

Effects of Radiation on Materials

Sixteenth International Symposium

**Kumar/Gelles/
Nanstad/Little, editors**



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Effects of Radiation on Materials: 16th International Symposium

*Arvind S. Kumar, David S. Gelles, Randy K. Nanstad, and
Edward A. Little, Editors*

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Foreword

This publication, *Effects of Radiation on Materials: 16th International Symposium*, contains papers presented at the symposium of the same name, held in Aurora, CO on 23–25 June 1992. The symposium was sponsored by ASTM Committee E-10 on Nuclear Technology and Applications. Arvind S. Kumar of the University of Missouri in Rolla, MO; David S. Gelles of Pacific Northwest Laboratories in Richland, WA; Randy K. Nanstad of the Oak Ridge National Laboratory in Oak Ridge, TN; and Edward A. Little of Harwell Laboratory in Oxfordshire, United Kingdom presided as symposium chairmen and are editors of the resulting publication.

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Overview

ASTM Committee E-10 on Nuclear Technology and Applications sponsors a biennial series of symposia on the effects of radiation on materials. The first symposium was held in 1960 and followed an earlier series begun in 1956 by Committee E-10, then called the Committee on Radioisotopes and Radiation Effects. Since that first meeting, these symposia have continued to grow in importance as nuclear energy has provided an increasingly larger fraction of the world's electrical capacity. The meetings have become a major international forum for the presentation and discussion of research on the influence of radiation on the microstructure and mechanical properties on structural materials. The proceedings of the Sixteenth International Symposium on the Effects of Radiation on Materials are published in this ASTM Special Technical Publication (STP) 1175. The Symposium was held in Denver, CO on the 23–25 June, 1992. In conjunction with the symposium, an ASTM Standards Technology Training Workshop on Condition Assessment and Surveillance of Nuclear Reactor Pressure Vessel Steels was held on 22 June.

The Sixteenth Symposium continued the precedent of the previous symposium in that more than half of the papers were presented by authors outside of the United States. Of the 84 papers in this book, only 37 had primary authors from the United States. The high level of international collaboration experienced in the previous meeting was again apparent in the Sixteenth Symposium as evidenced by the joint, multinational authorship of a large number of papers. Moreover, 44% of the 111 registrants at this symposium were from organizations outside the United States. Besides the obvious importance of such international participation in contributing to the published knowledge base in radiation effects, these symposia afford opportunities for interpersonal communication with the enhanced likelihood of further collaboration. In an era of shrinking research budgets and the need for highly specialized and expensive instruments for material characterization, the importance of wide collaboration cannot be overemphasized.

The papers presented in this STP are organized in 15 sections. The first section comprises two invited papers presented in a plenary session and authored by representatives from both private and government organizations that play important but different roles in charting the course of nuclear technology. As president of the American Nuclear Society, A. David Rossin forecast the need for more new nuclear power plants in the United States and other nations in his paper, "Meeting Future Power Needs in Licensing Space." He emphasized the need for reform of the nuclear licensing process, real progress on disposal of high- and low-level wastes, models for understanding rate effects and predicting radiation damage and annealing effects in reactor vessels, and the need for us, the technological experts, to document the answers to the critical questions of material performance over time. Alfred Taboada and Michael Mayfield of the U.S. Nuclear Regulatory Commission (USNRC) presented "Overview of USNRC Research on Reactor Pressure Vessel Steel Embrittlement" and emphasized the importance of research to understand the phenomenology of radiation embrittlement so as to allow for prediction of safety margins and for the mediation of embrittlement. They also discussed the NRC's ongoing efforts in the establishment of fracture toughness data for irradiated reactor pressure vessel steels, and in the ability to predict thermal annealing recovery and re-embrittlement.

The first technical session contains eight papers that discuss various general aspects of radiation damage. The relationships between void swelling and irradiation creep, and studies of dislocation loop nucleation based on a rate theory model comprise the discussions in the

first two papers. The next two papers deal with segregation effects in ferritic steels at different irradiation temperatures and displacement rates. Segregation effects are relevant to the reactor pressure vessel (RPV) steel embrittlement issues discussed earlier because of the increasing incidence of observations of intergranular fracture due to grain boundary segregation. The last four papers describe the results of various experimental studies: hardness anisotropy in molybdenum single crystals, nickel ion irradiations of chromium films, electrical resistivity measurements of nickel using electron irradiations, and mechanical properties of α -iron following irradiations in different neutron spectra.

