Microstructural Analysis of Niobium and Copper Alloys for Fuel Cladding Material

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About Nuclear Energy…

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Nuclear energy provided 55% of America’s carbon-free electricity in 2019, making it by far the largest domestic source of clean energy [1].

Nuclear power plants do not emit greenhouse gases while generating electricity [1].

-US DOE

Motivation

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- The microstructural analysis of alloys is of utmost importance since it must withstand extreme conditions within the core.

- Factors to be considered: oxidation resistance, corrosion rate, strength, high-temperature tolerance, irradiation tolerance, void swelling, creep resistance, etc.

- The niobium-copper binary model system analyzed is important to characterize at 500°C to 800°C (773 K- 1073 K) so that the behavior between these two elements can be better understood for future improvement of alloys.

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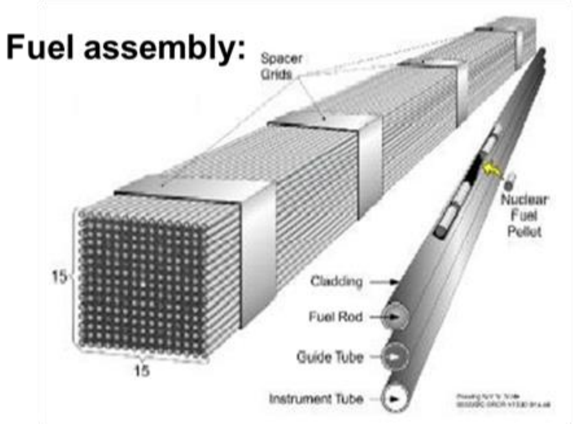
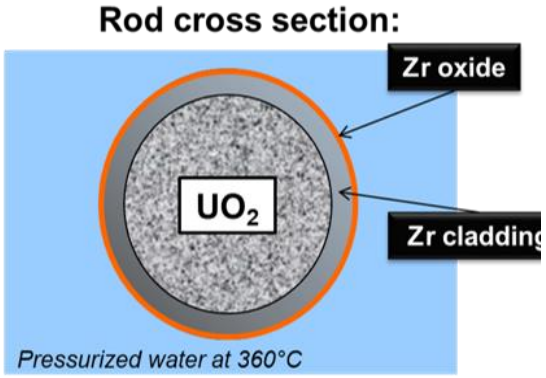
Background

- The development of new and refined elemental composition alloys has gained more attention due to the construction of Generation IV reactors.

- The addition of niobium (Nb) into alloy compositions has been proven to be beneficial because it increases the corrosion resistance of zirconium (Zr) alloys used for cladding [2-5]. Additionally, copper (Cu) was reported to be effective for reducing the corrosion rate of Nb-containing Zr alloys [6].



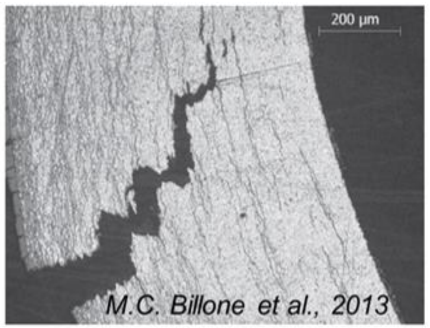


Corrosion reaction:

