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## International Journal of Fatigue

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# Fatigue model of domestic 316LN steel in simulated primary coolant environment of CAP1400

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## ARTICLE INFO

## Keywords:

Primary coolant pipe  
Low cycle fatigue  
Corrosion fatigue  
Fatigue model  
Environmental fatigue life

## ABSTRACT

Fatigue tests of domestic 316LN were carried out in the simulated primary coolant environment of CAP1400 (the advanced 3rd generation nuclear power plants developed in China). Effects of temperature, strain rate and dissolved oxygen (DO) on fatigue life were analyzed. Based on the results, a fatigue model was developed. Fatigue life in primary coolant environment increases logarithmically as the temperature decreases from 321 °C to 150 °C. When the temperature decreases to 150 °C, fatigue life in primary coolant environment is very close to that in air environment. Fatigue life increases as the strain rate increases from 0.004%/s to 1%/s. After the strain rate increases to more than 0.4%/s, fatigue life in primary coolant environment is very close to that in air environment. Effect of DO on fatigue life in primary coolant environment is not obvious in the DO range of 0.005 ppm to 8 ppm. Compared with NUREG6909 model, the present fatigue model is more accurate in lifetime prediction of domestic 316LN.

## 1. Introduction

Developing Nuclear Power Plant (NPP) is an utmost strategy to achieve win-win goal of social development and low-carbon green environment in the world. Operation safety and economy is the most important and critical issue in the development of NPP. The primary coolant pipe is the key component that related to operation safety and economy, as it is the third barrier to prevent radioactive substance leak from reactor core and act as the artery of a nuclear island [1]. In the long term operation of structures, the integrity should be analyzed using different methods, e.g., deterministic and probabilistic methods [2–9]. The different ageing mechanism and failure modes should also be studied and advanced crack detection setups are developed [8–10]. As a result, new structures can be designed tailored to the applications [11,12]. During operation, the primary coolant pipe is subject to the changes of pressure, temperature, and fluid. The resultant secondary induced stresses will cause fatigue damage of the piping material. The damage can be aggravated by the primary coolant water environment, which is of high temperature, high pressure, etc. [13,14] Therefore, in order to assess the integrity of the primary coolant pipe and determine its lifetime in service, a fatigue model in simulated primary coolant

environment should be developed [15].

Based on the experimental test, a lot of fatigue models used in primary coolant, e.g., NUREG6909, JNES1005 [16,17], have been proposed. According to these fatigue models, some critical factors, such as temperature [18–20], strain rate [21–23] and dissolved oxygen (DO) [17], have important influence on fatigue life. As recommended in the RG1.207 guideline, the fatigue model in simulated primary coolant usually includes 2 parts, i.e., the fatigue model in air environment and the Environmental Fatigue Correction Factor (Fen) which is defined as the ratio of fatigue life in air at room temperature to that in water at the service temperature [24]. In this paper, both fatigue model in air and in environment will be studied.

316LN stainless steel is used as the primary coolant pipe material of CAP1400 NPP, which is one kind of the advanced 3rd generation NPPs developed in China [25,26]. Thus, material performance of 316LN and its fatigue lifetime prediction in service is significant to the operation safety of NPPs. Our previous work tested the fatigue property of 316LN in simulation primary coolant environment and the relationship between fatigue life and different strain amplitudes was obtained [27,28]. It is shown that fatigue crack propagation was accelerated in the primary coolant environment due to Environmental Assist Cracking (EAC)

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<https://doi.org/10.1016/j.ijfatigue.2019.105297>

Received 3 June 2019; Received in revised form 15 September 2019; Accepted 22 September 2019

Available online 23 September 2019

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**Table 1**  
Chemical composition of 316LN steel.

Elements	w[%]	Elements	w[%]
C	0.012	Ni	13.12
Mn	1.23	Cr	17.01
Si	0.31	Mo	2.44
P	0.017	N	0.14
S	0.002	Co	0.01

and the EAC mechanism is most likely to be Hydrogen Induced Crack (HIC) [28].

The aim of the present work is to study the fatigue model of the piping material on the basis of the experimental investigation. The effect of temperature, strain rate and dissolved oxygen on fatigue life are studied. A fatigue model in primary coolant environment is proposed and compared with the NUREG6909 model. The result is used to provide research basis to fatigue design and lifetime evaluation of primary coolant pipe of the domestic 3rd generation NPP.

