Fusion Engineering and Design 173 (2021) 112830

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Creep-fatigue interaction on estimation of lifetime and fatigue damage of F82H

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ARTICLE INFO

Keywords:
Creep-fatigue lifetime
Creep-fatigue damage envelope
Thermo-mechanical analysis

In this study, creep-fatigue (CF) tests on F82H at 823 K were conducted according to the standard specimen and requirement of ASTM. Tension holding (TH) showed higher lifetime than compression holding (CH). Compared with 9Cr-1Mo-V steels, CF lifetime degradation was not observed at the holding time less than 0.05 h in case of CH and 0.17 h in case of TH. CF damages were summarized from the CF test results by Campbell method. The obtained damages distributed around CF damage envelope of Grade 91 in ASME NH. CF damage of cylindrical water-cooled ceramic breeder (WCCB) test blanket module (TBM) container at the zenith of hemisphere body under the ITER thermo-mechanical load was calculated. The calculated damage located within of the damage envelope of Grade 91. It was indicated that the present design of cylindrical WCCB TBM might resist CF interaction under the ITER thermo-mechanical load conditions.

1. Introduction

Test Blanket Module (TBM) program is aimed to demonstrate essential functions of prototype modules of DEMO breeding blankets in the real DT fusion plasma environment of ITER [1, 2]. The container of water-cooled ceramic breeder (WCCB) TBM is fabricated by F82H [3], which is considered as the primary candidate structural material. The container is cyclically loaded with coolant pressure, heat load and electromagnetic force at temperature ranges including creep field (> 648 K) [4-6]. Evaluation on structural integrity of TBM considering creep-fatigue (CF) damage of F82H is one of the important design issues..

In the existing construction code like ASME NH, CF damage envelope was defined as one of the structural criteria, and the envelope is arranged based on collected huge numbers of experimental data. However, existing CF tests results for F82H are limited and not sufficient to arrange CF damage envelope. This study aims to evaluate CF interaction on estimation of lifetime and fatigue damage of F82H and discuss structural integrity of the cylindrical WCCB TBM under the ITER thermo-mechanical loads.

2. Experiment and analysis

2.1. Material, specimens and creep-fatigue test

The examined material was F82H-BA07 heat fabricated by combining the vacuum induction melting and secondary refinement process using electro slug remelting [3]. The plate was normalized at 1313 K for 40 min and cooled in the air, then tempered at 1023 K for 60 min and cooled in the air. The round-bar (RB) threaded CF specimens with 5 mm of diameter and 15 mm of gage length referred from ASTM E-2714-13 were employed [8]. The loading axis of the RB specimen was machined from the 25 mm thick plate along the rolling direction. Surface of the specimens was polished along the loading axis until satisfied with $Ra < 0.2$ [8].

The push-pull loading CF tests were carried out at 823 K in the air with stress ratio of $R = -1$, which is recognized as the maximum service temperature of F82H, using a MTS fatigue testing system with ±100 kN load cell. CF tests were conducted at the strain rate of 10^{-3} /s with specimens being placed in an electric furnace and heated from room temperature to 823 K. The total strain ranges of 0.75% and 1%, and 180 s holding per a cycle at the peak compressive stress were selected. CF lifetime (N_{f_CF}) is defined as the number of cycles at which the peak stress is crossed to a dash line, that is created by 3/4 (25% decreased) of the peak stress in relatively stable variation stage.

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https://doi.org/10.1016/j.fusengdes.2021.112830
Received 30 November 2020; Received in revised form 30 July 2021; Accepted 31 July 2021
Available online 10 August 2021

