Novel Irradiation and Stress Corrosion Cracking Resistant Oxide-Dispersion-Strengthened Stainless Steels

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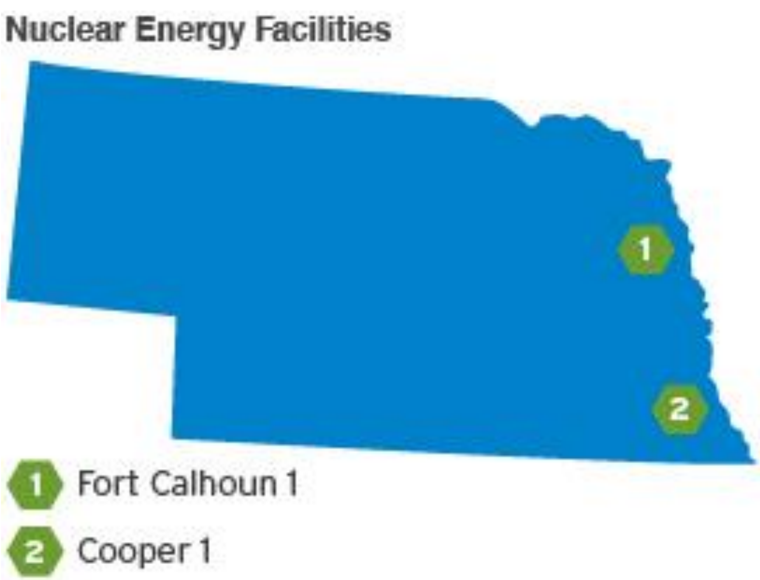
Nuclear Energy in Nebraska

- **Nuclear energy is important in generating a large amount of electricity: ~20% for US and ~31% for Nebraska**
- **It generates "clean" electricity without emissions of "greenhouse gases" (CO_2, SO_2, No_x)**
- **<u>It reduces electricity bills for every family in Nebraska!</u>**

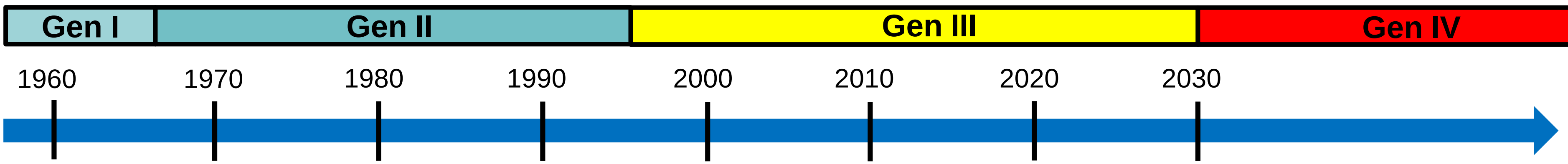


Cooper began generating electricity in 1974, and will continue operating until 2034.

http://casenergy.org/nuclear-basics/energy-in-your-state/nebraska/

Generation-IV Nuclear Energy Systems

- **Energy demand is predicted to grow ~66% by 2030**
- **Generation-IV nuclear power plant equipment must be more resilient**



Early Prototypes

Commercial light water reactors (LWRs): BWR, PWR…

Advanced LWRs: ABWR, APWR…

Super-critical water reactor, very high temperature reactor, molten-salt reactor, gas-cooled fast reactor…

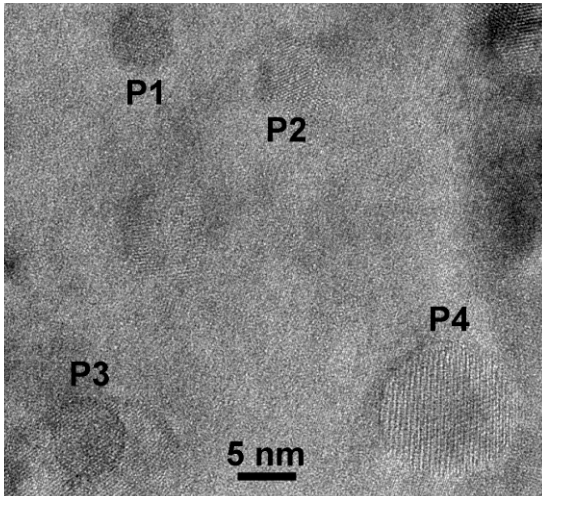
- **Advantages of Gen-IV nuclear systems:**
  - ✓ Highly economical
  - ✓ Enhanced safety
  - ✓ Minimal nuclear waste…
- **Materials for Gen-IV systems must endure:**
  - ✓ High neutron doses (> 300 dpa)
  - ✓ High operation temperatures (> 200 ˚C over 80 years)
  - ✓ Corrosive coolants (e.g. supercritical water, molten salt)

