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A PROBABILISTIC ASSESSMENT ON THE RANDOM S-N RELATIONS AND THE ASME DESIGN S-N CURVES OF 0CR18NI10TI PIPING STEEL

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ABSTRACT

A probabilistic assessment is made on the random S-N relation and ASME design S-N curves for 0Cr18Ni10Ti pipe steel. The material exhibits a character of random cyclic stress-strain and fatigue life responses. Both the S and N in the virtual stress amplitude-fatigue crack initiation life (S-N) data are then random variables. A generalized maximum likelihood method, which considers the randomness of the entire test S-N data, is applied to model the probabilistic S-N relations of the material. The design S-N curves with reduction factors of 20 on cycles and 2 on stress applied to the best-fit S-N curve of the present test data as used in the ASME code are assessed in a probabilistic sense. The results reveal, different from the previous investigation on 1Cr18Ni9Ti weld metal, that the ASME design curves are totally more conservative. The 2 reduction factor curves may be appropriate to reflect the probabilistic trend, while the 20 reduction factor curve is not ruled on the probabilistic sense. The design S-N curves should be appropriately determined by the synthetic probabilistic model combined considerations of the survival probability and the single-regional confidence of the test data.

Keywords: 0Cr18Ni10Ti steel; pipe; design curves; probabilistic safety assessment.

1. INTRODUCTION

The design S-N curves of ASME Boiler and Pressure Vessel Code Section III (1992) were constructed based on strain-controlled tests of small polished specimens at room temperature in air. The best-fit curves to the experimental data were expressed in terms of the Langer equation of the form (Langer, 1962)

$$(S - S_o)^b N = D \tag{1}$$

where b, D and S_o are material constants of the model, S is termed the virtual stress amplitude which is the product of the test strain amplitude ε_a and the elastic modulus E, i.e. $S=E\varepsilon_a$, and N is fatigue crack initiation life. The design curves were obtained by decreasing the best-fit curves by a factor of 2 on stress or 20 on cycles, whichever was generally considered more conservative at each point on the best-fit curves. These factors were intended to account for the differences and uncertainties in relating the fatigue lives of laboratory test specimens to those of actual reactor components. The factor of 20 on cycles is the product of three separate sub-factors of 2 on the scatter of test data, 2.5 on the size effects, and 4 on the surface finish, atmosphere, etc. (US Department of Commerce, 1958).

Probabilistic analysis helps assess the significance of the current ASME code fatigue design curves. An interesting work (Chopra, 1998; Chopra and Shack, 1997, 1998; Heald and Kiss, 1974; Jaske, 2000; Keisler, Chopra and Shack, 1995, 1996) has been made previously by the database of pressure boundary materials incorporated considerations of the effects of the size, geometry, and surface finish of a component on its fatigue

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life. It was revealed that the design curves are not conservative frequently in production situations. Same observation was obtained by author to 1Cr18Ni9Ti weld metal (Zhao, 2003).

0Cr18Ni10Ti pipe was used for constructing the primary cooling system of pipelines of Chinese new reactors. To investigate the design safety, an experimental study was made of smooth specimens of the production pipe by a probabilistic means. Previous work (Zhao, Yang and Li, 2004a-b) has investigated the random cyclic stress-strain (σ - ε) and cyclic strain-life (ε -N) relations of this material. Present work makes a probabilistic assessment on the design S-N curves.

2. EXPERIMENTS

Materials and Specimens. 0Cr18Ni10Ti pipe steel, as shown as in figure 1, was studied. Chemical composition (wt%) of the material is given in Table 1. Residual is Fe. Major mechanical properties of this material are shown in Table 2. Average σ -εand ε -N relations of this material are given, respectively, as

$$\varepsilon_a = \frac{\sigma_a}{243448} + \left(\frac{\sigma_a - 154.16}{8151.69}\right)^{\frac{1}{0.624026}} \tag{2}$$

$$\varepsilon_a = \frac{2823}{243448}(2N)^{-0.2198} + 0.1922(2N)^{0.452781} \tag{3}$$

Fits to the test data are exhibited in figure 2. Their random models see Refs. (Zhao, Yang and Li, 2004a-b).

