Stress intensity analysis of reactor vessel crack under thermal, irradiation and cyclic loading

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SUMMARY

The fatigue crack growth rate or propagation behavior of the base and weld materials of a liquid metal fast breeder reactor (LMFBR) or a light water reactor (LWR) pressure vessel under the thermal, irradiation (or irradiation and environment), and cyclic loading conditions is analyzed based on experimental results. The power function and exponential function crack (rate) laws and the theory of fatigue crack are introduced and postulated for the stress intensity factor, ΔK, or the effective stress intensity factor, K_{eff}, of the fatigue crack propagation behavior in the vessel materials. Experimental data of austenitic stainless steels 304 and 316, nickel alloy Inconel 600, and low-carbon alloy steels A516 and A533 of the LMFBR and LWR pressure vessels were measured, examined, analyzed, evaluated, and plotted for both the power function crack law and the exponential function crack law. The theoretical prediction and computerized experimental data are in excellent agreement and can be applied in the respective LMFBR and LWR pressure vessel design of a nuclear power reactor.

1 INTRODUCTION

The pressure vessel is one of the primary components of a light water reactor (PWR or BWR) or a liquid-liquid fast breeder reactor (LMFBR). The pressure or reactor vessel is normally operating under the conditions of elevated temperature, thermal cycling (due to reactor dynamics), coolant pressure, and irradiation effects (mainly, irradiation swelling, irradiation creep, irradiation hardening, and helium embrittlement in the inner wall surfaces). To study the design and operating experience of the large primary reactor component, it is necessary, required, and economical to test various specimens of feasible candidate materials of the reactor vessel in a laboratory, particularly, stress fatigue crack (SFC, or fatigue crack growth rate) and stress corrosion crack (SCC). The SFC or SCC could fail the component(s) and effect the reactor service lifetime [1,2].

The most commonly used vessel materials are of austenitic stainless steels (SS) AISI types 304, 304L, 308, 316, and 316L; some nickel alloys Inconel 600, 718, and Incoloy 800; and carbon alloy steels ASTM A516, A533, and A508; depending on reactor type and size.

In previous papers [3-8], the heat generation, temperature distribution, elastic thermal and pressure stresses, plastic stress and strains, irradiation swelling, irradiation creep, thermal fatigue analysis, etc. were carried out. The primary objectives of this paper are

1. To analyze the effects of elevated temperature, cyclic loading, and cyclic frequencies, and irradiation swelling, creep, hardening, and helium embrittlement on stress fatigue crack (SFC) of the vessel materials and to introduce the power function and exponential function laws of stress intensity factor range, $\overline{\Delta K}$, and effective stress intensity factor, K_{eff}, for predicting the fatigue crack growth rates in order to select reactor vessel material
2. To compare the environmental sensitivity of sodium, vacuum, and air or water to fatigue crack growth rate and to evaluate the irradiation effects on the base and weld materials of austenitic stainless steels for LMFBR reactor vessels and low-carbon alloy steels for LWR pressure vessels.

2 HEAT GENERATION, TEMPERATURE DISTRIBUTION, AND PEAK TEMPERATURE

Heat generation and temperature distribution with peak temperature in the inner wall of LWR or LMFBR reactor vessel are originated from the attenuation of primary and secondary gamma rays and absorption of fast and thermal neutrons from the reactor core [3].

The irradiation or test temperature is equivalent to the elevated temperature of a specimen irradiated in a fast or thermal neutron flux of a research reactor, such as the Experimental Breeder Reactor, EBR-II; the Ames Laboratory Research Reactor, ALRR; or the Advanced (Material) Test Reactor, ATR [9].

3 REACTOR DYNAMICS, THERMAL CYCLING, AND CYCLIC LOADING

Thermal cycling is induced by the inherent character of reactor dynamics. The thermal cycling induced by the reactor dynamics is called the thermal cyclic loading.

4 IRRADIATION EFFECTS

Pressure vessel or structural materials irradiated in a radiation environment of a nuclear reactor can induce various irradiation effects. The primary irradiation effects on a stress fatigue crack (SFC) of an LMFBR or LWR pressure vessel are irradiation swelling, irradiation creep, irradiation hardening, and helium embrittlement.

5 THERMAL, IRRADIATION CYCLING AND STRESS FATIGUE CRACK, THE CRACK THEORY

The combination and interactions of elevated temperature, thermal and irradiation cycling, cyclic loadings, and the irradiation effects can cause incipient thermal, irradiation, and stress fatigue cracks in the reactor vessel materials.

Under the yield condition of the distortion energy theory, the shearing stress nucleates cracks and the maximum principal stress propagates and extends cracks along the failure plane normal to the principal stress. This basic crack theory can adequately interpret the crack mechanisms and can apply to the thermal, irradiation, and mechanical crack in the vessel materials [6,9].

