JP9950652

3.11 DETERMINATION OF IRRADIATION TEMPERATURE USING SiC TEMPERATURE MONITORS

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ABSTRACT

This paper describes a method for detecting the change in length of SiC temperature monitors and a discussion is made on the relationship between irradiation temperature and the recovery in length of SiC temperature monitors.

The SiC specimens were irradiated in the experimental fast reactor "JOYO" at the irradiation temperatures around 417 to 645 °C (design temperature). The change in length of irradiated specimens was detected using a dilatometer with SiO_2 glass push rod in an infrared image furnace. The temperature at which recovery in macroscopic length begins was obtained from the annealing intersection temperature. The results of measurements indicated that a difference between annealing intersection temperature and the design temperature sometimes reached well over ±100 °C. A calibration method to obtain accurate irradiation temperature was presented and compared with the design temperature.

INTRODUCTION

The lattice parameter and macroscopic length of neutron-irradiated silicon carbide (SiC) decrease almost linearly with increasing postirradiation isochronal annealing temperature above irradiation temperature. On the basis of this characteristic, SiC has been used as an in-pile uninstrumented irradiation temperature monitor in fast breeder reactors and thermal reactors[1-4].

In the previous studies, the lattice parameter was measured to estimate the irradiation temperature. However, if SiC is irradiated to fluences higher than 1×10^{26} n/m^2, the amorphization occurs and due to the line broadening of X-ray diffraction patterns, the lattice parameters are no more determined. Thus SiC monitor is not applicable to the high irradiation region. Bramman [2] and Suzuki et al.[5] measured the dilatation of the irradiated SiC monitors and they pointed out that the onset of recovery was dependent on the heating rate which made it difficult to clearly identify the onset of recovery. Later on, the present author et al. [6] showed a simple method to measure the change in length of SiC temperature monitors by using a differential dilatometer and has shown that the onset of recovery detected by the step heating dilatometry gives a good agreement with those obtained with an X-ray diffractometer and a micrometer.

In regard to the relationship between irradiation temperature and the onset of recovery of SiC which was irradiated in fast reactors, Sharp[7] has reported that the estimated temperature from SiC agreed well with the thermocouple temperature within ± 20 to 25°C. However, Palentine[8] has indicated that there are considerable discrepancies between annealing intersection temperature of SiC and the thermocouple temperature irradiated in the Dounreay Fast Reactor (DFR). He derived the relationship between annealing intersection of specimen length and the irradiation temperature as

$$T_{irrad} = 1.0312T_{SiC}-44.71 \qquad (1)$$

where, T_{irrad} is the irradiation temperature and T_{SiC} is the annealing intersection temperature obtained by the specimen length measurement. He showed that the accuracy is ± 27 to 45°C.

In Japan Nuclear Cycle Development Institute, SiC has been used as one of the off-line temperature monitors to estimate the irradiation temperature of reactor materials. This paper gives the results of measurement of SiC temperature monitor irradiated in "JOYO" experimental fast breeder reactor and the relationship between irradiation temperature and the recovery behavior of SiC temperature monitors is discussed.

EXPERIMENTAL METHOD

The SiC specimens used for the temperature monitor were reaction bonded β-SiC having about 80% of theoretical density and manufactured by Toshiba Ceramics Co. Ltd. The specimens had dimensions typically of 1 mm x 1 mm x 15 mm or 1 mm in diameter and 15 mm long. They were irradiation in the experimental fast reactor "JOYO" to fluences from 0.1 to 63 x 10^{25} n/m^2 (E > 0.1 MeV) and the irradiation temperature around 417 to 645 °C (design temperature).

The SiC specimens were encapsulated in helium-filled capsules of stainless steel and loaded in the SMIR (Structural Materials Irradiation Rig) and INTA-S (Instrumented Test Assembly - S) irradiation test subassemblies. In SMIR test subassembly, the SiC temperature monitor was irradiated together with a tensile test specimen as shown in Fig. 1(a). In INTA-S test subassembly, two kinds of irradiation capsules were prepared. One is called a SMIR-simulated capsule which contains a tensile test specimen and SiC monitor equipped with a thermocouple. This capsule is designed so that it can accurately measure the irradiation temperature of the test specimen and SiC monitor as shown in Fig. 1(b). The other capsule is called a temperature monitor test capsule which contains SiC monitor as shown in Fig.1(c). Although it does not provide the thermocouple, the irradiation temperature of SiC monitor could be accurately estimated by taking the thermocouple temperature of SIMR-simulated capsule into account. The design irradiation temperature of SiC monitors in SMIR capsules was calculated from the heat transfer analysis with a universal computer code HEATING-5.

The irradiation temperature of SiC monitors in the temperature monitor test capsule of INTA-S capsules (Fig.1(b)) was calibrated against the thermocouple temperature in the SMIR-simulated capsule (Fig.1(c)).

