4 Fatigue ε–N Data

The relevant fatigue ε–N data for austenitic SSs in air include the data compiled by Jaske and O'Donnell[16] for developing fatigue design criteria for pressure vessel alloys, the JNUFAD* database from Japan, and the results of Conway et al.[17] and Keller.[18] In water, the existing fatigue ε–N data include the tests performed by General Electric Co. (GE) in a test loop at the Dresden 1 reactor,[19] the JNUFAD database, studies at Mitsubishi Heavy Industries, Ltd. (MHI),[20–25] Ishikawajima–Harima Heavy Industries Co. (IHI),[26,27] and Hitachi[28,29] in Japan, and the present work at ANL.[4–7,30–32]

4.1 Air Environment

In an air environment, the fatigue life of Type 304 SS is comparable to that of Type 316 SS; the fatigue life of Type 316NG is slightly higher than that of Types 304 and 316 SS, particularly at high strain amplitudes. The results also indicate that the fatigue life of austenitic SSs in air is independent of temperature from room temperature to 427°C. Although the effect of strain rate on fatigue life seems to be significant at temperatures above 400°C, variations in strain rate in the range of 0.4–0.008%/s have no effect on the fatigue lives of SSs at temperatures up to 400°C.[33]

The results indicate that the Code mean curve used to develop the current Code design curve for austenitic SSs does not accurately represent the available fatigue data.[6,16] At strain amplitudes <0.5%, the mean curve predicts significantly longer lives than those observed experimentally. The difference between the Code mean curve and the best–fit of the available experimental data is due most likely to differences in the tensile strength of the steels. The Code mean curve represents SSs with relatively high strength; the fatigue ε–N data obtained during the last 30 years were obtained on SSs with lower tensile strengths. Furthermore, because, for the current Code mean curve, the value of applied stress at a fatigue life of 10^6 cycles is greater than the monotonic yield strength of austenitic SSs in more common usage, the current Code design curve for austenitic SSs does not include a mean stress correction. Studies on the effect of residual stress on fatigue life[34] indicate an apparent reduction of up to 26% in strain amplitude in the low– and intermediate–cycle regime for a mean stress of 138 MPa.

4.2 LWR Environment

The fatigue lives of austenitic SSs are decreased in LWR environments. The decrease depends primarily on applied strain amplitude, strain rate, and temperature. The results presented in Section 3.1 indicate that the effect of the DO content of the water is influenced by material heat treatment. The critical parameters that influence fatigue life, and the threshold values of these parameters for environmental effects to be significant are summarized below.

4.2.1 Strain Amplitude

A slow strain rate applied during the tensile–loading cycle (i.e., up–ramp with increasing strain) is primarily responsible for environmentally assisted reduction in fatigue life. Slow rates applied during both tensile– and compressive–loading cycles (i.e., up– and down–ramps) do not cause further decrease in fatigue life than that observed for tests with only a slow tensile–loading cycle.[30–32] Nearly all of the existing fatigue ε–N data have been obtained under loading histories with constant strain rate, temperature, and strain amplitude. Actual loading histories encountered during service of nuclear power

* M. Higuchi, Ishikawajima–Harima Heavy Industries Co., Japan, private communication to M. Prager of the Pressure Vessel Research Council, 1992.

plants are far more complex. Exploratory fatigue tests have been conducted with waveforms in which the slow strain rate is applied during only a fraction of the tensile loading cycle.[23,25] The results indicate that a minimum threshold strain is required for environmentally assisted decrease in the fatigue lives of SSs (Fig. 18). The threshold strain $\Delta\varepsilon_{th}$ 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 is decreased.[25] The threshold strain may be expressed in terms of the applied strain range $\Delta\varepsilon$ by the equation

$$\Delta\varepsilon_{th}/\Delta\varepsilon = -0.22\ \Delta\varepsilon + 0.65. \tag{3}$$

The results suggest that the threshold strain $\Delta\varepsilon_{th}$ is related to the elastic strain range of the test, and does not correspond to the strain at which the crack closes. For fully reversed cyclic loading, the crack opening point can be identified as the point where the curvature of the load–vs.–displacement line changes before the peak compressive load is reached. In the present study, evidence of a crack opening point was observed for cracks that had grown relatively large, i.e., only near the end of life.

