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Evaluation of fatigue properties of reduced activation ferritic/martensitic steel, F82H for development of design criteria

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ABSTRACT

Reduced activation ferritic/martensitic (RAFM) steels are promising candidate for structural material of tritium breeding blanket in a fusion reactor. Database accumulation and definition of design criteria for RAFM have been intensively studied together with the progress of blanket design activities. As a part of database accumulation for fusion blanket, a RAFM steel, F82H was fatigue-tested at 573 and 673 K in the air. Axial strain-controlled fatigue tests were carried out with a cylindrical specimen with 8 mm of diameter with -1 of strain ratio condition in accordance with Japanese Industrial Standard, JIS Z 2279, “Method of high-temperature low cycle fatigue testing for metallic materials.” For high cycle tests, the maximum test cycles exceeded 10^6 cycles. Fatigue lifetime of F82H at temperatures ranging from room temperature to 673 K fell into the factor of 2 of the empirical fitting curve for 673 K. It was studied using experimental results that fatigue-related design limit based on RCC-MRx, such as fatigue design curves, half-life cyclic curves, and related coefficients.

1. Introduction

Reduced activation ferritic/martensitic (RAFM) steels are promising candidate for structural material of tritium breeding blanket in a fusion reactor [1]. A RAFM, F82H is a promising candidate of structural material for Japanese water-cooled breeding blanket concept [2]. Together with the progress in design activity on tritium breeding blanket, database accumulation for definition of design limits and design criteria for RAFMs have been intensively studied [3–5]. A previous work studied was fatigue properties of F82H at 823 K, where is the anticipated maximum service temperature for the steel [6]. It was revealed that fatigue lifetime of F82H in vacuum can be estimated using modified universal slope, which is derived from tensile properties [7]. The number of cycles to failure, N_f in the air was estimated by dividing N_f in vacuum by a factor and the factor increases with the test temperature. For water-cooling blanket concept, the anticipated average temperature of structural material is around 673 K [2,8,9]. This work aims to investigate fatigue properties of F82H at 673 K to define its limits and design criteria based on “Design and construction rules for mechanical components of nuclear installations: high temperature, research and fusion reactors, RCC-MRx” for water cooling blanket application [10].

2. Experimental procedures

The material used was F82H-BA07 heat which was produced by combining the vacuum induction melting and secondary refinement process using electro slag remelting [11]. The chemical composition of the material in wt% was Fe-0.091C-0.17Si-0.46Mn-0.009P-0.002S-8.00Cr-1.88W-0.019V-0.03Ta-0.019N-0.002B. The plate was normalized at 1313 K for 40 min and cooled by air, then tempered at 1023 K for 60 min and cooled by air. The cylindrical specimen with 8 mm of diameter and 12 mm of gage length were cut out from the 1/2 thickness position in the 25 mm thick plate which was used for the previous work [6]. As for specimen orientation, the longitudinal axis was parallel to the rolling direction. Fatigue tests were conducted at 573 and 673 K. The test was controlled with axial strain with constant strain rate of 0.25 %/s. The strain ratio, R = -1, a fully reversed push-pull condition was applied. The test procedure including specimen design conformed to JIS Z 2279 and ASTM E-606 [12,13]. The number of cycles to failure was defined as fatigue lifetime and summarized using several empirical equations such as Manson’s modified universal slope method and Langer’s equation [14]. Fatigue related coefficient was derived from the experimental data according to RCC-MRx and compared with those of high chromium martensitic steels, Eurofer and Grade 91 (X10CrMoVNb9 − 1) [10,15].

