MATERIAL DATA ACQUISITION ACTIVITIES TO DEVELOP THE MATERIAL STRENGTH STANDARD FOR SODIUM-COOLED FAST REACTORS

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Abstract

Adopting the 60-year design is one of the most effective means for the practical realization of a sodium-cooled fast reactor (SFR), which improves the economic efficiency and reduces the radioactive waste of the SFR. Since the severe accident (SA) at the Fukushima Daiichi Nuclear Power Plant, the structural integrity evaluation of the SA has also been emphasized on the SFR. As for its practical realization, the SFR is indispensable in improving the material strength standards, such as the extremely high-temperature material properties required for applying a structural integrity evaluation during an SA. To make it possible to evaluate the structural integrity during the 60-year design and the SA, the Japan Atomic Energy Agency is working on the sophistication of the material strength standards. Moreover, material strength tests, such as high-temperature tensile tests, creep tests, and fatigue tests, are systematically conducted. This paper presents the overall picture of the material testing we acquired or plan to acquire to establish the Japan Society of Mechanical Engineers (JSME) standard.

1. INTRODUCTION

A sodium-cooled fast reactor (SFR) is one of the Generation IV reactors expected to have a higher power generation efficiency, a higher uranium resource utilization efficiency, and a lower production of radioactive waste. The Japan Atomic Energy Agency (JAEA) has been conducting research and development for the practical application of the SFR and has developed the experimental fast reactor "Joyo" and the prototype fast breeder reactor "Monju". The SFR has various features, including the use of fast neutrons and sodium as the reactor coolant and the assumed operating temperature of approximately 550°C. The structural materials used in the SFR are required to withstand these fast reactor environments for a long time. The influence of creep occurs, especially at a high temperature; thus, high-temperature structural design standards and material strength standards for the SFR design must be established.

The JAEA developed a fast breeder reactor prototype, called "Monju," with a power generation function and a design life of 30 years. With the development of "Monju", the "structural design guide for class 1 components for prototype of the fast breed reactor for the elevated temperature service (BDS)" was prepared as the standards for the SFR (e.g., SFR high-temperature structural design standards and SFR material strength standards) based on the "structural design guide for experimental fast reactor 'Joyo'" approved for the experimental fast reactor "Joyo". The BDS was subsequently reflected in the Japan Society of Mechanical Engineers (JSME) code for design and construction of fast reactors.

In the SFR, the main structural materials are 316FR stainless steel with an improved creep resistance based on 316SS and the modified 9Cr–1Mo steel used in a thermal power plant. These two types of steels were standardized to the JSME code for the design and construction of fast reactors in 2012; however, the code is a BDS created by assuming a design life of 30 years. As a result, properties, such as time-dependent allowable stresses, are only applicable up to 300,000 h. However, to put the SFR into practical use, improve the economic efficiency, and reduce radioactive waste, extending the design life to 60 years is expected as an effective means. In addition, since the severe accident (SA) at the Fukushima Daiichi Nuclear Power Plant, the structural integral evaluation during an SA has been regarded as important in the SFR, and is applied to the structural integral evaluation during SA for the practical use of SFR. Possible ultra-high-temperature material properties are required. Therefore, to put the SFR into practical use, it is essential to improve the material strength standards.

To make the SFR material strength standards compatible with the 60-year design, the time-dependent allowable stresses specified in the JSME code must be extended from 300,000 h to 500,000 h. In addition, the fatigue evaluation method must be extended to up to 1×10^9 cycles. The JAEA conducted a long-term creep test to improve the material strength standards. Creep property equations were developed using the acquired data from the test. The creep property equations will be used in a revised proposal that is under development to extend the material strength standards to 500,000 h. Furthermore, the JAEA acquired high-cycle fatigue data of up to 1×10^9 cycles based on which they are developing a high-cycle fatigue evaluation method. The JAEA also acquired ultra-high-temperature material test data of 304SS to evaluate the structural integrity during the SA and extended the material strength standards to 1000°C. In the future, the JAEA plans to acquire ultra-high-temperature data for 316FR stainless steel and the modified 9Cr–1Mo steel, which are the main structural materials of the SFR, and extend the material strength standards to high temperatures.

To put the SFR into practical application, the JAEA is working on the sophistication of the material strength standard to enable a 60-year design and structural integral evaluation during the SA. Specifically, material strength tests, such as tensile, creep, and fatigue tests, at high temperatures are being conducted. This paper reports on the overall picture of the material tests that the JAEA acquired or plans to acquire in preparation for the revision of the JSME standards.

2. MATERIALS

In the SFR, 316SS developed for the fast reactor (316FR stainless steel) and the modified 9Cr–1Mo steel are the leading candidates for use as the main structural materials.

