ELSEVIER

Journal of Nuclear Materials 283–287 (2000) 1018–1022

journal of nuclear materials

www.elsevier.nl/locate/jnucmat

Effect of specimen size on fatigue properties of reduced activation ferritic/martensitic steels

T. Hirose [a,b,*,1], H. Sakasegawa [a,1], A. Kohyama [a,1], Y. Katoh [a,1], H. Tanigawa [b,2]

[a] *Institute of Advanced Energy, Kyoto University, Gokasho, Uji, Kyoto 611-0011, Japan*

[b] *Radiation Effects and Analysis, Materials Science, Japan Atomic Energy Research Institute, 2-4 Shirakata-Shirane, Tokai-mura, Naka-gun, Ibaraki-ken 319-1195, Japan* [3]

Abstract

Small specimen testing technology (SSTT) and related remote-control testing techniques are indispensable for the effective use of the limited volumes of materials test reactor and proposed intense neutron sources. As a part of this work, a new fatigue test machine with a laser extensometer for hot-cell usage has been developed. Materials used in this work were Japanese reduced activation ferritic/martensitic steel (RAFs), JLF-1 (Fe–9Cr–2W–V–Ta) and its weldment (WM). Correlations between fatigue life characteristics and fracture mechanisms were investigated for full- and mini-sized hourglass type specimens to clarify the effect of specimen size on fatigue properties. These tests revealed that there was not a significant difference in the number of cycles to failure in both specimens, except for the case of very low cycle fatigue. © 2000 Elsevier Science B.V. All rights reserved.

1. Introduction

Reduced activation ferritic/martensitic steels (RAFs) are leading candidates for the first wall and blanket structures of D–T fusion reactors. One of the Japanese RAFs, JLF-1, was reported to keep excellent mechanical properties and microstructural stability after heavy neutron irradiation up to 60 dpa [1]. Recently, the issue of degradation during long-term operation has been raised. In fusion applications, the structural materials will be exposed to cyclic stress caused by temperature cycling from reactor operation. Therefore, investigation of fatigue is essential to reactor design. Although fatigue tests on JLF-1 started recently [2], few data on fatigue properties of RAFs have been obtained up to now.

Small specimen testing technology (SSTT) is widely understood to be necessary for mechanical tests utilizing irradiated specimens. On the other hand, specimen size effects in some mechanical tests have been reported [3]. For fatigue tests, it is considered that fracture is governed by internal defects in the low cycle region. On the contrary, cracking occurs on the specimen surface and propagates inward in the high cycle region. Therefore, it is considered that fatigue properties depend on the specimens' dimension.

In this work, the effect of specimen size on fatigue properties of RAFs, JLF-1 and its weldment (WM) were investigated for better understanding of fatigue properties of irradiated specimens.

2. Experimental procedure

2.1. Materials

The materials used were base metal (BM) of RAFs (JLF-1 second heat) and its WM by tungsten inert gas (TIG), arc welding. The TIG welding used wire having a 1.2 mm diameter. The heat input was 14.5–15.8 kJ/cm. The welding direction was parallel to the rolling direction. The width of the welding line was about ~25 mm. The post-welding heat treatment condition was 740°C × 3 h/furnace cool. Table 1 shows the chemical

---

[*] Corresponding author. Tel.: +81-29 282 6551; fax: +81-29 282 5922.

E-mail address: hirose@iae.kyoto-u.ac.jp (T. Hirose).

[1] Tel.: +81-774 38 3466; fax: +81-774 38 3467.

[2] Tel.: +81-29 282 6551; fax: +81-29 282 5922.

[3] Correspondence address.

