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Development of a miniaturized hour-glass shaped fatigue specimen

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Abstract

Diametral strain-controlled push–pull fatigue tests with zero mean strain were carried out with miniaturized hour-glass shaped specimens of an austenitic stainless steel in solution annealed condition at room temperature. The specimens had a diameter of 1.25 mm at the minimum cross section and a total length of 25.4 mm. The number of cycles to failure (N_f) was equal to or slightly greater than that obtained with standard size specimens. N_f was also revealed to be rather insensitive to the specimen load axis offset, indicating that the requirement of the specimen alignment to the load axis was not very severe for the miniaturized specimen.

1. Introduction

It is widely accepted that an intense neutron source with spectrum relevant to that of the fusion neutron environment is indispensable for fusion reactor materials development. The International Fusion Materials Irradiation Facility (IFMIF), an accelerator driven D–Li stripping reaction neutron source, has been proposed for the materials development and the conceptual design of the facility has been carried out [1]. The irradiation volume of IFMIF available for the blanket structural materials development is 500 cm^3. Because a large number of specimens have been proposed for irradiation, application of miniaturized specimens is essential to use IFMIF. The specimen volume for the standard size push–pull fatigue test seems to be too large (the specimen volume in ASTM E606 is about 10 cm^3) [2,3]. It may be also true even for the subsized specimens of 1.27 cm^3 used for fission reactor irradiation [4–6]. Therefore, development of a much smaller fatigue specimen is planned.

Fatigue testing after irradiation will be carried out in hot cells with remote handling equipment. Considering the limited ability of specimen manipulation in the cells, the specimen and the test method need to be rather insensitive to specimen misalignment to the loading axis and simple for operation. Effects on the fatigue test results of surface preparation, specimen size and the misalignment of this new miniature specimen are evaluated.

2. Specimen and the fatigue test

2.1. Specimen

The specimen size effect has been reported to appear for such cases that the number of grains at the minimum cross section in the gage section was smaller than a critical value. The critical value was reported to range from 3 to 10 depending on the tests and materials. For instance, the critical number for a creep test on an austenitic steel was indicated to be about 10 [7]. The size of the new specimen at the minimum cross section was chosen to be greater than 1 mm: large enough to contain 10 grains for most commercial alloys.

Relatively large flat end tabs were used for the handling and specimen clamping. The configuration of the test area of the specimen was determined to be proportional to the flat-sheet fatigue specimen with circular cross section in ASTM E606. To minimize the effort for the irradiation capsule design and the development of remote handling equipment, total length of 25.4 mm and

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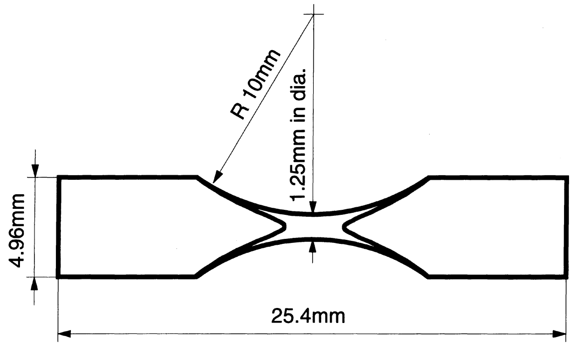

Fig. 1. Miniaturized fatigue specimen.

the end tab width of 4.95 mm were chosen to be same as those for our tensile specimens in current irradiation experiments. The configuration of the specimen is shown in Fig. 1.

Comparing the fatigue specimen with cylindrical gage section with an hourglass-shaped specimen, the resistance for buckling during push–pull fatigue testing at a high strain amplitude is rather high for the latter. This is one of the reasons for the choice of the hour-glass type configuration. On the other hand, there are some difficulties in estimating the axial strain range from the results of the diametric strain of hour-glass specimens. For this reason, the choice of a specimen configuration with a cylindrical gage section has been recommended by several researches [8].

2.2. Fatigue test

A solution annealed austenitic stainless steel was used. Chemical composition (in mass fraction) of this steel is 14.6% Cr, 16.2% Ni, 2,4% Mo, 0.06% C and 0.24% Ti. Some of the specimens were solution-annealed after machining for 0.5 h at 1273–1323 K in a vacuum and polished in the longitudinal direction. This was followed by electropolishing in a 20% H_2SO_4-80% CH_3OH solution. During the electropolishing, the end tabs were coated to prevent dimensional change. Hereafter, specimens of solution annealed, polished and electropolished after the machining will be called electropolished specimens.

