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ABSTRACT

This paper summarizes the work performed at Argonne National Laboratory on the fatigue of piping and pressure vessel steels in the coolant environments of light water reactors. The existing fatigue strain vs. life (ε–N) data were evaluated to establish the effects of various material and loading variables, such as steel type, strain range, strain rate, temperature, and dissolved–oxygen level in water, on the fatigue lives of these steels. Statistical models are presented for estimating the fatigue ε–N curves for carbon and low–alloy steels and austenitic stainless steels as a function of material, loading, and environmental variables. Case studies of fatigue failures in nuclear power plants are presented, and the contribution of environmental effects to crack initiation is discussed. Methods for incorporating environmental effects into the ASME Code fatigue evaluations are discussed. Data available in the literature have been reviewed to evaluate the possible conservatism in the existing fatigue design curves of the ASME Code.

INTRODUCTION

The ASME Boiler and Pressure Vessel Code provides rules for the construction of components in nuclear power plants. Appendix I to Section III of the Code specifies fatigue design curves for structural materials. However, the effects of light water reactor (LWR) coolant environments are not explicitly addressed by the Code design curves. Existing fatigue strain–vs.–life (ε–N) data illustrate potentially significant effects of LWR coolant environments on the fatigue resistance of carbon and low–alloy steels,[1–14] as well as austenitic stainless steels (SSs).[13–23] The key parameters that influence fatigue life in these environments are temperature; dissolved–oxygen (DO) level in water; strain rate; strain (or stress) amplitude; and, for carbon and low–alloy steels, S content in the steel. Under certain environmental and loading conditions, fatigue lives of carbon and low–alloy steels can be a factor of 70 lower in the coolant environment than in air.[2,11] Therefore, the margins in the ASME Code may be less conservative than originally intended.

Two approaches have been proposed for incorporating the environmental effects into ASME Section III fatigue evaluations for primary pressure boundary components in operating nuclear power plants: (a) develop new fatigue design curves for LWR applications or (b) use an environmental correction factor to account for the effects of the coolant environment. In the first approach, the best–fit curves to the experimental fatigue ε–N data in LWR environments are used to obtain both the design curves and the environmental correction factor. Environmentally adjusted fatigue design curves have been developed from fits to the experimental data in LWR environments; the same approach was followed as that used to develop the current fatigue design curves of the ASME Code. Interim fatigue design curves that address environmental effects on the fatigue life of carbon and low–alloy steels and austenitic SSs were first proposed by Majumdar et al.[24] Fatigue design curves based on a more rigorous statistical analysis of the experimental data were developed by Keisler et al.[25] These design curves have subsequently been updated on the basis of updated statistical models.[11,14,22]

The second approach, proposed by Higuchi and Iida,[2] considers the effects of reactor coolant environments on fatigue life in terms of an environmental correction factor F_{en}, which is the ratio of fatigue life in air at room temperature to that in water under reactor operating conditions. To incorporate environmental effects into the ASME Code fatigue evaluations, the fatigue usage factor for a specific load set, based on the current Code design curves, is multiplied by the correction factor. Specific expressions for F_{en}, based on statistical models[11,14,22] and on the correlations developed by the Environmental Fatigue Data Committee of the Thermal and Nuclear Power Engineering Society of Japan,[8] have been proposed.

This paper presents a critical assessment of three key components of the proposed methods: (a) the experimental data used to develop the method, (b) the applicability of the data to actual plant operating conditions, and (c) the possible conservatisms/nonconservatisms in the procedure.

FATIGUE ε–N DATA IN LWR ENVIRONMENTS

The existing fatigue ε–N data developed at various establishments and research laboratories worldwide are consistent with each other, and are also consistent with the large database for fatigue crack growth rates (CGRs) obtained on fracture mechanics specimens. In LWR environments, data on both fatigue crack initiation and fatigue crack growth show similar trends. For example, the effects of loading and environmental parameters such as strain rate, DO level in water, or S content in carbon and low–alloy steels are similar for fatigue crack initiation and fatigue crack growth.

Fatigue crack initiation has been divided into two stages: an initiation stage that involves the growth of microstructurally small cracks (i.e., cracks smaller than ≈200 µm), and a propagation stage that involves the growth of mechanically small cracks.[12,14,26,27] It appears that the decreases in the fatigue lives of both carbon and low–alloy steels and austenitic SSs in LWR environments are caused primarily by the effects of the environment on the growth of microstructurally small cracks and, to a lesser extent, on enhanced growth rates of mechanically small cracks.[14,26,27] In LWR environments, the growth of small cracks in carbon and low–alloy steels occurs by a slip oxidation/dissolution process, and in austenitic SSs, most likely, by mechanisms such as hydrogen–enhanced crack growth. A fracture mechanics approach and CGR data have been used to predict the fatigue crack initiation in carbon and low-alloy steels in air and LWR environments.[14]

Carbon and Low–Alloy Steels

The fatigue lives of carbon and low–alloy steels are reduced in LWR environments. Although the microstructures and cyclic–hardening behavior of carbon steels and low–alloy steels differ significantly, the effects of the environment on the fatigue life of these steels are very similar. The magnitude of the reduction depends on temperature, strain rate, DO level in water, and S content of the steel. The decrease is significant only when four conditions are satisfied simultaneously, viz., when the strain amplitude, temperature, and DO in water are above certain threshold values, and the strain rate is below a threshold value. For both steels, only a moderate decrease in life (by a factor of <2) is observed when any one of the threshold conditions is not satisfied. The S content in the steel is also important; its effect on life appears to depend on the DO level in water. The threshold values and the effects of the critical parameters on fatigue life are summarized below.

Strain Rate: When all other threshold conditions are satisfied, fatigue life decreases logarithmically with decreasing strain rate below 1%/s;[2,4,6] the effect of environment on life saturates at ≈0.001%/s.[10–14] When any one of the threshold conditions is not satisfied, the effects of strain rate are consistent with those observed in air, i.e., heats that are sensitive to strain rate in air show a decrease in life in water, although the decreases are much smaller than those observed when the threshold conditions are met.

Strain: A minimum threshold strain is required for environmentally assisted decrease in the fatigue lives of carbon and low–alloy steels.[10–14] Limited data suggest that the threshold value is ≈20% higher than the fatigue limit for the steel. Even within a given loading cycle, environmental effects are significant primarily during the tensile–loading cycle and at strain levels greater than the threshold value. This can be important if the strain rate varies over the loading cycle. Thus, for example, low strain rates at strains lower than the threshold strain and high strain rates for those portions of the cycle at strains greater than the threshold strain would not lead to significant reductions in life. Consequently, it is the loading and environmental conditions, e.g., strain rate, temperature, and DO level, during the tensile–loading cycle that are important for estimating environmental effects. Limited data indicate that hold periods during peak tensile or compressive strain have no effect on the fatigue life of these steels.[11]

Temperature: When other threshold conditions are satisfied, fatigue life decreases linearly with temperature above 150°C and up to 320°C.[2,4,6] Fatigue life is insensitive to temperatures below 150°C or higher temperatures when any other threshold condition is not satisfied.

