Mitigating Stress Corrosion Cracking and Irradiation Damage of Austenitic Alloys by Laser Shock Peening

Fei Wang[1], Xueliang Yan[1], Xiaoxing Qiu[1], Chenfei Zhang[2], Yongfeng Lu[2], Qing Su[3], Michael Nastasi[3], Bai Cui[1]

[1]Department of Mechanical & Materials Engineering, University of Nebraska–Lincoln., [2]Department of Electrical Engineering, University of Nebraska–Lincoln, [3]Nebraska Center for Energy Sciences Research, University of Nebraska–Lincoln

Background

Due to the increasing demand for energy and environmental concerns related to emissions from fossil fuels, DOE launched the "Generation-IV Initiative" in 2000 to further advance nuclear energy systems design. In Generation-IV reactors, structural materials need to endure much higher neutron doses (>300 dpa), higher operation temperatures (> 200 ˚C over an 80 year lifetime), and extremely corrosive coolants (such as supercritical water, gas, sodium, or Pb).

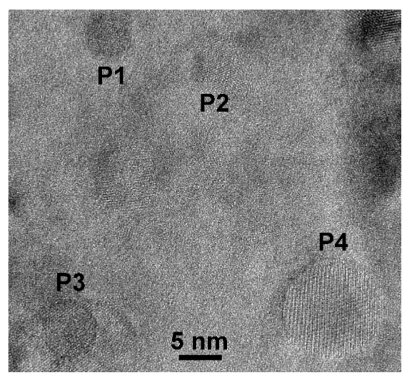


Figure 1. High-resolution TEM image of the ODS 310 **austenitic** stainless steel used in this project. Y-Ti-O nanoparticles ("P") are labeled.

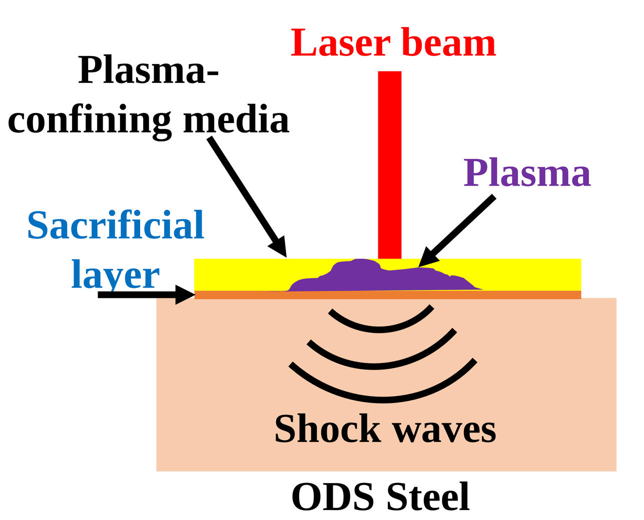
Oxide-dispersion-strengthened (ODS) alloys are promising candidate structure materials for Generation-IV reactors. In their microstructure, dispersions of Y-Ti-O nanoparticles (< 10 nm) in the stainless steel matrix (Figure 1) result in superior resistance to creep and irradiation damage at elevated temperatures. However, ODS **austenitic** alloys, such as ODS 304, 310 and 316 stainless steels, are susceptible to intergranular stress corrosion cracking (SCC) in primary and supercritical water environments. SCC is the growth of cracks due to the simultaneous action of a tensile stress and a corrosive environment. Material degradation due to SCC costs the U.S. nuclear industry over $10 billion in the last 30 years.

The goal of this research is to improve the SCC and irradiation damage resistances of ODS **austenitic** alloys using laser shock peening (LSP).

Experiment

- **Laser shock peening**

In the LSP process, the rapid expansion of a plasma on the surface generates shock waves into the bulk material, which induce significant compressive residual stresses (0.1-1 GPa). LSP is superior to the mechanical shot peening in the benefits of deeper penetration of compressive stress, shorter process, precise control, accuracy, flexibility and no contamination.



