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Ratchetting behavior of advanced 9–12% chromium ferrite steel under creep–fatigue loadings: Fracture modes and dislocation patterns

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ABSTRACT

In order to reveal the physical mechanisms of ratchetting process under creep–fatigue loadings, following ratchetting tests in advanced 9–12% chromium ferrite steel, a study of associated fracture modes and dislocation patterns explored by scanning electron microscopy (SEM) and transmission electron microscopy (TEM) observations is presented in this paper. Two main domains were observed depending both on the peak hold time and on the stress ratio, in which the ratchetting deformation and failure mechanisms were different. These two damage domains correspond to two distinct creep–ratchetting interaction mechanisms. Particular attention was paid to the dependence of ratchetting damage behavior on the stability of dislocation substructure. In addition, an attempt is made to correlate the results of the microstructural investigations with the variations of internal stress.

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1. Introduction

Progressive accumulation of strain will occur in materials and structures under the cyclic stressing. This phenomenon is called as ratchetting or cyclic creep. Over the past few decades, the ratchetting behaviors have been extensively studied as reviewed by Ohno [1,2] and Kang [3]. However, efforts were focused mainly on developing the phenomenological descriptions in those previous studies. Only a few works have been reported concerning physical arguments on the origin and the mechanism of ratchetting [4–12]. The dislocation features related to the cyclic accumulated deformation were firstly explored in copper [4–6]. Those studies showed a similar suggestion that cyclic creep occurred by a process involving localized cell wall breakdown producing regions of high uniform dislocation density from which new cells can form and grow during the subsequent cycling. Recently, Melisova et al. [8] reported that in copper cyclic softening is linked to the occurrence of cyclic creep which in turn is strongly associated to any kind of strain localization. More recently, qualitative TEM observations of the dislocation structures during ratchetting deformation were performed in 316L stainless steel [11] and 20 carbon steel [12]. These two studies focused on the evolutions of dislocation with the increasing number of cycles, therefore the relationship between the dislocation features and the steady ratchetting rate was not clearly investigated. The quantitative discussions for dislocations patterns, associated internal stresses, and their relations to steady cyclic creep rate were carried out in 316L stainless steel [9,10], which showed that only the dissolution of polarized walls promoted the cyclic creep. With respect to ratchetting damage behavior, Yang and Wang [7] SEM observations performed in spring steel SAE 5160 indicated that a transition from quasi-brittle fracture to ductile fracture took place with the prestrain increasing. However, the physical explanation of this damage transition had not been clearly discussed.

On the other hand, high temperature plants and their components are often exposed to the combined creep–fatigue loadings. The existence of time-dependent deformation and its interaction with time-independent deformation make the ratchetting behavior more complicated. The influences of time-dependent factors, such as stressing rate and stress hold time on ratchetting behavior of the materials have been shown in some works [13–18]. However, the creep–ratchetting interaction and its effect on life have not been clarified clearly in the case of creep–fatigue loading.

More recently, an experimental study was performed at 873 K with various hold times and stress ratios on high chromium ferritic steel concerning the ratchetting behavior under creep–fatigue loadings [19]. In addition, based on the macroscopic experimental results, a modified creep–fatigue damage evaluation approach [20] and a new creep–ratchetting constitutive model [21] considering the influence of anelastic creep were proposed by the author and his co-authors for advanced 9–12% chromium steels under stress controlled cycling. The effect of hold time on ratchetting behavior was highlighted in those studies. A transition in creep–ratchetting interaction and rupture behavior with increase of hold time has been observed [19]. These two domains were discussed in terms of

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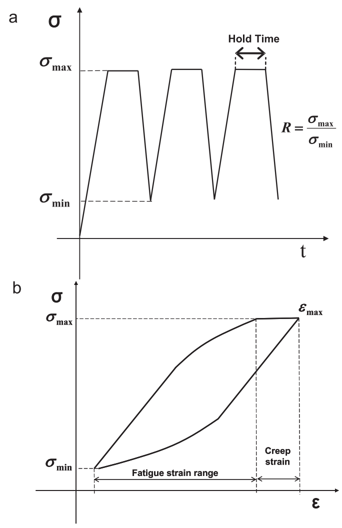

Fig. 1. Schematic of applied loading history (a) and hysteresis loop (b) for ratchetting test.

internal stresses variables measured using stress partition method. However, this discussion on the origin of this transition remains speculative without a precise microstructure observation.

The main objective of the present study is to evaluate the relationship between the microstructure evolution and the ratchetting rupture behavior. At the beginning, the fracture modes and dislocation patterns during the ratchetting process are observed by scanning electron microscopy (SEM) and transmission electron microscopy (TEM) methods, respectively. Then the stability of dislocation structures will be discussed in terms of the effects of loading factors and correlated with internal stress state.

