Assessment of the Probability of Spherical Tanks

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ABSTRACT

Five current models based on Coffin–Manson rule were presented to predict the corrosion fatigue life in low cycle regime. Fatigue test data of seven engineering alloys in air and corrosive environments were fitted to these models. The fitting results, the accuracy of the models and the scope of their application were discussed.

KEYWORDS

Fatigue life; corrosive environment; model; fit.

INTRODUCTION

It is well known that a corrosive environment can seriously degrade the mechanical properties of many engineering alloys and decrease the fatigue life of many components and structures. It is an important problem for components and structures that are subject to high stresses or overloads and that operate in corrosive environments.

Several investigators have tested the fatigue behavior of various metals in corrosive environments (Bernstein et al., 1987a, Fujiwara et al., 1986, Lachmann et al., 1983, Miller, 1985). A major problem is how to model the corrosion fatigue behavior in order to correctly show the relationship between the corrosion fatigue life, strain range, cyclic frequency and cyclic waveform.

Five models have been proposed for predicting the crack initiation life in corrosive environments. They are:

- Strainrange Model (SR),
- Strainrange Frequency Model (SRF),
- Dual Strain Frequency Model (DSF),

- Strainrange Dual Frequency Model (SRDF),
- Strainrange Strainrate Model (SRSR).

The purpose of this paper is to represent the corrosion fatigue behavior by the above five models fitted to some test data for investigating the effect of the strain range, cyclic frequency, and strain rate on the corrosion fatigue life and the scope of the application of these models.

DESCRIPTION OF THE MODELS

Strainrange Model (SR)

SR Model is described by the Coffin–Manson relationship below (Lachmann et al, 1983):

$$N_f^{\alpha'} \Delta\varepsilon_t = C \qquad (1)$$

where N_f is the fatigue life or cycles to failure, $\Delta\varepsilon_t$ is the total strain range, α' and C are material constants. Inverting Eq.(1) gives another form of the fatigue life vs. the total strain range,

$$N_f = A(\Delta\varepsilon_t)^{\alpha} \qquad (2)$$

where A and α are material constants which are related to the constants in Eq.(1). ($A = C^{1/\alpha'}$, $\alpha = -1/\alpha'$)

Obviously, Eqs.(1) and (2) are implicit to the cyclic frequency where the frequency term does not appear, but the material constants A and α, indicating the dependent fatigue behavior in corrosive environments change with the cyclic frequency and a decrease in the cyclic frequency leads to a further decrease in the fatigue life.

Strainrange Frequency Model (SRF)

The effect of the cyclic frequency on the fatigue life can be modeled by modifying Eq.(2) in total strainrange by a frequency term, ν, (Bernstein et al, 1987b)

$$N_f = A(\Delta\varepsilon_t)^{\alpha}(\nu)^{\gamma} \qquad (3)$$

where A, α and γ are material constants. Eq.(3) shows that the fatigue life in corrosive environments is reduced with decreasing the cyclic frequency. The constant, γ, directly indicates the effect of the cyclic frequency on the corrosion fatigue life.

Dual Strain Frequency Model (DSF)

Bernstein and loeby (1987a) have given DSF Model in which the corrosion fatigue life is predicted by modifying the elastic and plastic strain ranges versus life equation with a cyclic frequency term,

$$\Delta\varepsilon_t = \Delta\varepsilon_e + \Delta\varepsilon_p = A(N_f)^{\alpha}(\nu)^{\gamma_e} + B(N_f)^{\beta}(\nu)^{\gamma_p} \qquad (4)$$

where $\Delta\varepsilon_t$, $\Delta\varepsilon_e$ and $\Delta\varepsilon_p$ are the total strainrange, elastic strainrange and plastic strainrange respectively, A, α, γ_e, B, β and γ_p are material constants.

Another form of DSF Model is proposed here, which is given by a dual strainamplitude term instead of the dual strainrange term. Based on an elastic and plastic strain amplitudes vs. life equation for predicting the fatigue life in air (Brose, 1977), the frequency dependence of the fatigue behavior in corrosive environments can be modeled for test data. For the elastic strain amplitude component,

$$\frac{\Delta\varepsilon_e}{2} = \frac{\sigma_f'}{E}(2N_f)^{b}(\nu)^{\gamma_e} \qquad (5)$$

where $2N_f$ is reversals to failure, σ_f' is the fatigue strength coefficient, b is the fatigue strength exponent, and γ_e is a material constant that is used to account for the effect of the cyclic frequency on the corrosion fatigue life at the elastic strain amplitude component. For the plastic strain amplitude component,

$$\frac{\Delta\varepsilon_p}{2} = \varepsilon_f'(2N_f)^{c}(\nu)^{\gamma_p} \qquad (6)$$

where ε_f' is the fatigue ductivity coefficient, c is the fatigue ductivity exponent, and γ_p is a material constant that is used for considering the effect of the cyclic frequency on the corrosion fatigue life at the plastic strain amplitude component. Substituting Eq.(5) and (6) into Eq.(7) gives an equation between the strain amplitudes and reversals to failure in terms of the fatigue properties in corrosive environments,

$$\frac{\Delta\varepsilon_t}{2} = \frac{\Delta\varepsilon_e}{2} + \frac{\Delta\varepsilon_p}{2} = \frac{\sigma_f'}{E}(2N_f)^{b}(\nu)^{\gamma_e} + \varepsilon_f'(2N_f)^{c}(\nu)^{\gamma_p} \qquad (7)$$