2.1. 316FR stainless steel

316FR stainless steel is an austenitic stainless steel developed as a structural steel for the SFR based on the 316 series stainless steel. In general, when heat-resistant steel is used at a high temperature for a long time, structural changes, such as precipitation, will occur, and mechanical property deterioration, such as decrease in strength and decrease in ductility, will happen. To minimize the deterioration of material properties due to structural changes, 316FR stainless steel contains N, which has a high solid solution, instead of C, which has a low solid solution, as a reinforcing element. By suppressing C and adding N, the Laves phase, and not the carbides, precipitates at the grain boundaries during creep. The Laves phase maintains a fine structure for a long time, such that it does not cause an intergranular embrittlement. Therefore, the creep rupture time at 550°C is improved by about an order of magnitude in 316FR stainless steel compared to 316SS. In this way, 316FR stainless steel is a material that suppresses the characteristic deterioration during high-temperature use compared to conventional 316SS [1]. Table 1 shows the chemical composition of 316FR stainless steel and the chemical composition of the JIS SUS 316 (316SS) raw materials. In addition to the chemical composition shown in Table 1, the JSME code for the design and construction of fast reactors standardizes the mechanical properties of 316FR stainless steel at room temperature (Table 2).

TABLE 1. Chemical composition of 316FR stainless steel and 316SS.

%

	C	Si	Mn	P	S	Ni	Cr	Mo	Al	N
316FR Plate	**≦0.020**	**≦1.00**	**≦2.00**	**0.020–0.045**	**≦0.030**	**10.00–14.00**	**16.00–18.00**	**2.00–3.00**	**≦0.05**	**0.06–0.12**
316FR Forging	**≦0.020**	**≦1.00**	**≦2.00**	**0.020–0.045**	**≦0.030**	**10.00–14.00**	**16.00–18.00**	**2.00–3.00**	**≦0.05**	**0.06–0.12**
SUS316	**≦0.08**	**≦1.00**	**≦2.00**	**≦0.045**	**≦0.030**	**10.00–14.00**	**16.00–18.00**	**2.00–3.00**	–	–

TABLE 2. Specific value of 316FR stainless steel for room temperature.

	Tensile test				**Hardness test (1 or 2 or 3)**		
					1	**2**	**3**
	Min. tensile strength (MPa)	**Min. yield stress (MPa)**	**Elongation (%)**	**Reduction of area (%)**	**HB**	**HRBS or HRBW**	**HV**
316FR Plate	**≧520**	**≧205**	**≧40**	–	**≦187**	**≦90**	**≦200**
316FR Forging	**≧480**	**≧205**	**≧29**	**≧45**	**≦187**	–	–

2.2. Modified 9Cr–1Mo Steel

The modified 9Cr–1Mo steel is a tempered martensitic steel developed mainly in the US ORNL as a material for fast reactor steam generators. As a characteristic of the chemical composition, trace amounts of alloying elements V (0.18% to 0.25%) and Nb (0.06% to 0.10%) were added to the conventional 9Cr–1Mo steel (ASTM A387-G9, ASTM A213-T9). The Ni (0.40% or less) and N (0.030%–0.070%) contents were also limited.

Benefits, such as precipitation strengthening, carbide coarsening delay effect by V, and austenite grain refinement by Nb, can be obtained by adding V and Nb [1]. Due to these benefits, the modified 9Cr–1Mo steel has good tensile and creep strengths and toughness and has been used in thermal power plants.

The JSME code for the design and construction of fast reactors standardizes the chemical composition and the mechanical properties of room temperature, as shown in Tables 3 and 4. Moreover, we had the same material as the modified 9Cr–1Mo steel in the ASME (Gr.91, Table 3). The modified 9Cr–1Mo steel of the JSME also had the same chemical composition and mechanical properties as the 2011 ASME standard. The ASME standardizes the allowable stresses set by using the Gr.91 normalizing and tempering (NT) material. On the contrary, the modified 9Cr–1Mo steel used to set the allowable stresses in the JSME was subjected to the stress relief heat treatment after the NT treatment. Therefore, although the tensile strength of the modified 9Cr–1Mo steel was lower than that of the as-received material in Gr.91, the structure was stable, and the strength did not significantly decrease with aging.

TABLE 3. Chemical composition of the modified 9Cr–1Mo steel

%

	C	Si	Mn	P	S	Ni	Cr	Mo	V	Nb	Al	N	Ti	Zr
Mod.9Cr–1Mo Plate (JSME)	**0.08–0.12**	**0.20–0.50**	**0.30–0.60**	**≦0.020**	**≦0.010**	**≦0.40**	**8.00–9.50**	**0.85–1.05**	**0.18–0.25**	**0.06–0.10**	**≦0.02**	**0.030–0.070**	**≦0.01**	**≦0.01**
Mod.9Cr–1Mo Forging (JSME)	**0.08–0.12**	**0.20–0.50**	**0.30–0.60**	**≦0.020**	**≦0.010**	**≦0.40**	**8.00–9.50**	**0.85–1.05**	**0.18–0.25**	**0.06–0.10**	**≦0.02**	**0.030–0.070**	**≦0.01**	**≦0.01**
Gr.91 Plate (ASME, 2011)	**0.08–0.12**	**0.20–0.50**	**0.30–0.60**	**≦0.020**	**≦0.010**	**≦0.40**	**8.00–9.50**	**0.85–1.05**	**0.18–0.25**	**0.06–0.10**	**≦0.02**	**0.030–0.070**	**≦0.01**	**≦0.01**
Gr.91 Forging (ASME, 2011)	**0.08–0.12**	**0.20–0.50**	**0.30–0.60**	**≦0.020**	**≦0.010**	**≦0.40**	**8.00–9.50**	**0.85–1.05**	**0.18–0.25**	**0.06–0.10**	**≦0.02**	**0.030–0.070**	**≦0.01**	**≦0.01**
Gr.91 Type 1 Plate (ASME, 2019)	**0.08–0.12**	**0.20–0.50**	**0.30–0.60**	**≦0.020**	**≦0.010**	**≦0.40**	**8.00–9.50**	**0.85–1.05**	**0.18–0.25**	**0.06–0.10**	**≦0.02**	**0.030–0.070**	**≦0.01**	**≦0.01**
Gr.91 Type 1 Forging (ASME, 2019)	**0.08–0.12**	**0.20–0.50**	**0.30–0.60**	**≦0.020**	**≦0.010**	**≦0.40**	**8.00–9.50**	**0.85–1.05**	**0.18–0.25**	**0.06–0.10**	**≦0.02**	**0.030–0.070**	**≦0.01**	**≦0.01**

