Irradiation Embrittlement and Structural Integrity of Reactor Pressure Vessel

Background and Objective

The reactor pressure vessels (RPVs) of light water reactors (LWRs) are subjected to neutron irradiation that causes changes in the mechanical properties of RPV steels. This phenomenon, known as neutron irradiation embrittlement, is one of the most important issues that need to be accurately predicted for the long term and safe operation of aged nuclear power plants. CRIEPI has been promoting a research project on understanding the mechanism of embrittlement at the microstructural level, and has developed a new method to predict the amount of embrittlement, which has been adopted in Japan Electric Association Code, JEAC4201-2007. The improvement of embrittlement prediction capability at high fluence regime as well as the development of advanced methods for the evaluation of the structural integrity of RPVs are necessary for the expected long term operation of LWRs.

This project aims at understanding embrittlement mechanism at high fluence regime for the validation and improvement of current embrittlement prediction method, and at the development of new technology for reliable structural integrity evaluation.

Main results

1. Effect of neutron flux on embrittlement

Test reactor irradiation at high neutron flux conditions is the only way to achieve high neutron fluence levels, in short irradiation time, that correspond to extended end-of-life conditions of RPV steels. CRIEPI has studied, under a joint research project with the University of California, Santa Barbara, the effect of neutron flux on microstructural changes at the atomistic level by means of Atom Probe Tomography (APT) technique. It was found that the size and number density of solute atom clusters formed during irradiation (see Fig. 1) are smaller and higher at higher flux conditions, respectively. Furthermore, the changes in such microstructures after post-irradiation annealing are larger at higher flux conditions as shown in Fig. 2. These results suggest that microstructures formed during irradiation are affected by neutron flux [Q09021].

2. Computer simulation of microstructural evolution

Atomistic-scale computer simulation is a very promising tool to study the mechanism of solute atom cluster formation as observed by APT. In this study, first-principles molecular dynamics calculations were performed to calculate the interaction energies between a solute atom and a vacancy, and then the numerical simulation of cluster formation through the diffusion of solute atoms by vacancy mechanism. Cluster nucleation around a vacancy and cluster growth by agglomeration of solute atoms were identified as shown in Fig. 3 [Q09002].

3. High precision hardness measurement by nano-indentation

Hardness is known as a good measure of the amount of embrittlement although the scatter in measured hardness has often been a problem for precise evaluation of embrittlement. We investigated here the applicability of nano-indentation technique with a few grams weight and more than 1,000 measurements. The results show that the nano-hardness distribution in a 2mm x 2mm region has a one-to-one correspondence with the microstructure as shown in Fig. 4, and a comparison of the histogram of hardness allows us to detect a small change in hardness caused by neutron irradiation [Q09014].

Other reports [Q09029], [Q09026], [Q09015]

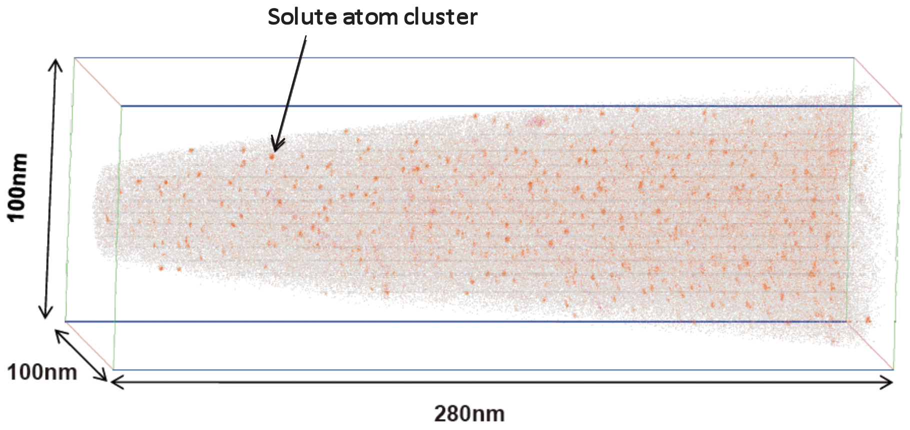

Fig. 1 Atom map obtained by 3-dimensional Atom Probe measurement
54 million atoms are contained in the measured volume. Only Cu and Si atoms are displayed as orange and gray dots, respectively. Formation of solute atom cluster containing Cu atoms at very high number density is evident.