The next three sections deal with three general areas of research in RPV steels: mechanical properties, weld metals, and microstructure and modeling. In the sections on mechanical properties and weld metals, seven and eight papers are presented, respectively. Five of the papers discuss the effects of irradiation temperature on properties of base metals and weld metals, while other papers include such diverse topics as: effects of loading rate on toughness, the use of subsize specimens, the correlations of various properties, the response of a weld metal to different thermal annealing temperatures, and the effects of irradiation and thermal aging on low-alloy welds and stainless steel weld overlay cladding. Many of the papers deal with relatively small specimens and reflect a growing interest in the use of such specimens for commercial reactor vessel surveillance testing, including the determination of fracture toughness properties.

The section on microstructure and modeling of pressure vessel steels includes nine papers, which is an indication of an increasing emphasis in recent years in developing greater understanding of embrittlement mechanisms in pressure vessel steels. The first three papers discuss the effects of irradiation temperature and displacement rate on embrittlement, while the next four present results of detailed microstructural characterization of steels (including a Russian RPV steel) and model alloys using small-angle neutron scattering (SANS), transmission and field emission gun scanning electron microscopy (TEM and FEGSTEM, respectively), positron annihilation (PA), and atom probe field ion microscopy (APFIM), with one of the papers providing some discussion of intergranular fracture due to phosphorous segregation at the grain boundaries. All of these techniques have specific advantages in such characterization studies; if used in a combined manner, however, they offer greatly enhanced capabilities towards the resolution of the mechanisms underlying the development of defect microstructures. Such combined studies, then, implore the increased collaboration mentioned earlier. The next paper provides an important look at the capabilities for examination of defect production offered by electron irradiations. The final paper discusses the limitations inherent in the use of displacements per atom (dpa) as a measure of embrittlement in RPV steels.

Five of the seven papers in the section on ferritic and ferritic-martensitic steels discuss experimental results while the other two report microstructural evolution results. The first paper discusses tensile property changes in terms of changes in the power law work hardening exponent for various binary Fe-Cr alloys, while the second paper provides data on a commercial martensitic steel showing minor effects of irradiation on the subcritical fatigue crack-growth, but strong effects on the ductile fracture toughness. The next two papers provide experimental results on fracture toughness and Charpy toughness, respectively, for irradiated Cr-Mo martensitic steels. The latter paper compared the effects of thermal aging to the irradiation results and also makes recommendations regarding the use of heat treatment to optimize properties. The fifth paper in this section discusses the differences in irradiation-induced precipitation between a weldment and the parent plate at relatively high exposure levels and states that observed differences in precipitation can be rationalized in terms of parameters that influence radiation-induced segregation. The sixth paper presents results

on the effects of irradiations on the notch toughness of a reactor core support material. The last paper showed that intergranular microcracking in HT-9 steel is dependent on helium content and was caused by bubble growth at the grain boundaries due to increased temperature and stress during welding.

The next four sections deal with different areas of research in austenitic alloys: mechanical properties, helium effects and swelling, microstructures and modeling, and stress-corrosion cracking. The section on mechanical properties contains seven papers with discussions of irradiation-induced changes in a number of properties: irradiation creep, creep rupture strength, tensile properties, fatigue crack growth, and fracture toughness. The first paper discusses successful miniaturization of pressurized tubes for use under conditions when limited irradiation space is available, while the second paper recommends an optimum level of cold work for specific applications. The next two papers discuss tensile and burst test behavior, respectively, of two different types of fuel cladding. The following two papers discuss the effects of relatively high temperature irradiations on the fatigue crack growth of a Nimonic alloy, and the effects of relatively low-temperature irradiations on the fracture toughness of stainless steel vessel weldments, respectively. The last paper in this section provides a review of irradiation effects on cold-worked 316 stainless steel and includes both mechanical properties and microstructural changes. In the section on helium effects and swelling, the first paper deals with welding of austenitic alloys in the irradiated condition. It suggests a method to at least suppress helium-induced cracking in 316 stainless steel. The next two papers discuss swelling of different austenitic alloys with the first of these demonstrating the complex and often nonmonotonic influence of three common solutes on swelling with increasing solute level. The second paper presents both radiation creep and swelling results for alloys irradiated to very high exposures. The next paper presents results of swelling and irradiation creep on two variants of austenitic steels used as core component materials in French fast reactors, while the last paper concludes that a substantial influence of aluminum and titanium on the helium bubble microstructure parameters has been established.

