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Fatigue crack initiation and growth of 16MnR steel with stress ratio effects

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ABSTRACT

The effects of stress ratio on the fatigue crack initiation and growth were investigated by a newly developed unified model, which is based on the cyclic plasticity property of material and a multiaxial fatigue damage criterion in incremental form. The cyclic elastic–plastic stress–strain field was analyzed using the general-purpose finite element software (ABAQUS) with the implementation of a robust cyclic plasticity theory. The fatigue damage was determined by applying the calculated stress–strain responses to the incremental fatigue criterion. The fatigue crack growth rates were then obtained by the unified model. Six compact specimens with a thickness less than 3.8 mm were used for the fatigue crack initiation and growth testing under various stress ratios (−1.0, 0.05, 0.1, 0.2, 0.3 and 0.5). Finite element results indicated that crack closure occurred for the specimen whose stress ratio was less than 0.3. The combined effects of accumulated fatigue damage induced by cyclic plastic deformation and possible contact of cracked surfaces were responsible for the fatigue crack initiation and growth. The predicted results agreed with the benchmark mode I fatigue crack growth experiments very well.

1. Introduction

The failure of the load bearing structural component induced by the fatigue damage generally consists of three stages: small crack (also known as the fatigue crack initiation), stable fatigue crack growth and final fracture. Jiang and Feng [1] argued that the differentiation of the first two stages was qualitatively distinguishable but quantitatively ambiguous. For the cracked structures, the cyclic plasticity of the material near the crack tip is the main reason for the fatigue damage resulting the fatigue crack initiation and growth [1]. The range of stress intensity factor which is an important parameter of the linear elastic fracture mechanics was utilized by Paris et al. [2] as the bulk measure of the cyclic plasticity at the crack tip, namely the driving force of fatigue crack growth. The famous Paris law can successfully describe the stable fatigue crack growth (stage II) under constant-amplitude loading. Following the pioneering work of Paris, most researchers related the fatigue crack initiation and growth to the range of stress intensity factor. However, if the influences of stress ratio [3–8], small cracks [9] or variable amplitude loading [10] on the fatigue crack growth behavior should be considered, the cyclic plasticity of the material near the crack tip cannot be properly approximated any more by the range of stress intensity factor. In order to obtain the true driving force of fatigue crack initiation and growth, modifications must be made to consider the effects of these widely existent cases in engineering. By investigating the influence of stress ratio on crack propagation and crack initiation region, Shahani et al. [6] proposed a unified model for the fatigue crack growth rate in variable stress ratio. Lee et al. [7] studied the effects of stress ratio, load history and environment on the fatigue crack growth behavior of 7075-T651 aluminum alloy. A unified two parameter driving force model for fatigue crack growth rate, accounting for the residual stress and stress ratio effects, was validated by the experimental results.

The crack closure concept has been widely regarded as the critical mechanism responsible to the stress ratio effects on fatigue crack growth since Elber's discovery [11,12]. The contact phenomenon of coupling crack surfaces was observed even though the applied load was tensile during the unloading portion of a loading cycle. The crack closure was attributed to the residual compressive stress induced by the cyclic plasticity of the crack tip material. To consider the crack closure, Elber [11] defined an effective range of stress intensity factor based on the assumption that the fatigue crack propagates only when the applied load range is between the maximum load and opening load of a loading cycle. The fatigue crack opening load is not a unique value which is influenced by many factors such as measurement location and technique, stress ratio as well as material [12,13]. Hertzberg et al. [14] and Jiang et al. [15] reexamined the plasticity-induced crack closure occurred in the fatigue crack propagation process by placing a shim into the crack mouth of the testing specimen. The experimental phenomenon revealed that the fatigue crack was still propagating even in the portion of a loading cycle associated with the crack closure. The compliance-based closure measurement of artificially induced crack closure experiment cannot be correlated quantitatively by Elber's effective range of stress intensity factor. In order

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to characterize the measurements by a consistent form of the effective range of stress intensity factor defined by Elber, Paris et al. [16] introduced a new concept of partial crack closure, which indicated that significant concerns should be given to the load range below the opening load while investigating the fatigue damage induced by cyclic loading. In other words, crack closure cannot completely shield the material at the crack tip from fatigue damage. Kujawski [13] argued that an apparent effectiveness of the crack closure phenomenon was dependent upon the maximum range of stress intensity factor and the crack tip opening profile, and developed an enhanced model of partial crack closure for correlation of stress ration effects in aluminum alloys. The crack closure concept is also used for analyzing the small crack growth properties within the notch plastic zone. Attempts have been made to bridge the fatigue crack initiation and propagation using the numerical stress–strain analysis together with a fatigue damage criterion [17]. By describing the crack growth at notches quantitatively with a detailed consideration of the cyclic plasticity, a unified model was developed based on the same fatigue damage mechanism of the fatigue crack initiation and propagation [1,18,19].

The current investigation focused on the stress ratio effect on the fatigue crack initiation and growth in the plane stress state. The finite element method was used to obtain the elastic–plastic stress–strain response with the implementation of a robust cyclic plasticity theory. A multiaxial fatigue criterion based on the critical material plane was used to access fatigue damage. The fatigue crack growth rate was then calculated by the unified model. The effects of stress ratio on the fatigue crack behavior and possible crack closure were discussed thoroughly based on the simulation results.

