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Room-temperature creep behavior on crack tip of commercially pure titanium

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ABSTRACT

The room-temperature creep behavior on crack tip of compact tensile (CT) specimen for commercially pure titanium (CP-Ti) was studied by experiment and finite element (FE) simulation in this paper. The experimental results indicated that the time-dependent deformation was observed on the crack tip of CP-Ti CT specimen at room temperature, which agreed with the primary creep, and crack propagation was not observed. In order to consider the creep behavior on crack tip, time-dependent *J*-integral was used to characterize the stress fields near crack tip. The room-temperature creep behavior on crack tip was analyzed by FE simulation, which was verified by experimental results. Then, the strain fields under different stress states were analyzed by FE simulation. The influences of the locations to crack tip and load on the room-temperature creep were analyzed, which shows that the creep significance on crack tip is enhanced with increasing of load and decreasing of distance to crack tip. The estimation formula of creep strain value along ligament direction of CP-Ti CT specimen was established and verified by FE simulation results.

1. Introduction

Time-dependent deformation of commercially pure titanium (CP-Ti) occurs at room temperature [1–3], called room-temperature creep, which is a common behavior in many metal materials [4–6]. Although creep behavior at ambient temperature is in the form of primary creep [7,8] and the creep strain is limited [9], the room-temperature creep will affect material mechanics performance [5,6,10–12]. Moreover, the creep significance will be more obvious if the stress is higher, and primary creep will occur at the stress concentration area near a crack tip [13], which will threaten the safety of structure with crack. Meanwhile, the high stress level will appear due to stress concentration in practical engineering, such as the discontinuous part of structure. According to ASME Boiler & Pressure Vessel Code VIII-2 [14], the stress level of primary membrane (general or local) plus primary bending stress intensity can be 1.5S_m (S_m is allowable stress), and primary plus secondary stress intensity can be 3.0S_m. Therefore, the stress level will be high enough to lead creep for the design of pressure vessel.

In this paper, the room-temperature creep experiments were conducted on CP-Ti compact tensile (CT) specimens to investigate the time-dependent deformation near the crack tip. Two groups of experiment were carried to investigate creep behavior. The first group used extensometer to record the load-line displacement (LLD) evolution, and another one used digital image correlation (DIC) system to observe the strain field near crack tip. Moreover, three-dimensional finite element (FE) simulations were used to analyze the room-temperature creep behavior of CP-Ti CT specimens, and verified by experimental results. Furthermore, the strain fields under different stress levels were obtained by FE simulation, and the factors which affect the creep strain near crack tip were investigated.

2. Experiment

2.1. Material and specimen

The nominal composition of CP-Ti is more than 99% titanium, and other chemical compositions (wt.%) are Fe 0.08, C 0.02, N 0.01, H 0.001, and O 0.13. The mechanical properties of CP-Ti were obtained by tensile experiment [10], where Young's modulus (E) is 111556 MPa, yield strength (σ_s) is 232.6 MPa, and tensile strength (σ_b) is 449 MPa.

CT specimens of 25 mm width were used in room temperature creep experiments to observe time-dependent deformation behavior near the crack tip. The samples were machined from a rolled CP-Ti plate with 7.6 mm in thickness. The specimen thickness was the same as the plate thickness, and the specimens were precracked by fatigue loading. Then constant load was applied to the specimen by the MTS 880 servo-hydraulic testing machine.

2.2. Experimental procedures

All experiments were performed in air environment, and the temperature was about 20 °C. The crack length was measured by a traveling microscope. Since the creep deformation behavior near crack tip is impacted by stress level [15], various initial stress intensity factors

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K_0 corresponding to various loading conditions were considered. Two groups of experiments were conducted. One group used extensometer to record the LLD evolution, and another one used DIC system to observe the strain fields near crack tip. The detailed experimental scheme is shown in Table 1.

3. Results and discussions

3.1. Load line displacement evolution

The variations of LLD with time under various stress levels are shown in Fig. 1. It's worth to note that the LLD of CP-Ti CT specimen continuously increases under constant load, and the increasing rate is decreasing. As shown in Fig. 1, the variation of LLD increases with increasing of K_0 level. When the K_0 level was as low as $0.7K_{IC}$, the variation of LLD was not obvious. And when the K_0 level was up to $1.05K_{IC}$, the crack tip would be blunting and in fully plastic state.

During the experiment under room temperature, the load is constant, and LLD of CP-Ti CT specimens increases with the extension of time regularly. Obviously, time-dependent deformation occurred at the crack tips. It is known that smooth specimen of CP-Ti exists in time-dependent deformations under room temperature [8], which is called room-temperature creep, and it is found that the variation law of LLD with time is similar with the deformation law of smooth specimen's room-temperature creep. The deformation is continuously increasing with the extension of time under constant load, while the deformation rate is decreasing, and the deformation is more obvious under higher load. Therefore, the variation of LLD is attributed to room-temperature creep at the crack tips, and the significance of creep is enhanced with the increasing of load. Meanwhile, the same as the room-temperature creep law of CP-Ti smooth specimen, load threshold also exists for the room-temperature creep at the crack tip. When the load corresponding to K_0 level is as low as $0.7K_{IC}$, the time-dependent deformation was not obvious.