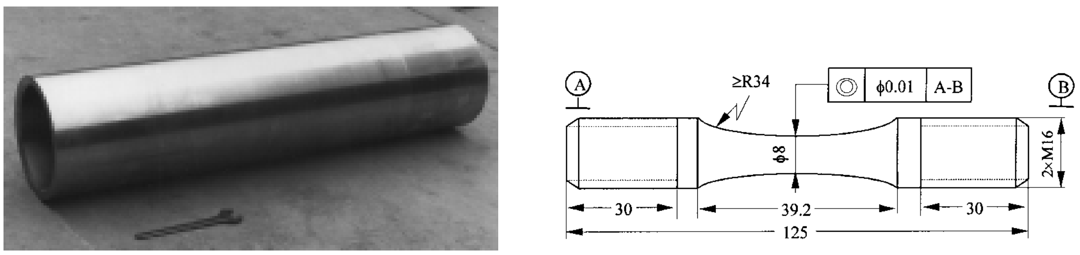
Smooth axial hourglass shaped specimens with 8 mm in diameter, as shown in Figure 1b, are used for this study. Before testing, the specimens were polished to a mirror finish with surface finish of 3-5 μm.

Table 1 Chemical composition of 0Cr18Ni10Ti steel

C	Si	Mn	Cr	Ni	Ti	Co	Nb+Ta	B
0.058	0.46	0.98	18.74	9.30	0.51	<0.07	<0.15	<0.0016
Cu	Sn	As	Sb	Pb	Ce	P	S	
0.14	<0.01	<0.01	<0.005	<0.001	0.003	<0.028	<0.009	

Table 2 Mechanical properties of the 0Cr18Ni10Ti steel

0.2% proof strength σ_s/MPa	Ultimate tensile strength σ_b/MPa	Elongation δ /%	Reduction of area ψ/%
243.28	521.03	72.41	76.17



(a) Production pipe (b) Schematic diagram of the specimens

Fig. 1 Production pipe and schematic diagram of the specimens (dimensions in mm).

Fatigue Tests and Results. Fatigue tests were performed on a MTS 809 servo-hydraulic machine at a room temperature in air under total strain-control. Asymmetrical push-pull triangular wave mode was applied in radial direction. Eight total strain amplitudes of (%) 0.10, 0.13, 0.18, 0.26, 0.36, 0.46, 0.60, and 0.76 were used. Seven specimens were at least tested at each total strain amplitude level, total 71 specimens were fatigued. A constant strain rate of 4×10^{-4} s^{-1} was employed.

Similar to the previous test observations to 1Cr18Ni9Ti weld metal (Zhao, 2003), a phenomenon of random cyclic stress-strain (CSS) responses was revealed in the present tests. A set of typical saturation hysteresis loops of the material is given in Figure 3. The difference between loops indicates that different stress, elastic- and plastic-strain amplitudes will be obtained even at a given strain load. The random CSS responses are then yielded. This difference should not be neglected in the nuclear engineering practice (Zhao, Gao and Wang, 2000; Zhao, Wang and Gao, 2000; Zhao, Yang and Li, 2004a-b), and the reliability analysis for this case is obviously different

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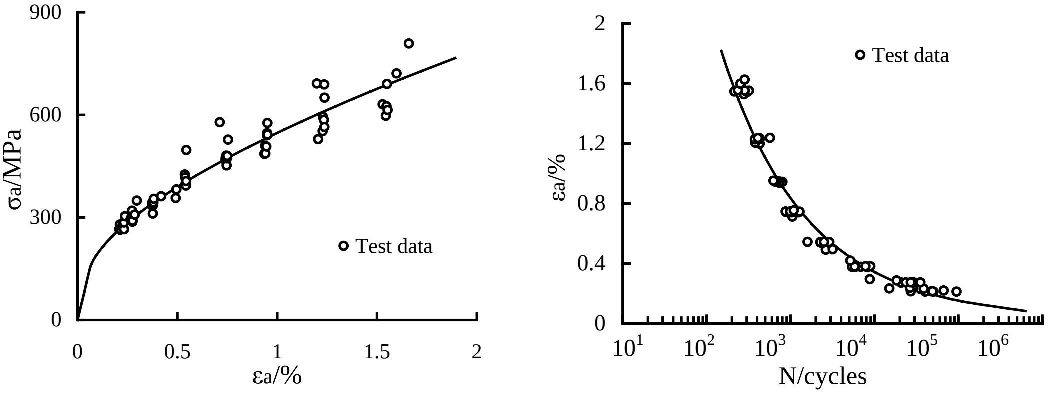
from that by the conventionally deterministic CSS treat (Bargmann, Rustenberg and Devlukia, 1994; Baldwin and Thacker, 1995; Wirsching, Torng and Martin, 1991; Zhao, 2000; Zhao, Tang and Wu, 1998).