2. Materials and experimental procedure

The material studied is an advanced high chromium ferrite steel X12CrMoWVNbN10-1-1 (German designation). Ratchetting tests have been performed in laboratory air at 873 K with load control and kept stable to exclude the influence of plastic strain history. Fig. 1 shows the schematic diagrams of applied loading history and hysteresis loop for ratchetting test. The parameters characterizing ratchetting process can be defined from this figure. The ratchetting tests are designed into two groups. In the first group, various hold times are introduced at the peak load to address the hold-time effect. Another aspect is to examine the stress ratio effect. The details of both the material and the ratchetting tests have been described in the previous work [19].

All the TEM observations in the present study are carried out on the ruptured specimens. The samples have been sectioned in the gauge portion (far from the fracture surface) which is perpendicular to the stress axis. Thin foils were prepared by the conventional double-jet electropolishing in a solution of 10% perchloric acid in ethanol. The TEM investigations were conducted using a FEI TECNAI field emission transmission electron microscopy. Fracture surfaces were examined by a VEGAII scanning electron microscopy to determine the fracture modes.

3. Experimental results

3.1. Ratchetting and fracture life

For integrity of the content, some important ratchetting experimental results in our pervious work [19] are still contained herein.

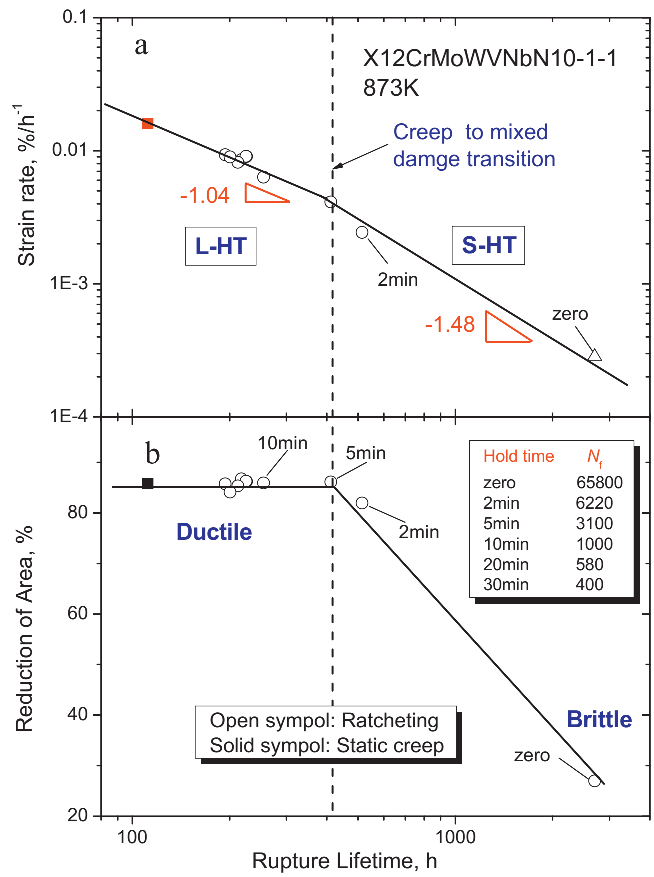

Fig. 2. Relation of steady ratchetting rate to lifetime [19] (a) and corresponding reduction of area after rupture (b) for steel X12CrMoWVNbN10-1-1. The dashed line divided the data points into two domains S-HT (short hold time) and L-HT (long hold time). The number of cycles to failure (N_f) for ratchetting tests is indicated in (b).

Fig. 2a shows the relationship between the ratchetting strain rate in the steady state and rupture lifetime of steel X12CrMoWVNbN10-1-1. Two domains with different relations of steady ratchetting rate to lifetime are observed. The experimental data in the long hold time (L-HT) domain can be well fitted by a single straight line with a slope of −1.04. Whereas, the data points in the short hold time (S-HT) domain appear to lie along a line with the slope of −1.48. Such a relationship between the steady strain rate and time to rupture suggests a difference in ratchetting rupture behavior between these two domains.

Fig. 2b shows the reduction of area measured after rupture as a function of rupture lifetime. The drop of ductility beyond a critical point indicates a transition in fracture modes from ductility to brittle. The transition point is in accordance with the boundary between domains L-HT and S-HT. This result confirms the difference in rupture behavior between these two domains.

It is worth noting that smooth (unnotched) cylindrical test specimens with a section diameter of 10 mm and a gauge length of 100 mm were used in this study. According to previous studies in 1045 steel [22,23], specimen notch tends to constrain the ratchetting strain because of the notch strengthening. Although it is beyond the scope of the present paper to clarify the effect of specimen shape, it seems that specimen geometry will have a great influence on the ratchetting process and corresponding facture modes under creep–fatigue loadings. In addition, the peak cyclic stress imposed in our ratchetting tests is only about 60% of the yield stress. If ratchetting tests with the same peak stress are performed on notched specimen, the

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