Dissolved Oxygen in Water: When the other threshold conditions are satisfied, fatigue life decreases logarithmically with DO above 0.04 ppm; the effect saturates at ≈0.5 ppm DO.[4,6] Only a moderate decrease in life, i.e., less than a factor of 2, is observed at DO levels below 0.04 ppm. In contrast, environmental enhancement of CGRs has been observed in low–alloy steels even in low–DO environments.[28] This apparent inconsistency with the CGR data may be attributed to differences in the environment at the crack tip. The initiation of environmentally assisted enhancement of CGRs in low–alloy steels requires a critical level of sulfides at the crack tip.[28] The development of this critical sulfide concentration requires a minimum crack extension of 0.33 mm and CGRs of 1.3×10^{-4} – 4.2×10^{-7} mm/s. These conditions not being achieved under typical ε-N tests is consistent with the absence of significant environmental effects on fatigue life in low–DO environments.

Sulfur Content of Steel: The effect of S content on fatigue life appears to depend on the DO content of the water. When the threshold conditions are satisfied, the fatigue life decreases with increasing S content for DO ≤1.0 ppm. Limited data suggest that environmental effects on life saturate at an S content of ≈0.015 wt.%.[11] For DO >1.0 ppm, fatigue life seems to be relatively insensitive to S content in the range of 0.002–0.015 wt.%.[8]

Flow Rate: The data for carbon steels indicate that, under the environmental conditions typical of operating boiling water reactors (BWRs), environmental effects on the fatigue life of carbon steels are a factor of ≈2 lower at high flow rates (7 m/s) than at 0.3 m/s or lower.[29,30]

Austenitic Stainless Steels

The fatigue lives of austenitic SSs are also decreased in LWR environments. The magnitude of the reduction in life depends on strain amplitude, strain rate, temperature, DO level in the water, and possibly the composition and heat treatment of the steel.[13–23] The effects of LWR environments on fatigue lives of wrought materials are comparable for Types 304, 316, and 316NG SSs; effects on cast materials differ somewhat. As in the case of the carbon and low–alloy steels, significant reductions in fatigue life are observed only when certain critical parameters meet certain threshold values. The critical parameters that influence fatigue life and the threshold values that are required for environmental effects to be significant are summarized below.

Strain Rate: Fatigue life decreases with decreasing strain rate. In low–DO pressurized water reactor (PWR) environments, fatigue life decreases logarithmically with decreasing strain rate below ≈0.4%/s; the effect of environment on life saturates at ≈0.0004%/s.[14–22] Only a moderate decrease in life is observed at strain rates >0.4%/s. A decrease in strain rate from 0.4 to 0.0004%/s decreases the fatigue life of austenitic SSs by a factor of ≈10. For some SSs, the effect of strain rate may be less pronounced in high– than in low–DO water. For cast SSs, the effect of strain rate on fatigue life is the same in low– and high–DO water and is comparable to that observed for the wrought SSs in low–DO water.[17,18]

Strain Amplitude: As in the case of the carbon and low–alloy steels, a minimum threshold strain is required for the environmentally induced decrease in fatigue lives of SS. Even within a given loading cycle, environmental effects are significant primarily during the tensile–loading cycle, and at strain levels greater than the threshold value. The threshold strain appears to be independent of material type (weld or base metal) and temperature in the range of 250–325°C, but it tends to decrease as the strain amplitude of the cycle is decreased.[19] The threshold strain appears to be related to the elastic strain range of the material[19] and does not correspond to the rupture strain of the surface oxide film.

Dissolved Oxygen in Water: In contrast to the behavior of carbon and low alloy steels, the fatigue lives of austenitic SSs are decreased significantly in low–DO (i.e., <0.01 ppm DO) water. The decrease in life is greater at low strain rates and high temperatures.[14–22] Environmental effects on the fatigue lives of these steels in high–DO water are either comparable to[17,18] or, in some cases, smaller[22] than those in low–DO water. A moderate decrease in life (less than a factor of 2) was observed for a heat of Type 304 SS when the conductivity of the water was maintained at <0.1 µS/cm and the electrochemical potential (ECP) of the steel was above 150 mV.[14] The composition or heat treatment of the steel may have an important impact on the magnitude of the effect in high–DO water.[23] In low–DO water, the fatigue lives of cast SSs are comparable to those for wrought SSs.[17–22] Limited data suggest that the fatigue lives of cast SSs in high–DO water are approximately the same as those in low–DO water.[22]

Temperature: The data suggest a lower threshold temperature of 150°C. Above this temperature the environment decreases fatigue life in low–DO water if the strain rate is below the threshold of 0.4%/s.[8,16] In the range of 150–325°C, the logarithm of fatigue life decreases linearly with temperature.

Sensitization Anneal: In low–DO water, a sensitization anneal has no effect on the fatigue life of Types 304 and 316 SS, whereas, in high–DO water, environmental effects are enhanced in sensitized steels. For example, the fatigue life of sensitized steel is a factor of ≈2 lower than that of solution–annealed material in high–DO water.[17,18] Sensitization has little or no effect on the fatigue life of Type 316NG SS in low– and high–DO water.

Flow Rate: The effects of flow rate on the fatigue life of austenitic SSs have not been investigated. Because the mechanism of fatigue crack initiation in LWR environments appears to be different in SSs than in carbon steels, the effect of flow rate may also be different.

STATISTICAL MODELS

Statistical models based on the existing fatigue ε–N data have been developed for estimating the fatigue lives of carbon and low–alloy steels and wrought and cast austenitic SSs in air and LWR environments.[11,14,22,23] In room–temperature air, the fatigue life N of carbon steels is represented by

$$\ln(N) = 6.564 - 1.975 \ln(\varepsilon_a - 0.113) \qquad (1)$$

and that of low–alloy steels by

$$\ln(N) = 6.627 - 1.808 \ln(\varepsilon_a - 0.151), \qquad (2)$$

where ε_a is applied strain amplitude (%). In LWR environments, the fatigue life of carbon steels is represented by

$$\ln(N) = 6.010 - 1.975 \ln(\varepsilon_a - 0.113) + 0.101\, S^* T^* O^* \dot{\varepsilon}^* \qquad (3)$$

and that of low–alloy steels, by

$$\ln(N) = 5.729 - 1.808 \ln(\varepsilon_a - 0.151) + 0.101\, S^* T^* O^* \dot{\varepsilon}^*, \qquad (4)$$

where S^*, T^*, O^*, and $\dot{\varepsilon}^*$ are transformed S content, temperature, DO, and strain rate, respectively, defined as follows:

