Available online at www.sciencedirect.com

ScienceDirect

Trans. Nonferrous Met. Soc. China 26(2016) 1729−1735

Transactions of Nonferrous Metals Society of China

www.tnmsc.cn

Primary-transient creep and anelastic backflow of pure copper deformed at low temperatures and ultra-low strain rates

Jun-jie SHEN[1], Ken-ichi IKEDA[2], Satoshi HATA[2], Hideharu NAKASHIMA[2]

1. School of Mechanical Engineering, Tianjin University of Technology, Tianjin 300191, China;
2. Department of Electrical and Materials Science, Faculty of Engineering Sciences, Kyushu University, Kasuga, Fukuoka 816-8580, Japan

Received 19 May 2015; accepted 2 May 2016

Abstract: Creep and anelastic backflow behaviors of pure copper (4N Cu) with grain size d_g=40 μm were investigated at low temperatures of T <0.3T_m (T_m is melting point) and ultra-low creep rates of $\dot{\varepsilon} \le 1\times10^{-10}\ s^{-1}$ by a high strain-resolution measurement (the helicoid spring specimen technique). Analysis of creep data was based on the scaling factors of creep curves instead of the conventional extrapolated steady-state creep rate. Power-law creep equation is suggested to be the best for describing the primary transient creep behavior, because the pre-parameter does not apparently change with elapsed time. The observed anelastic strains are 1/6 of the calculated elastic strains, and linear viscous behavior was identified from the logarithm plot of the anelastic strain rate versus anelastic strain (slope equals 1). Therefore, the creep anelasticity is suggested to be due to the unbowing of there-dimensional network of dislocations.

Key words: pure copper; creep; dislocation; anelasticity; constitutive creep equation

1 Introduction

It has been known that creep deformation can occur at very low strain rates of $\dot{\varepsilon} \le 1\times10^{-10}\ s^{-1}$ [1−3]. Analysis of creep data is conducted usually based on the creep rate in the secondary creep stage. However, at $\dot{\varepsilon} \le 1\times10^{-10}\ s^{-1}$, identification of the secondary creep stage requires very long testing time, even longer than 40 years [1]. Such long testing time cannot be accepted for systematic study of creep deformation at $\dot{\varepsilon} \le 1\times10^{-10}\ s^{-1}$. Therefore, steady-state creep rates extrapolated by fitting primary transient creep curves were used to study long-term creep deformation [4−6]. To obtain analyzable primary transient creep data at $\dot{\varepsilon} \le 1\times10^{-10}\ s^{-1}$, a helicoid spring specimen technique has been employed [4−6] due to its higher strain resolution than that of conventional uniaxial tension creep tests, even reaching 1×10^{-9} [7].

However, it is not clear whether the creep data analysis based on extrapolating steady-state creep rates by fitting primary transient creep curves is the best approach, because the steady-state creep stage is often not reached [8]. Actually, the steady-state strain rate is considered to be identical to the creep rate derived (directly) at the end of the creep curves [5]. In addition, this approach hides an error of taking a steady-state creep rate instead of the minimum creep rate. The physical meanings of the steady-state creep rate and the minimum creep rate are completely different. The former, steady-state creep rate, is associated with a balance of work hardening and creep recovery under the condition of a stable microstructure, whereas the latter, the minimum creep rate, may be related with a balance point of work hardening and recovery caused by deterioration of microstructure.

Here, an alternative approach was shown to analyze creep data at ultra-low strain rate, $\dot{\varepsilon} < 1\times10^{-10}\ s^{-1}$, using scaling factors of the creep curves. The scaling factors should determine shape of creep curves and are independent of the elapsed testing-time. The dependence of the scaling factors on stress and temperature is examined instead of examining the dependence of conventional steady-state creep rates on stress and temperature. We preformed helicoid spring creep tests on

Foundation item: Project (12JCYBJC32100) supported by the Tianjin Research Program of Application Foundation and Advanced Technology, China; Project ([2013]693) supported by the Scientific Research Foundation for the Returned Overseas Chinese Scholars, State Education Ministry, China

Corresponding author: Jun-jie SHEN; Tel: +86-13516233995; E-mail: sjj1982428@sina.com

DOI: 10.1016/S1003-6326(16)64285-1

pure copper (99.99% Cu) at $T<0.3T_m$ (T_m is the melting point) and ultra-low strain rate, $\dot{\varepsilon}<1\times10^{-10}$ s^{-1}. Creep curves were analyzed by the use of transient constitutive creep equations to find possible scaling factors. Then, dependence of the scaling factors on stress, temperature and testing time was analyzed. The characteristics of an anelastic process at $\dot{\varepsilon}<1\times10^{-10}$ s^{-1} were also firstly studied with regard to its magnitude and kinetics to better understand the creep behavior.

