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Contact size-independent method for estimation of creep properties with spherical indentation

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ABSTRACT

Steady-state creep constitutes a major portion in the creep (strain vs. time) curve and is usually analyzed in characterizing creep behavior. In this numerical study, adopting a power-law creep material model, we propose a contact size-independent method for deriving creep properties from short-time spherical indentation test. Using finite element (FE) method with a wide range of creep properties, we investigate the characteristics of steady-state creep, while a fixed observation point beneath the indenter is employed to measure the material response to the indentation. We then establish functions that map indentation load–depth data to stress–strain rate data which provides creep properties without measuring the contact area. The proposed method provides the creep coefficients and the creep exponents with great accuracy from the indentation load–depth curves.

1. Introduction

Creep is a time dependent deformation behavior of materials under application of load at a certain temperature. Some materials such as *high strength steel*, *lead* may show significant creep behavior even at room temperature. To choose a proper creep material for a particular application, one needs to understand its creep deformation behavior. Uniaxial creep tests [1,2] are the standard test method to measure creep deformation by applying constant tension or compression load for a specified time interval. However, a large number of standard specimens are required to accomplish these tests. Moreover, the results from this uniaxial creep test are not comparable for the difference of microstructure between the specimen and the material, and it is difficult to establish mechanics model.

Unlike uniaxial creep test, the creep parameters such as creep coefficient A and creep exponent m can be extracted from indentation load–depth curve of non-standard micro/nano specimens. Indentation creep test involves applying indentation load for a short-period and then observing the rate of indenter penetration into the specimen. The indentation creep differs from the uniaxial creep insofar as the material beneath the indenter is subject to a complex tri-axial stress state, which varies with position and time. Radok [3] analyzed the visco-elastic contact problem using a correspondence principle, in which the elastic constants in an elastic contact equation were replaced with time dependent operators. In recent years, the early work of Radok [3] is extended to analyze the indentation creep using either conical or spherical indenters [4–7]. These indentation tests were commonly carried out over relatively short timescales (30–3600 s) whereas conventional tests commonly run for many hours and even weeks.

The creep deformation usually shows three stages: (i) primary stage (*i.e. transient creep*), where strain rate is relatively high and then approaches to a constant value with time, (ii) secondary stage (*i.e. steady-state creep*), in which the strain rate reaches nearly constant, (iii) final stage (*i.e. tertiary creep*) where strain rate increases exponentially up to failure. At primary stage, by following the setting of the instantaneous elastic strain, the material deforms rapidly but at a decreasing strain rate. The duration of this stage is relatively short in relation to the total creep curve. In indentation creep tests, the timescales are too short; therefore primary creep can be neglected. Secondary stage occurs when there is a balance between the competing processes of strain hardening and recovery. Further, it often occupies the major portion in the total creep curve. The strain rate in this region for many creep resistant materials is sufficiently constant to be considered as a steady-state creep rate. The steady-state creep rate, which is widely used in the numerical analysis, can be related to the material's creep life. This study will focus on steady-state creep to extract the creep parameters from the indentation creep test.

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In the steady-state creep regime, the power law relation is the most common general description of creep deformation in terms of strain rate $\dot{\varepsilon}$ and steady-state stress σ. $\dot{\varepsilon}$ in the steady-state creep regime is related to the applied stress σ by [8–12]

$$\dot{\varepsilon} = A\sigma^m \tag{1}$$

where the creep coefficient A is a function of temperature [13] and the creep exponent m is related to the creep mechanism: diffusion-controlled ($m \leqslant 1$), grain boundary sliding-controlled ($m \approx 2$) and dislocation movement-controlled ($m \geqslant 3$) creep. By performing a series of conventional uniaxial creep tests, A and m can be determined by plotting the measured $\dot{\varepsilon}$ against σ in logarithmic scales [11,14].

This study aims at extracting the creep coefficient A and the creep exponent from the spherical indentation load–depth curve *without measuring the contact area*. By adopting the constitutive equation for a power-law creep material of Bower et al. [8], the steady-state creep is investigated under constant rate of depth (CRD) mode of indentation. The indentation stress–strain rate data are also compared with the stress–strain rate data from single element uniaxial tensile test. Finally, following the idea of Lee et al. [15,16], we establish functions to map indentation load–depth data to corresponding stress–strain rate curves, from which creep parameters are derived.

2. Background of indentation creep

Indentation is an effective method of determining the mechanical properties, most notably elastic modulus and hardness from load–depth data by adopting elastic contact equations. If there is a significant creep response, this elastic analysis becomes invalid. Because, creeping of material during indentation significantly affects the measured elastic modulus and hardness data via indentation test [17]. Indentation creep shows only the two stages of creep, while *tertiary creep* does not occur in compression region beneath the indenter [12]. It has been demonstrated that indentation creep test is a convenient method to obtain the creep coefficient and creep exponent with advantages over the uniaxial creep test [13,18–20].

