Aging Effect on Thermal Transient Behavior of Fuel Cladding of Sodium-cooled Fast Reactor

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1. Introduction

A detailed knowledge of fuel cladding behavior during reactor transients is required for core design and the safety analysis of both transient-over-power (TOP) and loss-of-flow (LOF) events [1]. The TOP accident was assumed to be initiated due to a control rod withdrawal by the driven motor failure. The LOF means the loss of core cooling capability due to a pumping failure of the primary pumps. The imbalance between the reactor power and primary flow rate is a main safety concern in the LOF [2].

Design and safety analyses of LMRs require understanding fuel pin responses to a wide range of off-normal events. In a loss-of-flow or over- power-transient, the temperature of the cladding is rapidly increased above its steady-state service temperature. Modeling of the fuel pin transient behavior requires knowledge of the cladding mechanical behavior during the stress and thermal conditions encountered in transient events [3]. Simulated transient tests have been performed on sections of fuel pin cladding and a large data base has been established for austenitic stainless steels [4–7] and for ferritic/martensitic steels [1,3,8,9].

However, the previous studies for simulated transient test with HT9 was carried out using as-received type specimen. As widely known, ferritic/martensitic steels showed that the mechanical properties of the steel degraded with aging time at over 500˚C [10–13]. In Sodium-cooled Fast Reactors (SFR) system, a fuel rod has been operated in the reactor core for 5 years at the designed temperature mostly over 500°C. The cladding tube is irradiated as well as thermally aged so that the aging effect on the mechanical property of HT9 should be considered.

The objective of this study is to evaluate the effect of thermal aging on the transient behavior of HT9 cladding tube. The peak temperature of the cladding tube is 650°C in SFR system so that the aging experiments at 650°C for 7000h and its tensile test and rupture test have been previously carried out at 650°C [13]. Using data from the previous mechanical test, the effect of thermal aging on the transient property was correlated and the transient behavior (after aging for 1 year) is calculated in this study.

2. Experimental

During the thermal transient events such as TOP and LOF, the simulated transient test has been carried out with schematic test methods as shown in Fig. 1. Simulated TOP test has been called as ramp test mode (Fig. 1) that the temperature is increased until failure occurred and there are different heating rates under constant hoop stress.

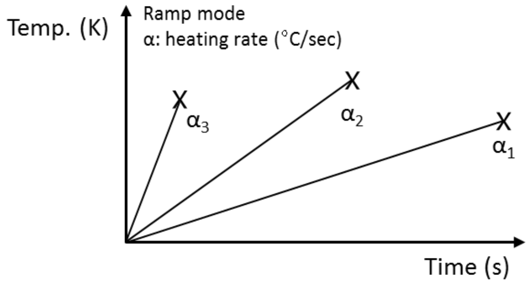

Fig. 1. Typical ramp test mode of transient test.

The experimental system consists of mainly 2 parts, temperature and pressure control parts. The temperature is controlled the eight radiant heaters which are located around the specimen. Duralumin mirror at most outer at heating system reflects and concentrates the heat into the specimen. Three points of spot welded K-type thermocouple are used to measure the temperature and the center one is used for PID control of the temperature of the center region of the specimen. The specimen is pressurized by high purity argon gas supplied from Ar booster which is stored in surge tank. The internal pressure of the specimen is controlled by solenoid valve, pressure sensor and back pressure regulator (BPR) during the ramp test, so that internal pressure of the specimen can be held as constant value.

For the test, the dimension of the HT9 cladding tube is 7.4mm in O.D, 0.5mm in thickness and 150mm in length. A end side of the specimen is closed by using an end plug fitting. The other end side of the specimen is connected to extension fitting to connect the pressurized line of the experimental system.

3. Results and discussion

3.1 Transient behavior of HT9 cladding tube

The ramp tests have been carried out. In each ramp test, the temperature and the internal pressure profiles were recorded through DAQ system. The temperature is measured and controlled by qualified K-type thermocouples which is spot-welded on the cladding tube specimen.

The results of the ramp tests are shown in Fig. 2. Three different heating rate with 0.56, 5.6, and 20°C/sec have been carried out. The general behavior among the ramp test is that the higher hoop stress results in the lower failure temperature. Also as the heating rate increased (0.56 to 20°C/sec), the failure temperature is shifted to higher failure temperature at the same hoop stress among the test. Authors found that the transient behavior at the ramp test is closely related the UTS value of the material. The UTS values of HT9 [14] (green triangle scatters) at high temperature are plotted and compared with the transient test results. In case of the UTS value in Fig.2, the X-axis should read by the test temperature. From shown in Fig. 2, it is expected that there are some correlation between the UTS value and the failure temperature of transient tests with 0.56, 5.6, and 20°C/sec.

