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Research Article

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Analysis on micro-mechanic field at SCC tip in the high hardness zone of a dissimilar weld joint

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ABSTRACT

Dissimilar weld joints in the safe end of nuclear pressure vessels are more susceptible to stress corrosion cracking (SCC). Microstructure and material property in the nickel-based alloy weld especially the high hardness zone (HHZ) are quite complicated and different from the bulk material, which make it more susceptible to SCC. To clarify the effect of sampling location on SCC driving force of an Alloy 182-A533B dissimilar weld joint, an inhomogeneous mechanical property model is established, the micro-mechanic fields at SCC tips in the HHZ with different sampling location are analyzed. The results indicate that the micro-mechanic field is obviously influenced by the material property of the HHZ. The equivalent plastic strain ahead of crack tip may be a more effective mechanical parameter in describing mechanical state close to the SCC tip. The crack growing will be retardant when the crack in Alloy 182 weld propagates from the dilution zone (DZ) towards low alloy steel (LAS). The yield stress jump in the HHZ will lead to a decreased crack growth rate.

Key words: Dissimilar weld joint, Nickel-based alloy, SCC, HHZ, Micro-mechanic field

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INTRODUCTION

In the primary loop recirculation (PLR) piping dissimilar weld joints, Alloy 182 are widely used as a weld filler metal to join LAS reactor pressure vessel (RPV) and pressure vessel nozzles to austenitic stainless steel (SS) [1]. The material and grain boundary properties of dissimilar metal weld make it has higher SCC susceptibility than bulk LAS or bulk SS. It has been found that the higher high-temperature yield strength of Alloy 182 could produce high weld residual stresses [2]. Recent work on complex microstructure characterization of FB region in an Alloy 182-A533B dissimilar weld joint revealed that the narrow zone near FB had the highest residual strain and hardness in weld region, which led to changing of mechanical property and corrosion resistance [3-5].

In previous fracture research, a weld joint was usually simplified as a sandwich-like configuration including the base metal (BM), the weld metal (WM) and the heat effect zone (HAZ) [6]. It is almost impossible to predict SCC growth rate around the FB line because of the discontinuous material mechanical parameters. In this paper, to clarify the effect of sampling location on SCC driving force in a dissimilar weld joint, an inhomogeneous mechanical property model is established to simulate the complex mechanical properties of the nickel-based alloy weld. Under the same load K_I, the local stress-strain fields ahead of propagating crack tips were calculated by using elastic-plastic finite element method (EPFEM). Moreover, the local micro-mechanic fields at SCC tips are analyzed with eleven 25 *mm* thick compact tension (CT) specimens in different sampling locations.

CALCULATION MODEL

Fig. 1 shows the result of Vickers hardness (HV) measurements in an Alloy 182-A533B LAS dissimilar weld joint, indicates the narrow HHZ around FB line had the highest hardness in the weld joint [7]. The focus region in this study is the HHZ around FB line, and its width is supposed to be 100 μm in Fig.1(b).

In Fig. 2, the dissimilar weld joint has five kinds of materials, i.e. Alloy 182 buttering & weld, the DZ, the HHZ, the heat affected zone (HAZ) and the A533B LAS. And there are eleven specimens near the FB region with different sampling positions. Mechanical relation of all these materials is represented as the Ramberg–Osgood equation:

$$\frac{\varepsilon}{\varepsilon_0} = \frac{\sigma}{\sigma_0} + \alpha\left(\frac{\sigma}{\sigma_0}\right)^n \quad (1)$$

Where, σ_0 is the yield strength of the material, ε_0 is the yield strain of the material, α is the dimensionless material constant and n is the strain hardening exponent. The corresponding yield strengths were calculated by a linear relationship between hardness and yield strength. Following the determination of yield strength σ_0, the strain-hardening exponents with different yield strengths will be estimated according to Eq. 1 [8].

$$n = \frac{1}{\kappa \ln(1390/\sigma_0)} \quad (2)$$

Where, κ= 0.163.

