Peening Effects on Surface Properties of Alloy 690

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1. Introduction

Primary water stress corrosion cracking (PWSCC) poses a threat to the safe operation and service life of pressurized water reactors (PWRs). Nuclear power plants have used methods to mitigate PWSCC by improving surface stresses, introducing stress corrosion cracking resistant materials, and coolant chemical control. Many studies have focused on improving surface stress: water jet peening (WJP), laser peening (LP), and ultrasonic nanocrystal surface modification (UNSM) [1,2]. These techniques improve surface stresses while also affecting hardness, roughness, and microstructure. Among them, LP and WJP have been used in some nuclear power plants in Japan and the United States [1]. The ASME code cases require ULP and WJP treatments to produce at least 1-mm depth of compressive residual stress on the surface [3,4]. However, there have been few studies on the changes in hardness, roughness, and microstructure of base materials under the condition of satisfying the 1-mm depth requirement for the residual compressive stress field. The study on these variations is of great value in evaluating the PWSCC resistance and mechanical properties. This study evaluates the effect of air laser peening (ALP), WJP and UNSM techniques on the surface roughness, hardness, stress, and microstructure of Alloy 690, which is one of main alloys used as nuclear components, especially weld regions. The effects of single and multiple treatments on their surfaces were also evaluated, considering the possibility of overlapping treatment areas and multiple treatments in practice.

2. Experimental Method

The chemical composition of alloy 690 used in this study is as follows: 60.2% Ni, 29.2% Cr, 9.5% Fe, 0.23% Mn, 0.23% Si, 0.2% Ti and 0.02% C. As shown in Fig. 1, a 25 mm x 25 mm central area of a plate specimen (70 mm x 50 mm x 10 mm) was treated by three techniques including WJP, ALP, and UNSM. Prior to the treatment, all specimen surfaces were heavily ground (HG) to simulate the actual surface conditions of nuclear components, especially weld regions. Surface roughness was measured using a Taylor Hobson surface roughness tester, and hardness values were measured at a depth of 1.5 mm from the surface using Vickers hardness. Surface residual stresses and the stress-depth profile were analyzed using X-ray diffraction (XRD) and hole-drilling stress measurement methods. The cross-sectional microstructure of the specimens was analyzed using electron backscatter diffraction (EBSD).

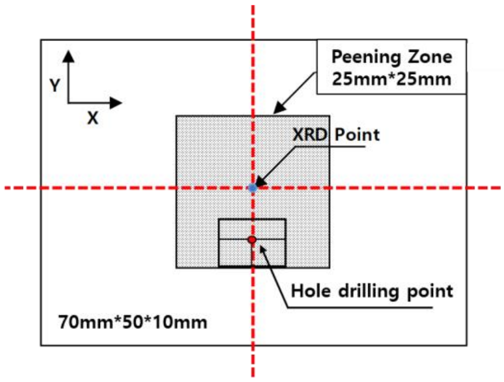


Fig. 1. Schematic of treatment specimen surface. Microstructural analysis specimens (x direction: grinding and peening process direction, y direction: treatments step direction).

3. Results

3.1 Surface roughness

The surface roughness measurements are shown in Fig. 2. The roughness of the base surface (HG surface) prior to the treatment is 1.4 µm or less. The roughness after single treatment of WJP was similar to that of HG surface before treatment, but with increasing number of treatments, the roughness increased, having the maximum roughness of 6.54 µm (x direction) after 8 treatments. The ALP treatment had very little effect on the roughness, although the maximum value was slightly increased to 2 µm (y direction) after 8 treatments. The roughness of UNSM increased to a maximum of 2.9 µm (y direction) after 2 treatments, and the other treatments were not significantly different from that of the HG surface.

