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Low cycle fatigue properties of 8Cr–2WVTa ferritic steel at elevated temperatures

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Abstract

The effects of test temperature and tension holding on the fatigue properties of reduced activation ferritic/martensitic 8Cr–2WVTa (F-82H) steel were investigated by conducting low cycle fatigue tests at temperatures ranging from RT to 650°C under the axial strain-controlled condition with strains ranging from 0.5% to 2.0%. Fatigue life data were formulated as strain-life equations. A large reduction in the fatigue life was recognized at temperatures above 600°C. Softening without showing a saturated region was observed in the fatigue softening curves at temperatures above 600°C. Tension holding during fatigue tests reduced the fatigue life at 400°C, 500°C and 600°C. The microstructural examination showed that the large softening during cycle was associated with carbide ($M_{23}C_6$) coarsening and Laves phase (Fe_2W) precipitation at 600°C.

1. Introduction

A reduced activation ferritic/martensitic steel, 8Cr–2WVTa (F-82H), is one of the candidate alloys for structural materials of the DEMO fusion reactor [1,2]. Many investigations for mechanical properties of 8Cr–2WVTa steel including neutron irradiation effects have been performed [1–5]. This steel has been also chosen as a reference material for the IEA round-robin test on the low activation ferritic/martensitic steels [6]. This steel shows a low ductile to brittle transition temperature, high creep rupture strength and adequate weldability [2,3]. A major incentive for using ferritic/martensitic steels is to increase the margin against degradation during high temperature service under irradiation. At high temperatures, the low cycle fatigue life is often reduced by creep processes. Cyclic straining process in the ferritic/martensitic steel usually causes softening, and also could lead to some cumulative damage [7]. Although many studies have been made on the low cycle fatigue behavior of ferritic/martensitic steels [8–11], very limited studies have been performed on 8Cr–2WVTa steel [5].

The main purpose of the present study is to evaluate the fatigue life and the cyclic stress response of NT (normalized and tempered) 8Cr–2WVTa steel at elevated temperatures. The influence of tension holding on the fatigue life and the cyclic stress response was also evaluated.

2. Experimental procedure

The material used in this study was the reduced activation ferritic/martensitic steel, 8Cr–2WVTa steel. Table 1 shows the chemical composition and heat treatment conditions. The microstructure of this steel consists mainly of tempered martensite. Round bar type specimens with a gauge section of 10 mm in diameter and 25 mm in length were prepared from the plate with 25 mm thickness. The longitudinal direction of the specimen was vertical to the final rolling direction.

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Table 1
Chemical composition (wt%) and heat treatments of 8Cr–2WVTa steel

C	Si	Mn	P	S	Cr	W	V	Ta	B	T.Al	T.N
0.097	0.12	0.10	0.003	<0.001	7.59	2.00	0.19	0.047	0.0003	<0.01	0.002

Heat treatment (PWHT: post weld heat treatment). Normalizing: 1040°C – 0.67 h (air cooled), tempering: 740°C – 1.5 h (air cooled).

Low cycle fatigue tests were performed at RT, 400°C, 500°C, 600°C and 650°C in a vacuum of $\sim 10^{-5}$ Pa under an axial strain-controlled condition. The strain control was a completely reversed push–pull type using a triangular wave form. Total strain ranges were controlled at 0.5%, 0.8%, 1.0%, 1.5% and 2.0% with an axial strain rate of 0.1%/s. Some fatigue tests were carried out with tension holding for 300 s. Test temperatures were kept constant within an accuracy of ±5°C using a high frequency induction heater. The number of cycles to failure was defined as a point at which the maximum tensile stress decreased by 25% from an extrapolation line of peak tensile stress vs. cycle [12].