Oxide-Dispersion-Strengthened (ODS) Steels

- **ODS steels are promising structural materials for Gen-IV nuclear energy systems.**
- **Dispersion of Y-Ti-O nanoparticles (<20 nm) inside a steel matrix.**

- **Advantages**
  - ✓ **Excellent creep resistance (retaining high strength at high temperatures)**
  - ✓ **Improved irradiation resistance**

- **Problem**
  - ✓ **Stress corrosion cracking in high-temperature water coolant**



High-resolution TEM image of ODS 310 austenitic stainless steel

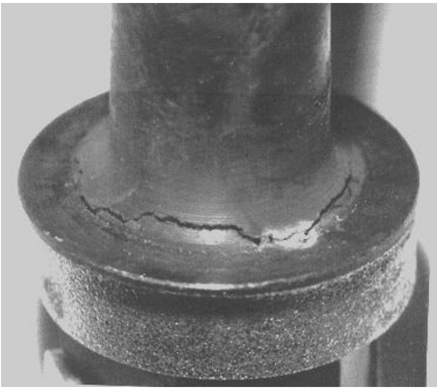
B. Cui, et al. Transactions of American Nuclear Society, 2015, 112, 292

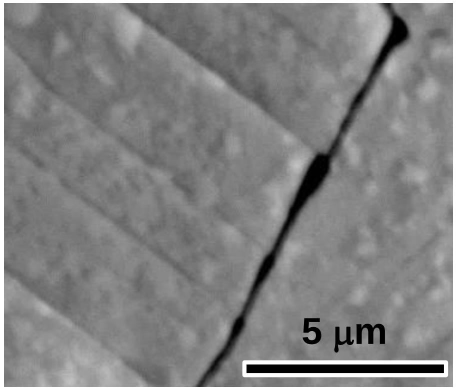
Research Goal

- **Stress corrosion cracking (SCC) and irradiation damage are two vital problems that limit the lifetime of stainless steel components in nuclear reactors**
  - ❖ **Cost of SCC for nuclear industry: > $330 million/year!**
- **Goal: develop new ODS stainless steels that are resistant to SCC and irradiation damage using laser shock peening (LSP).**

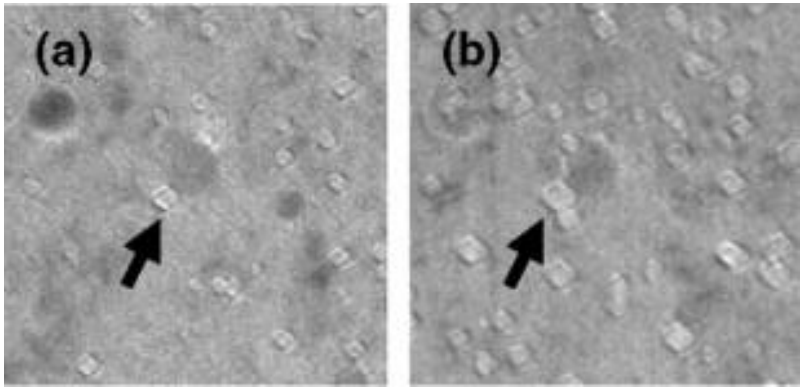
Macroscale

Microscale





SCC in an austenitic stainless steel baffle bolt in a pressurized water reactor (PWR)

