Pergamon

Acta mater. 49 (2001) 2017–2026

Acta MATERIALIA

www.elsevier.com/locate/actamat

MODELING THERMALLY ACTIVATED DEFORMATION WITH A VARIETY OF OBSTACLES, AND ITS APPLICATION TO CREEP TRANSIENTS

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(Received 6 October 2000; received in revised form 13 February 2001; accepted 13 February 2001)

Abstract—A material is modeled as an array of a variety of coupled elements of varied strength, each of which is characterized by a slip probability that is a function of local stress and temperature. A stochastic cellular automaton is used to run simulations of nominally constant structure creep where simple rules are used to ensure rough compliance with mechanical equilibrium and compatibility. Three cases are studied that incorporate distinctly different statistical and spatial strength distributions. For all three simulation conditions, a general form of creep curve is obtained. The general form, when plotted as log(strain) vs. log(time), has a slope near unity at short and long times which are connected by a region of minimum slope. The slope of the central region increases systematically with increasing temperature. These features are consistent with several experimental observations. The same simulation can also provide reasonable predictions of anelastic backflow. This analysis can be of value in interpreting experimental observations in both forward and reverse creep transients.

Keywords: Constitutive equations; Creep; Mesostructure; Structural behavior

1. INTRODUCTION

Most metals behave very similarly with respect to time-dependent deformation. For example, creep follows broadly similar behavior patterns for very different materials. Also, power laws empirically fit stress vs. strain, and stress vs. strain-rate curves for many materials. Further, there are often systematic trends in these data, such as rate sensitivity, increasing with temperature. These general features are common to many materials with varied crystal structures, strengthening mechanisms, and strength levels. One may surmise from this that mechanistic details of deformation do not have to be explicitly considered in order to develop a model for how materials deform in general. Certainly at some level the details must become important.

It is proposed that many materials behave similarly with respect to plastic deformation because their observed behavior is the result of a large number of discrete events that are coupled through load transfer. A few examples demonstrate this.

1. For amorphous materials, deformation takes place by the thermally activated motion of atoms or molecules from one location to another in a manner that allows the externally applied stress to locally deform the material. These discrete motions reduce stress in the immediate vicinity of the event. This load must be shed to nearby areas of the material, increasing the stress there.
2. In crystalline solids, a classical picture is that of a dislocation pinned by discrete obstacles (these may be produced by solutes, locally ordered regions, precipitates, jogs, etc.). If any one of the obstacles is overcome, the dislocation will move forward locally (and may or may not encounter another obstacle). The forward motion of the dislocation increases the angle the dislocation line makes with the adjacent obstacles. This increases the force on each of them, making them more likely to be overcome.
3. This argument of discrete slip and load re-distribution also holds on the subgrain and grain level. Again, if a slip event takes place in one subgrain, it will reduce the stress on that subgrain and increase the load on neighboring subgrains.

In all of these cases, there will also be a spectrum of obstacle 'strengths' that resist local deformation.

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1359-6454/01/$20.00
PII: S1359-6454(01)00089-1

For example, many types of dislocation locks exist, no two precipitates or locally ordered regions are exactly like one another. Due to local differences in orientation and/or microstructure, grains and subgrains will have a spectrum of strengths. The model proposed here emphasizes two features of plastic deformation: the effects of local stress or force redistribution, and the spectrum of obstacle strengths that must exist in real materials. The model is posed in a general and somewhat abstract way. After formulating the model, it will be demonstrated that it naturally produces the types of transients observed on the immediate loading of materials (primary creep) and immediate unloading of materials (anelastic backflow). In the model's present form, strain hardening and recovery processes are not considered. While this is obviously important in many cases, it can be ignored in the small strain regime and for materials with low hardening rates.

A variety of time laws have been proposed to describe the primary creep transient (see Ref. 1 for a review). The following types of behavior have been observed commonly:

1. *fast-plastic*—in most creep experiments, there is an initial plastic extension that takes place too rapidly for observation of the strain–time behavior within the experimental time resolution.
2. *logarithmic creep*—the time law may be expressed as:

$$\varepsilon = B\log(t) \text{ or } \dot{\varepsilon} = k\left(\frac{1}{t}\right) \quad (1)$$

   where ε represents plastic strain, t is time and the overdot denotes the time-derivative. This mode of creep is generally observed at low temperatures and moderately low stresses. This has been attributed to an exhaustion of sites with low activation energy with stronger regions of the material resisting further flow [2, 3].
3. *power-law transient*—in many cases it is found that transient creep strain follows the form:

$$\varepsilon = At^{a} \quad (2)$$

   where a is an exponent less than 1. In some cases, the power a takes on a value near 1/3. In such cases, this is classified as Andrade creep, based on the early observations that this form is observed in a number of polycrystalline metals at moderate temperatures [4, 5]. Other investigators have also found powers near 1/3. However, in many of the papers that gave support to the power of 1/3, the value of the exponent was taken as an assumption and remaining constants were set to obtain a best-fit with the data without examining the exponent [5–8]. In other investigations, the power-law exponent was determined by drawing a best-fit line through strain–time data plotted on log–log axes. In these cases [9–13] the power-law transient form fits well, but the 1/3 power does not appear to be general. In an especially careful study, Carreker [9] showed that for *Pt* the exponent increased systematically with temperature. By slightly extending the analysis of Lubban and Felgar [14], Neeraj *et al*. [15] demonstrated the exponent a can be related to those of the rate-sensitive Holomon equation ($\sigma = k\varepsilon^{N}\dot{\varepsilon}^{m}$, where σ represents stress) as:

$$a = \frac{m}{N + M} \quad (3)$$

   Thus, Carreker's observation of an increase with temperature is consistent with the commonly observed increase in strain rate sensitivity with increasing temperature. For both logarithmic creep and power-law transients, behavior that obeys the time-law over several orders of magnitude in time is often observed. In the case of logarithmic creep, the law usually does not persist beyond a few times the elastic strain and this is the predominant form at low homologous temperature [8]. Power-law transients seem to exist over a larger range in strain and they have been observed over a wide range of temperatures.
4. *steady-state*—at high temperatures or very long times, many systems show strain proportional to time, called steady-state creep, where it is supposed that the state of the material no longer changes. Andrade [4, 5] recognized this can accompany the power-law transient strain.

The three time-laws can all be expressed as a power-law relation of some type. Power-law relationships have often been observed in plasticity. Commonly power laws are regarded as being the empirical results of curve fitting. Recent theoretical analyses of interacting many-body systems show that power-law behavior may be expected and that the power-law exponents may be fundamentally related to the nature of the interactions, but often they can only be analyzed with simulation. Several general reviews of this work are available [16, 17] and these ideas have been applied to diverse problems such as earthquakes, sandpile behavior, granular flow and magnetic hysterisis and its noise as well as brain function and macroeconomics. Recently Cottrell [18, 19] has followed these themes and suggested that primary creep may represent the approach to a self-organized critical state and should be analyzed as such.

2. PHILOSOPHY OF THE MODEL

The model is based on the idea of simply (if approximately) linking many independent and simply