TABLE 4. Specific value of the modified 9Cr–1Mo steel for room temperature

	Tensile test				**Hardness test**
	Min. tensile strength (MPa)	**Min. yield stress (MPa)**	**Elongation (%)**	**Reduction of area (%)**	**HB**
Mod.9Cr–1Mo Plate (JSME)	**585 –760**	**≧414**	**≧18**	**–**	**–**
Mod.9Cr–1Mo Forging (JSME)	**≧585**	**≧414**	**≧20**	**≧40**	**–**
Gr.91 Plate (ASME, 2011)	**585 –760**	**≧415**	**≧18**	**–**	**–**
Gr.91 Forging (ASME, 2011)	**≧585**	**≧415**	**≧20**	**≧40**	**≦248**
Gr.91 Plate (ASME, 2019)	**585 –760**	**≧415**	**≧18**	**–**	**–**
Gr.91 Forging (ASME, 2019)	**≧620**	**≧415**	**≧20**	**≧40**	**190 –248**

3. MATERIAL TESTING FOR LONG-TERM CREEP PROPERTY EVALUATION

3.1. Overview of the long-term creep property evaluation

To realize the SFR 60-year design, the material strength standards must be extended from the current 300,000 h to 500,000 h. One of the most important matters for achieving this goal of extension is the development of a creep rupture equation that is excellent for the long-term creep property evaluation. The four main points for the development of a creep rupture equation are database preparation, selection of the creep strength extrapolation method, long-term extrapolation evaluation, and failure probability evaluation. The details are described in the paper of Onizawa et al. [2]. In the recent years, the long-term creep data for several steel grades revealed a decrease in the long-term creep strength of steels, and the creep rupture relational expression and allowable values are being reviewed [3]. Therefore, the database preparation is the most important point. The database preparation of 316FR stainless steel and the modified 9Cr–1Mo steel will be described herein as an outline of the development of the creep rupture equation.

Figure 1 shows an external photograph and the configuration of the creep test equipment owned by the JAEA. Creep tests can be performed on all test equipment to measure the creep strain. The JAEA conducts a large number of creep tests, such as a long-term creep test with a target of up to 500,000 h using approximately 100 creep test devices.

With reference to the ASME standard [4], the JAEA conducts a long-term creep test and uses public data [5–8] to obtain rupture data of up to 166,160 h at 550°C for 316FR stainless steel and on-going test data of up to 175,800 h at 550°C for the modified 9Cr–1Mo steel. For both kinds of steels, the JAEA prepared a database that can evaluate 500,000 h with triple extrapolation. In addition to acquiring long-term creep data, the JSME code for the design and construction of fast reactors [9] and ASME BPVC Sec. III, Div. 5 require data acquisition with a maximum temperature of 50°C higher than the maximum operation temperature for three heats or more for each product shape. Considering what is required, we acquired the data for multiple heats for each product shape. In the case of 316FR stainless steel, 255 creep data for nine heats of plate material and three heats of forged material were gathered. In the case of the modified 9Cr–1Mo steel, 553 creep data for 13 heats of plate material and four heats of forged material were gathered. Using these data, a database was prepared at intervals of 50°C up to 700°C.

Figure 2(a) shows the relationship between the creep rupture equation developed by the prepared database and the creep data for 316FR stainless steel. The JAEA clarified that the creep characteristics change between short- and long-term creeps and developed a creep rupture equation that uses the region splitting method. The developed creep rupture equation appropriately evaluates the long-term creep data better than the current JSME standard equation and can more appropriately evaluate the long-term creep property evaluation. Based on the developed creep rupture equation, a revision proposal was made to extend the material strength standards of the JSME code for the design and construction of fast reactors to 500,000 h, which is currently discussed by the JSME.

Figure 2(b) shows the relationship between the creep rupture equation of the current JSME standard for the modified 9Cr–1Mo steel and the prepared database for the modified 9Cr–1Mo steel. The creep rupture relational expression of the current JSME standard can appropriately evaluate long-term data up to 175,800 h for the modified 9Cr–1Mo steel. Therefore, a revision proposal was made to extend the material strength standards of the JSME code for the design and construction of fast reactors to 500,000 h, which is currently discussed by the JSME.

