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Effect of preload stress on the dynamic response of 9%Cr heat-resistant steels with various microstructures

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ABSTRACT

With a uniaxial oscillation load coupled to different preload stresses, the dynamic responses of 9%Cr heat-resistant steels with different microstructures (martensite and cell structure) were measured on a low-cycle fatigue machine at the elevated temperature of 823 K. The experiment results show that the internal friction of 9%Cr heat-resistant steel is dependent on not only the microstructure, but also the preload stress. The internal friction of 9%Cr heat-resistant steel with martensite reaches the minimum when the preload stress is close to half of its 0.2% offset strength. Within the present range of preload stress, however, the internal friction of cell structure monotonically increases with the preload stress. Based on the analysis of obtained results, it indicates that for the 9%Cr heat-resistant steels with martensite and cell structure, the different behaviors of internal friction with the preload stress are mainly attributed to various dynamic configurations of internal defects.

1. Introduction

High-chromium steels with a tempered martensitic structure have been widely applied to steam turbine and boiler components in power plants, petrochemical plants and oil refineries [1,2]. These components are often exposed to elevated temperature and subjected to the long term sustained loading. Under these service environments, the degradation of mechanical properties such as strength and fracture toughness arises easily from microstructure changes, creep, and combinations of these factors [3,4]. Thus, the microstructure change due to the recovery of martensite during creep becomes one of the most critical factors determining the structural integrity of components [5–7]. Usually, the metallographic observation is performed to study the microstructure change. However, this method exhausts much time for preparing specimen and the inspection area is limited to only a small fraction of components. In order to analyze the structural integrity of these components, it is necessary to investigate their microstructure changes by other convenient methods.

Previous experiments [8–10] show that at elevated temperatures, the anelasticity of 2.25Cr–1Mo steel with different matrices varied significantly. However, there were few experiments on the quantitative analysis of the relationship between anelasticity and microstructure for high-chromium steels. Generally, the anelasticity at elevated temperatures is caused by the dynamic configuration of internal structures. When an oscillation load is applied to the material, the anelasticity leads directly to the dynamic responses of internal friction and storage modulus. Thus, it is possible to evaluate the microstructure change of high-chromium steels with the measurement of dynamic responses.

In present work, the 9%Cr heat-resistant steels with the tempered martensite and cell structure were prepared to simulate the microstructure change due to creep in advance. Then, the uniaxial deformation with the oscillation load in a low-cycle fatigue machine was used to measure the dynamic responses of internal friction and storage modulus under different preload stresses at 823 K. According to experimental results, the influence of preload stress upon the dynamic response of 9%Cr heat-resistant steels with various microstructures was investigated in detail.

2. Experimental procedure

Two typical microstructures of the tempered martensite and cell structure were used as the principal alloy of 9%Cr heat-resistant steel. The chemical compositions of them are shown in Table 1. In order to obtain the martensite, steel A was normalized (1323 K 1 h AC) and then tempered (1033 K 1 h AC). Compared with steel A, steel B was quenched directly after normalizing, which has a cell structure obtained by sequential treatments

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Table 1
Chemical compositions (mass%) of the examined 9%Cr heat-resistant steels.

	C	Si	Mn	P	S	Cr	Mo	V	Nb	W	N	Al	B	Co
Steel A	0.0008	0.3	0.51	0.001	0.001	9.13	<0.01	–	–	2.95	0.054	0.001	0.0029	2.93
Steel B	0.0012	0.01	<0.01	<0.003	0.0016	9.1	–	<0.003	<0.003	<0.01	0.001	0.011	–	3.06

(1273 K 1 h AC+1323 K 1 h AC+1273 K 2 h WQ). The detailed description of their microstructures has already been reported elsewhere [9]. In addition, all specimens for the following experiments on the uniaxial tensile testing have a gauge with length of 15 mm and diameter of 4 mm.

In order to determine the 0.2% offset strength, the uniaxial tensile experiments on steel A and B at 823 K were firstly performed in air using an electrically controlled hydraulic machine (model EHF-FG50KN.T Servopulser, Shimadzu Co., Japan). The specimen strain was measured by an extensometer for high temperature. Subsequently, the measurements of internal friction and storage modulus for steel A and B at 823 K were conducted on the same machine. Before the specimen strain was recorded, various preloaded tensile stresses of 0, 1/6, 1/3, 1/2 and 2/3 of the 0.2% offset strength for steel A and B were forced, respectively. When the required preload stress reached, the uniaxial oscillation loads with the given amplitude of 60 MPa and various frequencies of 2 Hz, 1 Hz, 0.5 Hz and 0.1 Hz were coupled to the preload stress in sequence while the specimen strain was recorded. The schematic diagram of measured procedure can be seen in Fig. 1. The forced oscillation is holding for one minute. Consequently, the internal friction (tan ϕ) was characterized by the tangent phase lag ϕ, between the applied oscillation stress and resultant strain. Meanwhile, the storage modulus ($E' = \sigma^A/\varepsilon_m^A cos\phi$) was calculated by the obtained internal friction, applied stress amplitude σ^A and resultant strain amplitude ε_m^A at the exciting frequency, which can be obtained by the Fourier transformation.