0022-3115/00/$ - see front matter © 2000 Elsevier Science B.V. All rights reserved.
PII: S0022-3115(00)00141-0

Table 1
Chemical composition (wt%) and heat treatment condition of JLF-1 second Heat[a]

	C	Si	Mn	P	S	Al	Cr	W	V	Ta	N	Ti	B
BM	0.10	0.05	0.45	0.003	0.002	0.003	8.85	1.99	0.20	0.080	0.0231	–	0.0002
WM	0.061	0.13	0.43	0.005	0.003	0.003	9.16	1.91	0.25	0.081	0.0259	0.019	0.0001
WW	0.061	0.10	0.45	0.005	0.003	0.002	8.96	1.82	0.25	0.084	0.0332	0.028	0.0001

[a] Homogenizing – 1250°C × 3 h; normalizing – 1050°C ×1 h/A.C.; tempering – 780°C × 1 h/A.C.; BM – check analysis for BM; WM – weld metal; WW – welding wire.

composition and heat treatment conditions. Further detail of its characterization can be found elsewhere [4,5].

2.2. Specimens

The shape and dimensions of the specimens are presented in Fig. 1. It is well known that the hourglass type specimen has good resistance to buckling, which is a very important issue to miniaturize specimens for push–pull tests. Full-sized and mini-sized hourglass type fatigue specimens were machined from the 25^t mm × 320^w × 500^l mm TIG welded plate. Both BM and WM specimens were oriented in the transverse direction. As mentioned above, the width of the welding line was narrow. In the case of full-sized WM specimen, the hourglass specimen was fabricated across the WM. All relevant gauge volume consisted of the weld metal, with the heat affected zone (HAZ) being located outside the test section. A mini-sized WM specimen entirely made of the weld metal was also prepared. In order to reduce stress concentration, the root radius to minimum diameter (*R*/*d*) ratio of both specimens was selected to be 8, which is the upper limit of the ASTM E-606 recommendation of 4–8. The minimum diameter of full- and mini-sized specimens was 6 and 1.25 mm, respectively. The mini-sized specimens called SF-1 are proposed for use in accelerator driven D–Li stripping reaction neutron sources, such as IFMIF [6]. But other proposed neutron sources like the gas dynamic trap (GDT-ns) also requires the application of SSTT [7].

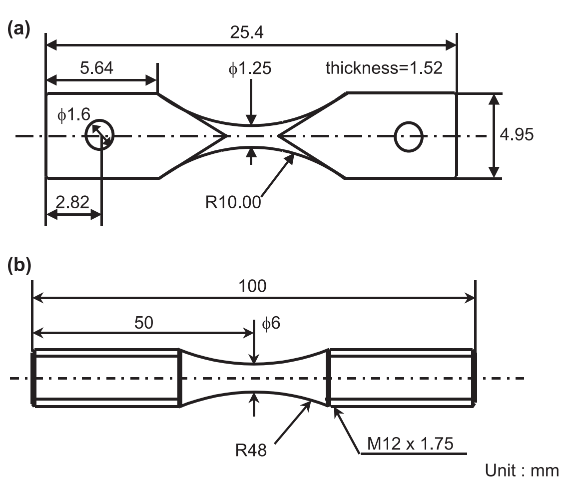

Fig. 1. Dimension of specimens used: (a) mini-sized specimen; (b) full-sized specimen.

2.3. Development of test machine for irradiated specimen

To develop mechanical testing machines for irradiated specimens, easy and remote-handling procedures are indispensable. Especially for fatigue tests, gripping of specimens and attaching of extensometers by remote handling are considered to be difficult. In this work, remote-handling issues were regarded as the most important. For measuring strain, a laser extensometer was applied, which enables monitoring deformation during the test without any specimen contact [8]. Fig. 2 shows the mini-sized specimen, clamping device, and a laser extensometer developed in the present study. As shown in this figure, the laser extensometer consists of a transmitter and a receiver joined directly to an actuator. The minimum diameter with the unloaded condition was defined as the reference diameter. Strain measurement during testing was carried out by measuring the deviation from the reference value at the minimum diameter. A measurement accuracy of 0.1 μm was obtained by averaging the measured values. The measured strain value was also used for controlling the actuator during the test. The upper limit of distance between the transmitter and receiver was about ~500 mm, which is enough to install an optional vacuum chamber in between.

