J MATER RES TECHNOL. 2014;3(3):280–288

Available online at www.sciencedirect.com

jmr&t Journal of Materials Research and Technology

www.jmrt.com.br

Review Article

Low temperature creep plasticity☆

Michael E. Kassner*, Kamia Smith

Department of Aerospace and Mechanical Engineering, University of Southern California, Los Angeles, United States

ARTICLE INFO

Article history:
Received 10 May 2014
Accepted 25 June 2014
Available online 13 August 2014

Keywords:
Creep
Time-dependent plasticity
Low temperature
Cryogenic
Power-law

ABSTRACT

The creep behavior of crystalline materials at low temperatures ($T < 0.3T_m$) is discussed. In particular, the phenomenological relationships that describe primary creep are reviewed and analyzed. A discussion of the activation energy for creep at $T < 0.3T_m$ is discussed in terms of the context of higher temperature activation energy. The basic mechanism(s) of low temperature creep plasticity are discussed, as well.

Michael E. Kassner graduated with a Bachelor in Science-Engineering from Northwestern University in 1972, and an M.S. and Ph.D. in Materials Science and Engineering from Stanford University in 1979 and 1981. Kassner accepted a position at Lawrence Livermore National Laboratory in 1981 and was employed there until 1990 where he was Head of the Physical Metallurgy and Welding Section. He accepted a faculty position in the Mechanical Engineering Department at Oregon State University in 1990 where he was Northwest Aluminum Professor of Mechanical Engineering. He received the College of Engineering Outstanding Sustained Research Award in 1995. He moved in 2003 to accept a position as Chairman, Mechanical and Aerospace Engineering Department at the University of Southern California (USC). He is also a Professor of Materials Science at USC. He is currently Choong Hoon Cho Chair and Professor. He is currently active in pursuing research at USC on creep, fracture, fatigue and thermodynamics. Most recently, he was assigned to Washington, D.C., as the Director of Research at the Office of Naval Research (ONR). He assumed the position in October 2009 until October 2012. He was responsible for overseeing the nearly one billion dollar basic-research budget for the US Navy. He was awarded the Navy's Meritorious Public Service Medal for his tenure at ONR. He has published three books, one on the fundamentals of creep plasticity in metals, hot deformation of aluminum and aluminum alloys and another on phase diagrams and has authored or co-authored over 220 published articles. He is a Fellow of American Society of Metals (ASM), a Fellow of the American Society of Mechanical Engineers (ASME) and a Fellow of the American Association for the Advancement of Science (AAAS).

☆ Paper presented in the form of an abstract as part of the proceedings of the Pan American Materials Conference, São Paulo, Brazil, July 21st to 25th 2014.

* *Corresponding author.*
E-mail: kassner@usc.edu (M.E. Kassner).

http://dx.doi.org/10.1016/j.jmrt.2014.06.009

Kamia Smith graduated from Wheaton College in Norton, Massachusetts in 2011 with a Bachelor of Arts degree in Chemistry. Smith then pursued graduate level studies at the University of Southern California. She completed her Masters of Science in Materials Materials Science and Engineering in 2013 and is now currently pursuing her PhD in the same field. Her research, under Dr. Michael Kassner, studies the mechanical behaviors of materials under various stress conditions. During her first year as a doctorate student, Smith accepted a fellowship position in a program called Body Engineering Los Angeles GK-12. As a fellow, she worked in a Downtown Los Angeles middle school in which she taught her research to students in order to spark more engineering interest in younger generations. Smith looks to complete her studies by 2016.

1. Introduction

Temperature ranges for creep can be subdivided into three categories: (1) high temperature creep ($T > 0.6T_m$), (2) intermediate temperature creep ($0.3T_m < T < 0.6T_m$), and (3) low temperature creep ($T < 0.3T_m$). Generally, creep studies investigate high temperature deformation; however, this paper reviews on the latter category. Less attention has been paid to low temperature creep due to the fact that materials generally neither fail nor experience significant plasticity at lower (especially ambient and cryogenic) temperatures.

Creep at low temperature can be understood as time-dependent plasticity that occurs at $T < 0.3T_m$ and at stresses often below the macroscopic yield stress (${\sigma_y}^{0.002}$). This is where creep is often not expected. Still, even with the low attention paid to this area of creep, many materials do experience very noticeable plasticity at lower temperatures. This has some commercial importance. These materials include Ti alloys and steels [1–10], Al–Mg [11], α-Brass [12], ionic solids [13], pure Au, Cd, Cu, Al, Ti, Hg, Ta, Pb, Zn [14–28] and precipitation hardened alloys [29], and glass and rubber [28].

Low-temperature creep has generally been investigated because of two reasons: (1) Materials may undergo plasticity that affects its intended performance. This category includes structural alloys, and creep of Cu at cryogenic temperatures; (2) There has been theoretical curiosity regarding low temperature deformation and the mechanism of plasticity, particularly at cryogenic temperatures. This includes the validity of the dislocation intersection mechanism proposed by Seeger et al. [30,31] as investigated by others [19]. Also there have been investigations of the proposition of quantum mechanical tunneling of dislocations at very low temperature [13,20,22,24,26,27].

1.1. *Phenomenology*

Generally, but not always, low temperature creep is a discussion of primary creep without the observation of a genuine mechanical steady state. One study has suggested steady state at 4.2 K, but there were problems with the data analysis [32]. At *high* temperatures, primary creep is described by the equations:

$$\varepsilon = \beta t^{1/3} + c_1 \quad (1)$$

as suggested long ago by Andrade [33] and Orowan [34]. Evans and Wilshire [35] reviewed the high-temperature primary creep equations and suggested a refinement. This refinement led to an equation of the form:

$$\varepsilon = at^{1/3} + ct + dt^{4/3} \quad (2)$$

This is now the common phenomenological equation used to describe primary creep. Variations to this equation include [36]:

$$\varepsilon = at^{1/3} + ct \quad (3)$$

and [37],

$$\varepsilon = at^{1/3} bt^{2/3} + ct \quad (4)$$

or,

$$\varepsilon = at^b + c^t \quad (5)$$

where [38],

$0 < b < 1$

or [1],

$$\varepsilon = at^b \quad (6)$$

where,

$0 < b < 1$

It is suggested that Eqs. (1)–(6) are all of a similar (power law) form. Another form of equations was suggested by Phillips [28], Laurent and Eudier [39] and Chévenard [40],

$$\varepsilon_p = \alpha \ln t + c_2 \quad (7)$$

Wyatt [18], long ago, suggested for pure metals, such as Al, Cd and Cu, that at higher temperatures, Eq. (1) was the proper descriptive equation, but at lower temperatures, he then suggested Eq. (7) was the proper form.

1.2. *Objectives*

The following discussion will describe the phenomenological trends in greater detail. The data appears to best be presented/described by material category (e.g. alloy, metal or ceramic). In particular, the low-temperature creep behavior of both alloys and pure metals will be described in separate sections. It will be shown that, generally, the descriptive equations generally fall within the forms of Eq. (1) or Eq. (2). Distinctions will be made for cases where the applied stress is above and below the conventional yield stress (at an ordinary strain-rate; e.g. $10^{-4}\,s^{-1}$), as well as at shorter times than a few hours and much longer times.