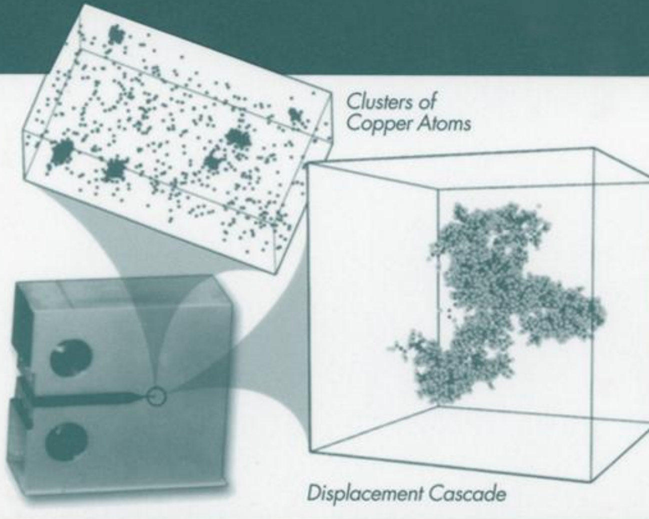
EFFECTS OF RADIATION ON MATERIALS

18th International Symposium



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Effects of Radiation on Materials: 18th International Symposium

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Foreword

This publication, *Effects of Radiation on Materials: 18th International Symposium,* contains papers presented at the 18th Symposium on Effects of Radiation on Materials, held 25–25 June, 1996, in Hyannis, Massachusetts. The symposium was sponsored by ASTM Committee E-10 on Nuclear Technology and Applications. The symposium chairman was Randy K. Nanstad, Oak Ridge National Laboratory. Margaret L. Hamilton and Frank A. Garner of Pacific Northwest National Laboratory and Arvind S. Kumar of the University of Missouri–Rolla served as co-chairs.

Cover Photo

The composite photograph on the cover depicts an irradiated fracture toughness test specimen of a nuclear pressure vessel steel that has been embrittled by high-energy neutron irradiation; the neutrons displace atoms from their lattice sites, causing a cascade of interstitials and vacancies, most of which are annihilated by recombination, but a small fraction of which survive as defects in the structure and eventually produce defects such as copper-rich precipitates and clusters that cause embrittlement. Photographs of the fracture toughness specimen, molecular dynamics simulation of a displacement cascade, and result of a three-dimensional atom probe measurement provided by Randy K. Nanstad, Roger E. Stoller, and Michael K. Miller, respectively, of Oak Ridge National Laboratory.

Through an extremely improbable series of random events (certainly chaotic), attendees at the *Effects of Radiation on Materials: 18th International Symposium* found themselves positioned conveniently for a group photo near the Tara Hyannis Hotel in Hyannis, Massachusetts.

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AUSTENITIC ALLOYS—SEGREGATION AND PROPERTIES

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 of structural materials. The proceedings of the Eighteenth International Symposium on the Effects of Radiation on Materials are published in this ASTM Special Technical Publication (STP) 1325. The Symposium was held in Hyannis, Massachusetts, June 25–27, 1996.

The Eighteenth Symposium continued the strong tradition of previous symposia with regard to significant participation by researchers from outside of the United States. One hundred thirty abstracts were submitted for presentation at the symposium and, of the 71 papers in this book, 36 have primary authors from countries other than the United States. The high level of international collaboration experienced in the previous meeting was again apparent in the Eighteenth Symposium as evidenced by the joint, multinational authorship of a large number of papers. Moreover, 77 of the 135 registrants (57%) at this symposium were from organizations outside the United States. Committee E-10 considers such international participation to be very important to this series of symposia not only because of the variety of research emphasis and interpretation, but also because of the enhanced likelihood of further collaboration. Given the decreasing funding available in many research institutions, collaboration is a sensible approach. The organizers extend a special thanks to those international participants for their contributions and their participation.

The papers presented in this STP are organized in 14 sections, seven on pressure vessel steels, two on austenitic alloys, one each on other structural alloys, ferritic and ferritic-martensitic alloys, copper and copper alloys, and vanadium alloys, and one section with papers on aluminum, beryllium, zirconium, and sapphire. The organization of the sections generally reflects that of the technical sessions of the symposium.