2 Experimental

Creep tests were performed on wires of 99.99% Cu (4N) with a diameter of 1.6 mm supplied by Nilaco Corporation (Japan). The following equations [9,10] were used to calculate the mean surface shear stress, τ, and the surface shear strain, γ, assuming pure torsion of the helicoid spring specimen:

$$\tau=\frac{8PD}{\pi d^3} \tag{1}$$

$$\gamma=\frac{\Delta\delta d}{\pi n D^2} \tag{2}$$

where P is the average load, D is the coil diameter (18.8 mm), d is the wire diameter (1.6 mm), n is the number of coils (5) measured and $\Delta\delta$ is the displacement of the mean coil−pitch spacing. In this work, torsion is the dominant component of deformation because D is much greater than d ($D/d>12$) [11] and the value of δ is between 2.5 and 4.0 mm [8]. Since the stress and strain in the helicoid spring have essentially shear components, they can be transformed to the equivalent tensile quantities using von Mises equations for tensile stress $\sigma=\sqrt{3}\tau$ and tensile strain $\varepsilon=\gamma/\sqrt{3}$. The minimum detectable value of strain for the helicoid spring creep test is evaluated from Eq. (2). For example, the minimum detectable strain for the present experiment is $\varepsilon=4.2\times10^{-8}$ under the following conditions: d=1.6 mm; D=18.8 mm; n=10; $\Delta\delta$ is measured using a light-emitting diode with a resolution of 0.5 μm. Details of the test apparatus were reported elsewhere [12−14].

3 Results and discussion

3.1 Creep curve description

The creep curves obtained at 298, 348 and 398 K are shown in Figs. 1(a)−(c), respectively. In all the creep curves, the creep rate which corresponds to the slope of the curves decreases with the increase of time. Figure 2 shows the strain rate on a logarithmic plot versus strain at 348 K and different stresses. Creep deformation of the pure copper consists of primary creep stages, in which the creep rate decreases with the increase of strain and no secondary (steady-state) creep stage is observed, in

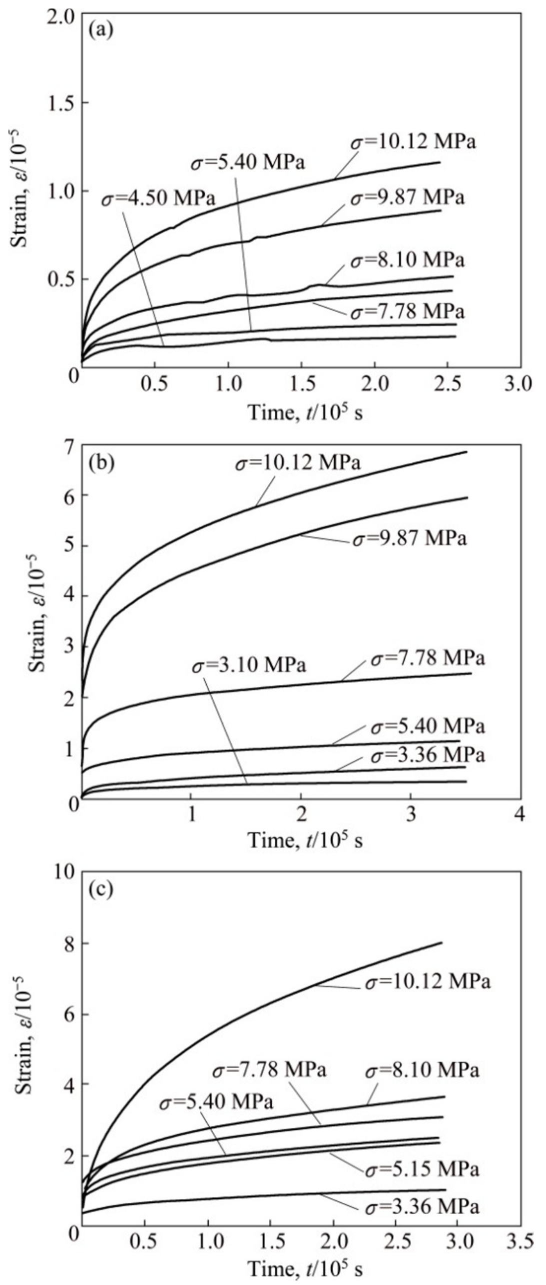

Fig. 1 Strain−time creep curves for Cu (4N) at 298 K (a), 348 K (b) and 398 K (c)

which the creep rate does not change with strain.

Therefore, constitutive creep equations expressing the primary stages should be used to analyze the experimental creep curves. We used the following constitutive creep equations that are widely accepted as basic equations [14,15].

Power law:

$$\varepsilon=\varepsilon_0+at^b \tag{3}$$

Exponential law:

$$\varepsilon=\varepsilon_0+a[1-\exp(-bt)] \tag{4}$$

Logarithmic law:

$$\varepsilon=\varepsilon_0+a\ln(1+bt) \tag{5}$$