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Low cycle fatigue properties of a low activation ferritic steel (JLF-1) at room temperature

A. Nishimura *, T. Nagasaka, N. Inoue, T. Muroga, C. Namba

National Institute for Fusion Science, 322-6 Oroshi, Toki, Gifu 509-5292, Japan

Abstract

To investigate fatigue properties of a low activation ferritic steel (9Cr–2W steel, JLF-1), low cycle fatigue tests were performed in air at room temperature under axial strain control for a complete push–pull condition. The strain rate was 0.4% s^{-1}. Cyclic strain-hardening was observed within the initial 20 cycles, and then cyclic strain-softening occurred gradually until the final failure, though the plastic strain range did not change significantly. Tensile peak stresses in hysteresis curves measured at around half the number of cycles to failure depended on the total strain range. The drop in the peak stress by the cyclic strain-softening increased with decreasing total strain range. The regression curve of the total strain range against the fatigue life was formulated using the Manson–Coffin equation and the fatigue life of JLF-1 steel was compared with that of 8Cr–2W steel.

1. Introduction

Low activation steels, 8Cr–2W (F82H) steel and 9Cr–2W (JLF-1) steel, have been developed as candidate structural materials for a fusion device/reactor [1,2]. These materials are ferritic/martensitic steels, and the irradiation effect of neutrons on the static mechanical properties of these materials has been investigated [3,4]. Since the low activation ferritic steel will be applied in the structural components in a plasma vacuum vessel and since it must support dynamic stresses during plasma operations, the fatigue properties of these steels must be clarified and stored in a database.

Although the fatigue response of F82H has been investigated up to 923 K [5–7], the fatigue tests of JLF-1 started only recently [8] and there is yet not enough data. So, in this study, low cycle fatigue tests under axial strain control were carried out in air at room temperature, and the basic fatigue properties of JLF-1 were clarified. In addition, a comparison of the fatigue life of JLF-1 steel with F82H steel was performed.

* Corresponding author. Tel.: +81-572 58 2118; fax: +81-572 58 2616.

E-mail address: nishi-a@lhd.nifs.ac.jp (A. Nishimura).

2. Experimental procedure

The chemical composition of the JLF-1 steel plate in wt% is Fe–0.10C–0.05Si–0.45Mn–0.003P–0.002S–0.003Al–8.85Cr–1.99W–0.20V–0.080Ta–0.0231N–0.0002B–<0.01Ni–<0.05Cu–<0.001Mo–<0.002Nb. The plate was 25 mm thick and heat-treated as follows: 1323 K/3.6 ks/air cooled (normalizing) and 1052 K/3.6 ks/air cooled (tempering). In addition, a 1013 K/10.8 ks/furnace cool was performed for the plate that was welded [9,10]. Fatigue test specimens were machined out of the base metal area of the welded plate, and the microstructure was tempered martensite [10]. The shape and dimensions of the test specimen are shown in Fig. 1. The round bar specimen was designed according to JIS Z 2279 [11].

Low cycle fatigue tests were carried out at room temperature in air under axial strain control using a Shimazu ServoPulser with a dynamic load capacity of +/−98 kN. The axial strain was measured by an extensometer (MTS Model 632.13F-21, G.L. is 10 mm.) attached to the specimen directly with two small springs. A completely reversed push–pull condition was applied, and the total strain range was controlled using a triangular wave with an axial strain rate of 0.4% s^{-1}. The number of cycles to failure was defined as (1) the point where the tensile peak stress decreased by 25% from an

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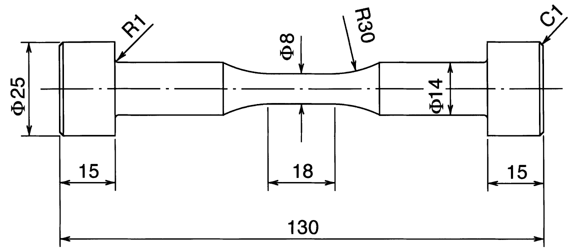

Fig. 1. Low cycle fatigue test specimen.

extrapolation curve of the tensile peak stress against number of cycles, or (2) as the number of cycles at fracture in the case that the specimen was broken. Before the tests, specimens were polished in the longitudinal direction with #1500 paper to erase the circumferential machining marks.