The first section contains seven papers that discuss various aspects of radiation damage mechanisms and modeling in reactor pressure vessel (RPV) steels, including the effects of thermal neutrons at relatively low temperatures and the effects of gamma rays on advanced boiling water reactors. In the first case, it was found that a very high ratio of thermal-to-fast neutrons can produce modest additional hardening, while in the second case it was concluded that the potential effects of gamma rays are not of practical interest to the operation of boiling water reactor RPVs. Studies using the technique of molecular dynamics have indicated that the mobility of small point defect clusters may be much higher than previously expected with a significant impact on the models used to predict radiation damage. Two papers present information on the basis of small-angle neutron scattering experiments showing effects of increasing copper and phosphorus content on nucleation and growth of copper-rich precipitates, while another paper demonstrates varying amounts of hardening due to thermal aging of model alloys and steels.

The second section presents various aspects of mechanical properties, to include subsize impact specimens and the description of a specially designed irradiation facility. The variability in Charpy impact toughness of a typical low upper-shelf submerged-arc weld was demonstrated to be extremely high, but was similar to that of a high upper-shelf weld. Moreover, the variability was the same as that of a thick-section plate of A 533 Grade B Class 1 steel. Other papers showed that the irradiation-induced shift of fracture toughness generally exceeds the Charpy shift for base metals, but is about the same for weld metals; the analysis, however, showed the uncertainties to be very high in both cases. Two papers discuss subsize Charpy impact testing, one relative to the potential use of side grooves and the other relative to the use of finite-element modeling to predict upper-shelf energy of full-size specimens from subsize specimens' test results. The last two papers of this section make a comparison of actual crack-arrest toughness measurements and estimates of crack-arrest toughness from instrumented traces of Charpy impact tests, and describe the details of a highly flexible irradiation facility for RPV steels.

The third and fourth sections deal with segregation effects in RPV steels and microstructural aspects of annealing, respectively. Segregation effects are relevant to the RPV steel embrittlement issues discussed earlier because of the increasing incidence of observations of intergranular fracture due to grain boundary segregation of phosphorous. The papers on segregation deal with (1) special procedures for the use of Auger spectroscopy to determine phosphorous coverage on grain boundaries, (2) determination of phosphorous free energy change in submerged-arc welds, (3) effects of different heat treatments on subsequent grain boundary coverage, and (4) studies of potential effects of such segregation on thermal annealing of irradiated RPV steels. The papers that deal specifically with microstructural aspects of post-irradiation thermal annealing include (1) small-angle neutron scattering experiments which validate other observations that annealing tends to decrease the number density and volume fraction but increase the size of scattering centers, (2) atom probe experiments that indicate some concern for high fluence irradiations relative to copper content in solution, and (3) hardness measurements on an A533B steel.

A separate section on recovery of properties by thermal annealing includes seven papers, one of which also discusses reirradiation effects and identified high phosphorous content for certain observations. Another paper observes "over-recovery" of Charpy upper-shelf energy and J_{Ic}, while other papers present results of annealing recovery and generally show nearly full recovery of transition temperature after annealing at 454°C and mixed but marginal recovery after annealing at 343°C. Two of the papers discuss observations of lower than expected sensitivity to irradiation by a low-alloy steel plate with relatively high nickel content. A section on embrittlement correlations for RPV steels presents the important role of thermal monitors in commercial reactor surveillance capsules, and various analyses of commercial reactor surveillance databases to develop predictive trend curves for both western steels and VVER-440 steels. The last section for RPV steels presents five papers on studies with the objective of characterizing radiation damage through the use of nondestructive techniques, such as positron annihilation, Barkhausen noise, electrical resistivity, eddy current, and magnetomechanical acoustic emission. Each paper indicates the ability to at least qualitatively detect embrittlement of RPV steels with various conclusions of potential quantitative evaluations.

