Effect of Reactor Power Drop during an Irradiation Testing of ARAA Material in HANARO

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1. Introduction

Advanced Reduced-Activation Alloy (ARAA) has been developed since 2011, as a structural material of fusion reactor in KAERI [1]. ARAA, which will be applied to the test-blanket module of ITER, is placed in an environment where 14 MeV high energy neutron irradiation and tritium breeding occur. In case of nuclear structural materials, neutron irradiation can produce the point defect and cluster, which can lead to material degradation and cause problems with integrity of the facility. Therefore, ARAA must be able to endure in these extreme environment and it will be very important to know the information about the defects occurring in the structural materials.

Recently, as part of the fusion reactor development's projects of KAERI and Korea Institute of Fusion Energy (KFE), irradiation testing of ARAA material that will be used as structural materials in a fusion reactor was required for up to 3 dpa at about 330°C temperature in HANARO. A typical HANARO irradiation material capsule for the ARAA material was designed and is being irradiated in HANARO [2]. During an irradiation testing of the capsule, abnormal reactor power drops from 30MW up to 15MW occurred by various reasons. The reactor power drops resulted in changes of the irradiation condition of the capsule. Although strong assertions have been made that the influence of a short transient irradiation would be completely eliminated by a prolonged irradiation [3], other variables such as differences in irradiation temperature or displacement rate may have a greater impact on the observed behavior [4,5]. In some cases, it has been known that changes of reactor history can dominate the microstrural development of the iradiated materials during neutron irrdiation experiment so as to produce very misleading results [5].

In this paper, changes of the irradiation condition of the capsule caused by the reactor power drop during the irradiation testing of the ARRA material in HANARO are discussed and the effect of the changed irradiation condition on the irradiation behavior is analyzed.

2. Irradiation Capsule and Testing

A 16M-02K capsule, as shown in Figure 1, was designed for an evaluation of the neutron irradiation properties of the core materials (ARAA) of a fusion reactor [2]. A nominal chemical composition of ARAA material is shown in Table I compared with RPV steel. The capsule has been irradiated in the CT test hole at 30MW of maximum thermal power for eight irradiation cycles. The specimens will be irradiated at up to a neutron fluence of 2.5×10^{25} n/m^2 (E>1MeV) equivalent to 3.0 dpa of radiation damage. The detailed information about the irradiation capsule and specimens were previously described elsewhere [2].

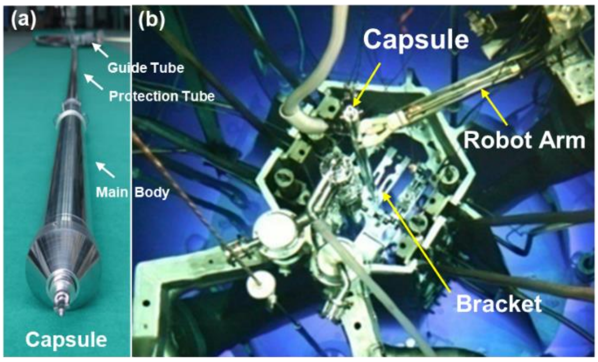

Fig. 1. HANARO irradiation capsule: (a) Irradiation capsule and (b) a capsule system installed in the reactor core.

Table I: Nominal chemical composition of ARAA compared with RPV steel (wt.%)

ARAA	Fe	Cr	W	Mn	V	C	Si	Ta	N	Ti	Zr
	Bal.	9	1.2	0.45	0.2	0.1	0.1	0.07	0.01	0.01	0.01
RPV [6]	Fe	Mn	Ni	Mo	Si	C	P	S			
(A533B)	Bal.	1.37	0.74	0.55	0.22	0.16	0.005	≤0.015			

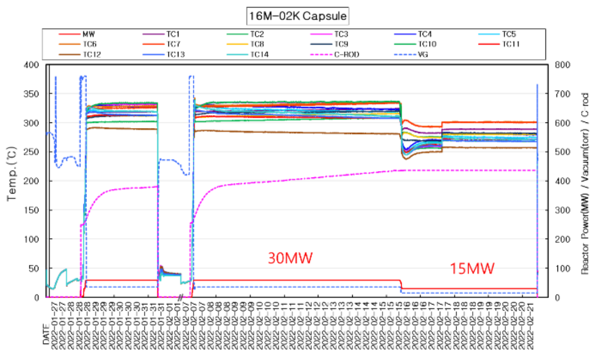

Fig. 2. Temperature variation of specimens during an irradiation testing of the 16M-02K capsule (102-2 cycle).