(a) Average σ - ε relation (b) Average ε -N relation

Fig. 2 Average σ- ε and ε -N relations of the present material

After tests, the test radial ε -N data were converted into axial ε -N data by following equation

$$\varepsilon_a = (1-2\nu)\frac{\sigma_a}{E} + 2\varepsilon_{da} \tag{4}$$

where ν, σ_a, E, ε_{da}, and ε_a are Poisson ratio with an approximate value of 0.33, cyclic stress amplitude, Young's modulus, radial strain amplitude, and axial strain amplitude. And then, the axial ε -N data were converted into virtual stress amplitude-life (S-N) data by the Langer's definition $S=\varepsilon_a \cdot E$. Due to the random CSS responses, the resulting S and N data, as shown subsequently as in Figures 4~6, are random variables, different from the test data from commonly group stress-controlled and maximum likelihood fatigue tests (Ling and Pan, 1997; Zhao, Gao and Wang, 2001).

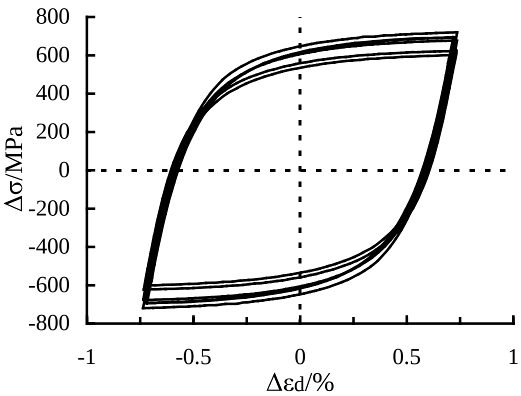


Fig. 3 Typical random CSS responses of 0Cr18Ni10Ti steel.

3. PROBABILISTIC S-N MODEL

Model. Both the S and N of the present S-N data are random variables. Therefore, the probabilistic S-N model should be different from the existent conventional and classical maximum likelihood models (Ling and Pan, 1997). A so-called "generalized maximum likelihood method" by Zhao, Gao and Wang (2001). is given to describe the probability S-N relations of the present test data:

Taking logarithm to the both sides of Equation (1) yields

$$\lg N = \lg D - b\lg(S - S_o) \tag{5}$$

Let

$$Y=\lg N,\ X=\lg(S-S_o),\ A=\lg D,\ B=-b \tag{6}$$

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from which a standard linearized equation can be obtained

$$Y=A+BX \tag{7}$$

Considering the dependency of the material constants and their randomness, general probabilistic S-N relations should be expressed

$$Y_P=A_P+B_PX_P \tag{8}$$

where P is survival probability and X_P=lg(S-S_{oP}). Assuming that the fatigue lives follow a lognormal distribution, the P-S-N relations should be reasonably approximated as the mean value- and standard deviation-S-N relations of the logarithm of fatigue life (lgN):

$$Y_m=A_m+B_mX_m \tag{9}$$

$$Y_s=A_s+B_sX_s \tag{10}$$

where subscripts m and s represent mean value and standard deviation of the parameters, respectively, and X_m=lg(S-S_{om}) and X_s=lg(S-S_{os}). When the mean value and standard deviation of the lgN at a given stress load are available, the statistical analysis can be conveniently made according the standard normal distribution function.

Measurement. Different from the existent conventional and classical maximum likelihood models, the material constants of the P-S-N relations should be measured by considering the randomness of the entire test S-N data.

