Engineering Fracture Mechanics 195 (2018) 242–252

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

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

Creep characteristics and deformation analysis of service-exposed material using small punch creep test

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ARTICLE INFO

Keywords:
Creep characteristics
Microstructure
Deformation evolution
Small punch creep test

ABSTRACT

In this study, the creep characteristics and deformation analysis of service-exposed Cr5Mo are performed. Similar creep curves and deformation trends are found in both the uniaxial creep test and small punch creep test; however, the transient and tertiary creep stages are more apparent in the small punch test. The contribution of secondary creep time to the overall creep life is proven to be greater in the small punch creep test, corresponding to the tertiary stage which occupied most of the creep strain in the uniaxial creep test. When the creep deflection continues to increase, the percentages of low-angle grain boundaries and local misorientation increase, and the largest value appears in the necking region. On the basis of the microstructure analysis, a creep cavity model for the small punch creep is proposed for service-exposed Cr5Mo. The results demonstrate that the growth of creep damage has a stage from the constant speed to the accelerated speed creep. Ductile fracture behaviour is characterized. Finally, the Larson-Miller method is introduced and applied to predict the creep life of service-exposed material from shorter rupture time data.

1. Introduction

The mechanical properties of service-exposed materials in nuclear energy systems vary at various positions under severe operation conditions. A typical case is the welded joint that is used in the neutron radiation environment. In order to estimate creep properties accurately and economically, the testing specimen should be representative but with a small specimen volume [1,2]. As a semi-non-destructive technique, the small punch creep test was first proposed in the early 1980s [3]. This method can characterize mechanical properties by means of a round disk measuring 0.5 mm in thickness. Both the small specimen volume requirement and accurate information characterization have resulted in this technology becoming widely adopted in engineering practice. Compared to other methods, such as indentation tests, a further advantage of the small punch test is that the destroyed specimen can be acquired for use. This feature makes it easier to reflect on fracture and damage characteristics of engineering materials. To date, the advantages of this method make it possible to determine material creep characteristics in lots of different situations. A smooth increasing trend from base metal to weld metal of material creep strength was found for welded joints [4]. Meanwhile, a simple relationship between small punch creep load and stress was established. Zhao et al. proposed that the relationship depended on the yield strengths of different weld regions [5]. For Al-Al_4C_3 composites, small punch threshold force was found and an analytical expression based on maximum stress was presented [6]. It can be found that small punch creep test technology has been widely applied to the creep properties estimation of steels, alloys, composites and different types of welded joints reasonably.

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https://doi.org/10.1016/j.engfracmech.2018.04.025
Received 2 March 2018; Received in revised form 6 April 2018; Accepted 13 April 2018
Available online 16 April 2018
0013-7944/

This technology is now developed nearly well enough for application to actual engineering problems. For this, the key factor appears to be the establishment of a reasonable creep life model of the small punch creep test. Considering the complex deformation form, previous investigations focused mainly on feasibility research and amending the creep analysis method. The creep design curve of the small punch creep test was proven to be coincident with the curves obtained by the uniaxial creep test [7]. Moreover, the equivalence relationship between small punch and uniaxial creep tests was analysed to assess the residual life of high-temperature material [8]. However, the application of this technique to the actual in-service material should consider the difference between new and in-service material. Furthermore, the dispersion of the in-service material creep results can not be ignored in the analysis. Komazaki analysed the creep behaviour of a welded joint in a long-term service-exposed boiler, and believes that film-like (Mo, Fe)$_6$C carbides precipitated along the grain boundaries leads to deterioration of material strength, particularly in a high stress state [9]. Meanwhile, Saucedomuñoz pointed out that the creep strength of service-exposed materials is superior to that of new material for SUS316 austenitic stainless steel at a low load level [10]. It should be noted that a challenge is still present in terms of whether this conclusion can be applied to other materials. Work in this area has also demonstrated that the change of creep strength may be attributable to the microstructural and deformation evolution. Therefore, estimation of the damage and deformation evolution under the multiaxial deformation process becomes a new issue.

Thus far, the small punch creep test has been utilized as an effective method for estimating the creep strength of a new material. However, detailed investigations on the creep characteristics of service exposed materials are yet to be conducted. In the present work, small punch creep tests were carried out on service-exposed Cr5Mo. Creep curves were obtained and the deformation characteristics were analysed. Based on the Gurson model and microstructure analysis, a new creep damage evolution model was established, and the multiaxial creep behaviour and damage mechanism were estimated. The final objective of this research is the development of the method in order to carry out creep property analysis and damage calculation, thereby accomplishing in-service component life prediction.

2. Experimental details

The principle of the small punch creep test is based on the deformation of a disk at a high temperature. The thin round specimen is compressed by a ball under a constant load. Due to the small sample thickness, apparent creep deformation can be identified, and the deflection-time curves are reported. As depicted as Fig. 1, the small punch test device consists of a ball, punch and fixtures. In the experiment, specimen was mounted on the fixture and placed in the high temperature furnace. A ball or spherical punch is commonly used to transfer the load from the weight. In this case, a ball was selected and five different loads were used. A micro-sample cutting machine was used in order to obtain the specimen with thin disk shape from the pipe. Then, the specimen was cut into Ø10 × 0.55 mm with wire cutting and grounded from both sides to at least 1200 grit by a succession of finer waterproof abrasive papers. The main parameters of the experimental process are selected as follows: the specimen diameter is 10 mm and the thickness is 0.5 ± 0.02 mm; the diameters of the lower die and ball are 4 mm and 2.4 mm, respectively; the temperature is 550 °C and the temperature control precision of the high-temperature furnace is ± 3 °C.

The service-exposed material used in this study is Cr5Mo, which was obtained from a coking furnace pipe. The pipe, with dimensions of DN356 × 11 mm, was in service at 505 °C for approximately 70,000 h. The small punch creep test is sampled from the middle of the thickness direction of the pipe and the composition (in wt.%) is listed here: 0.148C, 0.298Si, 0.34Mn, 4.323Cr, 0.45Mo,

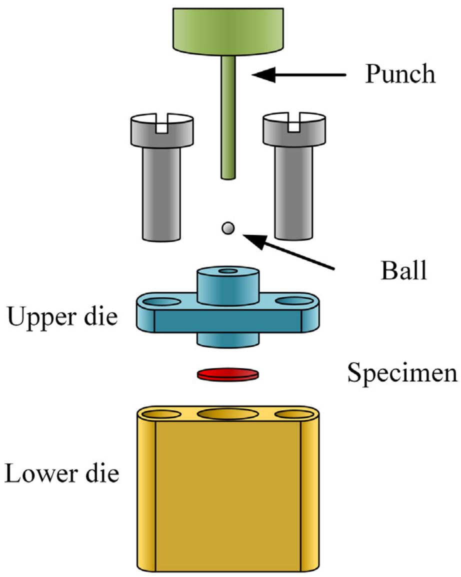

Fig. 1. Schematic diagram of small punch creep fixture.