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# Creep life analysis by an energy model of small punch creep test

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ABSTRACT

Currently most creep life prediction methods by small punch test are focused on the steady creep deformation phase which is similar to conventional uniaxial creep tests. This paper presents a novel creep life extrapolation approach by small punch creep test. An energy model believed to have advantages in modeling creep deformation process of small punch tests is introduced. Linear expression between general strain and creep deflection was recommended as the deformation criterion in the analytical prediction. Meanwhile, the combination of ball radius and hole size of the lower die was analyzed to accommodate the difference of experimental devices. Based on the small punch creep data with different materials and creep environments, the creep life in the multiaxial form of large deformation was analyzed. Finally, by selecting different creep displacements from initial creep phase, the results were in agreement with the expected trend. The creep life extrapolation method was verified.

## 1. Introduction

Engineering components often operate at high temperature and neutron irradiation environment which may easily result in creep damage and structure degradation [1]. Consequently, the experimental and analytical investigation on the failure mechanics and remaining life of structural materials is paramount to their safe operation. For the test of damage level and residual life analysis of in-service component, the miniature sample tests have received growing concern compared to the conventional testing methods for over twenty years. The reason is that a relatively smaller volume of sample is easier to obtain and economical for practical engineering, especially for the critical region with small volumes [2,3].

Among various micro-sample experiment methods, the small punch test (SPT) technology has been widely applied to acquire the creep properties and estimate the effects of long-term service. However, previous theoretical analysis is usually based on empirical relationships with a number of restrictions, which will limit further application of SPT in actual engineering [4,5]. In order to obtain enough information about deformation behavior of SPT, Yang and Wang [6] proposed a relation between small punch creep strain and center displacement based on the Chakrabarty model [7] by simplifying the deformation process and selecting appropriate geometry parameters.

As a large deformation process, the complex non-linear relation is responsible for the difficult comprehensive analysis of stress and strain states, which restricts the development of SPT. Considering the creep process which is similar to those obtained in the uniaxial creep test, numerous experimental results have been used to show how the load, deflection and minimum deflection rate correspond with the uniaxial creep tests [8–10]. On this basis, some extrapolation methods of small punch creep tests (SPCT) have been applied to estimate the remaining life of components [11]. Besides, the analyses of parameters such as activation energy provide a wide range of possibilities to analyze the interfaces between the uniaxial and multi-axial creep behaviors [12,13]. Moreover, the finite element method (FEM) was also applied to interpret the stress distribution and damage evolution with different constitutive equations [14,15]. It was clearly shown that different geometric factors of SPT would affect the results of creep properties [16]. However, the lack of consideration on apparatus geometric parameters and complication of the pre-existing expression may restrict the application of these methods. Consequently, this paper devotes to obtain the corresponding multi-axial stress parameters of SPCT by a new energy model [17].

As for the small punch creep life prediction, most of the literatures have been focused on the deflection rate and three stages of deformation, especially the steady creep phase. However in this paper, the law of energy conservation in creep deformation was introduced to establish a simple creep life prediction expression for the constant load deformation. Based on the results of a thorough investigation into the deformation process of small punch circular specimens pressed by constant force, the relationship between creep life and mechanical work was proposed. Meanwhile, the geometrical parameters of devices and specimen were taken into account. To approach a reasonable creep life analysis, the expression discussed in this work may provide some insights for SPCT.

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## 2. Experimental Process

As shown in Fig. 1, all the tests were performed on a self-made small punch creep system which consisted of ceramic ball, punch, temperature controller system, upper die and lower die. Before testing, the circular thin disks, 0.5 mm in thickness and 10 mm in diameter, were ground and polished for lowering surface roughness. The upper and lower dies would be clamped after the sample was put in the specimen holder. It was important to note that the dimension of center hole in the lower die which was mostly related to failure of specimen. Considering the relation of geometric parameters suggested, the lower die contained a receiving hole with diameter 4 mm was used in this paper. 12Cr1MoV with a composition (in wt%): 0.095C, 0.23Si, 0.558Mn, 0.963Cr, 0.25Mo, 0.17 V, 0.001S, 0.0127P was employed as the test material in this study, which was widely used in the high temperature components. The in-service materials of Cr5Mo were extracted from a furnace tube. The service temperature was 550 °C and the service time was ten years [18]. Carbon content of in-service material (0.12 C) increased apparently compared to that of new materials (0.095 C).

During the test, the load was transferred onto disk by a 2.4 mm ceramic ball extruded by punch. Near the fixture of SPT, three thermocouples were installed for controlling the temperature in the heating furnace. The deflection of specimen was monitored and recorded by displacement transducer during the creep deformation.

## 3. Model of Small Punch Creep Test

Considering a thin circular disk subjected to constant force by a rigid ball, as depicted in Fig. 2. The creep process obeys the law of energy conservation and momentum conservation, the relationship between mechanical work, internal energy and kinetic energy can be represented by Eq. (1) [17]:

$$\rho\frac{de}{dt}-\sigma_{ij}\frac{d\varepsilon_{ij}}{dt}+h_{ij}-\rho\gamma=0 \tag{1}$$

where $\rho$ is the density, $e$ is the internal energy unit mass, $\varepsilon_{ij}$ is the strain, $\sigma_{ij}$ is the stress, $\gamma$ is the heat supply unit mass, $h_{ij}$ is the heat flux and $t$ is time.