A unique clamping device was developed in order to grip an SF-1 type specimen. The specimen needs to stay parallel to the load direction to avoid buckling. The clamping device consists of two counter plates. One plate has a groove along the load direction and a small pin. The other plate has a serrated surface. This device permitted easy operation with remote handling. Incidentally, it was reported that misalignment of 0.1 mm did not introduce any significant effect on fatigue life of SF-1 specimen [6].

2.4. Test condition

For full-sized specimens, an electrohydraulic servo-controlled testing machine with a 10 ton load cell was used. For mini-sized specimen, an electromotive testing

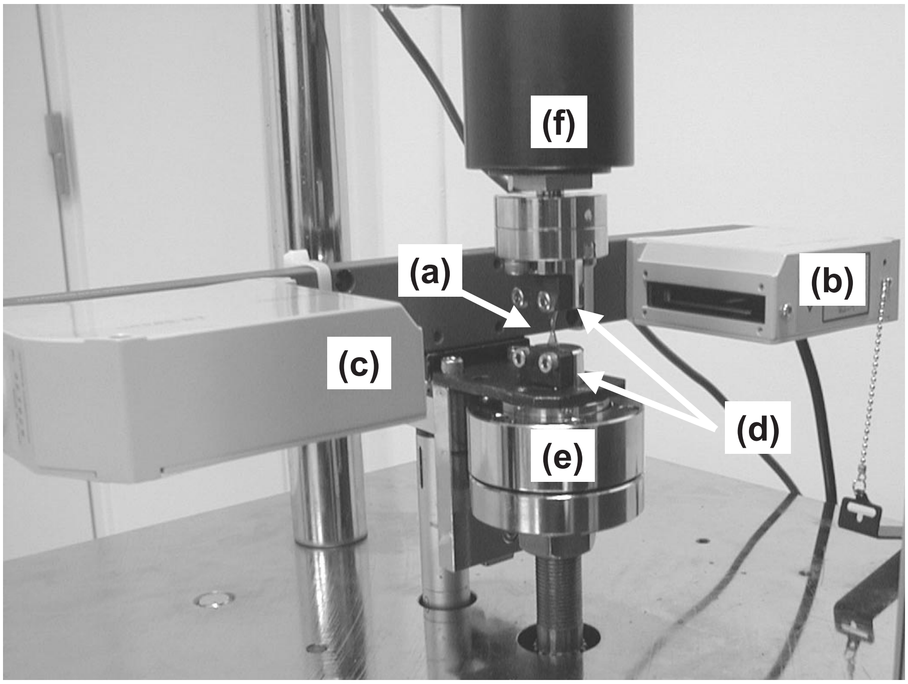

Fig. 2. Mini-sized fatigue test machine with laser extensometer: (a) Specimen; (b) Laser transmitter; (c) Laser receiver; (d) Clamping devices; (e) Actuator.

machine with a 200 kg load cell was used. Diametral strain controlled fatigue tests were carried out with a triangular stress waveform and a total diametral strain range, $\Delta\varepsilon_d$ of 0.2–3.0%. The diametral strain rate was 0.01%/s, the stress condition was push–pull. $\Delta\varepsilon_d$ was converted to total axial strain range, $\Delta\varepsilon_a$, by the following formula [9]:

$$\Delta\varepsilon_a = (\sigma/E)(1 - \nu_e) - 2\Delta\varepsilon_d, \tag{1}$$

where σ is applied stress, E the elastic modulus, ν_e is the elastic Poisson's ratio.

According to this formula, the converted axial strain range, $\Delta\varepsilon_a$, was about 0.3–6%. The number of cycles to failure, N_f, was defined at a point where a tensile peak stress decreased by 25% from an extrapolation curve of the tensile peak stress against number of cycle. Load controlled fatigue tests were carried out at 0.1–10 Hz, with a sinusoidal stress waveform and push–pull condition. All tests were performed at an ambient temperature in air.