2.2. Finite element analysis

Three-dimensional finite element analyses were performed using a commercial simulation code called ANSYS ver. 19.1. Using a plane symmetrical finite element (FE) model of a 1/4 TBM container consists of hemispherical body, cylindrical body was studied in the thermal and elastic thermo-mechanical analyses as shown in Fig. 1. The FE-model was meshed by three-dimensional hexahedral solid with 20-node brick elements. The number of mesh along the thickness of hemisphere and cylindrical body higher than three is conducted. The elements and nodes of the FE-model were, respectively, about 54,000 and 150,000. The minimum mesh size was around 0.2 mm. In case of thermal analyses, the nuclear heat generation along radial direction of the container as shown in Fig. 2 was calculated by the Monte Carlo N-Particle code and applied as initial condition. Meanwhile, the initial temperature of cooling water and heat transfer coefficient used for cooling channel are 343°C and 16000 W/m^{2}K, respectively. Due to the hemispherical first wall (FW), the input value of heat load is defined as 0.3 MW/m^2 × cosθ shown in Fig. 1. Thermal insulation was applied for other surfaces of the TBM container. In case of thermo-mechanical analysis, a pressure of 17.2 MPa is applied to the cooling channel. Material properties of 9Cr-1Mo-V steels [9] including Young's modulus, Poisson's ratio, thermal expansion coefficient and thermal conductivity were used for elastic FEM analysis. Previous studies showed that the physical properties of Grade 91 are similar to those of F82H [15]. Therefore, thermo-mechanical behavior in this study can represent that of TBM made of F82H. Due to lack of arranged CF damage envelope for F82H, all relevant properties and the CF damage envelope of Grade 91 were considered.

3. Evaluation methods of creep-fatigue damage

3.1. Creep-fatigue damage evaluation based on creep-fatigue test

Evaluation procedure of CF damage from CF tests following Campbell method is shown in Fig. 3 [10]. CF lifetime (N_{f_CF}) is defined as the number of cycles at which the peak stress is reduced to 3/4 (25% decreased) of sudden decrease point as shown in Fig. 3. Based on the test conditions as described in section 2.1, the CF lifetime has been recorded. Since the previous study showed good agreement with modified universal slope method in the low cycle fatigue (LCF) region at 823 K [11], the pure fatigue (PF) lifetime (N_{f_PF}) is assumed to be described using the method at the same total strain range loaded in CF test. The fatigue damage could be calculated as follows:

$$D_f = \frac{N_{f\_CF}}{N_{f\_PF}} \tag{1}$$

The creep damage was analyzed using hysteresis loops and stress relaxation curves around half a CF lifetime. According to the stress relaxation curve, the relationship between holding time and axial stress could be represented as follows:

$$\overline{\sigma_{CF\_k}} = (\sigma_{CF\_k} + \sigma_{CF\_k+1})/2 \tag{2}$$

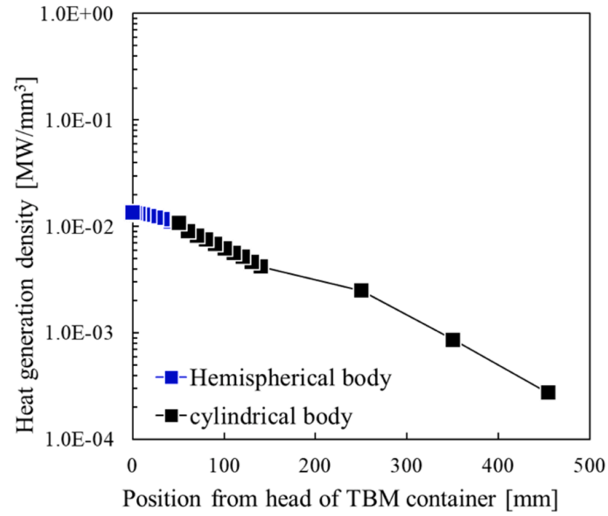

Fig. 2. Nuclear heat generation along radial direction of cylindrical WCCB TBM container

$$\Delta t_{CF\_k} = t_{CF\_k+1} - t_{CF\_k} \tag{3}$$

Where σ_{CF_k} is axial stress recorded from CF test within the duration of holding time in the cycle at half of CF lifetime. $\overline{\sigma_{CF\_k}}$ is mean axial stress calculated by neighboring stress. t_{CF_k} is testing time recorded from CF test. Δt_{CF_k} is sampling time. The time to failure at the stress level of $\overline{\sigma_{CF\_k}}$ could be derived from the master curve of the creep rupture test [14]. The creep damage could be calculated as follows:

$$D_{c_{Nf/2}} = \sum_{k=1}^{n-1} \frac{\Delta t_{CF_k}}{T_k} \tag{4}$$

$$D_c = N_{f\_CF} \cdot D_{c\_Nf/2} \tag{5}$$

Where n is ending of stress relaxation. Calculated creep and fatigue damage will be plotted in the CF damage diagram as shown in section 4.

