Corrosion Fatigue Mechanism of Nuclear-Grade Low-Alloy Steel in High-Temperature Water and Environmental Fatigue Design Model: Postprint

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Abstract

The service damage and life assessment of key components in light water reactor nuclear power plants are primarily based on the accumulation of material property data, understanding of environmental failure mechanisms, and construction of assessment models or methods. The currently widely used ASME fatigue design curves do not fully consider the effects of environment-load-material interactions. This paper investigates the environmental fatigue damage patterns and controlling mechanisms of nuclear-grade low-alloy steel through simulated corrosion fatigue testing in high-temperature high-pressure cyclic water representative of nuclear power plant conditions, constructs a fatigue design model incorporating environmental effects, provides environmental fatigue design curves convenient for engineering applications, and establishes an environmental fatigue safety assessment procedure for actual nuclear power plant components, with a trial implementation example presented.

Full Text

Preamble

Corrosion Fatigue Mechanism of Nuclear-Grade Low Alloy Steel in High Temperature Pressurized Water and Its Environmental Fatigue Design Model

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ABSTRACT

The service degradation and life assessment of key components in light water reactor nuclear power plants (NPPs) primarily depend on three pillars: the accumulation of service property data for component materials, understanding of environmental degradation mechanisms, and construction of reliable evaluation models or methods. The current ASME design fatigue code does not take full account of the complex interactions among environmental, loading, and material factors. In the present work, based on corrosion fatigue tests in simulated NPP high-temperature pressurized water, we investigated the environmental fatigue behavior and dominant mechanisms of nuclear-grade low alloy steel. A design fatigue model was constructed by incorporating environmentally assisted fatigue effects, and corresponding design curves were developed for engineering applications. Additionally, a process for environmental fatigue safety assessment of NPP components was proposed, with tentative assessment cases provided.

KEY WORDS nuclear-grade low alloy steel, high temperature pressurized water, corrosion fatigue, design model, environmental fatigue safety assessment

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1. ASME Fatigue Design Curve and EAF Effect

The pressure boundaries of light water reactor (LWR) nuclear power plants, including pressure vessels, main coolant pipes, and steam generators, operate in high-temperature pressurized water environments. Thermal stratification, start-up/shutdown cycles, and flow-induced vibrations can all contribute to environmental fatigue damage. Corrosion fatigue represents a potential failure mode that is critical for safety design, manufacturing, operation, inspection, regulation, safety assessment, and life management of nuclear power equipment. The widely used ASME fatigue design curves were originally derived from low-cycle fatigue data obtained in room-temperature air. The design curve was generated by applying safety margins to the best-fit curve—either dividing the strain by 2 or the life by 20, and taking the more conservative result. While the factor of 20 was intended to account for data scatter (2), size effects (2.5), surface finish, and environmental factors (4), it did not adequately consider the specific effects of LWR service environments.

Since Japanese researchers first identified that high-temperature pressurized water environments could affect material fatigue performance in the 1970s, decades of experimental research have confirmed that under specific combinations of environment, loading, and material conditions, high-temperature pressurized water can significantly reduce the fatigue life of nuclear structural materials—including carbon steels, low-alloy steels, stainless steels, and nickel-based alloys. This phenomenon is known as the environmentally assisted fatigue (EAF) effect. For example, low-alloy steels with sulfur content above 0.15 wt% tested at 300°C in water with dissolved oxygen greater than 1$×10ˆ{-6}$ and strain rates below $10^{-3}\ \%\cdot\mathrm{s}^{-1}$ can exhibit fatigue life reductions of more than 100 times compared to air environments. In response to these findings, Argonne National Laboratory in the United States, in collaboration with the Japan Nuclear Energy Safety Organization and other institutions, attempted to establish the ANL model and JSME model based on extensive experimental data. The ASME Code Committee has also begun addressing EAF effects, issuing Code Cases N-761 and N-792 in 2010 that recommend considering EAF in design curves, and is currently discussing how to revise the original ASME fatigue design curves. Based on the ANL fatigue model, the U.S. Nuclear Regulatory Commission (NRC) issued Regulatory Guide 1.207 in 2007, requiring that fatigue assessments for new LWRs must adequately consider environmental effects on structural material fatigue performance. This guideline recommends using the environmental correction factor $F_{en} = N_{air,rt}/N_{water,rt}$ (where F_{en} is the environmental factor, $N_{air,rt}$ is the fatigue life in room-temperature air, and $N_{water,rt}$ is the fatigue life in high-temperature pressurized water) to calculate the cumulative fatigue damage factor: $U = F_{en,1}U_1 + F_{en,2}U_2 + ... + F_{en,n}U_n$ (where $F_{en,i}$ is the environmental factor for fatigue damage process i, and U_i is the cumulative fatigue damage factor under room-temperature air conditions for process i).