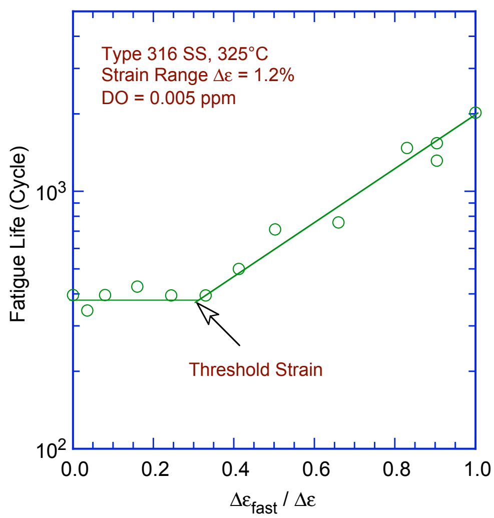


Figure 18.
Results of strain rate change tests on Type 316 SS in low–DO water at 325°C. Low strain rate was applied during only a fraction of tensile loading cycle. Fatigue life is plotted as a function of fraction of strain at high strain rate (Refs. 23, 25).

4.2.2 Hold–Time Effects

Environmental effects on fatigue life occur primarily during the tensile–loading cycle and at strain levels greater than the threshold value. Consequently, loading and environmental conditions during the tensile–loading cycle, e.g., strain rate, temperature, and DO level, are important for environmentally assisted reduction of the fatigue lives of SSs. Information about the effect of hold periods on the fatigue life of austenitic SSs in water is very limited. In high–DO water, the fatigue lives of Type 304 SS tested with a trapezoidal waveform (i.e., hold periods at peak tensile and compressive strain)[19] are comparable to those tested with a triangular waveform.[26]

4.2.3 Strain Rate

Fatigue life decreases with decreasing strain rate. In low–DO 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 (Fig. 19).[6,7,20–32] 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 by a factor of ≈10.

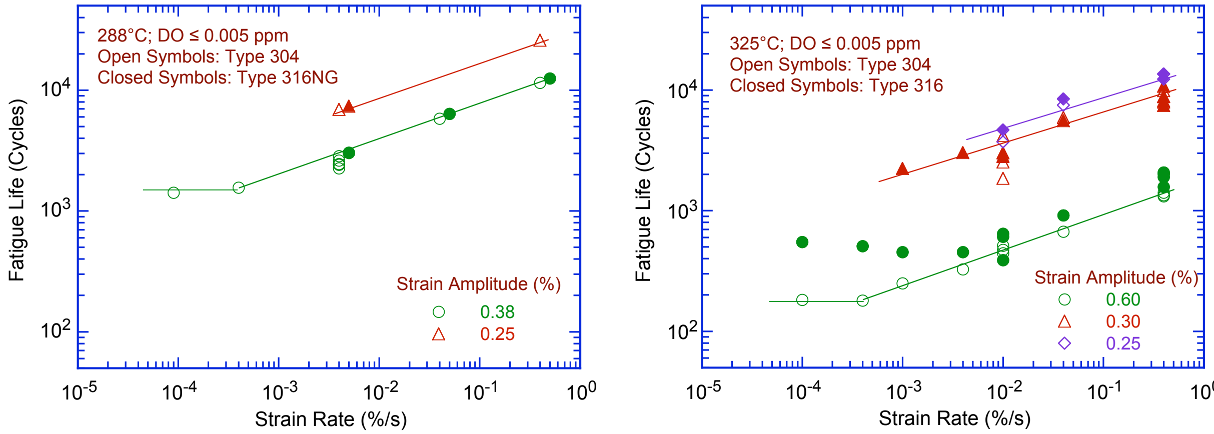
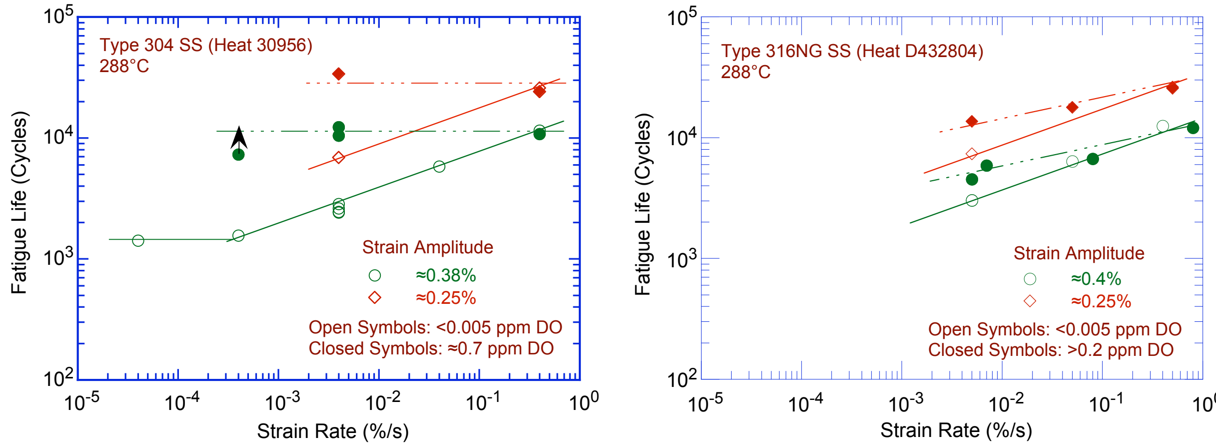