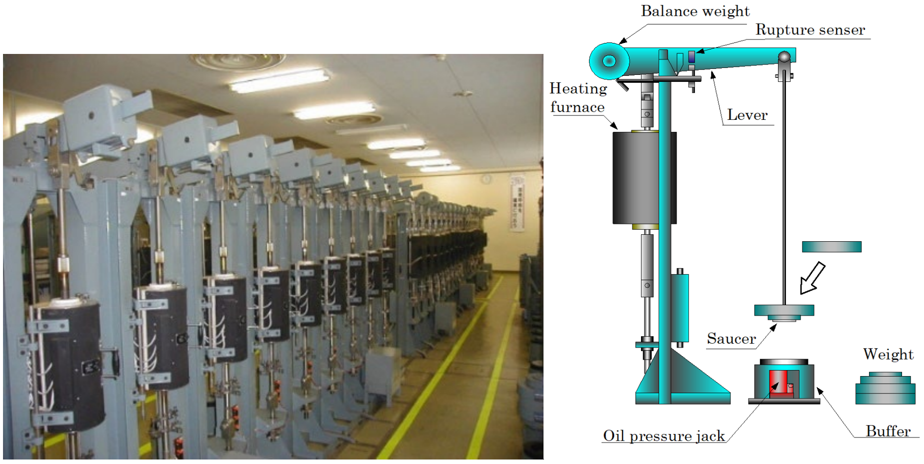

FIG. 1 Appearance of the creep testing machine.

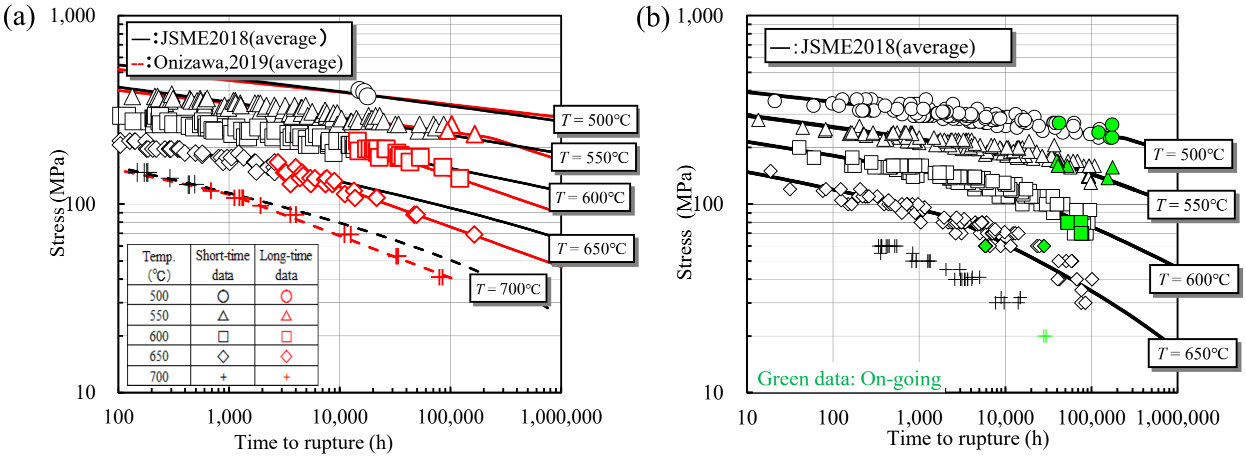

FIG. 2 Comparison of the creep data and the (a) developed equation of 316FR stainless steel and (b) JSME equation of the modified 9Cr–1Mo steel.

3.2. Future plan for the long-term creep tests

The JAEA plans to continue long-term creep tests to improve the reliability of the extrapolation evaluation, even after the JSME code for the design and construction of fast reactors is revised.

In addition, the JAEA is developing an evaluation method for the welded joint to be standardized in the JSME code for the design and construction of fast reactors. The evaluation method for the welded joint also assumes a 60-year operation; thus, it is also important to evaluate the long-term creep characteristics of the welded joint and the base metal. Similar to the base metal, the JAEA plans to acquire long-term creep data for welded joints up to 500,000 h.

4. MATERIAL TESTING FOR THE DEVELOPMENT OF HIGH-CYCLE FATIGUE EVALUATION METHOD

4.1. Overview of the development of the high-cycle fatigue evaluation method

The SFR designed for 60 years of operation assumes to cause a high-cycle fatigue of up to 1×10^9 cycles due to the effects of thermal striping and departure from the nucleate boiling vibration. The high-cycle fatigue evaluation method developed by the JAEA aims to calculate the high-cycle fatigue of up to 1×10^9 cycles with a usage factor (UF) of the order of 0.01. For this purpose, the design fatigue diagram is planned to be expanded to 1×10^{11} cycles. To set the design fatigue curve, it is necessary to confirm effects (e.g., mean stress) and make appropriate corrections in addition to extending the best-fit fatigue curve. Accordingly, the JAEA is conducting high-cycle fatigue tests in the temperature range centered on the assumed operating temperature of the SFR, which is 550°C, and acquiring fatigue data to develop the high-cycle fatigue evaluation method.

