1 Introduction

Cyclic loadings on a structural component occur because of changes in mechanical and thermal loadings as the system goes from one load set (e.g., pressure, temperature, moment, and force loading) to any other load set. For each load set, an individual fatigue usage factor is determined by the ratio of the number of cycles anticipated during the lifetime of the component to the allowable cycles. Figures I–9.1 through I–9.6 of Appendix I to Section III of the ASME Boiler and Pressure Vessel Code specify fatigue design curves that define the allowable number of cycles as a function of applied stress amplitude. The cumulative usage factor (CUF) is the sum of the individual usage factors, and the ASME Code Section III requires that the CUF at each location must not exceed 1.

The ASME Code fatigue design curves, given in Appendix I of Section III, are based on strain–controlled tests of small polished specimens at room temperature in air. The design curves have been developed from the best–fit curves to the experimental fatigue–strain–vs.–life (ε–N) data that are expressed in terms of the Langer equation[1] of the form

$$\varepsilon_a = A1(N)^{-n1} + A2, \tag{1}$$

where ε_a is the applied strain amplitude, N is the fatigue life, and A1, A2, and n1 are coefficients of the model. Equation 1 may be written in terms of stress amplitude S_a instead of ε_a, in which case stress amplitude is the product of ε_a and elastic modulus E, i.e., $S_a = E\,\varepsilon_a$. The fatigue design curves were obtained from the best–fit curves by first adjusting for the effects of mean stress on fatigue life and then reducing the fatigue life at each point on the adjusted curve by a factor of 2 on strain (or stress) or 20 on cycles, whichever is more conservative.

The factors of 2 and 20 are not safety margins but rather conversion factors that must be applied to the experimental data to obtain reasonable estimates of the lives of actual reactor components. Although the Section III criteria document[2] states that these factors were intended to cover such effects as environment, size effect, and scatter of data, Subsection NB–3121 of Section III of the Code explicitly notes that the data used to develop the fatigue design curves (Figs. I–9.1 through I–9.6 of Appendix I to Section III) did not include tests in the presence of corrosive environments that might accelerate fatigue failure. Article B–2131 in Appendix B to Section III states that the owner's design specifications should provide information about any reduction to fatigue design curves that has been necessitated by environmental conditions.

The existing fatigue ε–N data illustrate potentially significant effects of light water reactor (LWR) coolant environments on the fatigue resistance of carbon and low–alloy steels,[3–5] as well as of austenitic stainless steels (SSs).[4–7] Under certain environmental and loading conditions, fatigue lives of austenitic SSs can be a factor of 20 lower in water than in air.[6]

In LWR environments, the fatigue lives of austenitic SSs depend on applied strain amplitude, strain rate, temperature, and dissolved oxygen (DO) in water. A minimum threshold strain is required for environmentally assisted decrease in the fatigue life.[7] Environmental effects on life occur primarily during the tensile–loading cycle and at strain levels greater than the threshold value. Strain rate and temperature have a strong effect on fatigue life in LWR environments.[6,7] Fatigue life decreases logarithmically with decreasing strain rate below 0.4%/s; the effect saturates at 0.0004%/s. Similarly, the fatigue ε–N data suggest a threshold temperature of 150°C; in the range of 150–325°C, the logarithm of life decreases linearly with temperature. The effect of DO on fatigue life may depend on the composition and heat treatment of the steel. Limited data indicate that, in high–DO water, the magnitude of environmental effects is influenced by material heat treatment.[7] In low–DO water, material heat treatment seems to have little or no effect on the fatigue life of austenitic SSs.

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, following the same procedures used to develop the current fatigue design curves of the ASME Code, environmentally adjusted fatigue design curves are developed from fits to experimental data obtained in LWR environments. 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.[8] Fatigue design curves based on a more rigorous statistical analysis of experimental data were developed by Keisler et al.[9] These design curves have subsequently been updated on the basis of updated statistical models.[4,5]

The second approach, proposed by Higuchi and Iida,[10] 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 fatigue evaluations, the fatigue usage factor for a specific load set, based on the current Code design curves, is multiplied by the environmental correction factor. Specific expressions for F_{en}, based on the Argonne National Laboratory (ANL) statistical models[4,5] and on the correlations proposed by the Ministry of International Trade and Industry (MITI) of Japan,[11] have been proposed.

This report presents experimental data on the effect of heat treatment on fatigue crack initiation in austenitic Type 304 SS in LWR coolant environments. A detailed metallographic examination of fatigue test specimens was performed to characterize the crack morphology and fracture morphology in austenitic SSs in air, and boiling water reactor (BWR) and pressurized water reactor (PWR) environments. The key material, loading, and environmental parameters and their effect on the fatigue life of these steels are also described. Statistical models are presented for estimating the fatigue ε–N curves for austenitic SSs as a function of material, loading, and environmental parameters. The two methods for incorporating the effects of LWR coolant environments into the ASME Code fatigue evaluations are presented.