Fig. 2 shows the specimen, grips and a diametral extensometer. The specimen (A) was clamped between the flat body of a grip (B) and a counter plate (C) with bolts (D). A counter plate with smooth or serrated surface was used. Strain was measured by diametral extensometer (E) attached at the minimum cross section of the specimen.

An electrohydraulic closed-loop servo-controlled testing machine with a 5 kN load cell was used. Tests were performed with a sinusoidal waveform at zero mean strain. Total axial strain (ε_a) was estimated from the diametral strain (ε_d) with a form of $\varepsilon_a = -2\varepsilon_d$. The equivalent axial strain ranged from 0.8% to 1.5% at a strain rate of about 0.15%/s. All tests were performed at an ambient temperature in air.

3. Results and discussion

3.1. Effect of annealing and surface preparation

Tests were carried out with as-machined and electropolished specimens. Fig. 3(a) and (b) show the specimen surfaces in the gage section observed in the as-machined and the electropolished specimens, respectively. Flaws formed during machining are seen in the as-machined specimen.

The as-mentioned speciment failed after 6773 cycles, while the electropolished specimen failed after 16819

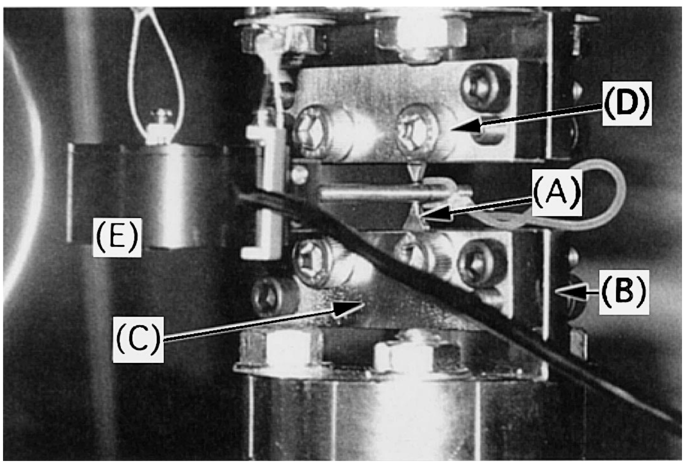

Fig. 2. A view of the miniaturized fatigue specimen clamped by grips and the extensometer.

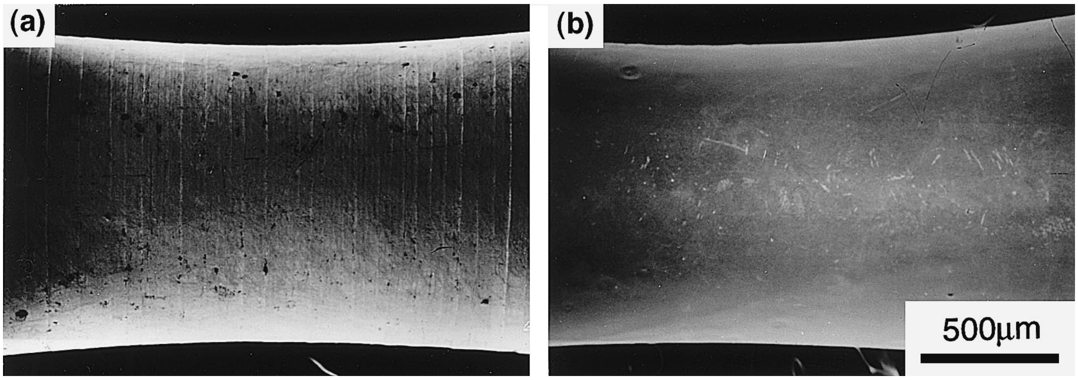

Fig. 3. Specimen surface in the gage section before testing. (a) As-machined specimen, (b) electropolished specimen.

cycles at a total axial strain range ($\Delta\varepsilon_t$) of 1%. Fatigue cracks in the as-machined specimen seem to be initiated at the flaws, as seen in Fig. 4(a). On the other hand, no particular site for enhanced crack nucleation is seen in the electropolished specimen (Fig. 4(b)).

The stress ranges of the as-machined specimens were higher by several percent than those of the electropolished specimens tested at the same $\Delta\varepsilon_t$. This may result from the hardened surface layer in the as-machined specimen introduced during specimen fabrication. The higher stress range corresponds to a larger elastic strain range and suggests a smaller plastic strain range. The smaller plastic strain range often leads to larger a number of cycles to failure (N_f). However, as-mentioned specimens exhibited smaller N_f. The surface flaws formed during machining might lead stress concentration to cause earlier micro-crack nucleation. N_f might be decreased by the earlier crack nucleation in the as-machined specimens.