3.2. Creep-fatigue damage evaluation based on finite element analysis of cylindrical WCCB TBM container

For a design to be acceptable in ASME NH [6], the creep and fatigue damage under the levels A, B, and C service loadings in shall satisfy the following relation [7]:

$$\sum_{j=1}^{P} \left(\frac{n}{N_d}\right)_j + \sum_{k=1}^{q} \left(\frac{\Delta t}{T_d}\right)_k \leq D \tag{6}$$

where, D is total CF damage. n is number of applied cycles, which is considered as summation of 3 × 10^4 cycles for pulsed operation and 500

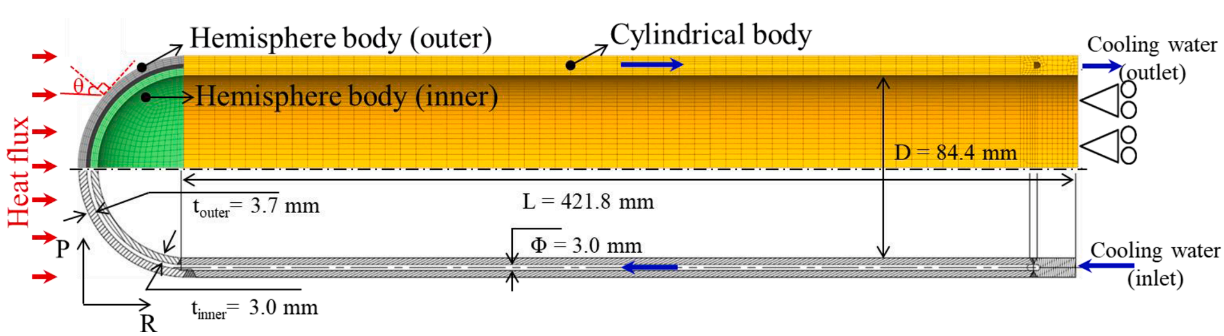

Fig. 1. FE-model of cylindrical WCCB TBM container

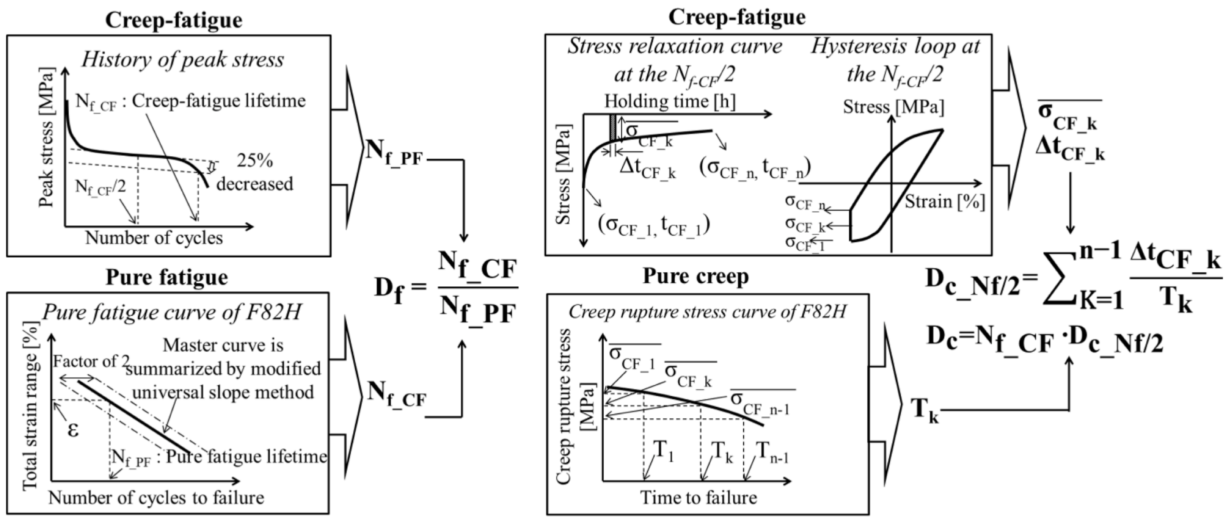

Fig. 3. Evaluation procedure of creep-fatigue damage using Campbell method

cycles for start and stop of a cooling loop for the TBM. $(N_d)_j$ is number of design allowable cycles. Δt is operating time, which is conservatively considered as 1.4×10^4 h (24 hours × 365 days × 2 years × 0.8 operation rate). $(T_d)_k$ is allowable time duration.