$$Zr + 2H_2O \rightarrow ZrO_2 + 2H_2 \rightarrow \text{Hydrogen pickup}$$

Pick-up Fraction: $f_H = \frac{H_{absorbed}}{H_{generated}}$

Hydrided Zr cladding



Materials and Methods

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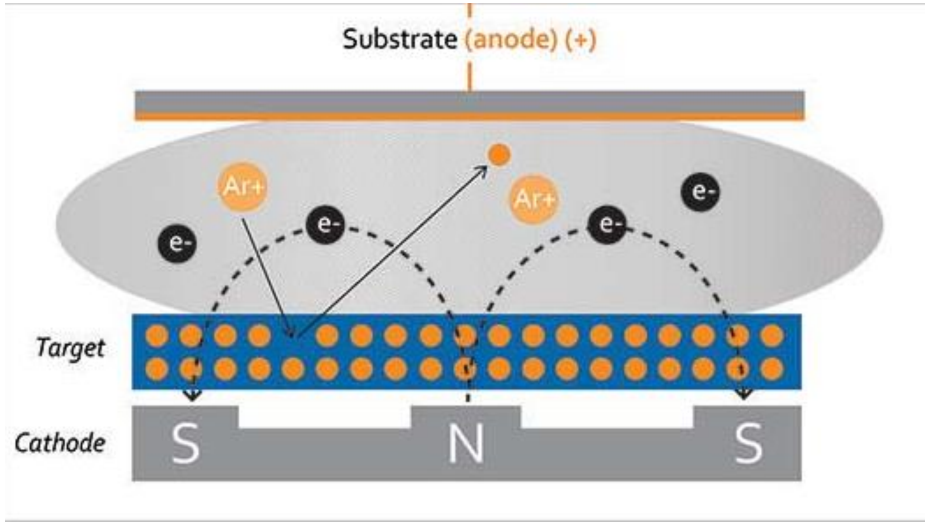
- The sample used was a mixture of Nb and Cu sputtered on a silicon nitride (Si_3N_4) based grid.
- The elemental composition was 90/10 Nb/Cu respectively.
- The film was characterized by transmission electron microscopy (TEM) and then annealed. Lastly, the sample was examined using energy-dispersive x-ray spectroscopy (EDS) techniques.



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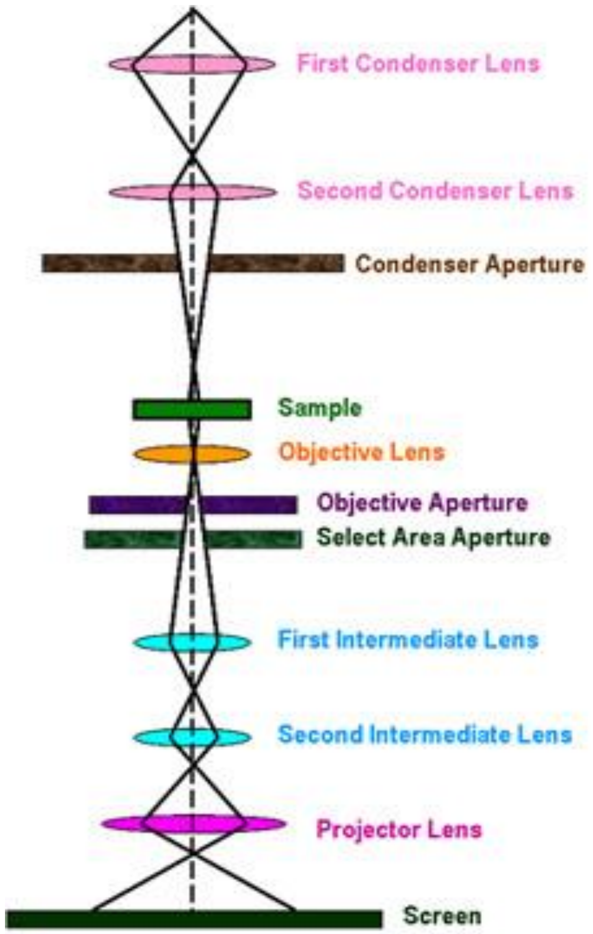
Transmission Electron Microscopy

- High-voltage electricity supply powers the cathode
- Beam of electrons is generated
- Lenses condense the beam
- Beam passes through the sample and magnifies the image that the user sees on the screen



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Experiment

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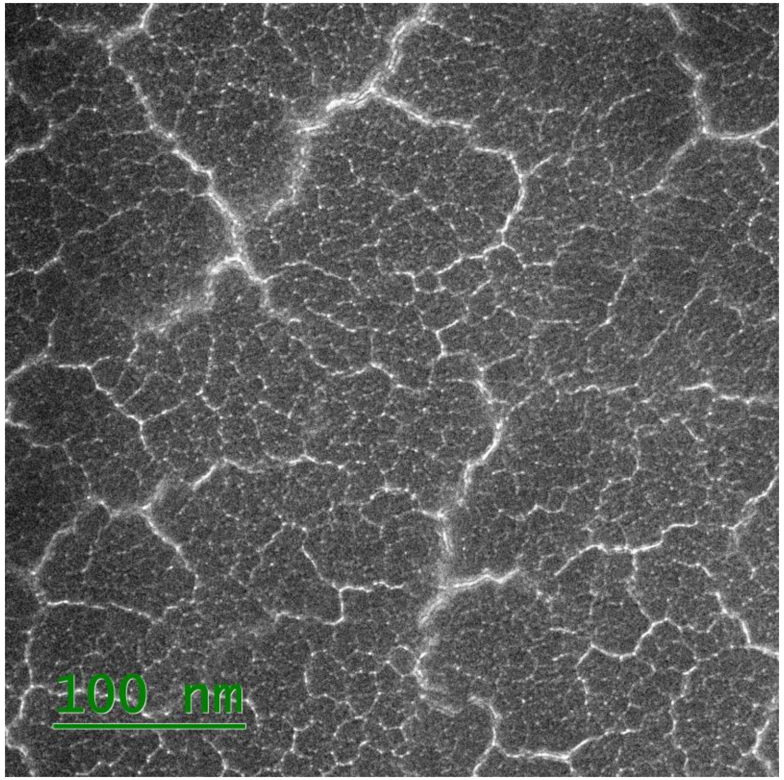
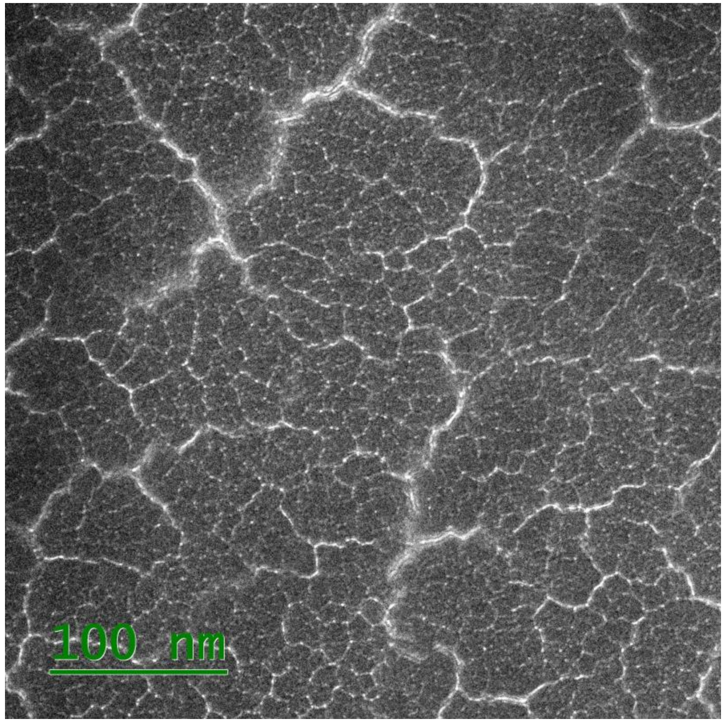
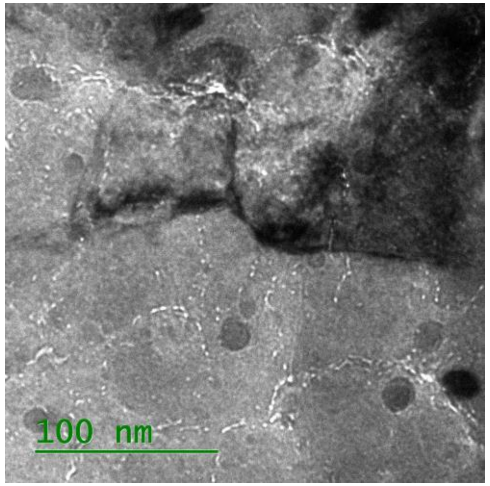
- The contrast in the amorphous Nb/Cu 90/10 sample before annealing is due to variations in film thickness.
- During annealing the temperature was set to increase 20°C per minute up to 800°C in the TEM.
- Afterwards the sample was characterized via scanning transmission electron microscopy (STEM-EDS). Data was collected for 45 minutes.

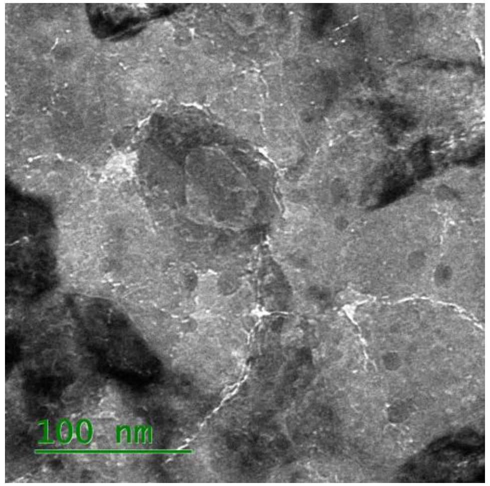


Results

- Agglomeration of particles can be observed.
- Based on phase diagram, we do not expect the elements to mix.







Lever Rule Calculation

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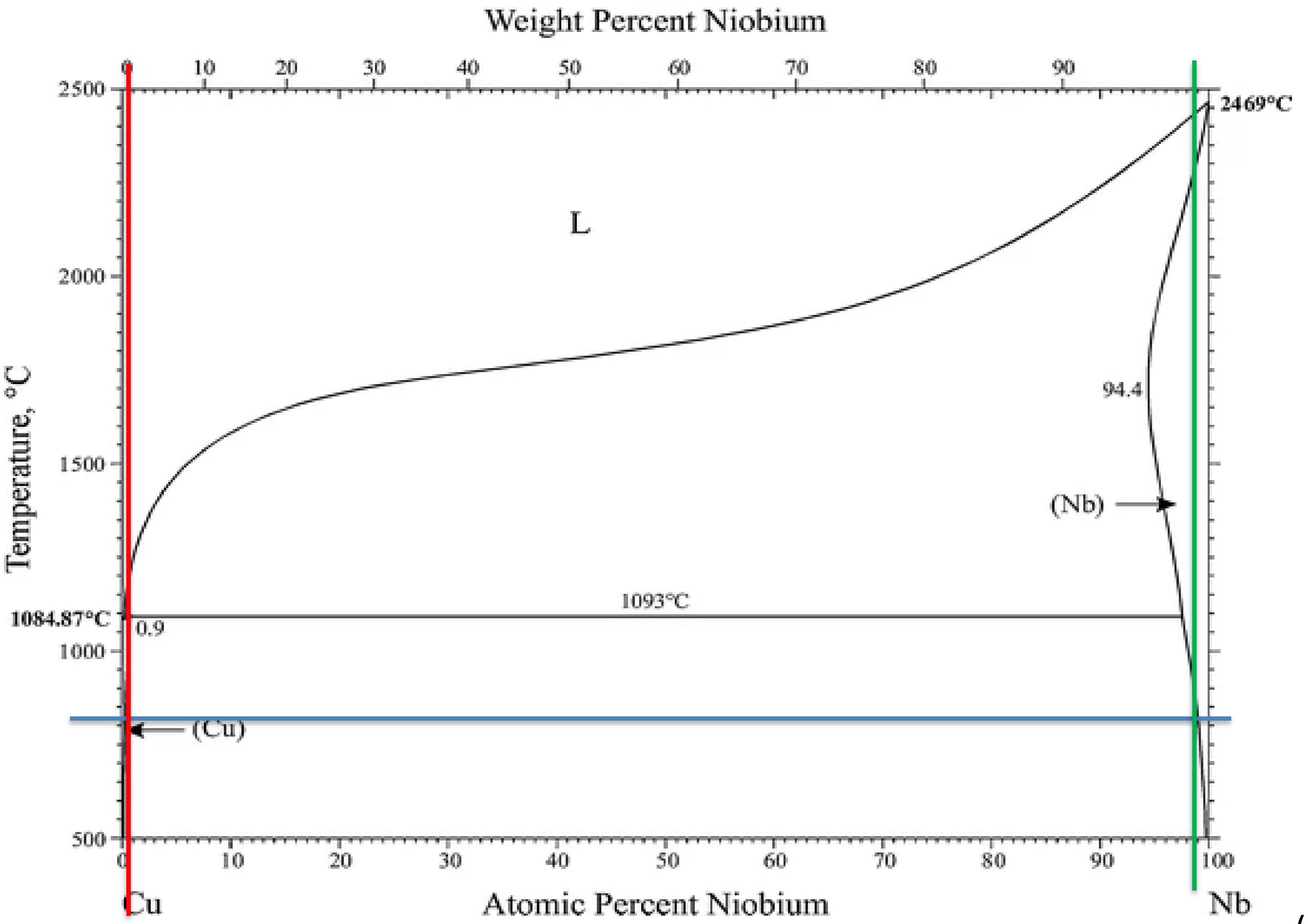
$$W_s = \frac{W_O - W_l}{W_s - W_l}$$