Figure 19. Dependence of fatigue lives of austenitic stainless steels on strain rate in low–DO water (Refs. 6,7).



(a) (b)

Figure 20. Dependence of fatigue life of Types (a) 304 and (b) 316NG stainless steel on strain rate in high– and low–DO water at 288°C (Ref. 7).

For some SSs, the effect of strain rate may be less pronounced in high–DO water than in low–DO water (Fig. 20). For example, for Heat 30956 of Type 304 SS, strain rate has no effect on fatigue life in high–DO water, whereas life decreases linearly with strain rate in low–DO water (Fig. 20a). For Heat D432804 of Type 316NG, some effect of strain rate is observed in high–DO water, although it is smaller than that in low–DO water (Fig. 20b). These results and the effect of DO on fatigue life are discussed further in the next section. The effect of strain rate on the fatigue life of cast austenitic SSs is the same in low– and high–DO water and is comparable to that observed for the wrought SSs in low–DO water.[23,24]

4.2.4 Dissolved Oxygen

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 effect of environment in low–DO water is not influenced by the composition or heat treatment condition of the steel. The fatigue life continues to decrease with decreasing strain rate and increasing temperature.[6,7,22–27]

In high–DO water, the fatigue lives of austenitic SSs are either comparable to[22,24] or, in some cases, higher[6] than those in low–DO water, i.e., for some SSs, environmental effects may be lower in high– than in low–DO water. The results presented in Section 3.1 and Fig. 20a and 20b, indicate that, in high–DO water, environmental effects on the fatigue lives of austenitic SSs are influenced by the composition and heat treatment of the steel. For example, for high–carbon Type 304 SS, environmental effects are insignificant for the MA material (Fig. 20a), whereas for sensitized material the effect of environment is the same in high– and low–DO water (Fig. 5). For low–carbon Type 316NG SS some effect of strain rate is observed in high–DO water although it is smaller than that in low–DO water (Fig. 20b).

The studies at ANL indicate that, for fatigue tests in high–DO water, conductivity of water and ECP of steel are important parameters that must be maintained constant. During laboratory tests, the time to reach stable environmental conditions depends on the autoclave volume, DO level, flow rate, etc. In the ANL test facility, fatigue tests on austenitic SSs in high–DO water required a soaking period of 5–6 days for the ECP of the steel to stabilize. The steel ECP increased from zero or a negative value to above 150 mV during this period. The results shown in Fig. 20a for MA Heat 30956 of Type 304 SS in high–DO water (closed circles) were obtained on specimens that were soaked for 5–6 days before the test. The same material tested in high–DO water after soaking for only 24 h showed significant reduction in fatigue life. The results shown in Fig. 20b for Heat 432804 of Type 316NG SS in high–DO water were obtained on specimens that were soaked for only a day and therefore the ECP of the steel may not have stabilized.