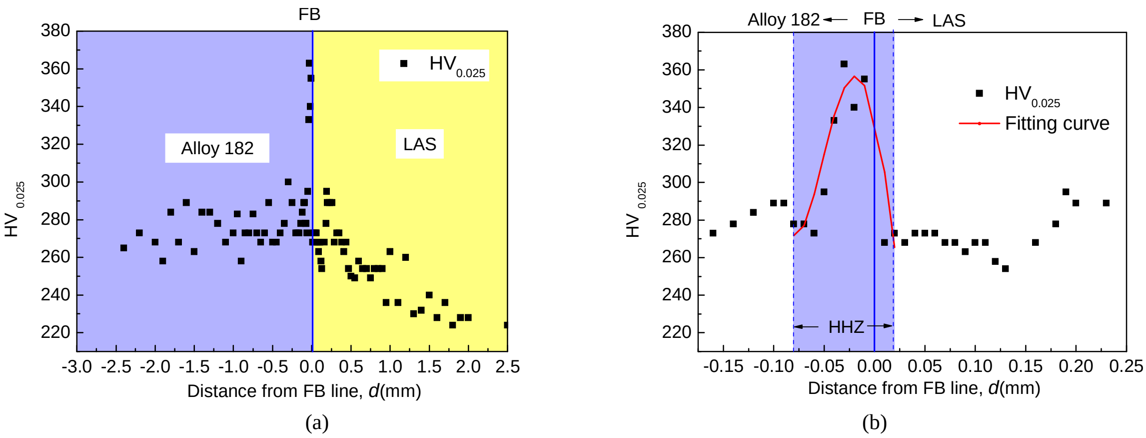


Fig.1 Profile of micro-hardness in the Alloy 182-A533B dissimilar weld joint (a) and in the HHZ (b) [7]

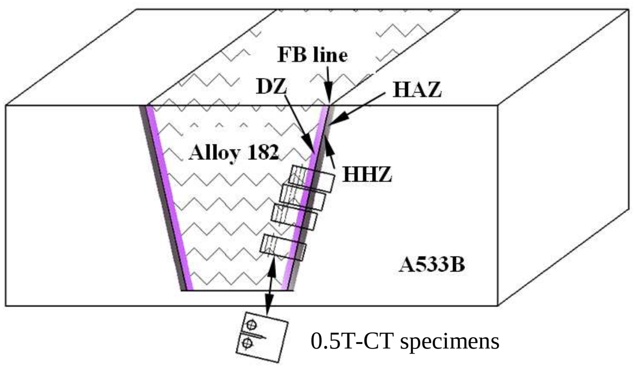


Fig.2 Schematic diagram of the sampling positions in an Alloy 182-A533B LAS dissimilar weld joint

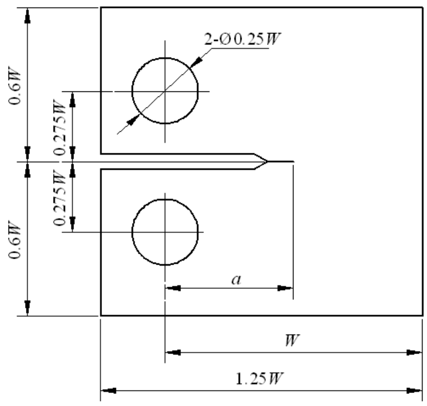


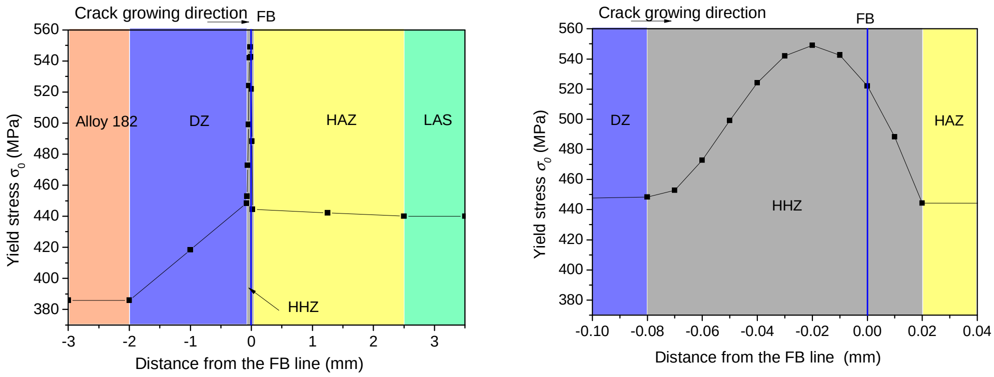
Fig.3 Geometric shape and size of a 0.5T-CT specimen. (where *W*=25 *mm*, *a*=0.5*W*)

A compact tension (CT) specimen with a constant load K_I was used to measure SCC growth rate in high temperature water environment [9]. Since the width of the HHZ was supposed to be about 100μm [7], the numerical tests with eleven 0.5T-CT specimens were performed to investigate the micro-mechanic field at SCC tip in the HHZ with different sampling location in an Alloy 182-A533B dissimilar weld joint. This numerical simulation process was guided by American Society for Testing and Materials (ASTM) standards [10]. Geometric shape and size of a 0.5T-CT specimen are shown in Fig. 3.