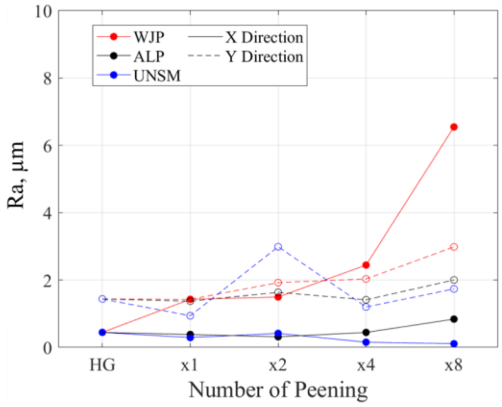
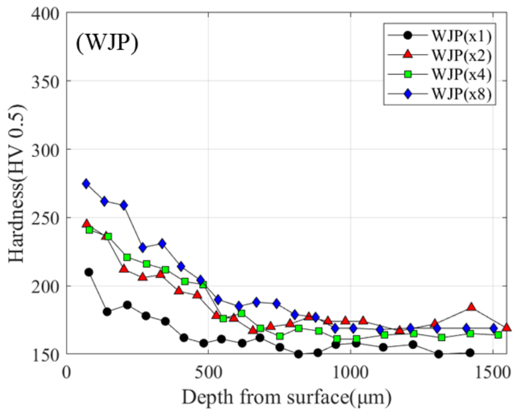


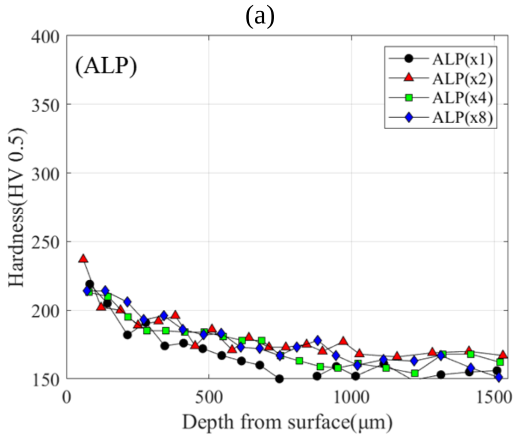
Fig. 2. Surface roughness measurement results.

3.2 Hardness

Figure 3 shows the hardness measurement results. The greatest increase in hardness was observed in the UNSM treated specimens, followed by the WJP and ALP. A 118% increase in surface versus baseline hardness was observed in the UNSM specimens after a single treatment, while 47% or 34% increase was observed in the WJP or ALP, respectively. All three techniques increased the hardness to a depth of approximately 1 mm. The effect of multiple treatments on the hardness depth profile was visible only in WJP, while ALP and UNSM showed insignificant changes.



(a)



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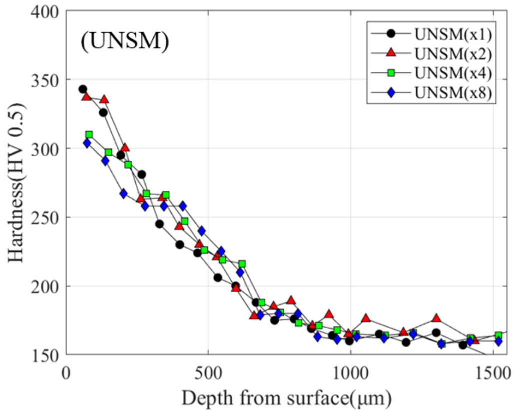

(c)

Fig. 3. Hardness measurements; (a) WJP specimens, (b) ALP specimens and (c) UNSM specimens.

3.3 Residual stress

Figure 4 shows the results of the surface residual stress. All three techniques induced compressive residual stresses on the surface, especially in the y direction, with the highest compressive stress value of about -1600 MPa after the UNSM treatment. The WJP treatment produced an equi-biaxial stresses of -520 MPa along x and y directions. The ALP treatment produced the highest y-direction stress of about -560 MPa and the lowest x-direction stress of about -250 MPa after a single treatment. The results of multiple treatments show that the compressive residual stress of ALP increases with the number of treatments, while the multiple treatment effects are minimal in WJP. The compressive residual stress on the UNSM surface decreased until 4 treatments but increased again after 8 treatments. Using the hole-drilling residual stress measurement method, it has been confirmed that all three techniques can produce a compressive residual stress field to the depth of 1 mm.