The material constants in the mean value relation Equation (9), i.e. the best-fit curve to the experimental data, should be estimated by a least squares method:

For a set of S_i-N_i (where i=1, 2, ···, n) data, a set of X_i-Y_i data at a given S_{om} value can be obtained by the definitions of Equation (6). Using the equations

$$A_m = \overline{Y} - B_m\overline{X} \tag{11}$$

$$B_m = \frac{\sum_{i=1}^{n}\left(X_i - \overline{X}\right)\left(Y_i - \overline{Y}\right)}{\sum_{i=1}^{n}\left(X_i - \overline{X}\right)^2} \tag{12}$$

$$\overline{X} = \sum_{i=1}^{n}\frac{X_i}{n}, \ \overline{Y} = \sum_{i=1}^{n}\frac{Y_i}{n} \tag{13}$$

the constants A_m and B_m can be evaluated. It should be noted that the X_i is a function of the material constant S_{om}. To estimate A_m and B_m, S_{om} should be first estimated, i.e. an additional equation is needed. From the best fit to the experimental data, this additional equation should come from the maximization of the linear relationship coefficient r_{XY}

$$r_{XY} = \frac{n\sum_{i=1}^{n}X_iY_i - \sum_{i=1}^{n}X_i\sum_{i=1}^{n}Y_i}{\sqrt{\left[n\sum_{i=1}^{n}X_i^2 - \left(\sum_{i=1}^{n}X_i\right)^2\right]\left[n\sum_{i=1}^{n}Y_i^2 - \left(\sum_{i=1}^{n}Y_i\right)^2\right]}} \tag{14}$$

Setting an initial value of S_{om} (=0), a current value of the coefficient r_{XY} can be calculated. Then taking an increase of ΔS_{om} to construct a new value of S_{om}, the next value of the coefficient r_{XY} can be obtained. Repeating and repeating until to the current r_{XY} value is greater than the next value, the S_{om} value corresponding to the current r_{XY} value is the solution. After the S_{om} value is determined, the A_m and B_m can be obtained by the Equations (11)-(13).

The material constants in the standard deviation relation Equation (10) should estimated by a general maximum likelihood method:

For n pairs of ordered independent fatigue test (S_i, N_i) data (where i=1, 2, ···, n), a likelihood function can be established

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$$L=\prod_{i=1}^{n}\frac{1}{\sqrt{2\pi}Y_{si}}\exp\left[-\frac{1}{2}\left(\frac{Y_i-Y_{mi}}{Y_{si}}\right)^2\right] \tag{15}$$

Substituting Equations (9)-(10) into Equation (15) yields

$$L(A_s,B_s,S_{os})=\prod_{i=1}^{n}\frac{1}{\sqrt{2\pi}(A_s+B_sX_{si})}\exp\left[-\frac{1}{2}\left(\frac{Y_i-A_m-B_mX_{mi}}{A_s+B_sX_{si}}\right)^2\right] \tag{16}$$

where X_{mi}=lg(S_i-S_{om}), X_{si}=lg(S_i-S_{os}), and Y_i=lgN_i. The material constants A_s、 B_s and S_{os} should be estimated by a mathematical programming method.

According to Equation (6), letting Y_m=lgN_m, b_m=-B_m, $D_m=10^{A_m}$, Y_s=(lgN)$_s$=lgN_s^*, b_s=-B_s and $D_s=10^{A_s}$, the mean value and standard deviation relations can be expressed as, respectively

$$(S-S_{om})^{b_m}N_m=D_m \tag{17}$$

$$(S-S_{os})^{b_s}N_s^*=D_s \tag{18}$$

Inter-regional Confidence Bounds. Confidence bounds at a given significance level α for the linear fit of Equation (7) meet a probabilistic equation

$$P\{Y_m-\delta<Y<Y_m+\delta\}=1-\alpha \tag{19}$$

That is

$$Y_U=Y_m+\delta\,,\ Y_L=Y_m-\delta \tag{20}$$

where Y_U and Y_L are upper and lower bounds of the function Y, respectively, and δ is a statistical error function, which is defined as

$$\delta=t_{\alpha/2}(n-2)S_r\sqrt{1+\frac{1}{n}+\frac{(X-\overline{X})^2}{L_{xx}}} \tag{21}$$

