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Abstract

The ASME Boiler and Pressure Vessel Code provides rules for the design of Class 1 components of nuclear power plants. Figures I–9.1 through I–9.6 of Appendix I to Section III of the Code specify design curves for applicable structural materials. However, the effects of light water reactor (LWR) coolant environments are not explicitly addressed by the Code design curves. The existing fatigue strain–vs.–life (ε–N) data illustrate potentially significant effects of LWR coolant environments on the fatigue resistance of pressure vessel and piping steels. Under certain environmental and loading conditions, fatigue lives of austenitic stainless steels (SSs) can be a factor of 20 lower in water than in air. 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. 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. Two methods for incorporating the effects of LWR coolant environments into the ASME Code fatigue evaluations are presented.

Foreword

This report examines the effects of various heat treatments and product forms (cast, welded or wrought) on the fatigue life of austenitic stainless steels (SSs) in light water reactor (LWR) environments. This report is one of a series dating back more than two decades, which has become increasingly relevant as licensees look forward to license renewal. This NUREG/CR report updates information presented in earlier reports by O. K. Chopra and his Argonne National Laboratory colleagues. The earlier reports include NUREG/CR-5704, Effects of LWR Coolant Environments on Fatigue Design Curves of Austenitic Stainless Steels; NUREG/CR-6717, Environmental Effects on Fatigue Crack Initiation in Piping and Pressure Vessel Steels; and, NUREG/CR-6787, Mechanism and Estimation of Fatigue Crack Initiation in Austenitic Stainless Steels in LWR Environments. The specific objective of this NUREG/CR is to present and discuss the effects of heat treatment on the fatigue life of stainless steels. Secondly, this test program takes advantage of improvements in test technique leading to more accurate data quality. Research such as reported here is required to support the realistic analysis of fatigue life of reactor components subjected to coolant environments and of cyclic changes in strain due to dead weight, thermal environment, and operating stresses.

Data from this research will be used to define the design curves in the ASME code or its equivalent. The data from this research and other published sources indicate that the existing code curves are non-conservative for austenitic stainless steels 304, 316 and 316NG. However, because of significant conservatism in quantifying other plant-related variables (such as the cyclic behavior, including stress and loading rates) involved in cumulative fatigue life calculations, the design of the current fleet of reactors is satisfactory, and the plants are safe to operate. The root of the problem with the realism of the code curves lies not in uncertainty about the degree of environmental degradation in specific environments or under specific heat treatments, but in the set of air environment results which were generated almost 30years ago and which serve as the basis for the stainless steel design curves. The air environment results are now known to be non-conservative and non-representative of most of the stainless steels used in actual nuclear component applications. The sources of the discrepancy reside in the specific choice of materials, test techniques and data analysis methods that were common practice when the database of air environment curves was developed more than forty years ago. Better specimen designs, improved test practices, and a better understanding of degradation mechanisms have produced a revised air environment baseline for stainless steels - one which is lower than the baseline which is now codified. The database described in this and earlier reports reinforces the NRC position that the design curves for the fatigue life of pressure boundary and internal components fabricated from stainless steel need revision. Several groups, including Argonne authors, a group of Japanese researchers, and the staff at Bettis Atomic Power Laboratory have proposed methods of establishing reference curves and safety factors for evaluation of the fatigue life of reactor components exposed to light-water reactor coolants and operational experience. This report presents a useful review of each of those proposed methods.

Carl J. Paperiello, Director
Office of Nuclear Regulatory Research

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Executive Summary

Section III, Subsection NB, of the ASME Boiler and Pressure Vessel Code contains rules for the design of Class 1 components of nuclear power plants. Figures I–9.1 through I–9.6 of Appendix I to Section III specify the Code design fatigue curves for applicable structural materials. However, Section III, Subsection NB–3121 of the Code states that effects of the coolant environment on fatigue resistance of a material were not intended to be addressed in these design curves. Therefore, the effects of environment on fatigue resistance of materials used in operating pressurized water reactor (PWR) and boiling water reactor (BWR) plants, whose primary–coolant pressure boundary components were designed in accordance with the Code, are uncertain.

The current Section–III design fatigue curves of the ASME Code were based primarily on strain–controlled fatigue tests of small polished specimens at room temperature in air. Best–fit curves to the experimental test data were first adjusted to account for the effects of mean stress and then lowered by a factor of 2 on stress and 20 on cycles (whichever was more conservative) to obtain the design fatigue curves. These factors are not safety margins but rather adjustment factors that must be applied to experimental data to obtain estimates of the lives of components. They were not intended to address the effects of the coolant environment on fatigue life. Recent fatigue–strain–vs.–life (ε–N) data obtained in the U.S. and Japan demonstrate that light water reactor (LWR) environments can have potentially significant effects on the fatigue resistance of materials. Specimen lives obtained from tests in simulated LWR environments can be much shorter than those obtained from corresponding tests in air.

This report presents experimental data on the effect of heat treatment on fatigue crack initiation in austenitic Type 304 stainless steel (SS) in LWR coolant environments. Fatigue tests have been conducted on two heats of Type 304 SS under various material conditions to determine the effect of heat treatment on fatigue crack initiation in these steels in air and LWR environments. A detailed metallographic examination of fatigue test specimens was performed, with special attention on crack morphology at the sites of initiation, the fracture surface, and the occurrence of striations.

