Designation: E521 – 23

Standard Practice for Investigating the Effects of Neutron Radiation Damage Using Charged-Particle Irradiation[1]

This standard is issued under the fixed designation E521; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

INTRODUCTION

This practice is intended to provide the nuclear research community with recommended procedures for using charged-particle irradiation to investigate neutron radiation damage mechanisms as a surrogate for neutron irradiation. It recognizes the diversity of energetic-ion producing devices, the complexities in experimental procedures, and the difficulties in correlating the experimental results with those produced by reactor neutron irradiation. Such results may be used to estimate density changes and the changes in microstructure that would be caused by neutron irradiation. The information can also be useful in elucidating fundamental mechanisms of radiation damage in reactor materials.

1. Scope

1.1 This practice provides guidance on performing charged-particle irradiations of metals and alloys, although many of the methods may also be applied to ceramic materials. It is generally confined to studies of microstructural and microchemical changes induced by ions of low-penetrating power that come to rest in the specimen. Density changes can be measured directly and changes in other properties can be inferred. This information can be used to estimate similar changes that would result from neutron irradiation. More generally, this information is of value in deducing the fundamental mechanisms of radiation damage for a wide range of materials and irradiation conditions.

1.2 Where it appears, the word "simulation" should be understood to imply an approximation of the relevant neutron irradiation environment for the purpose of elucidating damage mechanisms. The degree of conformity can range from poor to nearly exact. The intent is to produce a correspondence between one or more aspects of the neutron and charged-particle irradiations such that fundamental relationships are established between irradiation or material parameters and the material response.

1.3 The practice appears as follows:

1.4 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.5 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.6 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

C859 Terminology Relating to Nuclear Materials

E170 Terminology Relating to Radiation Measurements and Dosimetry

[1] This practice is under the jurisdiction of ASTM Committee E10 on Nuclear Technology and Applications and is the direct responsibility of Subcommittee E10.05 on Nuclear Radiation Metrology.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

E821 Practice for Measurement of Mechanical Properties During Charged-Particle Irradiation

E910 Test Method for Application and Analysis of Helium Accumulation Fluence Monitors for Reactor Vessel Surveillance

E942 Guide for Investigating the Effects of Helium in Irradiated Metals

2.2 *ICRU Documents:*[3]

ICRU 60 Fundamental Quantities and Units for Ionizing Radiation

ICRU 85a Fundamental Quantities and Units for Ionizing Radiation

3. Terminology

3.1 *Definitions of Terms Specific to This Standard:*

3.1.1 Descriptions of relevant terms are found in Terminology C859 and Terminology E170.

3.2 *Definitions:*

3.2.1 *damage energy,* T_{dam}—that portion of the energy lost by an ion moving through a solid that is transferred as kinetic energy to atoms of the medium; strictly speaking, the energy transfer in a single encounter must exceed T_d.

3.2.2 *displacement*—the process of dislodging an atom from its normal site in the lattice.

3.2.3 *path length*—the total length of path measured along the actual path of the particle.

3.2.4 *penetration depth*—a projection of the range along the normal to the entry face of the target.

3.2.5 *projected range*—the projection of the range along the direction of the incidence ion prior to entering the target.

3.2.6 *range*—the distance from the point of entry at the surface of the target to the point at which the particle comes to rest.

3.2.7 *stopping power (or stopping cross section)*—the energy lost per unit path length due to a particular process; usually expressed in differential form as $-dE/dx$.

3.2.7.1 *Discussion*—The stopping power is commonly divided into an electronic and a nuclear component (ICRU).

3.2.8 *straggling*—the statistical fluctuation due to atomic or electronic scattering of some quantity such as particle range or particle energy at a given depth.

3.3 *Symbols:*

3.3.1 A_1, Z_1—the atomic weight and the number of the bombarding ion.

A_2, Z_2—the atomic weight and number of the atoms of the medium undergoing irradiation.

depa—damage energy per atom; a unit of radiation exposure. It can be expressed as the product of $\bar{\sigma}_{de}$ and the fluence.

dpa—displacements per atom; a unit of radiation exposure giving the mean number of times an atom is displaced from its lattice site. It can be expressed as the product of $\bar{\sigma}_d$ and the fluence.

heavy ion—used here to denote an ion of mass >4.

light ion—an arbitrary designation used here for convenience to denote an ion of mass ≤4.

T_d—an effective value of the deposited energy required to displace an atom from its lattice site. Usual unit is eV.

$\sigma_d(E)$—an energy-dependent displacement cross section; $\bar{\sigma}_d$ denotes a spectrum-averaged value. Usual unit is barns.

$\sigma_{de}(E)$—an energy-dependent damage energy cross section; $\bar{\sigma}_{de}$ denotes a spectrum-averaged value. Usual unit is barns-eV or barns-keV.

4. Significance and Use

4.1 A characteristic advantage of charged-particle irradiation experiments is the precise, individual control over most of the important irradiation conditions such as dose, dose rate, temperature, and quantity of gases present. Additional attributes are the lack of induced radioactivation of specimens and, in general, a substantial compression of irradiation time, from years to hours, to achieve comparable damage as measured in displacements per atom (dpa). An important application of such experiments is the investigation of radiation effects that may occur in materials exposed to environments which do not currently exist, such as in first wall materials used in fusion reactors.

4.2 The primary shortcoming of ion bombardments stems from the damage rate, or temperature dependences of the microstructural evolutionary processes in complex alloys, or both. It cannot be assumed that the time scale for damage evolution can be comparably compressed for all processes by increasing the displacement rate, even with a corresponding shift in irradiation temperature. In addition, the confinement of damage production to a thin layer just (often ~1 µm) below the irradiated surface can present substantial complications. It must be emphasized, therefore, that these experiments and this practice are intended for research purposes and not for the certification or the qualification of materials.

4.3 This practice relates to the generation of irradiation-induced changes in the microstructure of metals and alloys using charged particles. The investigation of mechanical behavior using charged particles is covered in Practice E821.

5. Apparatus

5.1 *Accelerator*—The major item is the accelerator, which in size and complexity dwarfs any associated equipment. Therefore, it is most likely that irradiations will be performed at a limited number of sites where accelerators are available (a 1-MeV electron microscope may also be considered an accelerator).

5.2 *Fixtures,* for holding specimens during irradiation are generally custom-made as are devices to measure and control particle energy, particle fluence rate (recommended terminology for the deprecated term "flux"), and specimen temperature. Decisions regarding apparatus are therefore left to individual workers with the request that accurate data on the performance of their equipment be reported with their results.

[3] ICRU Report 60 has been superseded by ICRU Report 85a on Fundamental Quantities and Units for Ionizing Radiation, October 2011. Both of these documents are available from International Commission on Radiation Units and Measurements (ICRU), 7910 Woodmont Ave., Suite 800, Bethesda, MD 20814.