3. Results

3.1. Evaluation of the 0.2% offset strength for steel A and B

The tensile nominal stress–nominal strain curves for steel A and B at 823 K are shown in Fig. 2, respectively. It can be seen that for steel A with the martensite, the 0.2% offset strength reaches 309 MPa. In contrast to steel A, the 0.2% offset strength of steel B with the cell structure is smaller and only 216 MPa. Previous experiments by Sawada et al. [9] show that the steel A has a lath structure with high dislocation densities and the steel B is mainly composed of the coarse cell structures. Therefore, it indicated that the 0.2% offset strength for 9%Cr heat-resistant steel is strongly sensitive to its microstructure especially at elevated temperatures.

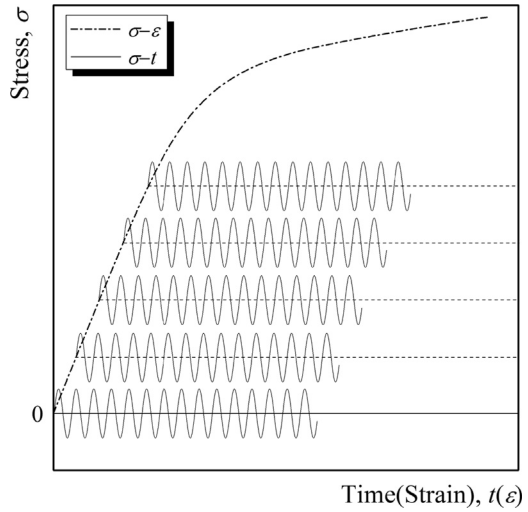

Fig. 1. Schematic diagram of the measurement procedure for internal friction and modulus when an oscillation load is coupled to different preload stresses.

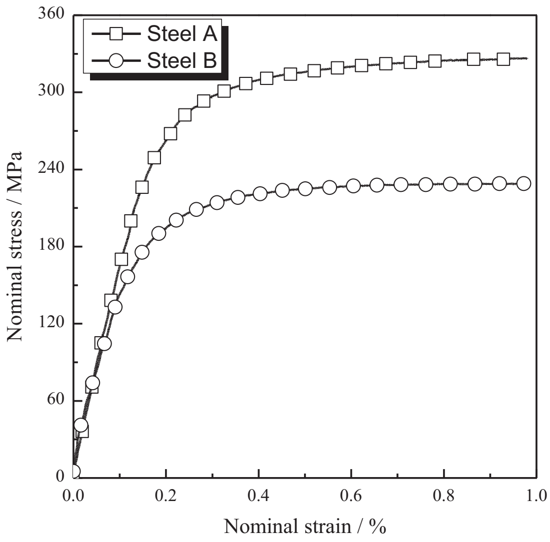

Fig. 2. Nominal stress–nominal strain curves of 9%Cr heat-resistant steels with different microstructures at 823 K.

3.2. Internal friction and storage modulus under different preload stresses

Fig. 3 presents the influence of preload stress upon the measured internal friction and storage modulus of steel A with various frequencies of 0.1 Hz, 0.5 Hz, 1 Hz and 2 Hz at 823 K. It is clear that the internal friction and storage modulus of steel A are strongly related to the preload stress and dependent on the frequency. At a given frequency, the internal friction of steel A monotonically decreases with the preload stress until the preload stress is close to 154.5 MPa (half of the 0.2% offset strength for steel A), as shown in Fig. 3a. On the contrary, the increase in internal friction of steel A occurs when the preload stress is larger than half of the 0.2% offset strength. Besides, the storage modulus of steel A at a given frequency increases under the small preload stress and reaches the maximum when the preload stress is close to half of the 0.2% offset strength, which can be seen in Fig. 3b. It indicated that the hardening process exists for the steel A due to the coupled preload stress. At the preload stress larger than half of the 0.2% offset strength, however, the storage modulus of steel A decreases indicating that there are different mechanisms of internal defect movement. Moreover, it is obvious that compared with the storage modulus, the internal friction of steel A at a fixed preload stress is more sensitive to frequency.

At 823 K, the effect of preload stress on the measured internal friction and storage modulus of steel B with various frequencies of 0.1 Hz, 0.5 Hz, 1 Hz and 2 Hz is given in Fig. 4. It can be seen that at a given frequency, the measured internal friction and storage