The change in length of irradiated specimens was measured as follows: The length of as-irradiated SiC specimen was first measured by using a conventional micrometer with accuracy of about ±2 μm. Then the specimen was placed in a dilatometer with SiO_2 glass push rod in an infrared image furnace and heated up to 900 ℃ in steps of 50 ℃ in a nitrogen atmosphere. The temperature was kept for 30 min at each holding temperature. After heating at 900℃, the specimen was cooled down to room temperature and then the same step heating dilatometry was repeated with the annealed specimen. Taking the difference of dilatation between first and second runs as shown in Fig. 2, the change in length by annealing of SiC specimen is obtained. The temperature at which recovery in macroscopic length begins was obtained from the annealing intersection temperature as shown in Fig. 3.

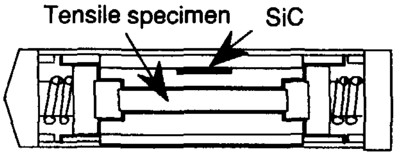

Fig. 1(a) SMIR capsule

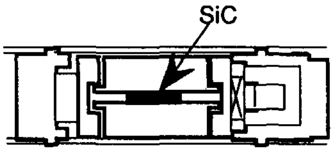

Fig. 1(b) Temperature monitor test capsule

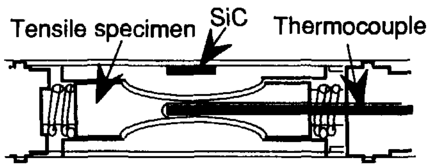

Fig. 1(c) SMIR simulated capsule

Fig. 1 Schematic diagram of irradiation capsules

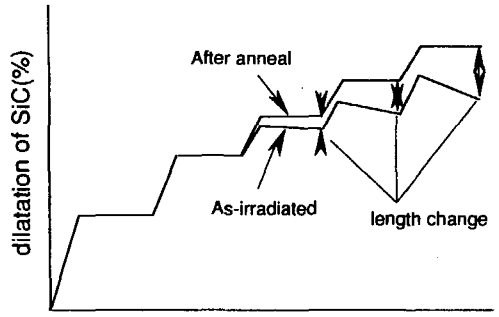

Fig. 2 Schematic diagram of step heating dilatometry

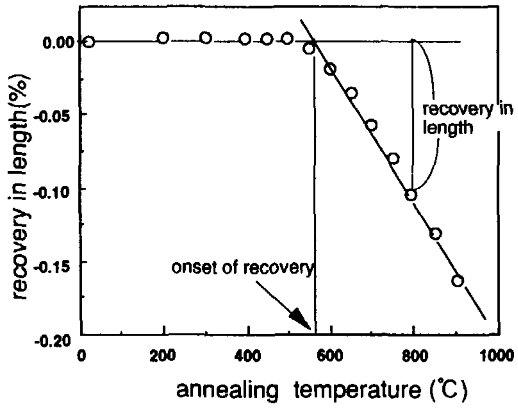

Fig. 3 Method for determining irradiation temperature of SiC monitors

RESULTS AND DISCUSSION

Fig. 4 shows the relationship between annealing intersection temperature T_{SiC} and the design irradiation temperature T_{irrad}. It is shown that the annealing intersection temperature T_{SiC} is underestimated at higher irradiation temperature, or overestimated at lower irradiation temperature. Even if we correct the temperature T_{SiC} by using equation (1) which was given by Palentine et al., the same tendency still remains and the agreement between T_{SiC} and T_{irrad} was not satisfactory.

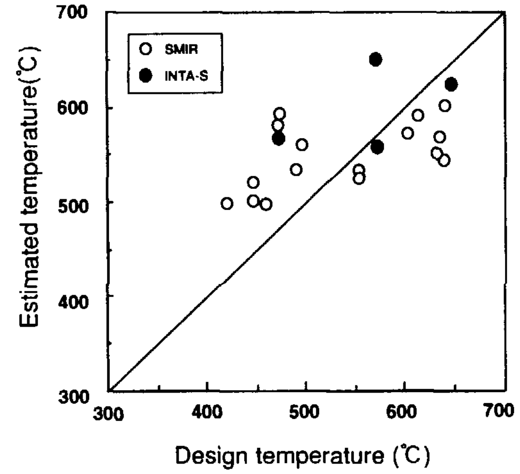

Fig. 4 Design temperature vs. estimated irradiation temperature of SiC monitors obtained from annealing intersection temperature

We compared the temperature difference between T_{SiC} obtained from annealing intersection temperature and the irradiation temperature T_{irrad} as a function of the axial position of SiC monitors in the irradiation subassemblies. As shown in Fig. 5, the temperature difference ΔT, given as

$$\Delta T = T_{SiC} - T_{irrad} \qquad (2)$$

is negative around the center region of reactor core and positive in the bottom or top region of reactor core. The temperature difference ΔT sometimes reached well over ±100 °C.

