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Small fatigue crack growth mechanisms of 304 stainless steel under different stress levels

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ABSTRACT

The aim of this paper was to clarify the fatigue crack initiation and small crack growth mechanisms of 304 austenitic stainless steel at different stress levels. Results showed that the stress level effect on small crack growth rates could hardly be distinguished for the stress levels tested. Grain boundaries might act as the crack initiation sites and played an important role on the propagation of small cracks. Once the surface crack length reached the critical size of 0.2 mm, the crack would propagate fairly quickly, resulting in fracture of specimen.

1. Introduction

In the past two decades, small fatigue cracks have been extensively studied for the reason that more than 70–80% of the total fatigue life may be spent in the crack initiation and small crack growth stages [1]. Previous researches [2–5] showed that cracks initiated at the very beginning of fatigue life and the propagation of small crack could be obviously influenced by the inherent microstructure, resulting in the abnormal propagation behavior as compared with the long crack behavior. Therefore, the precise measurement of small crack growth rate as well as the good understanding of small crack growth mechanism was very important in the reliable prediction of the fatigue life of materials.

The austenitic stainless steel has been widely used in process and power generating industries as piping and structural material. Fatigue is one of the main causes of failure for these components due to the dynamic or alternating stresses. There have been many investigations on long fatigue crack growth of austenitic stainless steels. For instance, Tsay et al. [6] performed fatigue crack growth tests to evaluate fatigue behavior of 304 stainless steel specimens with and without laser processing in air and gaseous hydrogen. They found that the extent of quasi-cleavage fracture was related to the formation of strain-induced martensite, which would contribute to an increased fatigue crack growth rate of all specimens in gaseous hydrogen. Kelestemur et al. [7] used compact tension specimens to investigate the threshold fatigue crack growth behavior of 304 austenitic stainless steel under three different atmospheres. Results showed that the material was sensitive to the hydrogen atmosphere. However, relatively few studies have focused on small fatigue crack growth mechanisms. For instance, Okazaki et al. [8,9] found that once the small cracks of 304 stainless steel grew up to a size of few grains, they predominantly propagated with strain cycling, while most of the small cracks stopped propagating when they grew up to one grain size. Furthermore, it was also shown that the small crack growth rate significantly slowed down where the crack length was integral multiple of the grain size. Ogata et al. [10] used tubular specimens to investigate the initiation and propagation behavior of small fatigue cracks of 304 stainless steel. Results showed that the biaxial low-cycle fatigue life could be estimated from the relationship between the crack propagation rate and the equivalent shear strain range. Suh et al. [11,12] obtained quantitative information such as the initiation, growth and coalescence behavior of small cracks in 304 stainless steel via surface replicas and photomicrographs. The results showed that the accurate determination of these parameters was critical for the application of fracture mechanics to fatigue life assessment. However, experimental photos or data showing a complete small crack propagation process have not yet been available in their researches. The reason was that small crack testing was more difficult to perform than long crack testing.

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In-situ scanning electron microscopy (SEM) and replica were the two main methods to quantitatively determine the small crack growth rate. The advantage of in situ SEM method was its high resolution, but the locations of the small crack cannot be easily determined until the crack length was on the order of several hundred of micrometers except for the specimens with pre-cracks. In such a case, the nucleation and propagation of the small fatigue crack in the early stage cannot be easily observed. However, the above mentioned problems could be solved by using the replication method in which the small cracks can be backtracked from the final replica to the earliest replica. There were two replication methods, namely acetate tape replication and two-part silicon based replica method commercially known as RepliSet. Although the traditional acetate tape method has been used for decades, it had several drawbacks since it could influence the fatigue life of the specimen and it would shrink by about 10% when the acetyl cellulose film was fully dried. The application of acetone during the replica process was thought to protect the crack tip from the ambient atmosphere laboratory environment, thus resulting in an apparent increase in fatigue life comparing with the non-replica tests [13]. As an alternative to the acetyl cellulose film, RepliSet did not have these drawbacks and was easy to conduct [14,15].

The aim of this paper was to clarify the initiation and propagation mechanisms of small fatigue crack of 304 austenitic stainless steel under different stress levels at room temperature. A complete process from crack initiation and propagation was recorded by using the two-part silicon based replica method. The effect of stress level on small fatigue crack growth rate was investigated.

