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Stress corrosion cracking of 316L HAZ for 316L stainless steel/Inconel 52M dissimilar metal weld joint in simulated primary water

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ABSTRACT

The stress corrosion cracking (SCC) behaviour of 316L heat affected zones (HAZ) in 316L stainless steel/Inconel 52M dissimilar metal welded joint (DMWJ) in simulated primary water was systematically evaluated using direct current potential drop (DCPD) methods. Crack growth rates (CGRs) of 316L HAZ increased with increasing temperature and dissolved oxygen (DO) contents. CGR in hydrogenated water was approximately one order of magnitude slower than in oxygenated water. The fracture surface shows typical mixed intergranular-transgranular SCC characteristics and several fast finger-like cracks. Several intergranular secondary cracks, perpendicular to the main crack and fusion boundary, were also observed.

1. Introduction

Dissimilar metal welded joints (DMWJ) are generally utilized to join low-alloy-steel nozzles of pressure vessels with austenitic stainless steel safe-ends or pipes in both boiling water reactor (BWR) and pressurized water reactor (PWR) nuclear power plants [1]. However, many serious incidents of stress corrosion cracking (SCC) have been identified in DMWJs [1–5]. The crack growth rate (CGR) of SCC in stainless steel heat affected zones (HAZ) in high temperature water is significantly higher than in the base metal [5–7]. Strain hardening resulting from weld shrinkage increases the yield strength, and sequentially promotes SCC in primary water. The residual strain in 316L HAZ decreases with increasing distance from the fusion boundary [8]. Though many laboratory studies have been performed on SCC CGRs in cold-worked (CW) stainless steels [6,9–11], limited information on the crack growth behaviour of 316L HAZ [5–7,12] with high residual strain is available in the literature.

In general, the primary water temperature in operating PWR is 290–338 °C [13]. However, during start up and shut down, the components in a nuclear power plant experience temperatures lower than 290 °C. The temperature significantly affects the SCC behaviour of 316L since it can universally affect the physical and chemical processes [14,15]. Andresen [14] reported that a peak in CGR of sensitized type 304 occurred at approximately 200 °C in oxygenated water with H_2SO_4 or HCl. Crack retardation above 330 °C in lower CW stainless steel was also clearly observed by Terachi et al. [16]. However, Arioka et al. [17], Zhang et al. [15] and Lu et al. [6] have shown that the CGR of CW 316 stainless steel increases monotonically with increasing temperature in both oxygenated and hydrogenated water. Therefore, it is important to clarify the influence of temperature on SCC CGR for 316L HAZ.

Under normal conditions, PWRs are operated with sufficient amounts of dissolved hydrogen (DH) in order to deaerate the primary water and maintain a low corrosion potential [18,19]. However, during refuelling and maintenance, aerated water or H_2O_2 may be added into the primary circuit [20]. The DO of primary water in dead-legs can reach a high level and is difficult to be eliminated using the circuit of primary water [21], which will make the 316L pipe more susceptible to SCC. DO can significantly affect the oxidation behaviour of materials [22–24] and can increase the CGR of stainless steels [7,9,11,25]. Lu et al. [7] presented that the CGRs of two different 316L HAZ specimens tested in 288 °C pure water with 7000 ppb (by weight) DO were about 1.4× and 1.9× higher than that with only 200 ppb DO, respectively. Zhang et al. [25] reported the CGR of 20% CW 316L with 2000 ppb DO as being 1.4× larger than that with <10 ppb DO. Du et al. [11] found that the CGR of 30% CW 316L with 2000 ppb DO was about 7× larger than that in argon deaerated water. Moreover, Arioka et al. [9] presented that the CGRs in oxygenated primary water were larger than those

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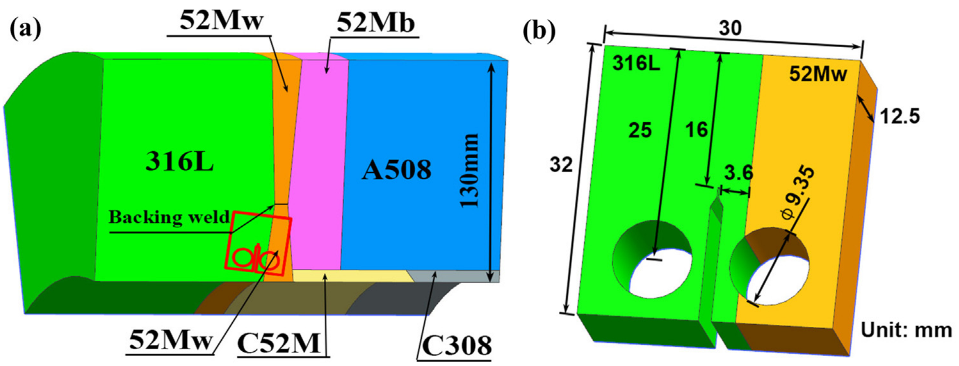

Fig. 1. (a) Structure of the DMWJ and the location of the CT specimen of 316L HAZ. (b) The dimensions of the 1/2T CT specimen.

in hydrogenated primary water, a difference which increased with decreasing CW levels. More detailed work is still required to fully understand the effects of DO and DH on SCC CGRs of 316L HAZ.