Eq.(7) and Eq.(4) are mathematically equivalent. In order to recognize them, Eq.(4) is called DSF-1 Model and Eq.(7) is called DSF-2 Model here. A mean stress correction to Eq.(7) and Eq.(4) is made as follows,

$$\frac{\Delta\varepsilon_t}{2} = \frac{\Delta\varepsilon_e}{2} + \frac{\Delta\varepsilon_p}{2} = \frac{\sigma_f' - \sigma_m}{E}(2N_f)^{b}(\nu)^{\gamma_e} + \varepsilon_f'(2N_f)^{c}(\nu)^{\gamma_p} \qquad (8)$$

and

$$\Delta\varepsilon_t = (A - 2^{\alpha+1}\frac{\sigma_m}{E})(N_f)^{\alpha}(\nu)^{\gamma_e} + B(N_f)^{\beta}(\nu)^{\gamma_p} \tag{9}$$

where σ_m is the mean stress. Eq.(8) is DSF-2 Model with the mean stress term, which is the common method for considering the effect of the mean stress on the corrosion fatigue life.

Strainrange Dual Frequency Model (SRDF)

When the tension-going frequency in a cycle is different from the compression-going frequency (defined as the reciprocal of the sum of the unloading time plus any compression hold time) and the compression-going frequency affects the life, it is necessary to modify the model by adding a term for the compression-going frequency or by separating the total frequency into the tension-going frequency and the compression-going frequency (Bernstein et al, 1987b),

$$N_f = A(\Delta\varepsilon_t)^{\alpha}(\nu_{ten})^{\gamma_t}(\nu_c)^{\gamma_c} \tag{10}$$

where ν_{ten} is the tension-going frequency, ν_c is the compression-going frequency and γ_t and γ_c are material constants which indicate the effect of the tension-going frequency and the compression-going frequency separately on the corrosion fatigue life.

Strainrange Strainrate Model (SRSR)

In some case, the following equation is used directly to indicate the effect of a strain rate on the fatigue life in corrosive environments,

$$N_f = A(\Delta\varepsilon_t)^{\alpha}(\dot{\varepsilon}_t)^{\gamma_r} \tag{11}$$

where $\dot{\varepsilon}_t$ is the strain rate and γ_r the material constant which indicates the effect of the strain rate on the corrosion fatigue life.

USE OF THE MODELS

Experimental data on seven materials tested in air and corrosive environments were gathered to apply the above five models (Bernstein et al, 1987a, Fujiwara et al, 1986, Lachmann et al, 1983, Miller, 1985). The data were fit to the models by simple or multiple regression to get the constants in each equation. The constants obtained for fitting the test data to the five models are given in Tables 1-5.

Table 1. Values of constants and accuracy in SR Model and SRF Model for three materials (2024-T4, 1045 steel and 304 stainless steel)

Environ.	Material	SR Model				SRF Model				
		A	α	R	L	A	α	γ	R	L
Air	2024	8078	−3.989	.997	1.06	−	−	−	−	−
	1045	7025	−2.096	.988	1.07	−	−	−	−	−
	304	6739	−2.483	.940	1.43	−	−	−	−	−
Salt water	2024	2304	−3.391	.903	1.45	2781	−2.876	.140	.995	1.09
	1045	2868	−1.656	.823	1.25	3976	−1.653	.121	.997	1.03
	304	4238	−3.181	.987	1.29	4145	−3.178	.002	.987	1.29

In order to analysis the accuracy of the above five models, a correlation coefficient, R, and a scatter band, L, were calculated for all the models in air and corrosive environments. The scatter band is defined as the data point having the largest ratio of predicted to observed life or the reciprocal of this ratio if the ratio is less than one (Bernstein, 1979),

$$L = \max\left\{N_p/N_f \text{ if } N_p > N_f,\ N_f/N_p \text{ if } N_p \le N_f\right\}$$

where N_p is the predicted life and N_f is the observed life. The values of the correlations and scatter bands obtained for the five models are also given in Tables 1-5.

Table 2. Values of constants and accuracy in DSF Model for 2024-T4, 1045 steel and 304 stainless steel

Environ.	Material	DSF Model							
		A	α	γ_e	B	β	γ_p	R	L
Air	2024	1.940	−.064	−	13177	−1.496	−	.997	1.07
	1045	1.654	−.158	−	141.2	−0.615	−	.988	1.07
	304	1.069	−.116	−	42.97	−0.476	−	.943	1.05
Salt water	2024	2.607	−.112	.032	3554	−1.404	0.128	.994	1.05
	1045	1.364	−.138	.022	481.7	−0.825	0.097	.997	1.04
	304	1.197	−.138	.008	15.89	−0.388	−.006	.986	1.31

