7.1 IRRADIATION TEMPERATURE DETERMINATION OF HFIR TARGET CAPSULES USING DILATOMETRIC ANALYSIS OF SILICON CARBIDE MONITORS

— T. Hirose, N. Okubo, H. Tanigawa (Japan Atomic Energy Agency), Y. Katoh, A.M. Clark, J.L. McDuffee, D.W. Heatherly, R.E. Stoller (Oak Ridge National Laboratory)

OBJECTIVE

The objective of this work is to determine the irradiation temperatures of the HFIR target capsules JP-26 and JP-27, which were conducted under the Collaboration on Fusion Materials between Japan Atomic Energy Agency and the US DOE.

SUMMARY

The irradiation temperatures of the HFIR target capsules JP-26 and JP-27 were determined by dilatometric analysis of silicon carbide (SiC) passive temperature monitors. The monitors from holders for SSJ3 tensile specimens demonstrated good agreement with the design temperatures derived from finite element model (FEM) analysis and were consistent with post-irradiation hardness of F82H. Although the irradiation temperatures for some bend-bar (PCCVN and DFMB) holders were higher than FEM analysis, hardness tests on irradiated F82H implied that actual irradiation temperatures were close to the design temperatures.

PROGRESS AND STATUS

Introduction

Previous work demonstrated that dilatometry-based passive thermometry is invaluable to determine irradiation temperature as well as the more commonly used resistivity-based passive thermometry [1]. This method was employed to determine the irradiation temperature, T_{irr} of non-instrumented target capsules JP-26 and JP-27 irradiated in the flux trap region of the HFIR reactor. These experiments were carried out within the framework of the JAEA- US DOE Collaboration on Fusion Materials, Annex I, which was started in its fourth phase [2, 3, 4]. In that phase, four target capsules, JP-26, JP-27 JP-28 and JP-29 were developed to evaluate irradiation response of reduced activation ferritic/martensitic steel. Specimen holders for these capsules have the common design and have been irradiated at the same T_{irr} with several dose levels. It is an important objective of these experiments to evaluate effects of heat treatment and additional minor elements on irradiation hardening, which strongly depends on T_{irr}, in reduced activation ferritic/martensitic steel, F82H. Therefore it is necessary to determine the T_{irr} to clarify the effects of the modifications. Since irradiation hardening has been evaluated for F82H irradiated in JP-26 and JP-27, the T_{irr} from the dilatometric analysis is discussed along with the hardening [5].

Experimental Procedure

The material of the temperature monitor was chemically-vapor-deposited (CVD) SiC manufactured by Rohm & Haas Advanced Materials. The SiC passive temperature monitor has rectangular shape and its dimensions are summarized in Table 1. The passive temperature monitor was irradiated in the target capsule JP-27. JP-27 consists of sixteen specimen holders designed to accommodate six types of specimens and irradiate them at 300, 400 and 500°C. Specimen holders have common design, and the details are presented elsewhere [2, 3]. The target capsule JP-26 was irradiated in the target region of the HFIR from cycle 398 to 402, and JP-27 was from cycle 400 to 412. The irradiation of JP-27 was interrupted for 1.5 year between cycle 407 and 409 due to installation of cold neutron source. The dilatometry was conducted up to 1000°C at a constant ramp rate of 2.5°C /minute using Workhorse TM I dilatometer system, Anter Corporation. The temperature monitor was placed in an upright position between a stage and a dilatometer probe made of silica. The shorter monitors, SSJ3 and DFMB were

placed on an extra spacer of aluminum oxide. Difference between initial heating and cooling curves were calculated to clarify inflection due to defect annealing.

Table 1: Dimensions of SiC passive temperature monitors.

Specimen type	Thickness (mm)	Width (mm)	Length (mm)
SSJ3	0.482	2.99	15.1
PCCVN	0.482	3.11	35.8
DFMB	0.482	3.11	18.1

The irradiation temperature, T_{irr} was defined as an intersection of trend lines before and after deflection. Otherwise, it was defined as the point the slope in the derivative of the differential turned negative.