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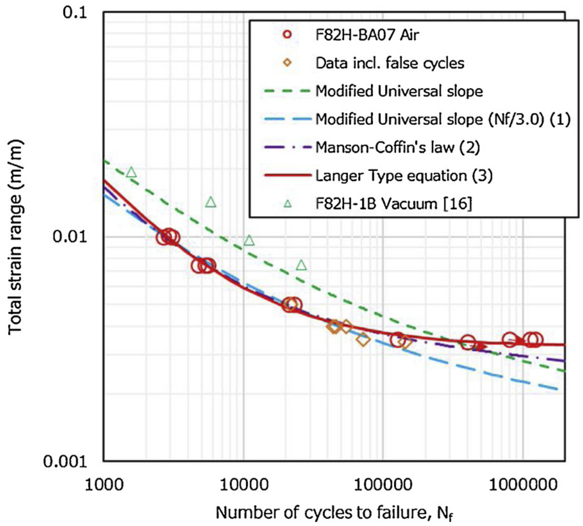

Fig. 1. Fatigue lifetime of F82H at 673 K. Plots with allow represents stop before failure.

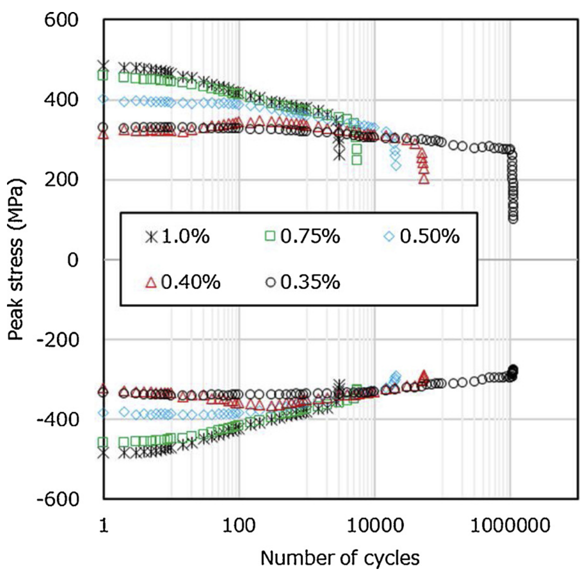

Fig. 2. Cyclic softening behavior of F82H at 673 K. The legends stand for total strain range.

Table 1
Coefficients for half-life cyclic curves of F82H.

Temperature (K)	ν	E (GPa)	K (MPa)	m
673	0.30	194	788	9.96×10^{-2}
823	0.30	181	538	1.38×10^{-1}

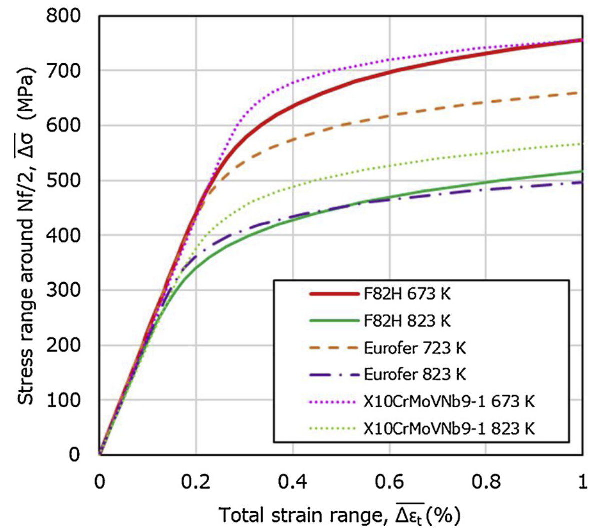

Fig. 4. Half-life cyclic curves of F82H.