To determine the possible influence of the shorter soak period, additional tests were conducted on another heat of Type 316NG (Heat P91576); these specimens were soaked for ≈10 days before testing to achieve stable values for the ECP of the steel. The results are shown in Fig. 21. Unlike the data obtained earlier on Heat D432804 (diamond symbols), the results for Heat P91576 (triangle symbols) indicate that the fatigue life of this heat is the same in low– and high–DO water. Most likely the microstructure of Heat P91576 differs from that of Heat D432804, making it more susceptible to environmental effects in high–DO water. To further investigate the effect of material microstructure on fatigue life, a specimen of Heat P91576 was solution annealed in the laboratory and tested in high–DO water at 289°C. The fatigue life of the solution–annealed specimen (inverted triangle symbol in Fig. 21) is a factor of ≈2 higher than that of the MA specimens. These results are consistent with the data presented in Section 3.1. In high–DO water, material heat treatment has a strong effect on the fatigue life of austenitic SSs.

In low–DO water, the fatigue lives of cast SSs are comparable to those of wrought SSs.[22,24] Limited data suggest that the fatigue lives of cast SSs in high–DO water are approximately the same as those in low–DO water.[6]

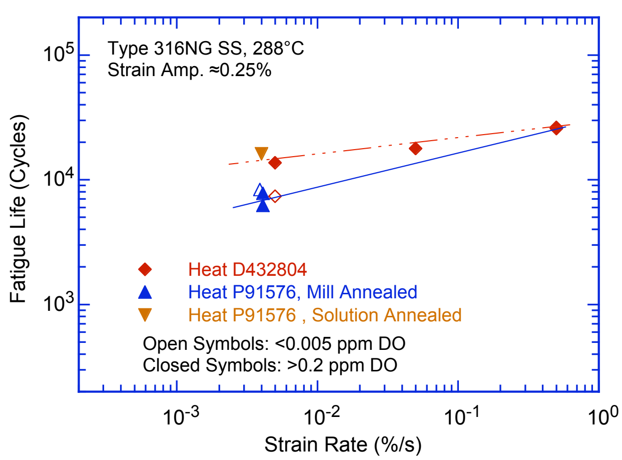


Figure 21.
Dependence of fatigue life of two heats of Type 316NG SS on strain rate in high– and low–DO water at 288°C (Ref. 5).

4.2.5 Water Conductivity

The effect of the conductivity of water and the ECP of the steel on the fatigue life of austenitic SSs is shown in Fig. 22. In high–DO water, fatigue life is decreased by a factor of ≈2 when the conductivity of water is increased from ≈0.07 to 0.4 μS/cm. Note that environmental effects appear more significant for the specimens that were soaked for only 24 h. For these tests, the ECP of steel was initially very low and increased during the test.

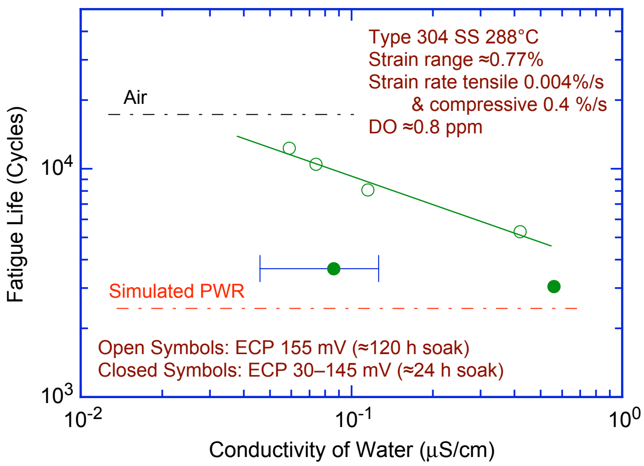


Figure 22.
Effects of conductivity of water and soaking period on fatigue life of Type 304 SS in high–DO water (Ref. 4).

4.2.6 Temperature

The change in fatigue lives of austenitic SSs with test temperature at two strain amplitudes and two strain rates is shown in Fig. 23. The results suggest a threshold temperature of 150°C, above which the environment decreases fatigue life in low–DO water if the strain rate is below the threshold of 0.4%/s. In the range of 150–325°C, the logarithm of fatigue life decreases linearly with temperature. Only moderate decrease in life is observed in water at temperatures below the threshold value of 150°C.

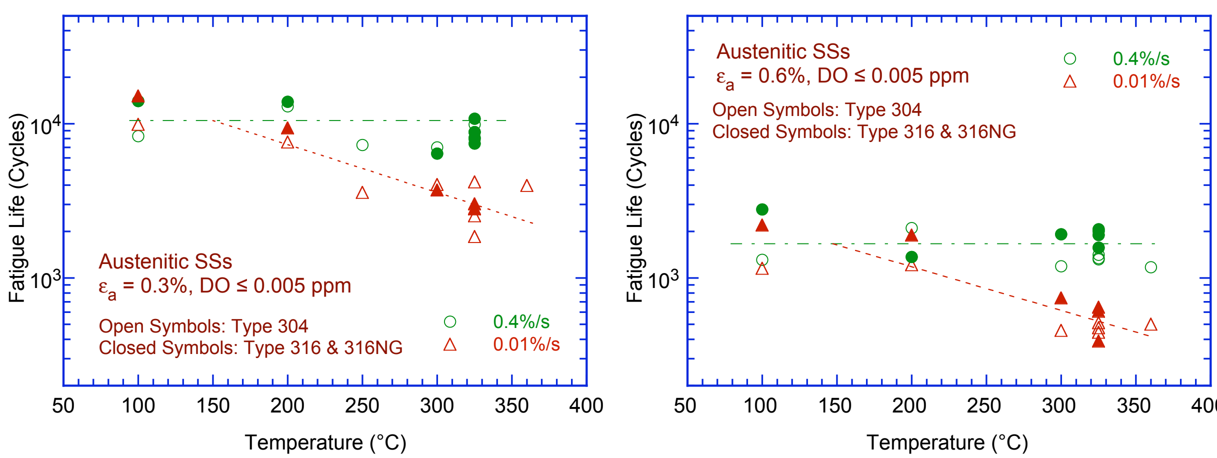


Figure 23. Change in fatigue lives of austenitic stainless steels in low–DO water with temperature (Refs. 5–7, 22–27).

Fatigue tests have been conducted at MHI in Japan on Type 316 SS under combined mechanical and thermal cycling.[23] Triangular waveforms were used for both strain and temperature cycling. Two sequences were selected for temperature cycling: an in–phase sequence, in which temperature cycling was synchronized with mechanical strain cycling; and a sequence in which temperature and strain were out of phase, i.e., maximum temperature occurred at minimum strain level and vice versa. The results are shown in Fig. 24, with the data obtained from tests at constant temperature.

For the thermal cycling tests, fatigue life should be longer for out–of–phase tests than for in–phase tests, because applied strains above the threshold strain occur at high temperatures for in–phase tests, whereas they occur at low temperatures for out–of–phase tests. An average temperature is used in Fig. 24 for the thermal cycling tests. The results from thermal cycling tests agree well with those from constant–temperature tests (open circles). The data suggest a linear decrease in the logarithm of life at temperatures above 150°C.