Results and Discussions

Typical length-temperature plots of SSJ3 type temperature monitor are shown in Figure 1. The temperature monitor exhibited a deflection around the T_{des} due to defect annealing. The slope (black cross), defined as derivative of the differential length change, decreased and approached -5 x 10^{-6} /^{o}C. The T_{irr} and the onset of defect annealing were 317°C, which was very close to the T_{des}, 314°C. Figure 2 shows a result of length-temperature plots of PCCVN type temperature monitor. As shown in this figure, it is difficult to determine a linear fitting after recovery due to gradual deflection. Therefore T_{irr} was determined as the point where the slope turned negative. This gradual deflection was observed in most of monitors for PCCVN. Figure 4 shows hardness distribution over the length of PCCVN bend-bar specimen irradiated in JP-27. The length of PCCVN is 36 mm and it is much longer than the others. The hardness has a peak at the middle of the length in most of specimen, though neutron flux decreases with a distance from the reactor midplane. It implies lowest T_{irr} at the middle, where is analyzed using FEM. Therefore the inhomogeneous hardness distribution is due to temperature distribution. From these results, it is considered the gradual deflection was caused by temperature distribution over the length of the holder.

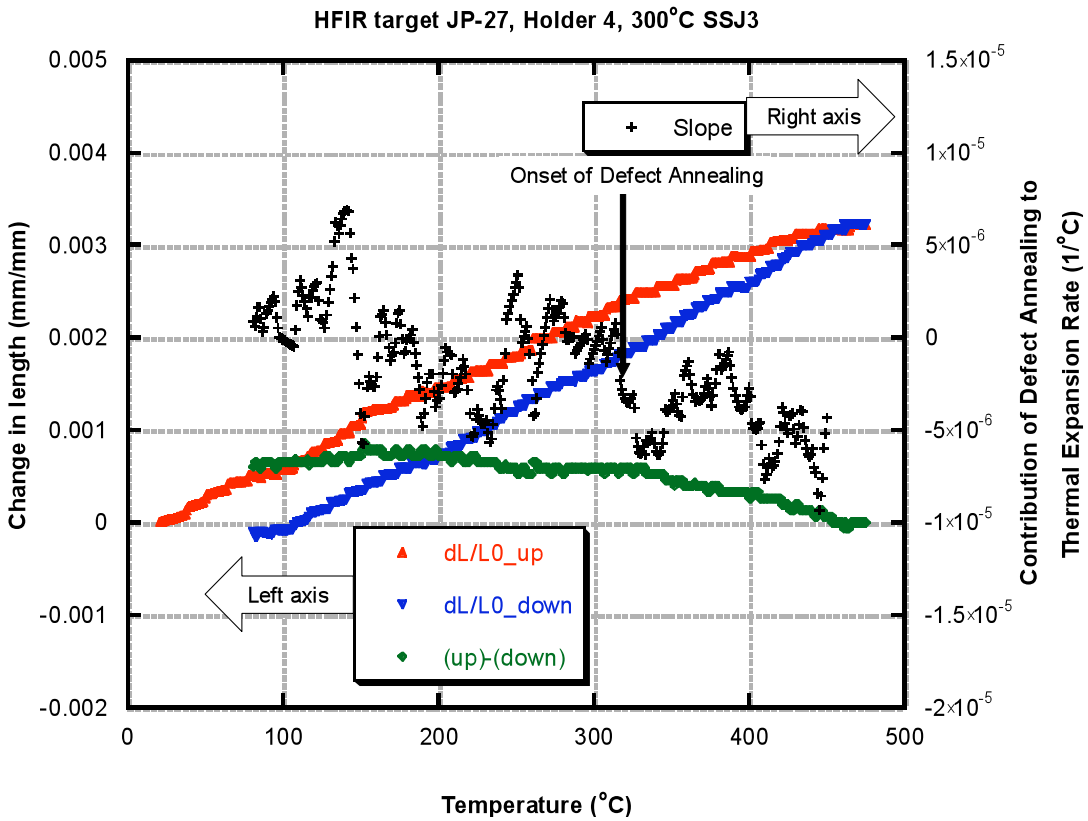

Figure 1. Fractional change in length of SSJ3 type thermometer from the holder 4 in JP-27. The nominal T_{irr} is 300°C.