$$\begin{aligned} S^* &= 0.015 && (\text{DO} > 1.0 \text{ ppm}) \\ S^* &= S && (\text{DO} \le 1.0 \text{ ppm and } S \le 0.015 \text{ wt.\%}) \\ S^* &= 0.015 && (\text{DO} \le 1.0 \text{ ppm and } S > 0.015 \text{ wt.\%}) \end{aligned} \qquad (5)$$

$$T^* = 0 \quad (T < 150°C)$$
$$T^* = T - 150 \quad (T = 150\text{–}350°C) \qquad (6)$$

$$O^* = 0 \quad (DO \le 0.04\ ppm)$$
$$O^* = \ln(DO/0.04) \quad (0.04\ ppm < DO \le 0.5\ ppm)$$
$$O^* = \ln(12.5) \quad (DO > 0.5\ ppm) \qquad (7)$$

$$\dot{\varepsilon}^* = 0 \quad (\dot{\varepsilon} > 1\%/s)$$
$$\dot{\varepsilon}^* = \ln(\dot{\varepsilon}) \quad (0.001 \le \dot{\varepsilon} \le 1\%/s)$$
$$\dot{\varepsilon}^* = \ln(0.001) \quad (\dot{\varepsilon} < 0.001\%/s). \qquad (8)$$

In air at temperatures up to 400°C, the fatigue data for Types 304 and 316 SS are best represented by

$$\ln(N) = 6.703 - 2.030 \ln(\varepsilon_a - 0.126) \qquad (9)$$

and those for Type 316NG, by

$$\ln(N) = 7.433 - 1.782 \ln(\varepsilon_a - 0.126). \qquad (10)$$

The results indicate that, in LWR environments, the fatigue data for Types 304 and 316 SS are best represented by

$$\ln(N) = 5.768 - 2.030 \ln(\varepsilon_a - 0.126) + T' \dot{\varepsilon}' O' \qquad (11)$$

and those of Type 316NG, by

$$\ln(N) = 6.913 - 1.671 \ln(\varepsilon_a - 0.126) + T' \dot{\varepsilon}' O', \qquad (12)$$

where T', $\dot{\varepsilon}'$, and O' are transformed temperature, strain rate, and DO, respectively, defined as follows:

$$T' = 0 \quad (T < 150°C)$$
$$T' = (T - 150)/175 \quad (150 \le T < 325°C)$$
$$T' = 1 \quad (T \ge 325°C) \qquad (13)$$

$$\dot{\varepsilon} = 0 \quad (\dot{\varepsilon} > 0.4\%/s)$$
$$\dot{\varepsilon} = \ln(\dot{\varepsilon}/0.4) \quad (0.0004 \le \dot{\varepsilon} \le 0.4\%/s)$$
$$\dot{\varepsilon} = \ln(0.0004/0.4) \quad (\dot{\varepsilon} < 0.0004\%/s) \qquad (14)$$

$$O' = 0.26 \quad (\text{all DO levels}). \qquad (15)$$

These models are recommended for predicted fatigue lives $\le 10^6$ cycles. Equations 11 and 13–15 should also be used for cast austenitic SSs such as CF-3, CF-8, and CF–8M. As noted earlier, because the influence of DO level on the fatigue life of austenitic SSs is not well understood, these models may be somewhat conservative for some SSs in high–DO water. Also, because the effect of S content on the fatigue life of carbon and low–alloy steels appears to depend on the DO level in water, Eqs. 3–8 may yield conservative estimates of fatigue life for low–S (<0.007 wt.%) steels in high–temperature water with >1 ppm DO.

OPERATING EXPERIENCE IN NUCLEAR POWER INDUSTRY

Experience with operating nuclear power plants worldwide reveals that many failures may be attributed to fatigue; such failures have occurred with piping components, nozzles, valves, and pumps.[31–37] In most cases, these failures have been associated with thermal loading due to thermal stratification and striping or with mechanical loading due to vibratory loading. Significant thermal loading due to flow stratification or striping was not included in the original design basis analyses. Furthermore, the effect of thermal loading may also have been aggravated by corrosion due to the high–temperature coolant environment. The significant occurrences of corrosion fatigue damage and failures in various nuclear power plants have been reviewed by Garud et al.[33]

Fatigue cracks have been observed in feedwater piping and nozzles of the pressure vessel in BWRs and steam generators in PWRs.[33–40] The mechanism of cracking in feedwater nozzles and piping has been attributed to corrosion fatigue[38,39] or strain–induced corrosion cracking (SICC).[40] Case histories and identification of conditions that lead to SICC in low–alloy steels in LWR systems have been summarized by Hickling and Blind.[41] Significant cracking has also occurred in nonisolable piping connected to the PWR reactor coolant system.[42–44] Hirschberg et al.[45] summarized the operating experience with thermal fatigue of nonisolable pipe sections. Leaks from thermal fatigue cracks have occurred in the regenerative heat exchanger in the chemical and volume control system[46] and in the residual heat removal system.[47] The U.S. experience related to PWR primary system leaks observed between 1985 and 1996 has been assessed by Shah et al.[44]

In most fatigue failures in the field, the importance of LWR coolant environments could not be determined, because information on the loading and environmental conditions was not available. However, fatigue monitoring in several nuclear power plants[36] and results from full–scale mock–up or component tests[31,37,48–52] have confirmed the applicability of laboratory data to component behavior. Measurements of temperatures and strains in feedwater nozzles in BWRs[36] and thermal shock tests on butt–welded pipe section[31,48] indicate that crack initiation occurred earlier than would be expected based on the ASME Code design curve. In a test on a bent pipe subjected to internal pressure and thermal shock, the first incipient crack appeared in 1200 cycles, compared to 1400 cycles for test specimens made of the same material under comparable conditions (8 ppm DO); these values are slightly above the ASME Code design curve.[49] Also, in thermal shock tests performed on a reactor pressure vessel nozzle, incipient cracking in austenitic SS cladding of the nozzle occurred after ≈450 cycles in water containing 8–ppm DO and ≈1050 cycles in 0.2–ppm DO water; the latter is close to the ASME Code design curve.[50] The observed fatigue life in 0.2–ppm DO water is close to the ASME Code curve, and that in 8–ppm DO water is a factor of 2 lower.

Full–scale mock-up tests to generate thermal stratification in a pipe have further confirmed the applicability of laboratory data to component behavior.[51] The material, loading, and environmental conditions were simulated on a 1:1 scale using only thermo-hydraulic effects. Stephan and Masson[52] subjected a full–scale mock–up of the steam generator feedwater system to various regimes of stratification. After 4000 cycles of fatigue, destructive examination performed between two stable states of stratification revealed 1– to 4–mm–deep cracks in the weld region; the fatigue usage factors were 1.3–1.9. However, because the average DO level in water was ≈5 ppb, environmental effects on life would be expected to be minimal.

