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# Effects of Underwater Laser Peening on Microstructure and PWSCC Initiation of Alloy 182

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## 1. Introduction

Alloy 182 has been widely used as a filler metal for dissimilar metal welds in nuclear power plants. However, with long-term plant operation, primary water stress corrosion cracking (PWSCC) of Alloy 182 welds has been reported worldwide, becoming a key concern for the structural integrity of pressurized water reactor (PWR) primary components [1]. Improving the PWSCC resistance of weld metals is therefore essential.

Surface stress improvement (SSI) technologies are an effective means of mitigating PWSCC initiation. Among them, underwater laser peening (ULP) irradiates the surface with high-energy laser pulses to induce a plasma, whose rapid expansion, confined by water, generates a shock wave that introduces compressive residual stress (CRS) into the near-surface material [2]. Compared with conventional shot peening, ULP produces a deeper CRS layer (>1 mm) without introducing foreign materials into the reactor, and has been applied to operating plants.

However, since ULP is performed without a protective coating, laser ablation forms a melted-and-resolidified recast layer on the surface, which exhibits oxidation and micro-porous features; our previous study reported that the ULP recast surface is characterized by Cr depletion [3]. Because PWSCC initiation is highly sensitive to surface conditions, whether the recast layer acts as a preferential initiation site remains unclear, and direct evidence from long-term initiation testing is lacking.

In this study, the recast layer on ULP-treated Alloy 182 was characterized, and constant-strain U-bend tests were conducted in simulated PWR primary water at 360°C. The recast layer before and after testing was analyzed by SEM and TEM to clarify its role in PWSCC initiation.

## 2. Experimental Method

Alloy 182 weld metal was deposited on a stainless-steel plate by multi-pass welding. The chemical composition of the weld metal was 72.54Ni–14.78Cr–3.5Fe–6.56Mn–1.83Nb–0.39Si–0.026Ti–0.051C (wt.%). To accelerate PWSCC initiation within a practical test duration, the weld metal was cold-forged to a thickness reduction of 20–22% prior to specimen fabrication. Flat specimens (3 mm in thickness and 10 mm in width) were machined from the cold-forged material and then bent into U-shapes to yield an inner bend diameter of 23 mm, as depicted in Fig. 1. The specimen surfaces were ground and polished up to 800-grit SiC abrasive paper. After U-bending, ULP treatment was applied to the apex region of the specimens. Surface residual stresses at the U-bend apex were measured by XRD using the $\sin^2\psi$ method before and after ULP treatment.

PWSCC initiation tests were conducted in simulated PWR primary water containing 1200 ppm B and 2 ppm Li at 360°C and 20 MPa (200 bar). The dissolved hydrogen (DH) concentration was maintained at 25 cc/kg, and the dissolved oxygen (DO) concentration was kept below 5 ppb. The specimens were periodically removed and examined for crack initiation.

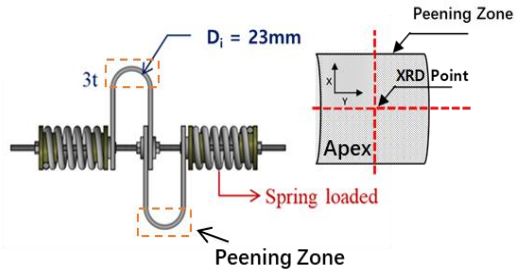



Fig. 1. Schematic of the U-bend specimen and the ULP-treated region.

## 3. Results

### *3.1 Surface Residual Stress*

The surface residual stresses at the U-bend apex before and after ULP treatment are shown in Fig. 2. The x-direction corresponds to the longitudinal (bending) direction, which is the primary tensile loading direction under constant strain. Before ULP, all specimens exhibited tensile stresses exceeding 600 MPa in the x-direction. After ULP, two specimens were converted to a compressive stress state, and the other two retained low tensile stresses below 110 MPa; substantial compressive stresses of −536 to −664 MPa were also established in the y-direction for all specimens. ULP thus effectively mitigated the tensile stress state on the apex surface, despite the constant-strain constraint imposed by the U-bend geometry.