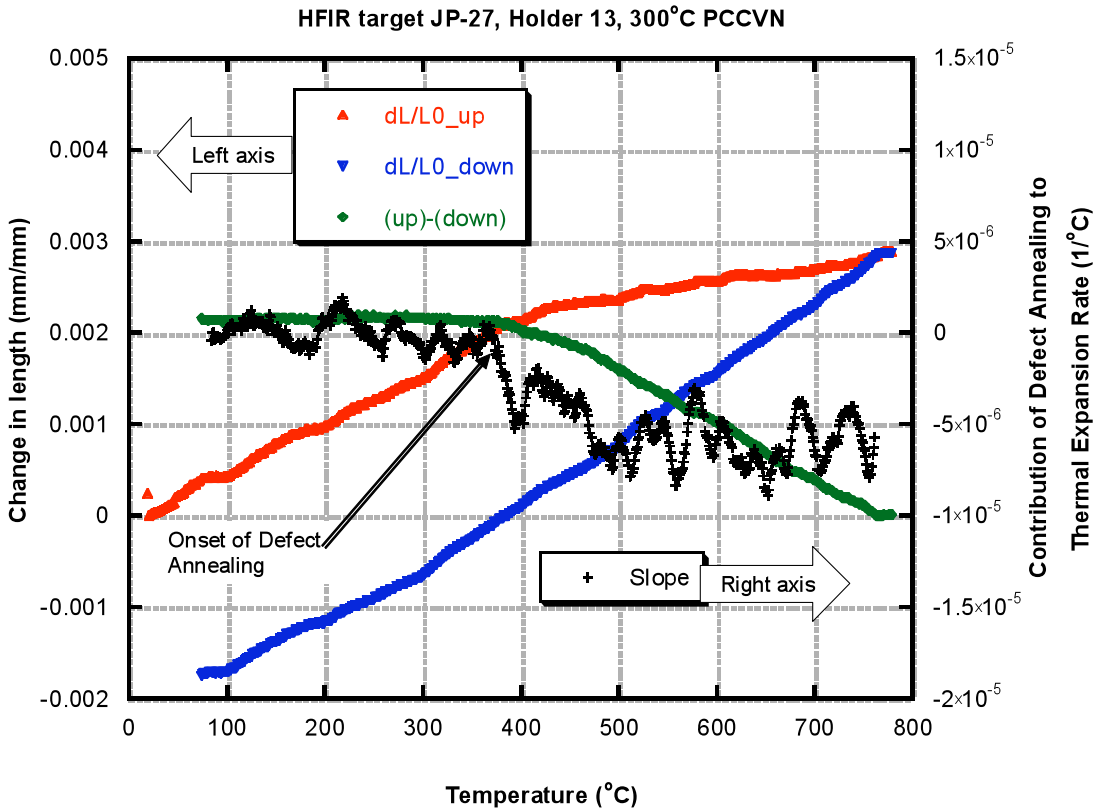

Figure 2. Fractional change in length of PCCVN type thermometer from the holder 13 in JP-27. The nominal T_{irr} is 300°C.