The material mechanical properties of different zones in three specimens are listed in Table 1. Yield stress and hardening exponent of the DZ, HHZ and HAZ are not listed because these parameters are changing along curves or straight lines. Fig. 4 delineates the changing yield stress of the DZ, HHZ and HAZ.

Table 1 Material mechanical parameters for the FEM simulation

Material	Young's modulus *E* (MPa)	Poison ratio ν	Yield stress σ_0 (MPa)	Hardening exponent *n*	Constant α
Alloy 182	193 000	0.288	385	4.779	1.0
DZ,HHZ,HAZ	193 000	0.288	--	--	1.0
LAS (A533B)	193 000	0.288	440	5.333	1.0



(a) (b)

Fig.4. Yield stress of the 0.5T-CT specimen(a) and near the HHZ zone (b)

RESULTS AND DISCUSSION

To investigate the mechanical affecting factors on the dissimilar weld joint SCC behavior, the local mechanical parameters such as stress, plastic strain and plastic zone in the crack tips under the loading parameter of stress intensity factor K_I were analyzed. The constant load K_I of 25 MPa·m$^{1/2}$ is adopted in this SCC experiment of simulated LWR environments.

1. Estimation of the characteristic distance

For a specific SCC system, the distance from a growing crack tip, '*r*', is expected to be dependent on mechanical properties and loading, which can be taken as a specific value of characteristic distance, 'r_0'. Therefore, before analyzing the local mechanical field, the critical issue is to estimate r_0. Considering that mechanical field near crack tip would be pertinent to SCC growth, it would be reasonable for r_0 to be a smaller value than the radius of plastic zone [9]. In Fig. 5, by comparing the radius of plastic zone in the crack tip when the equivalent plastic strain is 0.2% with different sampling locations, the reasonable distance is determined to be 20 μm. All the local mechanical parameters are taken at a characteristic distance (r_0=20 μm) ahead of crack tips with eleven sampling locations.

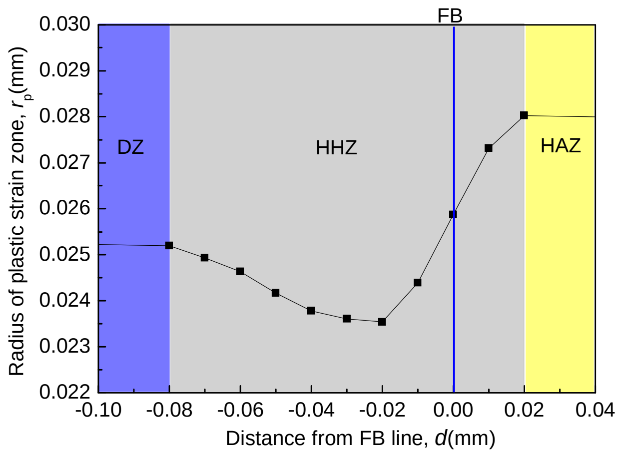


Fig.5 Radius of plastic zone in the crack tip when its equivalent plastic strain is 0.2%

2. Analysis of micro-mechanic field at SCC tip

Von Mises stress at a characteristic distance (r_0=20 μm) ahead of crack tips with different sampling locations is shown in Fig. 6 and Fig. 7, which means the stress near crack tip can be significantly higher in a high yield stress material than that in a low yield stress material under the same load K_I. In Fig. 6, the high stress areas are always close towards the zone with the highest yield stress, where the distance (*d*) reaches the FB line is -0.02 *mm*. Comparing Fig. 7 and Fig. 4(b), the stress is not the maximum in the zone (*d*=-0.02 *mm*) with the highest yield stress. It indicates that stress is obviously influenced by the material property of the HHZ around FB line.