The third section on austenitic alloys contains six papers that discuss various aspects of microstructures and modeling. The first two papers performed isotopic doping experiments with nickel and boron, respectively, to investigate helium effects. The third paper reports the results of fast neutron irradiations on three model Fe-Cr-Ni alloys with varying amounts of phosphorus as the minor constituent. The next two papers report on irradiations of stainless steels using electrons and nickel ions, respectively. The study using electrons noted that radiation-induced segregation and void formation could progress during irradiation by the same mechanism, while preliminary results from the ion irradiation study suggested a possible effect of stress-enhanced precipitation on cavity nucleation. The last paper in that section discusses results of irradiations of model austenitic alloys that were used to establish mechanistic modeling of swelling and other property changes under irradiation. Three of the four papers in the stress-corrosion cracking (SCC) section present experimental results on austenitic steels. The first paper showed that the SCC susceptibilities could not be correlated with the segregation of impurities but could be correlated with chromium concentration at the grain boundaries. The second paper reported the results of both tensile and microstructural analyses from high energy proton irradiations and postulated a potential effect of using protons because induced grain boundary etching and surface slip bands may have influenced the initiation of intergranular cracks in the SCC tests. The third paper reported results of slow strain rate tests on four different stainless steels and noted that steels with higher austenite phase stability seemed to be less susceptible to irradiation-assisted SCC. The last paper in this section presents results of scanning transmission electron mi-

croscopy analyses and corrosion tests of irradiated 304 stainless steel. It noted that the amount of chromium depletion tended to be greater in the commercial-purity heats than in a high-purity heat of steel at higher fluences, but lower at lower fluences.

The section on copper and copper alloys comprises five papers. The first two papers report on microstructural evolution under proton and electron irradiations, respectively. The third paper discusses the development of a specific brazing process for a commercial alloy, while the next paper reports on the effects of irradiation to a very high exposure level on the properties of oxide dispersion-strengthened commercial alloys. The last paper in this section used TEM and PA techniques to study evolution of the bubble microstructure in copper and has suggested that observed differences in bubble density arise from structural differences in the grain boundaries.

The section on zirconium alloys includes four papers. The first paper discusses the relationships between the microstructural and microchemical changes observed in X-ray diffraction (XRD) and analytical electron microscopy (AEM) studies and the observations of physical changes in the irradiated material. The second paper discusses the use of a self-consistent model to predict irradiation creep of polycrystals, while the third presents an analysis of experimental data to examine the suitability of two different empirical equations used for predicting the strain hardening parameter of Zircaloy-2. The last paper in this section reports on experimental results of irradiation growth on both annealed and cold-worked zirconium alloys.

The section on aluminum alloys contains two papers, both of which present results of mechanical property tests on type 6061 aluminum. The first paper relates to the acquisition of irradiation effects information for the design of a new high-flux reactor, the Advanced Neutron Source (ANS), and includes the first known fracture toughness data for irradiated 6061 aluminum. The second paper presents results of tensile and notch impact tests conducted on specimens removed from tubes of the High Flux Beam Reactor and relates the irradiation-induced changes to amorphous silicon precipitates with a proposed role of thermal-to-fast neutron flux ratio. The latter subject has relevance to the first paper in that the ANS will contain structural components subjected to widely varying thermal-to-fast neutron ratios.

The next section contains three papers on vanadium alloys, with the first on microstructural studies, the second on fatigue crack-growth, and the third on mechanical properties as affected by helium doping. The first paper relates the swelling and ductility changes in various irradiated vanadium alloys to the type of irradiation-induced precipitates. The second paper provides results of fatigue crack-growth tests on two different alloys with a chromium-bearing alloy exhibiting greater decreases in crack-growth resistance than the one with no chromium. The third paper discusses the results of mechanical properties changes in terms of the different states of helium clusters.

The final section in this book is on irradiation of nonmetallics and includes seven papers, with one on fast reactor nuclear fuel. The first three papers discuss various aspects of ceramic insulators. The first paper provides experimental results that showed that a gaseous environment can have a very detrimental effect on the electrical conductivity of alumina and silicon nitride under irradiation. The next two papers present modeling of internal stresses produced during irradiation of alumina, and the recrystallization behavior of alumina-based ceramics, respectively. The next two papers discuss studies directed at applications in fusion reactors. The first of those showed not only substantial reductions in thermal conductivity of carbon-carbon composites after irradiation, but also substantial recovery after thermal annealing. The second paper on fusion applications presents data on the effects of neutron irradiation on the swelling behavior of various compounds of carbon-boron-titanium. The sixth paper in this section discusses modeling development and calculations that showed

that the fission-gas bubbles at the phase boundaries in U-Pu-Zr metal fuel provide critical cavity sizes consistent with the observed incubation dose for the onset of rapid swelling and gas release. Finally, the last paper discusses the effects of neutron irradiation on the thermal conductivity of carbon-carbon fiber materials that showed that reductions in conductivity of up to 60% can occur at 400°C and 0.1 dpa.

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