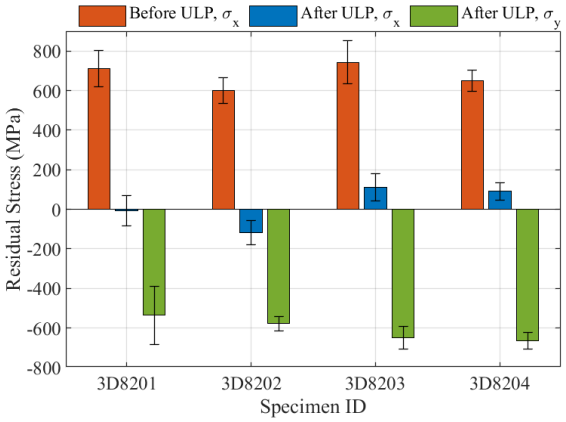



Fig. 2. Surface residual stresses at the center of the U-bend apex measured by XRD using the sin²ψ method before and after ULP treatment. σx denotes the stress in the longitudinal (bending) direction and σy the stress in the transverse (width) direction of the U-bend specimen.

### *3.2 Microstructure*

Figure 3 shows the cross-sectional EBSD analysis results of the U-bend specimens before and after ULP treatment. Before ULP, the mechanically polished surface exhibited a thin plastically deformed layer (<2 μm) with localized grain refinement. After ULP, this polishing-induced layer was removed by laser ablation, and the newly formed surface exhibited only moderate plastic deformation without distinct grain refinement.

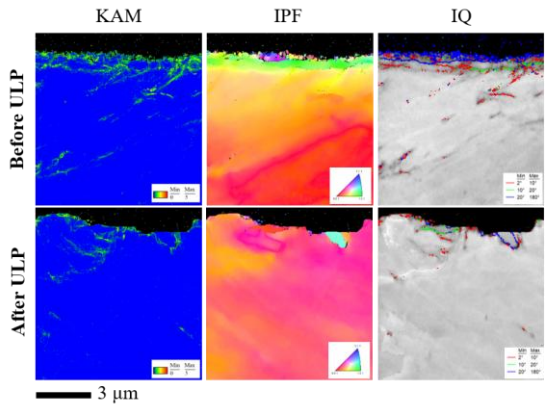



Fig. 3. Cross-sectional EBSD maps near the U-bend apex surface before and after ULP treatment (prior to the PWSCC test).

### *3.3 SCC Test*

The PWSCC initiation test results are summarized in Table 1. All four non-peened specimens cracked within 300 h of exposure, whereas none of the ULP-treated specimens showed crack initiation up to 4,166 h—more than an order of magnitude longer. Notably, PWSCC initiation was suppressed even in the two ULP specimens that retained low tensile stresses (~90–110 MPa) in the bending direction (see Fig. 2).

Table I: Results of Alloy 182 SCC test in Primary Water environment.

| Surface Condition | Specimen ID | Total Exposure Time, h | Cracking Time, h |
|---|---|---|---|
| ULP | 3D8201 | 4,166 | No crack |
| | 3D8202 | 4,166 | No crack |
| | 3D8203 | 3,166 | No crack |
| | 3D8204 | 3,166 | No crack |
| Non-peened (Only polished) | B8223 | 300 | 100-300 |
| | B8224 | 100 | 100 |
| | B8229 | 200 | 200 |
| | B8230 | 200 | 200 |

Figure 4 shows the post-test OM and SEM observations of the specimens. The non-peened specimens exhibited macroscopic cracks perpendicular to the bending direction at the apex (Fig. 4(a)), and the crack morphology, together with the faceted fracture features (Fig. 4(c)), indicates intergranular stress corrosion cracking (IGSCC), which is typical of PWSCC in Alloy 182. In contrast, no cracks were found on the ULP-treated surfaces; the apex surface was covered with the oxidized recast layer exhibiting a wavy, resolidified morphology (Fig. 4(b)), and cross-sectional examinations also confirmed the absence of crack initiation beneath the recast layer (Fig. 4(c)).

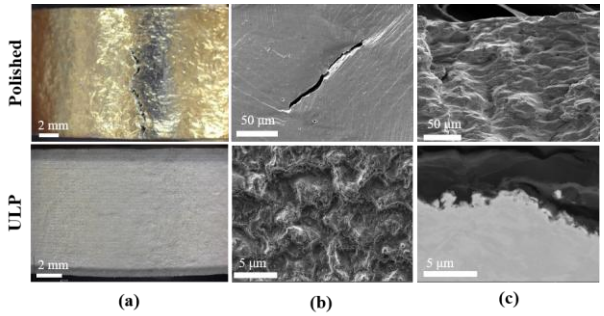



Fig. 4. Post-test (a) OM, (b) surface SEM, and (c) cross-sectional SEM images of the non-peened (upper) and ULP-treated (lower) specimens.