Spot Size (mm)	1
Pulse energy (mJ)	100-900
Duration time (ns)	7
Overlap	50%
Repetition-rate (Hz)	10
Wavelength (nm)	1064
Beam profile	Gaussian

- **In situ irradiation**

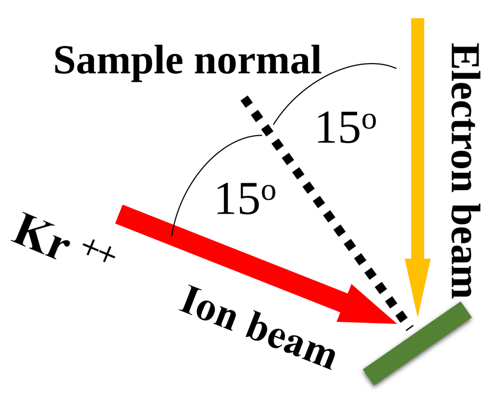


Figure 2. The IVEM-Tandem in-situ irradiation facility

- **Stress corrosion cracking**

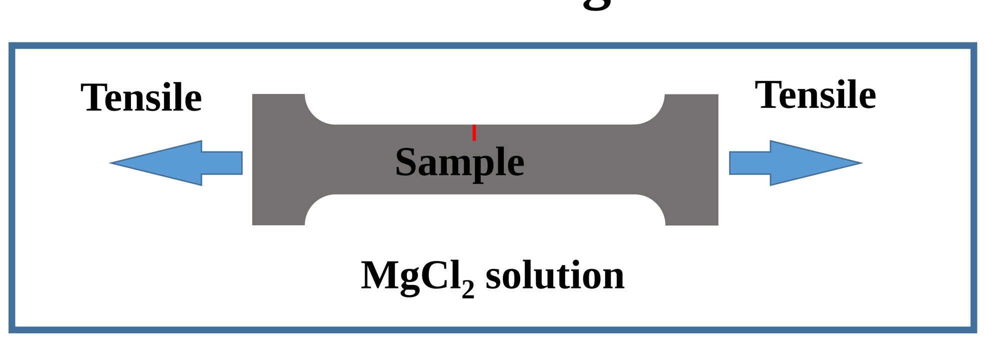


Figure 3. Schematic view of SCC set up.

Prevention of SCC by LSP

LSP is a new approach that can prevent SCC of **austenitic** stainless steels, but the mechanisms are poorly understood. Preliminary test data shows that:

(1) ODS **austenitic** alloys are susceptible to SCC. The crack growth rate in the ODS 304 stainless steel is slightly higher than the regular 304 steel (Figure 4).

(2) SCC occurred significantly in the original 304 stainless steel sample, which shows transgranular cracks (Figure 5a). In contrast, no apparent cracks are present in LSP-treated samples under the test environment (Figure 5b).

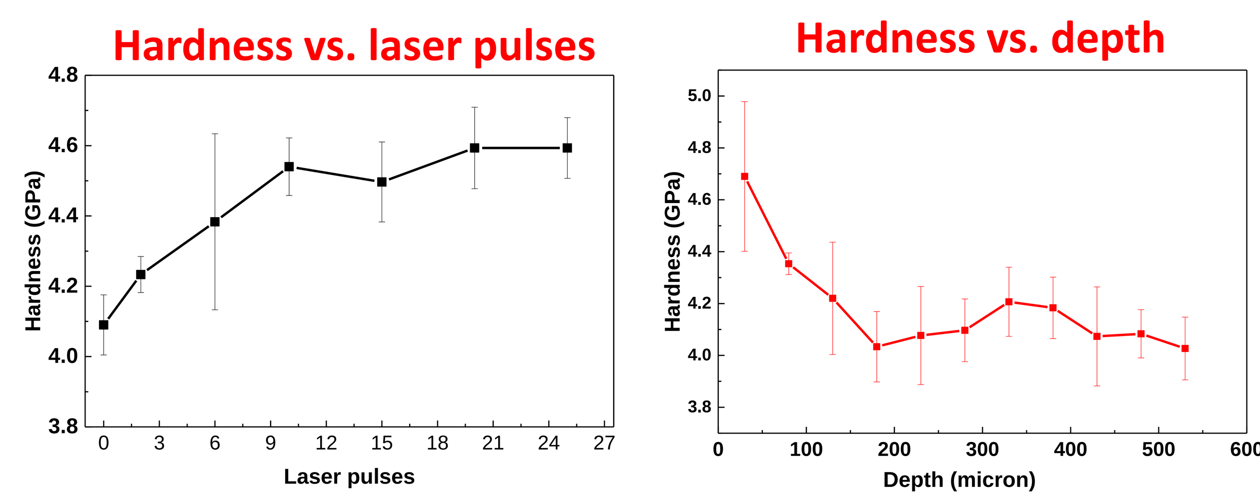


Figure 4. The hardness change of sample after laser peening: (a) hardness vs time; (b) hardness distribution along depth.

