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A Study on PWSCC Initiation of Strain-hardened Ni alloys using Finite Element Analysis of Tapered Tensile Specimen

Ki-Hyeon Eom*, Sung-Woo Kim, Eun-Hee Lee, Dong-Jin Kim
Nuclear Materials Research Division, Korea Atomic Energy Research Institute,
Daedeok-daero 989 beon-gil 111, Yuseong-gu, Daejeon 34057, Republic of Korea
**Corresponding author: eomgh@kaeri.re.kr*

1. Introduction

Ni-based Alloy 600 was widely used as structural materials in pressurized water reactors(PWRs) [1]. However, many forms of corrosion including stress corrosion cracking(SCC) have been reported in operating PWRs. To replace Alloy 600, which is susceptible to SCC, Alloy 690 that contains more Cr is used over the last decades [2]. Until now Alloy 690 has been considered to be 'immune' to SCC in a primary water environment, because SCC failures have been not reported for Alloy 690 basedcomponents in operating PWRs. However, recent laboratory experiments have shown that Alloy 690 is also susceptible to SCC in the presence of very high strain or stress exceeding its nominal yield strength which may be induced by welding, cold-working, or surface finishing in the fabrication or repair process [3].

The purpose of this work is to evaluate threshold stress of PWSCC initiation using tapered tensile specimens of strain-hardened Alloy 600 and 690, with the aid of a finite element analysis of stress and strain of the specimens during a constant extension rate test.

2. Methods and Results

2.1 PWSCC initiation test method

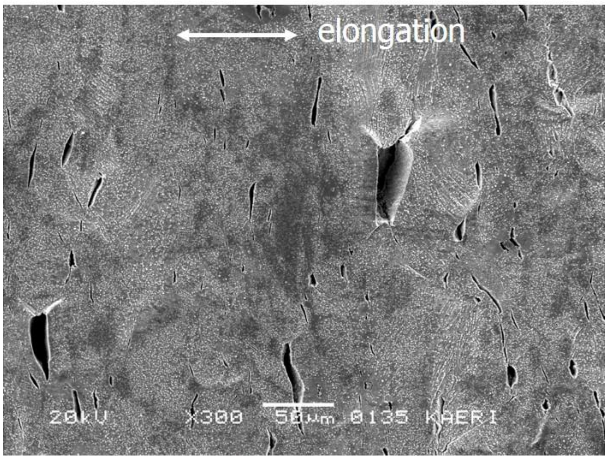
PWSCC initiation susceptibility and threshold stress were evaluated using tapered tensile specimens from constant extension rate test in a primary water at 360°C with a dissolved hydrogen content corresponding to Ni/NiO equilibrium potential at the test temperature [4].

2.2 PWSCC initiation test results

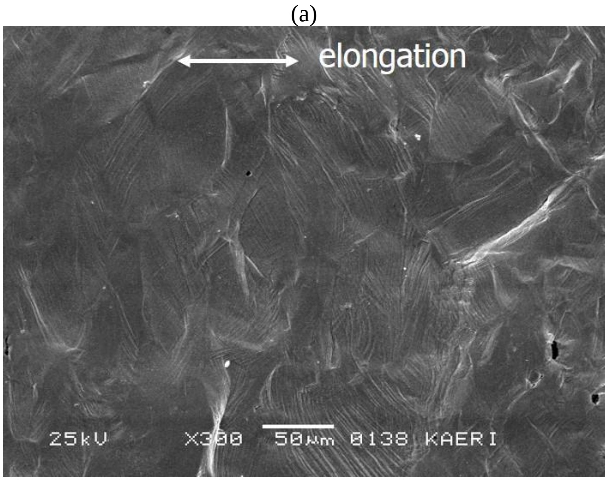
Fig. 1 shows the surface morphology of 40% cold-rolled Alloy 690 tested at constant strain rate of 1E-7/s to 7% strain for 140 h in two different environments of a primary water and air at the same test temperature. In Fig. 1(a), many shallow cracks were initiated in an intergranular (IG) and a transgranular (TG) mode with multiple slip bands, while no cracks were initiated in air, even similar slip bands were observed on the surface as shown in Fig. 1(b).

2.3 Threshold stress for PWSCC initiation

The tapered tensile specimen has been widely used to determine the threshold stress for cracking. The specimen fails generally near the smallest cross-section area of the gauge length, but additional cracks usually develops at lower stress portions. From the location of these additional cracks minimum stress for cracking can be estimated for the particular specimen. However, it is difficult to measure the exact stress and strain due to the different cross-section area along the gauge length and its change during the constant extension rate test. Therefore, 3D finite element model of the tapered tensile specimen was developed in this work to estimate the Von Mises stress and equivalent plastic strain at each location of the gauge length during the test, as shown in Fig. 2.

