model materials under the conditions of Di, pressure, ultimate tensile strength, K_{IH}, fatigue crack growth rate and regulations in both hydrogen and air were proposed quantitatively for materials selection and development for stationary hydrogen storage vessel.

Introduction

The high-pressure hydrogen storage has been developed for fuel cell vehicles. Metallic materials have been used for stationary hydrogen storage vessel, in particular for type I pressure vessel. Kanezaki et al. [1] reported that hydrogen accelerated the fatigue crack growth (FCG) rates in the hydrogen-charged meta-stable austenitic stainless steels from the viewpoint of diffused hydrogen content and microscopic fatigue mechanisms. Amaro et al. [2] proposed a fatigue crack propagation model for pipeline steel exposed to high-pressure hydrogen accounting for the acceleration in the FCG rate due to hydrogen. Hydrogen markedly enhances FCG rates and decreases K_{IH} of low alloy steels generally used for type I vessel [3–5]. Thus the design fatigue life evaluation using fracture mechanics is required by article KD-10 in the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section VIII, Division 3 to accommodate

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the environmental effect of gaseous hydrogen on fatigue and fracture properties of the high-pressure hydrogen vessels [6,7]. Calculation method of the design fatigue life is generally discussed in KD-10 and also described in High Pressure Gas Safety Institute of Japan (KHK)S 0220 as the crack growth analysis (CGA) quantitatively. Fatigue life of AISI4340 and 4137 type I pressure vessel was examined in high-pressure hydrogen [8,9] and that of type I pressure vessel from 4130X was examined in high-pressure hydrogen [10,11]. We have applied CGA to assess the effect of wall thickness, material strength and hydrogen sensitivity on the design fatigue life of type I vessel with the general inside diameter (Di) of 250 mm [12]. Previous studies have given attention to the effect of hydrogen on the fatigue life of steel pressure vessels, but the effect of Di on fatigue life has not been considered. Although various type I vessels with various Di have been used, hydrogen influence of Di on design fatigue life of type I vessel has not been clarified yet.

In this paper, CGA was applied to evaluate the design fatigue life of type I vessel for stationary hydrogen storage vessel in hydrogen station constructed of practical materials of low alloy steels, which are generally expected for type I vessel in spite of sensitivity to hydrogen embrittlement. We assumed the general cylinder model of Di of 150, 250 and 350 mm for type I vessel to examine the effect of Di on the design fatigue life of the vessel. We also applied CGA for five model materials to discuss the effect of Di, material strength and hydrogen sensitivity on the design fatigue life of the hydrogen storage vessel.

Procedure for design fatigue life calculation

A CGA approach based on the principles of linear elastic fracture mechanics assumes that an initial crack-like flaw begins to propagate on the first load without incubation time on the surface of the vessel. Surface flaws generally fix the fatigue analysis; thus we assumed inside surface cracks of type A to get the design fatigue life result. These cracks tend to propagate in a semielliptical shape with an aspect ratio a/l (equal to 1/3 initially), and are aligned with the longitudinal axis of the cylindrical vessel and propagating radially outward. Calculation is conducted following KHKS 0220 [13]. The steps in the CGA process are as follows.

Materials

The low alloy steel of AISI4340 (we call 4340), which is commercially available for type I vessel, was used for calculation. The chemical composition of 4340 steel follows Chinese national standard (GB)/T3077 and two heat-treatments were applied to the steel; one is oil-quenched (OQ) at 850 °C and tempered (T) at 600 °C in the standard (we call this steel as (GB) steel), the other is OQ at 850 °C and T at 640 °C out of standard (we call this steel as low strength (LS) steel) [12]. The low alloy steels of 4137 and 4130X were also used for calculation. Although these steels show severe hydrogen embrittlement, they have been practically used for hydrogen service.

Inside diameter and wall thickness

Based on the general model of type I vessel [9], the cylindrical model with Di of 150, 250 and 350 mm is assumed to discuss the effect of Di on the design fatigue life of the vessel, respectively. The wall thickness of the cylindrical model with three different Di in the hydrogen pressure of 45, 85 and 105 MPa was calculated following five regulations, namely KHK designated equipment rule (DER) in Japan [14], KHKS 0220 in Japan [13], Chinese special equipment regulation (TSG) R0002 in China [15], Chinese machinery industrial standard (JB) 4732 in China [16], and ASME Sec. VIII, Div. 3 in USA [17]. Details of the wall thickness calculation method by the five regulations were given in elsewhere [12].

The wall thickness of the pressure vessel from practical materials at pressure of 45, 85 and 105 MPa with Di of 150, 250 and 350 mm is shown in Table 1. The wall thickness by KHK DER is the thickest in the order of those by KHK DER, TSG R0002 or JB4732, KHKS 0220 and ASME Sec. VIII, Div. 3 for each Di. The wall thickness increases with increasing Di at a given pressure and the ratio of the thickness to Di remains unchanged for each regulation.

Design fatigue life and leak before burst

Design fatigue life was calculated by the summation of an interval of crack growth Δa during increment of cycle ΔN with pressure cycle between design pressure and 0 following the calculation method based on KHKS 0220 [13]. CGA was conducted until the critical crack size up to two situations; 1) maximum K_I is equal to the smaller of K_{IC} and K_{IH}, or 2) crack depth (a) is 80% of wall thickness (t), $a/t = 0.8$.

CGA assumes the initial crack depth (a_0) depending on t. a_0 determined by KHKS 0220 is as follows; ($t \leqq 16$ mm, $a_0 = 0.5$ mm), ($16 < t < 51$ mm, $a_0 = 1.1$ mm) and ($t \geqq 51$ mm, $a_0 = 1.6$ mm). Crack growth parameters of practical materials are shown in Table 2, which are followed by fitting of the literatures under the conditions as close as possible to the practical conditions [12].

Leak before burst (LBB) mitigates some of the consequence associated with failure of a pressure-containing equipment. The LBB mode is described previously elsewhere [12].

Results

Design fatigue lifetime of 4340 (GB) pressure vessel in hydrogen and air of 105 MPa with Di of 150, 250 and 350 mm are shown in Fig. 1, where the wall thickness is 43.6, 72.6 and 101.7 mm by KHK DER. In air, design fatigue life qualifies almost 10^5 cycles for each Di. For Di of 250 mm and 350 mm, both of the wall thicknesses are larger than 51 mm, thus their a_0 is the same. Design fatigue life attains 9.38×10^4 cycle for Di of 250 mm and 9.48×10^4 cycles for Di of 350 mm; design fatigue life increases slightly with increasing Di in air with the same a_0. For Di of 150 mm, its a_0 is smaller than those of other Dis, and its design fatigue life of 1.26×10^5 cycles in air is longer than those of Di of 250 and 350 mm. In hydrogen, design fatigue life obtained by K_{IH} is much shorter than that in air below 10^3 cycles for each Di; design fatigue life obtained by K_{IH} is 117, 121 and 245 cycles for