Radiation Response of Nickel-Chromium Binary Alloys

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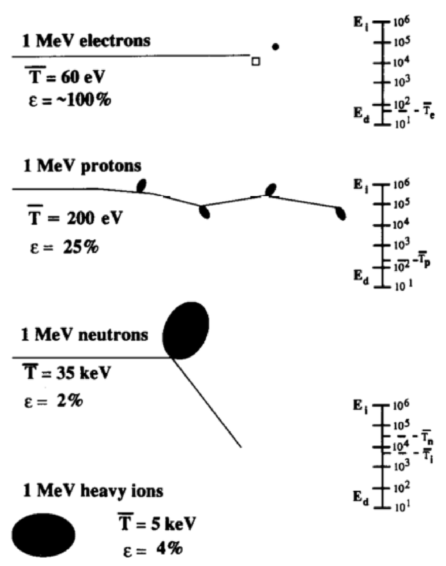
Research Motivation

- Austenitic and Ni-based alloys are widely used in steam generators in light water reactors and are candidate materials for in-core applications in next-generation sodium- and molten salt-cooled fast reactors.[1,2]
  - Examples of alloys include: X-750, X-718, IN600, Nimonic PE16, and 304 and 316 stainless steels.
  - Radiation response must be understood to design a Ni-based alloy that is well-suited for core components that receive large radiation fluences.
- Examples of radiation damage effects in Ni-based alloys include:
  - Dislocation loops – typically faulted Frank loops on {111} atomic planes. Primary contributor to radiation-induced hardening and embrittlement effects.[3]
  - Voids – empty cavities formed by agglomeration of vacancy-type point defects. Primary contributor to radiation-induced void swelling.
  - Radiation-induced segregation (RIS) – Composition gradients at point-defect sinks (typically grain boundaries) arising from differences in diffusion rates of alloying elements. Enrichment or depletion of specific elements can result in irradiation-assisted stress corrosion cracking (IASCC).
- Prior radiation effects studied have focused on Nimonic PE16 or austenitic steels.[4,5]
  - Few fundamental studies have investigated how varying Cr content or irradiation conditions can affect formation of these features.

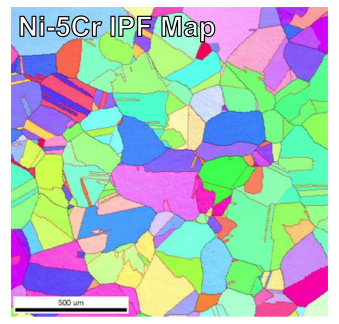
Research Goals

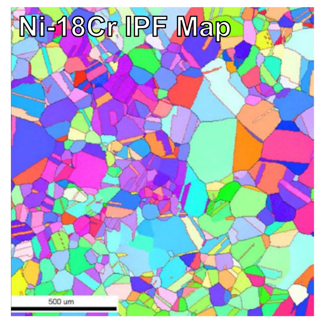
- **Investigate composition dependence of defect formation and solute segregation in binary Ni-Cr alloys.**
  - Cr is usually alloyed to enhance aqueous corrosion resistance, but it detrimental to performance in molten salt environments.[6]
- **Study effects of different irradiation conditions (irradiating species and temperature) on resulting microstructure.**
  - Determining how well ion irradiations simulate the effects of long-term neutron irradiations is important to predicting material performance in reactor environments.
  - Microstructural evolution of materials using ion beam irradiation depends on irradiating species, due to differences in dose rate and radiation damage cascade evolution. A schematic of how different particles impart their energy is shown to the right.[7]



