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Improving resistance of ferritic-martensitic steels to environmental degradation in advanced nuclear reactors

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ABSTRACT:

Advanced nuclear reactors rely on the advances in materials, which need to withstand the challenging operating conditions inside the reactor cores, such as intense fast neutron fluxes, high temperatures, and corrosive coolants. Compared with other candidate materials, ferritic-martensitic (FM) steels stand out because of their mature large-scale fabrication capabilities, exceptional resistance to radiation damage, and high thermal conductivity. However, crucial limitations also exist for using FM steels in modern fast reactor designs like molten salt reactors, which will take the materials to a larger irradiation dose (>200 dpa), a higher temperature (>600°C), and more aggressive coolants like molten fluoride salts. Under these extreme environments, FM steels will experience significant property degradation, such as creep at elevated temperatures, steady-state swelling after extended irradiation, and mass loss due to corrosion. All these challenges need to be overcome to advance FM steels to the next technology readiness level.

The proposed work will address the above limitations via two technical approaches. In the first approach, I will design creep-tolerant FM steels with superior swelling resistance by tuning the alloy nitrogen (N) content. Nano-sized nitride precipitates in high-N FM steels are believed to improve the steel thermal-creep strength. Meanwhile, N solute atoms released from dissolved precipitates at high dose can suppress void swelling. Therefore, tuning N content could provide a unique opportunity to simultaneously improve the steel resistance to thermal creep and void swelling. However, achieving this attractive goal requires a fundamental understanding of the evolution of nitride precipitates under extended irradiation. By combining state-of-the-art microscopy techniques with materials simulation, I will systematically investigate the kinetics of dissolution and reprecipitation of nitride precipitates, enabling us to identify the optimum N content that improves both thermal creep strength and swelling resistance at high-dose irradiation.

In the second approach, I will develop refractory high entropy alloy (HEA) coatings to suppress the corrosion of FM steels in molten fluoride salts. Due to the high chromium (Cr) concentration, FM steels are susceptible to fast Cr loss when contacting with molten salt. HEAs recently draw much attention from the nuclear materials community because of their excellent tolerance to radiation damage. Unlike conventional alloys which usually have one base solution element, multiple elements at nearly equal concentrations are randomly mixed in HEAs, providing a wide design space via tuning the number, types, and concentrations of alloying elements to achieve the desired thermomechanical properties. Refractory elements, like W, Ta, Nb, and Mo, are known for their high redox potentials and chemical inertness in molten salts. Based on high-throughput materials calculations, I will select refractory HEA coatings that are compatible with FM steels for protecting the steels from molten salt corrosion. The performance of the refractory HEA coatings will be examined against in-core molten salt corrosion tests.