Cracking has also occurred in austenitic SS channel heads in the experimental test loop used for stress corrosion cracking studies in a simulated PWR environment.[53] Cracks were observed in a region that was subjected to temperature fluctuations between 170 and 190°C at a frequency of 0.05 Hz. The cracks were initiated on the inner surface and exhibited a cracking morphology that was essentially transgranular, with fatigue–like striations visible in some regions of the fracture surface. Thermal fatigue, with possible effects of the PWR coolant environment, was considered the root cause of these failures.[53]

Lenz et al.[40] showed that thermal stratification is the primary cause of crack initiation in feedwater lines, and that strain rates are 10^{-3}–10^{-5}%/s due to thermal stratification and 10^{-1}%/s due to thermal shock. Estimates of strain amplitudes and strain rates for typical transients associated with low–cycle fatigue in nuclear power plants are given in Table *1*.[54] Under these loading and environmental conditions in laboratory tests, significant reduction in fatigue life has been observed for carbon and low alloy steels.[2,11]

Comparison of crack morphologies observed in the field and in smooth test specimens also indicates that environmental effects may have influenced some field failures. For tests in water, near–surface cracks grow entirely as tensile cracks normal to the stress axis, whereas in air, cracks grow at an angle of 45° to the stress axis. For carbon steels in water, cracks propagate across both the soft ferrite and hard pearlite regions, but in air they propagate only along the soft ferrite regions.[14] Similar characteristics have been observed in field failures.[41,55] Examination of cracks in a carbon steel elbow adjacent to a steam generator nozzle weld showed a straight, nonbranching, transgranular crack through both the ferrite and pearlite regions without any preference.[55] Hickling and Blind[41] reported transgranular crack propagation through both weld and base metal, without regard to microstructural features, in a pipe weld of a BWR.

Table 1. Typical chemical and cyclic strain transients

Component	Operation	DO (ppb)	Temp. (°C)	Strain Range (%)	Strain Rate (%/s)
FW Nozzle	Startup	20/200	216/38	0.2-0.4	10^{-2}
FW Piping	Startup	20/200	216/38	0.2-0.5	10^{-3}–10^{-2}
FW Piping	Startup	20/200	288/38	0.07-0.1	4–8x10^{-6}
FW Piping	Turbine Roll	<200	288/80	0.4	3–6x10^{-3}
FW Piping	Hot Stand-by	<200	288/90	0.26	4x10^{-4}
FW Piping	Cool Down	<20	288/RT	0.2	6x10^{-4}
FW Piping	Stratification	200	250/50	0.2-0.7	10^{-4}–10^{-3}

RT = room temperature

INCORPORATING ENVIRONMENTAL EFFECTS INTO FATIGUE EVALUATIONS

Two methods have been proposed for incorporating the effects of LWR coolant environments into the ASME Section III fatigue evaluations. In one case, a new set of environmentally adjusted fatigue design curves was developed;[11–14,22,23] in the other, a fatigue life correction factor F_{en} was used to adjust the ASME Code fatigue usage values for environmental effects.[8,23,56,57] Estimates of fatigue life based on the two approaches can differ because of differences between the ASME mean curves used to develop the current design curves and the best–fit curves to the current data that are used to develop the environmentally adjusted curves. However, both methods provide an acceptable approach to account for environmental effects.

Fatigue Design Curves

Fatigue design curves have been obtained from the statistical models, represented by Eqs. 1–8 for carbon and low–alloy steels, and by Eqs. 9,11,13–15 for austenitic SSs. To be consistent with the current ASME Code philosophy, the best–fit curves were first adjusted for the effect of mean stress by using the modified Goodman relationship. The adjusted curves were then decreased by a factor of 2 on stress and 20 on cycles to obtain design curves. Although the current Code fatigue design curve for austenitic SSs does not include a mean stress correction, the new design curve does. Studies by Wire et al.[58] indicate an apparent reduction of up to 26% in strain amplitude in the low– and intermediate–cycle regime (i.e., <10^6 cycles) for a mean stress of 138 MPa.

Examples of new fatigue design curves for carbon and low–alloy steels and austenitic SS in air and LWR environments are shown in Figs. 1–3. Because the fatigue life of Type 316NG is superior to that of Types 304 or 316 SS at high strain amplitudes, the design curves in Fig. 3 are somewhat conservative for Type 316NG SS. Also,

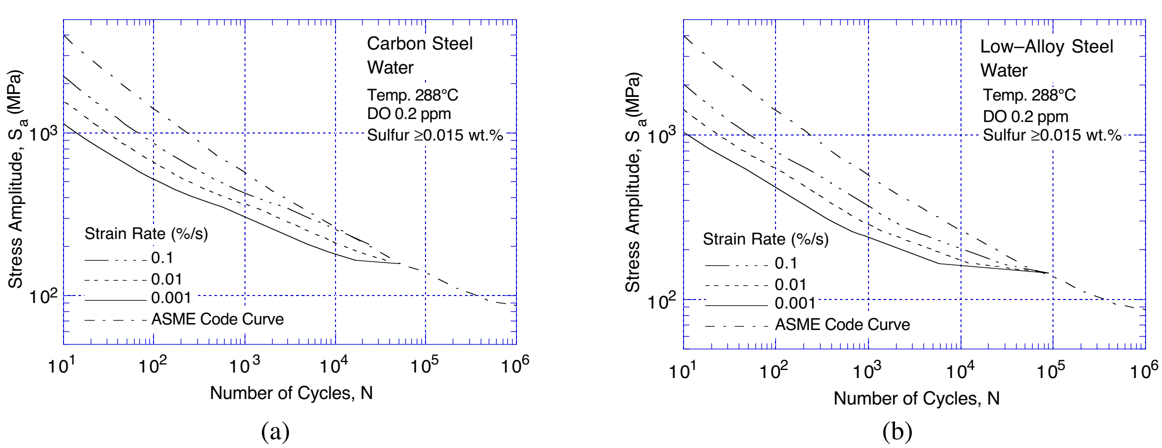
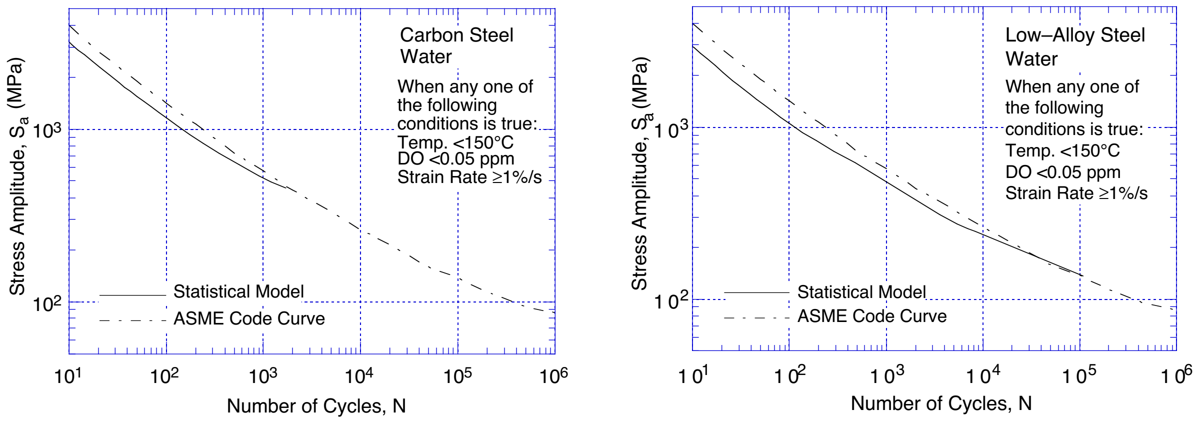
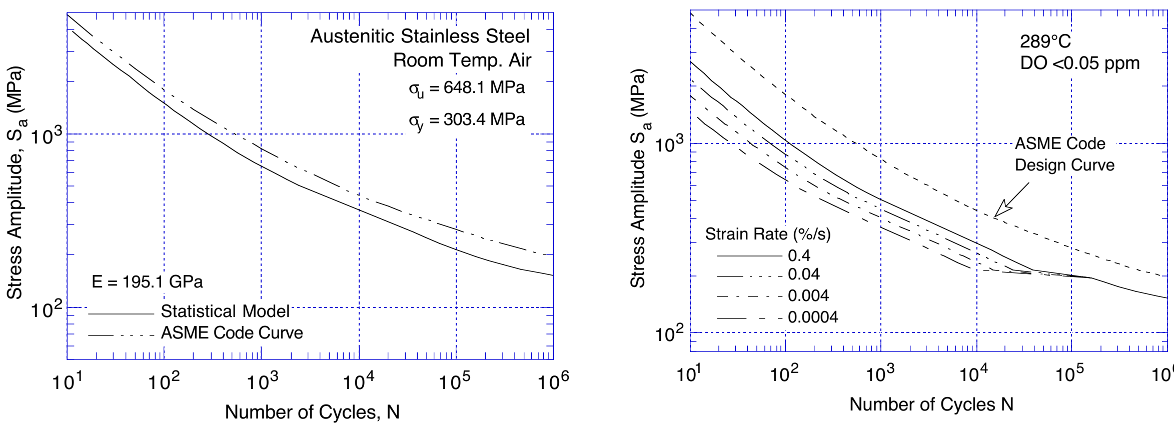


