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Project Title: Controlling Stress Corrosion Cracking of Alloys in Chloride Environments by Laser Shock Peening

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1. Research Progress

The ***overall goal*** of the proposed research is to determine the effects of laser shock peening (LSP) on the stress corrosion cracking (SCC) of alloys in chloride environments, which is by fulfilled by four objectives.

Objective 1: Determine a complete understanding of microstructural and micromechanical changes caused by LSP on alloys.

During the LSP process, a nanosecond-pulsed laser is shot to a material surface to form a plasma. The explosive expansion of the plasma generates shock waves that can penetrate into a depth of more than 1 mm from the surface. The compressive residual stress across the LSP-treated area is in a relatively uniform biaxial in-plane distribution along the depth. The magnitude of compressive residual stress is the highest on the surface, decreases gradually with the depth. Plastic deformation occurs in the material if the shock wave pressure is higher than the dynamic yield strength. Compressive surface residual stress can be introduced into the material surface due to the plastic deformation. The interaction of laser-driven shock waves with metallic materials results in typical microstructures of plastic deformation. Deformation twins, highly tangled dislocations, stacking faults, and dislocation cell structures have been observed in conventional and oxide-dispersion-strengthened (ODS) 304 steels using transmission electron microscopy (TEM) investigations (**Fig. 1a** and **1b**). The generation and multiplication of dislocations can lead to work hardening; twin boundaries can also resist the dislocation slip.

Objective 2: Identify the effects of LSP on the SCC susceptibility of alloys in chloride environments.

To quantify the benefit of LSP on SCC resistance of austenitic steels, the SCC initiation and propagation of LSP-treated 304 steel tensile specimens has been investigated. The LSP conditions are a power density of 15 GW/cm^2 and 15 scans, which results in a compressive residual stress of -252±12 MPa on the surface. The SCC test has been performed in a hot water environment with 42% $MgCl_2$ at 144 ºC under a constant tensile stress of 192 MPa. In the untreated 304 steel specimens, cracks had been initiated along grain boundaries and propagated after SCC test of 72 h (**Fig. 1c**). However, in the LSP-treated 304 steel, no cracks can be observed on the cross section grain morphology under the same condition, suggesting neither SCC initiation nor propagation (**Figure 1d**). In these specimens, there was no pre-fabricated notch crack and all the four surfaces of the gauge area were protected by the LSP-induced work hardening layers with a high-level compressive residual stress and thus resistant to SCC. The SCC crack growth rate of LSP-treated 304 steel tensile specimens with a pre-crack has been determined to study the propagation of SCC**.** The crack growth in untreated 304 steel is much faster than LSP-treated 304 steel. These results suggest that LSP improves the resistance to both SCC crack initiation and propagation.

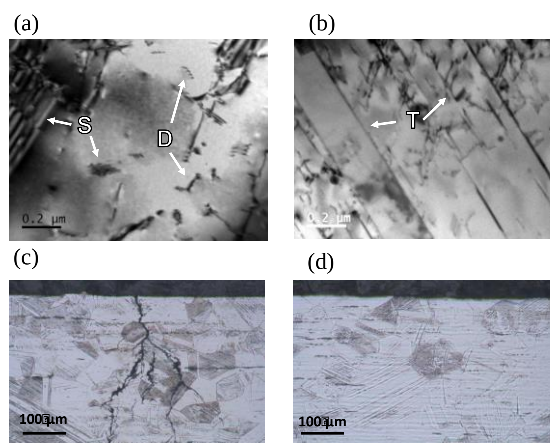

Fig. 1. (a)-(b) TEM images of near-surface microstructures of ODS 304 steels after LSP. S: stacking fault; D: dislocation; T: deformation twin. (c)-(d) Optical micrograph of the cross-section microstructures after SCC test of 72 hours: c) untreated 304 steels; d) LSP-treated 304 steels.

Objective 3: Determine mechanisms of the retardation of crack initiation and propagation in LSP samples.

