Cyclic Softening Behavior with Slip System of FMS Steel

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1. Introduction

9Cr steel has high strength and high thermal conductivity, low thermal expansion, and high resistance to the swelling by irradiation. 9C steel is applied to structures of future reactor such as cladding of nuclear fuel, heat exchanger, and reactor pressure vessel and pipe.

Thermal fatigue by temperature gradient due to heat-up and cool down is important factors to limit structural life. Cyclic softening was observed during low cycle fatigue of 9Cr steel. The mathematical form of the constitutive laws relating stress and strain is governed by the deformation characteristics of the material and complexity of the structure and the loading to which it is subjected. In this study, cyclic softening behavior was investigated in the viewpoint of dislocation density and texture of microstructure.

2. Experimental procedure

Chemical composition of commercial 9Cr-1Mo steel was shown in Table 1. Heat treatment was normalized at 1050℃ and tempered at 770℃.

Low cycle fatigue test specimen was 8 mm gage length and 7 mm diameter. Specimen was taken as rolling direction. The gage section of the specimen was polished using a 1000 grit sand paper with strokes along the specimen axis. Low cycle fatigue test was conducted at RT-600℃ under strain control. Low cycle fatigue tests at RT were interrupted at 1, 10, 100, 1000, 2000 cycles to investigate dislocation density and texture. Waveform was fully reversed triangular and strain rate was $2x10^{-3}$/s. All specimens were tested at air environment. Temperature was controlled within ±2℃.

Dislocation density was evaluated with cycle by line broadening measured with XRD. Texture was analyzed with cycle by EBSD.

Table 1. Chemical composition of 9Cr

C	Mn	Cr	Ni	Mo	Nb	V
0.085	0.379	9.37	0.09	0.91	0.08	0.19

3. Results and Discussion

Cyclic stress with cycle during low cycle fatigue was shown in Fig. 1. Cyclic softening was observed. Amount of cyclic softening was defined as the difference between stress at the first cycle to stress at each cycle. Amount of cyclic softening with cycle was shown in Fig. 2. Amount of cyclic softening increased great at an early stage of fatigue and gradually after 500 cycles. Amount of cyclic softening was little different to 500℃ and increased at 600℃.

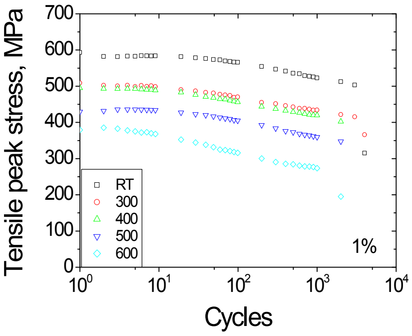


Fig. 1. Cyclic stress with cycle

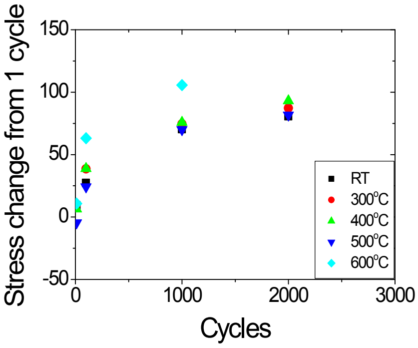


Fig. 2. Cyclic softening with cycle

Dislocation structure after test at RT was observed at each cycle. Cell structure was not observed to 10 cycles and shown after 100 cycles. Cell size and lath width increased with cycles to 100 cycles and was saturated after 1000 cycles. Dislocation density was proportional to square root of line broadening at full width at a half maximum (FWHM) of peak. Dislocation density with cycles was shown in Fig. 3. Dislocation density of (110) plane decreased to 10 cycles, increased at 100 cycles and decreased gradually above 1000 cycles. Dislocation density of (211) plane decreased to 100 cycles and increased above 1000 cycles. Dislocation density behavior was not consistent with the behavior of cell size and lath width.

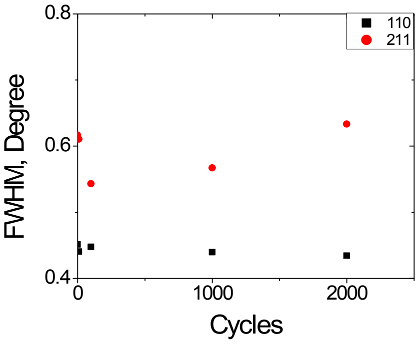


Fig. 3. Dislocation density with cycles

Pole figure and inverse pole figure investigated by EBSD were shown in Fig.4. Normal direction was parallel to load axis. At as-received condition, (110) plane was distributed at about 45° and 90° to normal direction and (211) plane was distributed at about 35° and 66° to normal direction. Distribution angle of (110) plane was similar with cycles but distribution angle of (211) plane was spread out between 35 and 66 degree with cycles.

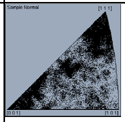
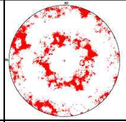
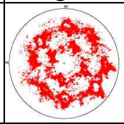
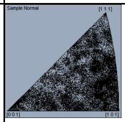
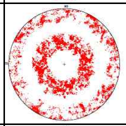
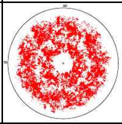
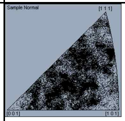
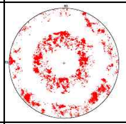
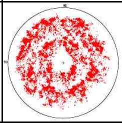
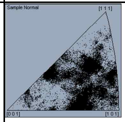
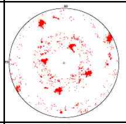
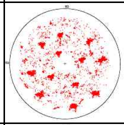
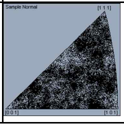
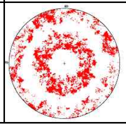
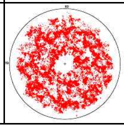
Cycle	Inverse pole figure	(110) pole figure	(211) pole figure
0			
10			
100			
1000			
2000			

Fig. 4. Inverse pole figure and pole figure with cycles

(110) and (211) planes were concentrated to any direction between rolling direction and transverse direction at as-received condition but distributed at whole direction at 10 cycles. FWHM of (110) and (211) planes decreased because slip was on (110) and (211) planes to reduce dislocation density at lath boundary and increase lath width.

Cyclic stress decreased at 100 cycles because dislocation density on (110) and (211) plane decreased due to cell structure formation and the increase of lath width. Dislocation density on (110) plane increased because (110) plane was concentrated to maximum resolved shear stress direction and less favorable to form cell structure than (211) plane.

Slip was preferential on (110) plane at high cycle and dislocation piled up at cell boundary and more stress was needed to move dislocation. (211) plane was activated for dislocation to move. Dislocation that piled up at cell boundary moved to (211) plane and dislocation could moved easily again at (110) plane. Dislocation density of (110) plane decreased slightly and dislocation density of (211) plane increased at 1000 and 2000 cycles.

4. Conclusion

The amount of cyclic softening is great at an early stage of fatigue life but a little at middle and last stage of fatigue life. Cell microstructure is not observed to 10 cycles but observed after 100 cycles. Cyclic softening behavior is not consistent with FWHM behavior of (110) and (211) plane. Cyclic softening during low cycle fatigue is due to the decrease of dislocation density by cell structure formation, the increase of lath width, and slip plane variation.