Effects of Peening on Material Properties and Primary Water Stress Corrosion Cracking Behavior of Alloy 600

Baosheng Bai[a*], Sungyu Kim[a], Joonho Moon[a], Wongeun Yi[b], Eunsub Yun[c], Chi Bum Bahn [a]
[a]*Pusan National University, 63 beon-gil 2, Busandaehag-ro, Geumjeong-gu,Busan 46241*
[b]*Doosan Enerbility, 22 Doosan-volvoro, Changwon Gyeongnam, 642-792*
[c]*Korea Hydro & Nuclear Power, 70, Yuseong-daero 1312beon-gil, Yuseong-gu, Daejeon, 34101*
E-mail: bahn@pusan.ac.kr

1. Introduction

Primary water stress corrosion cracking (PWSCC) poses a significant threat to the safe operation and lifespan of pressurized water reactors (PWRs). Alloy 600 is commonly utilized in various components, such as the reactor vessel head (RVH) penetrations, bottom-mounted instrumentation (BMI) penetrations, and nozzle safe-end welds. The first reported case of Alloy 600 PWSCC occurred in the Bugey Unit 3 vessel head penetration in France in 1991 [1]. Worldwide RVH replacement work is ongoing to maintain reactor safety.

Peening is a mechanical surface treatment technique that can alter the hardness, stress state, roughness, and microstructure of materials, among other characteristics. Several peening techniques have been developed, and in nuclear power plants, peening is used to induce high levels of compressive residual stress on finished parts and structures. which can mitigate stress corrosion cracking (SCC) initiation by removing tensile stress. Some peening techniques have been widely used in nuclear power plants in Japan and the United States [2]. Although some studies have reported the effectiveness of residual stress relaxation techniques, the mechanism for enhancing SCC resistance is still unclear due to the complexity of the SCC initiation mechanism [3]. Therefore, more research is required to investigate the effects of peening on surface residual stress, the microstructure beneath the peened surface, and SCC behavior.

The aim of this study is to evaluate the impact of underwater laser peening (ULP), water jet peening (WJP), and ultrasonic nanocrystal surface modification (UNSM) peening techniques on the SCC resistance of Alloy 600. The surface stress and microstructure of Alloy 600 after peening were analyzed, and the impact of peening on SCC behavior was evaluated by conducting U-bend tests.

2. Experimental Methods

The chemical composition of the Alloy 600 used in this study was analyzed, and the results showed that it contained 73.8% Ni, 16.1% Cr, 9% Fe, 0.2% Mn, 0.01% Nb, 0.29% Si, 0.19% Ti, and 0.07% C. Plate-type samples were used in this study to analyze the stress and microstructural changes of the samples after peening treatment, as shown in Figure 1(a). Three peening techniques, namely WJP, ULP and UNSM, were utilized to treat the 25 mm x 25 mm center area of the plate samples. Before peening, all sample surfaces were ground to simulate the actual surface condition of nuclear power components. U-bend samples were used to evaluate the SCC behavior in a simulated PWR high-temperature water environment. To increase the SCC sensitivity and shorten the experiment time, the Alloy 600 plate was cold-worked to about 16% before machining into U-bend samples. The schematic diagram of the sample is presented in Figure 1(b). The surface was polished to 800 grit before sample assembly, and the top surface area was peened after U-bend bending and assembly. The SCC test was conducted at 360 ˚C and 200 bar with B and Li concentrations of 1200 ppm and 2 ppm, respectively. The dissolved hydrogen (DH) concentration was about 25 cc/kg, and the dissolved oxygen (DO) concentration was maintained below 5 ppb. The microstructure of the samples after peening was analyzed by electron backscatter diffraction (EBSD), and residual stress was analyzed by X-ray diffraction (XRD).