$t_{\alpha/2}$(n-2) is t-distribution with degree-of-freedom of n-2 at significance level α/2, and S_r is residual standard deviation of the linear fit, which is defined as

$$S_r=\sqrt{\frac{1}{n-2}\frac{L_{xx}L_{yy}-L_{xy}^2}{L_{xx}}} \tag{22}$$

where $L_{xx}=\sum_{i=1}^{n}(X_i-\overline{X})^2$, $L_{yy}=\sum_{i=1}^{n}(Y_i-\overline{Y})^2$, and $L_{xy}=\sum_{i=1}^{n}(X_i-\overline{X})(Y_i-\overline{Y})$.

From Equation (21), there is a minimization of the statistical error of linear fit when the X is equal to $\overline{X}$. Large distance between the X and $\overline{X}$ yields a large statistical error. When n is large, the Equation (21) can be approximated by equation

$$\delta=t_{\alpha/2}(n-2)S_r\sqrt{1+1/n} \tag{23}$$

Therefore, the upper and lower bounds can be approximated by equations

$$Y_U=Y_m+t_{\alpha/2}(n-2)S_r\sqrt{1+1/n} \tag{24}$$

$$Y_L=Y_m-t_{\alpha/2}(n-2)S_r\sqrt{1+1/n} \tag{25}$$

Substituting Equation (9) into Equations (24)-(25), respectively, yields

$$Y_U=A_m+B_mX_m+t_{\alpha/2}(n-2)S_r\sqrt{1+1/n} \tag{26}$$

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$$Y_L = A_m + B_m X_m - t_{\alpha/2}(n-2)S_r\sqrt{1+1/n} \quad (27)$$

Letting Y_U=lgN_U, $D_U = 10^{\left(A_m + t_{\alpha/2}(n-2)S_r\sqrt{1+1/n}\right)}$, Y_L=lgN_L, and $D_L = 10^{\left(A_m - t_{\alpha/2}(n-2)S_r\sqrt{1+1/n}\right)}$, functions of the confidence bounds should be given as

$$(S - S_{om})^{b_m} N_U = D_U \quad (28)$$

$$(S - S_{om})^{b_m} N_L = D_L \quad (29)$$

Single-regional Confidence Bound. Single- regional confidence bound at a given significance level α for the linear fit of Equation (7) meet equation

$$P\{Y \geq Y_m - \delta_s\} = 1 - \alpha \quad (30)$$

That is

$$Y_{LL} = Y_m - \delta_s \quad (31)$$

where Y_{LL} is the lowest bound of the function Y and δ_s is a statistical error function, which is defined as

$$\delta = t_\alpha(n-2)S_r\sqrt{1+1/n} \quad (32)$$

$t_\alpha(n-2)$ is t-distribution with degree-of-freedom of n-2 at significance level α. Substituting Equation (9) into Equations (31) yields

$$Y_L = A_m + B_m X_m - t_\alpha(n-2)S_r\sqrt{1+1/n} \quad (33)$$

Letting Y_{LL}=lgN_{LL}, and $D_{LL} = 10^{\left(A_m - t_\alpha(n-2)S_r\sqrt{1+1/n}\right)}$, function of the confidence bound should be given as

$$(S - S_{om})^{b_m} N_{LL} = D_{LL} \quad (34)$$

Synthetic Model. Synthetic model incorporates together the survival probability P and single-side confidence C. It meets equation

$$P\{Y \geq Y_m - Z_P Y_s - \delta_s\} = 1 - \alpha \quad (35)$$

That is

$$\begin{aligned} Y_{P\text{-}C} &= Y_m - Z_P Y_s - \delta_s \\ &= A_m - Z_P A_s - t_\alpha(n-2)S_r\sqrt{1+1/n} + B_m \lg(S - S_{om}) - Z_P B_s \lg(S - S_{os}) \end{aligned} \quad (36)$$

where Z_P is survival probability index (percentage of the normal distribution at a probability level of P).