Figure 5 shows the TEM analysis of the ULP-treated specimen after 4,166 h of exposure, with the FIB specimen extracted from an inclusion-related surface defect site (Fig. 5(a)). The outermost surface was covered with a Ni–Fe oxide, beneath which a Cr–Fe oxide region was observed. This indicates that oxygen diffused into the Cr-depleted region of the recast layer [3], to a depth of approximately 250–300 nm. Although shallow intergranular oxidation was observed in the near-surface region, no intergranular cracking was found. The 250–300 nm oxidation depth measured at 4,166 h represents a single exposure point, so the kinetics cannot yet be determined. Longer-duration and interrupted exposure tests are required to clarify whether the oxidation saturates within the Cr-depleted recast layer and whether it remains benign under extended exposure.

Since the retained tensile stress (~90–110 MPa) corresponds to roughly 0.2σy of the cold-forged weld metal, it is likely below the threshold for PWSCC initiation, and the strong stress dependence of initiation alone accounts for the observed suppression. The large transverse compressive stress further reduces the hydrostatic stress at the surface and closes grain boundaries not aligned normal to the bending direction. The recast layer therefore appears to be permissive rather than protective: it removed the polishing-induced deformed layer and did not act as a preferential initiation site.

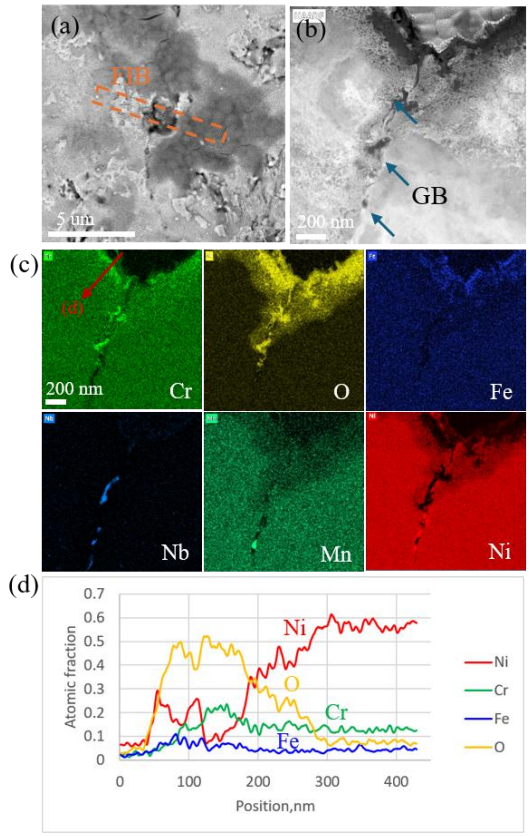



Fig. 5. TEM analysis of the ULP-treated specimen after 4,166 h of exposure: (a) surface SEM image showing the FIB lift-out location, (b) cross-sectional HAADF-STEM image, (c) EDS maps of (b), and (d) line-scan profile along the arrow in (c).

## 4. Conclusions and Future Work

The effects of ULP on the surface characteristics and PWSCC initiation behavior of Alloy 182 were investigated using U-bend tests in simulated PWR primary water at 360°C. The main conclusions are as follows:

(1) ULP effectively relieved tensile stress at the U-bend apex, reducing over 600 MPa of tensile stress to near-neutral or compressive values.

(2) ULP removed the polishing-induced deformed layer by ablation, and the new surface showed only moderate plastic deformation without grain refinement.

(3) All non-peened specimens cracked intergranularly within 300 h, whereas no ULP-treated specimen cracked up to 4,166 h.

(4) After exposure, no cracking occurred on the ULP recast layer surface; shallow intergranular oxidation along inclusion-rich grain boundaries was observed but did not develop into cracking.

Future work will focus on further TEM characterization of the surface oxides and their compositions to clarify the oxidation mechanism of the ULP recast layer.

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