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Fatigue life and strain hardening behavior of JLF-1 steel

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A B S T R A C T

Low cycle fatigue (LCF) properties of JLF-1 steel were studied from room temperature (RT) to 873 K in a vacuum condition using engineering size cylinder specimens with 8 mm in diameter. When the fatigue life was plotted against the plastic strain range, the fatigue life curves at RT, 673 K and 873 K were on different lines, which is not in agreement with the Coffin's model. The TEM images showed that dislocation rearrangements forming cell structure and keeping high density at room temperature. But dislocation cell structure was not observed at 873 K, dislocation density decrease to low level. Loss of dislocation pile up will result in reduction of strain hardening at high temperature. So, the loss of strain hardening will be responsible for the increase of fatigue life at high temperature when plotted against the plastic strain range.

1. Introduction

A reduced-activation ferritic/martensitic steel, JLF-1, is considered as one of the candidate alloys for the structure components of the fusion reactors and super critical-water reactors [1,2]. For the application as the structural materials, it is necessary to evaluate low cycle fatigue (LCF) properties at high temperature [3].

Temperature is one of the important external parameters influencing fatigue life. Coffin summarized the LCF properties of several materials in vacuum or inert gas atmosphere and conclude that the fatigue life in vacuum is independent of temperature when the fatigue life is plotted against the plastic strain range [4,5]. However, the fatigue life curves of RAFM steels is not in agreement with the Coffin's model [6–10].

In this paper, LCF tests of JLF-1 steel were carried out in vacuum under a fully reversed push–pull triangular wave at strain rate of 0.1%/s at room temperature (RT), 673 K and 873 K. The microstructure evolution during cyclic deformation was analyzed by transmission electron microscopy (TEM).

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 15 mm thick and heat-treated as follows: 1323 K/3.6 ks/air cooled (normalizing) and 1052 K/3.6 ks/air cooled (tempering) [6]. The microstructure is tempered martensite [11,12].

The fatigue specimen (8 mm in diameter and 20 mm in parallel length) is shown in Fig. 1. Two SM500 steel blocks were electron-beam welded (EB) on the both sides of the specimen. Specimens were polished in the longitudinal direction with #1500 emery paper to erase the circumferential machining defects.

LCF tests were carried out in vacuum ($\leqslant 5 \times 10^{-3}$ Pa) using a servo-hydraulic fatigue testing machine with dynamic load capacity of ±10 tons [6–9,12]. The axial strain was measured by a Shinko 1501-93-20 extensometer (differential transducer, gage length (G.L.) is 12.5 mm). The specimens were heated by 100 kHz induction coil. Two thermocouples (ϕ 0.32 mm) were welded in the gage length on the specimen. The temperature difference of the two thermocouples was kept less than 3 K. A fully reversed push–pull triangular wave was applied and the strain rate was 0.1%/s. The number of cycles to failure was defined as either the cycle when the tensile peak stress decreased by 25% from an extrapolation curve of the tensile peak stress against number of cycles, or the test signal became unstable [6–9,12].

To investigate the microstructure change during fatigue at elevated temperature, tests were terminated for some specimens at 10th and 500th cycle with total strain range of ($\Delta\varepsilon_t$) = 1.8% at RT, 673 K and 873 K. The ϕ 3 mm thin foils for TEM were prepared from JLF-1 plate as received, and center part of the fatigue specimen. All the thin foils were polished to less than 0.1 mm in thickness with #1500 emery paper, followed by electropolishing to perforation for TEM examination.

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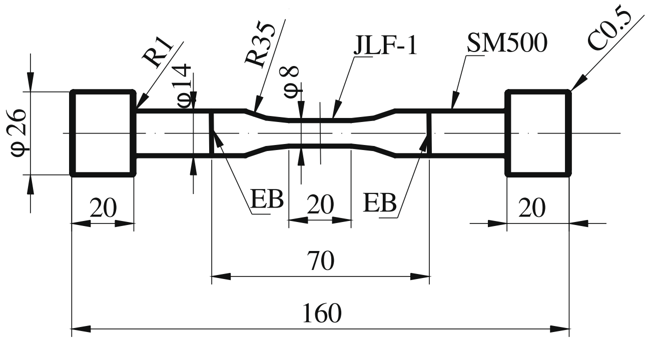


Fig. 1. Fatigue test specimen.

