Laser Shock Peening of Oxide-Dispersion-Strengthened **Austenitic** Alloys

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Background

Due to the increasing demand for energy and environmental concerns related to emissions from fossil fuels, the U.S. Department of Energy 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).

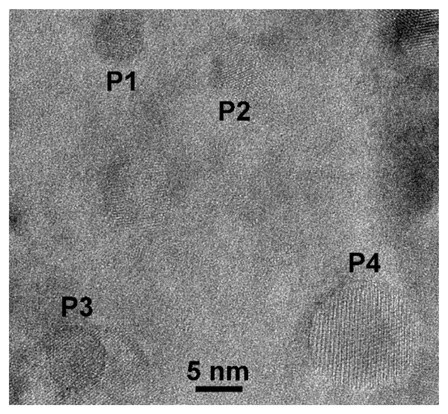


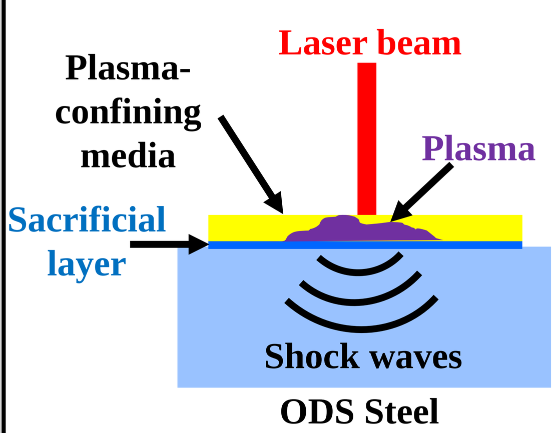
Figure 1. High-resolution TEM image of the ODS 310 **austenitic** stainless steel used in this project. Y-Ti-O nanoparticles ("P") are labeled.

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 develop new types of ODS **austenitic** alloys that are more resistant to SCC and irradiation damage using laser shock peening (LSP).

Laser Shock Peening (LSP)

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). The compressive stresses can extend to a depth of more than 1 mm from the surface. LSP is superior to the mechanical shot peening in the benefits of deeper penetration of compressive stress, shorter process time (7 ns for 1 laser pulse), 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

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.

