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Evaluation of multiaxial creep and damage evolution for small punch creep test considering critical-strain criterion

Sisheng Yang[a], Yangyan Zheng[a,b], Xiang Ling[a,*]

[a] School of Mechanical and Power Engineering, Nanjing Tech University, Nanjing 211816, China
[b] Jiangsu Special Equipment Safety Supervision Inspection Institute, Nanjing 211178, China

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ABSTRACT

Experiment and finite element analysis were performed in this study to estimate the deformation characteristics of small punch creep test. Considering the disadvantage of the traditional model owing to numerous unknown parameters, ductility exhaustion model was introduced and used to estimate the damage and multiaxial creep evolution process. The results show that the evolution trends of creep deflection and strain with three stages are similar. During deformation, apparent damage localization is observed. The maximum strain and damage also occurred in the necking region due to the stress concentration. Thus, a critical damage value is proposed for service-exposed Cr5Mo in this study. In the primary creep stage, a tensile deformation is observed at the lower surface and a compression deformation is observed at the upper surface. Subsequently, the stress triaxiality tends to be constant in the second creep stage. Thus, steady creep parameters of small punch test can be used to replace traditional creep results in the creep properties analysis of in-service components. Finally, the multiaxial creep and damage evolution characteristics of the small punch creep specimen are obtained.

1. Introduction

In practical engineering, it is imperative to assess the material strength of in-service components operating under severe conditions. However, in many situations, standard experiments with a significant volume of material will cause damage to the components [1,2]. In recent decades, the small punch creep test has been developed for safety reasons. This novel technique conducted with a limited quantity of material is widely used in the estimation of mechanical and creep properties of steels, composites, and service-exposed materials [3–5]. Small specimen size facilitates the assessment of the degradation mechanism of key components in a critical region. Thus, various evaluation methods have been presented to establish a reasonable evaluation system of the small punch creep test [6,7].

Notably, most of the previous studies on small punch creep test have relied on the correlation between small punch creep parameters and material creep properties. There have been very few studies on the analysis of deformation characteristics. However, as a complex multiaxial creep process, a reasonable cognizance of deformation and damage mechanism is the foundation of small punch creep analysis. Considering the difficulty of direct measurements, two approaches are mainly chosen to estimate the small punch creep deformation in the previous study. One is the theoretical model analysis. The most representative models are the membrane stretching model proposed by Yang [8] and the geometrical model proposed by Hyde [9]. The other approach is the finite element simulation. A detailed simulation can provide the deformation information that cannot be easily measured using the

* Corresponding author.
E-mail address: xling@njtech.edu.cn (X. Ling).

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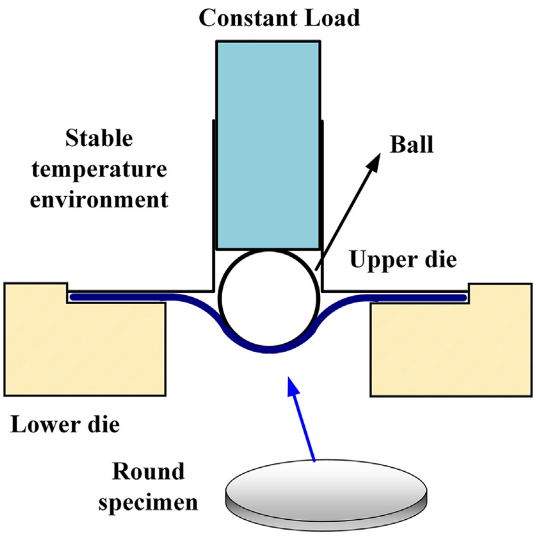

Fig. 1. Schematic of the small punch creep fixture.

experiment. Dymáček et al. analysed the deformation using two types of commonly used constitutive creep equations including the Norton relationship and exponential relationship [10]. The results indicated that the elastic–plastic and creep model provided more adequate prediction with a high load. To simulate the tertiary creep stage, Ling introduced the Kachanov–Rabotnov (K–R) constitutive model and discussed the damage distribution in the deformation [11]. However, the numerous constitutive parameters of the K–R constitutive model pose new challenges in the analysis. Especially for the in-service components, service conditions result in the changes of material parameters. This indicates that the number of undetermined material parameters should be minimised to satisfy the need of actual engineering.

As discussed above, the estimation of multiaxial creep deformation and damage evolution is a key problem in the small punch creep test. In this study, a novel creep damage model was introduced, and a finite element model was built to evaluate the creep characteristics of three creep stages of small punch test. Meanwhile, Scanning Electron Microscope (SEM) and Electron Backscattered Diffraction (EBSD) were also completed in order to investigate the creep deformation under multi-axial creep stress state. Finally, the damage evolution and deformation state of specimen were obtained. A critical damage value is proposed for service-exposed Cr5Mo. The multiaxial creep and damage behaviour was evaluated, which could aid the optimisation of the small punch creep evaluation method in a future study.

2. Experiment

Service-exposed Cr5Mo, obtained from a coking furnace pipe, was used in this study. The pipe was operated at 505 °C and 0.4 MPa for approximately 70,000 h. The composition (in wt%) is listed here as follows: 0.148C, 0.298 Si, 0.34 Mn, 4.323 Cr, 0.45 Mo, 0.007 S, and 0.012 P.

In this study, small punch creep test was performed in a self-designed fixture (Fig. 1) with the following main dimensions: lower hole diameter 4 mm, ball diameter 2.4 mm, and disk diameter 10 mm. Previous deformation damage analysis has proven that thickness tolerance about 0.02 mm is appropriate [12]. Thus, the specimen was ground from both sides to achieve a thickness of 0.5 ± 0.02 mm before test. A high temperature heating apparatus with three thermocouples was used. Meanwhile, 823 K was chosen as the experimental temperature in order to characterise the creep properties of service-exposed Cr5Mo. When temperature is stable, the thin specimen is punched by a ball with a constant load. Then, a series of material date points, such as creep deflection, creep life, and creep rate, are obtained. For comparison, uniaxial creep tests were also performed to obtain the creep parameters of service-exposed material.

3. Finite element simulation

Stress-based damage models such as the Liu–Murakami model and K–R model are widely used in creep damage analysis. The goal of these models is to establish a relationship between the creep life and representative stress, which can predict the creep life accurately [13]. However, owing to the large number of unknown creep parameters, the application of these models is limited in the actual engineering.

To overcome this limitation, the ductility exhaustion model was introduced and used here. Contrary to the stress-based damage models in the abovementioned studies, the ductility exhaustion model follows the critical-strain criterion. The creep failure strain was introduced and the multiaxial deformation state was considered in order to describe the creep deformation behavior of small punch test. Due to the advantage of strain-based model, the number of undetermined material parameters decreases.