3. Results and discussion

3.1. Fatigue life

Fig. 1 shows the number of cycles to failure, N_f, as a function of controlled strain range, $\Delta\varepsilon_t$, obtained by fatigue tests at RT, 400°C, 500°C, 600°C and 650°C. Strain-life curves drawn for each test temperature in this figure were represented by the following equation [13] based on the Manson–Coffin and the Basquin laws,

$$\Delta\varepsilon_t = \Delta\varepsilon_p + \Delta\varepsilon_e = C_p N_f^{(-k_p)} + C_e N_f^{(-k_e)}, \tag{1}$$

where, $\Delta\varepsilon_p$ and $\Delta\varepsilon_e$ are the plastic strain and the elastic strain ranges, respectively. C_p, C_e, k_p and k_e are material constants [14]. The following strain-life equations were determined;

$$\text{RT} \quad \Delta\varepsilon_t = 100.11 N_f^{(-0.5748)} + 0.7746 N_f^{(-0.0573)}, \tag{2}$$

$$400°\text{C} \quad \Delta\varepsilon_t = 148.60 N_f^{(-0.5916)} + 0.7502 N_f^{(-0.0790)}, \tag{3}$$

$$500°\text{C} \quad \Delta\varepsilon_t = 37.526 N_f^{(-0.4404)} + 0.4387 N_f^{(-0.0433)}, \tag{4}$$

$$600°\text{C} \quad \Delta\varepsilon_t = 15.800 N_f^{(-0.3605)} + 0.7578 N_f^{(-0.1364)}, \tag{5}$$

$$650°\text{C} \quad \Delta\varepsilon_t = 12.454 N_f^{(-0.3363)} + 0.2922 N_f^{(-0.0509)}. \tag{6}$$

No significant difference was recognized at temperatures below 500°C. At temperatures above 600°C, a large reduction in the fatigue life were observed, in particular, at the larger strain ranges.

3.2. Fatigue softening

Fig. 2 shows the stress amplitude as a function of number of cycles under the controlled strain range of 1.5%. The stress amplitude decreases markedly in the initial stage, and shows the saturated region afterwards. The curve which describes the reduction of stress amplitude up to failure during the strain-controlled fatigue test is called the fatigue softening curve [7]. The stress amplitude of the saturated region decreases with increasing testing temperature. Though the saturated region can be recognized on softening curves for RT, 400°C and 500°C, those for 600°C and 650°C show continuous softening without any saturated region.

Fatigue softening is a typical phenomenon for materials hardened by precipitation, solid solution, presence

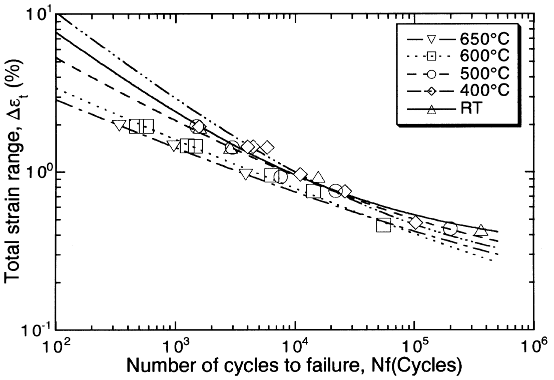

Fig. 1. Strain-life data of 8Cr–2WVTa steel for testing temperatures of RT, 400°C, 500°C, 600°C and 650°C.

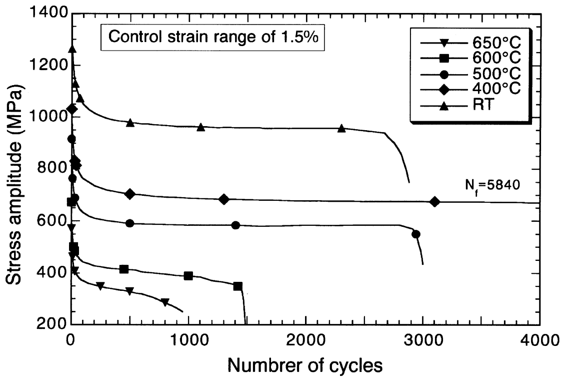

Fig. 2. Cyclic stress response curves for different temperatures at a control strain range of 1.5%.

of foreign particles and/or martensitic transformation [7]. Fatigue softening is caused by the gradual elimination of obstacles, such as precipitates, foreign particles and grain or lath boundaries, to the motion of dislocations. Although fatigue softening curves usually have a saturated region, the curves for 600°C and 650°C in Fig. 2 did not show any saturation. It is thought that change of the distribution and morphology of obstacles continuously occurred.

