Materials and Design 71 (2015) 1–16

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Dwell fatigue and cycle deformation of CP-Ti at ambient temperature

Jian Peng, Chang-Yu Zhou *, Qiao Dai, Xiao-Hua He

School of Mechanical and Power Engineering, Nanjing Tech University, Nanjing 211816, China

ARTICLE INFO

Article history:
Received 19 September 2014
Accepted 19 January 2015
Available online 31 January 2015

Keywords:
CP-Ti
Dwell fatigue
Failure mechanism
Life prediction method

ABSTRACT

The influences of stress and hold time on cycle deformation and failure life of CP-Ti dwell fatigue were systematically investigated. Two dwell fatigue regions were divided by dwell fatigue parameters. At high stress region, creep and ratcheting behaviors are significant, and the failure mechanism is the ductile fracture caused by large deformation. But at low stress region, creep and ratcheting behaviors are tempered, and the failure mechanism is the classical fatigue fracture. It is worth noting that, the influences of hold time on dwell fatigue parameters are different at different dwell fatigue regions. Moreover, the creep and ratcheting interaction was discussed, and the dwell fatigue strain changes from ratcheting strain controlled to creep strain controlled with hold time increasing. At last, since the dwell fatigue life debits are different at different dwell fatigue regions, the dwell fatigue life prediction model considering fatigue, creep and ratcheting was proposed for the dwell fatigue behavior of CP-Ti at ambient temperature.

1. Introduction

The fatigue damage appears during start, stop and load fluctuation processes, while the creep damage appears during the steady operation load process. Fatigue damage and creep damage are coupled when equipments are operating at the condition with both fatigue and creep appear. Creep fatigue behavior is a research hotspot in both material science field and engineering field. Most of researchers focused on the high temperature creep fatigue behavior. The researches about high temperature creep fatigue are comprehensive, containing mechanism investigation and life prediction [1–3]. Many creep fatigue interaction models were proposed. Linear damage law is the most widely used creep fatigue interaction model, and it was improved by some researchers [4,5]. The linear damage law has been introduced into practice codes such as ASME Section NH [6]. Continuum damage mechanics based model [7–9] is an important creep and fatigue life model, since it has strong theoretical foundation and good prediction precise. Moreover, based on energy conservation theory, the energy based model was proposed for the creep fatigue interaction of steel at high temperature [10].

The researches about ambient temperature creep fatigue behavior are much fewer than those of high temperature creep fatigue. Some researches about ambient temperature dwell fatigue of Ti alloy were reported, studying the influences of stress level, stress state [11], stress ratio [12], microstructure [13–15], hold time [12,13], hydrogen [16]. These reports about the ambient temperature dwell fatigue focused on Ti alloy, but the report about the ambient temperature dwell fatigue of CP-Ti was not found. At the same time, previous studies found that, significant creep behavior and strain rate sensitivity were observed at ambient temperature for CP-Ti [17–19]. Therefore, it is necessary to investigate the dwell fatigue of CP-Ti at ambient temperature.

In addition, ratcheting behavior appears in some materials and structures under fatigue load. Lin et al. [20,21] found that Mg alloy exhibited significant ratcheting behavior at ambient temperature. Kang et al. [22] investigated the interaction of ratcheting behavior and fatigue failure of stainless steel at ambient temperature. Wen et al. [23] focused on the ratcheting behavior of Zr alloy at room temperature. In our previous research of CP-Ti, significant ratcheting behavior was observed at ambient temperature [24]. Moreover, some researchers studied the interaction of creep and ratcheting at high temperature. Xuan's research group [25–27] studied the interaction of creep and ratcheting of steel at high temperature, and found that hold time had a great effect on the interaction of creep and ratcheting. Based on the previous studies of CP-Ti at ambient temperature, both fatigue damage and ratcheting damage appeared under cyclic load [24], and significant creep behavior was found under constant load [18]. Then, creep, fatigue and ratcheting behaviors will interact under dwell fatigue for CP-Ti at ambient temperature, and will accelerate the damage rate and shorten the failure life. Therefore, the relationship among fatigue behavior, rat-

* Corresponding author. Tel./fax: +86 025 58139951.
E-mail addresses: changyu_zhou@163.com, cy_zhou@njtech.edu.cn (C.-Y. Zhou).

http://dx.doi.org/10.1016/j.matdes.2015.01.007
0261-3069/

cheting behavior and creep behavior in the dwell fatigue of CP-Ti at ambient temperature needs to be discussed.

In this study, the dwell fatigue of CP-Ti at ambient temperature was studied by cycle deformation behavior and failure life. The influences of applied stress and hold time were focused. Based on fatigue parameter, ratcheting parameter, creep parameter, failure mechanism and energy parameter, creep ratcheting controlled dwell fatigue region and fatigue controlled dwell fatigue region were divided. Moreover, the relationship among fatigue behavior, ratcheting behavior and creep behavior was discussed. At last, a life prediction method considering fatigue damage, ratcheting damage and creep damage was proposed for the dwell fatigue of CP-Ti.