Available fatigue ε–N data for wrought and cast austenitic SSs in air and LWR environments are reviewed, and statistical models that describe the effects of material and loading variables, such as steel type, strain amplitude, strain rate, temperature, dissolved oxygen (DO) level in water, surface roughness, and heat treatment on the fatigue lives of austenitic SSs are developed.

The new experimental data indicate that heat treatment has little or no effect on the fatigue life of Type 304 SS in air and low–DO PWR environments. In a high–DO BWR environment, fatigue life is lower for sensitized SSs; the decrease in life appears to increase as degree of sensitization is increased. The cyclic strain–hardening behavior of Type 304 SS under various heat treatment conditions is identical, only the fatigue life varies in environments that differ.

In air, irrespective of the degree of sensitization, the fracture mode for crack initiation (crack lengths up to ≈200 μm) and crack propagation (crack lengths >200 μm) is transgranular (TG), most likely along crystallographic planes, leaving behind relatively smooth facets. With increasing degree of sensitization, cleavage–like or stepped TG fracture, and, occasionally, ridge structures on the smooth surfaces were observed. In the BWR environment, the initial crack appeared intergranular (IG) for all heat treatment conditions, implying a weakening of the grain boundaries. For all four tested conditions, the initial IG mode transformed within 200 μm into a TG mode with cleavage–like features. It appears, however, that the size of the IG portion of the crack surface increased with the degree of sensitization. By contrast, for all samples tested in PWR environments, the cracks initiated and propagated in a TG mode irrespective of the degree of sensitization. Prominent features of all fracture surfaces in the PWR case were highly angular, cleavage–like fracture facets that exhibited well–defined "river" patterns. Intergranular facets were rarely observed, but when they were found, it was mostly in the more heavily sensitized alloys.

Fatigue striations normal to the crack advance direction were clearly visible beyond ≈200 μm on the fracture surfaces for all material and environmental conditions. Striations were found on both the TG and IG facets of the samples tested in BWR conditions, or co-existing with the "river" patterns specific to the samples tested in the PWR environment. Evidence of extensive rubbing due to repeated contact between the two mating surfaces was also found.

The orientation of the cracks as they were initiated at the specimen surface was also a function of the test environment. For air tests, cracks were initiated obliquely, approaching 45°, with respect to the tensile axis. By contrast, for tests in either a BWR or PWR environment, crack initiation tended to be perpendicular to the tensile axis. In all environments, the overall orientation of the crack became perpendicular to the tensile axis as the crack grew beyond the initiation stage.

In air, the fatigue lives of Types 304 and 316 SS are comparable; those of Type 316NG are superior to those of Types 304 and 316 SS at high strain amplitudes. The fatigue lives of austenitic SSs in air are independent of temperature in the range from room temperature to 427°C. Also, variation in strain rate in the range of 0.4–0.008%/s has no effect on the fatigue lives of SSs at temperatures up to 400°C. The fatigue ε–N behavior of cast SSs is similar to that of wrought austenitic SSs.

Review of the available data shows that the fatigue lives of cast and wrought austenitic SSs are decreased in LWR environments. The decrease depends on strain rate, DO level in water, and temperature.

A minimum threshold strain is required for environmentally assisted decrease in the fatigue life of SSs, and this strain appears to be independent of material type (weld or base metal) and temperature in the range of 250–325°C. Environmental effects on fatigue 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. 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 fatigue lives of wrought and cast austenitic SSs are decreased significantly in low–DO (i.e., <0.01 ppm DO) water. In these environments, the composition or heat treatment of the steel has little or no effect on fatigue life. However, in high–DO water, the environmental effects on fatigue life are influenced by the composition and heat treatment of the steel. For a high–carbon heat of Type 304 SS, environmental effects were significant only for sensitized steel. For a low–carbon heat of Type 316NG SS, some effect of environment was observed even for mill–annealed steel in high–DO water, although the effect was smaller than that observed in low–DO water. Limited fatigue ε–N data indicate that the fatigue lives of cast SSs are approximately the same in low– and high–DO water and are comparable to those observed for wrought SSs in low–DO water.

Statistical models for the fatigue life of austenitic SSs as a function of material, loading, and environmental parameters have been developed. The functional form of the model and bounding values of the important parameters are based on experimental observations and data trends. The models are recommended for predicted fatigue lives $\leq 10^6$ cycles. Consistent with previous work by Jaske and O'Donnell, the present results indicate that, even in air, the ASME mean curve for SSs is not consistent with the experimental data; it is nonconservative. Results that correspond to the 50th percentile of the statistical model are considered to be the best fit to the experimental data.

Two approaches are presented for incorporating the effects of LWR environments into ASME Section III fatigue evaluations**.** In the first approach, environmentally adjusted fatigue design curves are developed by adjusting the best–fit experimental curve for the effect of mean stress and by setting margins of 20 on cycles and 2 on strain to account for the uncertainties in life associated with material and loading conditions. These curves provide allowable cycles for fatigue crack initiation in LWR coolant environments. The second approach 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, a fatigue usage factor for a specific load set, based on the current Code design curves, is multiplied by the correction factor.

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