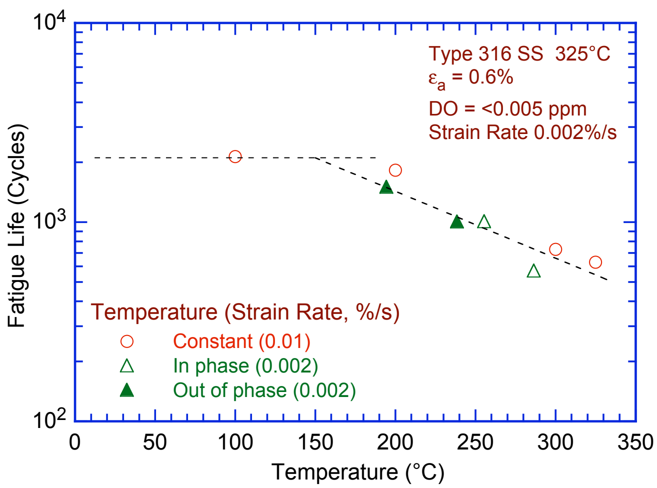
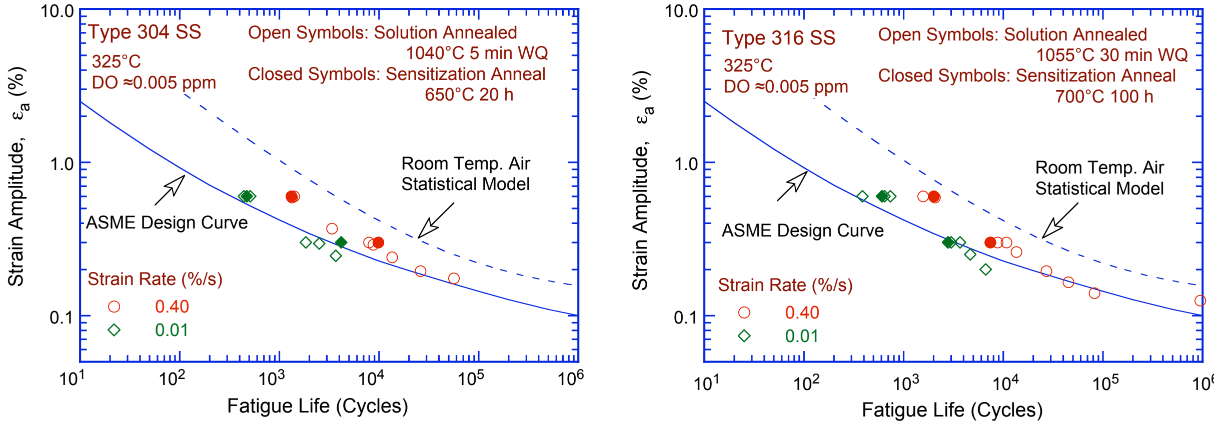


Figure 24.
Fatigue life of Type 316 stainless steel under constant and varying test temperature (Ref. 23).

4.2.7 Material Heat Treatment

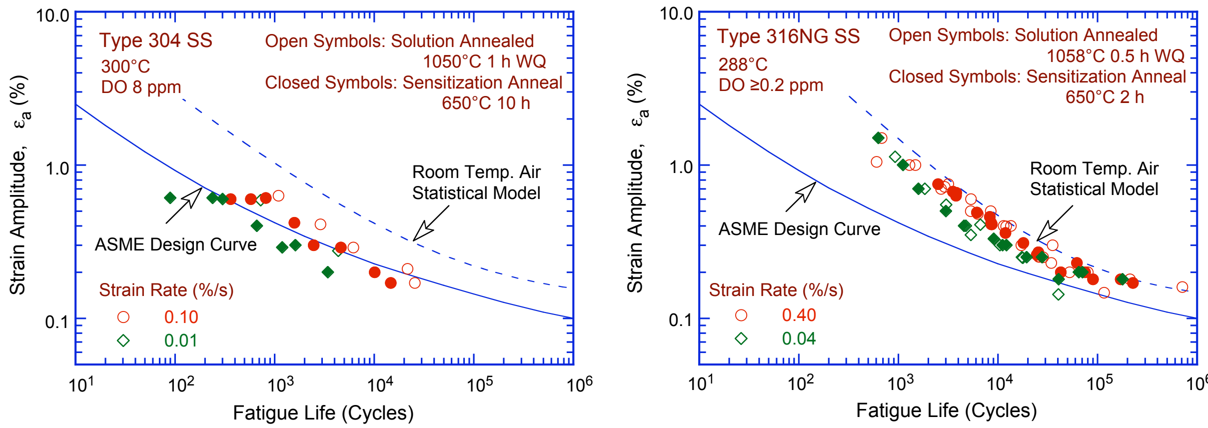
The results presented in Section 3.1 (Fig. 5) indicate that, although heat treatment has little or no effect on the fatigue life of austenitic SSs in low–DO and air environments, in a high–DO environment, fatigue life may be longer for nonsensitized or slightly sensitized SS.