Three sections on austenitic and other structural alloys contain 17 papers on various aspects of radiation-induced segregation, creep, irradiation-creep, and swelling. The three papers on segregation present (1) developments in the use of lattice rate theory to model segregation using a single set of input parameters, (2) the proposal of a new mechanism involving the radiation-induced release of manganese and sulfur into the alloy matrix from manganese sulfide precipitates, and (3) the modeling of combined effects of temperature and radiation on chromium segregation. These modeling efforts are important advances in the studies of irradiation-assisted stress corrosion cracking of austenitic stainless steels. Spectral tailoring experiments and low temperature irradiations were conducted to achieve helium levels in the alloys of interest to fusion reactor applications, and model alloys were used to investigate the phosphide effect on void swelling and the effects of helium on damage behavior, also for fusion reactor applications. The emphasis on fusion reactor applications continue in the next section in which various irradiation creep experiments are discussed. Relatively high displacements per atom exposures were used in these programs, which present data showing (1) little or no effect of cold work on irradiation of austenitic alloys at 300°C, (2) that creep rates normalized to the displacement rates are very similar to experiments conducted in three different test reactors, and (3) that the creep coefficients for a ferritic-martensitic steel appear essentially identical to those observed in iron-base austenitic steels. In the third section, a series of experiments were conducted to demonstrate the increasing helium production rate in and around fast reactor cores, and void swelling was found to be associated with the formation of a MoC phase in a modified 316 stainless steel. In another series of experiments, a series of relatively swelling-resistant steels exhibited a complex swelling response arising from synergistic effects of silicon and phosphorous additions on both void swelling and precipitate-related phase changes. Also, low-temperature irradiations of 316 stainless steel welds revealed no negative creep elongation at the beginning of irradiation and no development of alpha-ferrite during irradiation due to insufficient mobility of point defects. Various effects of radiation-induced segregation on swelling of these alloys are also discussed.

The section on ferritic and ferritic-martensitic alloys contains six papers that present results of mechanical properties experiments and microstructural studies. New procedures for thin foil transmission electron microscopy and Auger electron spectroscopy for segregation studies are described in one paper, while another reported on the hardening of a model alloy through copper precipitation. In a paper on oxide-dispersion-strengthened ferritic steel, the authors report that even after irradiation to 81 dpa, the alloy showed excellent dimensional stability but did show tensile hardening and strong ductility loss. One paper reports on experiments to investigate the effects of helium production on the embrittlement of these ferritic alloys, while two others present a significant amount of tensile and impact data on ferritic alloys that have been developed to minimize activation; the impact data show a wide range of radiation sensitivity on embrittlement that is dependent on chemical composition, and also show that thermal aging for 20,000 h had little effect on property changes.

The section on copper and copper alloys includes three papers that provided results of experiments showing that (1) satisfactory resistance to radiation by a copper-silver braze was offset somewhat by high residual radioactivity, (2) effects of nickel/zinc additions on void density and swelling induced by ion irradiations were found to be similar to those by fission neutron irradiations, and (3) very small diffusion coefficients for Ni^{63} in nickel and copper were measured by sputtering of electrons from an accelerator. The section on other alloy systems included papers on aluminum, beryllium, zirconium, and sapphire. Thermal irradiation of a common structural aluminum alloy showed that irradiation to a very high fluence resulted in increased strength and decreased elongation; however, decreases in fracture toughness were only observed at the highest test temperature of 150°C. Extremely high irradiation of zirconium alloys showed the most irradiation-resistant alloy to be a multicomponent alloy with tin, niobium, and iron. Irradiation of beryllium up to 750°C by neutrons and by cyclotron injection of helium showed an abrupt embrittlement of all samples at 700°C characterized by intergranular fracture due to helium bubble formation. For the sapphire experiments, radio-luminescence were observed in situ in the reactor, but substantial improvements in the techniques are needed before the silica-core optical fibers that are used to transmit the signals can function adequately. The final section on vanadium alloys includes three papers that show (1) development of a quantitative micromechanical model of fracture for irradiated vanadium alloys, (2) experiments with ion beams to distinguish the helium effect and chemical effects of doped boron on swelling behavior, and (3) the impact resistance of a vanadium alloy irradiated at various temperatures from 75 to 300°C.

The diverse nature and quality of the research presented in this STP reflect the continuing importance of the field of radiation effects on materials to the scientific community and the nuclear industry. The editors extend appreciation to the authors for their contributions and to the technical reviewers whose diligence has maintained the tradition of excellence shown in this series of symposia.

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