3. Results

Fig. 1 shows relationship between fatigue lifetime and total strain range of F82H obtained from tests at 673 K together with reference data [16]. Fatigue lifetime at 673 K was summarized using empirical equations such as Manson's modified universal slope (1), Manson Coffin's law (2), and Langer's (3) described as follows:

$$\Delta\varepsilon_t = 0.460\ N_f^{\ -0.56} + 7.70 \times 10^{-3}\ N_f^{\ -0.09} \tag{1}$$

$$\Delta\varepsilon_t = 1.77\ N_f^{\ -0.718} + 6.11 \times 10^{-3}\ N_f^{\ -0.0550} \tag{2}$$

$$\Delta\varepsilon_t = 1.80\ N_f^{\ -0.700} + 3.13 \times 10^{-3} \tag{3}$$

where $\Delta\varepsilon_t$ is total strain range in (m/m) and N_f is number of cycles to failure. Although the coefficients in the (2) should be derived from tensile properties, the coefficients include factor of $N_f/3$. It is because the derived coefficients from tensile properties give good fitting for

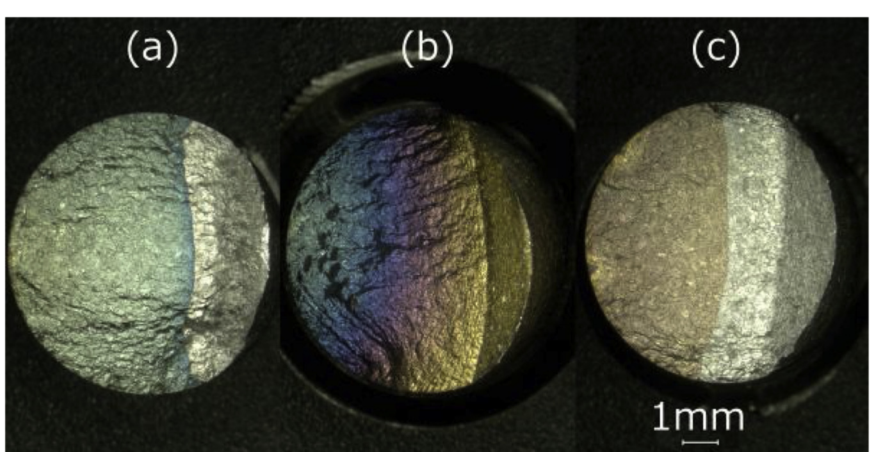

Fig. 3. Fracture apparatus of F82H tested at 673 K with 0.35 % of total strain range, (a) Specimen No. 3, N_f: 1.1×10^6, (b) Specimen No. 4, N_f: 1.3×10^5, and (c) Specimen No. 5, N_f: 1.2×10^6. Cracks propagate from left to right.

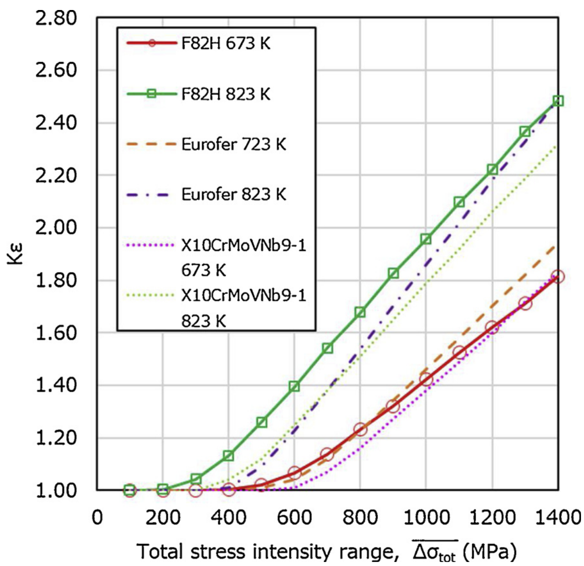

Fig. 5. Values of K_ε defined for F82H.