$(N_d)_j$ is determined by modified maximum equivalent stain range ($\Delta\varepsilon_{mod}$) following design fatigue curve. The most conservative estimate of $\Delta\varepsilon_{mod}$ was employed and calculated as [7]:

$$\Delta\epsilon_{mod} = K_e K \Delta\epsilon_{max} \tag{7}$$

where, K is the equivalent stress concentration factor and defined as effective primary plus secondary plus peak stress divided by effective primary plus secondary stress. K_e could be calculated as [7]:

$$K_e = 1 \text{ if } K\Delta\epsilon_{max} \leq \frac{3\overline{S_m}}{E} \tag{8}$$

$$K_e = K\Delta\epsilon_{max}E \ / \ 3\overline{S_m} \text{ for } K\Delta\epsilon_{max} > \frac{3\overline{S_m}}{E} \tag{9}$$

$$3\overline{S_m} = 1.5S_m + S_{rH} \tag{10}$$

where, S_m is allowable stress. S_{rH} is relaxation strength.

$(T_d)_k$ is determined by stress to rupture curves for a given stress and the maximum temperature at the evaluation point. Equivalent stress quantity could be calculated as [7]:

$$\sigma_e = \overline{\sigma} \exp\left[C\left(\frac{J_1}{S_s} - 1\right)\right] \tag{11}$$

$$J_1 = \sigma_1 + \sigma_2 + \sigma_3 \tag{12}$$

$$S_s = \left[\sigma_1{}^2 + \sigma_2{}^2 + \sigma_3{}^2\right]^{1/2} \tag{13}$$

Where σ_i (i = 1, 2, or 3) are the principal stresses. $\overline{\sigma}$ is von Mises stress. The constant C is defined as 0.16 ($J_1/S_s \geq 1.0$) or 0 ($J_1/S_s < 1.0$).

4. Results and Discussion

4.1. Estimation on creep-fatigue lifetime damage of F82H

Figure 4 shows relationship between holding time and lifetime of F82H, 9Cr-1Mo-V steels and Eurofer 97 [12, 13]. Compared with PF, CF lifetimes were decreased due to the tension or compression holding. Further reductions of CF lifetime were observed with increasing holding time. Meanwhile, tension holding (TH) preformed longer CF lifetimes

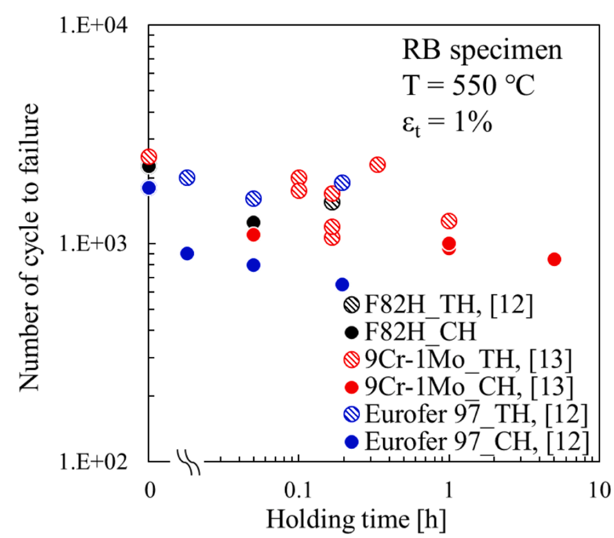

Fig. 4. CF lifetimes of F82H, 9Cr-1Mo-V steels and Eurofer 97

than compression holding (CH). It was indicated that the understanding and evaluation on real stress state in TBM derived from thermal and mechanical loads should be taken into accounted.

Compared with 9Cr-1Mo-V steels, no obvious differences in CF lifetime were observed regarding TH or CH. F82H preformed same or longer CF lifetimes than Eurofer 97 in TH and CH, respectively. F82H showed similar CF lifetime as 9Cr-1Mo-V and Eurofer 97 steels based on the limited data at the holding time less than 0.05 h on CH and 0.17 h on TH.

According to the Campbell method in section 3.1, the CF damages of F82H were calculated and shown in Fig. 5. Compared with the existing Grade 91 CF damage envelope in ASME NH, the obtained CF damages of F82H were distributed on the right and upper areas of the envelope. This indicated the absence of conflicting results. However, it is necessary to be verified evaluating further CF tests among others with longer holding times.

