NANOSTRUCTURED MATERIALS UNDER EXTREME ENVIRONMENTS

Nanostructured Materials under Extreme Environments

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Advanced nuclear reactors require materials that can sustain extreme conditions such as elevated temperatures, high radiation, severe corrosion, etc. Materials with designed micro- and nanostructures may exhibit unusual responses to heat and radiation. Understanding the behavior of nanostructured materials under extreme conditions therefore offers exciting opportunities to explore unprecedented structure–property correlations that cannot be obtained in conventional materials. This special topic focuses on nanostructured materials under irradiation environments.

Materials under energetic particle irradiation suffer severe damage in the form of a drastic increase of defect density and significant degradation of their mechanical and physical properties. Nanostructured materials with abundant internal defects have been extensively investigated for use in various applications. The field of radiation damage in nanostructured materials is an exciting and rapidly evolving arena, enriched with challenges and opportunities. The study of nanostructured materials under radiation environments may significantly improve the fundamental understanding of the mechanisms of radiation effects and eventually lead to the design of advanced nanostructures with enhanced radiation tolerance.

Nickel-based superalloys (γ -matrix) with L1₂-ordered Ni₃Al (γ') precipitates are generally designed for high-temperature applications. In the core of a nuclear reactor, materials must withstand an exceptionally intense irradiation flux. The study of the stability of γ/γ' interfaces at high temperatures and under irradiation is thus of great importance to their engineering applications in the nuclear industry. In “Phase stability of Ni/Ni₃Al

multilayers under thermal annealing and irradiation” by Sun et al., Ni/Ni₃Al multilayers with individual layer thicknesses varying from 5 nm to 100 nm, prepared by high-temperature magnetron sputtering, were used as model systems to investigate the stability of γ' precipitates and γ/γ' interfaces under thermal annealing (800°C) and heavy ion irradiation (~ 3.5 dpa at 500°C). The study provides insights into the understanding of the order–disorder transition, recovery, and dissolution of γ' Ni₃Al precipitates under thermal annealing and irradiation. Also, their research studied the degradation mechanism of order–disorder interfaces in extreme environments.

A novel material that has recently been shown to exhibit excellent irradiation tolerance at elevated temperature is amorphous silicon oxycarbide (SiOC). The authors of “Dual-beam irradiation stability of amorphous silicon oxycarbide at 300°C and 500°C,” Su et al., took advantage of an in situ irradiation facility that allows dual-beam irradiation, i.e., with helium (He) and krypton (Kr), at elevated temperature inside a TEM at the University of Huddersfield. In situ TEM observations revealed that, at 300°C and 500°C, He bubbles and voids were highly suppressed after irradiation up to 95 dpa with simultaneous He implantation up to 231 at.%. Atomic pair distribution functions suggested that the amorphous structures were barely changed before and after irradiation, and no crystallization or phase separation was detected. This observation further confirms the stability of amorphous SiOC under irradiation and thermal extremes.

It is well known that the continuous formation and growth of voids induced by radiation in metallic materials may lead to significant microstructure damage and degradation of mechanical properties. In contrast to the void swelling commonly observed in irradiated metallic materials, nanovoids in nanoporous metallic materials are found to shrink during radiation, indicating that nanovoids may

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enhance the radiation tolerance of metallic materials. In “Recent studies on void shrinkage in metallic materials subjected to in situ heavy ion irradiations,” Niu et al. reviewed recent studies on the size-dependent void shrinkage in various metallic materials, such as single-crystal Cu with voids, nanotwinned Cu with voids, and nanoporous Au, subject to in situ heavy ion irradiation. The physical mechanisms underlying such radiation-induced void shrinkage as revealed by simulation studies were summarized. Furthermore, the authors demonstrated the capability of machine learning to identify and track the evolution of nanovoids, which opens the door to the detection of tracking in the future studies. The integration of experiments and modeling is a new trend for efficient materials studies.

Another example of this integration is to develop models that can be used for rapid screening of new alloys. Solute nanoclusters are critical to the structural and mechanical integrity of numerous alloy candidates for use in advanced nuclear reactor applications. As irradiation can profoundly alter the morphology and composition of these solute nanoclusters, it is critical to understand and predict solute clustering behavior under irradiation. In “Rate theory model of irradiation-induced solute clustering in b.c.c. Fe-based alloys,” Swenson and Wharry advanced a simple theory to model the

evolution of irradiation-induced nanoclusters subject to different irradiating particles. The model was trained and validated with experimental data, following an approach similar to the training of a machine learning algorithm, resulting in an agile model that can be used for rapid screening of new alloys. By applying the model, nanocluster evolution was found to depend upon the disordering parameter (i.e., cluster morphology and dose rate) and irradiation temperature, and was most sensitive to the solute migration, vacancy formation, and vacancy migration energies. The results were discussed with respect to the irradiation temperature shift for varying irradiating particle types and dose rates.

The papers in this special topic on nanostructured materials under extreme environments can be accessed via the Table of Contents page of the November issue at <https://link.springer.com/journal/11837/72/11/page/1>.

CONFLICT OF INTEREST

On behalf of all the authors, the corresponding author states that there is no conflict of interest.

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