## 2. Experiment procedure

The test material is 316LN stainless steel that cut from a primary coolant pipe. The nominal chemical composition is listed in Table 1. The metallographic structure of the material is typical austenite, as shown in Fig. 1. It is shown that most of the grains are white and in polygon shape. The grain boundary is straight, and a lot of twin grain existed within the grain. The average grain size is about 135  $\mu\text{m}$ .

The cylindrical fatigue specimen is machined along the axial direction of the pipe, as shown in Fig. 2. The length and diameter of the gauge are 19 mm and 6.35 mm, respectively. Fatigue tests were carried out in Bairoe corrosion fatigue test machine at different temperature (100–325  $^{\circ}\text{C}$ ), strain rate (0.004–1%) and DO (0.1–8 ppm) in order to study the effect on fatigue property. The test environment is simulation CAP1400 first loop water environment. The detailed environment parameters are listed in Table 2. The triangular waveform loading with the strain ratio of  $-1$  is applied.

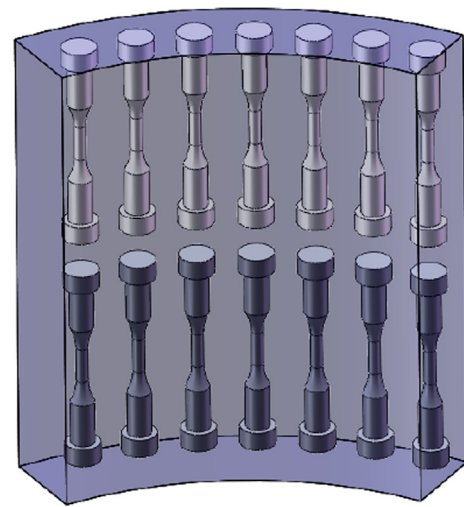
Fatigue life ( $N_f$ ) is defined as the number of cycles for tensile stress to drop 25% from its peak value [29].

## 3. Results

Fatigue life tested in primary coolant environment at different strain rate is shown in Fig. 3. Fatigue life increases from around 2000 to 6000 cycles as the strain rate increases from 0.004%/s to 1%/s; fatigue life decreases logarithmically as the strain rate decreases. In order to study the difference between fatigue behavior in air environment and primary



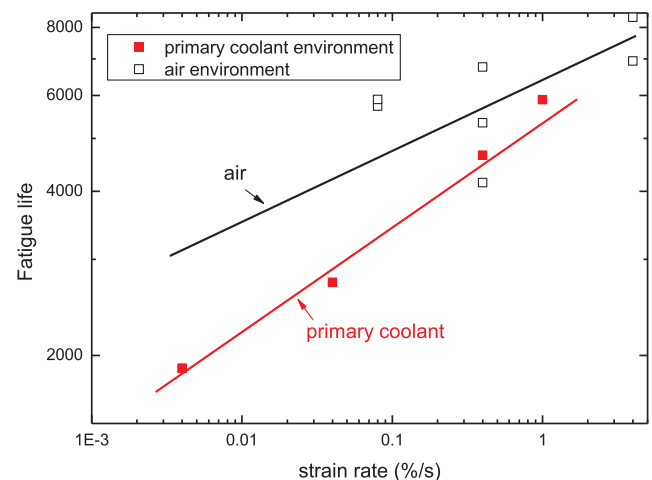
**Fig. 1.** Metallograph of domestic 316LN stainless steel.



