International Journal of Fatigue 32 (2010) 1081–1089

Contents lists available at ScienceDirect

International Journal of Fatigue

journal homepage: www.elsevier.com/locate/ijfatigue

Fatigue properties of 316 stainless steel and its failure due to internal cracks in low-cycle and extremely low-cycle fatigue regimes

Masayuki Kamaya *

Institute of Nuclear Safety System, Inc., 64 Sata, Mihama-cho, Mikata-gun, Fukui 919-1205, Japan

A R T I C L E I N F O

Article history:
Received 9 June 2009
Received in revised form 6 November 2009
Accepted 10 December 2009
Available online 16 December 2009

Keywords:
Low-cycle fatigue
Extremely low-cycle fatigue
Stainless steel
Internal crack
Surface crack
Bulk damage

A B S T R A C T

It is important to know residual fatigue strength of materials in the extremely low-cycle fatigue (ELCF) regime in order to assess structural integrity after large cyclic strain caused by an earthquake. In the ELCF regime, it was pointed out that not only surface cracking but also additional bulk damage reduces the fatigue life. In this study, the fatigue strength of stainless steel in the low-cycle and ELCF regimes and the effects of bulk damage on fatigue strength were investigated. Type 316 stainless steel was subjected to axial cyclic strain up to strain amplitude of 6%. Also, the change in fatigue life was investigated when the surface layer of the specimens was removed during the fatigue tests. It was shown that not only the surface cracking but also the bulk damage affected the fatigue life. It was also shown that the bulk damage consisted of two factors: internal cracking and local damage. Internal cracks were observed on the fractured surface when the strain amplitude was more than 1%, and in some cases the specimen was fractured by these internal cracks. Local damage reduced the incubation period before crack initiation and fatigue life decreased as the strain amplitude increased. In all cases, the experiment conducted under the strain amplitude $\varepsilon_a = 0.5\%$, neither the internal cracks nor the local damage affected the fatigue life.

1. Introduction

Plant components are occasionally subjected to large cyclic deformation due to earthquakes, and so it is important to know the fatigue strength under large cyclic strain, particularly for nuclear power plant components that have recently been subjected to a large earthquake [1]. Shimada et al. [2] investigated the fatigue strength in the extremely low-cycle fatigue (ELCF) regime, in which plastic strain amplitude ε_{pa} was more than 2.5% and the number of cycles was less than 100 as the minimum case. They showed that the fatigue life of annealed carbon steel was less than that predicted from the so-called Manson–Coffin relation obtained from conventional low-cycle fatigue tests, of which strain amplitude ε_a was less than 1.5%. In the ELCF regime for carbon steel, the pearlite structure fractured inside the specimen prior to the initiation of surface cracks. Furthermore, exhaustion of ductility due to large strain in addition to the pearlite fracture reduced the fatigue life [2,3]. Komotori and Shimizu [4] pointed out that work hardening caused by cyclic strain reduced the ductility of materials.

On the other hand, in the low-cycle regime up to $\varepsilon_{pa} = 1.27\%$ for 70/30 brass specimens, Murakami et al. [5,6] showed that the ductility was reduced not by cyclic strain hardening but by the initiation of small cracks of surface length more than 0.4 mm. They also pointed out, through low-cycle fatigue tests up to $\varepsilon_{pa} = 2.0\%$ of S45C, that the fatigue life is dominated by surface crack growth and cyclic damage has no influence on the crack growth rate. They concluded that the Manson–Coffin relation can be regarded as an alternative expression for a crack growth law, which is determined by the crack length and applied stress–strain [6]. This conjecture has been confirmed by experiment, in which fatigue life was extended when the surface layer of specimens was removed during the fatigue tests [7,8].

These results suggest that some additional damage process should be considered in the ELCF regime, although surface crack growth dominates the fatigue life in the low-cycle regime. In the above-mentioned study by Komotori and Shimizu [4] for ELCF, the reduction in ductility was not recovered by removing the surface cracks. Tateishi et al. [9] showed that the fatigue life was lower than the Manson–Coffin relation at more than $\varepsilon_a = 4\%$ in bending tests, in which the cracks were initiated only from the surface. Accordingly, not only surface cracks but also the "damage" (hereafter called "bulk damage") accumulated in the material due to cyclic strain seems to affect the fatigue life in the ELCF regime. Kuroda [10] showed that the fatigue life of ELCF could be represented by a Manson–Coffin type relation which was modified to incorporate additional damage effects such as exhaustion of ductility.

The damage mechanism depends on the material and it is still not clear whether or not the bulk damage reduces the fatigue life

* Tel.: +81 770 379114; fax: +81 770 372009.
E-mail address: kamaya@inss.co.jp.

0142-1123/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijfatigue.2009.12.003

of stainless steel, which is commonly used in nuclear power plant components and is free from the pearlite structure. It was shown that, in the ELCF regime up to ε_{pa} = 20%, the fatigue life of pure iron fractured due to surface cracking agreed well with the Manson–Coffin relation from the conventional low-cycle regime [2].

The main objective of this study was to investigate the fatigue strength of stainless steel in the ELCF regime and to examine the effect of bulk damage on fatigue strength. First, the low-cycle and extremely low-cycle fatigue strengths of Type 316 stainless steel were examined under axial cyclic strain up to ε_a = 6%. Then, in order to assess the role and magnitude of the bulk damage, the change in fatigue life by removing the surface layer of specimens during the fatigue tests was investigated. Finally, the damage process due to cyclic deformation as well as the fatigue strength in the ELCF regime of stainless steel was discussed.