3. Test results and discussion

The number of cycles to failure, N_f, as a function of the total strain range, $\Delta\varepsilon_t$, is shown in Fig. 2. The specimens designated A cracked inside the gage length (G.L.) and ones designated B cracked at the edge of the extensometer. Type C means that a fatigue crack initiated outside the gage length. The characters in parenthesis show secondary or additional crack types. One example of the specimen surface is shown in Fig. 3. A Type B crack initiated at the edge of the extensometer, and a Type A crack was formed independently inside the gage length. Since the fatigue life is strongly affected by crack initiation, a Type B crack would reduce the fatigue life when it initiated fast and propagated.

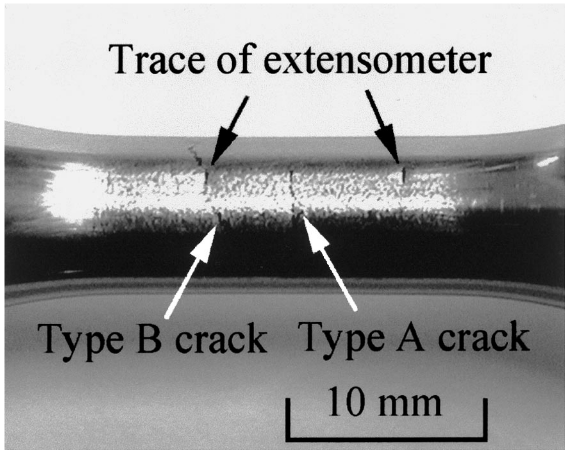

Fig. 3. Example of fatigue cracks on specimen surface. ($\Delta\varepsilon_t$; 1.6%).

Relations between plastic and elastic strain ranges, $\Delta\varepsilon_p$, $\Delta\varepsilon_e$, and N_f are shown in Fig. 4. The plastic and elastic strain ranges are obtained from hysteresis curves at around $N_f/2$. Excluding the three points for which N_f is less than 700 cycles, the data fall on the line. Since a Type B crack propagated widely on these three specimens, the data were not used for making a regression curve. Omitting these data, a Manson–Coffin type regression formula was obtained as follows:

$$\Delta\varepsilon_t = 91.02N_f^{(-0.5956)} + 1.023\ N_f^{(-0.09462)}. \qquad (1)$$

The first term is related to $\Delta\varepsilon_p$ and the second one to $\Delta\varepsilon_e$.

The change in the tensile and compressive peak stresses during fatigue life is shown in Fig. 5. Both of the peak stresses increased initially and decreased gradually until the final failure. Near the final failure, the peak

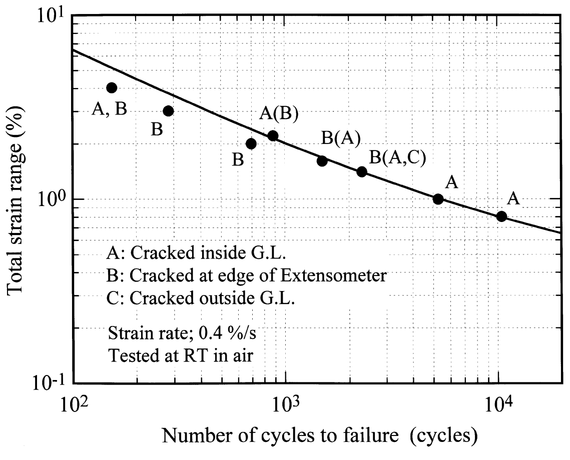

Fig. 2. Fatigue life of JLF-1 under axial strain-controlled testing conditions.