3.2. Effect of the specimen grip surface and the alignment of the specimen

Two kinds of counter plates with smooth and serrated surfaces were used. The serrated surface contained 10 teeth per 10 mm. N_f values for the specimens clamped with serrated counter plates were much smaller than those clamped with smooth surface counter plates. Because the teeth of the serrated counter plates were too rough to clamp the specimen end tabs uniformly, specimens were bent during the clamping. This introduced bending motion at the minimum cross section during testing. The bending motion during testing might increase strain amplitude locally to cause smaller N_f. On the other hand, flat counter plates clamped the specimen end tabs rather uniformly.

To evaluate the effect of misalignment of the loading train on N_f, fatigue tests were conducted with the lateral displacement of about 100 μm for load axis, as illus-

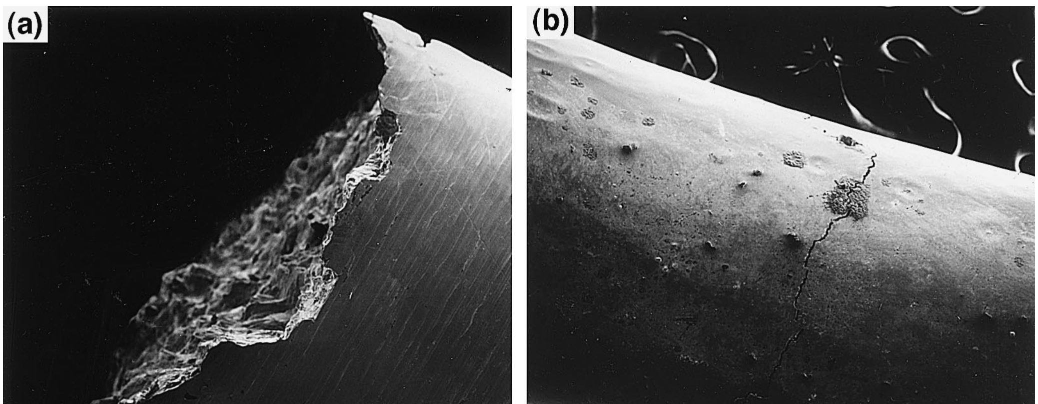

Fig. 4. Cracks nucleated in the gage section of (a) as-machined and (b) electropolished specimens.

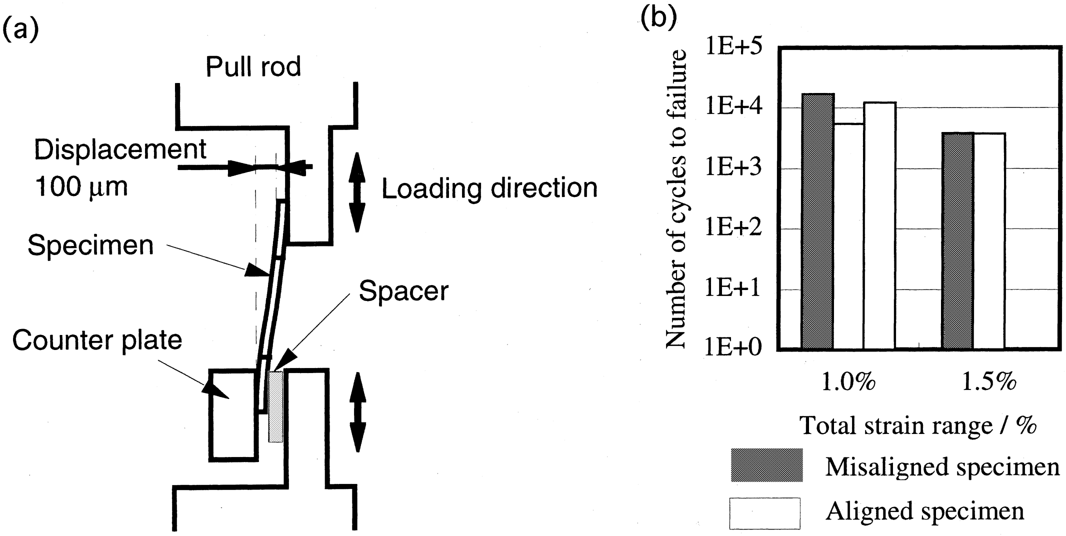

Fig. 5. Off set of the specimen to the loading axis and the effect on N_f. (a) schematic illustration to introduce specimen offset to the loading axis by the insertion of a plate (spacer), (b) effect of misalignment by the offset on N_f.

trated in Fig. 5(a). Insertion of a 100-μm-thickness metal sheet between the specimen end tab and a flat body of a grip introduced the displacement. Fig. 5(b) shows the comparison of N_f between aligned and misaligned specimens. Total axial strain ranges were 1% and 1.5%. No large difference of N_f between them was obtained. The displacement might not introduce significant bending strain at minimum cross section in the hourglass-shaped specimen.