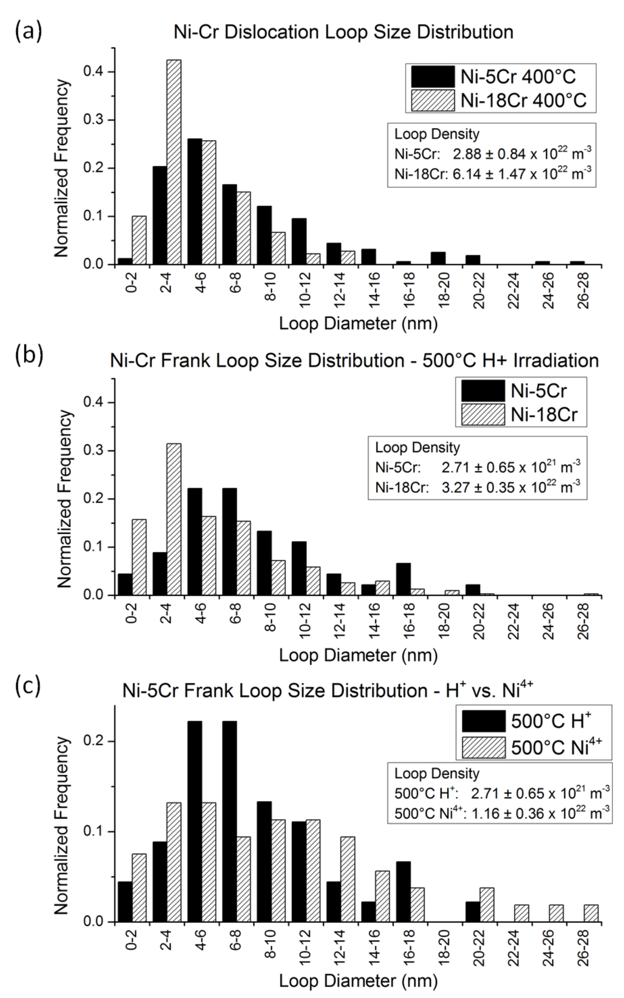
Experimental

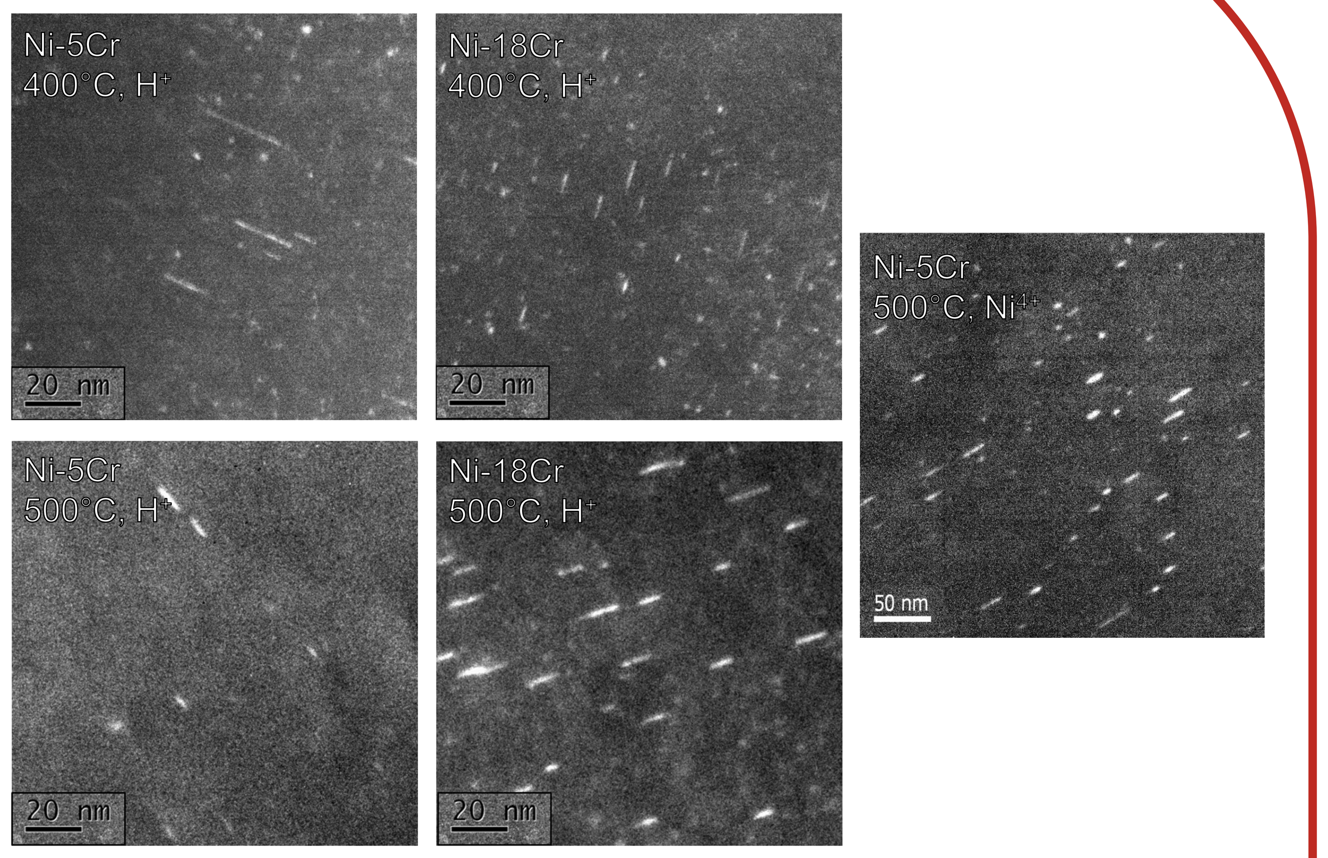
- **Samples**
  - Bulk Ni-5Cr and Ni-18Cr samples
  - ~100-150μm grain size (inverse pole figure maps shown to the right)
  - Grain boundaries targeted during TEM sample prep using FIB
- **Equipment & Irradiation Treatment**
  - 3.4 MV Pelletron Tandem Accelerator
    - 2.0 MeV protons at 400 & 500˚C to 1.6dpa
  - 6 MV Tandem Van de Graaff Accelerator
    - 20 MeV Ni^{4+} ions at 500˚C
  - FEI TITAN Aberration-corrected (S)TEM
  - Tecnai-TF30 TEM