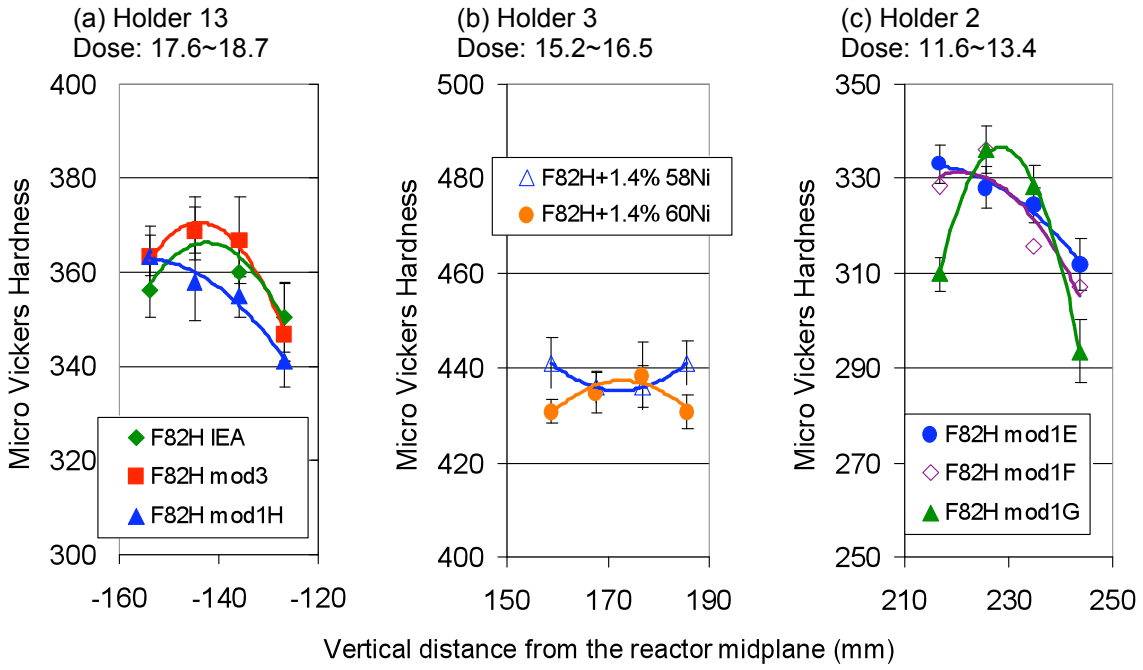

Figure 4. Hardness distribution over length of PCCVN specimen of F82H irradiated in the holder 13 in JP-27. (a) holder 13, (b) holder 3 and (c) holder 2. The nominal T_{irr} is 300°C.

The results of dilatometer analysis are summarized in Table 2. A couple of measurements were conducted on the holder 4, 6 and 11 in JP-27, and the results demonstrated good reproducibility. It is considered that the results are consistent with the design temperature, because it is anticipated that ±20°C of error range is included in determining irradiation temperature using dilatometric analysis [1]. The temperature monitors from SSJ3 holders showed good agreement with the T_{des} for various T_{irr} and dose levels. However, it is obvious that the T_{irr} of PCCVN holder has large uncertainty. T_{des} of PCCVN holder was defined at the vertically middle position. Therefore it is considered that this uncertainty is due to temperature gradient in its length direction. Figure 5 shows micro Vickers hardness of F82H and its variants irradiated at nominal T_{irr} = 300°C in JP-27. The specimens were prepared from the same materials, and the difference in hardness simply depends on the T_{irr}. It is reported that irradiation hardening of F82H-IEA irradiated in holder 4 showed good agreement with some reference work [5, 6]. Therefore it is assumed that T_{irr} of holder 4 was close to the T_{des}. A dilatometry on holder 3 demonstrated 40°C higher T_{irr} than T_{des}. Nickel doped F82H irradiated in holder 3 demonstrated less hardening than that in holder 4, and it is consistent with the dilatometric analysis. In contrast, an inconsistency was found between holders 4 and 13. Dilatometry on holder 13 showed 45°C higher T_{irr}. However, F82H-IEA and mod3 irradiated in the holders 4 (SSJ3) and 13 (PCCVN) showed very similar hardness. It is considered that these holders were irradiated at similar temperature, and the dilatometry overestimated T_{irr}. From these results, it is considered that JP-26 and JP-27 were successfully irradiated at the design temperature.

Table 2. Summary of irradiation temperature of HFIR target capsules, JP-26 and JP-27.

Holder	Specimen	Dose (dpa)	Nominal T_{irr} (°C)	Design temp. at SiC monitor location, T_{des} (°C)	T_{irr} from SiC monitor, T_{meas} (°C)	T_{meas} - T_{des} (°C)
JP26-4	PCCVN	6.3	300	320	342	22
JP26-5	SSJ3	7.5	300	314	315	1
JP26-6	SSJ3	8.1	400	422	449	27
JP26-14	DFMB	6.6	300	327	348	21
JP27-2	PCCVN	12.5	300	315	301	-14
JP27-3	PCCVN	15.8	300	320	357	37
JP27-4	SSJ3	18.4	300	314	317	3
					332	18
JP27-5	SSJ3	20.2	400	416	440	24
JP27-6	SSJ3	21.4	400	422	432	10
					438	16
JP27-7	PCCVN	21.9	400	430	417	-13
JP27-10	DFMB	21.7	400	426	442	16
JP27-11	PCCVN	20.9	400	426	383	-43
					396	-30
JP27-12	DFMB	19.7	300	327	358	31
JP27-13	PCCVN	18.0	300	325	370	45
JP27-14	SSJ3	15.5	300	314	332	18
JP27-15	SSJ3	12.3	300	308	313	5