4.2. Evaluation on creep-fatigue damage of cylindrical WCCB TBM container

Because the creep temperature of ferritic metal in ASME is considered higher than 648 K, the temperature distribution of creep field (>

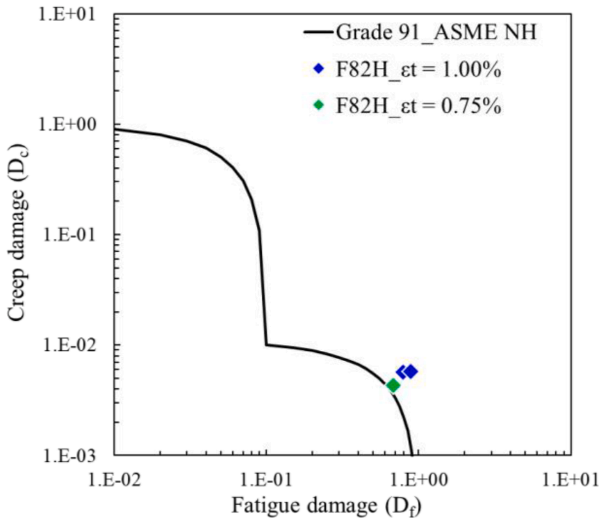

Fig. 5. Relationship between CF damages of F82H and damage envelope of Grade 91.

648 K) in TBM container was evaluated and shown in Fig. 6. Maximum temperature of 685 K was observed at the zenith of outer hemispherical body. It was shown that creep field is limited in FW. Distribution of maximum principal stress focused on the outer hemispherical body was shown Fig. 7. Due to the contribution of higher inner pressure, the compression stress caused by heat load was canceled. Tension stress state was obtained in FW with the creep field. Considering the different CF lifetimes between TH and CH shown in Fig. 4, it was indicated that application of CH CF tests could be conservative. Based on the thermo-mechanical analysis result and CF damage evaluation method in section 3.2, the relationship between envelope of Grade 91 and CF damage of cylindrical WCCB TBM container at the zenith of hemisphere body is shown in Fig. 8. Data obtained from thermo-mechanical analysis are summarized in table 1. CF damages and calculation process with its constant are summarized in table 2. Design fatigue curve of Grade 91 at 823 K (only choice) and minimum creep rupture curve of Grade 91 at 673 K from ASME NH were employed to calculate $(N_d)_j$ and $(T_d)_k$, respectively. CF damage of TBM at the zenith of hemisphere body was located in the inner area of damage envelope. It was indicated that the present WCCB TBM might resist loads of CF interaction under the periodic thermo-mechanical loads in ITER. CF damage envelope for F82H should be developed for an exact evaluation on structural integrity of WCCB TBM.

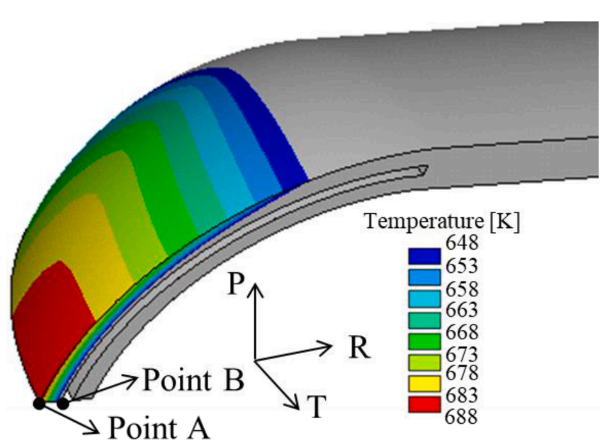

Fig. 6. Temperature distribution of cylindrical WCCB TBM container higher than the creep field.

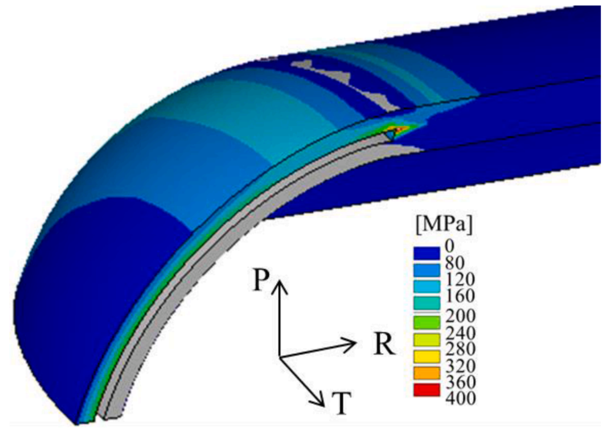

Fig. 7. Maximum principal stress distribution of cylindrical WCCB TBM container.