During the irradiation testing of the 16M-02K capsule, most irradiation testings were performed at the planned 30MW reactor thermal power. However, abnormal reactor power drops from 30MW up to 15MW occurred several times by various reactor reasons. Figure 2 shows a typical abnormal reactor power drop from 30MW to 15MW occurred at the 102-2 cycle.

3. Effect of Reactor Power Drop

The reactor power drop from 30MW to 15MW will cause changes in irradiation condition of the specimen. The neutron flux and gamma heating of the specimen will decrease approximately to a half value by the reactor power drop.

The required neutron fluence of the specimen can be obtained by extending the irradiation testing duration. Neutron flux, in particular, appears to play an important role in 'accelerated' embrittlement of RPV steels at lower neutron fluence [7]. Lots of works on the effects of neutron flux on embrittlement of RPV steels have been conducted at an operating power reactor temperature of around 290℃ [7-13]. Most of the results showed that the radiation-induced embrittlement of the steels were greater at lower neutron fluxes [7-11]. The neutron flux effect on embrittlement tended to be more pronounced at a low neutron flux level of ~6x10^{14} n/m^2·sec (E>1 MeV) than those for neutron flux levels of ~7x10^{15} n/m^2·sec and in the lower neutron fluence range of ~6x10^{21} to ~1x10^{22} n/m^2 than in the higher neutron fluence level of ~7x10^{22} n/cm^2 [7]. In contrast, no flux effects were also reported [7,14,15]. Therefore, the flux effects on the embrittlement of ARAA material still constitute an issue that requires further understanding. The experimental difficulties of studies on the flux effect arise because the effect depends on a number of parameters other than flux, such as fluence, irradiation temperature, alloy composition, the initial state of test samples, and so on [7].

Figure 3 shows normalized ∆DBTTs as a function of neutron flux, defined as ∆DBTT divided by a square root of the neutron fluence [7].

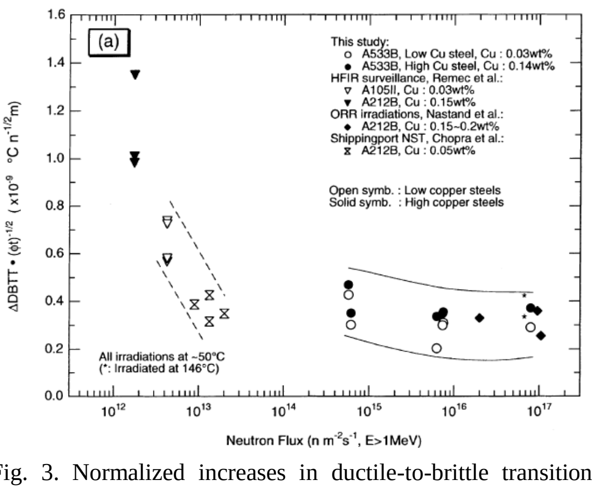

Fig. 3. Normalized increases in ductile-to-brittle transition temperature as a function of neutron flux, defined as increase in ductile-to-brittle transition temperature divided by a square root of the neutron fluence [7].

Considering the higher neutron flux of the CT hole of 1.54x10^{18} n/m^2·sec and the neutron fluence of 2.5x10^{25} n/m^2, the 'accelerating' effects on embrittlement of the ARRA materials at lower neutron fluxes by the reactor power drop seems to be negligible. In the core region of power reactors and test reactors, high-energy electrons with energies up to 2 MeV are produced by gamma ray irradiation through Compton scattering and pair production processes. Thus, electron-induced damage is actually involved in the radiation damage process in RPV steels. The contribution of gamma ray-induced displacement to radiation embrittlement was intensively examined and discussed in HFIR [16] and commercial reactors [17,18]. Unexpectedly large DBTT in surveillance materials of the HFIR RPV can be attributed to gamma ray-induced displacement, while gamma ray-induced displacement has negligible effects on DBTT shift for the RPV in commercial LWRs.

The reduced gamma heating will also cause a decrease of the temperature of specimen. Table II shows the variation of the typical irradiation temperatures of the specimens by the reactor power drop from 30MW to 15MW. The temperature of the specimens is initially increased by gamma heating and then adjusted to the optimum value by vacuum and heating systems. Figure 2 shows the variation of temperatures of the ARAA specimens of the 16M-02K capsule measured by inserted thermocouples during an irradiation cycle (102-2 cycle). The temperature was stably controlled in the range of 289-333℃ during a reactor operation cycle at HANARO of 30MW thermal power. By the reactor power drop to 15MW, the temperature of the specimens decreased by the range of 21-65℃ and controlled in the range of 257-301℃ as shown in Table II.