Using the fatigue data obtained so far, the design fatigue curves of 316FR stainless steel and modified 9Cr–1Mo steel were standardized to the JSME code for the design and construction of fast reactors in 2012. In that standard, the number of fatigue repetitions was limited to 1×10^6 cycles, which was limited to the low cycle fatigue evaluation.

The JAEA developed a strain-controlled very-high cycle fatigue testing machine (Fig. 3). They are also conducting a high-cycle fatigue test to acquire data on the high-cycle fatigue by strain control exceeding 1×10^6 cycles. The strain-controlled very-high cycle fatigue testing machine characterized in that strain control was implemented by using a conventional quartz stick and a laser level meter together. At the start of the test, with the quartz stick installed on the test piece, strain was applied at 0.1 [Hz] strain rate, and the entire strain range was measured with both the quartz stick and the laser level meter. Subsequently, the quartz stick value was used as a reference. The laser level meter value was automatically calibrated (Fig. 4) to control the strain range. To support repetitive work hardening, the strain-controlled very-high cycle fatigue testing machine can automatically calibrate during the test according to the set number of cycles and the stress change rate. The quartz stick was pressed against the test piece only during the calibration. By developing a method that uses a quartz stick and a laser level meter together, the JAEA made it possible to perform high-cycle fatigue tests at a maximum of 100 [Hz] by strain control.

Figure 5(a) depicts the fatigue test results of 316FR stainless steel at 550°C. The JAEA has so far acquired the high-cycle fatigue data of 316FR stainless steel exceeding 1×10^6 cycles using a strain-controlled very-high cycle fatigue testing machine at a conventional strain rate of 0.1 [Hz] to 1.0 [Hz]. The test results of the above and of the fast strain rate (up to 79 [Hz]) were consistent. Cracks may occur from the inside of the specimen in tests exceeding 1×10^6 cycles, but no significant difference was found in the fatigue strength between the internal and surface crack-type fatigue fractures.

The JAEA will use a strain-controlled very-high cycle fatigue testing machine to expand the high-cycle fatigue data of 316FR stainless steel and modified 9Cr–1Mo steel (Fig. 5(b)) from 1×10^6 cycles to 1×10^9 cycles for the SFR structural materials. The best-fit fatigue curve ($\sim 1 \times 10^9$ cycles) will be standardized by the JSME.

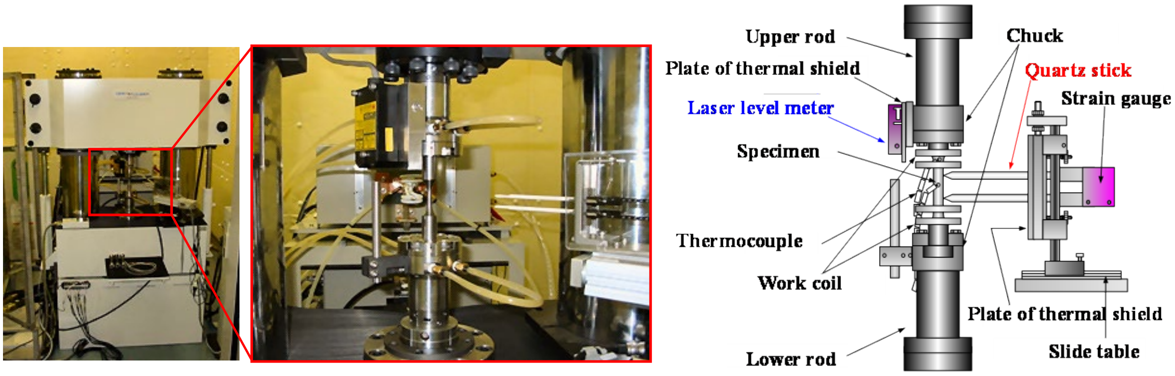

FIG. 3 Appearance and schematics of the strain-controlled very-high cycle fatigue testing machine [10].

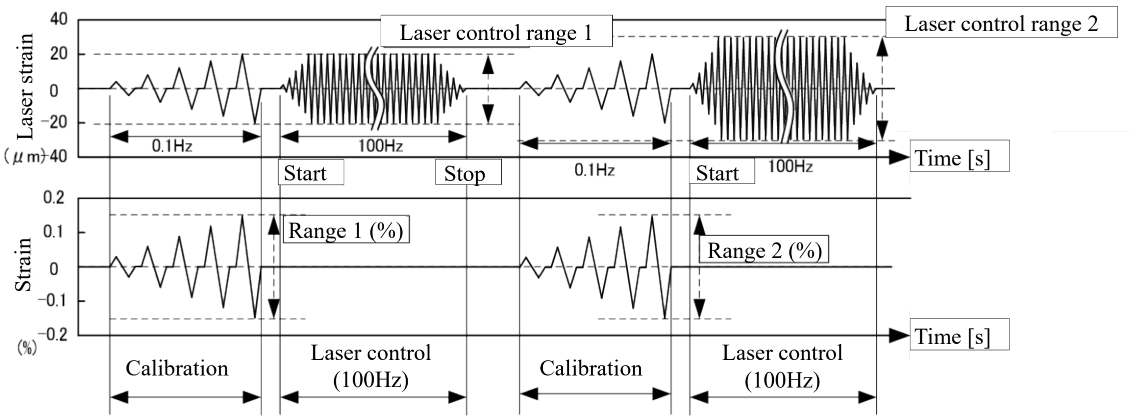

FIG. 4 Strain control method by the laser level meter [10].

