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Effect of Peening on Stress Corrosion Cracking of Alloy 182 in Simulated Pressurized Water Reactor Environment

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1. Introduction

Alloy 182 is commonly used as a weld filler metal in welding between nickel-based alloys, low-alloy steels, and austenitic stainless steels in nuclear power plants (NPPs) [1]. However, the sensitivity of Alloy 182 stress corrosion cracking (SCC) in the pressurized water reactor (PWR) high-temperature water environment affects the operational safety and component life of PWR nuclear power plants, and cracking cases have been reported. It is well known that the main reasons for PWSCC are tensile surface stresses, susceptible material, and the corrosive environment of PWR coolant [2]. Therefore, SCC can be mitigated by removing one or more of those three factors. Peening can introduce a high level of compressive residual stress on the finished parts and structures so that it can mitigate SCC initiation by removing the tensile stress. After peening, plastic deformation occurs on the surface, and high dislocation density causes changes in the surface microstructure, which can lead to hardening and improvement of mechanical properties. Various peening techniques have been developed, and some have been widely used in nuclear power plants in the United States and Japan [3]. A few studies have reported effects of residual stress mitigation techniques, but the mechanism of improvement in SCC resistance is not well understood [4]. Therefore, more studies are needed on the effects of the peening on the surface residual stress, microstructure underneath the peened surface, and SCC behavior.

In this study, it was intended to evaluate the effects of three peening techniques on SCC resistance of Alloy 182. Surface stresses and microstructure were analyzed after peening treatment on Alloy 182. The effect of the peening on SCC behavior was evaluated by conducting U-bend tests.

2. Experimental Methods

The chemical composition of Alloy 182 used in this study was analyzed: 72.54% Ni, 14.78% Cr, 3.5% Fe, 6.56% Mn, 1.83% Nb, 0.39% Si, 0.026% Ti, and 0.051% C. The microstructure and residual stress analysis using plate-type specimens were conducted as shown in Fig. 1(a). Three peening techniques of water jet peening (WJP), underwater laser peening (ULP), and ultrasonic nanocrystal surface modification (UNSM) were used to treat the 25mm*25mm area in the center of the plate specimen. All sample surfaces were ground before peening to simulate actual surface conditions of nuclear power components.

Evaluation of SCC behavior in simulated PWR high-temperature water environments was conducted using U-bend specimens. A schematic of the specimen are shown in Fig. 1(b). The top surface area of each U-bend specimen was peened after bending and assembly. The SCC experiment temperature was 360˚C, and the B and Li concentrations were 1200 ppm and 2 ppm, respectively. Dissolved hydrogen (DH) concentration was about 25 cc/kg. Dissolved oxygen (DO) concentration was maintained less than 5 ppb. Alloy 182 plate was cold-forged to ~20% before machining out U-bend specimens to increase the SCC sensitivity of Alloy 182 materials. The microstructure after peening was analyzed by electron backscatter diffraction (EBSD). The residual stress on the sample surface was analyzed by x-ray diffraction (XRD).

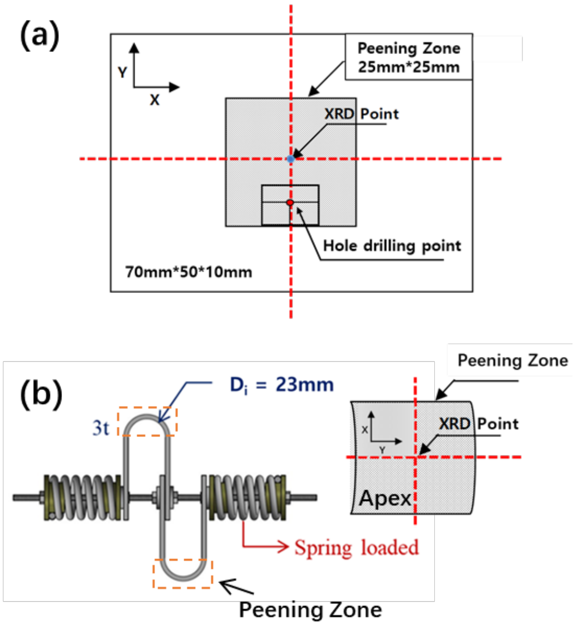

Fig. 1. Schematic of peening sample surface. (a) Microstructural analysis samples (x-direction: grinding and peening process direction, y-direction: peening step direction). (b) U-bend specimen. (x-direction: peening process and tensile direction, y-direction: peening step direction)

3. Results

3.1 Microstructure

The EBSD microstructure analysis results of the specimens after peening are shown in Fig. 2. The results show that near-surface microstructure changes caused by peening are dependent on the peening method. From the kernel average misorientation (KAM) images, it can be deduced that the ULP and WJP can produce a plastic deformation layer of less than 20~30μm deep. The UNSM peening method, however, can produce a significant plastic deformation layer of ~300μm deep. High dislocation density and changes in crystal orientation were also observed in image quality (IQ) and inverse pole figure map (IPF) images. The UNSM specimen shows almost non-discernible microstructure by EBSD images near the surface. However, it can be confirmed by transmission kikuchi diffraction (TKD) analysis if nano-scale grains are formed near the surface after peening. TKD analysis on peened specimen surfaces are planned.

