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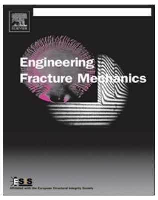

Fatigue crack tolerance design for stainless steel by crack growth analysis

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ABSTRACT

Fatigue damage of stainless steel was assessed by crack growth analysis. In order to characterize small crack initiation and growth, fatigue cracking behavior was observed by periodical replica investigations during a strain-controlled fatigue test in air at room temperature. It was shown that fatigue cracks with depths of several tens of micrometers were initiated in the early stage of the fatigue test and fatigue life could be estimated as a sum of the cycles for crack initiation of 100 μm in depth and those for growth to 3 mm. Use of the equivalent stress intensity factor allowed prediction of the crack growth for a given strain range. The crack growth analysis was also made to estimate the fatigue life prescribed by the design fatigue curve. Then, the growth prediction was made for thermal transient conditions to take advantage of the stress gradient in the depth direction and the relationship between the cumulative usage factor (CUF) and crack size was shown. It was concluded that fatigue damage accumulated in a stainless steel component can be estimated from an identified crack size, or the maximum CUF can be determined even if no crack was detected by the inspection.

1. Introduction

In structural design of nuclear power plant components, magnitude of fatigue damage is assessed using the cumulative usage factor (CUF), which is the ratio of the number of cyclic loadings expected during plant operation to the number of allowable cycles determined from the design fatigue curve (DFC) prescribed in design codes [1,2]. The CUF is used not only for designs but also for assessing structural integrity of operating plants [3,4], for which the factual CUF is calculated from the loading history actually experienced. Although the CUF is controlled at less than unity in the design, the factual CUF may exceed the critical value due to long term plant operation. Particularly, for components in the primary loop of nuclear power plants, the factual CUF is amplified by considering the detrimental effect of the high-temperature coolant water environment [5–8].

Even if the factual CUF exceeds unity during plant operation, the component does not necessarily fail due to the fatigue damage because design factors are considered in determining the DFC from test results. Actually, to the author's knowledge, no crack has been found in nuclear plant components for which fatigue damage was assessed in the design. In order to manage the fatigue damage of operating plants reasonably, it is important to know the actual fatigue damage accumulated in the components. Since the fatigue damage is brought about by crack initiation and growth [9,10] and failure of specimens in fatigue tests is caused by a grown crack, the fatigue damage assessment can be replaced with crack initiation and growth analysis. If the relationship between the crack size and the CUF is determined, the actual CUF can be estimated from the crack size identified by inspections [11]. Even if no crack is detected, possible damage can be estimated from the crack size detectable by the inspection technique applied.

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The crack growth analysis permits more reasonable fatigue damage assessment. For example, the crack growth analysis may derive a longer fatigue life for thermal fatigue than the assessment using the CUF. The thermal fatigue, which is caused by a fluid temperature fluctuation, is accompanied by a steep stress gradient in the depth direction [12–14] and the stress intensity factor (SIF) used for the crack growth prediction can incorporate the stress gradient in the growth analysis [15,16]. It should be noted that most cyclic loadings considered for nuclear power plant component designs are caused by a thermal transient such as plant startup and shutdown [17]. The stress gradient also appears at the notch root, where the peak stress is used for calculating the CUF. The crack growth analysis also allows the critical crack size to be taken into account. The critical crack size for component failure depends on geometrical and loading conditions of each component. The allowable cycles are extended if the component can tolerate a large crack.

The crack growth analysis for fatigue damage assessment has already been implemented in the flaw tolerance analysis prescribed in Section XI Appendix L of the ASME (the American Society of Mechanical Engineers) Boiler Pressure Vessel Code (hereafter, ASME code) [18,19]. The flaw tolerance analysis is performed if the CUF exceeds unity. The residual allowable cycle is calculated by a crack growth analysis according to the fitness-for-service (FFS) assessment procedure prescribed in Section XI for a postulated crack when no crack is found by an inspection. If the crack growth analysis can be made for a small crack, which corresponds not to CUF = 1 but to CUF $\ll$ 1, it is possible to assess the fatigue damage by the crack growth analysis.

Treatments of loading conditions and material properties in the crack growth analysis made for the FFS assessment [18,20] are different from those for the CUF calculation for design, although both CUF calculations and crack growth analysis are made for the same plant components and loading conditions. For example, the strain range is used as the fatigue damage driving force in the design, while the stress range (the SIF range) is used for the crack growth prediction. The crack growth rates used for the FFS assessment have been obtained under the small scale yielding condition [21], while strain-controlled fatigue test results were used for determining the DFC [22,23]. The effect of plastic strain was considered using a correction factor (Ke factor) [24] in design assessments, whereas no correction is made for general yielding in the crack growth analysis for FFS assessments. As for an influence of temperature, the growth rate used for FFS assessments depends on the temperature [20], although the same DFC is used for various temperature conditions [23,25]. The mean stress effect is considered according to the modified Goodman's diagram in the DFC [23], although the stress ratio is used for the crack growth analysis [20]. The structural factor (safety margin) is considered in the DFC by a fixed ratio [23], whereas no explicit structural factor is given for the growth rate in FFS assessments. In order to assess the fatigue damage by the crack growth analysis and correlate the CUF to crack size, the gaps between the CUF calculation and crack growth analysis for FFS assessments should be closed.

This study aimed at adopting crack growth analysis to the design and maintenance of stainless steel components. First, the fatigue crack initiation and growth on specimen surface was observed by periodical replica investigations in Chapter 2. Then, in Chapter 3, fatigue life was estimated by predicting crack growth with an incubation period before a small crack initiation. Furthermore, allowable cycles prescribed in the DFC were simulated using the crack growth rate for FFS assessments. In Chapter 4, the procedure for predicting crack growth for thermal stress was developed and it was shown that the fatigue damage was reasonably assessed by the crack growth prediction. Further discussions were made in Chapter 5 for treatments of mean stress, environmental effect and safety margin.

2. Observations of crack initiation and growth

2.1. Fatigue test procedure

The material used for the fatigue test was solution heat-treated Type 316 austenitic stainless steel. Its chemical composition (in mass%) was: C, 0.06; Si, 0.50; Mn, 1.30; P, 0.031; S, 0.027; Ni, 10.18; Cr, 16.94; Mo, 2.02 and balance Fe. The average 0.2% proof strength, tensile strength, elongation and reduction of area from two tensile tests were 297 MPa, 611 MPa, 0.58 and 0.79, respectively.

Fig. 1 shows the specimen geometry. The diameter was 10 mm at the minimum cross section and it was changed gradually in order to localize the crack initiation to the center in the axial direction. The stress and strain were derived assuming that the specimen had a parallel gage section. The 12.5 mm gage length extensometer was used for strain measurements. The surface of the specimen was polished using up to 3 μm diamond paste.

The pull-push axial strain-controlled fatigue test was conducted in a room temperature laboratory environment using a servo-electric test machine. Strain range $\Delta\varepsilon$ was controlled to 0.6% under a constant strain rate of 0.4%/s and the number of cycles to failure (fatigue life) N_f was 41,500. The crack growth during the tests was monitored by taking replicas of the specimen surface using acetyl cellulose films. The interval of the replica investigations was 2000 cycles at the beginning of the test and it was reduced to 500 cycles before the specimen failure.

2.2. Test results

Fig. 2 shows the change in the measured surface length ($2c$) of a primary crack, which caused specimen failure. The primary crack was first observed at the number of cycles of N = 4000. The initial length was 12.5 μm and it grew continuously. The crack coalescence was not observed for the primary crack, although many cracks were observed on the specimen surface.