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Predicting structural material degradation in advanced nuclear reactors with ion irradiation

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Swelling associated with the formation and growth of cavities is among the most damaging of radiation-induced degradation modes for structural materials in advanced nuclear reactor concepts. Ion irradiation has emerged as the only practical option to rapidly assess swelling in candidate materials. For decades, researchers have tried to simulate the harsh environment in a nuclear reactor in the laboratory at an accelerated rate. Here we present the first case in which swelling in a candidate alloy irradiated ~2 years in a nuclear reactor was replicated using dual ion irradiation in ~1 day with precise control over damage rate, helium injection rate, and temperature and utilize physical models to predict the effects of radiation in reactors. The capability to predict and replicate the complex processes surrounding cavity nucleation and growth across many decades of radiation dose rate highlights the potential of accelerated radiation damage experiments. More importantly, it demonstrates the capability to predict the swelling evolution and the possibility to predict other features of the irradiated microstructure evolution that control material property degradation required to accelerate the development of new, radiation-tolerant materials.

The continued contribution of nuclear power to carbon-free electricity generation will require the development of more efficient advanced reactors while maintaining safety and security. These advanced reactor designs impose harsher environments of higher temperatures and more intense radiation fields than current light water reactors and necessitate accelerated materials development to ensure components withstand radiation-induced degradation¹. Reactor irradiation campaigns to understand radiation effects on microstructure and properties take years to complete, are extremely expensive, and hampered by the paucity of test reactors, all of which contribute to the historical problem of a glacial pace of research to assess candidate materials. For decades, researchers, individual laboratories and international organizations^{2–4} have been searching for methods and theory to accelerate radiation damage in structural materials for nuclear energy applications to speed the development of new, more radiation resistant materials. Ion irradiation offers the capability to shrink the irradiation time from many years in a reactor to days using an accelerated damage rate to predict microstructure and mechanical property changes at lower cost^{5,11,12}. Therefore, ion irradiation is the only viable means to study many damaging degradation processes that could limit component lifetime, such as irradiation-induced swelling.

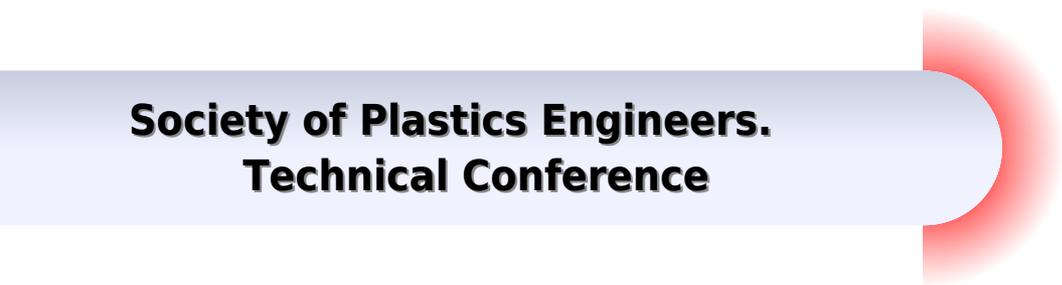
The dimensional instability from swelling can cause operational tolerances to be quickly exceeded and arises from cavities in irradiated materials¹³ as observed and the subject of further research^{2,11–14}. Cavity nucleation depends on the coalescence of defects generated from irradiation damage. The generation of gases by transmutation, such as helium, stabilizes cavity embryos and results in bubble formation, further complicating the nucleation process, which also depends on the crystal structure and alloy microstructure. Ion irradiation can simulate the reactor environment by creating damage with self-ions while simultaneously injecting helium as a surrogate for transmutation. The high damage rates (quantified as displacements per atom per second, dpa/s) accessible with ion irradiation (10^{-4} to 10^{-1} dpa/s) compresses the irradiation time by about three orders of magnitude. Yet for accelerated irradiations to be a useful tool for studying and qualifying nuclear materials, the roles and interdependencies of damage rate, helium content, and irradiation temperature on cavity nucleation and growth, along with the radiation-damaged microstructure, must be understood predictively.