Figure 1. Design fatigue curves developed from statistical model for (a) carbon steels and (b) low–alloy steels at 288°C and under service conditions where all other threshold values are satisfied



(a) (b)

Figure 2. Design fatigue curves developed from statistical model for (a) carbon steels and (b) low–alloy steels under service conditions where one or more critical threshold values are not satisfied



(a) (b)

Figure 3. Fatigue design curves developed from the statistical model for austenitic stainless steels in (a) air at room temperature and (b) LWR environments at 289°C

Fig. 3a indicates that even in air at room temperature the current ASME Code design curve for austenitic SSs is nonconservative with respect to the design curve based on the statistical model. The margins between the current Code curve and experimental data are ≈1.5 on stress and 10–16 on cycles instead of the 2 and 20 originally intended.

Fatigue Life Correction Factor

The effects of reactor coolant environments on fatigue life have also been expressed in terms of a fatigue life correction factor F_{en}, which is defined as the ratio of life in air at room temperature to that in water at the service temperature. Values of F_{en} can be obtained from the statistical model, where

$$\ln(F_{en}) = \ln(N_{RTair}) - \ln(N_{water}). \quad (16)$$

The fatigue life correction factor for carbon steels is given by

$$F_{en} = \exp(0.554 - 0.101\ S^*\ T^*\ O^*\ \dot{\varepsilon}^*), \quad (17)$$

for low–alloy steels, by

$$F_{en} = \exp(0.898 - 0.101\, S^* T^* O^* \dot{\varepsilon}^*), \tag{18}$$

and for austenitic SSs, by

$$F_{en} = \exp(0.935 - T' \dot{\varepsilon}' O'), \tag{19}$$

where the constants S^*, T^*, $\dot{\varepsilon}^*$, and O^* are defined in Eqs. 5–8, and T', $\dot{\varepsilon}'$, and O' are defined in Eqs. 13–15. A strain threshold is also defined, below which environmental effects are modest. The strain threshold is represented by a ramp, i.e., a lower strain amplitude below which environmental effects are insignificant, a slightly higher strain amplitude above which environmental effects are significant, and a ramp between the two values. Thus, the negative terms in Eqs. 17–19 are scaled from zero to their actual values between the two strain thresholds. The two strain amplitudes are 0.07 and 0.08% for carbon and low–alloy steels, and 0.10 and 0.11% for wrought and cast austenitic SSs. To incorporate environmental effects into a Section III fatigue evaluation, the fatigue usage for a specific stress cycle based on the current Code design fatigue curve is multiplied by the correction factor.

CONSERVATISM IN FATIGUE DESIGN CURVES

Conservatism in the ASME Code fatigue evaluations may arise from (a) the fatigue evaluation procedures and/or (b) the fatigue design curves. The overall conservatism in ASME Code fatigue evaluations has been demonstrated in fatigue tests on piping and components.[59,60] Mayfield et al.[59] have shown that, in air, the margins on the number of cycles to failure for elbows and tees were 40–310 and 104–510, respectively, for austenitic SS and 118–2500 and 123–1700, respectively, for carbon steel. The margins for girth butt welds were significantly lower at 6–77 for SS and 14–128 for carbon steel. Data obtained by Heald and Kiss[60] on 26 piping components at room temperature and 288°C showed that the design margin for cracking exceeds 20, and for most of the components it is greater than 100. In these tests, fatigue life was expressed as the number of cycles for the crack to penetrate through the wall, which ranged in thickness from 6 to 18 mm. Consequently, depending on wall thickness, the actual margins for crack initiation may be lower by a factor of more than 2.

Deardorff and Smith[61] discussed the types and extent of conservatism present in the ASME Section III fatigue evaluation procedures and the effects of LWR environments on fatigue margins. The sources of conservatism in the evaluation procedures include design transients that are significantly more severe than those experienced in service, grouping of transients, and higher stresses due to simplified elastic–plastic analysis. The authors estimated that the ratio of the cumulative usage factors (CUFs) computed with the mean experimental curve for test specimen data in air to the CUFs computed with the Code fatigue design curve were ≈60 and 90, respectively, for PWR and BWR nozzles. The reductions in these margins due to environmental effects were estimated to be factors of 5.2 and 4.6 for PWR and BWR nozzles, respectively. Thus, Deardorff and Smith[61] argue that, after accounting for environmental effects, factors of 12 and 20 on life for PWR and BWR nozzles, respectively, account for uncertainties due to material variability, surface finish, size, mean stress, and loading history.