2. Unified model for fatigue crack initiation and growth

The fatigue crack initiation and crack growth is based on the same mechanism of accumulative fatigue damage. A fresh crack tip is created while the accumulative fatigue damage of the material elements located at the crack tip reaches the critical damage D_0. The fatigue crack growth can be regarded as a process of continuous crack nucleation of material elements at the crack tip.

A general multiaxial fatigue damage model incorporating the critical plane concept was used to determine the accumulative fatigue damage induced by the cyclic loading. The critical plane is defined as the maximum damaging plane. The fatigue damage criterion takes the following incremental form [20]:

$$dD = < \sigma_{mr}/\sigma_0 - 1 >^m (1+\sigma/\sigma_f)[b\sigma d\varepsilon^p + (1-b)\tau d\gamma^p/2] \tag{1}$$

where D is the fatigue damage, σ_{mr} is a material memory parameter, σ_0 is the endurance limit, σ_f is the true fracture stress, ε^p and γ^p are plastic strains corresponding to the normal stress σ and the shear stress τ respectively, b is a parameter characterizing the cracking behavior, m is a material constant, and the symbol $\langle\ \rangle$ denotes the Macauley bracket. The details of determining the material constants σ_0, σ_f, D_0, m and b were given in Ref. [20]. The material constants for 16MnR steel used in the fatigue crack growth experiments were reported in the paper [21] and they are: $\sigma_0 = 240$ MPa, $\sigma_f = 632.2$ MPa, $D_0 = 3200$ MJ/m^3, $m = 0.85$ and $b = 0.38$. The value of b is larger than 0.375, which means that the 16MnR steel displays shear cracking under shear loading but normal cracking under tension–compression loading.

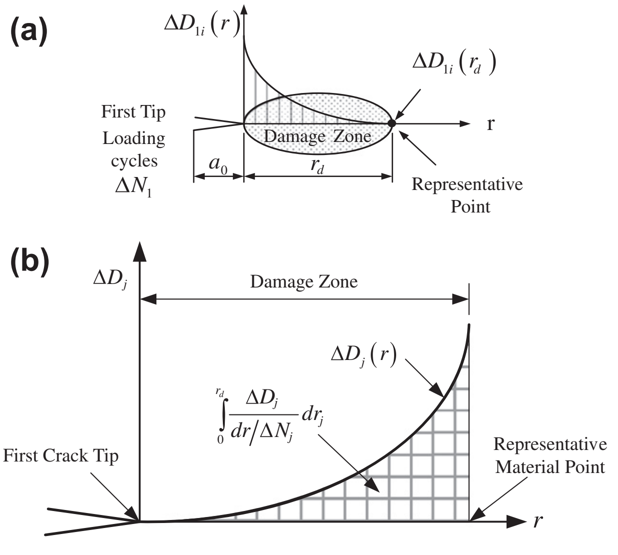

Fig. 1. Accumulative fatigue damage for representative point.

The typical accumulative process of the fatigue damage for the representative point was illustrated in Fig. 1a. In the period of the fatigue crack tip propagating from the current position ($r = 0$) to the target material element ($r = r_d$), every loading cycle causes the fatigue damage $\Delta D(r)$ to the representative point, as given in Fig. 1b. If the relationship between the loading cycles $N(r)$ and the fatigue damage $\Delta D(r)$ is determined, the accumulative fatigue damage can be easily obtained. We have [19]:

$$\int_0^{r_d} \frac{\Delta D dr}{dr/\Delta N} = D_0 \tag{2}$$

where, ΔD, ΔN and $dr/\Delta N$ are the functions of the radial coordinate r. The critical fatigue damage parameter D_0 is a material constant. If the region between $r = 0$ and $r = r_d$ is divided into k parts, the fatigue crack growth rate at the representative point can be derived as [19]:

$$\frac{da}{dN} = \frac{\int_{r_{k-1}}^{r_d} \Delta D(r)dr}{D_0 - \left(\frac{\int_{r_0}^{r_1} \Delta D(r)dr}{(dr/dN)_1} + \frac{\int_{r_1}^{r_2} \Delta D(r)dr}{(dr/dN)_2} + \cdots + \frac{\int_{r_{k-2}}^{r_{k-1}} \Delta D(r)dr}{(dr/dN)_{k-1}} \right)} \tag{3}$$

3. Modeling of fatigue crack initiation and growth

3.1. Experiments

The 16MnR steel is a low carbon steel, which is widely used in the low and medium pressure vessels and pipelines in China. The detailed chemical composition, microstructures, and basic mechanical properties of 16MnR steel have been reported in the paper [22]. Standard compact tension specimens with different notch root radius at the tip of the slot, as shown in Fig. 2, were used in the fatigue crack initiation and growth experiments. The fabrication procedure of specimens and experiment scheme refer to an early publication [23]. With the aim of convenient for observation of fatigue crack initiation and growth, one surface of each compact specimen was polished before testing. Therefore, the thickness of each specimen listed in Table 1 is less than the designed value, 3.8 mm. Six different stress ratios, −1.0, 0.05, 0.1, 0.2, 0.3 and 0.5, were tested under the constant amplitude loading. The detailed loading conditions and the geometry of each specimen were listed in Table 1, in which r_0 is radius of the circular notch, a_0 is distance between the notch root and the line of action of the externally applied load, R-ratio is the stress ratio defined as the minimum load over the maximum load in a loading cycle, and $\Delta P/2$ is the loading amplitude.

According to the ASTM standard E647-05 [24], the stress intensity factor range for the standard compact tension specimen can be calculated by the following formula: