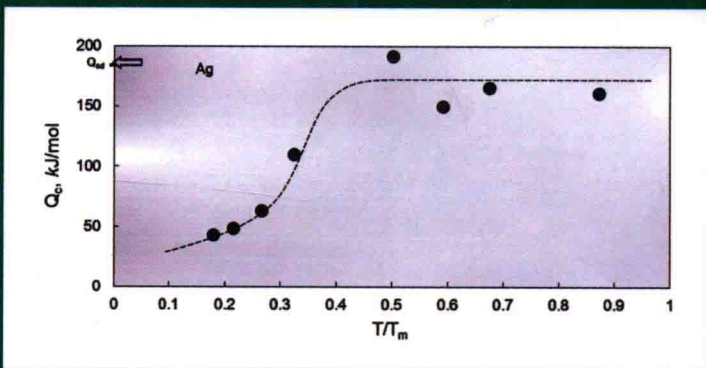
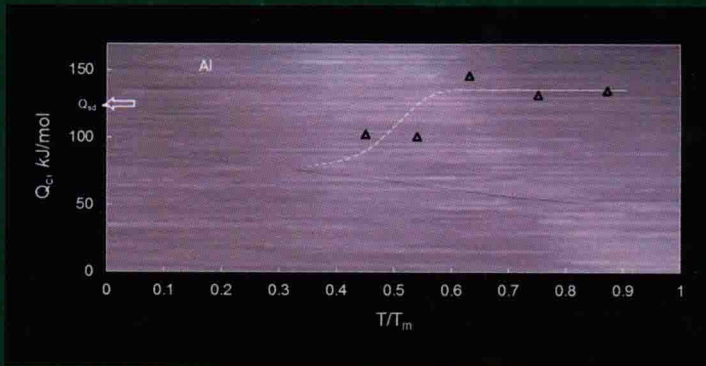


THIRD EDITION

# Fundamentals of Creep in Metals and Alloys



The variation of the activation energy for creep versus fraction of the melting temperature for Al (top) and Ag (bottom)

M. E. KASSNER



# Fundamentals of **CREEP IN METALS AND ALLOYS**

THIRD EDITION

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225 Wyman Street, Waltham, MA 02451, USA  
The Boulevard, Langford Lane, Kidlington, Oxford, OX5 1GB, UK

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ISBN: 978-0-08-099427-7

#### **British Library Cataloguing in Publication Data**

A catalogue record for this book is available from the British Library

#### **Library of Congress Cataloging-in-Publication Data**

A catalog record for this book is available from the Library of Congress

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Printed in the United States of America

## PREFACE

This book on the fundamentals of creep plasticity is a review and analysis of investigations in a variety of areas relevant to creep plasticity. These areas include five-power-law creep, which is sometimes referred to as dislocation climb-controlled creep (in metals, alloys, and ceramics), viscous glide or three-power-law creep (in alloys), diffusional creep, Harper–Dorn creep, superplasticity, second-phase strengthening, and creep cavitation and fracture. Many quality reviews and books precede this attempt to write an extensive review of creep fundamentals and the improvement was a challenge. One advantage with this attempt is the ability to describe the substantial work published subsequent to these earlier reviews. An attempt was made to cover the basic work discussed in these earlier reviews but especially to emphasize more recent developments.

This is the second edition of this book and one aspect of this recent edition is correcting errors in the first edition, also, many advances occurred over the five years since the first edition and these are also incorporated. Dr Maria-Teresa Perez-Prado was a co-author of the first edition. While she did not participate in the formulation of the second and third editions, Chapters 5, 6, and 9 remain largely a contribution by Dr Perez-Prado, and her co-authorship is indicated on these chapters.

