7–4 Optimization of Alloying Components of Nuclear Core Materials

— Development of an Estimation Method for Irradiation-Induced Point Defect Behavior —

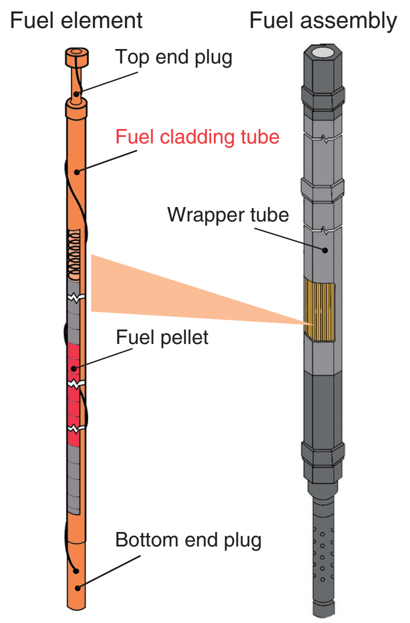

Fig.7-8 Example fuel structure design in a sodium-cooled fast reactor
Fuel pellets and their fission products are covered in a fuel cladding tube and top/bottom end plugs. This integrated structure is called the fuel element and is bundled in a fuel assembly and loaded into the core.

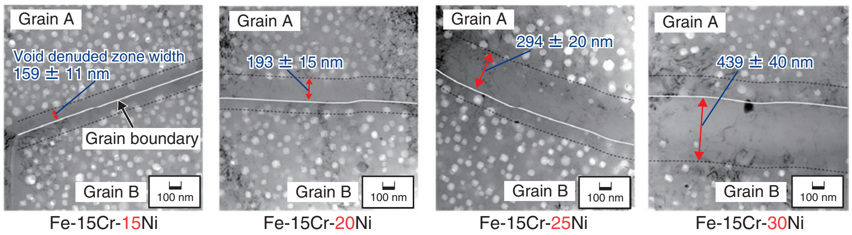

Fig.7-9 Void denuded zone formed in neutron-irradiated Fe–Cr–Ni austenitic steels (476 °C, 18 dpa※)
The void denuded zone (VDZ) of each steel sample was measured using the average width formed between grains A and B at multiple points. The width of the VDZ, which depends on the vacancy diffusion behavior, increased with increasing Ni concentration, indicating that the vacancy diffusion differs depending on the steel type.
※ The dpa (displacement per atom) represents a unit of neutron irradiation dose.

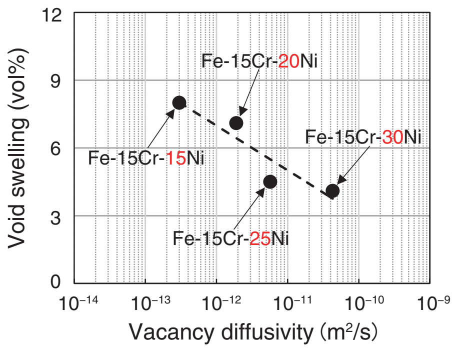

Fig.7-10 Relationship between vacancy diffusivity and void swelling of each steel sample
Using the widths of the VDZs presented in Fig.7-9, the vacancy diffusivities were estimated to establish a quantitative relationship between them and the void swelling. For the four types of steel studied, increasing the Ni concentration caused the void swelling to decrease due to the high vacancy diffusivity.

Fuel pellets inside a nuclear reactor are covered with a thin metal tube, i.e., the fuel cladding tube, to prevent the leakage of radioactive materials released by nuclear fission (see Fig.7-8). The material used for the fuel cladding tube must be resistant to irradiation and not deteriorate in the presence of the neutron irradiation occurring in the reactor.

We are currently developing long-life cladding tubes that exceed the performance of the existing modified SUS316 steel cladding to reduce radioactive waste and support research into fast reactors. In particular, swelling causes material deterioration and must be reduced. Swelling is due to the behavior (diffusion and quantity) of irradiation-induced point defects (vacancies and self-interstitial atoms) in the material. Therefore, the behavior of these defects must be understood and controlled to suppress swelling; however, the quantitative relationship between defect behavior and swelling has not been addressed. Further, methods to evaluate these behaviors have not yet been established. Clarifying the relationships between defect behavior and swelling in various steel types with different alloy components thus would allow an appropriate design strategy for selecting major alloy components and additional elements to be constructed to supplement the existing cladding design method.

Therefore, we aimed to develop a method to estimate the behavior of defects in Fe–Cr–Ni austenitic steel (i.e., the base material of modified SUS316 steel) by focusing on the void denuded zone (VDZ) at grain boundaries by irradiation. The width of the VDZ depending on the vacancy diffusion behavior was measured using transmission electron microscopy. Using the measured widths and calculations combining the existing VDZ formation theory (i.e., diffusivity dependence) and the existing rate theory (i.e., concentration dependence), we estimated the vacancy diffusivity and concentration. The observed VDZ formation within four steel samples irradiated in Joyo is shown in Fig.7-9, where the Cr content of these samples was fixed at 15wt%, and the Ni content was ranged from 15 to 30wt%. The VDZ width varied with Ni concentration. The relationship between the vacancy diffusivity and the void swelling is shown in Fig.7-10. Our methodology thus quantitatively clarified that the swelling suppression in the four steels was due to the increase of vacancy diffusivity. Future efforts will focus on using neutron-irradiated samples with various alloy components to improve the accuracy of the observed relationship, thereby contributing to efforts to optimize the design of alloy components.

This research is a part of the results from the joint research with Hokkaido University, "Research on quantitative evaluations of point defect behavior in Fe–Cr–Ni steel".

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Reference

Sekio, Y. et al., Effect of Nickel Concentration on Radiation-Induced Diffusion of Point Defects in High-Nickel Fe–Cr–Ni Model Alloys during Neutron and Electron Irradiation, Materials Transactions, vol.60, issue 5, 2019, p.678–687.