6 CYCLIC THERMAL, IRRADIATION AND MECHANICAL LOADINGS, IRRADIATION EFFECTS ON WELDMENTS

Metallic pressure vessels of LMFBR and LWR are made by welding the base and weld materials; particularly, 316/316L or 304/308 SS for LMFBR pressure vessels and A516/A508 or A533/A508 for LWR pressure vessels. The main concerns of welding the base and weld materials are (1) to prevent cracking in and near the weldments, (2) to maintain stress corrosion resistance at and near the welded area, i.e., free from the stress corrosion crack, SCC, and (3) to control the chemical composition and ferrite content of the welded joint.

7 CYCLIC TEMPERATURE, MECHANICAL LOADINGS, IRRADIATION AND ENVIRONMENT EFFECTS OF SFC PROPAGATION CRITERION

To analyze the behavior of stress fatigue crack, SFC, for a given material-environment combination, the growth rate of SFC propagation, da/dN, as defined, is commonly considered as a unique function of the stress intensity factor, K, or effective stress intensity factor, K_{eff}, where a is the half crack length, and N is the number of cycle of the cyclic loading. The values of K and K_{eff} are independent of any geometry of test specimen predicting the crack behavior of the reactor vessel to which the computerized test data are measured, collected, and then applied in design.

The stress fatigue crack propagation criterion of any reactor primary component can be expressed in terms of fatigue crack propagation or growth rate, da/dN, as a single function of stress range, σ, initial stress range, σ_o, half crack length, a, initial crack length, a_o, and combined material-environment constant, C.

$$\frac{da}{dN} \equiv f(\sigma,\ a,\ C) = f(\sigma/\sigma_o,\ a/a_o,\ C) \tag{1}$$

The stress intensity factor, K, consists of the thermal cycling factor, K_T, cyclic mechanical loading factor, K_M, cyclic irradiation factor, K_I, and cyclic environment factor, K_E. Hence,

$$K = K_T + K_M + K_I + K_E \tag{2}$$

In terms of the thermal stress range, σ_T, mechanical stress range, σ_M, irradiation stress range, σ_I, and environment stress range, σ_E, and the geometric function of a plate test specimen of thickness, h, half crack length, a, crack depth, d, and initial crack length, a_o; the components of the stress intensity factor are represented by

$$K_T \equiv \sigma_T f_T(a,\ d,\ h) = \sigma_T f_T(a/a_o,\ d/h) \tag{3}$$

$$K_M \equiv \sigma_M f_M(a,\ d,\ h) = \sigma_M f_M(a/a_o,\ d/h) \tag{4}$$

$$K_I \equiv \sigma_I f_I(a,\ d,\ h) = \sigma_I f_I(a/a_o,\ d/h) \tag{5}$$

$$K_E \equiv \sigma_E f_E(a,\ d,\ h) = \sigma_E f_E(a/a_o,\ d/h) \tag{6}$$

in which the geometric function of thermal, mechanical loading, irradiation, and environment cyclings includes enhancement factors for the effects of the irradiation temperature, irradiation creep, and irradiation corrosion in the specimen. The range of the enhancement factor varies by the order of 10 up to 100.

If the specimens are tested in the static or steady state and the static stress intensity factor is K^{sta}, then the specimen tests performed at the dynamic or transient state is denoted by K^{dyn}. The relationship between static and dynamic stress intensity factors of the stress fatigue crack propagation criterion can be expressed as

$$K = K^{dyn} \equiv K^{sta}\ F(cs,t) = F(c_s t/a_o) \tag{7}$$

where c_s is the sound wave speed of dynamic impact, and t is the time.

Equations (1) through (7) are basic equations that deal with the fatigue crack propagation or growth rate of the combined cyclic temperature, mechanical loading, irradiation, and environment effects in the steady state and at the unsteady state of the test specimens or the reactor vessel SFC propagation criterion.

8 THE J INTEGRAL, POWER, AND EXPONENTIAL FUNCTION CRACK LAWS

The path-independent integral or the J integral can be considered as a parameter of the fatigue crack propagation criterion. The J integral is an average measure of the crack tip elastic-plastic field that can be evaluated analytically and experimentally and is equivalent to the stress intensity factor, K. Therefore, the crack tip region can be characterized by the unique parameter K or the J integral of strain energy. The energy line integral J near the crack tip of an elastic-plastic material with strain energy density, W, displacement vector, u, traction vector, T (= $\sigma_{ij} n_i$), prescribed by the outward normal, n, along a contour, Γ, is defined as

$$J \equiv \int_\Gamma \left[w dy - T\left(\frac{\partial u}{\partial x}\right)\right] ds \tag{8}$$

where

$$w = w(\varepsilon_{mn}) = \int_0^{\varepsilon_{mn}} \sigma_{ij}\ d\ \varepsilon_{ij} \tag{9}$$

ε_{mn}, ε_{ij}, and σ_{ij} are strain and stress tensors near the crack tip of the elastic-plastic material of any closed curve, s.