Table II: Variation of the irradiation temperature of the specimens by the reactor power drop from 30MW to 15MW (102-2 cycle) [℃]

Stage	TC	30MW (A)		15MW (B)		Difference (A-B)	
		He 1atm	IT He 35torr	He 1atm	IT He 15torr	He 1atm	IT
1	TC1	227	319	145	289	82	30
	TC2	226	328	147	301	79	27
	TC3	226	326	145	301	81	25
	TC4	224	312	145	280	79	32
2	TC5	224	302	141	281	83	21
	TC6	234	312	156	282	78	30
3	TC7	241	331	157	271	84	60
	TC8	240	333	149	268	91	65
	TC9	241	313	156	271	85	42
	TC11	235	289	155	257	80	32
4	TC10	249	326	156	279	93	47
	TC13	244	312	160	268	84	44
5	TC12	235	319	154	274	81	45
	TC14	230	319	146	271	84	48
* IT: Typical Irradiation Temperature							

Considering a complicated recovery process of the irradiated materials [19], the effect of the temperature decrease on the irradiation properties of the ARAA material should be carefully discussed. At an initial stage of irradiation damage of W, defect size of the samples was also known to be more strongly influenced by irradiation temperature than either dpa or neutron spectrum [20]. Both gradual and abrupt decreases in irradiation temperature have also been shown to have pronounced effects on neutron-induced microstructural evolution of stainless steels and thereby strongly enhance their void swelling and irradiation creep behavior [21]. Only several percent of exposure to neutrons at lower temperatures is found to result in a one hundred percent difference of radiation induced microstructures in some cases [22]. All differences can be understood from the microstructural development mechanisms, i.e. from the temperature dependence of the stability of point defect clusters and from the relationship of the transient temperature to the temperature for nucleation and growth.

The irradiation temperature has a significant influence on the processes in steel providing hardening and non-hardening embrittlement mechanisms. The whole irradiation temperature range (T_{irr}) taking into account the melting temperature (T_m) can be divided into four ranges [23]. Irradiation in each temperature range demonstrates specific features of radiation defects formation and microstructure evolution:

- The cryogenic irradiation: ($T_{irr} < 0.06 \cdot T_m$) - irradiation temperature range implying almost no mobility of interstitial atoms and vacancies
- Low temperature irradiation: ($0.06 \cdot T_m < T_{irr} < 0.3 \cdot T_m$) - irradiation temperature range in which interstitial atoms are mobile while vacancies do not have diffusion mobility
- Intermediate temperature irradiation: ($0.3 \cdot T_m < T_{irr} < 0.6 \cdot T_m$) - irradiation temperature range in which both vacancies and interstitial atoms exhibit mobility, but mobility of vacancies is not high enough to provide a sufficient level of recombination and thus the concentration of point defects exceeds the value for thermal equilibrium.
- High temperature irradiation: ($T_{irr} > 0.6 \cdot T_m$) - irradiation temperature range in which the mobility of point defects is so high that their intensive spontaneous recombination leads to saturation of point defects concentration almost at the thermal equilibrium value.

The melting temperature T_m is about 1500 ℃ for ARAA alloys [24]. Irradiation at temperatures in the range of 167- 261 ℃ (up to $0.3 \cdot T_m \sim 261$ ℃) is the low temperature irradiation for low alloy steel, while irradiation at temperatures in the range of 261-791 ℃ is intermediate temperature irradiation. The irradiation temperature of the ARAA specimens in HANARO (Table II) exists in the intermediated temperature irradiation range, even after the reactor power drop. Therefore, it seems to have a same irradiation-related defect behavior during the irradiation testing, resulting in a negligible effect of the reactor power drop.

4. Summary

Changes of the irradiation condition of the capsule caused by the reactor power drop during the irradiation testing of the ARRA material of a fusion reactor in HANARO are discussed and the effect of the changed irradiation condition on the irradiation behavior is analyzed.

During the irradiation testing of the 16M-02K capsule, abnormal reactor power drops from 30MW up to 15MW occurred and resulted in decreases of the neutron flux, gamma heating, and specimen temperature.

Considering the higher neutron flux of the CT hole, the effect of lower neutron fluxes by the reactor power drops on embrittlement of the ARRA materials seems to be negligible.

The temperature of the specimen in the range of 289-333℃ was changed to the range of 257-301℃ by the reactor power drop from 30MW to 15MW. These temperatures exist in the same intermediated temperature irradiation range which has specific features of radiation defects formation and microstructure evolution. Therefore, it seems to have a same irradiation-related defect behavior during the irradiation testing, resulting in a negligible effect of the reactor power drop.

Acknowledgement

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