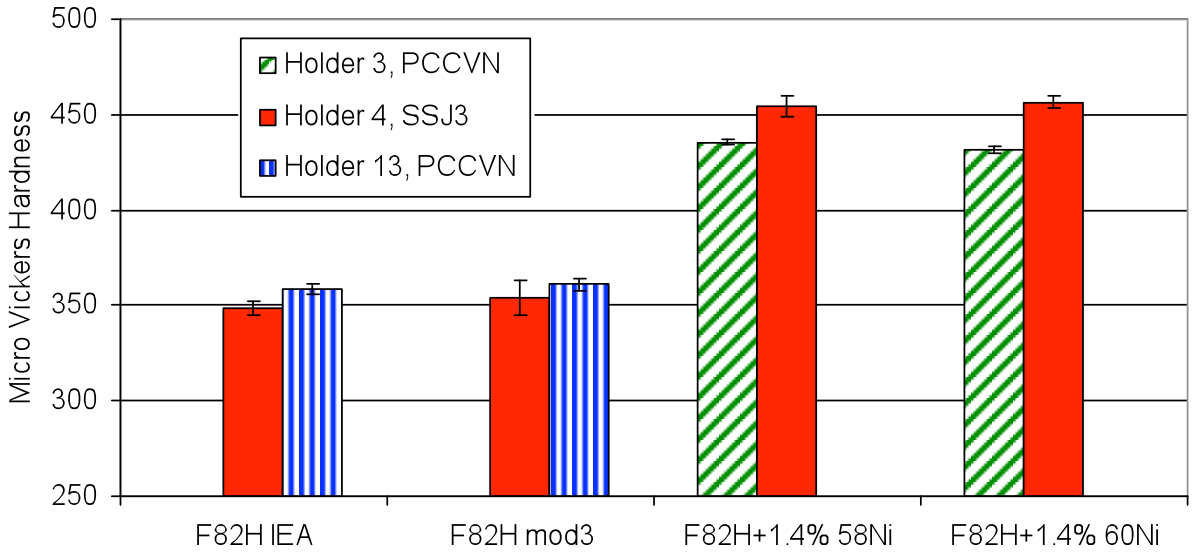

Figure 5. Micro Vickers hardness of F82H and its variants irradiated n JP-27. The nominal T_{irr} is 300°C.

References

[1] Y. Katoh, A. Clark, K. Ozawa, "Dilatometry of irradiated silicon carbide as a method for determination of irradiation temperature," Fusion Materials Semi-annual Progress Report DOE/ER/0313/48, (June 2010) 158.

[2] D. K. Felde, K. R. Thoms, D. W. Heatherly, S. H. Kim, R. G. Sitterson, R. E. Stoller, H. Tanigawa, "Assembly of the US-Japan JP-27 experiment and start of irradiation in the HFIR," Fusion Materials Semi-annual Progress Report DOE/ER/0313/36, (June 2004) 124.

[3] K. R. Thomas, D. W. Heatherly, S. H. Kim, R. G. Sitterson, R. E. Stoller, H. Tanigawa, "Assembly of the US-Japan JP-26 experiment and start of irradiation in the HFIR," Fusion Materials Semi-annual Progress Report DOE/ER/0313/35, (December 2003) 250.

[4] D. K. Felde, D. W. Heatherly, S. H. Kim, R. G. Sitterson, R. E. Stoller, C. Wang, M. Ando, H. Tanigawa, "Assembly of the US-JAPAN JP-28 and JP-29 experiments and start of irradiation in the HFIR," Fusion Materials Semi-annual Progress Report DOE/ER/0313/38, (June 2005) 164.

[5] T. Hirose, N. Okubo, H. Tanigawa, M. Ando, M. A. Sokolov, R. E. Stoller, G. R. Odette, Journal of Nuclear Material (in press), doi:10.1016/j.jnucmat.2010.12.044

[6] B. V. Schaaf, C. Petersen, Y. De Carlan, J. W. Rensman, E. Gaganidze, X. Averty, "High dose, up to 80 dpa, mechanical properties of Eurofer 97," J. Nucl. Mater. 386-388 (2009) 236-246.