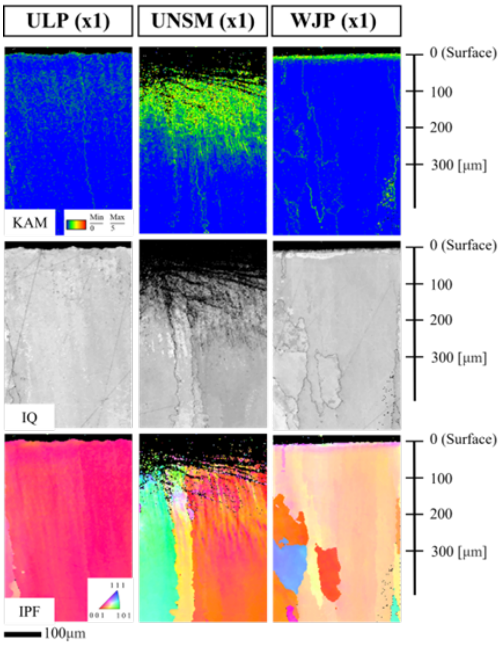

Fig. 2. EBSD microstructure analysis result of Alloy 182 plate specimen.

3.2. Residual Stress

The residual stress at the apex of U-bend specimen was measured by XRD stress measurement method. The results are shown in Fig. 3. Before peening, the level of stress on the U-bend apex surface ranges from 600~900 MPa. After ULP treatment, the x-direction stress is about -110~110MPa and the y-direction stress is about -530~-660MPa. After UNSM treatment, the x-direction stress is about -340~-450MPa and the y-direction stress is about ~-1400MPa. After WJP treatment, the x-direction stress is about -630~-720MPa. U-bend specimens treated with UNSM show higher levels of stress change due to the peening, and WJP may induce the similar level of stress change. UNSM specimens have relatively high compressive residual stresses in the x- and y-directions, which appears to be consistent with the microstructure analysis results.

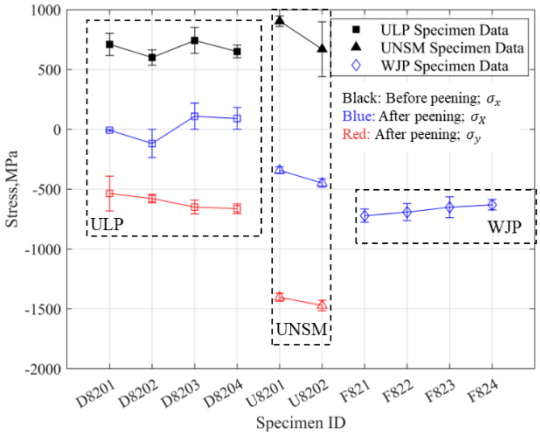

Fig. 3. Comparison of stress before and after peening of U-bend samples. The measurement location is the apex center. x-direction is peening process and tensile direction, y-direction is peening step direction.

3.3. SCC Test

Table 1 shows the SCC test results up to the exposure time of maximum 3,000 hours. Cracks were observed after 100, 200, and 300 hours of testing for samples without peening. One of the two UNSM samples showed a crack after 1000 hours of testing. The other had no cracks observed by 3000 hours. No cracks were observed for ULP and WJP specimens after 3000 hours of testing. According to the experimental results, it is shown that the surface treatment by peening improves the SCC resistance in the simulated PWR environments. Since the UNSM specimens showed higher compressive stresses than ULP specimens, the reason for the SCC initiation of UNSM specimen cannot be explained from the surface residual stress point of view alone. Further analysis on the surface microstructure is necessary, such as crystal orientation, dislocation density, and degree of cold work at the peened surface.

Table I: Results of 3000 h of exposure on Alloy 182 U-bend samples.

Surface Condition	Sample ID	Crack Observed Time, h
WJP	F821	No crack
	F822	No crack
	F823	No crack
	F824	No crack
ULP	D8201	No crack
	D8202	No crack
	D8203	No crack
	D8204	No crack
UNSM	U8201	1000
	U8202	No crack
Not peened	B8223	300
	B8224	100
	B8229	200
	B8230	200

4. Conclusion and Future Work

The effects of WJP, ULP, and UNSM peening on the microstructure, surface residual stress, and SCC behavior were evaluated. The following conclusions were drawn based on the test results obtained:

After the WJP, ULP, and UNSM treatment, the UNSM had the most pronounced effect on the microstructure. UNSM specimen showed an affected layer with a depth of ~300 μm. ULP and WJP specimens showed less than 20~30 μm deep affected layer.

The high level of tensile stress on the initial U-bend surface was clearly eliminated by the peening treatment. The WJP treated samples had a higher level of compressive stress in the x-direction, ranging from -630 to -720 MPa, but the UNSM showed smaller compressive residual stress than the WJP samples, ranging from -340 to -450 MPa. The residual stresses of ULP-treated U-bend samples were relatively insignificant compressive or slight tensile, ranging from -110 to 110 MPa.

According to the results of SCC experiments, the WJP, ULP, and UNSM can improve SCC initiation resistance of Alloy 182. The samples without peening were all cracked within 300 hours of testing. Only one of the UNSM treated samples showed cracking after 1000 hours. No cracks were observed in the ULP and WJP specimens even after 3000 hours of testing.

The surface microstructure characteristics caused by peening specimens will be analyzed using TKD and transmission electron microscope. The relationship between fracture surface characteristics and microstructure of cracked samples will be analyzed.

Acknowledgment

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