The fracture surfaces of LSP-treated 304 steel were characterized by scanning electron microscopy (SEM) (**Fig. 2**). In the center of the facture surface of the LSP-treated 304 steel, intergranular cracks are dominant (**Fig. 2a**). However, near the surface of the specimen, where is within the LSP-affected-depth (about 500 µm), the fracture surface shows ductile features (**Fig. 2b**). In contrast, the entire fracture surface of the untreated 304 steel is dominated by intergranular cracks. The intergranular stress corrosion cracking (IGSCC) of austenitic steel is attributed to the Cr depletion due to sensitization, or impurity element segregation (e.g., Si) at grain boundaries. For the untreated 304 austenitic steel, the crack grows in form of IGSCC. The crack front is straight and parallel to the notch (yellow dashed lines in **Fig. 2c)**. While for the LSP-treated 304 austenitic steel, a LSP-treated layer of about 500 µm in depth with significant compressive residual stresses is present under both the top and bottom surfaces of the specimen. This layer is more resistant to SCC because the high-level compressive residual stress can retard the SCC initiation and inhibit the propagation of the cracks. However, the central part of the specimen is still susceptible to IGSCC due to the absence of compressive residual stress. Thus, the crack growth rate in the center of the specimen is much faster than in the near surface, leading to a curved crack front (yellow dashed lines in **Fig. 2d)**. With the propagation of the cracks, the thin LSP-treated layers is left behind. The local stress concentration in the LSP-layer is increased and eventually higher than the fracture strength. Then the near-surface LSP-treated layers is fractured in the ductile mode (**Fig. 2b**).

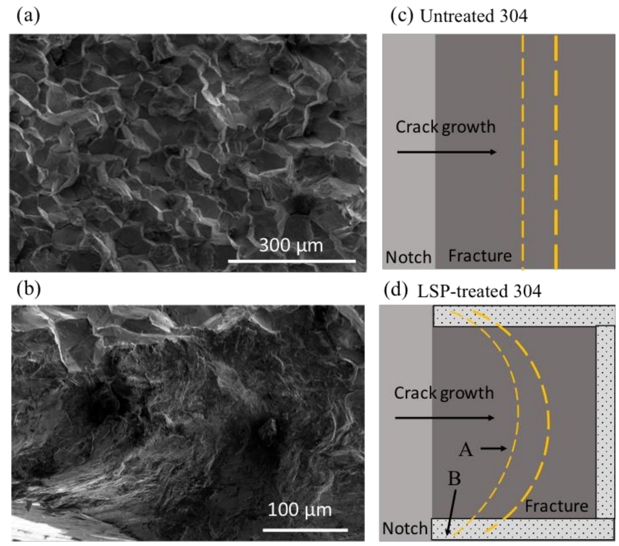

Fig. 2. (a)-(b) SEM images of fracture surface of LSP-treated 304 steel: (a) in the center (indicated by A in d); (b) near the surface of the specimen (indicated by B in d). (c)-(d) Schematic diagram of crack growth process in the cross-section of (c) untreated 304 steel and (d) LSP-treated 304 steel.

Objective 4: Optimization of LSP parameters for better mitigation of SCC in chloride environments.

Important LSP parameters include the laser pulse energy, power density, overlapping ratio, pulse number, temperature, and thickness of the sacrificial coating, all of which can influence the nature of the plasma and plasma-driven shock waves. We have investigated the effect of LSP parameters, such as laser pulse energy, laser pulse number and spot diameter, on SCC behavior. The LSP parameters can change the state of residual stress and the mechanical properties of austenitic steels, which can influence the SCC behavior. The magnitude of compressive residual stress generated by LSP is increased with the laser pulse energy and power density. The compressive residual stress on the surface increases with the number of LSP scans and becomes saturated after 20 LSP scans.

2. Impact on my career and the participated students

This two-year PRF grant is an important support for my early career as a tenure-track assistant professor. It has helped me establish my research lab, work in a cutting-edge research area, and build the collaboration with laser experts. I have become the vice chair for Corrosion and Environmental Effects Committee in the Minerals, Metals, and Materials Society (TMS) in 2017-2018 and an organizer of the "Environmentally Assisted Cracking" symposium in TMS annual meetings since 2017. This project has trained a graduate student and a postdoctoral fellow. They have published three papers from the hard work in this project. The postdoctoral fellow will present an oral presentation in the 2019 TMS annual meeting in San Antonio, TX.