China is actively developing its nuclear power industry with the goal of achieving self-reliance in design, manufacturing, operation, and evaluation technologies. However, neither the ASME Code Cases N-761 and N-792 nor the U.S. ANL model or Japanese JSME model include environmental fatigue strength data for domestic Chinese nuclear structural materials. Consequently, China' s nuclear power design, operation, safety review, and life assessment processes also face EAF challenges. Therefore, accumulating environmental fatigue strength data for domestic nuclear structural materials, developing independent fatigue life models and design curves, and evaluating the environmental fatigue safety margins of Chinese LWR components are of great significance.

2. Experimental Technology for Simulating NPP High-Temperature Cyclic Water Environments

The service environment of LWR pressure boundaries is characterized by high-temperature pressurized cyclic water with specific water chemistry conditions. Therefore, developing experimental apparatus to simulate these conditions is a prerequisite for research. The main technical challenges include: (1) High-temperature pressurized water environment simulation, such as achieving conditions up to 360°C and 20 MPa; precise control of water chemistry parameters including dissolved oxygen, dissolved hydrogen, pH, conductivity, and ion concentrations; dynamic sealing of fatigue loading shafts in autoclaves; and ensuring long-term stability and safety of equipment during extended test durations. (2) In-situ measurement and analysis techniques in high-temperature pressurized water, such as in-situ strain measurement and control in the gauge section of fatigue specimens, and in-situ monitoring of crack initiation and propagation.

Currently, only a few companies—including TOSHIN in Japan, CORMET in Finland, and CORTEST in the United States—can produce complete test systems, but these are expensive, structurally complex, and functionally limited. Moreover, their use, maintenance, and technical support are subject to external constraints, while domestic manufacturers lack the technology and capability to produce such integrated equipment. Due to these limitations, research on EAF in high-temperature pressurized water has been virtually non-existent in China. To enhance China's capability in simulating corrosion damage in nuclear power high-temperature water environments, the Institute of Metal Research, Chinese Academy of Sciences, has successfully developed key technologies for high-temperature pressurized water loops, precise water chemistry control, in-situ loading, and in-situ strain measurement in high-temperature pressurized water. This breakthrough has enabled experimental research on corrosion fatigue in simulated NPP environments and resulted in proprietary patented technologies.

3. Corrosion Fatigue Damage Mechanism of Nuclear-Grade Low Alloy Steel in High-Temperature Pressurized Water

The corrosion fatigue damage mechanism of nuclear-grade low-alloy steel in high-temperature pressurized water remains controversial, with two primary hypotheses: hydrogen-induced cracking mechanism and film rupture/slip dissolution mechanism. Due to the lack of direct experimental evidence for the microscopic processes of crack initiation and propagation, it remains difficult to definitively identify which mechanism controls environmental fatigue damage. Both hydrogen-induced cracking and film rupture/slip dissolution satisfy thermodynamic and kinetic conditions at the crack tip in high-temperature pressurized water, suggesting they may act synergistically.

Figure 1 [Figure 1: see original paper] presents the corrosion fatigue life data obtained for domestic nuclear-grade low-alloy steel SA508-III in simulated NPP high-temperature pressurized water. For comparison, the figure also includes environmental fatigue strength data for similar materials reported in NUREG/CR-6909. The results clearly show that high-temperature pressurized water environments significantly reduce the fatigue life of nuclear-grade low-alloy steel compared to room-temperature air, particularly under low strain rates and high dissolved oxygen conditions where fatigue performance deteriorates dramatically. Some data points even fall below the ASME fatigue design curve.

In low-alloy steels, fatigue cracks in high-temperature water primarily initiate at the specimen surface or subsurface. At low dissolved oxygen levels, cracks mainly nucleate at $MnS+Al_2O_3$ composite inclusions, while at high dissolved oxygen levels, they initiate primarily at surface corrosion pits. Figure 2 [Figure 2: see original paper] shows typical surface fatigue crack morphologies in nuclear-grade low-alloy steel. At high strain rates ($0.1\ \% \cdot s^{-1}$), fatigue cracks propagate in a zigzag manner with macroscopic branching, and failure typically results from continuous extension of a single dominant crack (Figure 2b). As the strain rate decreases to $0.01\ \% \cdot s^{-1}$, fatigue cracks become straighter (Figure 2c). At even lower strain rates ($0.001\ \% \cdot s^{-1}$), fatigue cracks propagate completely straight with numerous straight secondary cracks (Figure 2d). Statistical analysis reveals that the number of cracks per unit surface area in the gauge section increases with decreasing strain rate, demonstrating that crack initiation resistance in high-temperature pressurized water depends on strain rate: lower strain rates result in lower crack initiation resistance.

Figure 3 [Figure 3: see original paper] shows typical fatigue fracture morphologies. At high strain rates, the fracture surface is extremely rough (Figures 3a and 3c) with step-like features, fan-shaped quasi-cleavage patterns associated with MnS inclusions (Figure 3d), tear ridges, and terrace-like cracking characteristics (Figure 3b)—features somewhat consistent with typical hydrogen-induced cracking mechanisms observed in hydrogen-charged materials or stress corrosion tests. At low strain rates, the fracture surface becomes relatively flat (Figure 3e), with cracks propagating straight and perpendicular to the loading axis and showing slight crack arrest marks along the propagation direction (Figure 3f)—features somewhat consistent with the film rupture/slip dissolution mechanism. These results indicate that the controlling mechanism for corrosion fatigue cracking in nuclear-grade low-alloy steel transitions from hydrogen-induced cracking to film rupture/slip dissolution as strain rate decreases. The dissolution of MnS inclusions or increased dissolved oxygen content accelerates the electrochemical corrosion process within the fatigue crack system, thereby promoting corrosion fatigue cracking in high-temperature pressurized water.

4. Environmental Fatigue Design Model and Design Curves for Nuclear-Grade Low Alloy Steel

Although extensive experimental results have confirmed that LWR high-temperature pressurized water environments affect fatigue damage mechanisms and life, how to reasonably incorporate EAF effects into design curves remains a critical challenge for fatigue design and safety assessment of NPP pressure boundary components. For nuclear-grade low-alloy steel, constructing an environmental fatigue design model requires quantifying the effects of various factors on fatigue life in high-temperature pressurized water, which must be based on substantial environmental fatigue test data.

In this work, we investigated the environmental fatigue design model for nuclear-grade low-alloy steel based on corrosion fatigue test data for domestic SA508-III steel combined with collected and analyzed data for similar foreign materials (such as ASTM A508 Cl. 3 and A533B Cl. 1). Following the approach of Wu et al. for establishing environmental fatigue design models for nuclear-grade stainless steels and in accordance with ASME Code requirements, the fatigue design model is based on the simplified Langer equation. Assuming that environmental degradation reduces fatigue life by a product of influence factors (X_1, X_2, ···, X) multiplied by the air fatigue life, the Langer equation incorporating environmental effects becomes:

$$N_{25} = \frac{C}{\varepsilon_a - P} \cdot X_1 \cdot X_2 \cdot ... \cdot X_n$$

where N_{25} is the fatigue life corresponding to a 25% drop in peak stress, is the strain amplitude, C is a material fatigue strength constant, P is a material- and temperature-related constant, B is a material-related constant, and Q is an environment-related constant. By determining the coefficients P, B, Q and establishing boundary conditions for the influence factors X_1, X_2, ···, X , the fatigue life design equation considering EAF effects can be obtained.

Based on fatigue data for nuclear-grade low-alloy steel in air (Figure 4a [Figure 4: see original paper]), the best-fit equation is:

$$\varepsilon_a = 36.13 \cdot N_{25}^{-0.5625} + 0.132$$

Fitting error analysis (Figure 4b) shows good agreement. Corrosion fatigue test results in simulated NPP environments indicate that the main factors affecting environmental fatigue life include strain rate factor X (Figure 5a [Figure 5: see original paper]), dissolved oxygen factor X_{DO} (Figure 5b), steel sulfur content factor X_S (Figure 5c), temperature factor X_T (Figure 5d), and thermal aging factor X_{ta} (Figure 5e). By combining the air and environmental fatigue life models with boundary values for these primary influence factors, the equation coefficients P and Q were solved to obtain the environmental fatigue life model for nuclear-grade low-alloy steel:

$$\ln N_{25} = -1.786 \ln(\varepsilon_a - 0.0135) - 4.154 \ln\left(X_\varepsilon + X_{DO} + X_S + X_T + X_{ta}\right) + 6.406$$

where w_{DO} is dissolved oxygen content, w_S is steel sulfur content, $\dot{\varepsilon}$ is strain rate, T is environmental temperature, and t_a is thermal aging time. For engineering applications, following the ASME approach for constructing fatigue design curves, the strain amplitude in the environmental fatigue design model is converted to stress by multiplying by the elastic modulus and corrected for mean stress using the Goodman relationship. Further conservative adjustments are made to account for data scatter, specimen size, and surface roughness by dividing the fatigue life by a factor of 20 and the stress by 2, and taking the minimum values to obtain the environmental fatigue design curve (Figure 6 [Figure 6: see original paper]).