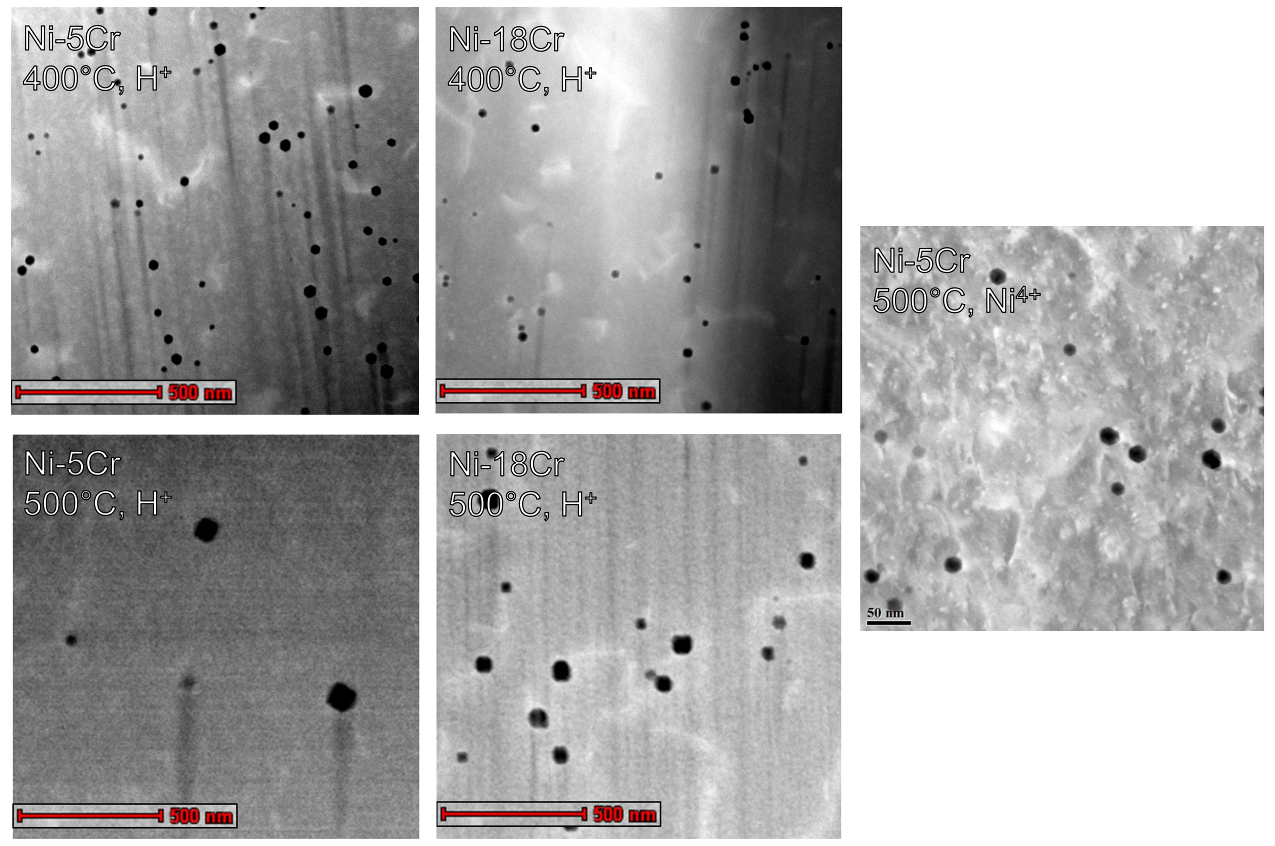
Dislocation Loop Analysis

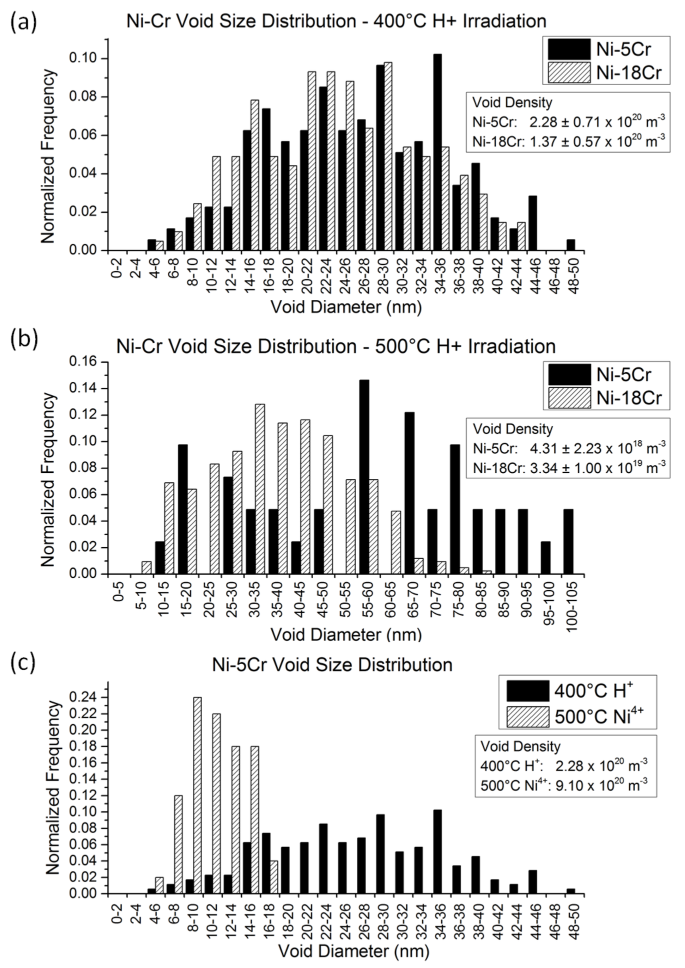




- Frank loops on {111} planes imaged using dark-field relrod imaging techniques.