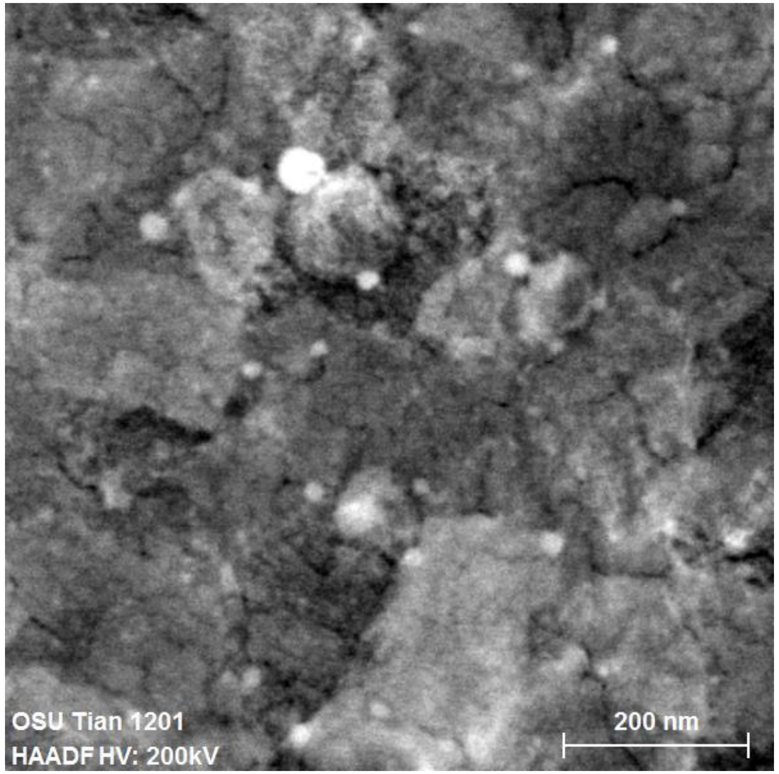
$$W_s = \frac{90 - 0.8}{98 - 0.8} = 0.9177$$
$$= 91.77\%$$

