Structural alloys

Reassembled nanoprecipitates resisting radiation

Outstanding resistance to destructive radiation damage in structural alloys is realized by ultra-high density reversible nanoprecipitate inclusions, and the improvement is attributed to the reordering process of low-misfit superlattices in highly supersaturated matrices.

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Nuclear energy, as a reliable baseload power, provides constant and carbon-free electricity.[1] Searching for better radiation-resistant structural alloys has been a persistent yet scientifically exciting challenge for next-generation fission and future fusion energy systems. In a reactor environment, structural alloys are struck by fast-moving neutrons. As energetic neutrons or ions penetrate a solid, the displacement of atoms by elastic collisions typically produces a collection of small defects, while much of the energy transfer to target electrons creates local inelastic thermal spikes that affect atomic mobility and defect recovery. In addition, some collision cascades may partially or fully disintegrate nanoscale precipitates.[2,3] Aggregation of small defects into extended defects leads to elemental segregation, void formation, phase separation, radiation hardening, embrittlement, and eventual performance degradation and failure. Now writing in Nature Materials, Jinlong Du and colleagues reveal an outstanding resistance to destructive damage accumulation of a steel under ion radiation over a range of elevated temperatures, attributed to concurrent high-density nanoprecipitates dissolving and reforming during the irradiation, a process called as a reversible disordering-ordering transition.[3]

Historically, development of advanced structural alloys has relied on incorporating impurities that effectively mitigate radiation-induced defects or nanoscale features with complex interfaces that can act as recombination sites to anneal radiation damage.[2] As concentrated solid-solution alloys with tunable chemical complexity have been gathering speed,[4,5] research on conventional approaches appears to be slowing down. The work of Du and colleagues[3] represents a counterintuitive strategy to effectively annihilate defects generated during irradiation by the dissolving and re-nucleation of nearly coherent nanoprecipitates. These nanoprecipitates, which form superlattices in the steel, possess high elemental supersaturation and low-misfit interfaces with the matrix. Interfaces can serve as sinks or sources for radiation-induced defects, which further facilitates resistance or degradation of structural alloys. Comparing to misfit phase interfaces, coherent nanoprecipitates, while having various sink strengths for defect annihilation, are generally considered to be unstable under radiation. This work reveals that short-range reshuffling of radiation-induced point defects and excess solutes right after the transient ballistic disordering effectively prevents the defects and solutes from capillary-driven long-range diffusion and successfully promotes re-nucleation or rapid self-reassembling, thus resists irradiation-induced degradation. The beneficial weak temperature dependence arises from the combination of short-range atomic reshuffling and low energy barrier for nanoprecipitate reassembling. This work not only encourages researchers to revisit the strategy that relies on the incoherent or semi-coherent interfaces to trap radiation-induced point defects, but also provides a path forward that allows fundamental development and even control of the combined stability and sink strength at interfaces. Furthermore, the fabrication of these materials is achievable by low-cost conventional methods, which implies strong practicality for their use in engineering applications.

Remaining issues that haven't been addressed in this work[3] but should be further explored include filling the gaps between defect evolution induced by energetic neutrons or ions, and taking into account the coupled

electronic and atomic effects as pronounced ionization effects that create nonequilibrium conditions, alter atomic processes and modify defect dynamics. For reactor applications, neutron exposure is a critical test for any structural alloys to be considered viable. Ion radiation, often a surrogate for neutrons, is the most amenable method to reach high doses in sensible times and has greatly accelerated research on radiation effects in materials.[6-9] Radiation studies from either neutrons or ions need to include four intertwined aspects: *recoil spectra*, *dose rates*, *configurations and distribution of defects*, and *temporal and spatial coupling of the collision and energy dissipation processes* (Fig. 1). While collision cascades along the ion path stirs up the atomic arrangement within tens of picosecond and can destroy the nanoprecipitates,[3] whose formation is often elemental specific and depends on the local chemical environment.[2-5] An in-depth understanding to correlate how the chemical effects can be tuned to enhance nanoprecipitate formation and how the transient process restores structural order (i.e., self-healing) remains to be further explored. Intense inelastic thermal spikes in which energy dissipation is influenced by the local environment can reduce energy barriers and drive materials to a far-from-equilibrium state that encourages defect recovery.[4,10] Self-healing could lead to longer-lasting components and provide a science base for the desirable reactor lifetime extension. The continuous exploitation of materials far-from-equilibrium may lead researchers to identify, understand, and ultimately control the energy and mass transport processes, which could offer new pathways for developing irradiation-tolerant alloys, and more crucially, materials by design with targeted structural and functional properties.