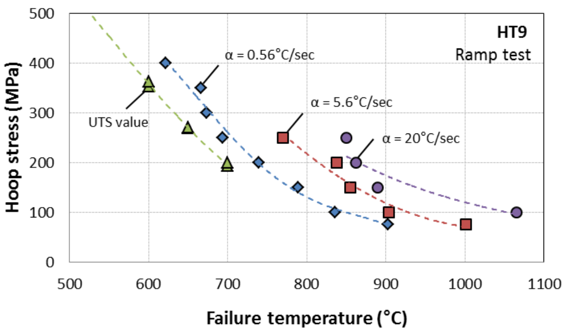

Fig. 2. Result of the ramp tests (with ramp rate of 0.56, 5.6, and 20°C/sec, respectively) compared to the UTS value [14] of HT9.

At 200MPa, the failure temperature of the transient tests is 739°C for 0.56°C/sec, 838°C for 5.6°C/sec, and 862°C for 20°C/sec. Normalized temperature when the UTS become 200MPa is 695°C.

The failure temperature, T_f, with 0.56, 5.6, and 20°C/sec at a certain hoop stress and the normalized temperature is used to calculate ΔT. The ΔT is figured as function of the heating rate as shown in Fig. 3.

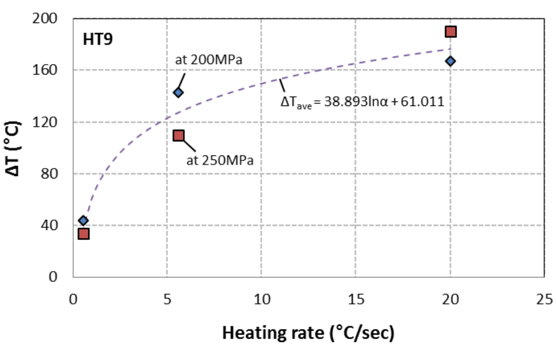

Fig. 3. Temperature difference (between a uniform temperature during the tensile test and a failure temperature of a transient) as function of heating rate.

As the heating rate is increased from 0.56°C/sec to 20°C/sec, the failure temperature is increased. In the UTS case, the fitting finds the correlation between UTS and test temperature, so that author found out the temperature that the UTS became 200 and 250 MPa. In case of the transient tests, the predetermined pressure is used for each test. So the ΔT is quasi-state. However, it is convenient to estimate the failure temperature of the transient test based on the high-temperature UTS value.

3.2 Aging effect on the transient test results

As shown in Fig. 4, the UTS and the YS of HT9 which aged at 650°C, decreased as function of aging time. Moreover, the rupture strength also decreased as function of aging time. To calculate the aging effect of HT9 cladding tube at high temperature, the UTS and the YS of the aged specimens were correlated as function of aging time as shown in the figure.

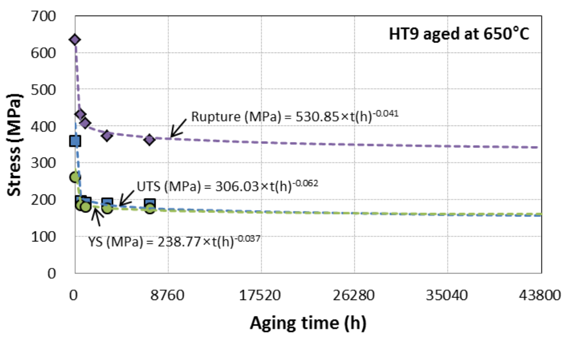

Fig. 4. Mechanical properties change of HT9 as function of aging time [13].

In Fig. 5, the UTS and the test result of the ramp test are summarized with the heating rate with 0.56, 5.6, and 20°C/sec and the correlation between the UTS and the result of the ramp test is shown. In general, the UTS and the transient behavior with equivalent temperature (σH vs. (T_f - $\Delta T_{ave.}$)) show similar values and the aging effect on the UTS (× $t^{-0.062}$) and the transient behavior with aging effect and equivalent temperature ($\sigma_H \times t^{-0.062}$ vs. (T_f - $\Delta T_{ave.}$)) show also similar values. It indicates that the aging effect on the correlation between the UTS and the transient behavior (ramp mode) is valid. The aging effect on the UTS results in reducing the UTS as a function of aging time at 650°C. Also in Fig. 4, the UTS is dramatically reduced as aging started at 650°C and the slope is almost constant after 7000h. In this study, 1 year (8760 h) is used to calculate the aging effect due to a year of the fuel cycle in the reactor core and the aging effect on the UTS is almost constant after 7000h.

The aging effect on the cladding tube is considered, because, at high temperature, the mechanical properties of HT9 has been reduced as aging time is increased [13]. The calculation of the aging effect on transient behavior of fuel cladding is a theoretical study which includes hypotheses. In this study, the full aging process is considered on the calculation of the mechanical behavior of fuel cladding.

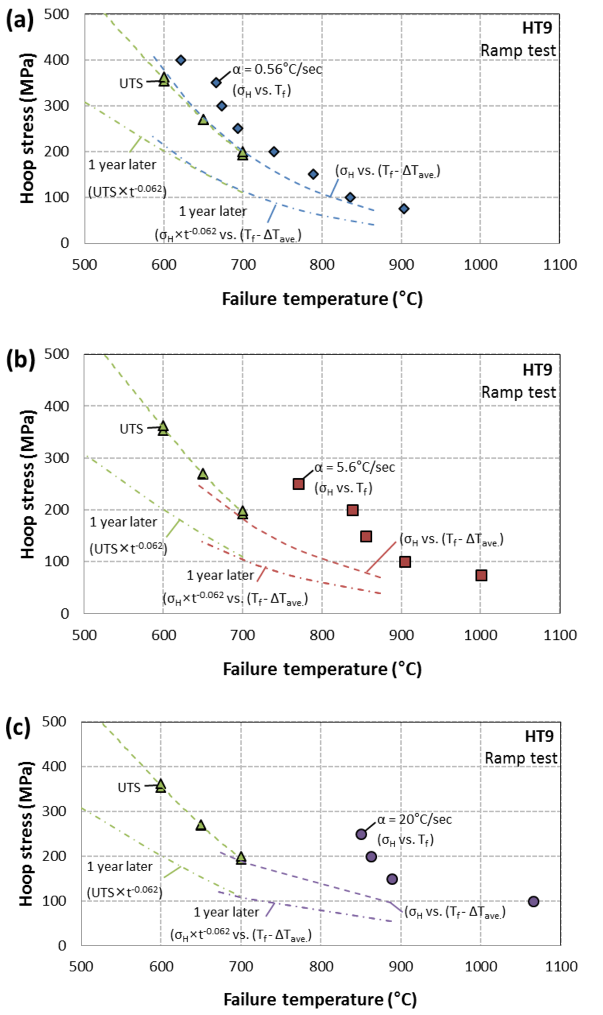

Fig. 5. Aging effect of HT9 cladding tube on transient (ramp test) behavior at (a) 0.56°C/sec, (b) 5.6°C/sec, and (c) 20°C/sec.

Cumulative damage fraction (CDF) is used to calculate the safety margin in this study. When CDF reaches a unity, it means the failure occurs. At the pressurized cladding tube, CDF reaches a unity, the cladding fails. To calculate the life time of the fuel cladding, Dorn parameter is used in this study. Dorn parameter and CDF equation is summarized in [1].

The appropriate value of θ can then be calculated for each given stress σ. Data from the transient tests at heating rates of 0.56, 5.6, and 20°C/sec were used to develop the correlation for HT9 cladding as shown Fig. 6. For a given hoop stress, the value of θ is obtain from as-received specimen and the aging effect, for 1 year at 650°C, on hoop stress is plotted. After a year (8760h) later, the Dorn parameter is reduced at a certain hoop stress. WHC data [1] showed similar value with the Dorn parameter with as-received data in this study. Dorn parameter is typically used for understanding the mechanism of creep of steels which caused from diffusion mechanism, however, it is conveniently used, in this study, to compare with WHC data.

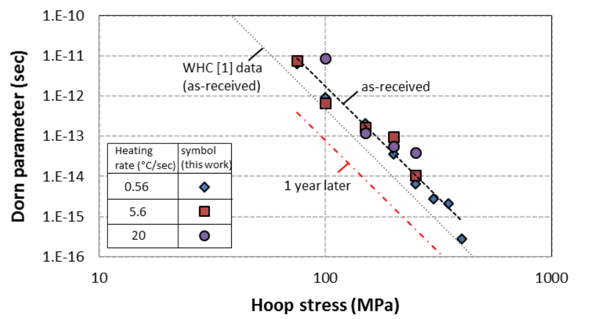

Fig. 6. Dorn parameter from as-received and estimated aging effect with 1 year later as a function of hoop stress.

3. Conclusions

In this study, mechanical properties from the ultimate tensile strength, and the rupture strength data of the aged HT9 specimens has been summarized and used to calculate an aging effect on a transient behavior. The calculation of the aging effect on transient behavior of HT9 has been carried out and compared with the experimental results.

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