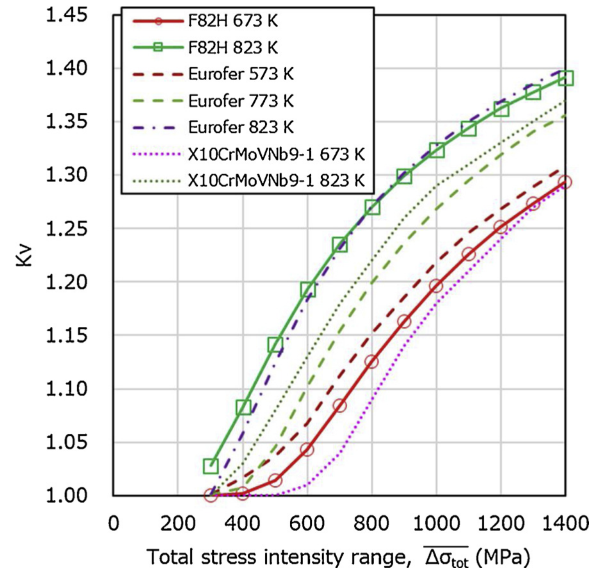

Fig. 6. Values of K_ν defined for F82H.

lifetime in a vacuum, and $N_f/3$ well estimates the lifetime in the air. As reported in the previous work, lifetime at 823 K in a vacuum condition was successfully estimated with the modified universal slopes from tensile properties. However, $N_f/4$ gives good estimation for the N_f at the same temperature in the air [6,16].

Fitting with modified universal slope with factor of $N_f/3$ and Manson-Coffin's law can be applicable below 10^5 cycles. Langer type equation gives good fitting for data above 10^6 cycles.

The rhombus plots in Fig. 1 stand for the fatigue lifetime including false cycles, which did not reach target peak strain within initial hundreds cycles. Cyclic behavior of peak stress during the fatigue tests are presented in Fig. 2. Magnitude of softening was significant in the test under greater strain range. Although F82H demonstrated cyclic softening behavior, some data around 0.4 % of total strain range showed increase in peak stress. However, it was found that peak strain at initial cycles did not reach target strain range. Such cycles were up to several hundred cycles and it was less than 1 % of number of cycles to failure. Moreover, these cycles did not have significant impact on the lifetime.

Lifetime of F82H exhibited large scattering below 0.35 % of $\Delta\varepsilon_t$, and some points exceeded 10^6 cycles under the axial strain-controlled tests.

The fracture surfaces tested at 673 K with 0.35 % of $\Delta\varepsilon_t$ are presented in Fig. 3. All specimen exhibited typical fatigue fracture, surface crack propagation and beach mark. Moreover, neither buckling nor inclusion jeopardizing fatigue properties were found.

4. Discussions

4.1. Cyclic curves for F82H

The relationship between total strain range, $\bar{\Delta\varepsilon_t}$ and total stress range around half life, $\bar{\Delta\sigma}$ was summarized using the following equation [10]:

$$\bar{\Delta\varepsilon_t}\ (\%) = 100\,\frac{2(1+\nu)}{3E}\,(\bar{\Delta\sigma}) + \left(\frac{\bar{\Delta\sigma}}{K}\right)^{1/m} \tag{4}$$

where ν is Poisson's ratio, E is Elastic modulus, K and m were calculated to fit the experimental results using the Eq. (4) [17–19]. The parameters for this equation are summarized in Table 1. Fig. 4 shows cyclic curves of F82H obtained from strain-controlled fatigue tests compared with those of

Eurofer [10]. The curves were derived from the Eq. (4), and temperature dependence of tensile properties of F82H are similar to those of Eurofer. The same tendency was found in the cyclic curves.

4.2. Fatigue related coefficients, K_ε, K_ν, and K_s

Fatigue related coefficients, K_ε and K_ν are defined in RCC-MRx to estimate the allowable total strain range intensity under the cyclic load [4]. The coefficient K_ε, which describes elastic component of the total strain range $\bar{\Delta\varepsilon_1}$ and plastic strain measured of the cyclic stress strain curve $\bar{\Delta\varepsilon_3}$, were calculated for F82H using Table 1 and the following equations:

$$\bar{\Delta\varepsilon_1} = \frac{2(1+\nu)}{3E}\,\bar{\Delta\sigma_{tot}} \tag{5}$$