3. Results and discussion

The relationships between fatigue life (N_f) and total strain range ($\Delta\varepsilon_t$) are shown in Fig. 2 (the data of 'RT, 0.4%/s, air' were taken from [6]). The total strain range and stress range were obtained from hysteresis curves at around the half of fatigue life ($N_f/2$). The fatigue life at elevated temperature was almost as same as that at RT when the life was plotted against the total strain range. The phenomenon of ($\Delta\varepsilon_t$)–N_f relationship in vacuum is temperature independent which was also reported on F82H from RT to 773 K [10], and MANET I from RT to 723 K, Mod. 9Cr–1Mo from 755 K to 977 K [13].

However, the temperature effect on the fatigue life of JLF-1 was significant when fatigue life was plotted against the plastic strain range. The fatigue life curves for RT, 673 K and 873 K of JLF-1 were on different lines when the life was plotted against the plastic strain range (Fig. 3). The fatigue life increases with temperature when the plastic strain range is same. This tendency is not in agreement with Coffine's model which is independent of temperature when the fatigue life is plotted against the plastic strain range. Thus, it is necessary to investigate the mechanism of this unusual phenomenon on the basis of microstructure analysis since the mechanical properties of martensitic steels are strongly related to their complex microstructure [14].

TEM images of dislocations before and after fatigue at RT were shown in Fig. 4. The dislocation density was measured according to

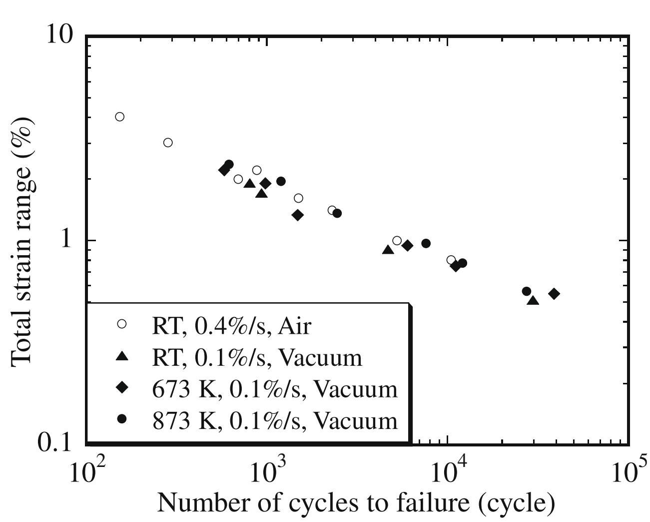


Fig. 2. Relationship between total strain range and number of cycles to failure.

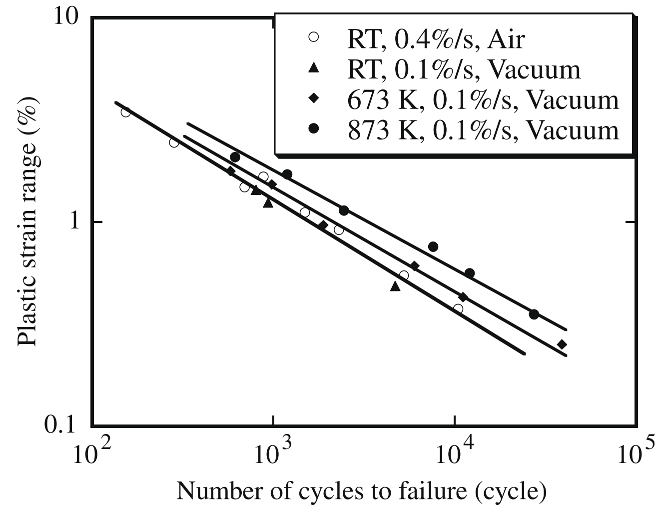


Fig. 3. Relationship between plastic strain range and number of cycles to failure.