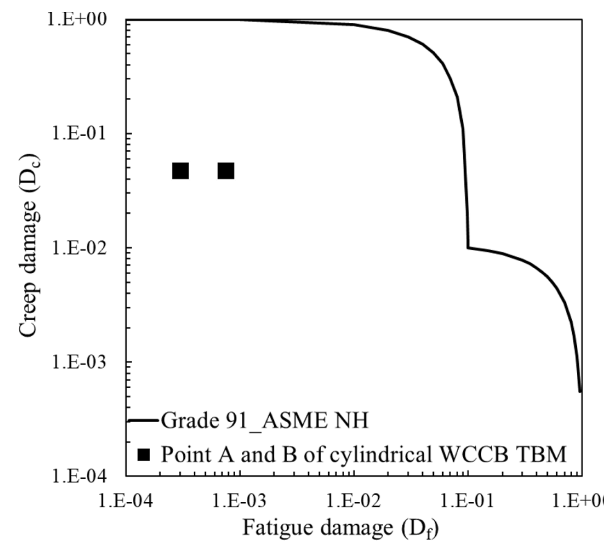

Fig. 8. Relationship between CF damage of cylindrical WCCB TBM container and damage envelope of Grade 91.

Table 1
Summary of data from thermo-mechanical analysis

	Point A	Point B
P+Q+F (MPa)	227	
P+Q (MPa)	218	
σ_1 (MPa)	18.9	210
σ_2 (MPa)	18.8	210
σ_3 (MPa)	0.11	-17.4
$\bar{\sigma}$ (MPa)	18.7	227
$\Delta\varepsilon_{max}$ (%)	0.01	0.12

Conclusions

In this study, CF tests of F82H were conducted at 823 K for evaluating lifetime and CF damage in comparison with 9Cr-1Mo-V steels. Also, CF damage of TBM container under ITER load conditions was investigated based on the requirement of ASME NH and CF damage envelope of Grade 91. The conclusions were summarized as below:

1 CF tests of F82H following standard specimen and ASTM standard were conducted. TH exhibited higher CF lifetimes than CH. Compared with 9Cr-1Mo-V steels and Eurofer 97, CF lifetime

Table 2
Calculated data obtained from equations (7) to (13).

		Point A	Point B
Fatigue damage	K	1.04	1.04
	Ke	1	1
	$\Delta\varepsilon_{mod}$ (%)	0.01	0.12
	$(N_d)_j$	1×10^8	4×10^7
Creep damage	J_1	37.8	403
	S_s	26.7	297
	C	0.16	0.16
	σ_e (MPa)*	20.0	240
	$(T_d)_k$ (h)**	3×10^5	3×10^5
Creep-fatigue damage		(3.05E-4, 0.05)	(7.63E-4, 0.05)

*Effect of stress relaxation was not considered.
**Maximum allowable time duration at 673 K is 3×10^5 h in ASME NH

degradation was not observed in F82H based on the limited data at the holding time less than 0.05 h in case of CH and 0.17 h in case of TH. Compared with the existing Grade 91 CF damage envelope in ASME NH, the obtained CF damages of F82H were distributed on the right and upper areas of the envelope. This indicated the absence of conflicting results. However, it is necessary to be verified evaluating further CF tests among others with longer holding times.

2 The highest CF damage in cylindrical WCCB TBM container was found at the zenith of hemisphere body under the ITER thermo-mechanical load. Considering CF damage envelope of Grade 91 in ASME NH, the CF damage was located in the inner area of the damage envelope. It was indicated that the present WCCB TBM might resist loads of CF interaction under the periodic thermo-mechanical loads in ITER. This conclusion needs to be verified by further assessment using material data of F82H in FEM analysis.

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.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Acknowledgments

The authors are grateful to Mr. M. Yoshikawa, M. Okada and K. Suzuki of Kobe Material Testing Laboratory Group for their assistances of the Creep-fatigue tests. The authors are grateful to Dr. A. Nitta of Kobe Material Testing Laboratory Group for discussion on creep-fatigue damage using the Campbell method.

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