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Influence of temperature histories during reactor startup periods on microstructural evolution and mechanical properties of austenitic stainless steel irradiated with neutrons

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ABSTRACT

This paper addresses influence of two different temperature profiles during startup periods in the Japan Materials Testing Reactor and a boiling water reactor upon microstructural evolution and mechanical properties of austenitic stainless steel irradiated with neutrons to about 1 dpa and 3 dpa. One of the temperature profiles was that the specimens experienced neutron irradiation in both reactors, under which the irradiation temperature transiently increased to 290 °C from room temperature with increasing reactor power during reactor startup periods. Another was that the specimens were preheated to about 150 °C prior to the irradiation to suppress the transient temperature increase. Tensile tests at 290 °C and Vickers hardness tests at room temperature were carried out, and their microstructures were observed by FEG-TEM. Difference of the temperature profiles was observed obviously in interstitial cluster formation, in particular, growth of Frank loops. Although influence of neutron irradiation involving transient temperature increase to 290 °C from room temperature on the yield strength and the Vickers hardness is buried in the trend curves of existing data, the influence was also found certainly in increment of in yield strength, existence of modest yield drop, and loss of strain hardening capacity and ductility. As a result, Frank loops, which were observed in austenitic stainless steel irradiated at doses of 1 dpa or more, seemed to have important implications regarding the interpretation of not irradiation hardening, but deformation of the austenitic stainless steel.

1. Introduction

To evaluate the integrity of core structures and components in boiling water reactors (BWRs), it is indispensable to understand radiation effects of austenitic stainless steel at approximately 290 °C. Examinations of neutron-irradiated materials in BWRs core could furnish direct and beneficial information for understanding radiation effects under BWR core environments, but there are not always enough data because of limited opportunities to perform such examinations on the irradiated materials. Therefore, material test reactors (MTRs) have been utilized widely as neutron irradiation fields onto the structural materials for integrity evaluation of the BWR core structures. When MTRs are used for this evaluation, the irradiation conditions are designed to simulate the BWR core environments by considering how changes in irradiation parameters, such as irradiation temperature, neutron dose and dose rate, and neutron energy spectrum, affect the materials [1].

It is known that startup periods of MTRs accompanying transient temperature increase are often inevitable and undesirable until the intended irradiation temperature is attained; Kiritani et al. revealed that neutron irradiation under transient temperature increase during the startup periods leads to uncertainty in mechanical properties and microstructural evolution in pure Ni irradiated with neutrons on the order of 10^{23} n/m^2 [2–4]. From these studies, the transient temperature change is recognized as significantly affecting the uncertainty of the material properties due to neutron irradiation. Associated studies have been performed to evaluate influence of varied temperature on radiation effects of austenitic

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stainless steel, as well as pure metals, under neutron doses of the order of 10^{24} n/m^2 or less over 300 °C [5–7].

In consideration of the above studies, the Japan Material Testing Reactor (JMTR) has adopted specifically designed irradiation capsules and devices to suppress the transient temperature increase; that is, specimens are heated up to the intended temperature (or as close as possible) prior to the reactor startup. This temperature control is expected to reduce the uncertainty of the data due to undesirable low-temperature irradiation during reactor startup periods, and has been applied to neutron irradiation of austenitic stainless steel specimens in order to evaluate radiation effects on the BWR core structures. On the contrary, typical BWR operation indicates that temperature of the primary coolant rises with increasing reactor power by γ-ray heating during the startup period [8]; hence, radiation effects on the austenitic stainless steel under the recent JMTR temperature control may differ from those of the BWR core structures and components, because of the difference of temperature change during the startup periods. For further discussion of irradiation correlations between MTRs and BWRs, the influence of the transient temperature increase on the irradiation properties of austenitic stainless steel is considered as one of controversial issues, although a previous study concluded that influence on the radiation effects would be diminished by prolonged irradiation [9].

The objective of this paper is to evaluate the influence of neutron irradiation under different temperature histories during reactor startup periods (which involve transient temperature increase below the intended irradiation temperature) upon the microstructural evolution and mechanical properties of commercial austenitic stainless steel (SS).

2. Experimental procedures

Specimens used in this paper were made from the solution-annealed 316L SS, and originally irradiated with neutrons for previous studies [10–12]. Their identifications, chemical compositions and neutron irradiation conditions are given in Table 1. The specimens of B3, B5 and E134 were irradiated in the JMTR under neutron doses of 5×10^{24} (low) and 2×10^{25} (high) n/m^2 ($E \geq 1$ MeV) with neutron dose rate of 2×10^{18} n/m^2/s, and the specimen N1 was irradiated in a BWR under a dose of 2.0×10^{25} n/m^2 ($E \geq 1$ MeV) with an approximate dose rate of 8×10^{17} n/m^2/s, which was estimated from the fact that the irradiation period was 1 cycle (10–12 months) [12]. In this paper, neutron dose was calculated as displacement per atom (dpa) by a factor of 7×10^{24} n/m^2/dpa [1] for N1 irradiated in a BWR.

Fig. 1 shows examples of the relations between temperature and reactor power during a startup period of one-cycle operation in the JMTR. Irradiation temperature was set by controlling temperature of feedwater in irradiation capsules under γ-ray heating due to the reactor power. Fig. 1 (a) indicates the temperature history of "conventional control" irradiation, which associated with the studies by Kiritani et al. [2,3]. Temperature of the specimens to approximately 290 °C from room temperature rose almost proportionally with increasing the reactor power. The conventional control is similar to that of a BWR [8], and was applied to the irradiation of B3 and B5 specimens as a simulated condition of temperature history during the startup period of a BWR. Another temperature profile shown in Fig. 1 (b) is called "modified control" irradiation in this study, and applied to E134. As shown in this figure, the specimens were heated stepwise to about 150 °C before reactor startup, and then to the intended irradiation temperature to minimized transient temperature increase. The times for the startup periods were about 25 h under both the conventional and the modified control, lasting approximately 6% of one cycle of the JMTR (about 672 h). One cycle of neutron irradiation was performed on B3 and E134, and four cycles on B5. Therefore, B5 eventually experienced the conventional control four times during entire neutron irradiation periods.

Tensile tests and micro Vickers hardness tests were performed on B3, B5, and E134 specimens. Configuration of tensile specimens

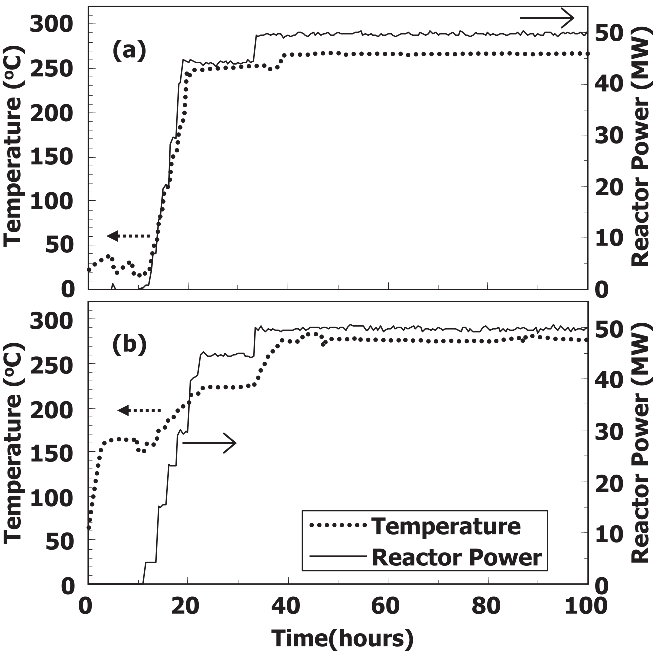

Fig. 1. Temperature-reactor power histories during the rector startup periods in the JMTR under (a) the conventional control and (b) the modified control.

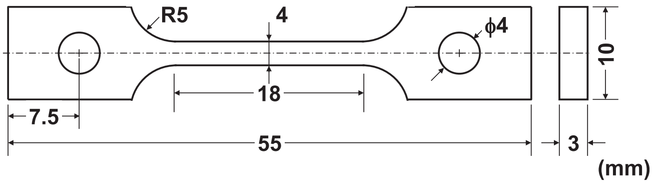

Fig. 2. Configuration of the tensile specimen for evaluation of the conventional control.

Table 1
Chemical compositions (mass%) and neutron irradiation conditions of at 290 °C of the specimens.

ID	C	Si	Mn	P	S	Ni	Cr	Mo	Neutron fluence (n/m^2, ≥1 MeV)	Neutron dose	Remarks	Ref.
B3	0.008	0.51	0.95	0.018	0.006	12.58	16.49	2.16	5×10^{24}	0.8 dpa	Conventional	[10]
B5	0.008								2×10^{25}	3.3 dpa	Conventional	[10]
E134	0.008	0.43	0.83	0.023	0.001	12.55	17.54	2.11	5.2×10^{24}	0.9 dpa	Modified	[11]
N1	0.010	0.50	0.88	0.012	0.001	12.18	16.62	2.16	2.0×10^{25}	2.9 dpa	BWR	[12]