**Fig. 2.** Sampling site of billet.

**Table 2**  
Primary coolant environment parameters of CAP1400.

Parameters	Primary coolant environment
Temperature	321 [ $^{\circ}\text{C}$ ]
Pressure	15.5 [MPa]
Dissolved oxygen	5–100 [ppb]
pH control agent	2.2 [ppm] LiOH + 1200 [ppm] $\text{H}_3\text{BO}_3$
Conductivity	20–35 [ $\mu\text{S}/\text{cm}$ ]
pH	6–7



**Fig. 3.** Effect of strain rate to fatigue life in primary coolant environment.

coolant environment, fatigue life in air environment [30] is presented in Fig. 3. It is seen that fatigue life of air environment is higher than that in primary coolant environment. The variation of fatigue life with strain in air environment is similar to that in primary coolant environment, except that the slope of trend line is much steeper in primary coolant, indicating the effect of strain rate is more pronounced in primary coolant. Furthermore, as the strain rate increases from 0.004%/s to 1%, the fatigue data in different environment is approaching to each other. After the strain increases to more than 0.4%/s, fatigue life in primary coolant environment approaches to that in air environment. This aforementioned behavior indicated that when the strain rate is high enough, fatigue life won't be reduced in primary coolant environment. The similar behavior is also found for other stainless steel, e.g., 304, 316NG [16,17]. Actually for a long lifetime operation of nuclear power

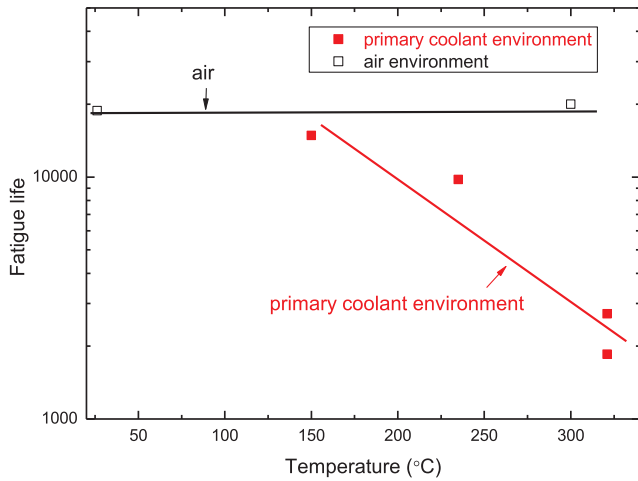


Fig. 4. Effect of temperature to fatigue life in primary coolant environment.

plant, the structures and components may be subjected to longer loading of cycles, i.e., longer than  $10^7$  cycles. In this sense, very high cycle fatigue is an important topic. However, the focus of this paper is on low and high cycle fatigue. The scenario considered are some big loadings and the loading frequency is quite low. In the next phase, the study will be moved to very high cycle fatigue with similar methods and considerations.

Effect of temperature on fatigue life in primary coolant environment is shown in Fig. 4. As the temperature increases from 150 °C to 150 °C, fatigue life of 316LN S.S is which tested at the strain amplitude of 0.4% decreases from around 15,000 to 2000 cycles. Fatigue life decreases linear as the temperature decreases from 321 °C to 150 °C. Fatigue life in air environment is also presented in this figure. It is seen that temperature doesn't display pronounced effect on fatigue life. As the temperature decreases from 321 °C to 150 °C, fatigue life is approaching to each other. After the temperature decreases to 150 °C, fatigue life of primary coolant environment is very close to that of air environment. The above behavior is similar to other stainless steel.

Effect of DO on fatigue life in primary coolant environment is shown in Fig. 5. The listed data includes fatigue life of 316LN tested in different DO and strain amplitude. The variation of fatigue life with DO and strain amplitude is also shown. It is seen that as DO increases from 0.005 ppm to 8 ppm, fatigue life of the specimens tested at the same strain amplitude does not change significantly. This indicates that the effect of DO on fatigue life of 316LN S.S is not obvious, which is in agreement with the behavior of other stainless steels [16,17]. This is

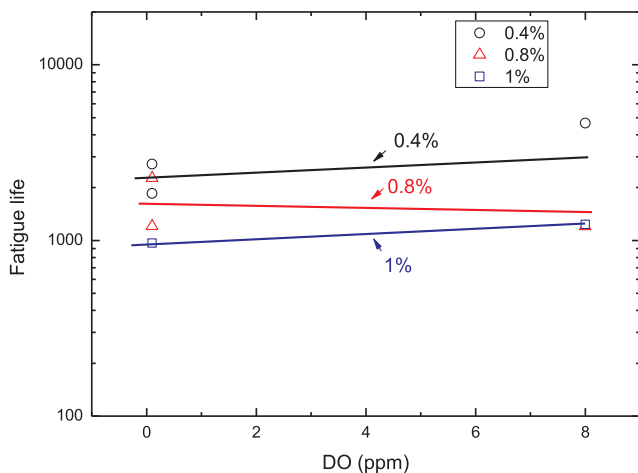


Fig. 5. Effect of DO to fatigue life in primary coolant environment.

because that for 316LN, the environmental assisted cracking mechanism in primary coolant environment is most likely to be hydrogen-induced cracking. This mechanism is not determined by the dissolved oxygen [16,17].