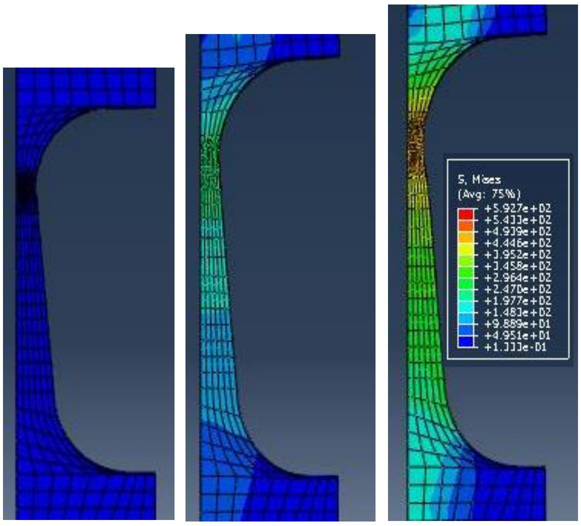


(a)

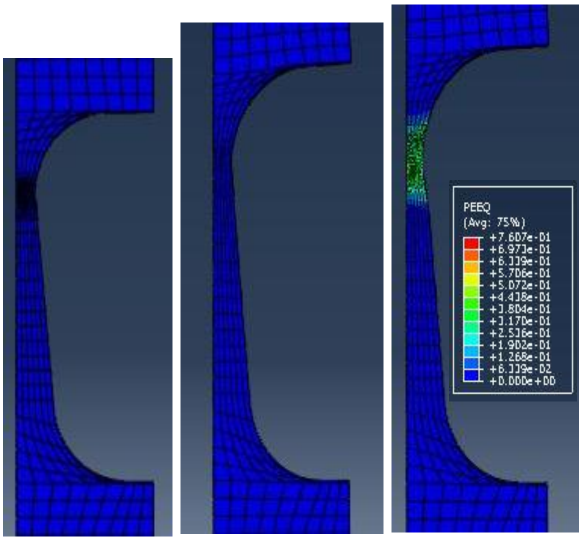


(b)

Fig. 1. The surface morphology of 40% cold-rolled alloy 690 after constant extension rate test (a) in a primary water and (b) in air at 360°C



(a)



(b)

Fig. 2. Von Mises stress (a) and equivalent plastic strain (b) of tapered tensile specimen during constant extension rate test using 3D FE model using ABAQUS^{TM}

Fig. 3 presents the plot of total cracking length per area vs. ratio of the applied stress to yield strength, measured on the tapered tensile specimens of strain-hardened Alloy 600 and 690. The intersection of the plot to the x axis can be interpreted as a threshold stress ratio of the particular specimen, with the aid of the finite element analysis developed in this work. The threshold stress ratio decreased from 1.5 for as-received Alloy 600 to 0.75 for 20% strain-hardened material with remarkable increase of susceptibility (total crack length per area). For Alloy 690, the threshold stress ratio decreased slightly when strain-hardened to 20% and 40%, but the susceptibility increased remarkably.

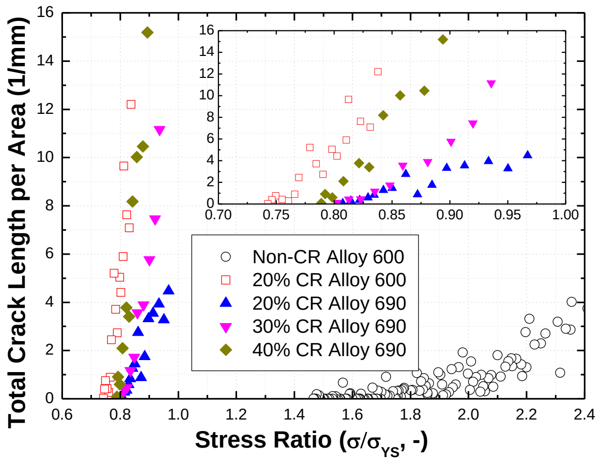


Fig. 3. Total crack length per area measured on tapered tensile specimens with different stress ratios.

3. Conclusions

In this work, the threshold stress and susceptibility of strain-hardened Ni alloys to PWSCC initiation was evaluated using the tapered tensile specimen design, with the aid of 3D finite element analysis. For strain-hardened Alloy 690, PWSCC initiated in both IG and TG modes when strain-hardened over 20%. The threshold stress ratio to yield strength measured on tapered tensile specimens decreased with strain-hardening, and more strain-hardened material revealed to be more susceptible to PWSCC initiation.

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