These results are consistent with the data obtained at MHI on solution–annealed and sensitized Types 304, 316, and 316NG SS (Figs. 25 and 26). In low–DO (<0.005 ppm) water at 325°C, a sensitization annealing has no effect on the fatigue lives of Types 304 and 316 SS (Fig. 25). However, in high–DO (8 ppm) water at 300°C, the fatigue life of sensitized Type 304 SS is a factor of ≈2 lower than that of the solution–annealed steel (Fig 26a). A sensitization anneal appears to have little or no effect on the fatigue life of Type 316NG SS in high–DO water at 288°C (Fig. 26b). Fatigue lives of solution–annealed and sensitized Type 316NG SS are comparable.



(a) (b)

Figure 25. Effect of sensitization annealing on fatigue life of Types (a) 304 and (b) 316 stainless steel in low–DO water at 325°C (Refs. 22, 24). WQ = water quenched.



(a) (b)

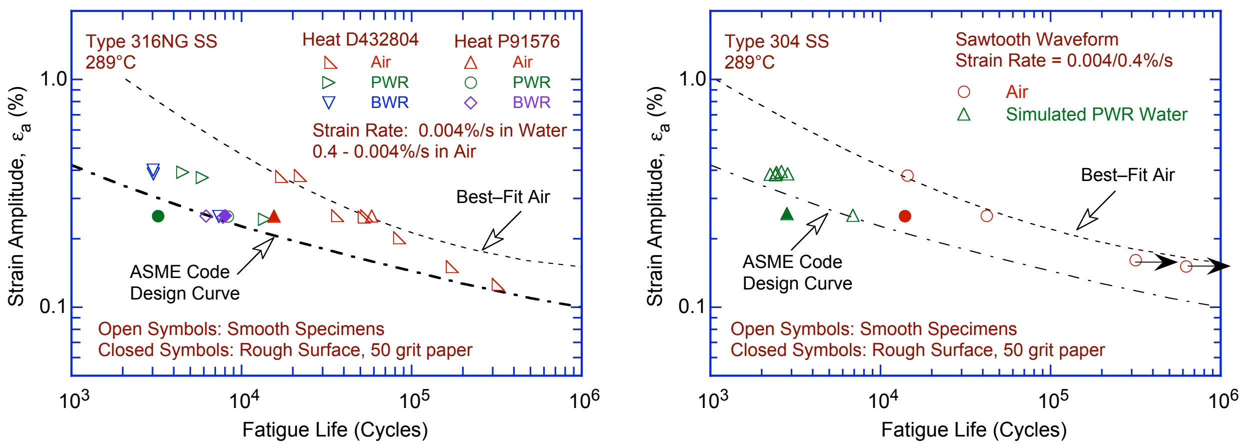
Figure 26. Effect of sensitization anneal on the fatigue lives of Types (a) 304 and (b) 316NG stainless steel in high–DO water (Refs. 20, 26). WQ = water quenched.

4.2.8 Flow Rate

It is generally recognized that flow rate most likely has a significant effect on the fatigue life of materials because it may cause differences in local environmental conditions in the enclaves of the microcracks formed during early stages in the fatigue ε–N test. Information about the effects of flow rate on the fatigue life of pressure vessel and piping steels in LWR environments has been rather limited. Recent results indicate that, under typical operating conditions for 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 low flow rates (0.3 m/s or lower).[35,36] However, the effect of flow rate on the fatigue life of austenitic SSs has not been evaluated. Because the mechanism of fatigue crack initiation in austenitic SSs in LWR environments appears to be different from that in carbon and low–alloy steels, the effect of flow rate on fatigue life of SSs may also differ.

4.2.9 Surface Finish

Fatigue life is 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 are important for crack initiation. Fatigue tests have been conducted on Types 304 and 316NG SS specimens that were intentionally roughened in a lathe, under controlled conditions, with 5-grit sandpaper to produce circumferential cracks with an average surface roughness of 1.2 µm. The results are shown in Figs. 27a and b, respectively, for Types 316NG and 304 SS. For both steels, the fatigue life of roughened specimens is lower than that of the smooth specimens in air and low–DO water environments. In high–DO water, the fatigue life of Heat P91576 of Type 316NG is the same for rough and smooth specimens.