3. Results and discussions

3.1. Diametral strain controlled fatigue test

Typical hysteresis loops obtained by laser extensometer are presented in Fig. 3. As shown in the figure, the laser extensometer was successfully applied to diametral strain controlled fatigue tests. Furthermore, emphasis has been put on a strictly parallel alignment of the specimen axis to the load direction. The clamping device was successfully applied, because buckling did not occur even at a large strain range of $\Delta\varepsilon_a = 6\%$. All specimens broke in the vicinity of the minimum diameter. Full-sized WM specimens broke in the weld metal.

The N_f values with the mini-sized specimens were compared with those of full-sized specimens. The relationship between N_f and the converted total axial strain

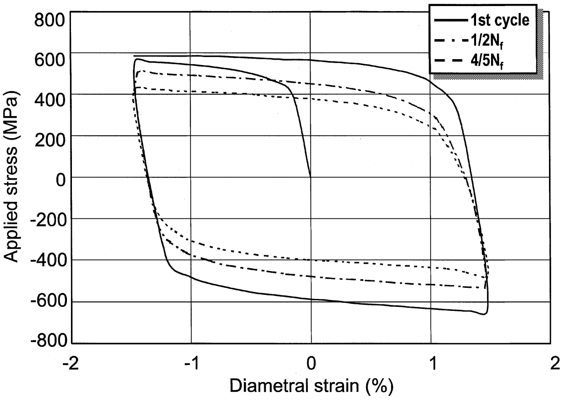

Fig. 3. Typical hysteresis loops obtained by laser extensometer, test condition: $\Delta\varepsilon_d = 3\%$ ($\Delta\varepsilon_a = 6\%$).

range, $\Delta\varepsilon_a$, is presented in Fig. 4. As shown in this figure, fatigue lifetime of WM was slightly shorter than BM, and a strong size effect on fatigue lifetime was not observed.

Cyclic stress response curves are presented in Fig. 5. As in Fig. 4, cyclic softening was observed in all tests. The tensile stress increased, however, during an initial stage in several tests performed at higher strain range. On the other hand, the plastic strain range was fairly stable during tests, except at the end of tests. It is believed that the difference in both stress range and decrease in stress range did not depend on specimen size. The difference in stress range and decrease in stress range between specimen sizes were less than 5%. According to these results, fatigue properties are not sensitive to the specimen sizes studied in this work.

3.2. Load controlled fatigue test

Fig. 6 shows the results of the stress controlled fatigue tests on mini-sized specimens compared with those of full-sized specimens, where specimen size effects on fatigue life appear small except at the very low cycle fatigue region. However, the total number of tests was insufficient for statistical significance, and the stress controlled testing made it more difficult to analyze the results. From the limited data shown in this figure, the stress to initiate a slight decline of the fatigue curve in the low cycle fatigue region seems to shift to higher stress for mini-sized specimens. In the very low cycle fatigue region, the fracture initiation site was internal defects, not surface flaws. This may explain the fact that the smaller size specimen has the longer fatigue life due to its small volume.

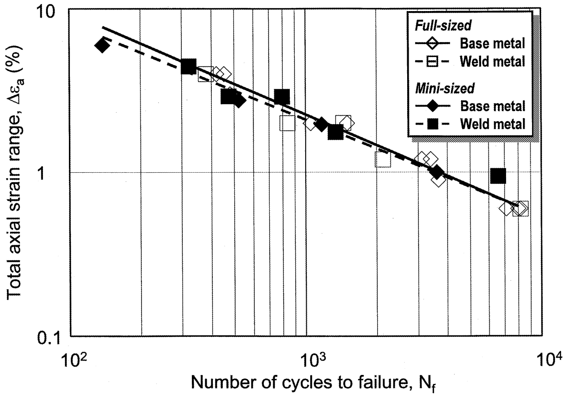

Fig. 4. Results of diametral strain controlled fatigue test.