3.3. Tension holding effect and microstructural evolution

Fig. 3 shows the effect of tension holding on the fatigue softening curves. Tension holding for 300 s reduced the fatigue life at all temperatures tested. The tension holding effect is especially obvious for the softening curves at 600°C.

Microstructural examinations using carbon extraction replicas were performed by a Scanning Electron Microscope (SEM) and a Transmission Electron Microscope (TEM) on the specimen tested at 600°C with the control strain range of 1.5% with and without tension holding. The microstructure of the specimens as-received and aged at 600°C for 200 h were also examined for comparison.

Fig. 4 shows SEM images of the extraction replicas. Tension holding for 300 s coarsened greatly $M_{23}C_6$ type carbides at grain boundaries. From the result of fatigue tests on the modified 9Cr–1Mo steel at 538°C [11], the mechanical cycling accelerated the development of equiaxed subgrains with low dislocation density and much coarsened MC and $M_{23}C_6$ type carbides. In particular, these microstructural changes were very clearly observed on the specimen with longer compressive holding which caused marked softening during fatigue test. In the present study, it is considered that $M_{23}C_6$ type carbide coarsening induced by tension holding for 300 s as shown in Fig. 4(b) caused continuous softening without showing the saturated region in the fatigue softening curve.

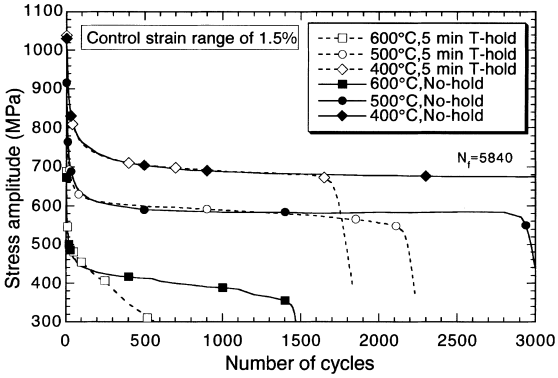

Fig. 3. Effect of tension holding on fatigue softening curves.

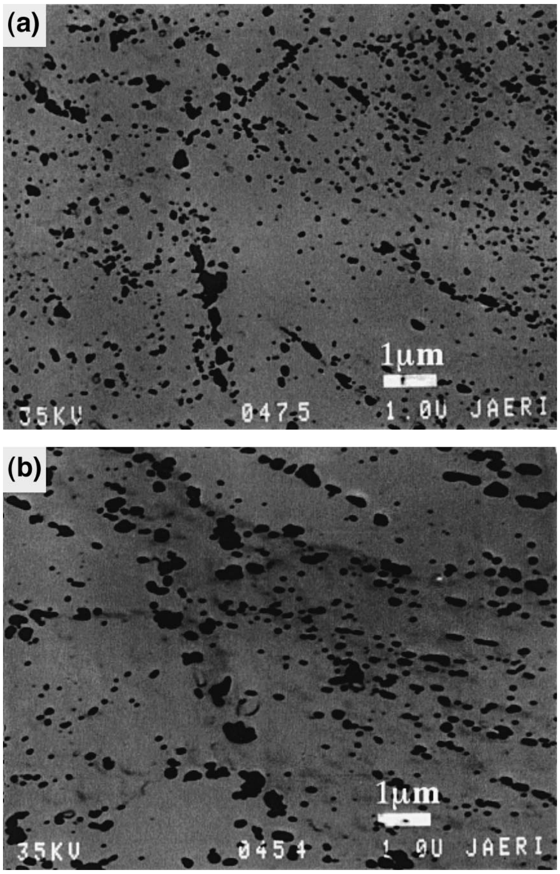

Fig. 4. SEM images of carbon extraction replicas of the specimen tested at 600°C with 1.5% control strain range: (a) without tension holding; (b) with 300 s tension holding.