#### 4. Discussion

As mentioned above, effects of primary coolant environments on fatigue life is expressed in terms of environmental fatigue correction factor, i.e.,  $F_{en}$ , which is defined as the ratio of fatigue life in air at room temperature to that in primary coolant environment. Thus, in order to develop fatigue life model in primary coolant environment, both fatigue life models in air environment and  $F_{en}$  should be studied firstly.

##### 4.1. Fatigue life model in air environment

The commonly used fatigue life model is Mason-Coffin model according to the test standards. However, for the sake of engineering application, the Langer model is implemented in the NUREG6909 and JNES1005 as the fatigue life model. Therefore, the Langer model is also used in this paper to fit the fatigue life model of domestic 316LN steel in air environment. It is fitted according to the data in [27], as

$$\ln(N_f) = 6.91 - 2.26 \times \ln(\epsilon_a - 0.086) \quad (1)$$

where,  $N_f$  is fatigue life,  $\epsilon_a$  is strain amplitude.

Fig. 6 shows the fatigue data and life model of domestic 316LN tested in air environment. It is seen that the fatigue behavior of domestic 316LN is similar to that of reference, i.e., NUREG6909 and JNES1005.

Fig. 7 compares the model prediction data of domestic 316LN in air environment with the experimental data. A general agreement is found and the ratio of prediction data to the test data is within 3. The NUREG6909 model also demonstrates good agreement with the test data. Nevertheless, the prediction is not as accurate as the model of this paper.

##### 4.2. $F_{en}$ and fatigue model in primary coolant environment

Fatigue model in primary coolant environment is established based on  $F_{en}$  and fatigue property in air environment.  $F_{en}$  is usually proposed based on the effect of different important factors.

Substantial researches confirmed that [16,17] a lot of factors, i.e., strain rate, temperature, strain rate, DO, load waveform and rate of flow, etc., have important influence on  $F_{en}$ . Among these factors,

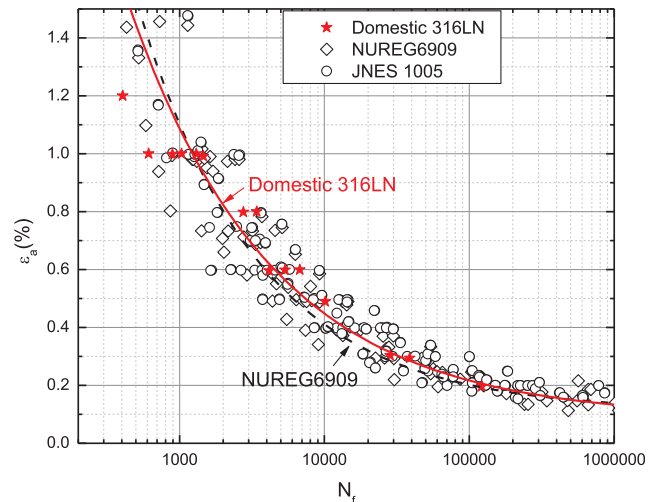


Fig. 6. Fatigue data and life model of domestic 316LN in air environment.

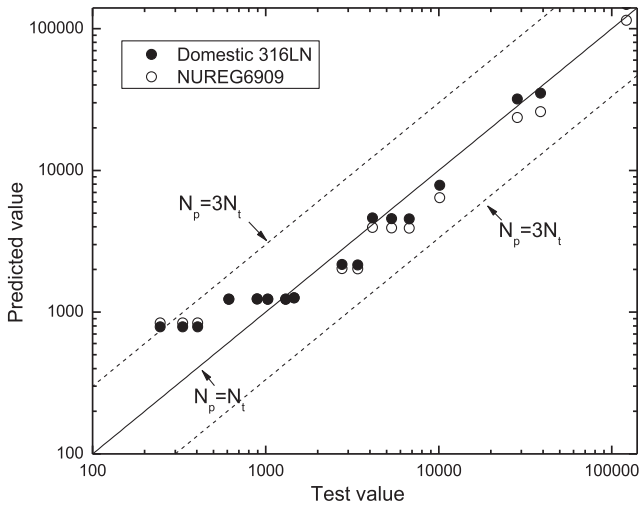


Fig. 7. Comparison of test data and model prediction data of domestic 316LN steel in air environment.