3.2. Creep strain at crack tip

Another group of experiments adopted DIC system to capture the strain fields of CP-Ti CT specimens under constant load at room temperature. The variations of strain field of specimen surface with time under load $0.95K_{IC}$ are shown in Fig. 2. The shape of strain contours indicates that the specimen surface is in the plane strain state. It is obviously that the strain distributions were changed with extension of time, which indicates that time-dependent deformation occurs.

In order to obtain the law of time-dependent deformation at the crack tip, the variation of strain values with time is investigated. Ahead of the crack tip, three points are considered to get the strain evolution with time. The distances of these points to the crack tip are 0.06 mm, 0.24 mm and 0.48 mm, respectively, and their locations are shown in Fig. 3. The variations of maximum principal strain values with time at these points are shown in Fig. 4. It is indicated that the strain values are increasing with time, and the increasing rates are decreasing. This deformation is typical primary creep, which is agreed with the creep behavior of CP-Ti specimen without crack at room temperature [8]. Once again, it is indicated that there exists room-temperature creep at crack tip of CP-Ti CT specimen. From Fig. 4, it is also found that the shorter the distance for point to the crack tip is, the greater the strain rate is, and the more significant the room-temperature creep phenomenon is. This is because of stress concentration at the crack tip, and the higher stress value leads to the more obvious room-temperature creep deformation.

Table 1
CT specimen room-temperature creep experiment scheme.

No.	Initial crack length a_0/mm	Load P/kN	K_0/K_{IC}	Measurement method
1	13.06	2.38	0.70	Extensometer measuring LLD
2	13.06	2.55	0.75	
3	12.80	2.94	0.85	
4	12.82	3.28	0.95	
5	13.03	3.54	1.05	
6	12.46	3.06	0.85	DIC capturing strain
7	12.55	3.39	0.95	

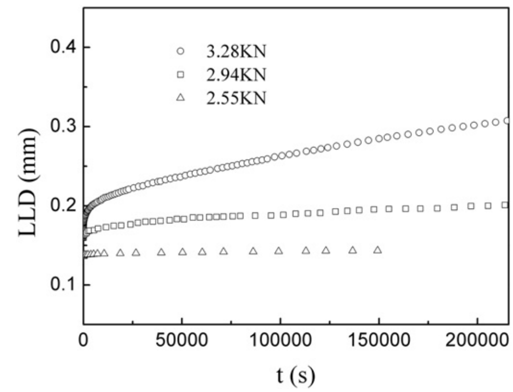

Fig. 1. The variation of LLD with time for CP-Ti CT specimen under loads $0.75K_{IC}$, $0.85K_{IC}$, and $0.95K_{IC}$.

In all cases, there was no crack propagation observed on CP-Ti CT specimens under constant load at room temperature. Although the deformation increases with the extension of time, the rate of deformation was continuously decreasing, which is so slow (lower than 1×10^{-8}/s) that it is difficult to accumulate enough deformation for crack propagation. Meanwhile, after room temperature creep experiments, the specimens were applied with fatigue load until rupturing. One of the fracture surfaces of specimen is shown in Fig. 5, which also indicates that there was no crack propagation during room temperature creep experiment, and similar results are obtained from other specimens.

3.3. Characterizing stress fields near crack tip

Brust [12] proposed time-dependent J-integral to characterize the stress fields for primary creep near crack tip under room temperature creep condition, which had been verified by FE simulation and experimental data. The J-integral can be determined by several methods, and the following equation could contain the contribution of time-dependent creep [16].

$$J = K^2(1-\nu^2)/E + g_2\sigma_{net}\Delta_{ne} \tag{1}$$

where, K is the linear elastic stress intensity factor, ν is Poisson's ratio, which is used as 0.34 here, σ_{net} is net section stress, Δ_{ne} is nonelastic load-line deflection, which can be calculated by load using compliance functions [17], and g_2 is related to the functions h_1, h_3 and η given in [18] by

$$g_2 = \frac{W-a}{a}\frac{h_1}{1.455\eta h_3} \tag{2}$$

where, W and a are specimen width and crack length, respectively.

Therefore, if Δ_{ne} contained creep effects, the J-integral calculated by Eq. (1) would contain the contribution of time-dependent creep, which would be a time-dependent parameter. Based on the material properties of CP-Ti obtained by tensile experiment in reference [8], the time-dependent J-integral of room temperature creep experiment for CT specimens can be calculated, as shown in Fig. 6.

The variation of J-integral with time is agreed with the variation of LLD with time, since the time-dependent J-integral is derived from the