Fig. 5 shows a TEM image of the carbon extraction replica and a typical energy-dispersive X-ray (EDX) spectrum of the Laves phase (Fe_2W) at grain boundaries for the specimen with tension holding. W-rich Laves phases appearing like a tail of $M_{23}C_6$ were observed. No Laves phase could be detected for the specimens thermally aged for 200 h at 600°C and fatigue tested without tension holding. From the Time–Temperature-Precipitation (TTP) diagrams for Laves phase for 8Cr–2WVTa steel [2], thermal aging for 10^4 ks at 600°C is expected to be needed for the Laves phase precipitation. The total fatigue testing time for the specimen in which the Laves phase precipitation was recognized was only about 2×10^2 ks. Therefore, it is clear that tension holding at 600°C accelerated the Laves phase precipitation.

Based on the above observations, it is considered that the $M_{23}C_6$ carbide coarsening and the Laves phase precipitation are believed to be the dominant factors for the acceleration of fatigue softening of 8Cr–2WVTa steel.

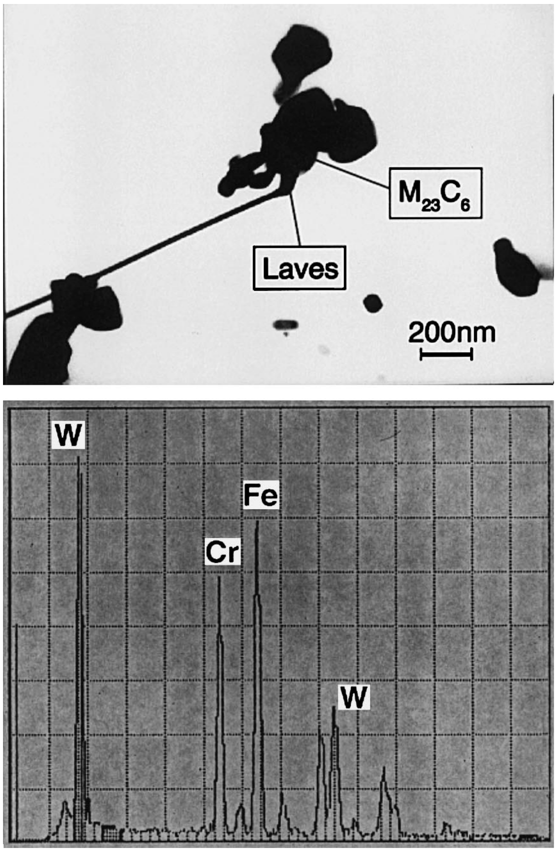

Fig. 5. TEM image of the carbon extraction replica and typical EDX spectrum of the Laves phase observed at grain boundaries of the specimen tested at 600°C with 0.5% control strain range and 300 s tension holding.

4. Conclusions

Low cycle fatigue tests of the 8Cr–2WVTa steel were performed at RT, 400°C, 500°C, 600°C and 650°C. The main results obtained were as follows:

1. Fatigue life data were formulated as strain-life equations.
2. Softening without showing a saturated region was observed in fatigue softening curves at temperatures above 600°C at the controlled strain range of 1.5%.
3. Tension holding reduced the fatigue life of 8Cr–2WVTa steel.
4. The fatigue softening at 600°C was affected by tension holding, i.e., tension holding for 300 s reduced continuously the stress amplitude after the initial softening stage in comparison with the softening curve without holding.
5. The $M_{23}C_6$ carbides coarsening and the Laves phase precipitation were the factors for the acceleration of fatigue softening of 8Cr–2WVTa steel.

Acknowledgements

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