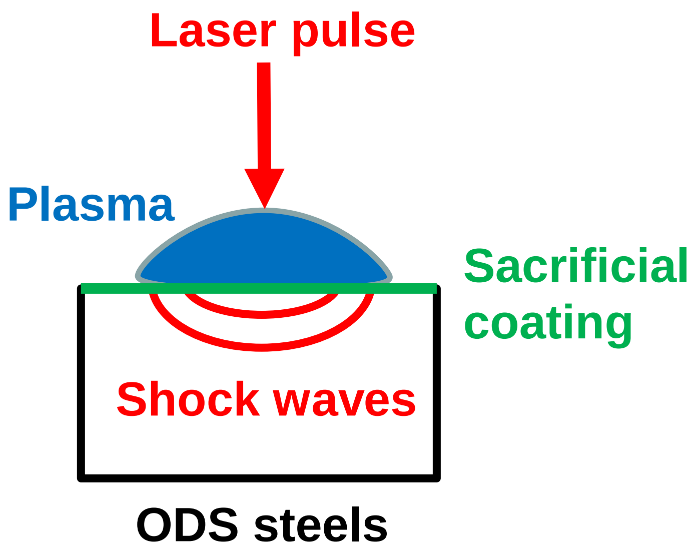


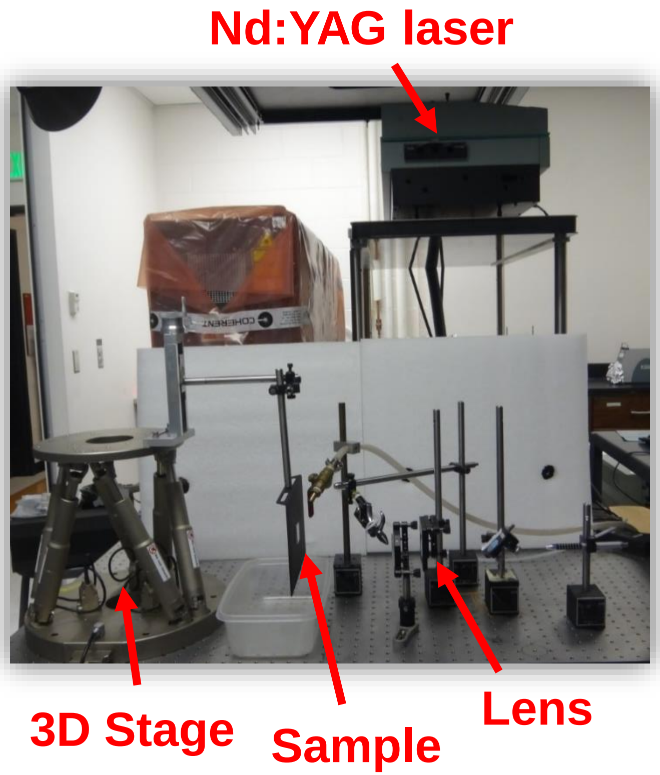
Helium bubbles in ODS 316 steel with 100 appm He irradiated to (a) 5.1 and (b) 8.9 dpa at 550 ˚C.

H. Oka, et al. Journal of Nuclear Materials, 2011, 417, 279.

Laser Shock Peening (LSP)

- **LSP is a novel surface modification process which uses laser treatment to prevent the failure of metal components.**



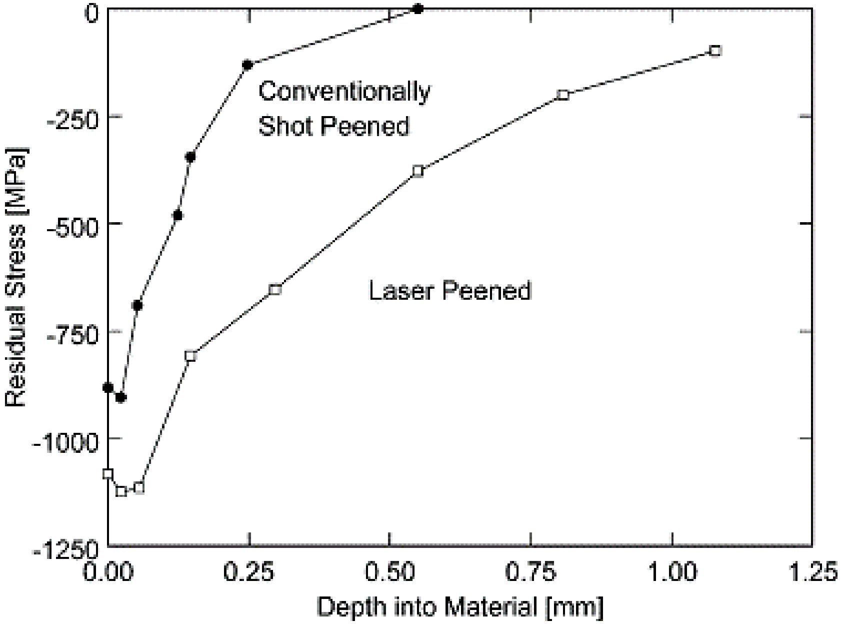


Pulse energy (mJ)	100-900
Spot diameter (mm)	1
Pulse duration (ns)	7
Overlap ratio	50%
Repetition-rate (Hz)	10
Laser wavelength (nm)	1064
Beam profile	Gaussian

Laser Shock Peening vs. Shot Peening

- **LSP is superior to 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.**

Shot peening uses small glass or ceramic particles to hit the surface of a metal part, preventing the failure of metals.