[15]. Before fatigue (Fig. 4(a)), the dislocation network was observed, and the dislocation density was very high. After fatigue (Fig. 4(b) and (c)), the dislocation structure of JLF-1 steel was changed from network to cell after cyclic deformation at RT. The dislocation density was reduced with the cyclic deformation (the dislocation forming cell structure was not included in this counting). Correlated to the change in dislocation, strong strain hardening was observed at 10th and 900th cycles from the stress–strain hysteresis curves (Fig. 4(d)). That means the dislocation tangled to form cell structure during cyclic deformation at RT.

The dislocation structure of 10th and 716th cycle at 673 K was shown in Fig. 5(a) and (b). Weak cell structure was observed at 10th cycle. However the cell structure did not remain during the following fatigue and were not observed at the TEM images at 500th cycle and the final failure at 673 K. The dislocation density at 673 K was lower that at RT, and also reduced by cyclic deformation. The stress-strain hysteresis curve of 10th and 716th cycle at 673 K was shown in Fig. 5(c). Strain hardening decreased during cyclic plastic deformation, and little strain hardening at 700th cycle. Based on dislocation structure change at 673 K, the dislocation behavior was tangled to form cell structure at original few cycles, then pass through the lath during cyclic plastic deformation.

At 873 K, the cell structure was not observed (Fig. 6(a) and (b)). The dislocation density decreased with cycles, and was lower than that of 673 K. The stress–strain hysteresis curve of 10th and 800th cycle at 873 K was shown in Fig. 6(c). Little strain hardening was observed at 10th and 800th cycle. Based on the dislocation structure change, the dislocation pass through the lath during cyclic deformation at 873 K.

Thus, the dislocation interaction during fatigue is dependent on temperature. At RT, dislocation rearranges to form cell structure and keeps high density. At 673 K, dislocation density decreases to a medium level. At 873 K, dislocation decreases to a low level. The loss of dislocation pile up will result in reduction of strain hardening at high temperature. Thus, the loss of strain hardening will be responsible for the increase of fatigue life at high temperature when plotted against the plastic strain range.

4. Summary

Low cycle fatigue tests of JLF-1 steel was carried out in vacuum with strain rate of 0.1%/s at RT, 673 K and 873 K. Results are summarized as follows:

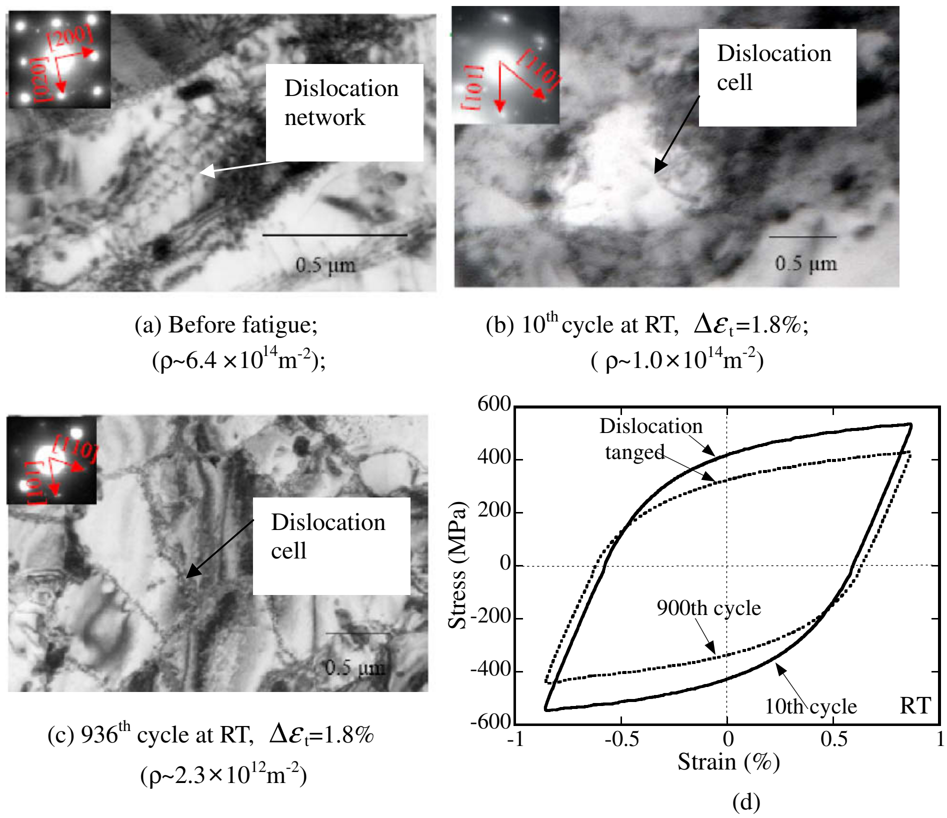


Fig. 4. Effect of cyclic plastic deformation on dislocation structure ((a)–(c)) and stress–strain hysteresis curves (d) of ($\Delta\varepsilon_t$) = 1.8% at RT.