temperature, strain rate and DO are the critical ones that should be considered carefully. As the experiment results proved that DO may not affect the fatigue life of 316LN, only temperature and strain rate are considered in this paper. The focus of the paper is on the effect of strain rate, temperature and different environmental medias on fatigue life. The fatigue range is more on low and high cycle fatigue, where the stress range is relatively high. Crack initiation mainly started from the specimen surface due to surface cracks and persistent slip band. In environmental media, fatigue crack initiated under the synergistic effect of stress and hydrogen.

4.2.1. Effect of temperature

Effect of temperature on  $F_{en}$  of primary coolant pipe is shown in Fig. 8. In addition to the experiment data, the reference data with similar material parameter is also collected and is presented in this figure [16–18]. It can be seen that for the domestic 316LN, the logarithm of  $F_{en}$  decreased linear as the temperature decreased from 321 °C to 150 °C.  $F_{en}$  is constant as the temperature decreases to below 150 °C. The variation trend of domestic 316LN is similar to that of reference material. According to the experimental data and reference data, the relationship between temperature and  $F_{en}$  at the temperature range of 325 °C to 150 °C is fitted as

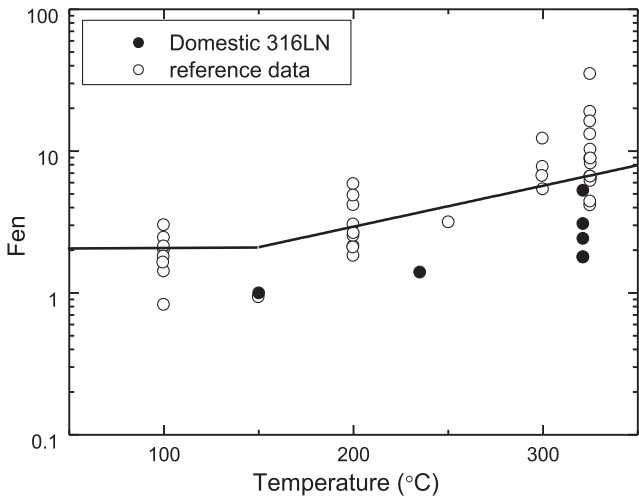


Fig. 8. Effect of temperature to  $F_{en}$  of primary coolant pipe in primary coolant environment.

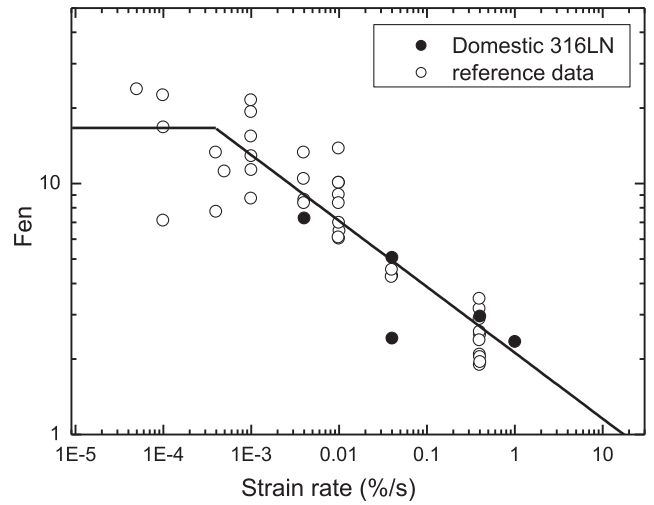


Fig. 9. Effect of strain rate to  $F_{en}$  of primary coolant pipe in primary coolant environment.

$$\ln(F_{en}) = 0.0066 \times T - 0.254 \quad (2)$$

where  $F_{en}$  is the environmental fatigue correct factor,  $T$  is the temperature in °C.

4.2.2. Effect of strain rate

Effect of strain rate on  $F_{en}$  of primary coolant pipe is shown in Fig. 9. The experimental data of domestic 316LN, together with the reference data which the test material and test parameter are similar to 316LN, are listed in the figure [16,31]. It is seen that in the strain rate range from 0.004%/s to 0.4%/s, the experimental data is in good agreement with the reference data.  $F_{en}$  decreases as strain rate decreases in the range from 0.0004%/s to 0.4%/s, and it keeps constant as the strain rate decreases to below 0.0004%/s.

As the test data and reference data illustrate similar property, effect of strain rate on  $F_{en}$  can be studied according to the data of both materials. The relationship between strain rate and  $F_{en}$  is fitted as

$$\ln(F_{en}) = 0.750 - 0.263 \times \ln(\dot{\epsilon}) \quad (3)$$

where  $\dot{\epsilon}$  is the strain rate in %/s, the strain rate is from 0.0004%/s to 0.4%/s.

4.2.3. Fatigue design curve considering effect of primary coolant environment

According to the discussion of research results [16], the  $F_{en}$  of domestic 316LN can be express as:

$$\ln(F_{en}) = A + B \times X_T \times X_\epsilon \quad (4)$$

where,  $A$  and  $B$  are coefficients that can be calculated out according to the test data,  $X_T$  and  $X_\epsilon$  are transformed temperature and strain rate, respectively, defined as

$$\begin{cases} X_T = 0 & (T \leq 150^\circ\text{C}) \\ X_T = (T - 150) & (T > 150^\circ\text{C}) \end{cases} \quad (5)$$

$$\begin{cases} X_\epsilon = 0 & (\dot{\epsilon} > 1\% \text{ s}^{-1}) \\ X_\epsilon = \ln(\dot{\epsilon}) & (0.001\% \text{ s}^{-1} \leq \dot{\epsilon} \leq 1\% \text{ s}^{-1}) \\ X_\epsilon = \ln(0.001) & (\dot{\epsilon} < 0.001\% \text{ s}^{-1}) \end{cases} \quad (6)$$

According to the test data,  $F_{en}$  of domestic 316LN is fitted as

$$\ln(F_{en}) = 0.498 - 0.203 \times X_T \times X_\epsilon \quad (7)$$

Further, by combining the fatigue life model in air environment and  $F_{en}$ , fatigue life of domestic 316LN in primary coolant environment is obtained as

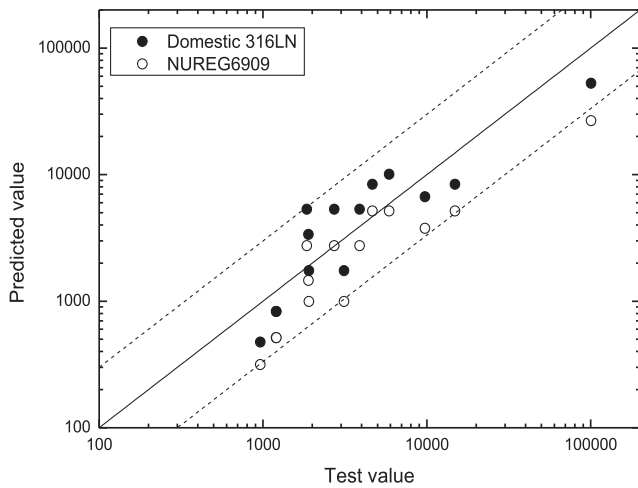


Fig. 10. Comparison of test data and model prediction data of domestic 316LN in primary coolant environment.

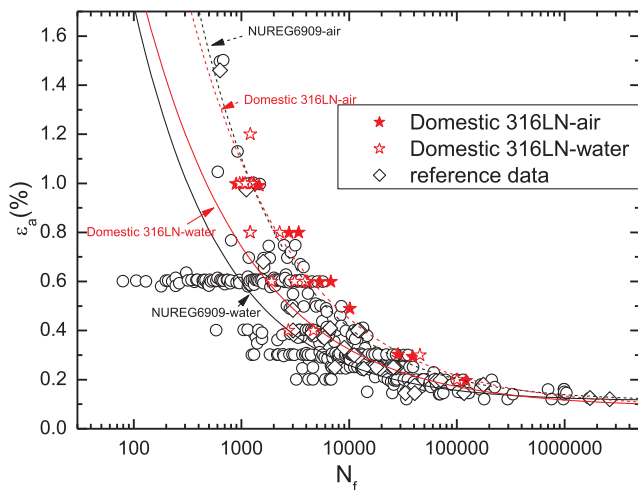


Fig. 11. Relationship of fatigue life and strain amplitude of domestic 316LN in different environment.

$$\ln(N_f) = 6.412 - 2.26 \times \ln(\varepsilon_a - 0.086) + 0.203 \times X_T \times X_\varepsilon \quad (8)$$

Fig. 10 shows the comparison of test data and model prediction data of domestic 316LN in primary coolant environment. It is seen that the model prediction shows good agreement with the test data. The ratio of prediction data to the test data is within 3. The prediction data by NUREG-6909 model are slightly lower than the model prediction in this paper, indicating that the predicted values of NUREG6909 model is not as accurate as the model developed in this paper.

The relationship between fatigue life and strain amplitude of primary coolant pipe in different environment is shown in Fig. 11. It is clear that all the test data fall within the range of reference data. The fatigue life of domestic 316LN in primary coolant environment is lower than that in air environment, which indicates pronounced EAC effect in primary coolant environment. Compared to NUREG6909 model, fatigue life prediction in this paper is slightly higher than that of NUREG6909 model. The model developed in this paper shows better agreement with the fatigue data of domestic 316LN, indicating that the presented model is more applicable for fatigue life prediction.

In order to characterize the dispersion, we need to perform a P-S-N analysis based on probabilistic analysis. The probabilistic fatigue study is an important aspect, especially for the engineering application of the experimental data. There are some fundamental models started from micro crack distributions. The existing models for the uncertainty

analysis are comprehensively reviewed by Qian and Lei [2]. For a solid of volume ( $V$ ) subjected to a cyclic load ( $S$ ) for a certain number of loading cycles ( $N$ ), its fatigue failure is a random event. This indicates that the cumulative probability ( $P$ ) for the occurrence of fatigue failure depends on the cyclic load ( $S$ ), number of loading cycles ( $N$ ), and specimen size ( $V$ ). This allows one to describe the cumulative probability ( $P$ ) of fatigue failure of a solid as a function of cyclic load ( $S$ ), number of loading cycles ( $N$ ) and the volume ( $V$ ) of solid as follows:  $P = F(S, N, V)$ .

On one hand, the experimental data tested in different environmental medias, different strain ratio and temperatures help to understand the fundamental effect on fatigue life. On the other hand, the experimental data can be used to perform lifetime prediction and extension for a nuclear power plant. Using the S-N curve, the lifetime can be predicted, which is a part of fatigue design curve. Furthermore, a probabilistic modelling of the S-N curve gives a confidence level of the lifetime prediction.

## 5. Conclusions

In this paper, fatigue property of domestic 316LN in primary coolant environment of NPP was investigated. Effect of temperature, strain rate and dissolved oxygen on fatigue life were studied. A fatigue life model was developed and compared with the NUREG6909 model. The following conclusions are drawn:

- 1) Fatigue life in primary coolant environment increases as the temperature decreases from 321 °C to 150 °C. After the temperature decreases to 150 °C, fatigue life in primary coolant environment is very close to that in air environment.
- 2) The logarithm of fatigue life increases with the decrease of strain rate, in the strain rate range of 0.0004%/s–0.4%/s. Effect of strain rate on fatigue life in primary coolant environment is similar to that in air environment. After the strain increases to more than 0.4%/s, the fatigue life in primary coolant environment is very close to that in air environment.
- 3) Effect of DO on fatigue life of 316LN S.S in primary coolant is not obvious in the range of DO from 0.005 ppm to 8 ppm.
- 4) The model presented in this paper is more accurate than the NUREG6909 model in fatigue life prediction of domestic 316LN.

## Acknowledgement

Financial support by National Natural Science Foundation of China (No. 11872364) and by CAS Pioneer Hundred Talents Program is acknowledged.

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