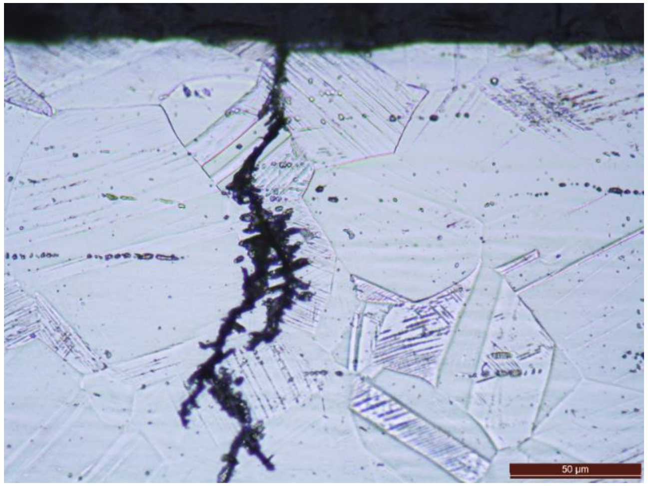
Residual compressive stresses induced by LSP and mechanical shot peening on the surface of Inconel 718 alloy

Shukla et al. J. Journal of Engineering Manufacture 228, 639-652 (2014)

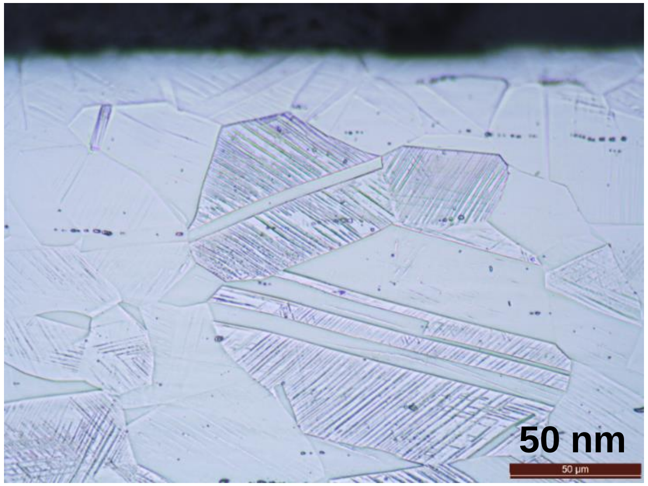
Prevention of Stress Corrosion Cracking by Laser Shock Peening

- **Cracks propagate in untreated stainless steels.**
- **No apparent cracks are in laser-peened stainless steels.**
- **Laser peening will extend the lifetime of stainless steel components in piping system and heat exchangers in nuclear power plants!**

Without Laser Peening



With Laser Peening



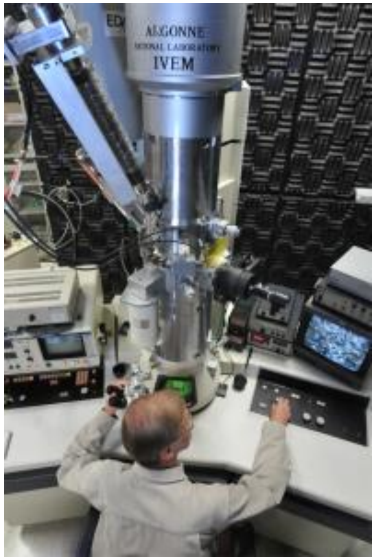
❖ Material: 304 steel (Fe-18Cr-8Ni)

❖ SCC test conditions: tensile stress = 300 MPa, 42% $MgCl_2$ solution, 144 ºC, 168 h.