2. Experimental procedure

2.1. Material and specimen

The material used in this study was a 304 austenitic stainless steel supplied in the form of a rolled bar with a diameter of 30 mm, and with the chemical compositions in wt.%: 0.015 C; 0.53 Si; 1.74 Mn; 0.0048 S; 0.03 P; 18.37 Cr; 8.16 Ni; 0.019 Mo; 0.059 N; balance Fe. The mechanical properties of the steel were listed in Table 1. A single edge notch tensile (SENT) specimen was used to produce naturally occurring cracks, as shown in Fig. 1. The SENT specimen had a notch at the center of the specimen with a radius of 3.2 mm. The local stress concentration would be created by the existence of the notch and small cracks were allowed to initiate naturally at the root of notch. The semicircular geometry provided easy access to the notch surfaces to allow monitoring of the cracks by replicas. In order to remove the micro-defects as well as control the roughness of the machined surface of specimen and to identify the prevailing microstructure, the surface of the notch was polished with sandpapers up to a mirror finish and etched in an oxalic acid solution for 2 min prior to fatigue tests. The microstructure of 304 stainless steel was shown in Fig. 2. The initial grain structure consists of equiaxed austenitic grains with a few annealing twins. The average grain size of the steel was estimated to be 40 μm. The direction of the surface crack growth was perpendicular to the rolling direction of the specimens.

2.2. Fatigue tests

The axial tensile fatigue tests were carried out using a stress-controlled sine-wave loading mode on an Instron 8800 servo-hydraulic test machine. The frequency of fatigue testing was 8 Hz and the stress ratio was 0.1. Three different values of maximum stress were loaded at the center of specimen, namely 370, 350 and 330 MPa, to study the effect of stress level on small crack growth. The stress applied was the equivalent on the cross section of the reduced area of the specimen. All tests were terminated when one continuous crack propagated across the notch root. Each cyclic test with replica was interrupted sequentially at a given time interval while a tensile load of 80% of σ_{max} was kept when the replica was applied on the specimen surface. However, the time interval was estimated according to the number of cycles to fracture of the parallel specimen that was not interrupted for replica. Generally, the above procedure for making replicas was repeated at intervals of approximately 1000 cycles, such that about 25–30 replicas were made during the fatigue test. A static tip mixing nozzle combined with dispensing gun was used to dispense the RepliSet material onto the notch. The detailed procedure of replicating process can be found in Ref. [15]. After the tests, the major crack that led to the final fracture could be identified from the replicas and the crack initiation can be backtracked through observing the replicas at different time intervals. The crack morphologies, which were recorded by the dried replicas, were observed by using optical microscopy (OM) with a resolution of 0.1 μm when the crack lengths were smaller than 0.3 mm. For the cases that the crack lengths were longer than 0.3 mm, the replicas were observed by using scanning electron microscopy (SEM). The crack length

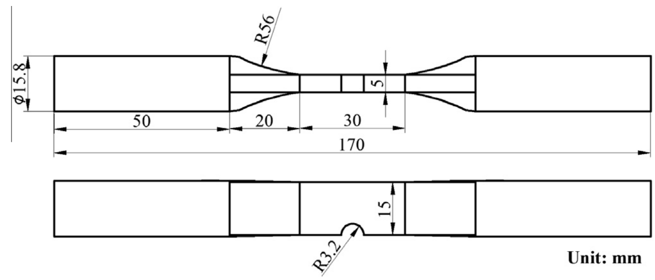

Fig. 1. Shape and dimensions of single edge notch tension specimen used in fatigue tests.

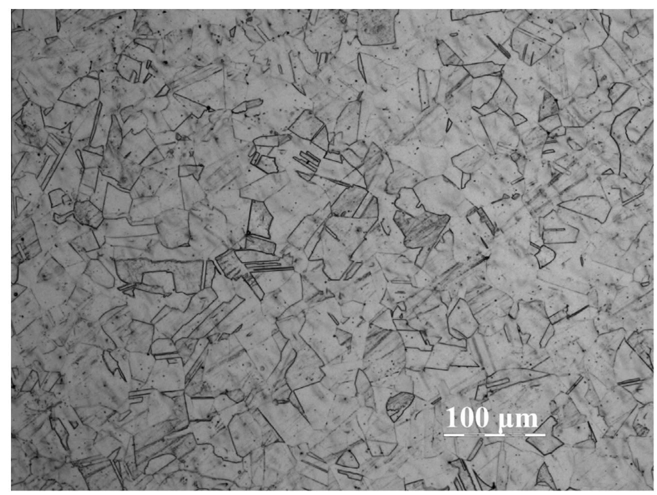

Fig. 2. Optical micrograph of 304 austenitic stainless steel.

Table 1
Tensile properties of the 304 austenitic stainless steel.

Material	Yield strength $R_{p0.2}$ (MPa)	Ultimate tensile strength R_m (MPa)	Elongation A (%)	Reduction of area Z (%)
304 stainless steel	297.55	668.64	57	70