However, other studies on piping and components indicate that the Code fatigue design procedures do not always ensure large margins of safety.[62,63] Southwest Research Institute (SWI) performed fatigue tests in room–temperature water on carbon and low–alloy steels vessels with a 0.914–m diameter and 19–mm walls.[62] In the low–cycle regime, ≈5–mm–deep cracks were initiated slightly above (a factor of <2) the number of cycles predicted by the ASME Code design curve (Fig. 4a). Battelle–Columbus conducted tests on 203–mm or 914–mm carbon steel pipe welds at room temperature in an inert environment, and Oak Ridge National Laboratory (ORNL) performed four–point bend tests on 406–mm diameter Type 304 SS pipe removed from the C–reactor at the Savannah River site.[63] The results showed that the number of cycles to produce a leak was lower, and in some cases significantly lower, than that expected from the ASME Code fatigue design curves (Fig. 4a and b). The most striking results are for the ORNL "tie–in" and flawed "test" weld; these specimens cracked completely through the wall (12.7–mm thick) in a life 6 or 7 times shorter than would be expected from the Code curve. Note that the Battelle and ORNL results represent a through–wall crack; the number of cycles to initiate a 3–mm crack may be a factor of 2 lower.

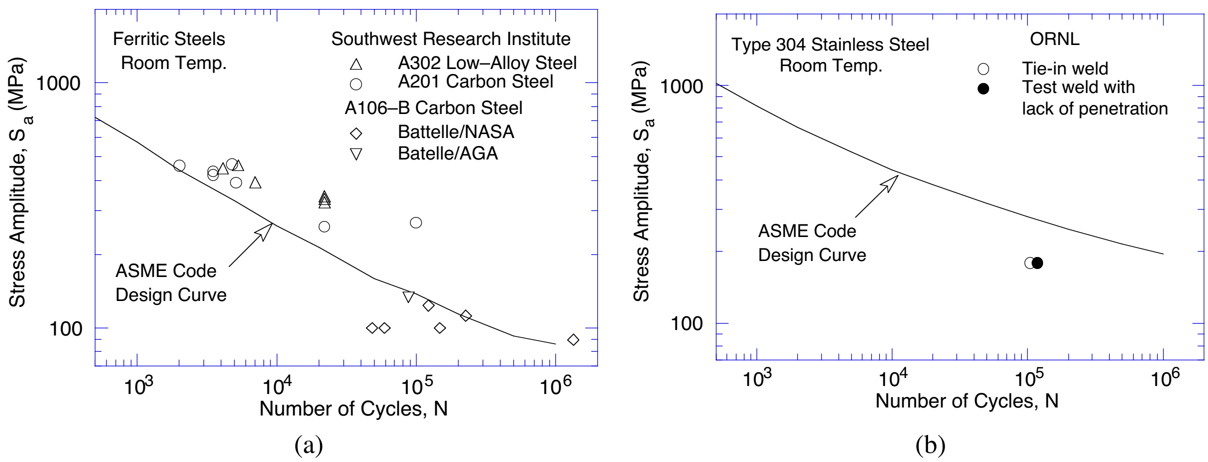


Figure 4. Fatigue data for (a) carbon and low–alloy steel and (b) Type 304 stainless steel components (Refs. 62,63)

Much of the margin in the current evaluations arises from the design procedures (e.g., stress analysis rules and cycle counting), which, as discussed by Deardorff and Smith,[61] are quite conservative. However, the ASME Code permits new and improved approaches to fatigue evaluations (e.g., finite–element analyses, fatigue monitoring, and improved K_e factors) that can significantly decrease the conservatism in the current fatigue evaluation procedures.

Another source of possible conservatism is the margin on stress and cycles built into the Code design curves. The factors of 2 on stress and 20 on cycles were intended to cover the effects of variables that can influence fatigue life but were not covered by the fatigue data used in obtaining the curves. The development of the design curves identified four groups of variables that needed to be considered in obtaining design curves applicable to components: material variability and data scatter, size and geometry, surface finish, and loading history (Miner's rule).

Material variability and data scatter. The effects of material variability and data scatter must be included to ensure that the design curves not only describe the available test data well, but also adequately describe the fatigue lives of the much larger number of heats of material that are found in the field. To assess the effect of material variability, the best–fit curves determined from tests on individual heats of materials were considered as a sample of the much larger population of heats of materialS of interest. The fatigue behavior of each of the heats was assumed to be characterized by the value of the constant term in the statistical models, denoted as A. The values of A for the test heats were ordered, and median ranks were used to estimate the cumulative distribution of A for the population.[64,65] This distribution can be fit reasonably well by a lognormal distribution; results for low–alloy steels in air and high–DO water are shown in Fig. 5.

The values of A that describe the 5th percentile of these distributions give fatigue ε–N curves that are expected to bound the fatigue lives of 95% of the heats of low–alloy steel. There are two sources of error in the distributions shown in Fig. 5. The mean and standard deviation of the population have to be estimated from the mean and standard deviation of the sample.[66] Confidence bounds can be obtained on the population mean and standard deviation in terms of the sample mean and standard deviation. Even this, however, does not fully address the uncertainty in the distribution, because of the large uncertainties in the sample values themselves, i.e., the "horizontal" uncertainty in the actual value of A for a heat of material as indicated by the error bars in Fig. 5. A Monte Carlo analysis was used to address both sources of uncertainty. The results of the Monte Carlo analysis are summarized in Table 2 in terms of values for A that provide bounds for the portion of the population and the confidence that is desired in the estimates of the bounds. Note that with small sample sizes, demanding too high a confidence level can lead to very conservative estimates of the percentile values. Because the cumulative distribution in Fig. 5 does not properly account for all uncertainties, it should only be considered as a qualitative description of expected variation, and Table 2 should be used for quantitative estimates. The 5th percentile value of parameter A at a 50% confidence level, i.e, the best–estimate of the 5th percentile, is 5.912 in air and 5.049 in

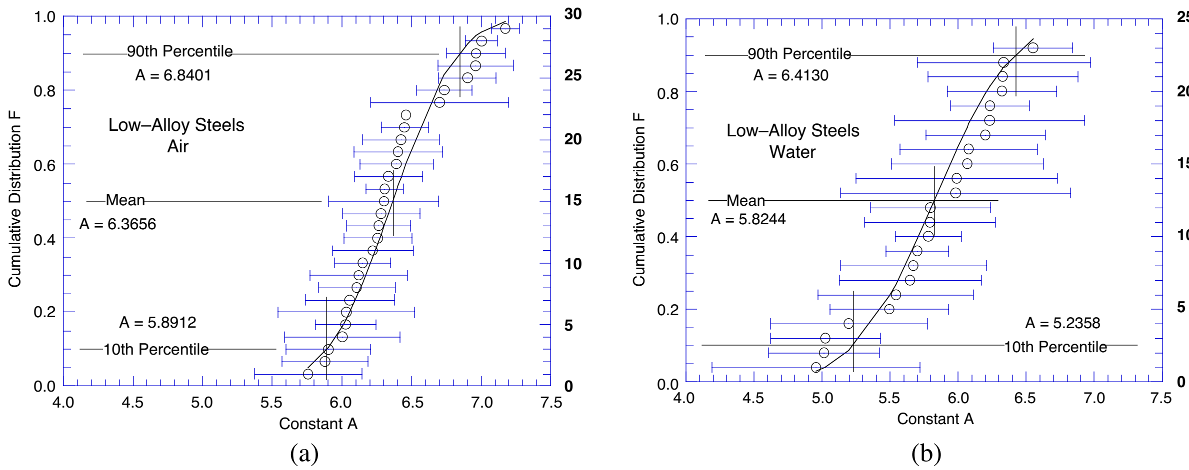


Figure 5. *Estimated cumulative distribution of the parameter A in the statistical models for fatigue life for heats of low–alloy steel in (a) air and (b) high–DO water.*

high–DO water. From Fig. 5, the mean value of A for the sample is 6.366 and 5.824, respectively, in the two environments. For low–alloy steel, a margin of 1.6 and 2.2 on life is predicted by the mean curve (determined from the ratio of the sample mean and the 95/50 value given in Table 2) in air and high–DO water environments, respectively. These margins are needed to provide reasonable confidence that the resulting life will be greater than that observed for 95% of the materials of interest. Similar analyses can be performed on the fatigue ε–N data for carbon steels and austenitic SSs.

Size and geometry. In NUREG/CR–6717,[14] Chopra and Shack reviewed literature data to determine the effect of size and geometry on the fatigue life of components. They concluded that a factor of ≈1.4 on cycles and ≈1.25 on strain would account for size and geometry effects.

Surface finish. Fatigue life can be sensitive to surface finish; cracks can initiate at surface irregularities that are normal to the stress axis. The height, spacing, shape, and distribution of surface irregularities can be important for crack initiation. Investigations of the effects of surface roughness on the low–cycle fatigue of Type 304 SS in air at 593°C clearly demonstrated that fatigue life decreases as surface roughness increases.[67] The results in Ref. 67 indicate that typical surface roughness associated with the metal–working processes, such as drawing/extrusion, grinding, honing, and polishing, would decrease fatigue life by a factor of ≈ 3. Fatigue test data on rectangular bars of austenitic SSs with differing surface finish, under compressive load, in the high–cycle–fatigue regime (i.e., $>10^5$ cycles) indicate that a factor of ≈ 1.6 on stress (or strain) is needed to account for the effect of the surface finish on fatigue life.[47]

Table 2. Values of parameter A in the statistical model for low–alloy steels as a function of the percentage of the population bounded and the confidence level

Confidence Level	Percentage of Population Bounded (Percentile Distribution of A)				
	95 (5)	90 (10)	75 (25)	67 (33)	50 (50)
			Air Environment		
50	5.912	6.000	6.180	6.242	6.370
75	5.640	5.738	5.927	5.992	6.119
90	5.395	5.503	5.700	5.768	5.893
95	5.249	5.362	5.563	5.633	5.758
			High–Dissolved Oxygen Water		
50	5.049	5.210	5.496	5.623	5.820
75	4.699	4.876	5.182	5.315	5.508
90	4.383	4.575	4.898	5.037	5.227
95	4.194	4.396	4.729	4.871	5.059

In an earlier report,[22] Chopra argued that the effect of surface finish may not be as significant in LWR environments, because austenitic SSs develop a strongly adherent corrosion scale. He further argued that the factor on life to account for the surface finish effect could be as low as 1.5 or perhaps eliminated completely. To check the validity of this argument, fatigue tests were conducted on Type 304 SS and carbon steel (A106–Gr. B) specimens that had been roughed under controlled conditions (in a lathe with 50–grit sandpaper) to produce circumferential scratches. The average surface roughness R_a was 1.2 μm and the RMS value of surface roughness R_q was 1.6 μm. The fatigue tests were conducted at 289°C in air for Type 304 SS and carbon steel, in low–DO water (i.e., < 5 ppb DO and ≈ 23 cc/kg dissolved hydrogen) for Type 304 SS, and in high–DO water (≈ 700 ppb DO) for carbon steel. The results and comparisons with data obtained on smooth specimens are shown in Fig. 6. For Type 304 SS, the fatigue life of the rough specimens is a factor of ≈ 3 lower than that of the smooth specimens in both air and water environments. For carbon steel, the fatigue life of rough specimens is lower than that of smooth specimens only in air. The fatigue lives of rough and smooth specimens are the same in high–DO water. These results suggest that factors of 2–3 on cycles and 1.3–1.6 on strain would account for effects of surface finish on the fatigue life of austenitic SSs in both air and water environments and for carbon and low–alloy steels in air. The effect of surface finish may be insignificant for carbon steels in LWR environments.

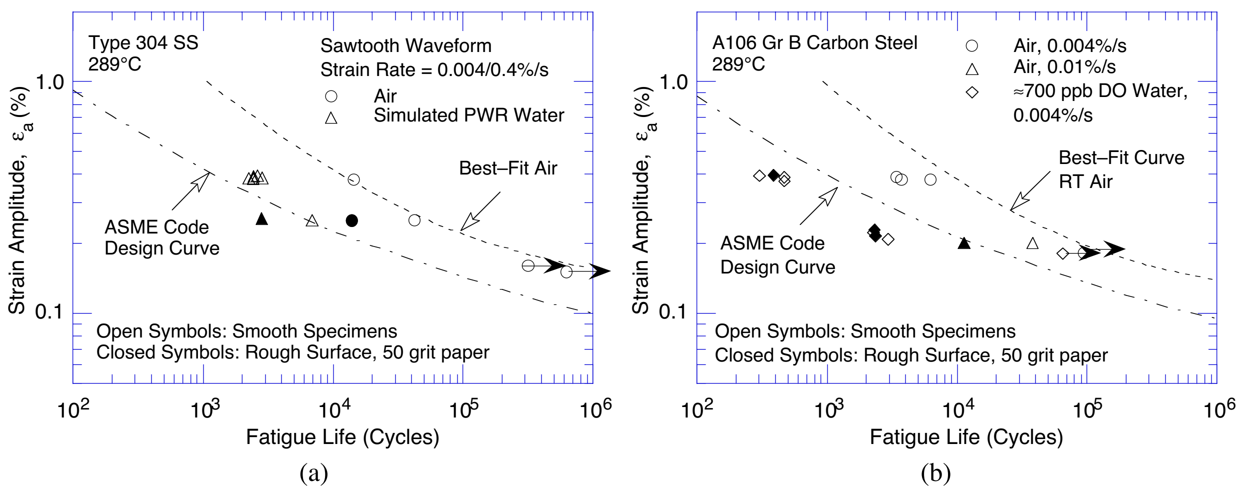


Figure 6. Effect of surface roughness on fatigue life of (a) Type 304 stainless steel and (b) A106–Gr. B carbon steel in air and water environments at 289°C

The decrease in fatigue life of both SSs and carbon steels is caused primarily by the effect of the environment on the growth of microstructurally small cracks.[26,27] The observed effects of surface finish on the fatigue life of SSs and carbon steels in LWR environments appear to be consistent with the hypothesis that the mechanisms of the growth of microstructurally small cracks are different in austenitic SSs and carbon steels. The results for carbon steels are consistent for a mechanism of growth by a slip oxidation/dissolution process, which seems unlikely to be affected by surface finish. The reduction in life of SSs is consistent with a hydrogen–enhanced crack growth mechanism, which seems more likely to be influenced by surface roughness.

Loading history. The effects of variable amplitude loading on smooth specimens are well known.[68–72] The presence of a few cycles at high strain amplitude in a load history causes the fatigue life at smaller strain amplitude to be significantly lower than that at constant amplitude loading at the same strain. Also, fatigue damage and crack growth in smooth specimens occur at strain levels below the nominal fatigue limit of the material. Studies on fatigue damage in Type 304 SS under complex loading histories[72] have shown that the fatigue life of the steel decreased by a factor of 2–4 under a decreasing–strain sequence (i.e., high strain level followed by low strain level). The studies also indicate that a loading sequence of decreasing strain levels is more damaging than one of increasing strain levels. In general, the mean fatigue ε–N curves should be lowered to account for damaging cycles that occur below the constant–amplitude fatigue limit of the material.

Moderate or acceptable environmental effects. A pressure vessel research council (PVRC) working group has been compiling and evaluating data on the effects of LWR coolant environments on the fatigue life of pressure boundary materials. One of the tasks in the PVRC activity consisted of defining a set of values for material, loading, and environmental variables that lead to moderate or acceptable effects of environment on fatigue life. A factor of 4 on the ASME mean life was chosen as a working definition of "moderate" or "acceptable" effects of environment, i.e., up to a factor of 4 decrease in fatigue life due to the environment is considered acceptable and does not require further fatigue evaluation.[73] The basis for this criterion was the discussion presented by Cooper[74] regarding the initial scope and intent of the Section III fatigue design procedures. Cooper stated that the factor of 20 on life was the product of the three subfactors: scatter of data (minimum to mean), 2.0; size effect, 2.5; and surface finish, atmosphere, etc., 4.0. Cooper[74] also notes that the term "atmosphere" was intended to reflect the effects of an industrial atmosphere in comparison with an air–conditioned laboratory, not the effects of a specific coolant environment.

The criterion for "acceptable" effects of environment developed by the working group is based on the assumption that the current Code design curve includes a factor of 4 (i.e., the third subfactor listed above) to account for the effects of environment. The third subfactor, however, also was intended to account for the effect of surface finish on fatigue life. Figure 6 shows that surface finish can decrease the fatigue life of austenitic SSs by a factor of 3 in both air and water environments.

Fatigue design curve margins. The factors that are needed to account for the effects of various material, loading, and environmental variables on fatigue life are summarized in Table *3*. As shown by "total adjustment," a factor of at least 10 on cycles with respect to the mean ε–N curve for laboratory test specimens in air is needed to account for the effects of data scatter, material variability, component size, surface finish, and loading history. A factor of 14 on cycles with respect to the mean ε–N curve for laboratory test specimens in LWR environments is needed for austenitic SSs. Recent data on the effects of surface finish suggest that the margin on cycles needed for carbon steels may be smaller (Fig. 6b). The factors on strain are needed primarily to account for the variation in the fatigue limit of the material caused by material variability, component size and surface finish, and load history. Because these variables affect life through their influence on the growth of short cracks (<100 µm), the adjustment on strain to account for such variations is typically not cumulative but is controlled by the variable that has the largest effect on life. Thus, in relating the fatigue lives of laboratory test specimens to those of actual reactor components, a factor of 1.6–1.7 on strain with respect to the mean ε–N curve for laboratory test specimens is needed to account for the differences and uncertainties associated with material variability, component size, surface finish, and load history. These results suggest that the current ASME Code requirements of a factor of 2 on stress and 20 on cycle to account for differences and uncertainties in fatigue life that are associated with material and loading conditions are quite reasonable.

Table 3. Factors on cycles and strain applied to mean ε–N curve in an environment

Parameter	Factor on Life (Air)	Factor on Life (Water)	Factor on Strain
Material variability & experimental scatter	1.6	2.2	1.2–1.7
Size effect	1.4	1.4	1.25
Surface finish	3.0	3.0[a]	1.6
Loading history	1.5–2.5	1.5–2.5	1.3–1.6
Total adjustment	10.0–20.0	14.0–23.0	1.6–1.7

[a]For austenitic stainless steels; factor for carbon steels may be lower.

SUMMARY

The existing fatigue ε–N data for carbon and low–alloy steels and wrought and cast austenitic SSs have been evaluated to define the effects of key material, loading, and environmental parameters on the fatigue life of these steels. The ε–N data developed at various laboratories worldwide are consistent with each other and are consistent with the available data for fatigue CGRs obtained from fracture mechanics specimens. In LWR environments, data for both fatigue crack initiation and fatigue crack growth show similar trends. Statistical models that can be used to estimate fatigue lives in LWR environments have been developed.

Under the loading and environmental conditions associated with typical reactor operating transients or thermal stratification, the fatigue life was significantly reduced in the laboratory tests on carbon and low–alloy steels and austenitic SSs. Case studies of fatigue failures in nuclear power plants, results from fatigue monitoring in several nuclear power plants, and mock–up and component tests confirm the applicability of laboratory data to component behavior.

Two methods for incorporating the effects of LWR coolant environments into the ASME Section III fatigue evaluations are described. In one case a new set of environmentally adjusted fatigue design curves was developed; in the other, a fatigue life correction factor F_{en} was used to adjust the current ASME Code fatigue usage values for environmental effects. Estimates of fatigue life based on the two approaches can differ because of differences between the ASME mean curves used to develop the current design curves and the best–fit curves to the existing current data that are used to develop the environmentally adjusted curves. However, both methods provide an acceptable approach to account for environmental effects.

Much of the conservatism in the current ASME Code fatigue evaluation procedures arises from current design procedures, e.g., stress analysis rules, and cycle counting. However, the ASME Code permits alternative approaches, such as finite–element analyses, fatigue monitoring, and improved K_e factors, that can significantly decrease the conservatism in the current fatigue evaluation procedures. Because of material variability, data scatter, and component size and surface, the fatigue life of actual components is different from that of laboratory test specimens under a similar loading history, and the mean ε–N curves for laboratory test specimens must be adjusted to obtain design curves for components. Data available in the literature have been reviewed to evaluate the margins on strain and cycles that are needed to account for the differences and uncertainties. The results indicate that the current ASME Code requirements of a factor of 2 on stress and 20 on cycle are quite reasonable.

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