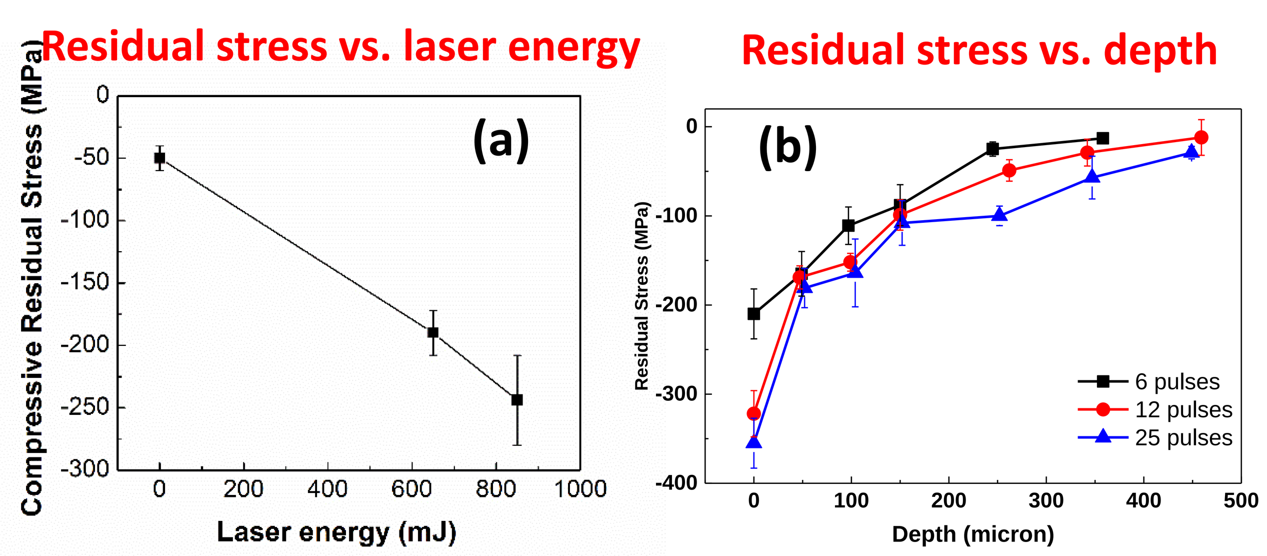


Figure 5. (a) The surface residual stress of sample after laser peening. (b) residual stress distribution along depth.

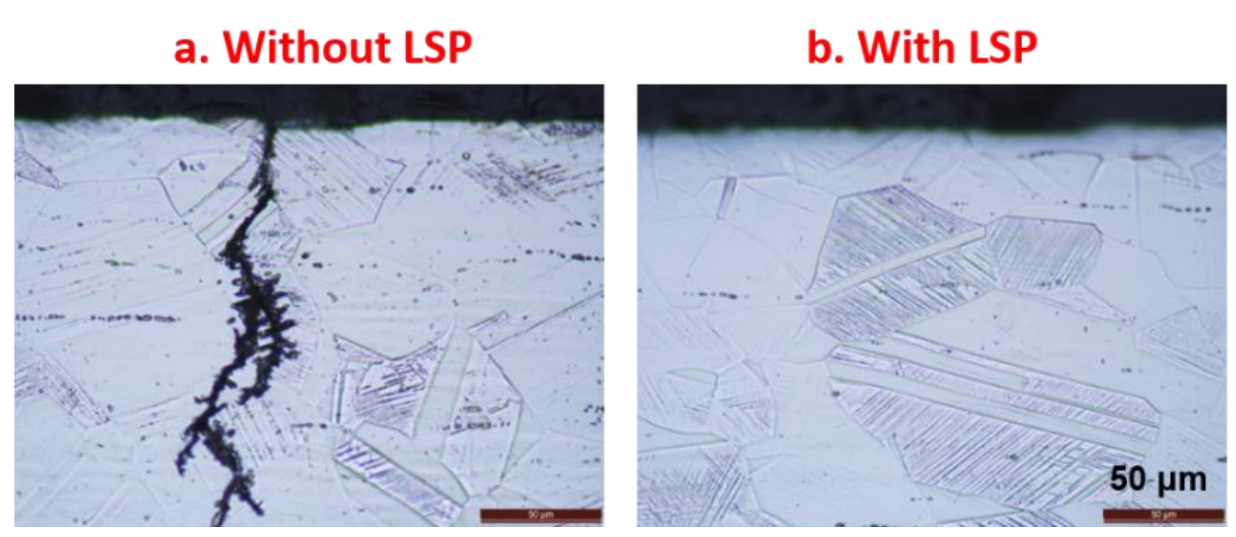


Figure 6. Stress corrosion cracking (SCC) test results in in a hot water environment with 42% $MgCl_2$ at 144 ºC for 168 hours: (a) original 304 stainless steel; (b) 304 stainless steel treated by LSP with 850 mJ laser pulse energy and 4 laser pulses. The images are optical micrographs of the cross-section microstructure.

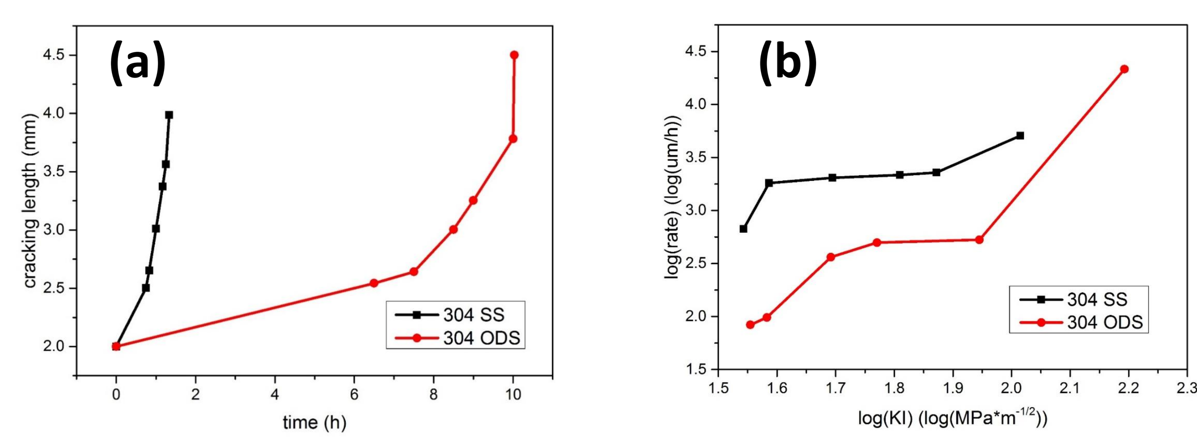


Figure 7. The SCC behavior of 304 stainless steel and 304 ODS: (a) crack length vs time; (b) crack rate vs stress intensity factor K_I.

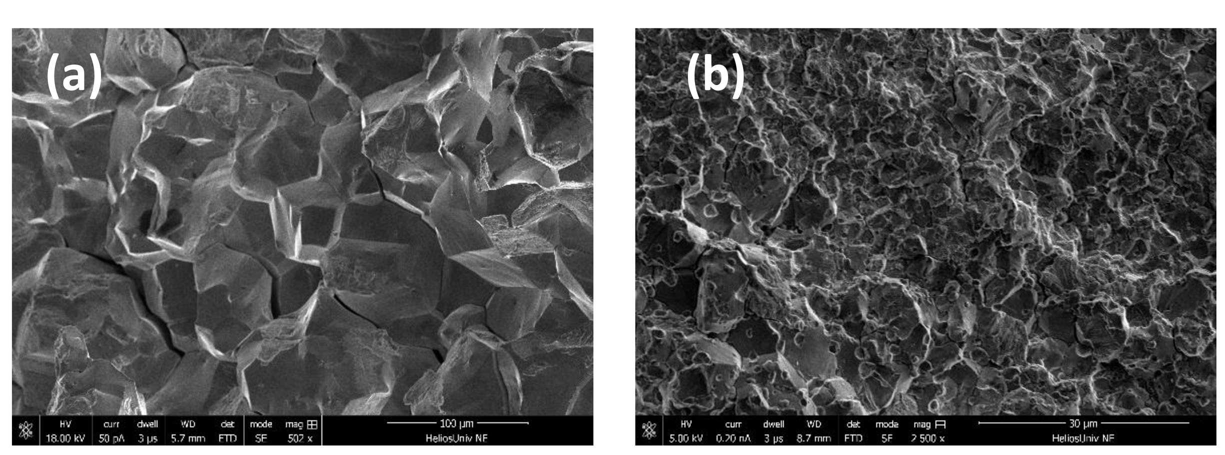


Figure 8. Fracture surface of (a) 304 stainless steel and (b) 304 ODS alloy.

Microstructures of Laser-Peened Stainless Steels

Interaction of laser-driven shock waves with **austenitic** stainless steels results in dislocation networks, stacking faults, and deformation twins in the near surface, suggest that significant plastic deformation occurred in stainless steels during the LSP process. When the pressure of shock waves exceed the yield strength of an alloy, it will experience an extremely high strain-rate (10^6–10^8 s^{-1}) during a short period of time and be dynamically yielded.

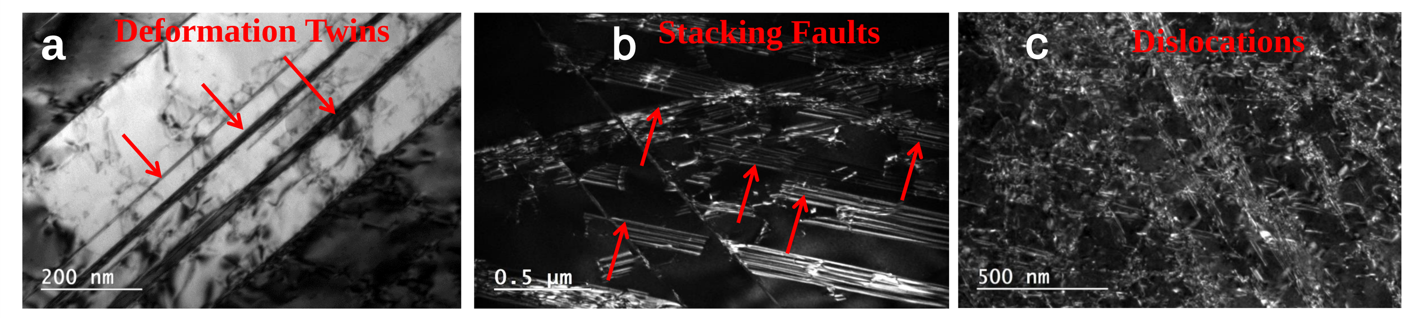


Figure 9. Typical transmission electron microscopy (TEM) images of near-surface microstructures of 304 **austenitic** stainless steel treated by laser shock peening (LSP): (a) deformation twins (arrowed); (b) stacking faults (arrowed); (3) high-density dislocations.

During *in situ* TEM irradiation experiments observed that twin boundaries and dislocations in laser-peened 304 steels can serve as effective sinks for the annihilation of irradiation defects. As a result, the irradiation defect density in laser-peened 304 steels is just 15~25% of that in untreated samples.

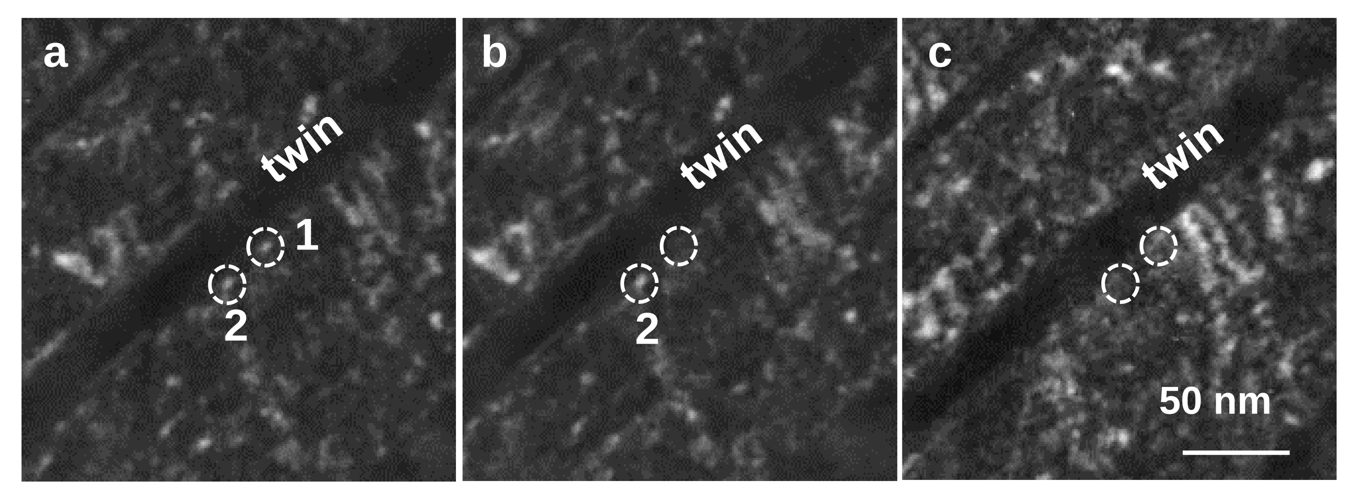


Figure 10. Annihilation of irradiation defects by a twin boundary in laser-peened 304 steel sample: (a) two defect clusters 1 and 2 (bright spots in circles) formed at 0s; (b) defect cluster 1 was annihilated at 4s; (c) defect cluster 2 was annihilated at 32s.

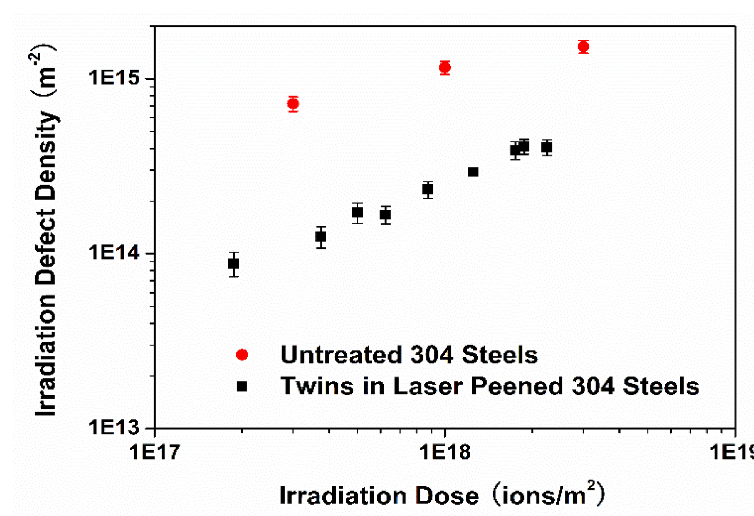


Figure 11. Evolution of irradiation defect density in untreated and laser-peened 304 steels (twin region) under 1 MeV Kr^+ irradiation at room temperature

Conclusions

- The LSP process has been used to prevent SCC and reduce the irradiation damage of ODS austenitic alloys in high-temperature water environment.
- These effects are related to a deep penetration of compressive residual stress, and the microstructural changes in the near surface by the interaction of laser-driven shock waves with the materials.
- The laser-driven shock waves in the LSP process can produce severe plastic deformation in austenitic stainless steels. Dislocation networks, stacking faults, and deformation twins were generated in the near-surface region of laser-peened 304 stainless steels.
- The dislocation network and incoherent twin boundaries can serve as high strength sinks for the annihilation of irradiation defects clusters during the heavy ion irradiation.

Acknowledgement

We gratefully acknowledge the Energy Research Grants from the Nebraska Center for Energy Sciences Research. This work was supported by the Nebraska Public Power District through the Nebraska Center for Energy Sciences Research, Research Council Faculty Seed Grant from the University of Nebraska-Lincoln, and the Department of Energy (DOE) Office of Nuclear Energy, Nuclear Energy Enabling Technologies [grant number DE-NE0000533]

NCMN Nebraska Center for Materials and Nanoscience University of Nebraska
LASER ASSISTED NANO ENGINEERING LAB (LANE) DEPARTMENT OF ELECTRICAL ENGINEERING
University of Nebraska Lincoln NEBRASKA CENTER FOR ENERGY SCIENCES RESEARCH
Argonne NATIONAL LABORATORY