(a) (b)

Figure 27. Effect of surface roughness on fatigue life of (a) Type 316NG and (b) Type 304 stainless steels in air and high–purity water at 289°C.

4.2.10 Cast Stainless Steels

Available fatigue ε–N data[6,22,24,32] indicate that, in air, the fatigue lives of cast CF–8 and CF–8M SSs are similar to that of wrought austenitic SSs. It is well known that the Charpy impact and fracture toughness properties of cast SSs are decreased significantly after thermal aging at temperatures between 300 and 450°C.[37–39] The cyclic–hardening behavior of cast austenitic SSs is also influenced by thermal aging.[6] At 288°C, cyclic stresses of steels aged for 10,000 h at 400°C are higher than those for unaged material or wrought SSs. Also, strain rate effects on cyclic stress are greater for aged than for unaged steel, i.e., cyclic stresses increase significantly with decreasing strain rate. The available fatigue ε–N data are inadequate to establish the effect of thermal aging on the fatigue life of cast SSs. Thermal aging may or may not affect the fatigue life.[22,24,32]

In LWR coolant environments, the fatigue lives of cast SSs are comparable to those observed for wrought SSs in low–DO water. Limited data suggest that the fatigue lives of cast SSs in high–DO water are approximately the same as those in low–DO water.[6] The results also indicate that thermal aging for 10,000 h at 400°C decreases the fatigue lives of CF8M steels.

The reduction in life in LWR environments depends on strain rate (Fig. 28). Effects of strain rate are the same in low– and high–DO water. For unaged material, environmental effects on life do not appear to saturate even at strain rates as low as 0.00001%/s.[22,24] Also, the fatigue lives of these steels are relatively insensitive to changes in ferrite content in the range of 12–28%.[22,24] Existing data are too sparse to define the saturation strain rate for cast SSs or to establish the dependence of fatigue life on temperature in LWR environments; the effects of strain rate and temperature are assumed to be similar to those for wrought SSs.

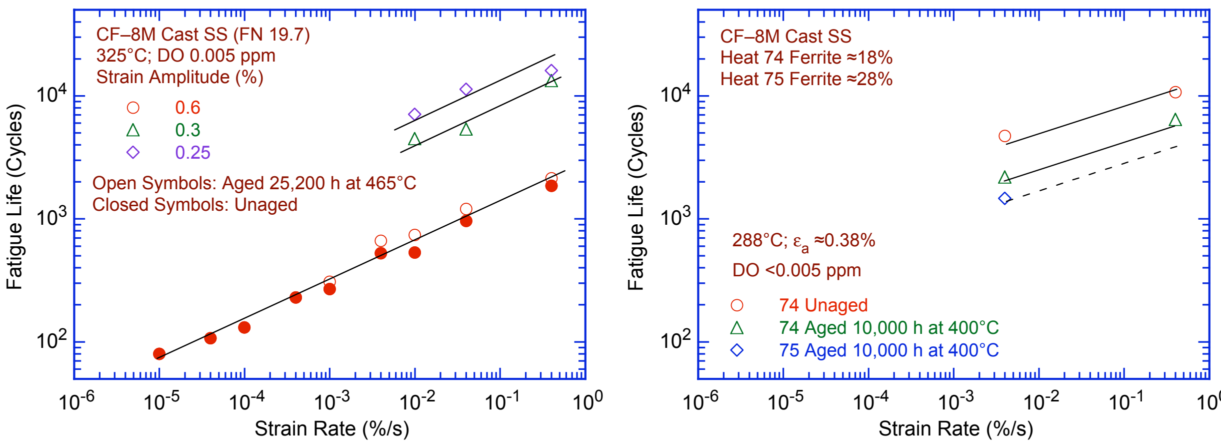


Figure 28. Dependence of fatigue lives of CF–8M cast SSs on strain rate in low–DO water at various strain amplitudes (Refs. 6,22,24,32).