2. Experimental procedure

Pull–push (axial) strain-controlled fatigue tests were conducted in ambient air at room temperature. The material used for the fatigue tests was a solution heat-treated Type 316 austenitic stainless steel, whose alloying constituents and mechanical properties are as listed in Tables 1 and 2, respectively. Hourglass-type specimens with the configuration and dimensions shown in Fig. 1 were used. The surface of the specimens was polished using up to 3 μm diamond paste in order to observe cracks on the surface.

Table 1
Chemical content of test material (wt.%).

Fe	C	Si	Mn	P	S	Ni	Cr	Mo
Bal.	0.05	0.25	1.31	0.032	0.030	10.17	16.81	2.00

Table 2
Mechanical properties of test material.

0.2% Proof strength	Tensile strength	Elongation	Reduction of area
294 MPa	602 MPa	0.60	0.76

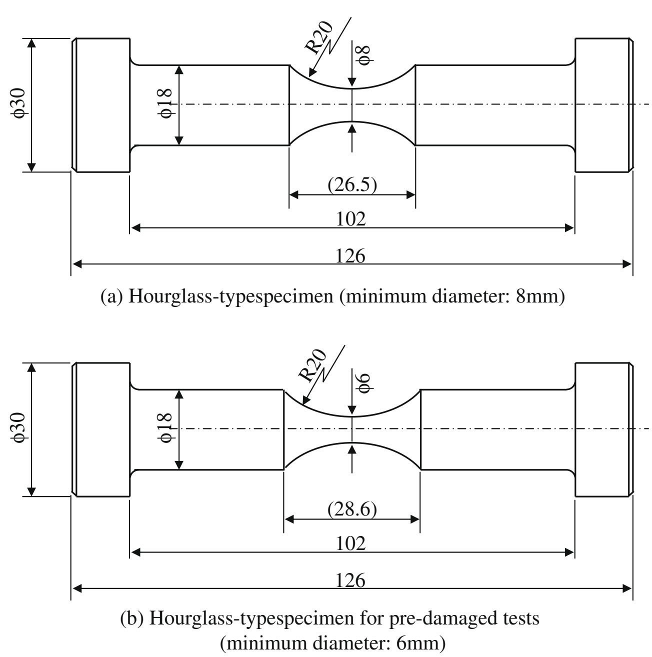

Fig. 1. Geometry of test specimen.

First, a series of tests was performed at constant strain amplitude to obtain the $\varepsilon - N$ curve using specimens with a minimum diameter of 8 mm (Fig. 1a). The strain was measured by the change in diameter and the nominal axial strain amplitude, which was estimated by assuming the constant volume, was changed from 0.5% to 6%.

Secondly, pre-damaged tests were carried out. In these tests, first the damaged specimen was prepared by an interrupted fatigue test using the hourglass-type specimen shown in Fig. 1a. The test was stopped at 50% or 80% of the predicted total life, and the diameter of the specimen was reduced from 8 mm to 6 mm by machining as shown in Fig. 1b. Then, the specimen was subjected to the fatigue test of the same strain amplitude. If the fatigue life is dominated by crack growth, removal of all cracks from the surface should make the fatigue life equal to that of undamaged specimens.

The strain rate during the fatigue tests was set to 0.4%/s for all conditions. Two specimens were tested for each test condition.

3. Experimental results

3.1. Fatigue tests of undamaged specimens

Fig. 2 shows the obtained ε–N curve and Table 3 summarizes the test results. The number of cycles to fracture N_f was defined

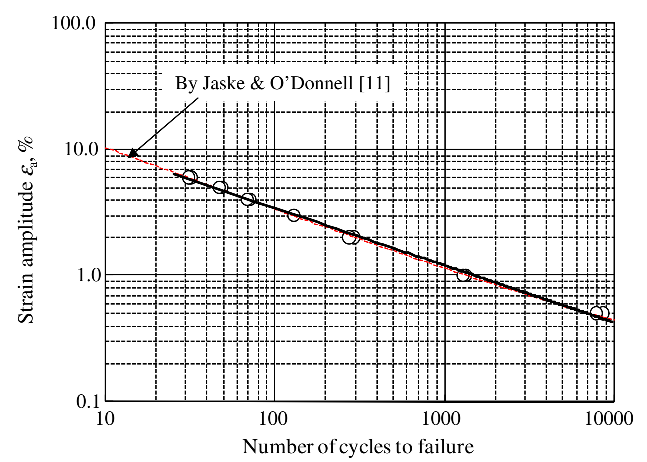

Fig. 2. Fatigue properties of Type 316 stainless steel obtained using Hourglass-type specimen.

Table 3
Summary of fatigue tests.

Strain ε_a (%)	N_f	Internal cracks
0.5	8634	–
0.5	7840	No
1	1340	No
1	1294	No
2	293	No
2	275	Primary
3	130	Sub
3	130	Sub
4	71	Sub
4	69	Sub
5	49	Sub
5	47	–
6	32	No
6	31	No

Primary: specimen fractured due to internal cracks.
Sub: several internal cracks were observed at fractured surface while specimen fractured due to surface cracks.