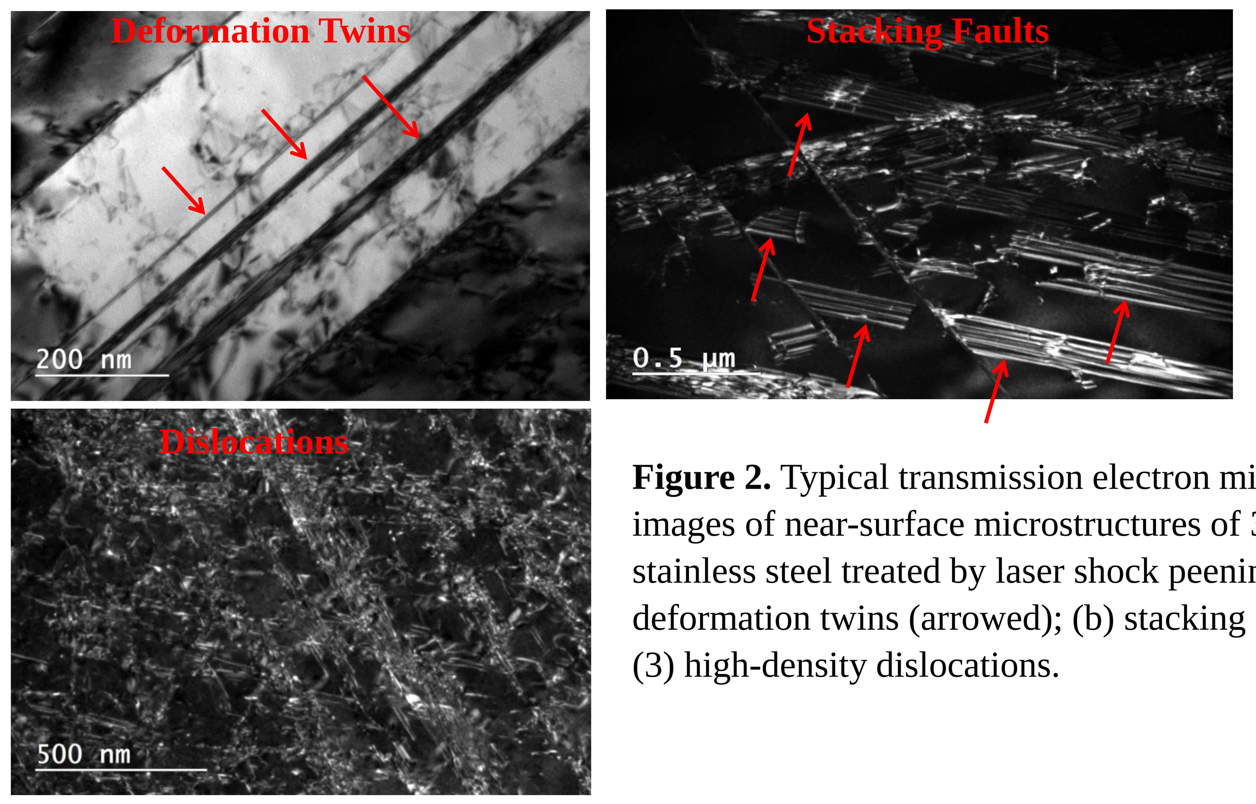


Figure 2. Typical transmission electron microscopy (TEM) images of near-surface microstructures of 304 **austenitic** stainless steel treated by laser shock peening (LSP): (a) deformation twins (arrowed); (b) stacking faults (arrowed); (3) high-density dislocations.

Prevention of SCC by LSP

LSP is a new approach that can prevent SCC of regular **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 steels is slightly higher than the regular 304 steel (Figure 3).

(2) SCC occurred significantly in the original 304 stainless steel sample, which shows transgranular cracks (Figure 4a). In contrast, no apparent cracks are present in LSP-treated samples under the test environment (Figure 4b).

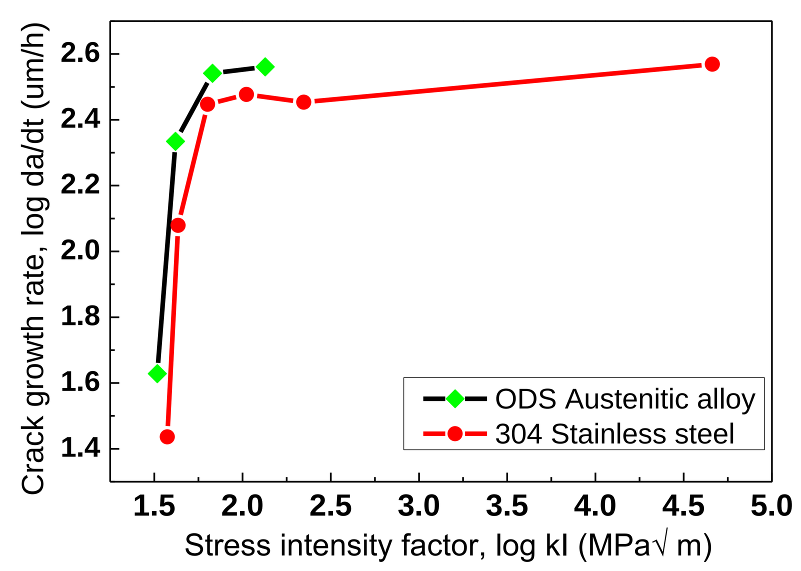


Figure 3. Crack growth rate diagram of the ODS **austenitic** alloy in comparison with 304 stainless steel.

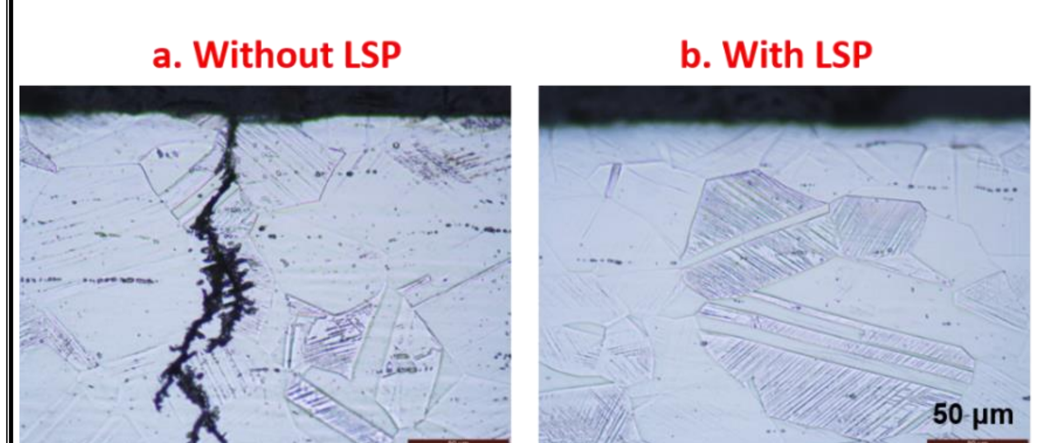


Figure 4. Stress corrosion cracking (SCC) test results in in a hot water environment with 42% $MgCl_2$ at 144 ℃ for 168 hours: (a) original 304 stainless steel; (b) 304 stainless steel treated by LSP with 850 mJ laser pulse energy and 4 laser pulses. The images are optical micrographs of the cross-section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

The next step will determine: (1) the relationship between LSP parameters and SCC prevention effects; (2) the mechanisms that enable LSP to prevent SCC.

Improved Irradiation Resistance by LSP

The irradiation tolerance of materials can be improved by the introduction of nanoscale interfaces as sinks to irradiation defects. In laser peened ODS steels, we envision that a high density of sinks for defect annihilation is present in the microstructure, which include a large number of dislocation networks, twin boundaries and grain boundaries generated by laser peening, in addition to the oxide-particle/matrix interfaces.

During 1 MeV Kr^+ irradiation, *in situ* TEM irradiation experiments at Argonne National Laboratory 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.

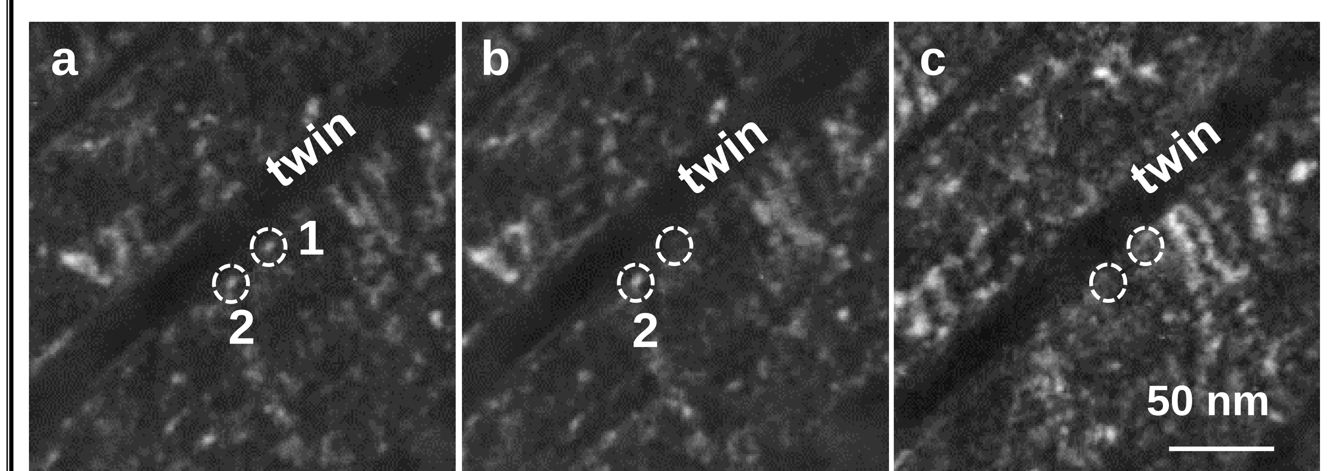


Figure 5. Annihilation of irradiation defects by a twin boundary in laser-peened 304 steel sample: (a) two defect clusters 1 and 2 (bright spots in circles) formed at 0s; (b) defect cluster 1 was annihilated at 4s; (c) defect cluster 2 was annihilated at 32s.

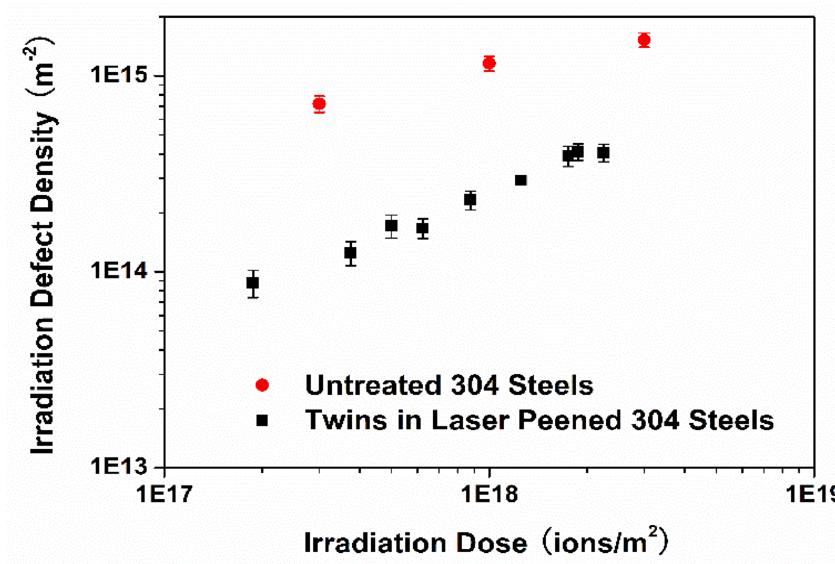


Figure 6. Evolution of irradiation defect density in untreated and laser-peened 304 steels (twin region) under 1 MeV Kr^+ irradiation at room temperature

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.

References

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