Irradiation Effects in Nuclear and Their Related Materials

Prof. **Masayuki Hasegawa** (1997.8~)

【Staff Members】

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【Research Activities】

Mid-term Research activities are as follows.

(1) Fundamental studies of radiation damage mechanisms in reactor materials of aged light water reactors by nano-materials-science techniques to enhance their future safety evaluation,

(2) Promotion of close and global collaborations on the above projects with domestic and international leading research groups.

The first project

We developed the following advanced positron annihilation techniques:

(a) A slow positron beam apparatus for detection of near-surface defects associated with stress corrosion cracking (SCC) in stainless steel of reactor-core shrouds,

(b) A newly developed positron age-momentum correlation (AMOC) apparatus using digital oscilloscope for the studies of Cu nano-precipitation in Fe, especially the number densities of the precipitates.

(c) Installation of energy-compensated 3 dimensional atom probe (3D-AP) apparatus of NIMS, under collaboration with Dr. Kazuhiro Hono, in the radiation-safety controlled area in the Oarai Center. Thus our laboratory has unique and invaluable nano-materials experimental tools in the world; we can measure advanced positron annihilation spectra as well as 3D-AP to have integrated information on the mechanisms of irradiation-induced embrittlement and damage in nuclear materials, especially reactor pressure vessel steels (RPVs) (**Ref.** ***1***, ***2***).

Fundamental studies to clarify the mechanisms of the irradiation-induced embrittlement in surveillance test specimens of commercial nuclear power reactors are very limited and have been hardly done in universities in the world. However they are very necessary from the viewpoint of nuclear safety. Our study is a pioneering one in this sense

The second project

Based on the above, we have the following collaborations to enhance the studies of light water reactor materials.

(a) NIMS (Dr. K. Hono): Close and critical comparison studies by 3D-AP and positron annihilation,

(b) JEARI (Drs. M. Suzuki and T. Tsukada): Irradiation-induced embrittlement of RPV steels and stress corrosion cracking (SCC) of core-shrouds of light-water reactors

(c) SCK/CEN, Belgium (Dr. van Walle Eric): Nano-materials studies of surveillance test specimens from commercial reactors (Doel reactors, Belgium) and exchange young researchers and graduate course students,

(d) University of California at Santa Barbara (UCSB), USA (Prof. B. Odette): Nano-materials studies of RPV and model alloys,

(e) University of California at Berkeley (UCB), USA (Prof. B. Wirth): Nano-materials studies of RPV and model alloys,

(f) Oak Ridge National Laboratories, USA (Dr. Y. Osetzky): Modeling of mechanical properties of Fe containing Cu nano-precipitates and nanovoids, Molecular dynamics simulations and nano-materials experiments,

(g) Riso National Laboratory, Denmark (Dr. M. Eldrup): Analysis of nano-voids and bubbles in metals.

These collaborations are also much augmented by state-of-art computer simulations, mostly first-principles calculations using IMR Super Computer as well as our work stations

Based on the above experimental set-ups and collaborations, we had the following main results.

(a) Studies of real surveillance test specimens from commercial reactors: Tokai I Calder Hall Type Reactor (CHR) (dismantled about 5 yeas before) and Doel reactors (pressurized water reactors: PWRs). Interesting irradiation flux effects in the CDR surveillance test specimens [**Ref.*3*** and submitted to Phys. Rev. Lett.] and fluence effects in the specimens from the PWRs.

(b) Development new theories of positron and positronium states in solids. Many-body theory (GW approximation) calculation of positron states has been performed on Si crystal (submitted to Phys. Rev. Lett.). Bethe-Salpeter equation method has been applied to positronium in SiO2 crystals and comparisons between excitons (electron-hole bound states) and Ps (electron-positron bound states) are made [To be submitted to Phys. Rev. Lett.].

(c) Using positron lifetime and 2 dimensional angular correlation spectra, we have studied various SiO_2 based glass and model radioactive waste glass to probe their structural nanovoids which are possible containers of radioactive nuclides in atomic scales (**Ref.*5***).

1. Y. Nagai, T. Toyama, Z. Tang, M. Hasegawa, T. Ohkubo, K. Hono:
"Embedded Ultrafine Clusters Investigation by Coincidence Doppler Broadening Spectroscopy",
Mater. Sci. Forum 445-446 (2004) 11-15.

2. T. Toyama, Y, Nagai, Z. Tang, H. Hasegawa, T. Ohkubo, K. Hono:
"Irradiation-Induced Defects and Cu Precipitates in Ternary Fe-Based Model Alloys for Nuclear Reactor Pressure Vessel Steels Studied by Positron Annihilation and 3D Atom Probe",
Mater. Sci. Forum 445-446 (2004) 195-197.

3. Z. Tang, M. Hasegawa, Y. Nagai, M. Saito:
"First-Principle Calculation of Positron Annihilation Characteristic in Solids: From Positron

to Positronium",
Mater. Sci. Forum 445-446 (2004) 390-394.

4. K. Inoue, Y. Sasaki, Y. Nagai, H. Ohkubo, Z. Tang and M. Hasegawa:
"Structural Subnanovoids in Silica-Based Glasses Probed by Positronium",
Mater. Sci. Forum 445-446 (2004) 304-306.

5. T. Honma, S. Yanagita, K. Hono, Y. Nagai and Y. Hasegawa:
"Coincidence Doppler broadening and 3DAP study of the pre-precipitation stage of an Al-Li-Cu-Mg-Ag alloy",
Acta Mater. 52 (2004) 1997-2003

【Plan】

Our objective is to clarify the mechanisms of irradiation-induced embrittlement of reactor pressure vessel (RPV) steels of aged commercial nuclear power reactors to be reflected in the prediction of the embrittlement. Using nano-materials science tools, such as advanced positron annihilation and 3 dimensional atom probe (3D-AP), we will study "real surveillance test specimens for RPV steels" as well as their model alloys. We develop advanced experimental and theoretical methods and enhance close collaborations with leading research groups in the world. Furthermore we will apply these methods to the other fields of materials science, such as metallic, silica-based glass and semiconductor materials. In particular, we are much interested in defect structures in nuclear radioactive waste glasses, Si and SiC. The followings are main targets in our program.

(i) Model alloys of RPV steels: Clarification of formation and evolution processes of nano-precipitates and defects in model alloys, such as Fe-Cu-Mn, Ni, P, induced by thermal aging and by irradiation.

(ii) RPV surveillance test specimens and those irradiated under the similar and accelerated conditions: Clarification of nano-processes causing the embrittlement in the RPV steels and suggestions for the prediction of embrittlement.

(iii) Development of advanced experimental and computational methods to study the embrittlement in RPV steels and application of them to the other field of the materials science