$$\bar{\Delta\sigma_{tot}}\ \bar{\Delta\varepsilon_1} = \bar{\Delta\sigma}(\bar{\Delta\varepsilon_1} + \bar{\Delta\varepsilon_3}) \tag{6}$$

$$\bar{\Delta\varepsilon_1} + \bar{\Delta\varepsilon_3} = \frac{2(1+\nu)}{3E}\,\bar{\Delta\sigma} + 0.01\left(\frac{\bar{\Delta\sigma}}{K}\right)^{1/m} \tag{7}$$

$$K_\varepsilon = \frac{\bar{\Delta\varepsilon_1} + \bar{\Delta\varepsilon_3}}{\bar{\Delta\varepsilon_1}} \tag{8}$$

where $\bar{\Delta\sigma_{tot}}$ represents total stress intensity range. The calculated K_ε is

Table 2
Coefficient K_ε for F82H.

	100 MPa	200 MPa	300 MPa	400 MPa	500 MPa	600 MPa	700 MPa	800 MPa	900 MPa	1000 MPa	1100 MPa	1200 MPa	1300 MPa	1400 MPa
673 K	1.00	1.00	1.00	1.00	1.02	1.07	1.14	1.23	1.32	1.42	1.52	1.62	1.71	1.81
823K	1.00	1.00	1.04	1.13	1.26	1.40	1.54	1.68	1.83	1.96	2.10	2.22	2.37	2.48

Table 3
Coefficient K_ν for F82H.

	300 MPa	400 MPa	500 MPa	600 MPa	700 MPa	800 MPa	900 MPa	1000 MPa	1100 MPa	1200 MPa	1300 MPa	1400 MPa	1500 MPa
673 K	1.000	1.002	1.014	1.043	1.084	1.126	1.163	1.196	1.226	1.251	1.274	1.293	1.311
823K	1.028	1.083	1.142	1.193	1.235	1.270	1.299	1.324	1.344	1.362	1.378	1.391	1.403

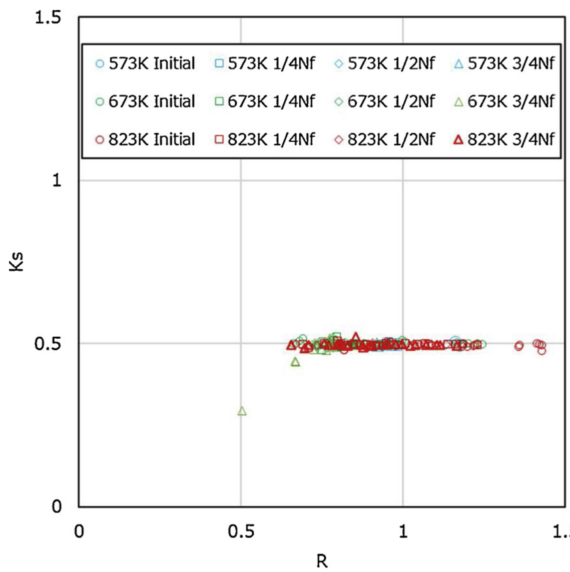

Fig. 7. Values of K_s defined for F82H.

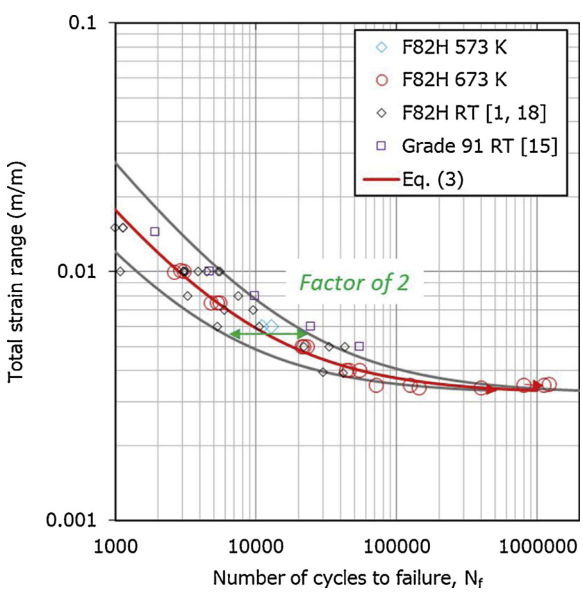

Fig. 8. Fatigue lifetime of F82H temperature ranging from room temperature, RT to 673 K.