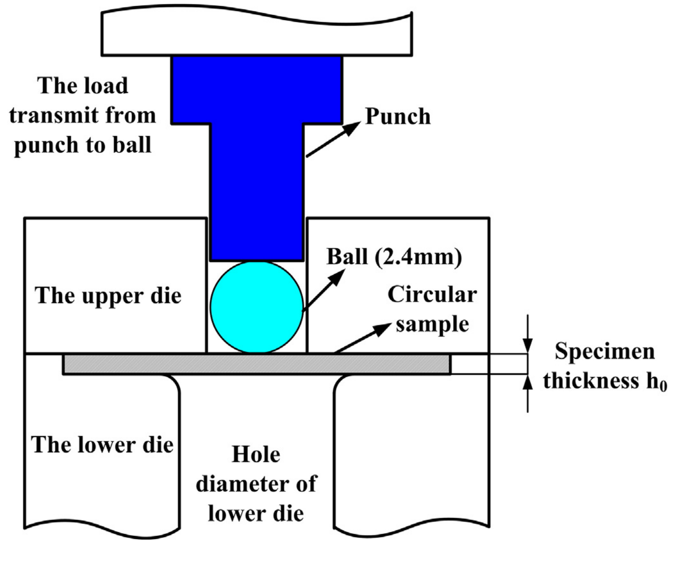

**Fig. 1.** Schematic representation of small punch creep test.

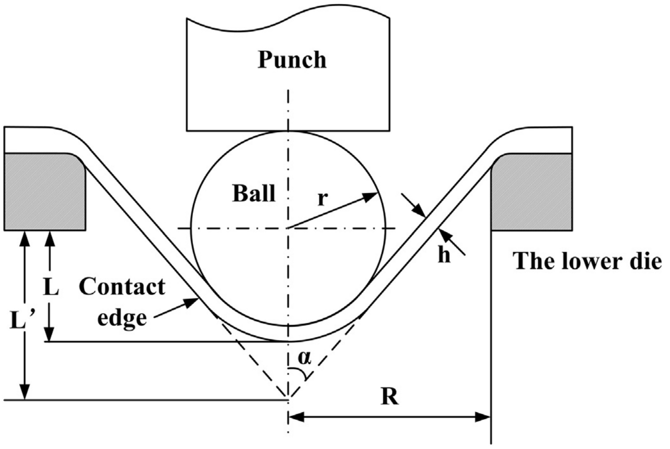

**Fig. 2.** Schematic diagram of deformation form of small punch creep specimen.

Due to the constant temperature, there is no effect of heat fluxes on local deformation behavior of materials in a steady-state environment such as SPCT. Any change of entropy must be linked to changes of the mechanical work. Thus, the entropy change can be expressed as:

$$\rho T\frac{ds}{dt}=\rho T\frac{dv^{*}}{dt}-h_{ij}+\rho\gamma=\rho T\frac{dv^{*}}{dt}+\left(\rho\frac{de}{dt}-\sigma_{ij}\frac{d\varepsilon_{ij}}{dt}\right)=f\left(\frac{dW}{dt}\right) \tag{2}$$

where $s$ is the entropy per mass, $v^{*}$ is the entropy generation per mass, $T$ is the temperature, $W$ is the mechanical work.

It can be found that only the irreversible part of the entropy will lead to the damage of the material, thus:

$$\rho T\frac{ds_i}{dt}=f\left(\frac{dW}{dt}\right)-\rho T\frac{ds_r}{dt}=\eta\frac{dW}{dt} \tag{3}$$

where $s_i$ is the irreversible entropy increase per mass, $s_r$ is the reversible entropy increase per mass.

According to the assumption of conventional creep tests, there is a ratio of conversion form mechanical work to the entropy increase. Here, $\eta$ was used to express the ratio which can be defined as the function of time [17]. Meanwhile, mechanical work per unit is the function of stress $\sigma$ and strain $\varepsilon$, thus:

$$\rho T\frac{ds_i}{dt}=\eta\frac{dW}{dt}=Ct^{q}\frac{\sigma d\varepsilon}{dt} \tag{4}$$

where $C$ and $q$ are constants.

It is worthy to note that the internal energy is a state parameter and the irreversible entropy is a constant value in an identical external condition. Consequently, Eq. (5) is capable to describe the deformation process from initial creep to final failure:

$$\int_0^{t_r}\eta\frac{dW}{dt}dt=\int_0^{t_r}Ct^{q}\frac{\sigma d\varepsilon}{dt}dt=\int_0^{t_r}Ct^{q}\sigma d\varepsilon=const \tag{5}$$

In such instances, the estimation of equivalent stress and strain value must be performed through a robust analytical approach. Previous investigations have proved that there is a linear relationship between equivalent stress and load applied to small punch specimens [19]. A general expression provided by the CEN (The European Committee for Standardization) [5] is given by Eq. (6):

$$\frac{F}{\sigma}=b_1r^{b_2}R^{b3}h_0 \tag{6}$$

where $R$ is the radius of the lower hole, $r$ is the radius of ball and $h_0$ is the initial thickness of specimen.

After introducing a correlation factor ($K_{sp}$) to account for the influence of material, temperature and necking in creep deformation, a