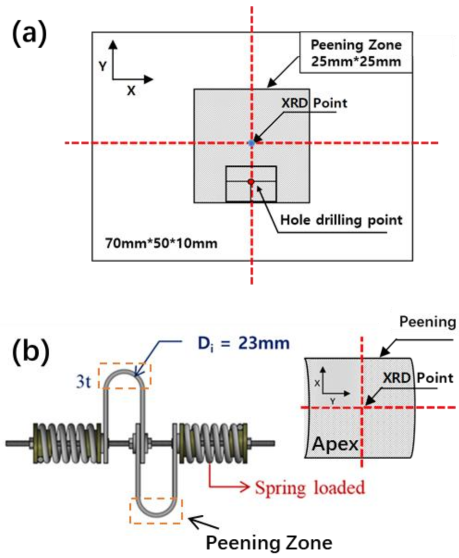

Fig. 1. Schematic of peening sample surface. (a) Microstructural analysis samples (x direction: grinding and peening process direction, y direction: peening step direction). (b) U-bend specimen. (x direction: peening process and tensile direction, y direction: peening step direction) [4]

3. Results

3.1 Microstructure

Figure 2 shows the results of microstructure analysis of the samples after peening using EBSD. The microstructure changes near the surface caused by peening are dependent on the peening method used. The Kernel Average Misorientation (KAM) image indicates that ULP produces a plastic deformation layer of about 200 µm deep, whereas WJP produces a plastic deformation layer less than 20 ~ 30 µm deep. In contrast, the UNSM peening method produces a significant plastic deformation layer of about 300 µm deep. Changes in high dislocation density and crystal orientation are also observed in the Image Quality (IQ) and Inverse Pole Figure (IPF) images. Previous studies have reported that the high plastic deformation of UNSM is the key to the formation of nanocrystals in the layer, and that high plastic deformation leads to grain refinement and dislocation increase [5]. Therefore, it is challenging to observe the microstructure clearly in the EBSD images of UNSM samples, and high-resolution Transmission Kikuchi Diffraction（TKD）analysis of peened specimen surfaces is planned for further investigation.

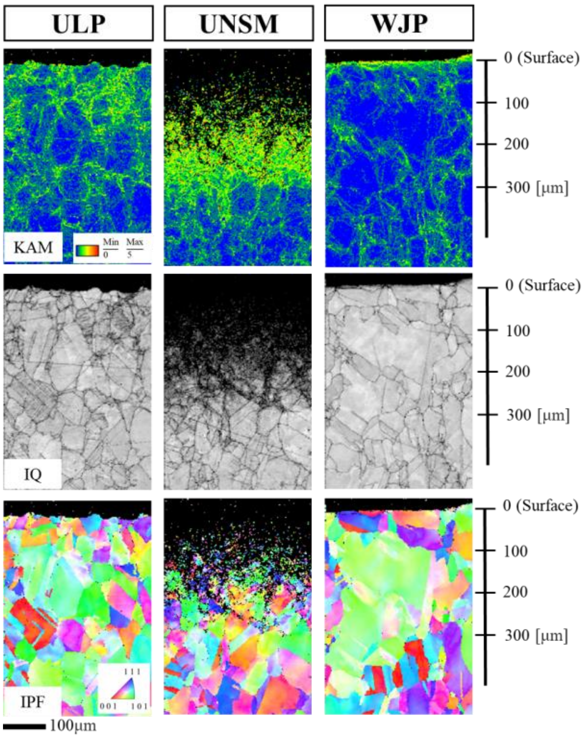

Fig. 2. EBSD microstructure analysis result of Alloy 600 plate specimen

3.2. Residual Stress

Figure 3 displays the XRD stress measurement results of residual stresses at the apex of U-bend specimens. Before peening, the surface of the U-bend had stress levels ranging from 600 to 900 MPa. Each peening method induced a compressive stress state on the surface. After ULP treatment, the stress level in the x direction was reduced to -120 to -200 MPa. The UNSM treatment resulted in x direction stress of about -120 MPa, while the y direction showed the highest compressive residual stress of about -1000 MPa. The WJP sample showed a compressive residual stress state of -300 to -400 MPa in the x direction. The shift of the surface from a tensile stress state to a compressive residual stress state can improve the resistance to SCC initiation. It is worth noting that the UNSM sample had the highest compressive residual stress among all three peening methods.