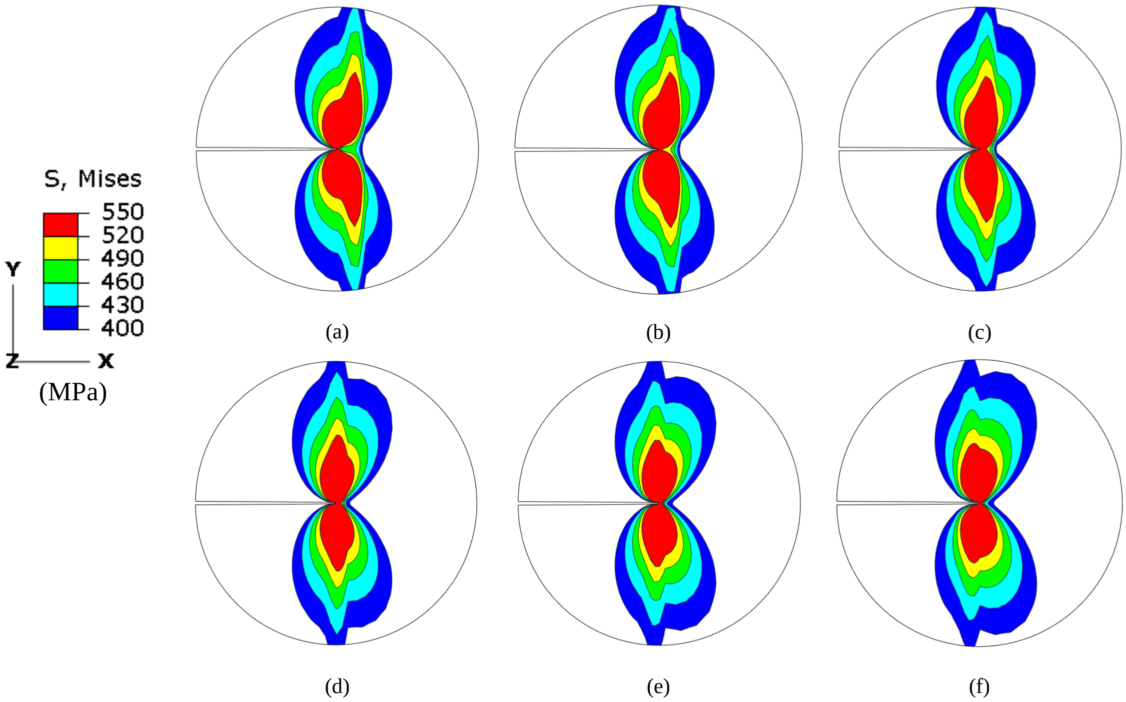


Fig.6 Von Mises stress distribution in the HHZ when *d*=-0.08 *mm*(a), *d*=-0.06 *mm*(b), *d*=-0.04 *mm*(c), *d*=-0.02 *mm*(d), *d*=0 *mm*(e) and *d*=0.02 *mm*(f)

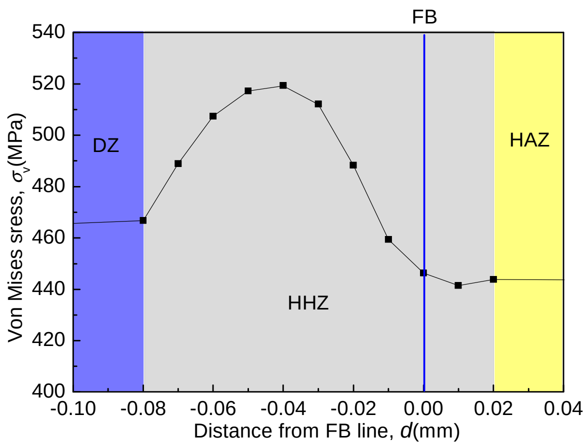


Fig.7 Von Mises stress at a characteristic distance ahead of crack tips

Equivalent plastic strain and plastic zone ahead of crack tip is shown in Fig. 8 and Fig. 9, where the strain is significantly lower in a high yield stress material than that in a low yield stress material. In Fig. 8, the low plastic strain areas are always close towards the zone with the highest yield stress, where the distance (*d*) reaches the FB line is -0.02 *mm*. Comparing Fig. 9 and Fig. 4(b), the strain is the minimum in the zone (*d*=-0.02 *mm*) with the highest yield stress. This result indicates that the effect of material properties in the HHZ around FB line on strain is smaller than that on stress. The equivalent plastic strain ahead of crack tip may be a more effective mechanical parameter in describing mechanical state close to the SCC tip. The crack growing will be retardant when the crack in Alloy 182 weld propagates from the DZ towards LAS.