During the indentation creep test, the indentation strain rate $\dot{\varepsilon}$ is measured with time t by pressing the indenter onto the material surface with an indentation load P. Similarly, at the steady-state creep regime, $\dot{\varepsilon}$ can be related to the applied stress σ as follows [11,21,22]

$$\dot{\varepsilon} = B\sigma^m \quad (\sigma = P/A_P) \tag{2}$$

where B is the indentation creep coefficient and m is the creep exponent. Applied stress σ beneath the indenter is defined as the ratio of indentation load P to projected area A_p (cross-sectional area of the indenter at current depth). An equivalent strain rate can be defined as $\dot{h}/h$ [23–25], $\dot{h}/\sqrt{A}$ [26] or $\dot{h}/a$ where h, $\dot{h} = dh/dt$, A and a are indentation depth, indentation depth rate (or indentation speed), projected contact area and contact radius, respectively. Storakers and Larsson [20] analyzed the spherical (Brinell) and cylindrical (Boussinesq) indentation of power-law creeping materials with the Tabor [27] formula for strain-hardening plastic solids. It was proved that the creep rate depends only on the resulting projected contact area but not on indenter shapes. Considering pile-up/sink-in behavior of indented material, they defined the equivalent strain rate as $\dot{a}/D$, where $\dot{a}$ and D are the rate of contact radius and the indenter diameter, respectively. Similarly, many studies on indentation creep use the contact area to calculate the equivalent stress and strain rate [9–12,28–31]. However, there are some difficulties to match the indentation test data with those obtained via uniaxial tensile tests due to some assumptions taken during the creep property estimation. One of the main reasons for the incompatibility is the contact area measurement, which is very hard to get during the indentation creep tests. A more convenient method without using contact area would thus be desirable.

3. Indentation techniques: constant load and hold vs. constant rate of depth

In ISO 14577 [32], indentation creep is simply expressed as a change in depth (or load) over time for fixed load, or fixed displacement loading. The indentation creep test is performed commonly in two ways: (i) constant load and hold (CLH) and (ii) constant rate of depth (CRD). In the CLH mode of indentation, by pressing the indenter onto the specimen up to a specified maximum load and then holding the maximum load over a time period, an increasing indentation depth is observed with time [22,25,33]. The CLH mode has some limits to apply to the indentation creep test. The first one is that the CLH mode takes a long time to reach steady-state creep due to indentation with small strain rates, therefore the indentation data is more likely affected by thermal drift [10]. Another limit in the CLH mode of indentation is that only material beneath the flat-ended cylindrical punch shows steady-state creep, whereas self-similar indenters such as conical, pyramidal or even spherical indenters are unable to produce the steady-state creep in the material [21]. Because the hardness and the stress induced from the creep process decrease with time under constant load [34]. In contrast, by pressing the indenter onto the specimen up to a maximum indentation depth h_{max} with constant indentation rate $\dot{h}$, the indentation strain rate $(=\dot{h}/h)$ is controlled in the CRD mode. Hence one can decrease the test duration by switching the strain rate [35]. Moreover, spherical and self-similar indenters also show the steady-state creep with the CRD mode.

Chu and Li [36,37] conducted the indentation creep test for molecular crystals at room temperature, while they indented the flat-ended cylindrical punch onto the specimen surfaces with the CLH mode. Accordingly they observed constant indentation strain rate after a long period of transient stage in a 4 h test. The obtained creep coefficient/activation energy and creep exponent agreed with the values from conventional compression test. However, the radius of the cylinder essentially defines the volume of material being deformed [38]; therefore this technique requires indenters smaller in diameter to obtain plastically deformed volume with shallow indentation depth. Nevertheless the errors associated with the contact area become pronounced for smaller indenters [34]. By using the CRD mode with spherical and self-similar indenters, one can overcome these errors in the indentation creep test.

Bower et al. [8] proved that the creep exponent calculated from indentation creep test is equivalent to the uniaxial tensile creep exponent through similarity transformation. In addition, they expressed the correlation between the effective stress and effective strain rate as a function of contact pressure and the indentation rate. However, their method also requires an accurate and *continuous* measurement of contact area to obtain creep parameters. Sohn [31] obtained the uniaxial creep variables by using the FE analysis for the indentation creep tests with the spherical and conical indenters. It was shown that the generalized depth-time and load–depth curves are sensitive to the creep exponent whereas they are insensitive to the elastic modulus. The predicted uniaxial tensile creep coefficient A, however, showed a relatively large error for creep exponent ($m > 3$).

Similarly, some researchers [30,34] evaluated the creep exponent values of power-law creep materials from indentation creep tests; those values had a close agreement with the uniaxial creep data. To properly characterize uniaxial creep response [Eq. (1)], indentation creep test has to provide proper values of creep