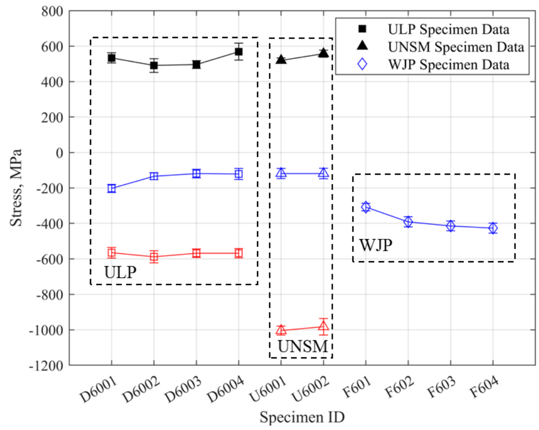

Fig. 3. Comparison of stress before and after peening of U-bend samples. The measurement location is the apex center. (x direction: peening process and tensile direction, y direction: peening step direction)

3.3. SCC Test

Table 1 presents the results of SCC tests for the longest exposure time of 5166 hours. For the two not peened samples (B6031, B6032), cracks smaller than 200µm were detected at 4166 hours, and one sample (B6024) showed cracks smaller than 200 µm after 5166 hours. The leg distance of sample B6023 was shortened after 3166 hours, leading to an increase in load, and cracks larger than 200 µm were observed after 5166 hours. In contrast, no cracks were observed in the WJP, ULP, and UNSM samples. These experimental results suggest that surface treatment by peening can enhance the SCC resistance of Alloy 600 in simulated PWR environments.

Table I: Results of Alloy 600 SCC test in Primary Water environment.

Surface Condition	Sample ID	Crack Observed Time, h	Total time, h
WJP	F601	No crack	5166
	F602	No crack	5166
	F603	No crack	5166
	F604	No crack	5166
ULP	D6001	No crack	5166
	D6002	No crack	5166
	D6003	No crack	5166

UNSM	D6004	No crack	5166
	U6001	No crack	5166
	U6002	No crack	5166
Not peened	B6023	5166	5166
	B6024	5166	5166
	B6031	4166	4166
	B6032	4166	4166

4. Conclusion and Future Work

Based on the test results obtained, the following conclusions can be drawn regarding the effects of WJP, ULP, and UNSM peening on microstructure, surface residual stress, and SCC behavior:

UNSM peening had the most significant influence on the microstructure, with an affected layer depth of about 300 μm. The affected layer in ULP specimens was about 200 μm, while the affected layer in WJP specimens was less than 20 ~ 30 μm.

Peening treatment eliminated the high-level tensile stress on the initial U-bend sample surface. The WJP-treated samples had a higher level of compressive residual stress in the x-direction, ranging from -630 ~ -720 MPa. The UNSM showed a lower residual compressive stress than the WJP sample, ranging from -120 MPa. The residual stress range of ULP-treated U-bend samples was -120 ~ -200 MPa.

The WJP, ULP, and UNSM peening processes have improved the SCC resistance initiation of Alloy 600. After 5166 hours of testing, no cracks were observed in the peened samples, whereas cracks were observed in the non-peened samples as early as 4166 hours.

The microstructure characteristics of the peened specimens will be analyzed using TKD and transmission electron microscopy. The relationship between the fracture surface characteristics of cracked samples and microstructure will be analyzed.

In summary, peening treatment effectively improved the microstructure and surface residual stress of Alloy 600, which contributed to its improved resistance to SCC initiation. Further analysis of the microstructure characteristics of the peened specimens will provide a better understanding of the mechanisms behind these improvements.

Acknowledgment

This work is financially supported by Korea Hydro & Nuclear Power Co.

REFERENCES

[1] Hwang S S. Review of PWSCC and mitigation management strategies of Alloy 600 materials of PWRs[J]. Journal of nuclear materials, 443(1-3): 321-330, 2013.

[2] Technical Basis for Primary Water Stress Corrosion Cracking Mitigation by Surface Stress Improvement: Materials Reliability Program, (MRP-267, Revision 2), EPRI, Palo Alto, 3002008083, 2012

[3] Telang, A. A Study of the Effects of Mechanical Surface Treatments on Residual Stresses, Microstructure and Stress Corrosion Cracking Behavior of Alloy 600 (Doctoral dissertation, University of Cincinnati), 2015.

[4] Effect of Peening on Stress Corrosion Cracking of Alloy 182 in Simulated Pressurized Water Reactor Environment. Transactions of the Korean Nuclear Society Autumn Meeting, 2022.

[5] Liu R, Yuan S, Lin N, et al. Application of ultrasonic nanocrystal surface modification (UNSM) technique for surface strengthening of titanium and titanium alloys: A mini review[J]. Journal of Materials Research and Technology, 11: 351-377, 2021.