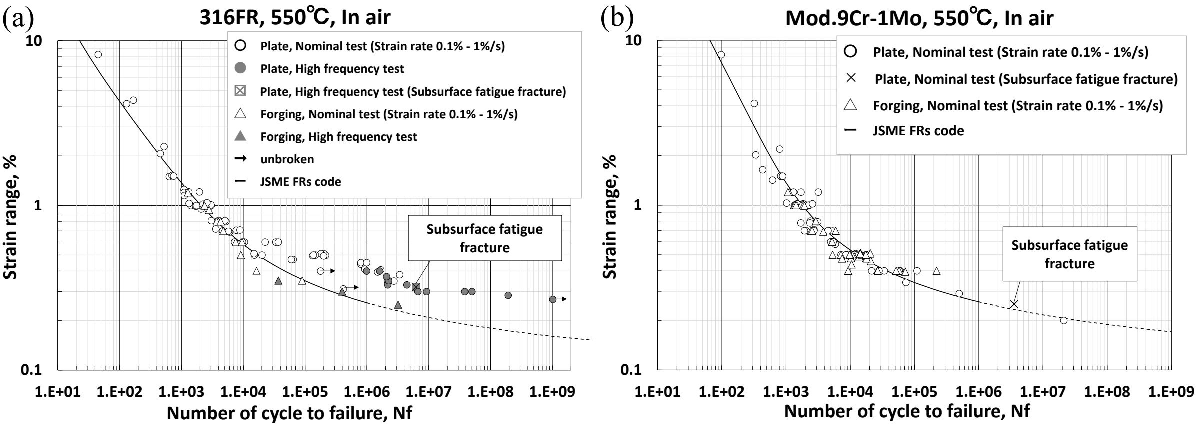

FIG. 5 Fatigue life of (a) 316FR stainless steel [11] and (b) modified 9Cr–1Mo steel [12].

4.2. Future plan for the high-cycle fatigue test

The current JSME standard standardizes plates and forged steel products of 316FR stainless steel and modified 9Cr–1Mo steel. The JAEA aims to extend the best-fit fatigue curve to 1 × 10^9 cycles for the plate materials and forged steel products of 316FR stainless steel and modified 9Cr–1Mo steel, similar to the current JSME code for the design and construction of fast reactors.

The best-fit fatigue curve up to 1 × 10^6 cycles was created and standardized by the fatigue data of multiple heats to show that no difference exists in the fatigue intensity due to chemical composition (heat). Similarly, to standardize the best-fit fatigue curve up to 1 × 10^9 cycles, the high-cycle fatigue data of 1 × 10^6 cycles to 1 × 10^9 cycles must be acquired in multiple heats. As shown in Fig. 5(a), the fatigue strength of the plate material greatly exceeded that of the forged steel products for 316FR stainless steel in the high-cycle region. In the current JSME standard, the plate material of 316FR stainless steel and the forged steel product use the same best-fit fatigue curve, but a rational best-fit fatigue curve can be created for each product shape by acquiring high-cycle fatigue data.

As described earlier, both the test results with a large number of repetitions and with multiple heats and for each type of product shape are required to standardize the best-fit fatigue curve up to 1×10^9 cycles. The JAEA plans to perform high-cycle fatigue tests on 316FR stainless steel, modified 9Cr–1Mo steel plates, and forged steel products to expand the database.

The high-cycle fatigue evaluation method currently under development by the JAEA aims to calculate the UF up to 0.01 order; thus, it is necessary to be standardized up to 1×10^{11} cycles. However, with a strain-controlled very-high cycle fatigue testing machine, it is difficult to acquire data of 1×10^9 cycles or more due to the test time. Therefore, the JAEA plans to acquire high-cycle fatigue data of 1×10^9 cycles to 1×10^{11} cycles using an ultrasonic fatigue testing machine. The ultrasonic fatigue testing machine enables testing at a maximum of 20 [kHz] by resonating a specimen with sound waves. The ultrasonic fatigue test method at room temperature is currently being standardized in Japan [13]. At high temperatures, the test method was not standardized, but Furuya et al. obtained the fatigue data of 12Cr–2W steel at 650°C and a maximum of 1×10^{10} cycles; hence, it is expected to be applied to fast reactor materials [14]. However, the way to handle the data requires further discussion because the data acquired in the ultrasonic fatigue test have a higher intensity than those acquired by the conventional test equipment due to the rate effects, etc. [15].

As described earlier, the best-fit fatigue curve can be expanded, and the extrapolation value can be set by selecting an appropriate testing machine from the number of repetitions (test time) of the acquired data.

To standardize the high-cycle fatigue evaluation method, it is necessary to extend the best-fit fatigue curve and consider the presence of the mean stress effect. In light water reactors, mean stresses, such as internal pressure and residual stress, are known to reduce the fatigue life. Moreover, the ASME standard and the JSME light water reactor standard correct the mean stress effect in the high-cycle region. Internal pressure and residual stress are also generated in the SFR, but the temperature is different from that in light water reactors; hence, the presence of the mean stress effect must be confirmed before making corrections.