The resulting environmental fatigue design curve is more conservative than the ASME standard design curve. Comparison with experimental data reveals that the ASME standard design curve has insufficient safety margins under certain conditions, with some high-temperature pressurized water corrosion fatigue data points falling below the curve. In contrast, the environmental fatigue design curve covers all experimental data points with adequate safety margins.

5. Environmental Fatigue Safety Assessment Process for Actual Components and Tentative Implementation Cases

In engineering practice, fatigue assessment primarily involves calculating the fatigue cumulative usage factor U based on Miner' s linear fatigue cumulative damage theory: $U = \Sigma(n_i/N_i)$ (i = 1, 2, 3, ···, n), where N is the number of cycles to failure under stress S , and n is the actual number of cycles at stress S . According to ASME Code, a component is considered safe if U < 1 and unacceptable if U > 1.

Figure 7 [Figure 7: see original paper] presents a schematic flow chart for environmental fatigue life assessment of specific NPP components. The process begins by selecting the component for assessment and identifying the typical operational transients it experiences during plant operation, such as shutdown, startup, heat-up, cool-down, hydrostatic testing, inspection, reactor trip, and refueling. Design documents are reviewed to obtain the design life (allowed number of cycles) for each operational transient (n$_1$, n$_2$, ···, n , ···, n). Based on design documents and field monitoring data, stress, temperature, and pressure versus time curves are obtained for each transient. Finite element simulation is then used to determine the stress distribution and identify a series of maximum and minimum stress values at critical locations (P$_1$, P$_2$, ···, P , ···, P). Following ASME Code procedures, stress amplitudes S   (S$_1$, S$_2$, ···, S , ···, S) are calculated from the maximum and minimum stresses. Using the ASME fatigue design curve, the corresponding fatigue lives in air N   (N$_1$, N$_2$, ···, N   , ···, N   ) are determined for each stress amplitude. Using the environmental fatigue design curve proposed in this work, the corresponding environmental fatigue lives N   (N$_1$, N$_2$, ···, N   , ···, N   ) are obtained. The cumulative damage factors are then calculated: $U_{air} = \Sigma(n_i/N_{i,air})$ for room-temperature air and $U_{env} = \Sigma(n_i/N_{i,env})$ for the high-temperature pressurized water environment. If both U_{air} and U_{env} are less than 1, the component is safe. If both exceed 1, the component is unacceptable. If $U_{air} < 1$ but $U_{env} > 1$, an EAF risk exists that requires further confirmation through more detailed analysis or other means.

Table 1 provides a tentative implementation case for environmental fatigue safety assessment of a boiling water reactor carbon steel feedwater pipe safe end. The parameters related to plant operational transients, such as S , T, $\dot{\varepsilon}$, and design cycles, were taken from references [29-31]. Following the assessment process in Figure 7, the calculated fatigue cumulative usage factors are $U_{air} = 0.317$ and $U_{env} = 2.81$. Although U_{air} based on the ASME design fatigue curve is less than 1, U_{env} based on the EAF-incorporated environmental fatigue design curve exceeds 1, indicating that the feedwater pipe safe end may have insufficient safety margins under service conditions and potential failure risk that warrants serious attention.

Based on the total design cycles for typical operational transients and the anticipated cycles for 40-year and 60-year lifetimes (Table 2), the environmental fatigue cumulative usage factors for the inlet nozzle can be calculated as $\mathrm{U}_{40} = 0.472$ and $\mathrm{U}_{60} = 0.708$ using the process in Figure 7 (Table 3). Both values are less than 1, indicating that the inlet nozzle has adequate safety margins in the service environment and can be considered for life extension from 40 to 60 years.

Conclusions

This work has quantified the key factors affecting the corrosion fatigue life of nuclear-grade low-alloy steel in high-temperature pressurized water, including strain rate, dissolved oxygen content, steel sulfur content, temperature, and thermal aging time. An environmental fatigue design model incorporating EAF effects has been constructed, and engineering-friendly environmental fatigue design curves have been developed. The established environmental fatigue design curves for nuclear-grade low-alloy steel are more conservative than ASME standard design curves with adequate safety margins. A process for environmental fatigue safety assessment of actual NPP components has been established, with tentative implementation cases provided.

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