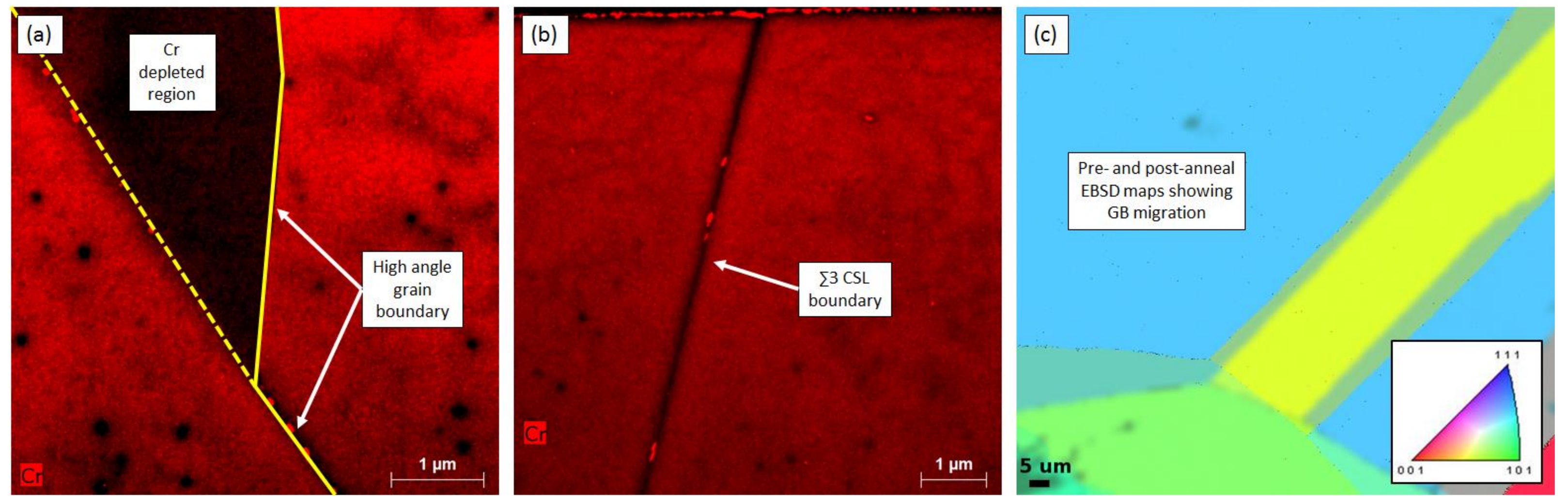
Void Analysis





- Voids imaged using STEM HAADF imaging techniques

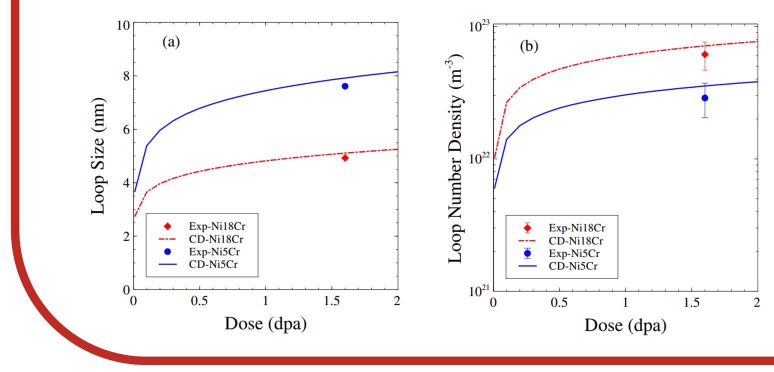
RIS Measurements



- Large Cr depleted regions were observed in all materials due to grain boundary migration occurring from long irradiation times (approximately 100 hours) at 500˚C.
- Not observed at Σ3 coincidence site lattice (CSL) boundaries, which have different mobilities from other GBs.
- Unirradiated annealing study shows shift in grain size commensurate with the observed depleted region size.

Cluster Dynamics Modeling

- Cluster dynamics (CD) simulations have been employed to investigate dislocation loop nucleation and growth behavior in both Ni-Cr alloys.
- Results demonstrate that changes in Cr content can be accounted for by adjusting the dimer interstitial binding energy.



- Comparison of model results to experimental data is shown to the left.

Conclusions

- **Increasing radiation temperature tends to result in a lower density of larger-sized defects.**
  - Likely due to increased instability of smaller, immature defects resulting from increased thermal emission.
- **Changes in Cr content affect nucleation behavior of defects.**
  - Cluster dynamics (CD) modeling efforts have demonstrated a good fit with experimental data is achieved by varying interstitial binding energy between the two compositions.
- **Ni-ion irradiations cause increased in-cascade clustering, but allow less time for defects to agglomerate.**
  - Demonstrated primarily via higher density of smaller voids in Ni-irradiated specimens.
- **RIS analysis revealed a radiation-enhanced GB migration phenomena.**
  - Potentially the most rapid instance of GB migration ever reported.

Future Work

- **Compare results of H^+ and Ni^{4+} ion irradiation to neutron irradiation experiments.**
  - Ultimate goal of ion irradiation is to emulate radiation damage in reactor environments.
- **Extend study to ternary and more advanced alloy systems.**
  - Materials used for in-core applications will not be simple binary alloys.
  - Results of this study serve to aide in advanced alloy design efforts.

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