Small Specimen Test Technology for Evaluation of Fatigue Properties of Fusion Structural Materials

Takanori Hirose1,2, Hiroyasu Tanigawa2, Masami Ando2, Akira Kohyama1, Yutai Katoh1 and Shiro Jitsukawa2

Institute of Advanced Energy, Kyoto University, Uji 611-0011, Japan
Japan Atomic Energy Research Institute, Tokai, Naka 319-1195, Japan
1Institute of Advanced Energy, Kyoto University
2Department of Material Science, Japan Atomic Energy Research Institute

Fatigue tests of ferritic/martensitic steels for fusion reactor application were carried out at room temperature using mini-sized and full-sized hourglass type fatigue specimens, as the basic study of small specimen testing techniques, which are indispensable for the effective use of the limited volumes of material testing reactor and proposed intense neutron sources. The FIB micro-sampling technique was applied to make the cross sectional thin foil specimen from the fatigue crack tip nearby the fractured surface. Effects of specimen size on fatigue properties, such as lifetime, plastic strain range and stress range, were not significant in the specimens used. TEM examination around the crack tip revealed original martensitic lath structure had changed to polygonization-like-structure and fatigue crack had been initiated along pre-austenite grain boundary.

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1. Introduction

Reduced activation ferritic steel, RAFs, is the leading candidate material for the first wall and blanket structures of the future D-T fusion reactors, because of their excellent resistance to neutron irradiation. In fusion reactor application, the structural materials will be exposed to cyclic stress caused by temperature cycling from reactor operation. Thus it has been recognized the investigation of fatigue properties are essential to reactor design.

Small specimen testing technology 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. For fatigue tests, cracking occurs on the specimen surface and propagates inward across the cross section. Therefore it is considered that fatigue properties are influenced by specimens' dimension. In this work, the effect of specimen size on fatigue properties of reduced activation ferritic/martensitic steels; F82H and JLF-1 were investigated for better understanding of fatigue properties of irradiated specimen using miniaturized fatigue specimen. Microstructural evolution after fatigue tests was also investigated with FIB micro-sampling system and TEM.

2. Experimental Procedure

The materials used were Japanese reduced activation ferritic/martensitic steels, F82H IEA heat (Fe-0.1C-8Cr-2W-0.2V-0.04Ta) and JLF-1 2nd large heat (Fe-0.1C-9Cr-2W-0.2V-0.08Ta). The details of these steels are presented in elsewhere.

To clarify the effect of specimen size on fatigue properties, two types of hourglass specimens have been fabricated. The longitudinal direction of the specimen was perpendicular to the final rolling direction. It is well known that the hourglass type specimen has good resistance to buckling. Furthermore the hourglass specimen is desirable for ion implantation, because fracture initiation site is limited to around the specimen's waist portion. The ratio of root radius to diameter of waist portion, R/d of both specimens was 8, which satisfies the recommendations of ASTM E-606. The minimum diameter of hourglass for full- and mini-sized specimen was 6 mm and 1.25 mm, respectively. The mini-sized specimens called SF-1 are proposed to use in accelerator driven D-Li stripping reaction neutron sources, such as IFMIF. The geometry of specimens used in this work is presented in Fig. 1. The hourglass portion of SF-1 specimens was finished electrolytically.

Diametral strain controlled low cycle 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 0.04%/s, the stress condition was push-pull. \( \Delta \varepsilon_d \) was converted to total axial strain range, \( \Delta \varepsilon_a \), by the following formula described in ASTM E-606.

\[
\Delta \varepsilon_a = (\sigma/E)(1 - v_e) - 2\Delta \varepsilon_d
\]

where:
- \( \sigma \): Applied stress,
- \( E \): Elastic modulus,
- \( v_e \): Elastic Poisson’s ratio.

The number of cycles to failure, \( N_f \), was defined as a point where a tensile peak stress decreased by 25% from an extrapolation curve of the tensile peak stress against number of cycle. All tests were performed at an ambient temperature in air.

Figure 2 shows procedure of making TEM thin foil out of deformed region nearby a crack tip on fatigue-fractured specimen, utilizing focused ion beam (FIB) micro-sampling sys-
3. Results and Discussion

3.1 Evaluation of fatigue properties using mini-sized specimen

The shape of hysteresis loop revealed plastic strain range, $\Delta \varepsilon_p$, of JLF-1 and F82H did not change during tests except for the end of tests. The relationship between $N_f$ and the converted total axial strain range, $\Delta \varepsilon_a$, is presented in Fig. 3. The $N_f$ values with the mini-sized specimens were compared with those of full-sized specimens. Supplemental data of full-sized F82H were obtained from cylindrical specimen.\(^7\) As shown in this figure, fatigue lifetime of F82H was slightly shorter than that of JLF-1. By comparison with lifetime of cylindrical specimen, that of hourglass specimen was short, especially in small strain range. Cyclic stress response curves are presented in Fig. 4. As shown in this figure, cyclic softening was observed in all tests. The tensile stress increased, however, at initial stage in several tests performed at higher strain range. Stress range of F82H was larger than that of JLF-1, it was reason why the difference in lifetime between F82H and JLF-1. Fatigue properties, such as $\Delta \varepsilon_p$, stress range and $N_f$, did not depend on specimen size in this work. It implies that fatigue properties was evaluated properly utilizing SF-1 specimen, as well as utilizing conventional full-sized specimen.
3.2 Mechanical understanding of fatigue fracture on F82H based on microstructure observation

Typical SEM micrographs of surface of fatigue-tested specimen are shown in Fig. 5. It is clear that most of cracks on the side of the specimen are emerging along with pre-austenite grain boundary. Rough surface region, which correspond to heavily deformed region, were observed along the cracks. TEM micrographs around a crack tip are shown in Fig. 6. The micrographs suggest that the crack was initiated at the portion of pre-austenite grain boundary open to the surface and poligonization was occurred around the crack. Peculiar shaped sub grains were observed beneath the crack tip along pre-austenite grain boundary. No vein structure or persistent slip band were observed.

From these results, the microstructural process of fatigue on F82H was presumed; i.e. first, cyclic deformation introduce poligonization, and particularly weak region is formed along pre-austenite grain boundary, where are large difference of crystal orientations between adjacent grains and a lot of carbide formed, and then the crack propagate through the weak region.

4. Summary

Diametral strain controlled fatigue tests, utilizing mini-sized specimen, on RAFs had been carried out at ambient temperature. The fatigue-fractured specimen was observed by TEM and SEM.

(1) RAFs demonstrated the cyclic softening until the fracture on the other hands, the plastic strain range, $\Delta \epsilon_p$ did not change during the fatigue life except for near the final fracture.

(2) The stress range, $\Delta \epsilon_p$ and number of cycles to failure, $N_f$ did not depend on specimen size in this work.

(3) Fatigue cracks were initiated along with pre-austenite grain boundary. Rough surface region, which correspond to heavily deformed region, were observed along the cracks.

(4) Poligonization was occurred around the crack. Peculiar shaped sub grains were observed beneath the crack tip along pre-austenite grain boundary.

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