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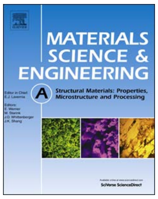

Stress softening and hardening during compression and tensile consecutive cyclic loading of Mn18Cr18N austenitic stainless steel

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ABSTRACT

The compression and tensile consecutive deformation behavior and microstructure evolution of Mn18Cr18N steel were investigated by cyclic loading tests at room temperature and strain amplitude from 0.005 to 0.15. The results indicated that the cyclic loading stress-strain curves of the steel show plastic deformation characterized by almost the same working hardening rates without yield plateaus at various strain amplitudes. At the lower strain amplitudes from 0.005 to 0.01, the stress amplitudes and subsequent yield surface radius decreased with cycles, which suggest that stress softening occurs during cyclic loading. At the strain amplitudes from 0.02 to 0.15, the stress amplitudes and subsequent yield surface radius increased with cycles, which imply that stress hardening occurs during cyclic loading. With the increasing of strain amplitudes, the cyclic hardening coefficients monotonically increased, while the cyclic softening coefficients rapidly decreased. The maximum flow stress increased up to 1549.6 MPa after three cycles at the strain amplitude of 0.15, which increased by 395.4 MPa compared to the maximum uniaxial tensile flow stress. It was also demonstrated that the cyclic loading stress-strain behaviors (cyclic softening and hardening) depend on internal stress component rather than effective stress component. TEM observation shows that planar slip with parallel substructures along one direction at high number cycles evolved from various dislocation configurations at low number cycles occurs at the lower strain amplitude of 0.005; double planar slip with grid substructures along two directions at high number cycles evolved from parallel substructures along one direction at low number cycles occurs at the higher strain amplitude of 0.04. Internal stress could be released by dislocation rearrangement and activation of cross slips during cyclic loading process, which induce stress softening at lower strain amplitudes; while slipping and twining alone two intersectional directions caused stress hardening at higher strain amplitudes.

1. Introduction

As one of key components of turbo-generators, the retaining ring subjects to a complex and large load in its working condition so that it has to meet the higher yield and tensile strength requirements [1,2]. The yield strength of 300 MW large retaining rings is required generally to be more than 1000 MPa. For 600 MW and 1000 MW heavy retaining rings, the yield strengths at room temperature are required to be over 1200 MPa and 1300 MPa respectively [2]. Mn18Cr18N, a high-nitrogen austenitic stainless steel, is widely used to manufacture retaining rings of generators due to its distinctive advantages such as high strength and toughness, non-magnetic property and excellent stress corrosion resistance [3–6]. Because Mn18Cr18N is the steel without phase transformation during hot working, strain strengthening becomes the way adopted to increase its strength [7]. However, the yield ratio of the steel is close to 1 gradually during the unidirectional tensile deformation, which limits the unidirectional tensile deformation used for strengthening larger retaining rings. Some researches about cyclic loading indicate that cyclic loading can be used for obtaining higher strength than the unidirectional tensile loading by increasing accumulative plastic deformation [8].

Many researches on mechanical behaviors of cyclic loading have been reported for metal materials (e.g, magnesium alloys [9,10], aluminum alloys [11], copper [12,13] and stainless steels [6,8,14–19]). The cyclic deformation behavior of as-extruded Mg-3%Al-1%Zn was investigated by Yin et al. [9]. A significant cyclic hardening asymmetry was observed under cyclic loading. It could be verified that both twinning and un-twinning play an important role in the cyclic deformation response of this material. Chang et al. [14] have studied the low cycle fatigue behavior of a high nitrogen austenitic stainless steel, explained that the relation between mechanical behavior and microstructures of the high nitrogen austenitic stainless steel during cyclic

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loading. It pointed out that the cyclic stress behavior of 316LN has a strong dependence on the strain amplitude applied. In addition, the cyclic stress response and cyclic stress-strain curves were determined mostly by the internal stress component. In the study of Feaugas [17], the hardening process in terms of internal and effective stresses was analyzed, and the internal stress can be considered to be decomposed into the intragranular stress and the intergranular stress components. However, most studies of cyclic deformation focus on fatigue properties of materials under low strain amplitudes. And it can hardly find studies on cyclic deformation behavior of steels under large strain amplitudes. Dusicka et al. [8] investigated the cyclic response of plate steels under large inelastic strains range from ± 1% to ± 7%. In the study, the hardening phenomenon was observed in cyclic deformation of five plate steels, which occurred mainly within the first three cycles. The maximum cyclic stress was found to be dependent on steel type and strain amplitude. The cyclic stress for structural steels with lower yield stresses increased up to 2.0 times the yield strength with strain increasing up to 4.8 times.

The main purpose of this study is to investigate the cyclic loading mechanical behavior and the corresponding microstructure mechanism of Mn18Cr18N steel by cyclic loading tests at large strain amplitudes ranging from 0.005 to 0.15 at room temperature. Cyclic hardening and softening of Mn18Cr18N steel were characterized by terms of cyclic hardening and softening coefficients and subsequent yield radius. The relation between microstructure and the effective stress or the internal stress component was investigated by TEM observation.