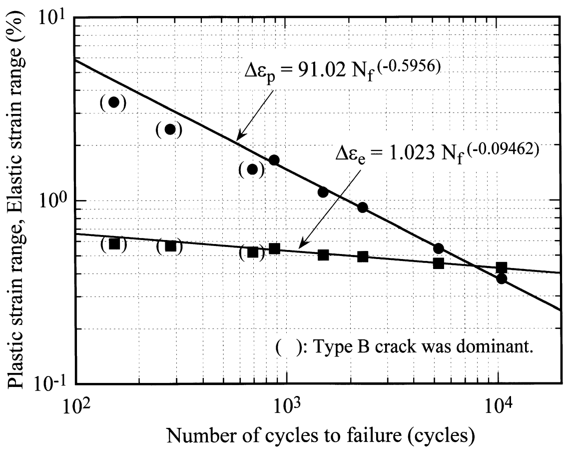

Fig. 4. Relations between plastic strain range, elastic strain range and number of cycles to failure.

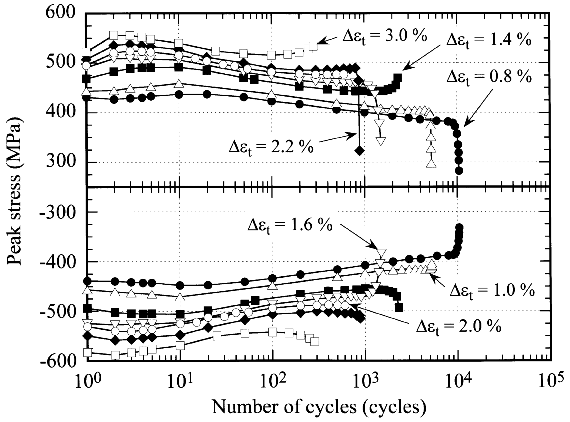

Fig. 5. Change in peak stresses during fatigue tests.

stresses increased in the case that a Types B or C crack initiated. On the other hand, the plastic strain range did not change much during the fatigue life except near the final fracture, as shown in Fig. 6. (In Figs. 5 and 6, the data for the 4% total strain range were not shown, as sufficient hysteresis curves of the specimen were not successfully obtained.) From these results, it is recognized that JLF-1 steel demonstrates cyclic strain-hardening initially and then cyclic strain-softening occurs continuously. The number of cycles where the tensile peak stress becomes the largest depends on $\Delta\varepsilon_t$, and the largest peak stress point shifts to a larger number of cycles when $\Delta\varepsilon_t$ becomes smaller. So, it is clear that the strain-hardening depends on the total strain range. In the case of F82H steel, such cyclic strain-hardening was not reported [6].

Fig. 7 shows hysteresis curves of several specimens at around $N_f/2$, and a static stress–strain curve is also plotted. The curve connecting the tensile peak stresses presents a cyclic stress–strain curve. The cyclic stress–strain curve lies below the static stress–strain curve in the smaller strain range, and approaches the static stress–strain curve when $\Delta\varepsilon_t$ becomes larger. This shows that no microstructural transformation occurs in the fatigue process. The difference of the static and cyclic stress–strain curves is generated by the initial strain-hardening and the subsequent strain-softening, and the stress drop by the strain-softening exceeds the stress drop by the strain-hardening in the smaller total strain range. From these results, it is believed that when the total stain range is large, dislocations would be tangled strongly during the initial fatigue process and would not be released so easily during the following alternating stresses.

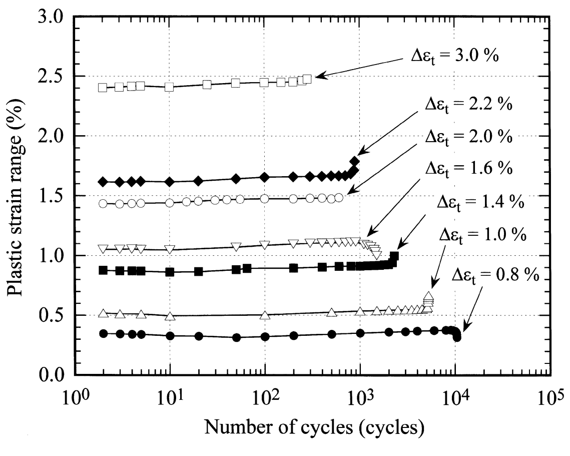

Fig. 6. Change in plastic strain range during fatigue tests.