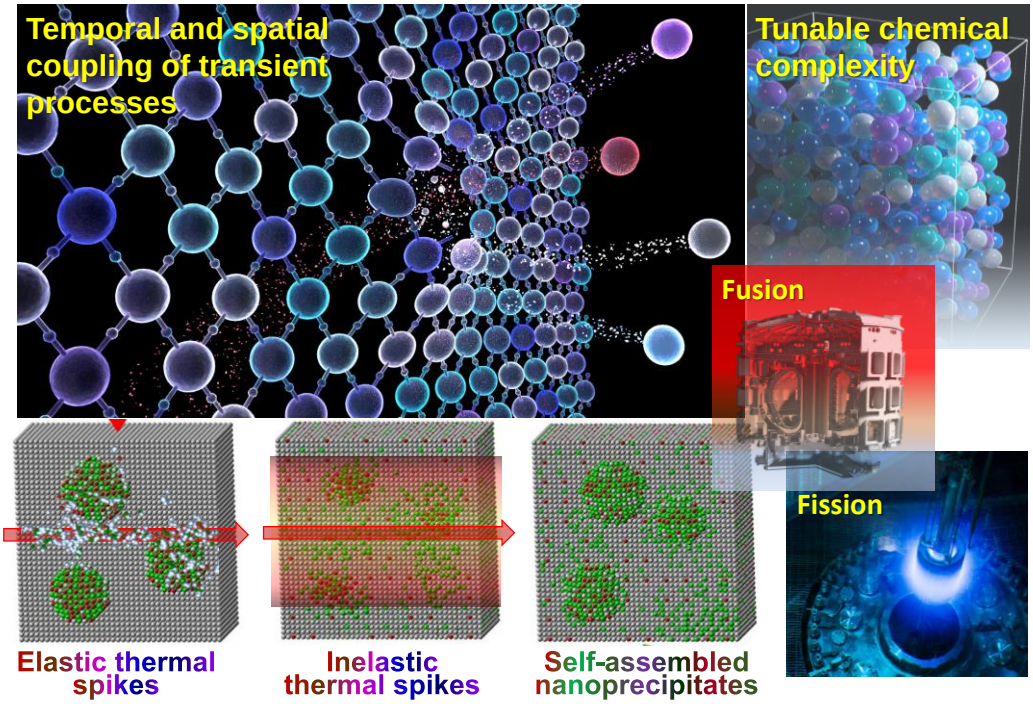

Fig. 1. **Exploit of materials far-from-equilibrium for developing irradiation-tolerant alloys.** Top left: schematic illustration of coupled energy transfer to electrons and nuclei that introduce atomic displacements, bond breaking, and lattice distortion. Bottom left: thermal spikes along an ion path dissolve the nanoprecipitates, followed with a rapid self-reassembling process[3]. Right: schematic illustrations of further research to include tunable complex alloys for nuclear energy applications, ITER demo (fusion) and the high flux isotope reactor at Oak Ridge National Laboratory (fission). Bottom left figure adapted from Ref. 3, Springer Nature Ltd.

(Author's remarks to art editor: Three drawings at the bottom left are taken from the original article describing the disordering-ordering process of coherent nanoprecipitates. For other components in Fig. 1, there are no copyright concerns, as they are made for research projects at ORNL.)

Scientific advances and technical development often go hand-in-hand. Exploiting ions to accelerate damage evolution in a neutron-relevant manner requires understanding and quantifying differences from the above four standpoints. To lay the groundwork for bridging neutrons and ions in developing advanced structural alloys to meet global electricity needs, one should take advantage of current knowledge on nonequilibrium processes,[10] tunable chemical complexity,[4,5] and recent developments in leadership computing capabilities, in combination with advances in electronic structure codes, physics-based simulation and deep learning techniques. Complex transient defect processes can thus be tackled and taken into consideration, and a revolutionary advance in predicting materials performance in various reactor environments can be expected.

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Competing interests

The author declares no competing interest.