Using following equation to fit the S-N data calculated by the above equation

$$Y_{P\text{-}C} = A_{P\text{-}C} + B_{P\text{-}C} \lg(S - S_{oP\text{-}C}) \quad (37)$$

Letting $Y_{P\text{-}C}$=lg$N_{P\text{-}C}$, $D_{P\text{-}C} = 10^{A_{P\text{-}C}}$, and $b_{P\text{-}C}$, functions of the synthetic model should be given as

$$(S - S_{oP\text{-}C})^{b_{P\text{-}C}} N_{P\text{-}C} = D_{P\text{-}C} \quad (38)$$

Parameters and Fits. Basic parameters of the present test data for the present probabilistic model, A_m, B_m, S_{om}, A_s, B_s, S_{os}, n, and S_r are 9.375172, -2.0, 359.09, 0.619728, -0.159025, 5.6391, 71, and 0.109338, respectively.

The P-S-N relations of the present test data are

$$(S - 359.09)N = 3.237231 \times 10^{10} \quad (39)$$

$$(S - 5.639076)N_s^{*0.159025} = 4.16608 \quad (40)$$

Typical curves at the given reliability levels are shown in figure 4. The scattering regularity of the test data should be well characterized.

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The inter-regional confidence bounds at a significance level of 0.05 (confidence of 95%) of the present test data are

$$(S-359.10)^{1.9998} N_U = 0.392889 \times 10^{10} \tag{41}$$

$$(S-359.10)^{1.9998} N_L = 0.142877 \times 10^{10} \tag{42}$$

Figure 5 shows the character of the data fit. The random characteristics of test data have been well described by the model.