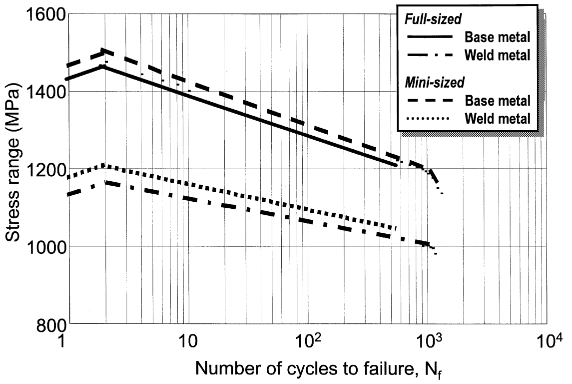

Fig. 5. Cyclic stress response curves at $\Delta\varepsilon_a = 2\%$.

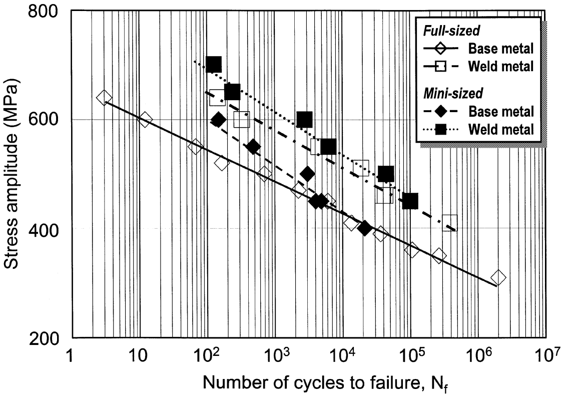

Fig. 6. Results of stress controlled fatigue test.

4. Summary

A fatigue test machine with a laser extensometer for testing irradiated specimens has been successfully developed. Strain controlled fatigue tests on JLF-1 and its WM were carried out using full-sized and mini-sized specimens. The number of cycles to failure, plastic strain range and applied stress are independent of the specimen size. Cyclic softening was observed in both BM and WM. The fatigue lifetime of WM was shorter than that of BM. Stress controlled fatigue tests were also performed. There was no significant specimen size effect except in the very low cycle fatigue region. According to these results, fatigue properties were not sensitive to specimen size studied in this work. Neutron irradiation of JLF-1steel and its WM is ongoing in Japanese fission reactors, such as the JMTR and the JOYO. Post-irradiation fatigue test will be carried out in the near future.

Acknowledgements

The authors would like to express their sincere appreciation to Professor Namba, Professor Nishimura, Professor Muroga and Dr Nagasaka of NIFS, Dr Shiba, Dr Miwa and Dr Jitsukawa of JAERI for their useful help in many aspects to this work.

References

[1] Y. Kohno, A. Kohyama, T. Hirose, M.L. Hamilton, M. Narui, J. Nucl. Mater. 258–263 (1998) 145.

[2] A. Nishimura, T. Nagasaka, N. Inoue, C. Namba, these Proceedings, p. 677.

[3] Y. Kohno, A. Kohyama, M.L. Hamilton, T. Hirose, Y. Katoh, F.A. Garner, these Proceedings, p. 1014.

[4] A. Kohyama, Y. Kohno, M. Kuroda, A. Kimura, F. Wan, J. Nucl. Mater. 258–263 (1998) 1319.

[5] N. Inoue, T. Muroga, A. Nishimura, O. Motojima, J. Nucl. Mater. 258–263 (1998) 1248.

[6] Y. Miwa, S. Jitsukawa, A. Hishinuma, J. Nucl. Mater. 258–263 (1998) 457.

[7] U. Fischker, A. Möslang, A.A. Ivanov, Trans. Fus. Technol. 35 (1) (1999) 160.

[8] C. Brillaud, T. Meylogan, P. Salathe, ASTM STP 1270 (1996) 1144.

[9] ASTM E-606, Annual Book of ASTM, ASTM, 1996.