Characterization and Modeling of Secondary Phase Evolution in an Irradiated Zr-1.0Nb Alloy

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The objective of this study is to characterize the evolution of Nb-rich clustering and solute migration in a Zr-1.0%Nb alloy irradiated with either neutrons or Kr^{2+} ions to otherwise similar conditions (5 dpa at 310°C), enabling isolation of the dose-rate effects. Zirconium-based alloys are commonly used as cladding materials in existing reactor applications because of their low thermal-neutron absorption cross section, good corrosion resistance at high temperature, and high resistance to irradiation-induced swelling and creep. More recent development of Zr-based alloys with small amounts of niobium has also demonstrated improvement in corrosion resistance and the ability to minimize irradiation-induced linear growth. In this study, an RXA Zr-1.0%Nb alloy was irradiated with Kr^{2+} or neutrons to a common dose of ~5 dpa (each at 310°C). Atom-probe tomography is used to quantify any solute-cluster morphology and the solute concentrations in the matrix, clusters, and preexisting β-Nb precipitates before and after each irradiation. This approach enables systematic characterization of the Nb-solute migration as a result of irradiation, along with an evaluation of dose rate effects and the ability for Kr^{2+} ions to emulate neutron irradiation at low dose.

Results

In this study, atom-probe tomography (APT) is used to systematically quantify the migration of Nb solutes due to each irradiation. Prior to irradiation, only β-Nb precipitates are observed, with a surrounding matrix containing 0.59 at% Nb, which is close to the solubility limit for Nb [1,2]. Following both irradiations, nanoscale Nb-rich clusters are found within the matrix, consistent with prior observations [1,3,4], and are likely elongated or needle-shaped, with an average aspect ratio of ~2:1 measured using APT. The irradiation-induced clustering coincides with a reduction in matrix composition of Nb to 0.36 at% and 0.49 at% following Kr^{2+} ion or neutron irradiation, respectively. This evidence suggests the solutes migrate from the matrix to irradiation-induced clusters. The size of the Nb clusters are 4.51 ±1.09 nm and 4.17 ±2.23 nm following Kr^{2+} and neutron irradiation, respectively, while number density of the Nb clusters are 379×10^{21} m^{-3} and 253×10^{21} m^{-3} following the same irradiation conditions. Therefore, Kr^{2+} irradiations have resulted in higher volume fraction of Nb clustering at the same dose and temperature as neutron irradiation.

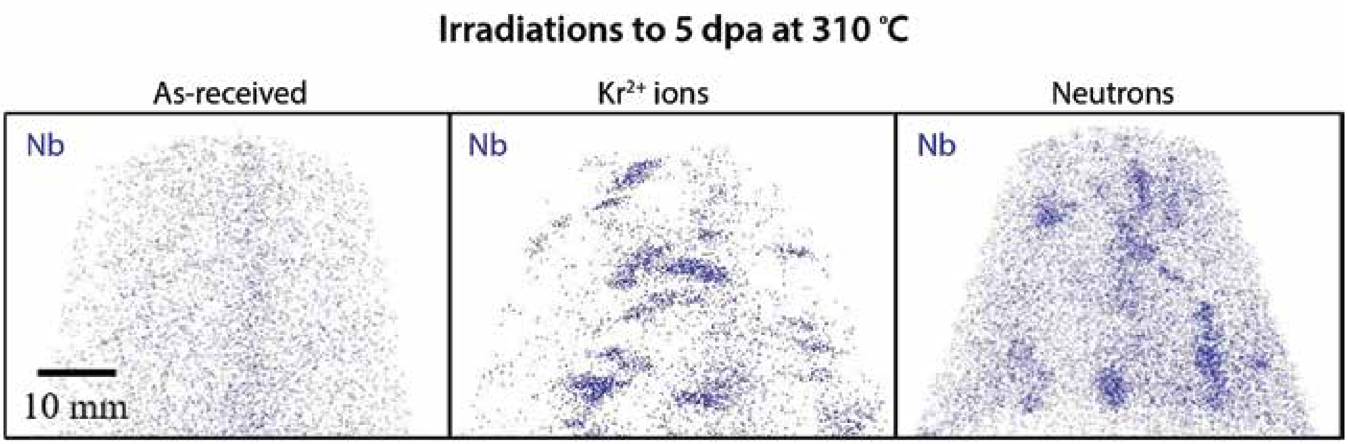

Figure 1. Atom Probe concentration maps for Nb in Zr-1.0%Nb matrix. Following each irradiation, small Nb-rich nanoclusters are observed, with comparable size and number density.

Conclusion

Irradiation with either Kr^{2+} ions or neutrons to 5 dpa at 310°C have each led to the development of Nb-rich nanoclusters in a Zr-1.0%Nb alloy. Nanoclusters rich in Nb are expected to impede the growth of <c> loops in Zr-based alloys, likely reducing the effects of irradiation-induced linear growth [5,6]. The Nb clustering also lowers the amount of Nb in solid solution within the matrix, likely improving the corrosion resistance of the alloy [1]. The Kr^{2+} ion irradiation appears to be a reasonable emulation of neutron-irradiation effects on Nb solute migration, but some key differences are noted.