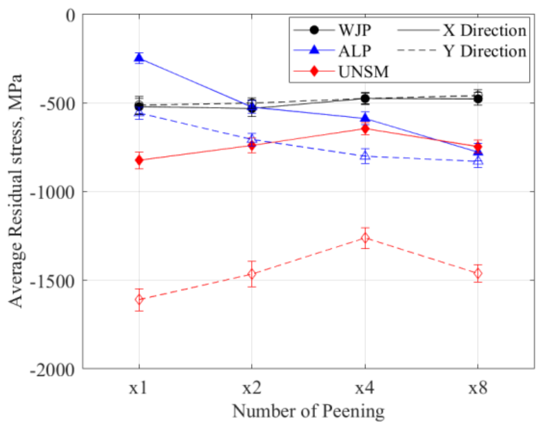

Fig. 4. Results of XRD residual stress measurements on specimen surfaces.

3.4 Microstructure

The cross-sectional microstructure analysis results of the treated specimens are shown in Fig. 5. The UNSM treatment method produced the largest plastic deformation after the single treatment, to the depth of about 300 µm. The high degree of plastic deformation near the surface made difficult for EBSD to observe crystalline information. This confirms that UNSM is heavily cold-worked more than ALP and WJP. The plastic deformation depth caused by ALP or WJP is about 30 µm after the single treatment. Within the affected layer, the accumulation of plasticity causes changes in grain orientation and grain refinement. Moreover, multiple treatments increased the depth of the affected layers in ALP and UNSM specimens, whereas WJP exhibited minimal effects of the multiple treatment.

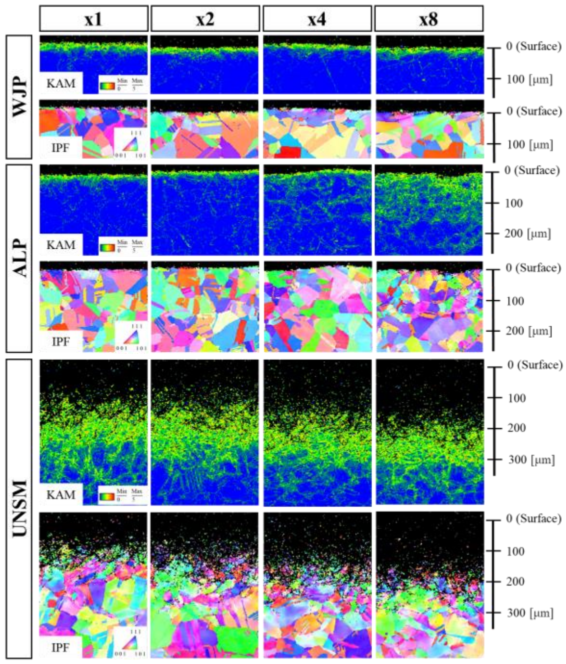

Fig. 5. Results of the EBSD microstructure analysis.

4. Conclusion

Based on the experimental results obtained, the following conclusions can be drawn regarding the effects of the WJP, ALP and UNSM treatment techniques on the surface roughness, hardness, microstructure and residual stresses of the heavily ground Alloy 690 specimens:

- All three techniques had no significant effect on roughness after a single treatment. However, WJP showed a trend of increasing roughness with increasing the number of treatments, while ALP and UNSM showed no significant change in roughness even after multiple treatments.
- All three techniques showed that hardness and compressive residual stresses were affected to a depth of around 1 mm after treatment.
- UNSM is capable of producing the highest compressive residual stress on the surface (about -1600 MPa). WJP can produce an equi-biaxial stress of -520 MPa, and ALP produces a minimum compressive residual stress of about -250 MPa along the peening direction. Multiple treatments do not increase the compressive residual stress values significantly except for ALP.
- UNSM has the greatest effect on the microstructure, followed by ALP and WJP. Within the affected layer, the accumulation of plasticity causes changes in grain orientation and grain refinement. Multiple treatments increase the thickness of the affected layers for ALP and UNSM, while the change in the affected layer thickness is insignificant for WJP.

Acknowledgment

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