Table 3. Values of constants and accuracy in SR Model for four materials

Material		304 s.s., sensitized		AH36-GL		13CrMo44 (base metal)		13CrMo44 (welded joint)	
Environment		Air	High D.O. water	Air	Salt water	Air	Salt water	Air	Salt water
SR Model	A	6648	551	9436	940	6143	3119	3450	1702
	α	-3.333	-2.834	-2.544	-1.630	-2.273	-2.326	-2.054	-2.079
	R	0.984	0.889	0.999	0.950	0.998	0.995	1.000	0.980
	L	1.27	3.29	1.10	1.43	1.14	1.22	1.000	1.36

Table 4. Values of constants and accuracy in SRF and SRDF models for 304 s.s., sensitized

Environ.	SRF Model					SRDF Model					
	A	α	γ	R	L	A	α	γ_{ten}	γ_c	R	L
high D.O. water	6231	-1.783	.503	.991	1.50	3881	-1.86	.356	.141	.996	1.25

Table 5. Values of constants and accuracy in SRF and SRSR Models for three materials

Environ.	Material	SRF Model					SRSR Model				
		A	α	γ	R	L	A	α	γ_r	R	L
Salt water	AH36-GL	1667	-1.271	.239	.998	1.14	1413	-1.510	.239	.998	1.14
	13CrMo44 (base metal)	3791	-2.249	.077	.998	1.19	3594	-2.326	.077	.998	1.19
	13CrMo44 (welded joint)	2754	-1.889	.190	.999	1.11	2415	-2.079	.190	.999	1.11

The tests were predicted by usinig SR Model in air and corrosive environments respectively for above seven materials. The results indicated that the correlation coefficients for air (R = 0.940 - 1.000) were greater those for corrosive environments (R = 0.823 - 0.995) and the scatter bands for air (L = 1.43 - 1.06) were less than those for corrosive environments (L = 3.29 - 1.22) (see Table 1 and 3). This showed that SR Model was an excellent fit to the test data for air but needed further improvement for corrosive environments.

The tests were predicted by using SR Model and SRF Model in corrosive environments for the seven materials. The results indicated that the correlation coefficients for SRF Model (R = 0.988 - 0.997) were greater those for SR Model (R = 0.823 -0.995) and the scatter bands for SRF Model (L = 1.50 - 1.03) were less than those for SR Model (L = 3.29 -1.22) (see Tables 1, 3-5). This showed that SRF Model which has improved SR Model by adding the frequency term was a good fit to the test data for corrosive environments.

The tests were predicted by using SRF Model and DSF Model for 2024-T4, 1045 steel and 304 stainless steel in corrosive environments. the correlation coefficients and the corresponding scatter bands for SRF Model were very close to those for DSF Model for these three materials respectively (see Table 1 and 2). This showed that both of DSF Model and SRF Model had quite high accuracy for the low cycle corrosion fatigue. However, DSF Model is mechanically more reasonable than SRF Model in that it has improved SRF Model by using the elastic strain range term and the plastic strain range term instead of the total strain range term and it is easy for it to be modified to account for the effect of the mean stress on the corrosion fatigue life under a complex loading.

The tests were predicted by using SRF Model and SRDF Model for 304 Sensitized stainless steel in corrosive environments. The results indicated that the correlation coefficient for SRDF Model (R = 0.996) was greater than that for SRF Model (R = 0.991) and the scatter band for SRDF Model (L = 1.25) was less than that for SRF Model (L = 1.50) (see Table 4). This showed that SRDF Model which has improved SRF Model by using the tension-going frequency term and the compression-going frequency term instead of the total frequency term was an excellent fit under the condition tested.

The tests were predicted by using SRF Model and SRSR Model for AH36-GL, 13CrMo44 (base metal and 13CrMo44 (welded joint). The results indicated that the constant, γ, of SRF Model was the same as that, γ_r, of SRSR Model for the three materials respectively (see Table 5). In fact, for the triangular waveform, there is a relationship between the total frequency, ν, and the strain rate, $\dot{\varepsilon}_t$, (Conway et al, 1975)

$$\dot{\varepsilon}_t = 2\nu\Delta\varepsilon_t \tag{12}$$

CONCLUSION

For the conditions examined,

The Strainrange Frequency Model (SRF) which has improved Strainrange Model (SR) by adding the frequency term was the good fit to the test data in corrosive environments.

The Dual Strain Frequency Model (DSF) in which the fatigue life is predicted by modifying the elastic strain range and plastic strain range vs. life equation by a cyclic frequency term was the excellent fit to predict the corrosion fatigue life in the low cycle regime when the elastic strain range and the plastic strain range in the test were known.

The Strainrange Dual Frequency Model (SRDF) which has improved SRF Model by using the tension-going frequency term and the compression-going frequency term instead of the total frequency term was the excellent fit when the test indicated that the tension-going frequency in a cycle was different from the compression-going frequency and the compression-going frequency affected the fatigue life in corrosive environments.

The DSF-1 Model and DSF-2 Model are mathematically equivalent and Eq.(8) is the common method for considering the effect of the mean stress on the corrosion fatigue life.

There was the certain relationship between the Strainrange Strainrate Model (SRSR) and SRF Model.

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