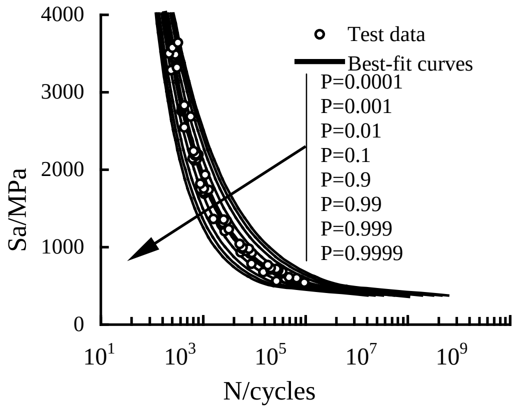

Fig. 4 Typical P-S-N curves of 0Cr18Ni10Ti steel

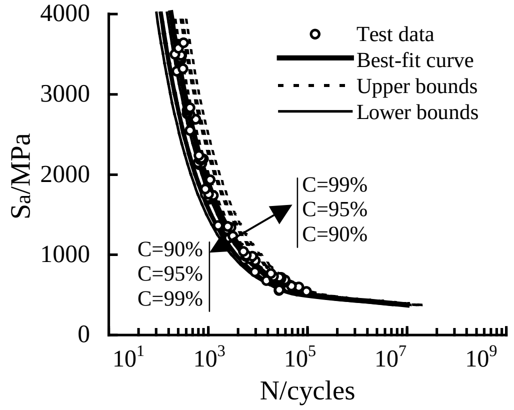

Fig.5 The typical inter-regional confidence bounds of 0Cr18Ni10Ti steel

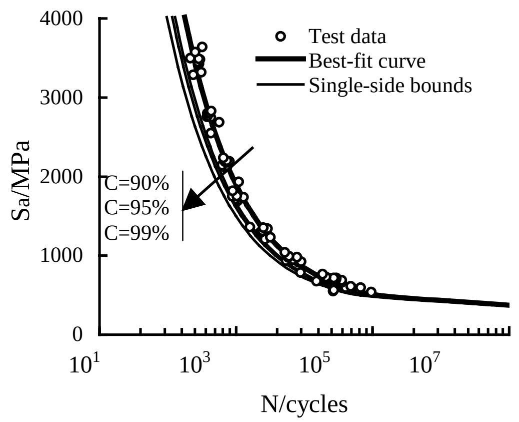

Fig.6 Typical single-regional confidence bounds of 0Cr18Ni10Ti steel

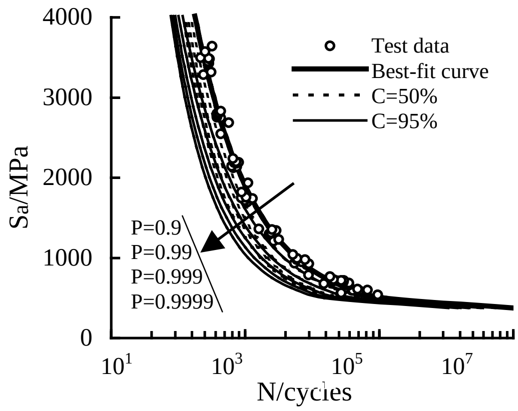

Fig. 7 Typical synthetic probabilistic curves of 0Cr18Ni10Ti steel

The single-regional confidence bound at a confidence of 95% of the present test data is

$$(S-359.10)^{1.9998} N_{LL} = 0.155255 \times 10^{10} \tag{43}$$

Fits of the bounds to the test data are given in figure 6. These bounds may be more suitable to practice than the above inter-regional bounds.

The synthetic probabilistic assessment of the present test data with P=0.99 and C=95% is

$$(S-363.89)^{1.726886} N_{P\text{-}C} = 0.125042 \times 10^{9} \tag{44}$$

Typical synthetic probabilistic curves of the present test data are exhibited in figure 7. Obviously, these curves are suitably applied in practice. Parameters of the typical synthetic probabilistic S-N curves of the present test data are given in Table 3.

Table 3 Typical parameters of the synthetic probabilistic S-N curves of the present test data

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C/%	P	b_{P-C}	D_{P-C}	S_o
50	0.5	1.9998	0.2369×10^{10}	359.10
	0.9	1.8491	0.5897×10^{9}	361.80
	0.99	1.7269	0.1908×10^{9}	363.89
	0.999	1.6387	0.8438×10^{8}	365.32
	0.9999	1.5662	0.4318×10^{8}	366.44
90	0.5	1.9998	0.1707×10^{10}	359.10
	0.9	1.8491	0.4247×10^{9}	361.80
	0.99	1.7269	0.1375×10^{9}	363.89
	0.999	1.6387	0.6078×10^{8}	365.32
	0.9999	1.5662	0.3110×10^{8}	366.44
95	0.5	1.9998	0.1553×10^{10}	359.10
	0.9	1.8491	0.3864×10^{9}	361.80
	0.99	1.7269	0.1250×10^{9}	363.89
	0.999	1.6387	0.5529×10^{8}	365.32
	0.9999	1.5662	0.2829×10^{8}	366.44
99	0.5	1.9998	0.1295×10^{10}	359.10
	0.9	1.8491	0.3224×10^{9}	361.80
	0.99	1.7269	0.1043×10^{9}	363.89
	0.999	1.6387	0.4613×10^{8}	365.32
	0.9999	1.5662	0.2361×10^{8}	366.44

4. PROBABILISTIC ASSESSMENT

From the best-fit curve, the design curve with a reduction factor (RF) of 2 on stress can be given as,

$$\left(2S - S_{om}\right)^{b_m} N = D_m \tag{45}$$

and the design curve with RF of 20 on cycles can be described by

$$\left(S - S_{om}\right)^{b_m} 20N = D_m \tag{46}$$

Figure 8 gives the ASME design curves with RFs of 2 on stress and 20 on cycles to the best-fit curve of the test data. It is known that

- In the higher S regime, a more conservative prediction is obtained by the design curve with 20 RF on cycles.
- In the lower S regime, the 2 RF curve on stress shows a more conservative prediction.

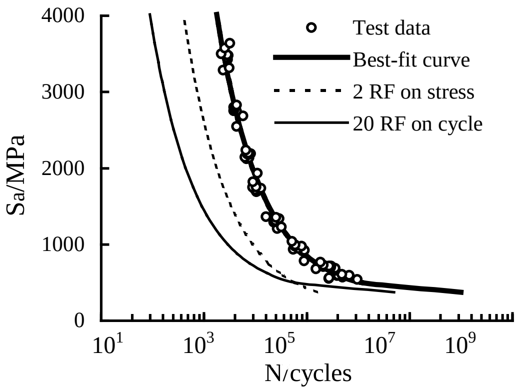

Fig. 8 ASME design curves with RFs of 2 on stress and 20 on cycles to the best-fit curve