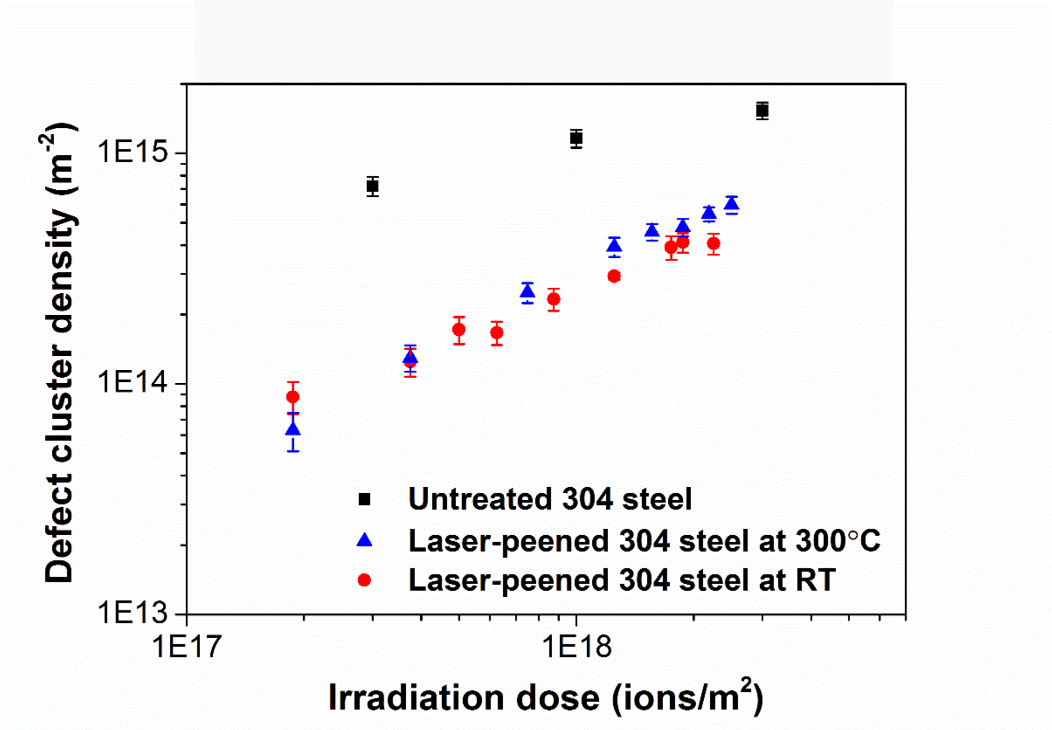
❖ LSP conditions: 850 mJ laser pulse energy, 4 laser pulses.

Improved Irradiation Resistance by Laser Shock Peening

- ❖ Irradiation damage is directly observed in an electron microscope which is linked with a particle accelerator.
- ❖ Irradiation defects in laser-peened stainless steels is much less than that in untreated stainless steels



The IVEM-Tandem facility at Argonne National Lab for *in situ* irradiation experiment



Evolution of irradiation defect density in untreated and laser-peened 304 steels (deformation twin region) under 1 MeV Kr^+ irradiation

Summary of Progress

Cost of building a new nuclear power station is more than $5 billion. Once a nuclear power station is built, we hope it can generate electricity for 50-100 years! Therefore, advanced materials are needed which can endure nuclear reactor environments for many years without replacement.

- **Laser shock peening (LSP) prevents the stress corrosion cracking (SCC) of stainless steels in high-temperature water environment.**
- **LSP improves the irradiation resistance of stainless steels in nuclear reactor environment.**
- **Thus, LSP can extend the lifetime of ODS steel components in piping system, heat exchangers and nuclear fuel cladding of Gen-IV nuclear energy systems!**
- **Next step: uncover the mechanisms why LSP can prevent SCC.**

Products: External Grants

Energy Research Grant has been carefully used to generate new data, make collaborations with national laboratories, and develop strong proposals to apply for external funding.

Funded grants ($458,336 in total):

- **American Chemical Society Petroleum Research Fund, PI, $110,000, 2 years.**
- **NSF, PI, $348,336, 3 years. co-PIs: Yongfeng Lu, Michael Nastasi.**

Pending grants:

- **NSF, PI, $352,185, 3 years. co-PIs: Yongfeng Lu, Michael Nastasi.**
- **QuesTek Innovations, $39,999, PI, 1 year.**

Future Grant Applications:

- **2015 Summer: NSF Faculty Early Career Development Program**
- **2016 Fall: DOE Nuclear Energy University Program (NEUP) program**
- **2016 Fall: DOE Office of Science Early Career Research Program**
- **2017: Nuclear Regulatory Commission Faculty Development Grant**

Acknowledgement

- **Nebraska Public Power District through the Nebraska Center for Energy Sciences Research**

- **Materials for Extreme Environments (ME^2) Lab**

PI: Prof. Bai Cui
Members: Dr. Xueliang Yan, Fei Wang, Xiaoxing Qiu, Qiaofeng Lu

- **Laser-Assisted Nanoengineering (LANE) Lab**

PI: Prof. Yongfeng Lu
Members: Chenfei Zhang, Dr. Leimin Deng

- **Prof. Mike Nastasi and Dr. Qing Su**

- **IVEM-Tandem Facility at Argonne National Laboratory**

Dr. Mark Kirk, Dr. Meimei Li, Peter M. Baldo, Edward A. Ryan