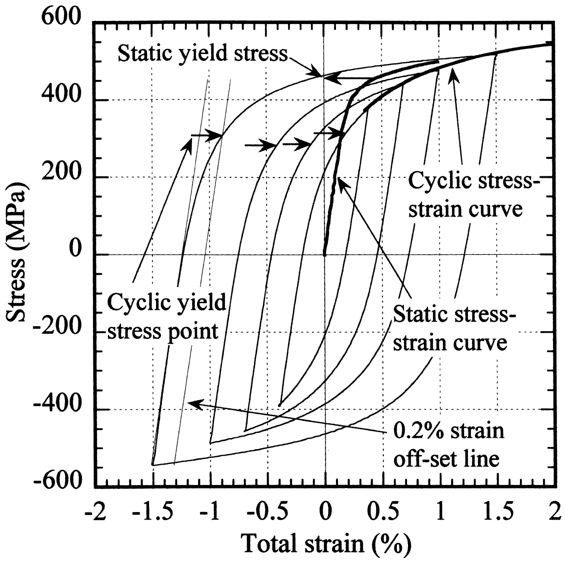

Fig. 7. Hysteresis curves at around $N_f/2$ and static and cyclic stress–strain curves.

When a cyclic yield stress point is defined in the same manner as a static yield stress (0.2% strain off-set stress from the compressive peak stress), the cyclic yield stress point would not be very different. Also, the cyclic yield stress, which is the stress increment from the compressive peak stress to the cyclic yield stress point, becomes larger according to the increase of the total strain range. It is believed to come mainly from the static strain-hardening.

To investigate the fatigue life of JLF-1 steel relative to F82H steel, the present data were compared with the published data as shown in Fig. 8. The marks show the results of F82H steel tested in air at room temperature [7] and solid lines designate the results in this study. It is clear that the fatigue life of JLF-1 steel is about twice as long as the life of F82H steel. Dotted lines are the results of F82H steel tested in vacuum at room temperature [6]. Both steels show almost the same relationship between

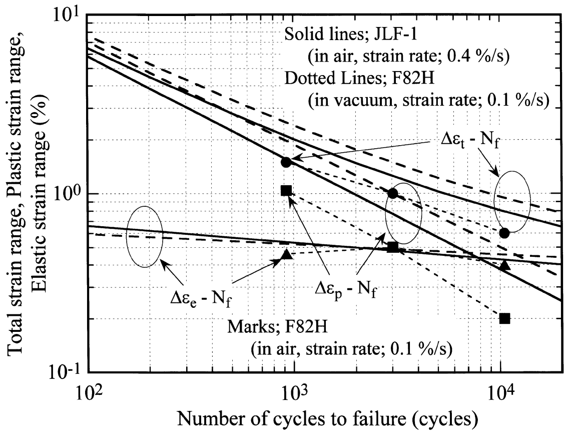

Fig. 8. Fatigue life diagrams of JLF-1 steel in air and F82H steel in air and vacuum at room temperature.

$\Delta\varepsilon_t$ and N_f. However, the fatigue life of JLF-1 steel in air becomes about 2/3 of F82H steel tested in vacuum. Since the dislocations near the specimen surface could move reversibly in vacuum, the crack initiation would be delayed resulting in a longer fatigue life.

4. Summary

Low cycle fatigue tests were carried out in air at room temperature under axial strain control, and the fatigue properties of JLF-1 steel were investigated. The main results obtained in this study are summarized as follows:

1. The fatigue life can be represented as a function of the total strain range, and the regression curve is shown as follows:

$$\Delta\varepsilon_t = 91.02\ N_f^{(-0.5956)} + 1.023\ N_f^{(-0.09462)}.$$

2. JLF-1 steel demonstrates cyclic strain-hardening initially and a gradual cyclic strain-softening until the final failure. The cyclic stress–strain curve lies near the static stress–strain curve, and it means that major transformation does not occur during the fatigue life. The drop in the tensile peak stress from the first cycle to around $N_f/2$ increases with decreasing total strain range.
3. The fatigue life of JLF-1 steel was about twice as long as the life of F82H steel in air at room temperature. However, JLF-1 steel shows about 2/3 shorter fatigue life than F82H steel tested in vacuum at room temperature.

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