The ASME standard Gr.91 experimentally showed that the mean stress due to the residual stress does not need to be considered in the high-temperature and -cycle region [16]. In addition, the mean stress caused by the internal pressure could be considered in the creep fatigue damage evaluation; thus, it is not necessary to consider the mean stress. The JAEA plans to conduct a strain-loading test on 316FR stainless steel and modified 9Cr–1Mo steel at the start of the test, simulating residual stress, similar to the Gr.91 experiment. As a test result, if there is no effect of the mean stress due to the residual stress in the high-temperature region, the JSME standard will set a rational design fatigue curve that does not perform the mean stress correction as Gr.91 of the ASME standard.

5. MATERIAL TESTING FOR THE DEVELOPMENT OF ULTRA-HIGH-TEMPERATURE MATERIAL STRENGTH STANDARDS

5.1. Overview of the development of the ultra-high-temperature material strength standards

The practical application of the SFR requires ultra-high-temperature material properties that can be applied to the structural integrity evaluation during the SA. To evaluate the structural integrity during the SA, the JAEA acquired ultra-high-temperature material test data for 304SS, which is the main structural material of “Monju” and “Joyo,” and extended the material strength standards to 1000°C [17]. The JAEA also started acquiring ultra-high-temperature data for 316FR stainless steel and 316SS. The outline of the acquisition of the ultra-high-temperature material test data and the material strength standards extended to 1000°C based on the acquired data will be described herein.

The JAEA conducted a short-term creep test for up to approximately 1000 h considering the SA events. The maximum test temperature was 1000°C, which is the maximum temperature that can be used with JAEA's existing equipment. There is concern about the effects of oxidation at ultra-high temperatures; hence, all tests were performed using the φ10 solid round-bar specimens shown in Fig. 6 in addition to the air atmosphere. Some tests were also conducted in an inert atmosphere. Figure 7(a) presents the creep data up to 1000°C acquired in air and inert atmospheres. Within the range of the acquired test conditions, we found no significant difference in the creep strength acquired in the air and inert atmospheres; thus, the creep rupture equation applicable up to 1000°C was formulated using the data of both atmospheres [17]. The creep rupture equation formulated shown in Fig. 7(a) can accurately evaluate the creep data up to 1000°C. Regarding the acquisition of ultra-high-temperature creep data, 316FR stainless steel and 316SS were also obtained in addition to 304SS. Figure 7(b) shows the creep test data of 304SS, 316FR stainless steel, and 316SS up to 1000°C. These three steel types have a significant difference in the creep strength in the operating temperature range of the SFR (e.g., 550°C), but no significant difference in the creep strength was observed at high temperatures exceeding 750°C. Therefore, the ultra-high-temperature creep rupture equation formulated based on the 304SS data is also applicable to 316FR stainless steel and 316SS.

In addition, data up to 1200°C were acquired for the tensile tests. An elastoplastic stress–strain equation applicable up to 1200°C was then formulated based on the acquired data. The material strength standards were expanded to 1000°C by setting physical property values (i.e., modulus of the longitudinal elasticity, Poisson's ratio, and coefficient of thermal expansion) up to 1000°C with reference to public data [18] and ASME standards. The details were described in the paper of Onizawa et al. [17]

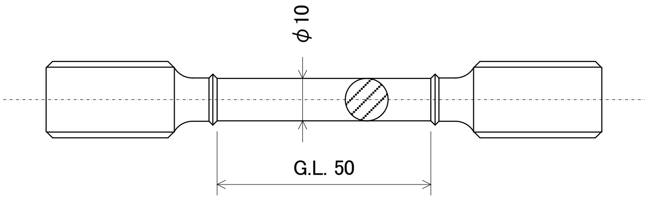

FIG. 6 Specimen shape used in the ultra-high-temperature creep test.

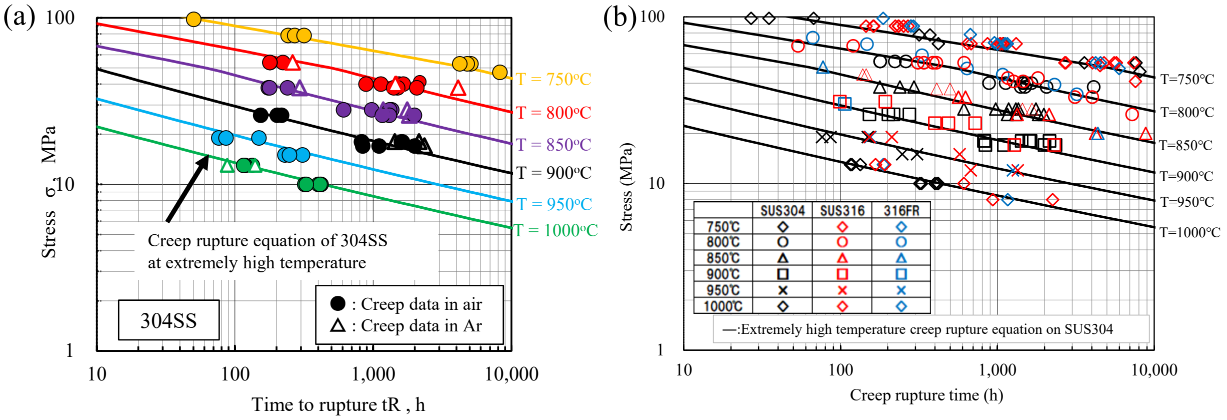

FIG. 7 (a) Comparison of the experimental data to the extremely high-temperature creep rupture equation of 304SS and (b) comparison of the creep test data of the 304SS, 316SS, and 316FR stainless steel to the extremely high-temperature creep rupture equation of 304SS.