2. Dwell fatigue experiment

The material was CP-Ti with the grade TA2 which is a widely used material in chemical equipments in China. The chemical composition (wt.%) was (0.055)Fe, (0.01)C, (0.001)H, (0.125)O, (bal.)Ti. Tensile mechanical properties were tested by Instron electronic universal test system with the constant strain rate $5 \times 10^{-4}\ s^{-1}$ at room temperature, and they are given in Table 1. The material CP-Ti used in dwell fatigue experiment was consistence with that previously used in pure fatigue experiment [24] and creep experiment [18]. The specimen dimension used in dwell fatigue experiment was the same as that used in pure fatigue experiment. Dwell fatigue experiments were conducted on the MTS 880 material testing system. Previous researches of CP-Ti fatigue paid attention to the symmetric cycle fatigue with strain ratio $R = -1$ [28–31]. But the rarely reported pulsation cycle fatigue with $R = 0$ is important in practice. Our previous research focused on the pure fatigue of CP-Ti with pulsation cycle [24]. This paper paid attention to the dwell fatigue of CP-Ti with pulsation cycle. The difference between dwell fatigue and pure fatigue is the loading path. The loading path of dwell fatigue is shown in Fig. 1, and the steady load is given during hold time. The loading/unloading time is 0.2 s the same as pure fatigue. The dwell fatigue experiment program and pure fatigue experiment program are given in Table 2. An axial extensometer was used to measure strain development until the specimen failure during experiments. The experimental details of pure fatigue experiment and creep experiment were given in the previous reports [18,24].

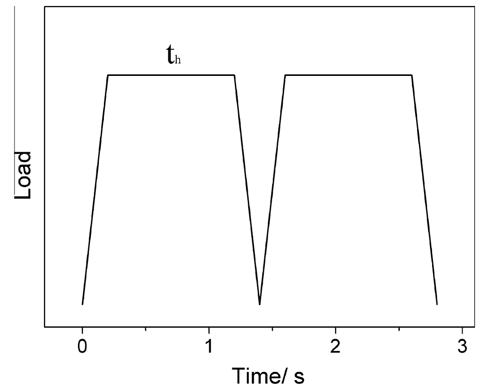

Fig. 1. The loading path of dwell fatigue experiment.

Table 2
Experiment program of dwell fatigue and pure fatigue.

Spec. no.	Max stress/MPa	Min stress	Hold time/s
F 1	236	0	0
D 1	236	0	1
F 2	255	0	0
D 2	255	0	1
F 3	267	0	0
D 3	267	0	1
F 4	281	0	0
D 4	281	0	1
F 5	299	0	0
D 5	299	0	1
F 6	310	0	0
D 6	310	0	1
D 7	236	0	5
D 8	299	0	0.2
D 9	299	0	5

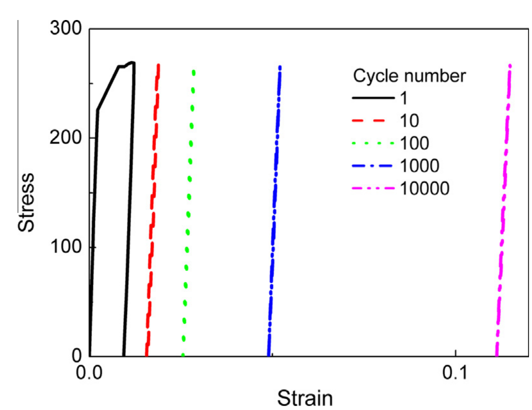

Fig. 2. Hysteresis loop of dwell fatigue.

3. Results and discussions

3.1. Strain evolution of dwell fatigue

In order to study the strain evolution of dwell fatigue, strain characteristic parameters containing hysteresis loop, cycle strain range and mean strain were measured by dwell fatigue experiments. The influences of stress, hold time and cycle number were focused.

3.1.1. Stress, hold time and cycle number dependences of hysteresis loop

Fig. 2 shows the development of hysteresis loop with cycle number corresponding to specimen No. D 3, and the results of other specimens are similar. As shown in Fig. 2, with cycle number increasing, the hysteresis loop moves to large strain. The strain accumulation of dwell fatigue contains ratcheting strain and creep strain, and the dwell fatigue behaviors of many metals have similar phenomenon, such as chromium ferrite steel [27] and Ti alloy [16]. Therefore, it is necessary to study the strain characteristic parameters of dwell fatigue for CP-Ti. In order to examine the influences of stress and cycle number on hysteresis loop, Fig. 3 draws the hysteresis loops at different stresses and different cycle numbers with 1 s hold time.

As shown in Fig. 3(a), the surrounded area of hysteresis loop increases with stress. As shown in Fig. 3(b) and (c), the accumulated strain increases with stress at the same cycle number. It is worth noting that, there is a strain accumulation platform during the hold time, which indicates that creep behavior appears. The creep behavior during dwell fatigue is commonly observed at high

Table 1
Tensile mechanical properties of CP-Ti at room temperature.

Temperature/K	Elastic modulus/MPa	Yield stress/MPa	Tensile strength/MPa
293	115,604	228.05	442.95