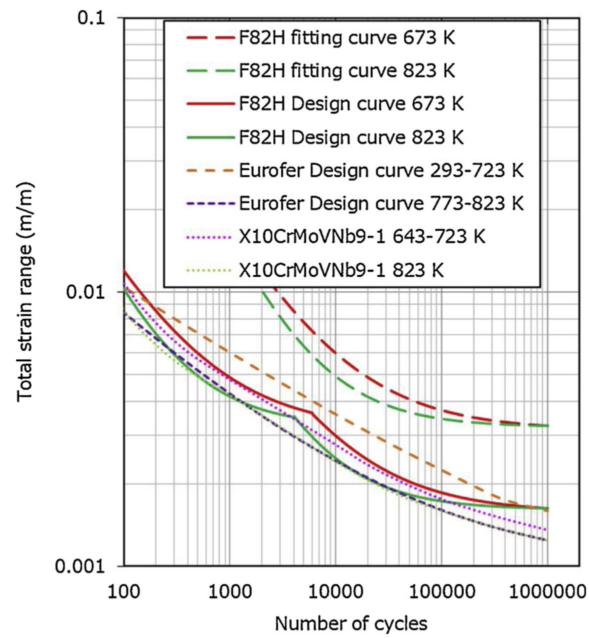

Fig. 9. Fatigue design curves for F82H.

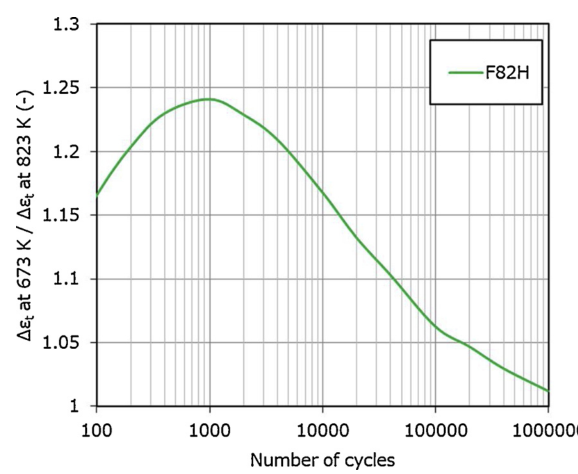

Fig. 10. Comparison of allowable total strain range between 673 K and 823 K.

summarized in Fig. 5 and Table 2.

The coefficient is required to estimate $\Delta\bar{\varepsilon}_4$ which represents triaxiality effects in total strain range intensity, $\Delta\varepsilon_{tot}$ using the following relationship:

$$\Delta\bar{\varepsilon}_4 = (K_\nu - 1)\,\Delta\bar{\varepsilon}_1 \tag{9}$$

The coefficient K_ν was defined using the following relationship:

$$K_\nu = [3(1-\nu) + (4\nu - 2)t]/(1+\nu) \tag{10}$$

$$t + At^r(\Delta\bar{\sigma}_{tot})^{r-1} = 1 \tag{11}$$

$$A = E/[200(1-\nu)K^r] \tag{12}$$

$$r = 1/m \tag{13}$$

where t was defined to satisfy the Eqs (10) and (11). The calculated K_ν is summarized in Fig. 6 and Table 3.