Limited SCC CGR data of 316L HAZ are available, let alone data on the effects of water chemistry in high temperature water on them. This study aims to determine the actual effects of temperature, DO and DH on CGR of 316L HAZ for 316L stainless steel/Inconel 52M DMWJ in simulated primary water.

2. Materials and methods

2.1. Materials and specimen preparation

The structure of the as-welded DMWJ manufactured by Shanghai Electric Nuclear Power Equipment Co., Ltd. is presented in Fig. 1(a). The materials of the vessel nozzle and the safe-end pipe are A508 LAS and 316L, respectively. The DMWJ was fabricated by a buttering technique using Inconel 52M as the buttering and weld material. Here, the buttering layer metal and weld metal were denoted as 52 Mb and 52 Mw, respectively. The width of 52 Mb and 52 Mw were 25–32 mm and 7–16 mm respectively, and the thickness of the DMWJ was approximately 130 mm. A cladding layer of 52M and 308L SS was buttered on the inner surface of the nozzle and buttering. The chemical compositions of 316L and 52 Mw are given in Table 1.

The micro-hardness across the fusion boundary of 316L/52 Mw was measured using an MHVD-1000AP Vickers hardness instrument with a load of 300 g and a holding time of 15 s. The grain boundary character and the local strain distribution of 316L HAZ were analysed by electron back scattering diffraction (EBSD) with the help of orientation image microscope software. Samples for EBSD examination were polished using 1.5 μm diamond paste, followed by MasterMet 2 Polishing Suspension to remove surface deformations caused by mechanical polishing. The acceleration voltage for EBSD measurement was 25 kV and the step size was 2 μm.

One 1/2T compact tension (CT) specimen was cut from the 316L HAZ according to ASTM E647 standards, with dimensions as shown in Fig. 1(b). The initial notch was inside 316L HAZ, approximately 3.6 mm away from the fusion boundary and almost parallel to the fusion boundary. The initial notch was chosen to be located at the hardest area in 316L HAZ, with a hardness of 230 $HV_{0.3}$ (Fig. 2).

Prior to being tested in high temperature water, the 1/2T CT specimen was pre-cracked in air with a maximum stress intensity factor (K_{max}) of 15 MPa$\sqrt{m}$, a load ratio ($R = K_{min}/K_{max}$) of 0.2 and a frequency of 20 Hz. The length of the pre-crack was about 2 mm. The specimen was then side-grooved to 5% of the specimen thickness on each side to guide the main crack growth in a straight line parallel to the fusion boundary, thus making the micro-hardness and microstructure along the crack path relatively homogeneous.

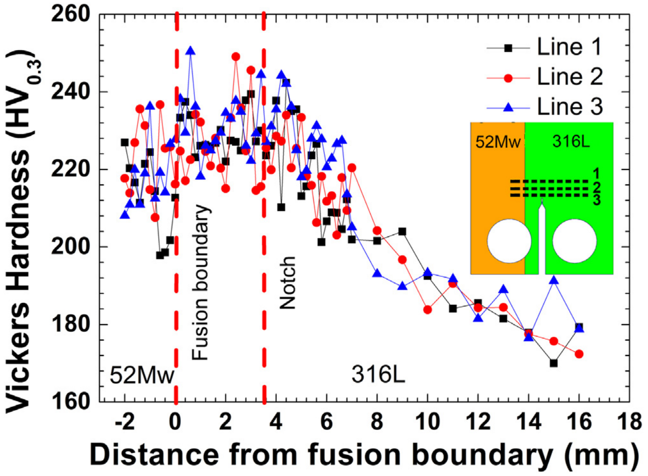

Fig. 2. The distribution of Vickers hardness (HV) of the 316L HAZ area.

2.2. SCC tests in simulated primary water

CGR was measured in a 6-L Hastelloy C-276 alloy autoclave equipped with a recirculating water system to precisely control the water chemistry (Fig. 3). The CT specimen was electrically isolated from the clamp and autoclave using zirconia bushings and spacers. The crack length of the CT specimen was continuously monitored by a direct current potential drop (DCPD) system. Generally, the CGR is determined by the slope of the crack length vs. time curve. Detailed description of this DCPD technique has been provided elsewhere [25].

The specimen was first corrosion fatigued (CF) by triangle loading at a K_{max} of 20 MPa$\sqrt{m}$, frequency of 0.01 Hz and R values of 0.3, 0.5, and 0.7 in turn to achieve the transition from mechanical pre-crack to corrosion crack. During SCC growth tests, the CT specimen was held at a constant load for 3 h, followed by a 500 s unload, 500 s reload cycle at an R value of 0.7.

The simulated primary water with a flow rate of 12 L/h contained 1500 ppm (by weight) B as H_3BO_3 and 2.3 ppm Li as LiOH. Tests were first performed at different temperatures ranging from 240 °C to 340 °C in simulated primary water containing 2000 ppb of DO. The DO content was then successively changed to 500 ppb, 100 ppb and <10 ppb at 320 °C. Eventually, the test was conducted in the simulated primary water containing 2800 ppb of DH (experimental details and conditions are summarized in Table 2). The crack extension during each test period was at least 4× (often more than