2. Experimental procedures

The material in this study was Mn18Cr18N austenitic stainless steel with processing history of ingot cogging and blocking followed by solution treatment at 1050 °C for 3 h. The chemical composition of the steel was shown in Table 1. The starting microstructure with average austenite grain size of 100 μm was shown in Fig. 1. Some annealing twins can be observed in Fig. 1, which is common in austenitic stainless steel [5,6]. Then the dumbbell shape specimens with a gauge length of 14 mm and a diameter of 7 mm were machined, as shown in Fig. 2a.

The cyclic loading tests controlled by certain total strain were carried out on a MTS810 machine at a constant strain rate of 0.002 s^{-1} and room temperature. The test strain amplitudes were in the range of 0.005–0.15 with the cycle numbers ranged from 3 to 10. The cycle loading procedure expressed in the stress-strain curve of cycle loading was shown in Fig. 2b. In the first one cycle loading, the sample was first compressed under the forward compression loading up to the strain amplitude $\Delta\varepsilon$, next unloading and stretched under the reverse tensile loading up to $2\Delta\varepsilon$, then unloading and compressed under the compressive loading again up to $2\Delta\varepsilon$. The followed each cycle loading is composed of the compression and tensile consecutive loading with the strain of $2\Delta\varepsilon$.

The specimens after cyclic loading were sectioned along the axes longitudinally. Then the sectioned samples were prepared for X-ray diffraction (XRD) and transmission electron microscopy (TEM) testing. Thin foils for TEM testing were first mechanically polished down to about 50 μm thickness, then electro-polished in a 5vol pct perchloric acid and 95vol pct acetic acid mixture at 25 V and 30 mA at room temperature. The structure constitutes in the specimens after cyclic loading were analyzed by X-ray diffraction (XRD). The substructures and the dislocation arrangements in samples after cyclic loading were analyzed by TEM on Tecnai F30 G2.

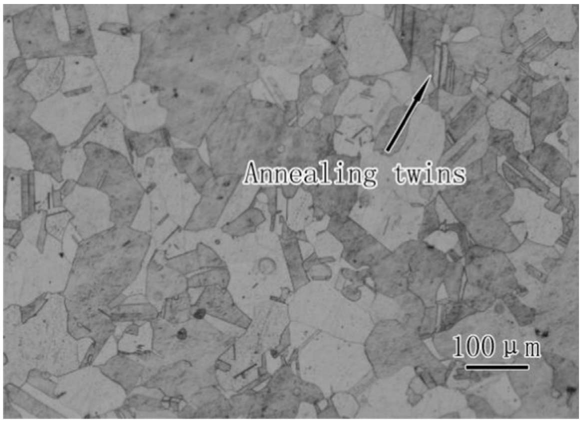

Fig. 1. The starting microstructure of the tested steel.

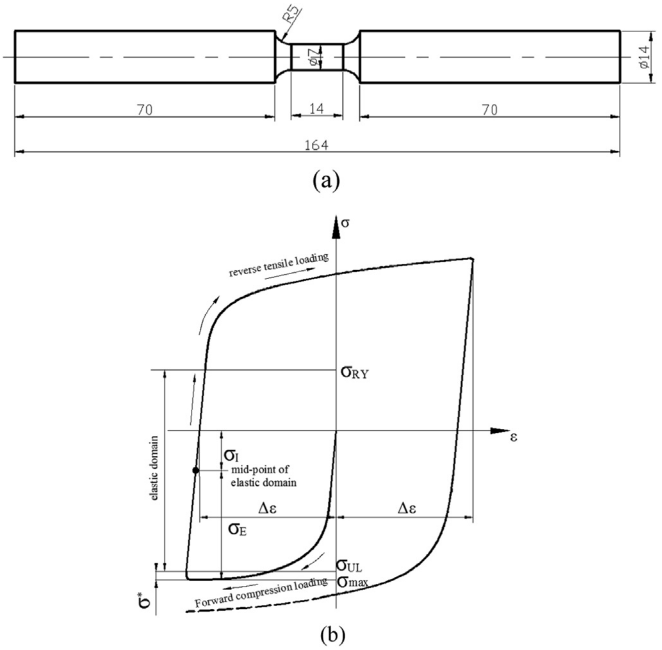

Fig. 2. The tested sample (a) and the loading procedure (b).

3. Results

3.1. The cyclic loading stress-strain curves

Fig. 3 shows the stress-strain curves of Mn18Cr18N steel under compression and tensile consecutive cyclic loading with various strain amplitudes. It can be seen that the cyclic loading stress-strain curves in Fig. 3 show plastic deformation characterized by almost the same working hardening rates without yield plateaus at various strain amplitudes. The initial 0.2% yield strength of Mn18Cr18N steel was about 604 MPa. The cyclic stress amplitude increased with the increase of strain amplitude. The maximum flow stress increased up to 1549.6 MPa after three cycles at the strain amplitude of 0.15, which is about 2.6 times the initial 0.2% yield strength. In the previous study [2], the uniaxial tensile tests were carried out at room temperature with the

Table 1
Chemical composition of Mn18Cr18N steel (wt%).

C	Mn	Si	P	S	Ni	Cr	Mo	V	Cu	Al	N	Nb	Fe
0.069	19.58	0.6	0.015	0.002	0.13	19.98	0.022	0.12	0.04	0.04	0.62	0.001	Bal.