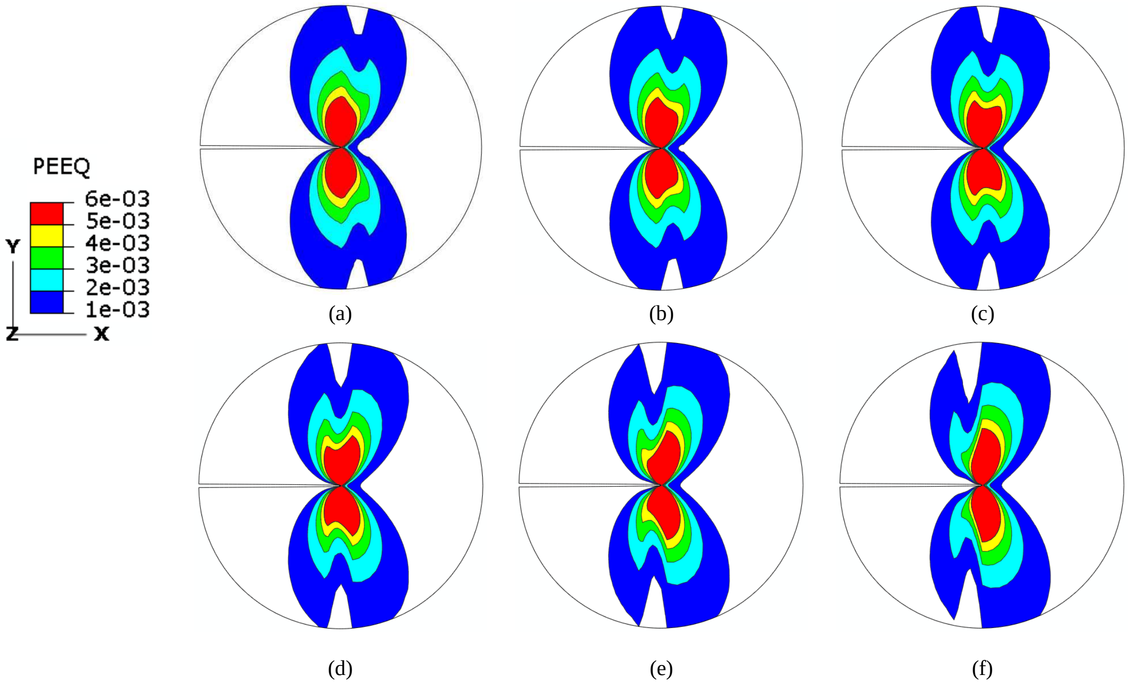


Fig.8 Equivalent plastic strain distribution in the HHZ when *d*=-0.08 *mm*(a), *d*=-0.06 *mm*(b), *d*=-0.04 *mm*(c), *d*=-0.02 *mm*(d), *d*=0 *mm*(e) and *d*=0.02 *mm*(f)

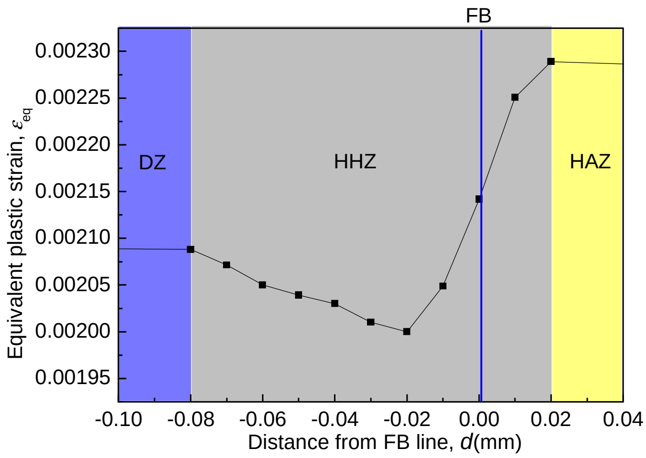


Fig.9 Equivalent plastic strain at a characteristic distance ahead of crack tips

CONCLUSION

Significantly higher stress and lower plastic strain near crack tip can be found in a high yield stress material than that in a low yield stress material under the same load K_I. The effect of material properties in the HHZ around FB line on strain is smaller than that on stress. The equivalent plastic strain ahead of crack tip may be a more effective mechanical parameter in describing mechanical state close to the SCC tip. The crack growing will be retardant when the crack in Alloy 182 weld propagates from the DZ towards LAS. The yield stress jump in the HHZ will lead to a decreased crack growth rate.

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