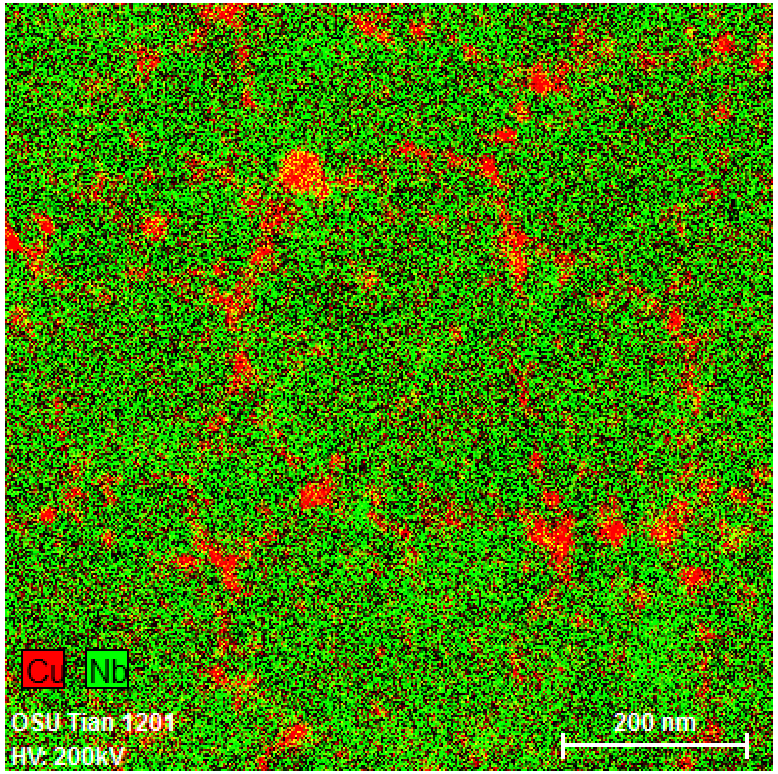
$$1 - 0.9177 = 0.08230$$
$$= 8.230\%$$

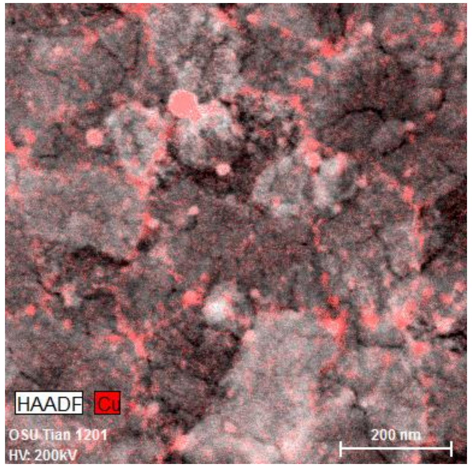


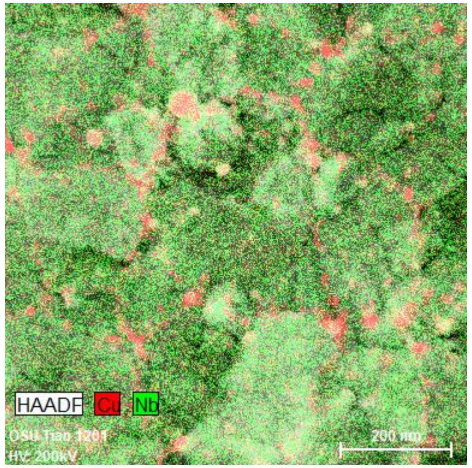
Results

- Segregation of Cu to interfaces of the material









Conclusions

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- Data confirms the phase diagram; elements are immiscible
- Not useful for a coherent structure
- Binary model system can be used to add to other alloys i.e. zirconium

Future Work

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- Further analysis to repeat this experiment with varying compositions of Nb and Cu, other temperatures ranges, and sample preparation techniques is needed to get a deeper understanding of copper's segregation behavior.
- Additionally, the characterization of these elements also serves as a model system for advanced oxide dispersion-strengthened (ODS) steels.

References

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Figures

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(1) https://nuclearmaterialslab.wiscweb.wisc.edu/current-work/modeling-corrosion-of-zirconium-alloys-fuel-cladding/

(2) https://www.dentonvacuum.com/products-technologies/magnetron-sputtering/

(3) http://www.nanoscience.gatech.edu/zlwang/research/tem.html

(4) https://www.amazon.com/APO16000-Apollo-Model-Overhead-Projector/dp/B00KTHKYK0

(5) https://link.springer.com/article/10.1007/s11669-012-0051-y/figures/1?shared-article-renderer

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Questions?

Thank you