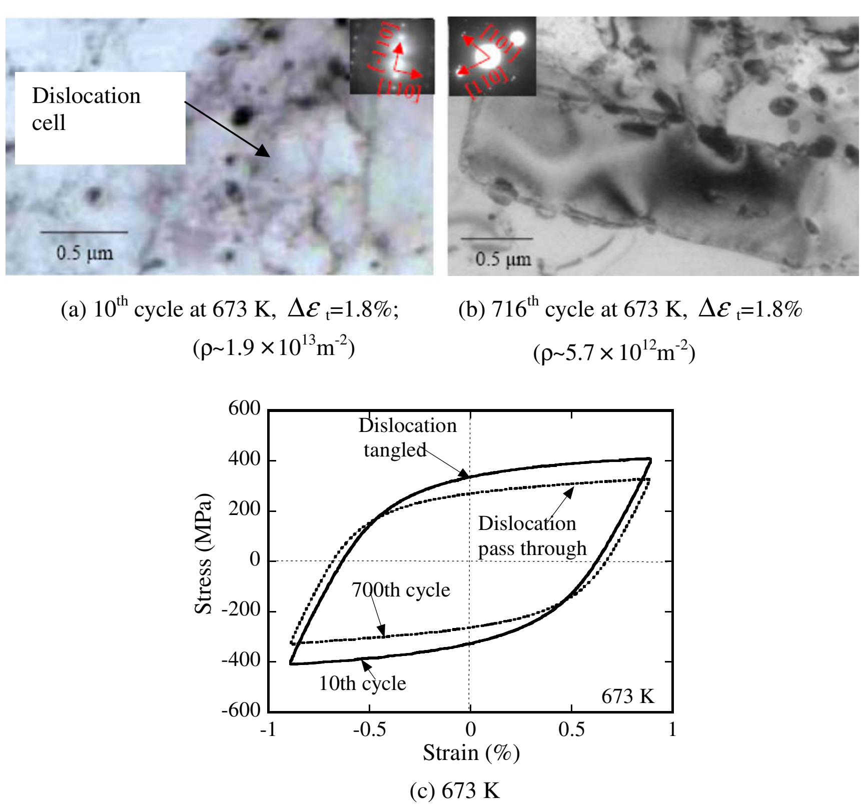
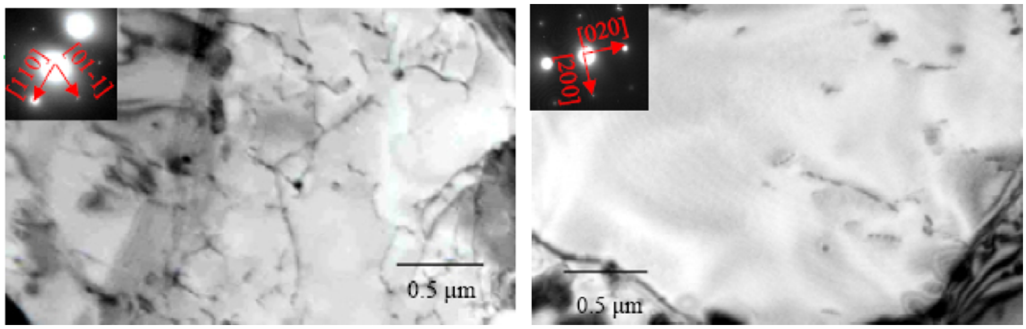
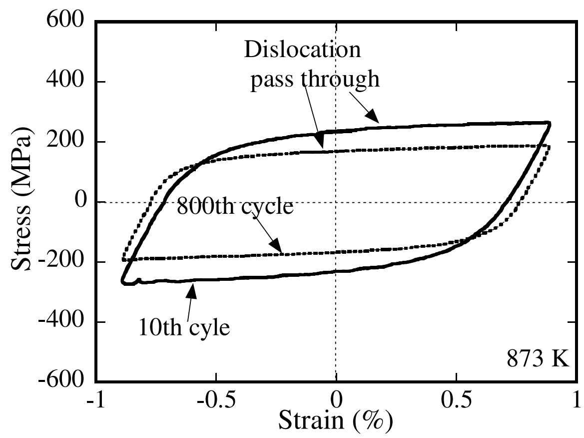