This paper identifies the underlying processes governing cavity nucleation and early stage growth in a ferritic-martensitic steel, T91, neutron irradiated in the BOR-60 reactor¹⁵ at a dose rate between 6×10^{-7} dpa/s and 9×10^{-7} dpa/s to doses between 15 and 35 dpa at 376–524 °C and applies that understanding to successfully

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Proceedings of the Fourth International Conference on Durability of Building Materials and Components Gyoujin Cho, 2013-10-02 Proceedings of the Fourth International Conference on Durability of Building Materials and Components Volume I contains the proceedings of the Fourth International Conference on Durability of Building Materials and Components held in Singapore on November 4-6, 1987. The conference provided a forum for reviewing advances that have been made with regards to the durability of building materials and components and tackled topics ranging from concrete materials and structures to fiber reinforced concrete, plastics, surface coatings, and building codes and specifications. Comprised of 67 chapters, this volume first summarizes the technical barriers to service life prediction and outlines research directions for overcoming such barriers. The discussion then turns to the deterioration of slate tiles containing iron sulfides, prediction of durability of building sealants, and the durability of building ceramics in agricultural environments. Subsequent chapters focus on the influence of seawater curing on the pore structure of flyash blended cement mortar, effect of cement composition on the durability of natural fibers in mortar, permeability control of concrete protective layers in products, and theory and experimental evidence concerning maximum and minimum strength of composite materials. The applications of surface integral techniques to fracture analysis are also considered. This book will be of interest to practitioners and research workers in engineering.

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[Solid Waste-Based Materials for Environmental Remediation](#) Guanyi Chen, Ning Li, Zhanjun Cheng, 2024-11-21 This book provides a multifaceted examination of solid waste management methods, the preparation, properties, and application of solid waste materials in the remediation of various environmental media, as well as the combination of solid waste materials and artificial intelligence. Based on the latest research results and cutting edge technologies from around the world, the contributors combine the design principles of solid waste materials with application examples, including a complete system, clear routes, and illustrations. They integrate the idea of ecological civilization, the concept of sustainable development, and engineering innovation, providing a reliable reference for resource recycling and contributing to global low carbon emission. The book is suitable for teachers and students, as well as researchers, industrial technicians, and managers involved in solid waste resources and environmental remediation.

Coatings for High-Temperature Structural Materials National Research Council, Division on Engineering and Physical Sciences, National Materials Advisory Board, Commission on Engineering and Technical Systems, Committee on Coatings for High-Temperature Structural Materials, 1996-05-13 This book assesses the state of the art of coatings materials and processes for gas turbine blades and vanes, determines potential applications of coatings in high temperature environments, identifies needs for improved coatings in terms of performance enhancements, design considerations, and fabrication processes, assesses durability of advanced coating systems in expected service environments, and discusses the required inspection, repair, and maintenance methods. The promising areas for research and

development of materials and processes for improved coating systems and the approaches to increased coating standardization are identified with an emphasis on materials and processes with the potential for improved performance quality reproducibility or manufacturing cost reduction

Atmospheric Deterioration of Technological Materials, a Technoclimatic Atlas Miroslav Rychtera,1990 This is the second of a number of volumes presenting a new synthetic approach to the problems of material degradation in different parts of the world The method of deriving atmospheric stress on materials described in Part A is further worked out in Part B to include the details of the calculation procedures involved It is shown that the method originally intended for technological materials only can be used for predicting deterioration of simple constructional parts The degradation processes typical of extreme climates in various parts of the world are compared to those encountered in the temperate climatic zone The author shows how to predict the deterioration of a range of materials used in technology and how to apply the results obtained in order to extend their lifetime and increase their reliability This volume concentrates on the particular environmental conditions prevailing in the Asia Australia and Oceania continent The information is presented in the form of maps each accompanied by a wealth of detailed data giving calculated predictions of the sorption desorption temperature corrosion and microbiological stresses acting upon materials

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