It can be said that N_f of the hourglass shaped specimen was rather sensitive to bending motion during testing. On the other hand, it was rather insensitive to the lateral displacement.

3.3. Effect of specimen size on the fatigue property

Fig. 6 shows the fracture surface of a miniaturized specimen tested at $\Delta\varepsilon_t$ of 1%. The crack initiated at the specimen surface and propagated transgranularly. The crack surface was observed to be almost perpendicular to the loading direction. Fatigue striations were observed on the surfaces. The fracture surfaces of the miniaturized specimens were similar to those of the standard size specimens.

The N_f values with the miniaturized specimens were compared with those with standard size specimens of solution annealed type 304 or 316 stainless steels tested

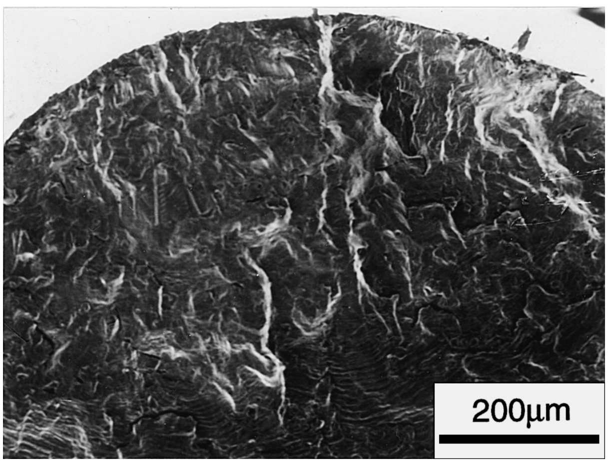

Fig. 6. Fracture surface of a fatigue tested specimen.

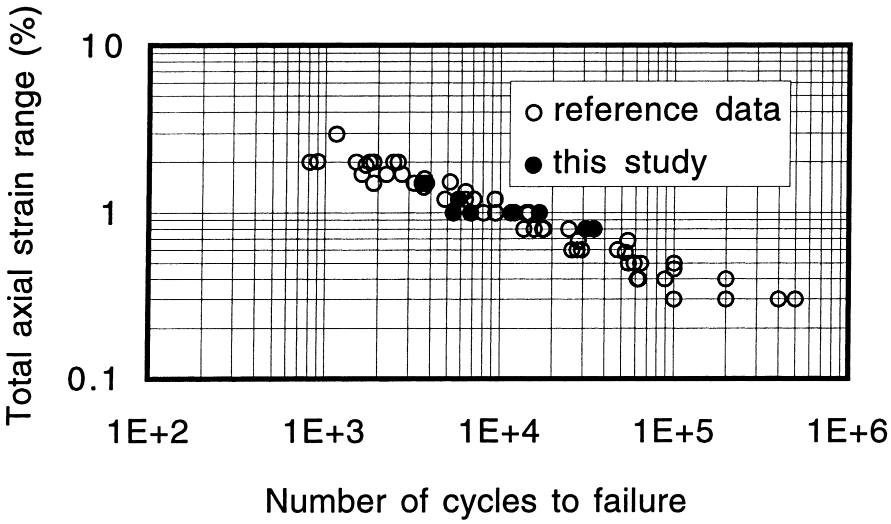

Fig. 7. Total axial strain range ($\Delta\varepsilon_t$) to the number of cycles to failure (N_f) relation obtained with the miniaturized fatigue specimens and the standard size specimens. The axial strain range for the miniaturized specimen was calculated from the diametric strain range.

in air at room temperature. As seen in Fig. 7, the N_f values with the miniaturized specimens were equal to or slightly greater than those with standard smooth bar specimens. No strong effect of specimen size on N_f was found for this miniaturized specimen.

4. Conclusions

1. The N_f of electropolished specimens was three times higher than those of the as-machined specimens. The N_f results of the electropolished specimens were in the same range as the data of standard size specimens.
2. The misalignment introduced by the lateral displacement of 100 μm to loading axis did not introduce any significant effect on N_f.
3. The specimen size effect on N_f was not large, and no effect on fracture surface was observed.

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