Fig.8 shows the S-N curves with a 2 RF on stress. The S-N curve with a survival probability index of 13.27, which crosses the point B with (S, N) value of (374.49 MPa, 15606 cycles) of the 2 RF curve, is also given. The S-N curve, which crosses the point A with (S, N) value of (4016.17 MPa, 40.29 cycles) of the 2 RF curve, is known to have a survival probability index of 13.78. It is seen that:

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• Points A and B have closely survival probability indexes. This indicates that the 2 RF curve may appropriately reflect the probabilistic trend of the test data.

• The larger indexes indicate that the 2 RF curve is much conservative.

Figure 9 shows the S-N curve with 20 RF on cycles of the best-fit curve of the test data. The curve, which crosses the point B with (S, N) value of (374.49 MPa, 500000 cycles) of the 20 RF curve, has a survival probability index of 6.15. The curve, which crosses the point A with (S, N) value of (4016.17 MPa, 8.8690 cycles) of the 2 RF curve, has a survival probability index of 27.84. It can be seen that:

• There is a larger difference between the survival probability indexes of point A and point B. This indicates that the 20 RF curve can reflect the probabilistic regularity of the present S-N data.

• In the lower S regime, the curve with 20 RF on cycles may be appropriate non-conservative. But in the higher S regime, this curve is more conservative.

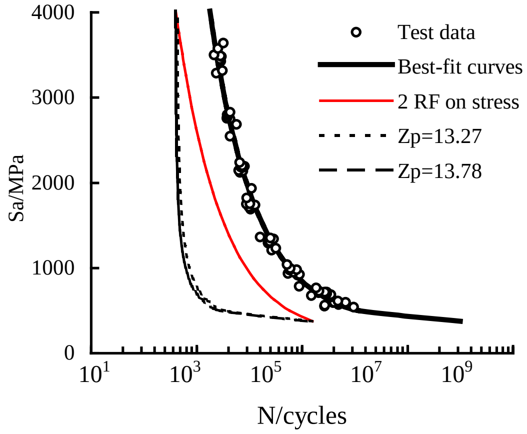

Fig. 8 S-N curves with a RF of 2 on stress to best-fit curve of the test data

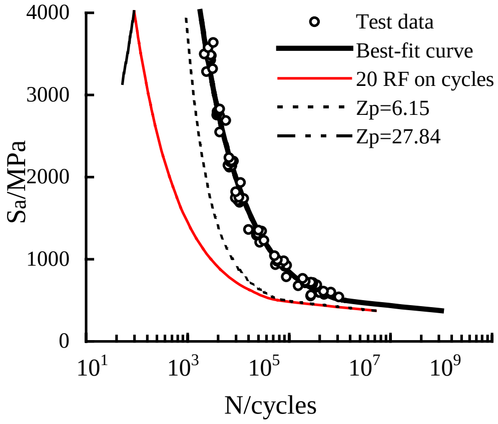

Fig. 9 S-N curves with a reduction factor of 2 on the stress to the best-fit curve of the test data

5. SUMMARY AND CONCLUSIONS

A probabilistic assessment is made of the random S-N relation and ASME design S-N curves for 0Cr18Ni10Ti piping steel. The material exhibits a character of random cyclic stress-strain and fatigue life responses. Then, both the S and N in the virtual stress amplitude-fatigue crack initiation life (S-N) data are random variables. A generalized maximum likelihood method, which considers the randomness of the entire test S-N data, is applied to model the probabilistic S-N relations of material. The design S-N curves with reduction factors of 20 on cycles and 2 on stress applied to the best-fit S-N curve of test data as used in the ASME code and general practice, are assessed in a probabilistic sense. The results reveal, different from the previous investigation on 1Cr18Ni9Ti weld metal,

• The ASME design curves are totally more conservative for the present material.

• The 2 reduction factor curves may be appropriate to reflect the probabilistic trend, while the 20 reduction factor curve is not ruled on a probabilistic sense.

• The design S-N curves should be appropriately determined by the synthetic probabilistic model combined considerations of the survival probability P and the single-regional confidence C of the test data.

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