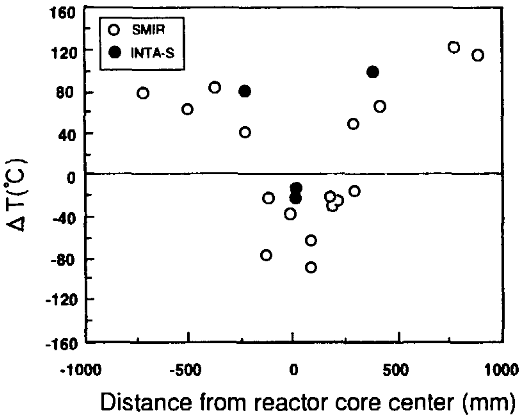

Fig. 5 Difference between design temperature and estimated temperature as a function of distance from reactor core center

In order to find out the cause of the large difference between T_{SiC} and T_{irrad}, the difference between design temperature and the estimated temperature ΔT was plotted as a function of neutron fluence. However, the effect of neutron fluence on the temperature difference was not clearly observed. On the other hand, when we plotted the ΔT as a function of neutron flux, ΔT is positive when neutron flux is smaller than about 9×10^{18} n/(m$^2\cdot$s) (E > 0.1 MeV) and becomes negative when it is larger than 1×10^{19} n/(m$^2\cdot$s), as shown in Fig. 6.

Palentine[8] has shown that the use of the thermal reactor calibration equation between T_{SiC} and T_{irrad}, would lead to serious errors for fast reactor experiments such that the thermal reactor calibration could cause the temperature in a fast reactor irradiation to be overestimated by up to 23°C at lower temperatures, or underestimate by up to 50°C at higher temperature. He pointed out that the difference is due to the different dose rate between thermal and fast reactors. The dose rate of fast reactor was about one order of magnitude higher than that of thermal reactor. When Palentine made his investigation of SiC monitor in DFR, the neutron flux was in the region of approximately 8 x 10^{18} n/($m^2 \cdot s$) and T_{SiC} was higher than T_{irrad} by about 30°C at about 560°C. The relationship between ΔT and the neutron flux given in Fig. 6 yields the ΔT around 40°C, which qualitatively agrees with the correlation eq.(1) given by Palentine.

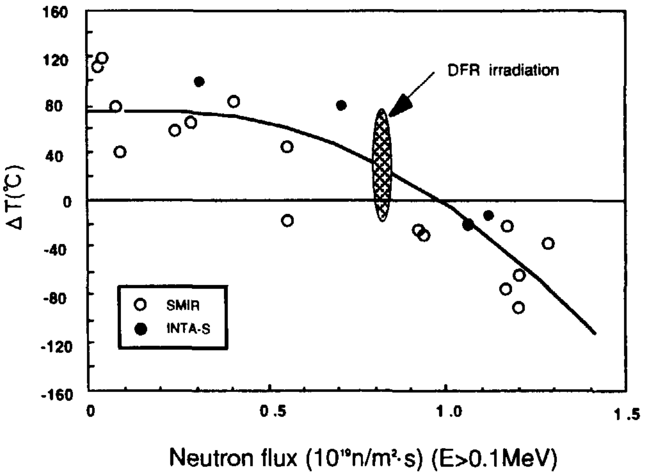

Fig. 6 Neutron flux vs. difference in irradiation temperature and the estimated temperature. Here, ΔT is given as $\Delta T = T_{SiC} - T_{irrad}$.

Thus, it is suggested that SiC monitors which were irradiated in the high flux region resulted in underestimation of irradiation temperature, and those irradiated in lower flux region resulted in overestimation of irradiation temperature. On the other hand, as shown in Fig. 4, the SiC monitors which were irradiated at higher temperature resulted in underestimation of annealing intersection temperatures and those irradiated at lower temperature resulted in over estimation of the annealing intersection temperatures. In the present investigation, the SiC which was irradiated in high flux environment had higher irradiation temperature and low flux at lower irradiation temperature. Since irradiation experiment is not available for the specimens which have been irradiated at high temperature and low flux or at low temperature at high flux, it is difficult to clearly indicate that the onset of recovery in length of SiC is influenced by the neutron flux or the irradiation temperature.

Furthermore, in the present investigation, the most of design irradiation temperature is based on the heat transfer calculation which sometimes brings about ambiguity as to the accuracy of irradiation temperature and makes it difficult to compare the irradiation temperature and the temperature derived from SiC monitors. Therefore, in determining irradiation temperature of SiC monitors, it is necessary that the SiC temperature should be directly measured with thermocouples.

We consider that further systematic investigation is needed to elucidate effect of neutron flux and/or irradiation temperature on the recovery behavior of SiC temperature monitors.

SUMMARY AND CONCLUSION

In the present investigation, the change in length of SiC temperature monitors was measured by a step heating dilatometry. The temperature at which recovery in macroscopic length begins was obtained from annealing intersection temperature and we obtained the following results and conclusion.

(1)The results of measurements indicated that a difference between annealing intersection temperature and the design temperature sometimes reached well over ±100 °C.
(2) Higher irradiation temperature resulted in lower annealing intersection temperature of SiC monitors and vise versa.
(3) It was suggested that the onset of recovery of SiC is influenced either by the neutron flux or the irradiation temperature.
(4) Since the specimens were available only for those irradiated at high temperature and high flux or low temperature and low flux, the origin of the difference is not clear at present.
(5) Systematic irradiation experiment is needed to elucidate the cause of difference between irradiation temperature and that obtained from SiC monitors, where, the temperature of SiC monitors should be directly measured with thermocouples.

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