Fig. 5. Effect of cyclic plastic deformation on dislocation structure ((a) and (b)) and stress–strain hysteresis curves (c) of ($\Delta\varepsilon_t$) = 1.8% at 673 K.



(a) 10th cycle at 873 K, $\Delta\varepsilon_t$=1.8%; (ρ~1.1×10^{13}m^{-2})

(b) 851st cycle at 873 K, $\Delta\varepsilon_t$=1.8% (ρ~1.3×10^{12}m^{-2})



(c) 873 K

Fig. 6. Effect of cyclic plastic deformation on dislocation structure ((a) and (b)) and stress–strain hysteresis curves (c) of ($\Delta\varepsilon_t$) = 1.8% at 873 K.

1) The fatigue life curves of JLF-1 at RT, 673 K and 873 K were independent on temperature when plotted against the total strain range.
2) The fatigue life curves of JLF-1 at RT, 673 K and 873 K were on different lines when plotted against the plastic strain range. This is not in agreement with Coffin's model. The loss of strain hardening will be responsible for the increase of fatigue life at high temperature when plotted against the plastic strain range.
3) The dislocation interaction during fatigue of JLF-1 steel is dependent on temperature. At RT, dislocation rearranges to form cell structure and keeps high density. At 673 K, dislocation density decreases to a medium level. At 873 K, dislocation decreases to a low level.

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References

[1] A. Kohyama, Y. Kohno, K. Asakura, H. Kayano, J. Nucl. Mater. 212–215 (1994) 684.
[2] Huailin Li, Wen Yang, Qifa Yang, in: The Third International Symposium on Supercritical Water-Cooled Reactor (SCWR2007), Shanghai China, 12–15 March 2007, p. 327.
[3] K. Shiba, A. Hishinuma, A. Tohyama, K. Masamura, JAERI-Tech 97-08.
[4] L.F. Coffin, in: Proceedings of Institution of Mechanical Engineers, vol. 188, 1974, p. 109.
[5] M. Klesnil, P. Lukas, Fatigue of Metallic Materials, Elsevier Scientific Publishing Company, 1980.
[6] A. Nishimura, T. Nagasaka, N. Inoue, T. Muroga, C. Namba, J. Nucl. Mater. 283–287 (2000) 677.
[7] Huailin Li, A. Nishimura, Zaixin Li, T. Nagasaka, T. Muroga, Fus. Eng. Des. 81 (2006) 241.
[8] Huailin Li, A. Nishimura, T. Nagasaka, T. Muroga, Fus. Eng. Des. 81 (2006) 2907.
[9] Huailin Li, A. Nishimura, T. Nagasaka, T. Muroga, Fus. Eng. Des. 82 (2007) 2595.
[10] T. Ishii, K. Fukaya, Y. Nishiyama, M. Suzuki, M. Eto, J. Nucl. Mater. 258–263 (1998) 1183.
[11] A. Nishimura, N. Inoue, T. Muroga, J. Nucl. Mater. 258–263 (1998) 1242.
[12] Huailin Li, A. Nishimura, T. Muroga, T. Nagasaka, J. Nucl. Mater. 367–370 (2007) 147.
[13] R.L. Klueh, D.R. Harries, ASM Stoch, Number: Mono 03.
[14] N. Mebarki, D. Delagnes, P. Lamesle, F. Delmas, S. Levaillant, Mater. Sci. Eng. A 387–389 (2004) 171.
[15] J. Pesika, R. Kluze, A. Dronhofer, G. Eggeler, Acta materialia 51 (2003) 4847.