5.2. Future plan for the high-temperature material test

In the future, the JAEA plans to acquire ultra-high-temperature data for 316FR stainless steel, which is the main structural material of the SFR and modified 9Cr–1Mo steel and extend the material strength standards to high temperatures. The material properties of the modified 9Cr–1Mo steel are expected to significantly change due to the Ac1 transformation temperature at approximately 800°C to 820°C. Therefore, the temperature must be classified considering the transformation temperature in the formulation of the material property equations. In addition to the base metal, the JAEA plans to acquire ultra-high-temperature material property data for the welded joint such that the structural integrity of the welded joint can be evaluated during the SA.

6. SUMMARY

To put the SFR into practical application, the JAEA is working on the sophistication of the material strength standards to enable the 60-year design and a structural integral evaluation during the SA. This paper reported on the material tests conducted by the JAEA for evaluating the long-term creep properties, the material tests for the development of high-cycle fatigue evaluation methods, and the material tests for the development of ultra-high-temperature material strength standards. In addition, the overall picture of the material tests that the JAEA acquired or plans to acquire in preparation for the revision of the standards of the JSME was also presented herein.

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REFERENCES

[1] JWES, 1999, "ASU NO Energy NO ISHIZUE NI," Atomic Energy Research Committee, The Japan Welding Engineering Society, Chiyoda-ku, Tokyo, (in Japanese).

[2] Takashi ONIZAWA and Ryuta HASHIDATE, Development of creep property equations of 316FR stainless steel and Mod.9Cr-1Mo steel for sodium-cooled fast reactor to achieve 60-year design life, Mechanical Engineering Journal, Vol.6, No.1, 2019.

[3] Kimura, K. and Yaguchi, M., Re-evaluation of long-term creep strength of base metal of ASME grade 91 type steel (2016), pp.PVP2016-63355.

[4] The American Society of Mechanical Engineers, ASME Boiler and Pressure Vessel Code Section III Division 5, Nonmandatory Appendix HBB-Y (2017).

[5] National Institute for Material Section (NIMS), NIMS Creep data sheet No.45A (2005).

[6] National Institute for Material Section (NIMS), NIMS Creep data sheet No.M-10 (2013).

[7] National Institute for Material Section (NIMS), NIMS Creep data sheet No.M43A (2014).

[8] Takahashi, Y., Shibamoto, H. and Inoue, K., Long-term creep rupture behavior of smoothed and notched bar specimens of low-carbon nitrogen-controlled 316 stainless steel (316FR) and their evaluation, Nuclear Engineering and Design 238 (2008), pp.310–321.

[9] The Japan Society of Mechanical Engineers, Code for Nuclear Power Generation Facilities, Rules on Design and Construction for Nuclear Power Plants, Section II Fast Reactor Standards (2018), (in Japanese).

[10] Susumu ODAKA, et al, "Very-High Cycle Fatigue Test Technology under Strain Control in High Temperaturel", Proceedings of the 42nd Symposium on Strength of Materials at High Temperatures, 2004

[11] Takashi ONIZAWA, et al, "Development of 2012 Edition of JSME Code for Design and Construction of Fast Reactors (2) Development of The Material Strength Standard of 316FR Stainless Steel", PVP2013-97608, 2013

[12] Takashi ONIZAWA, et al, "Development of 2012 Edition of JSME Code for Design and Construction of Fast Reactors (3) Development of The Material Strength Standard of Modified 9Cr-1Mo Steel", PVP2013-97611, 2013

[13] The Japan Welding Engineering Society, "Standard method for ultrasonic fatigue test in metallic materials" WES 1112, 2017

[14] Yoshiyuki FURUYA, et al, "Development of High-Temperature Ultrasonic Fatigue Testing System", Transactions of The Japan Society of Mechanical Engineers Series A, 2012 Volume 78 Issue 789 Pages 718-727, 2012

[15] Isamu NONAKA, "Prospect of Life Prediction in Long-Term Fatigue, Creep and Creep-Fatigue for Components Operated at Elevated Temperatures", Journal of the Society of Materials Science, Japan, Vol.64, No.2, pp.65-73, Feb.2015

[16] Y. Wang, et al, "Evaluation of Mean Stress Correction on Fatigue Curves of Grade 91 and Alloy 617 in ASME Section III Division 5", PVP2020-21572, 2020

[17] Takashi ONIZAWA and Takashi WAKAI, Development of extremely high temperature material property equations and physical property values on austenitic stainless steel, SMiRT-25, Charlotte, NC, USA, August 4-9, 2019

[18] Material properties data book at high temperature for dissimilar metal welding in reactor pressure vessel, JNES-RE-Report series, JNES-RE-2012-0024.