References

[1.] Z. Yu, A. Couet, M. Bachhav, Irradiation-induced Nb redistribution of ZrNb alloy: An APT study, J. Nucl. Mater. 516 (2019) 100–110. doi:10.1016/j.jnucmat.2019.01.015.

[2.] J.P. Abriata, J.C. Bolcich, The Nb-Zr (Niobium-Zirconium) System, Bull. Alloy Phase Diagrams. 3 (1982) 34–44.

[3.] J. Ribis, S. Doriot, F. Onimus, Shape, orientation relationships and interface structure of beta-Nb nano-particles in neutron irradiated zirconium alloy, J. Nucl. Mater. 511 (2018) 18–29. doi:10.1016/j.jnucmat.2018.08.042.

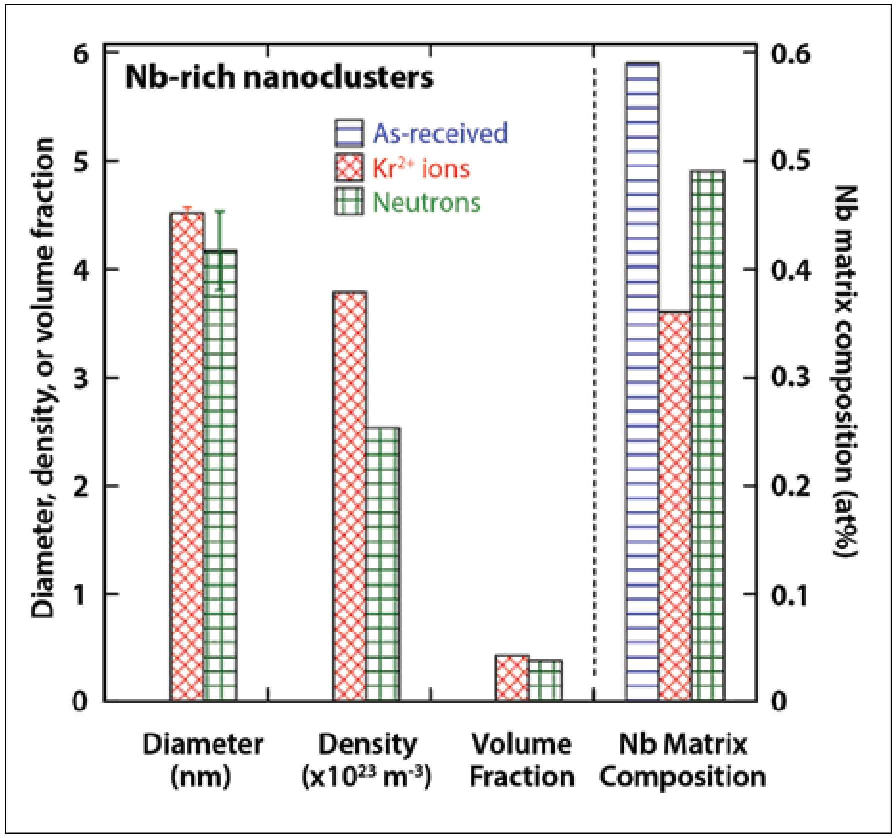

Figure 2. Summary of Nb-rich cluster morphology follow each irradiation and the resulting evolution in the matrix composition of Nb in at%. Error bars for diameter represent the standard deviation of the mean.

[4.] S. Saini, N. Gayathri, S.K. Sharma, A. Devi, A.P. Srivastava, S. Neogy, P. Mukherjee, P.K. Pujari, Microstructural investigation of irradiation damage behavior of proton irradiated Zr-1 wt.% Nb fuel cladding alloy, J. Nucl. Mater. 528 (2020) 151894. doi:10.1016/j.jnucmat.2019.151894.

[5.] E. Francis, R.P. Babu, A. Harte, T.L. Martin, P. Frankel, D. Jädernäs, J. Romero, L. Hallstadius, P.A.J. Bagot, M.P. Moody, M. Preuss, Effect of Nb and Fe on damage evolution in a Zr-alloy during proton and neutron irradiation, Acta Mater. 165 (2018) 603–614. doi:10.1016/j.actamat.2018.12.021.

[6.] M. Griffiths, R.W. Gilbert, The formation of c-component defects in zirconium alloys during neutron irradiation, J. Nucl. Mater. 150 (1987) 169–181.

Publications

[1.] S.B. Adisa, J. Hu, M.J. Swenson. Evaluation of Nb-rich clustering in a Zr-1.0%Nb allow following Kr2+ or neutron irradiation at 310 °C, Materials, Manuscript in preparation.

[2.] S. Adisa, J. Hu, M. Swenson. Evaluation of irradiation-induced Niobium clustering in Zr-1.0Nb alloy. Transactions of the American Nuclear Society Annual Meeting, Minneapolis MN, June 2019. (published)

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