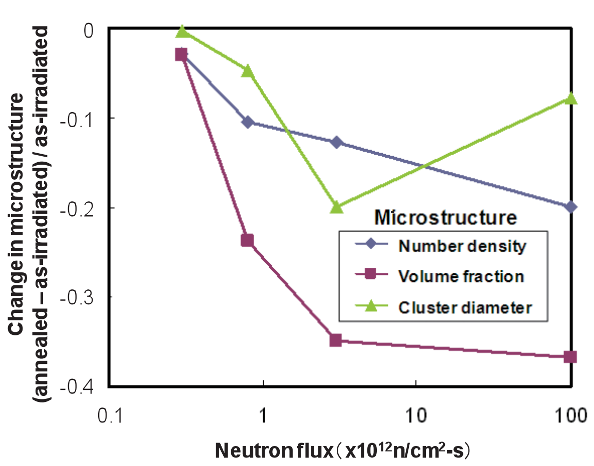

Fig. 2 Microstructural changes after annealing
Changes due to annealing are small at low flux, while they are large at higher flux. This result suggests that the characteristics of microstructures are affected by flux.

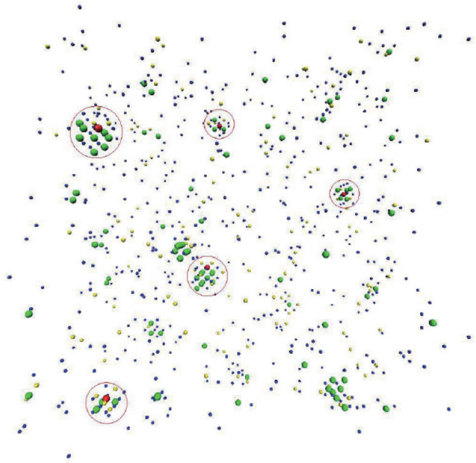

Fig. 3 Formation of solute atom clusters by diffusion of vacancies (Cu, Ni, Si and vacancy are shown in green, blue, yellow and red dots, respectively)
Clusters are formed around vacancies.

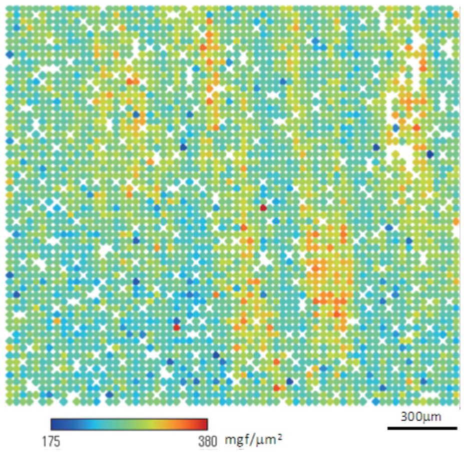

Fig. 4 Hardness distribution in 2mm x 2mm region measured by nano-intentation
The harder regions that consist of yellow and red data points contain many carbides indicating good correlation between hardness and microstructure.

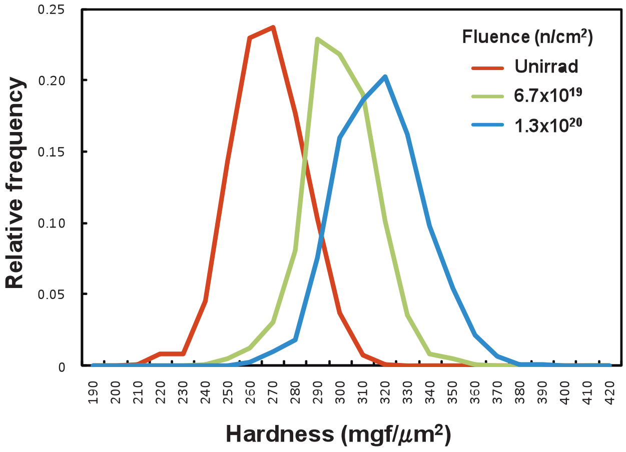

Fig. 5 Histograms of the hardness of neutron irradiated reactor pressure vessel steel
Comparison of histogram allows us to measure small changes in hardness with sufficient accuracy.