8.1 Power function fatigue crack law

The fatigue crack propagation or growth rate is commonly expressed in terms of the power function law of crack rate at a relatively low irradiation temperature and high cyclic frequency [11-20].

$$\frac{da}{dN} = A(\Delta K)^n \tag{10}$$

in which $\Delta K = K_{max} - K_{min}$, K_{max}, K_{min} are maximum and minimum stress intensity factors. A and n are constants for a given material-environment combination or material-operation condition. Alternatively, the fatigue crack growth rate in the power function is

$$\frac{da}{dN} = A[K_{max}(1 - R)]^m \tag{11}$$

where m is another parameter, and $R = K_{max}/K_{min}$. By taking account of the effective stress ratio, the effective stress intensity factor, K_{eff}, is

$$K_{eff} = K_{max}(1 - R)^m \tag{12}$$

Introducing this into Eq. (10), the fatigue crack growth rate becomes

$$\frac{da}{dN} = A(K_{eff})^n \tag{13}$$

From the power function law of ΔK, or K_{eff}, various empirical equations for different material-environment combinations to predict da/dN have been proposed [17-20].

8.2 Exponential function crack law

At a relatively high temperature, high cyclic stress, and low frequency. The fatigue crack growth rate can be represented by the exponential function law [17-19]

$$\frac{da}{dN} = B \exp - \frac{\Delta K}{kT} \tag{14}$$

$$\frac{da}{dN} = B \exp - \frac{cK_{eff}}{kT} \tag{15}$$

where B is a constant; c is the conversion constant; $c\Delta K$ and cK_{eff} are the apparent activation energy; k is the Boltzmann constant, and T is the mean irradiation or test temperature. The factor $c\Delta K/kT$ or cK_{eff}/kT represents the combination of elevated temperature, cyclic loadings, and irradiation effects of the pressure vessel.

9 EXPERIMENTAL RESULTS OF REACTOR VESSEL MATERIALS

Fatigue crack specimens were tested in the EBR-II, ALRR, or ATR for type 304 and 316 stainless steels, nickel alloy Inconel 600, and alloy steels A516 and A533 at different combinations of temperature, cyclic frequency, stress ratio, neutron fluence, and heat treatment. The computer data were measured, calibrated, and analyzed from various sources [7,8,10,20] and are shown in Figs. 1 and 2.

The crack theory applied to the fatigue crack growth rate has a firm foundation. The exponential function fatigue crack law can be derived from the hyperbolic function law.

10. MAIN CONCLUSIONS

From the preceding analysis, the following main conclusions are made.

1. Under the cyclic thermal, mechanical loadings, and irradiation conditions; elevated temperature and low cyclic loadings have a great effect on the fatigue crack growth rate or SFC propagation behavior. For a given value of stress intensity factor range, K, or effective stress intensity factor, K_{eff}, the fatigue crack growth rate of austenitic stainless steels 304 and 316, nickel alloy Inconel 600, and alloy steels A516 and A533 can be adequately predicted for the LMFBR or LWR pressure vessel. The fatigue crack growth rate, da/dN, increases monotonously with ΔK or K_{eff}.

2. At a given temperature and neutron fluence, a low cyclic fre-

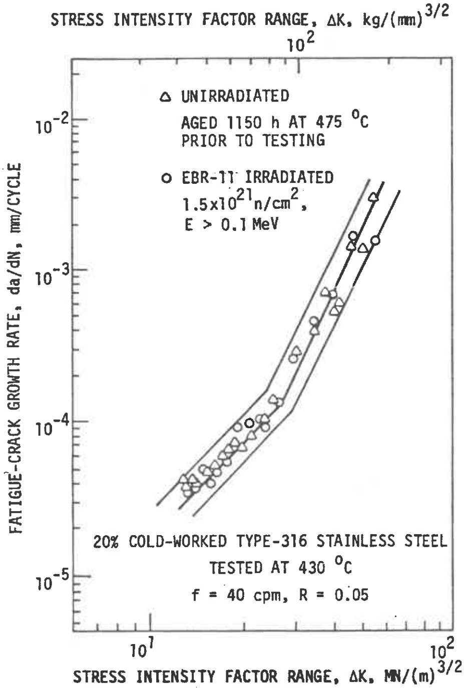

Fig. 1. Stress intensity factor range varies with fatigue crack growth rate of 20% cold-worked stainless steel 316 at temperature 430° C.

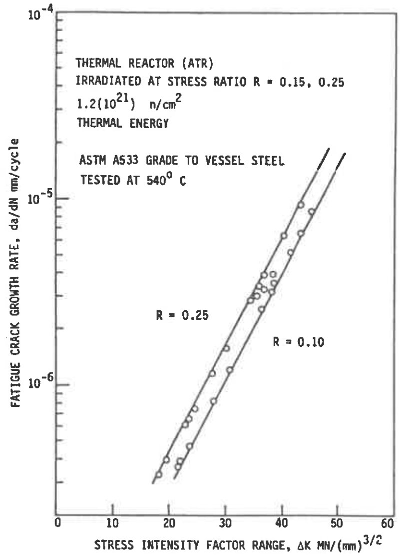

Fig. 2. Stress intensity factor range varies with fatigue crack growth rate of A 516 vessel steel tested at 540° C.

quency or high cyclic loading can cause high fatigue crack growth rate in the base and weld materials of the LMFBR or LWR pressure vessel.

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