Both K_ε and K_ν increases at lower total stress intensity range $\Delta\bar{\sigma}_{tot}$ with higher temperature, and the increments getting larger with temperature. These tendencies are found in those of Eurofer. Moreover, the value defined for F82H seems similar to those of Eurofer and X10CrMoVNb9−1.

Fig. 7 shows symmetrisation coefficient K_s defined for F82H calculated for the representative cycles such as, initial, $1/4N_f$, $1/2N_f$, and $3/4N_f$. The coefficient is defined in RCC-MRx to estimate damage under creep fatigue interaction. It was summarized using a function, R which consists of the measured stress range, $\Delta\bar{\sigma}^*$ and the minimum yield strength $S_{y,min}$ at test temperature, θ^* as follows:

$$R = \Delta\bar{\sigma}^* / 2S_{y,min}(\theta^*) \quad (14)$$

$$K_s = \sigma_{max} / \Delta\sigma \quad (15)$$

where σ_{max} is the maximum stress, and $\Delta\sigma$ is stress amplitude.

Although K_s decreased with number of cycles just before N_f, it can be assumed 0.5 for F82H at 673 and 823 K, as well as that for Eurofer and X10CrMoVNb9 − 1. The function, R tends to be greater than 1 at initial cycles and decreases with cycle increases. No obvious temperature dependence was observed in K_s and R.

4.3. Fatigue design curves for F82H

Fig. 8 shows fatigue lifetime at room temperature, 573 and 673 K in the air together with commercial 9% chromium steel, Grade 91 [1,15,18]. Most of fatigue data is found to be fell into the factor of 2 of the empirical equation for 673 K, and the rest appears to be longer lifetime. A fatigue design curve for Eurofer in RCC-MRx is defined to stand for temperatures ranging from 293 to 723 K.

Fig. 9 shows fatigue design curves for F82H together with those of Eurofer and X10CrMoVNb9 − 1 [10]. The design curves were derived using design factors $\Delta\varepsilon_t/2$ and $N_f/20$. At lower cycle $N_f/20$ gives conservative curve and $\Delta\varepsilon_t/2$ at higher cycle. The transition was found at around 0.36 % of $\Delta\varepsilon_t$, 6×10^3 at 673 K and 4×10^3 at 823 K in number of cycles. Although design curves for F82H are discontinuous at the transition points, these curves are similar to those of X10CrMoVNb9 − 1 below 5×10^5 cycles. The difference seems come from data points of F82H above 10^6 cycles.

Allowable strain range was compared between 823 and 673 K using the fatigue design curves and presented in Fig. 10. As shown in this figure, the difference in allowable strain range is less than 25 % in these temperatures. Therefore, design curve for 823 K gives less than 25 % of margin for 673 K of service temperature.

5. Conclusions

F82H-BA07 were fatigue tested at 573 and 673 K in the air under axial strain-controlled condition over 10^6 cycles. Fatigue related coefficients defined in RCC-MRx were derived from the experimental results including previous works. The main conclusions are as follows;

1 The fatigue lifetime of F82H at 673 K is superior to 10^6 cycles with 0.35 % of total strain range.
2 For fitting of lifetime, Manson's modified universal slope and Manson-Coffin method is applicable below 10^5 cycles. On the contrary, Langer type equation gives good fitting over 10^6 cycles.
3 Fatigue lifetime of F82H at temperature ranging from room temperature to 673 K fell into the factor of 2 of the empirical equation for 673 K.
4 Cyclic stress strain curves and related coefficients were defined for F82H, and these are comparable with those of Eurofer.
5 Fatigue design curves were preliminarily defined for temperatures, 673 K and 823 K. Difference in allowable strain range at these temperatures was less than 25 %.

CRediT authorship contribution statement

Takanori Hirose: Conceptualization, Investigation, Data curation, Writing - original draft. **Taichiro Kato:** Investigation, Resources. **Hideo Sakasegawa:** Formal analysis. **Hiroyasu Tanigawa:** Project administration. **Takashi Nozawa:** Data curation, Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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