# LIST OF SYMBOLS AND ABBREVIATIONS

$a$	Cavity radius
$a_0$	Lattice parameter
$A' - A'''$	Constants
$A$	Solute dislocation interaction parameters
$A_F$	
$A_{C-J}$	
$A_{APB}$	
$A_{SN}$	
$A_{CR}$	Grain boundary area
$A_{gb}$	Harper—Dorn equation constant
$A_{HD}$	Constants
$A_{PL}$	Projected area of void
$A_v$	Constant
$A_0 - A_{12}$	Antiphase boundary
<b>APB</b>	Burgers vector
$b$	Constant
$B$	Bulk metallic glass
<b>BMG</b>	Concentration of vacancies
$c$	Crack growth rate
$c^*$	Concentration of jogs
$c_j$	Concentration of vacancies in the vicinity of a jog
$c_p$	Steady-state vacancy concentration near a jog
$c_p^*$	Equilibrium vacancy concentration
$c_v$	Vacancy concentration near a node or dislocation
$c_v^D$	Initial crack length
$c_0$	Constants
$c_{1-2}$	Concentration of solute atoms
$C$	Integral for fracture mechanics of time-dependent plastic materials
$C^*$	Constant
$C_{1-2}$	Larson—Miller constant
$C_{LM}$	Convergent beam electron diffraction
<b>CBED</b>	Cooperative grain boundary sliding
<b>CGBS</b>	Crystallographic slip
<b>CS</b>	Complex stacking fault
<b>CSF</b>	Coincident site lattice
<b>CSL</b>	Constant
$C_0$	Constants
$C_0 - C_5$	Average spacing of dislocations that comprise a subgrain boundary
$d$	General diffusion coefficient or constant
$D$	Constant
$D'$	

$D_c$	Diffusion coefficient for climb
$D_{\text{eff}}$	Effective diffusion coefficient
$D_g$	Diffusion coefficient for glide
$D_{\text{gb}}$	Diffusion coefficient along grain boundaries
$D_i$	Interfacial diffusion
$D_s$	Surface diffusion coefficient
$D_{\text{sd}}$	Lattice self-diffusion coefficient
$D_v$	Diffusion coefficient for vacancies
$D_0$	Diffusion constant
<b>DRX</b>	Discontinuous dynamic recrystallization
$\tilde{D}$	Diffusion coefficient for the solute atoms
$e$	Solute—solvent size difference or misfit parameter
$E$	Young's modulus or constant
$E_j$	Formation energy for a jog
<b>EBSP</b>	Electron backscatter patterns
$f$	Fraction
$f_m$	Fraction of mobile dislocations
$f_p$	Chemical dragging force on a jog
$f_{\text{sub}}$	Fraction of material occupied by subgrains
$F$	Total force per unit length on a dislocation
<b>FEM</b>	Finite element method
$g$	Average grain size (diameter)
$g'$	Constant
$G$	Shear modulus
<b>GBS</b>	Grain boundary sliding
<b>GDX</b>	Geometric dynamic recrystallization
<b>GNB</b>	Geometrically necessary boundaries
$h_r$	Hardening rate
$\bar{h}_m$	Average separation between slip planes within a subgrain with gliding dislocations
$h$	Dipole height or strain-hardening coefficient
<b>HAB</b>	High angle boundary
<b>HVEM</b>	High voltage transmission electron microscopy
$j$	Jog spacing
$J$	Integral for fracture mechanics of plastic material
$J_{\text{gb}}$	Vacancy flux along a grain boundary
$k$	Boltzmann constant
$k' - k''$	Constants
$k_y$	Hall—Petch constant
$k_{\text{MG}}$	Monkman—Grant constant
$k_R$	Relaxation factor
$k_1 - k_{10}$	Constants
$K$	Strength parameter or constant
$K_1$	Stress intensity factor
$K_0 - K_7$	Constants
$\ell$	Link length of a Frank dislocation network
$\ell_c$	Critical link length to unstably bow a pinned dislocation

$l_m$	Maximum link length
$l$	Migration distance for a dislocation in Harper—Dorn creep
$L$	Particle separation distance
<b>LAB</b>	Low angle boundary
<b>LM</b>	Larson—Miller parameter
<b>LRIS</b>	Long-range internal stress
$m$	Strain-rate sensitivity exponent ( $=1/M$ )
$m'$	Transient creep time exponent
$m''$	Strain-rate exponent in the Monkman—Grant equation
$m_c$	Constant
$\bar{M}$	Average Taylor factor for a polycrystal
$M_p$	Dislocation multiplication constant
$n$	Steady-state creep exponent or strain-hardening exponent
$n^*$	Equilibrium concentration of critical sized nuclei
$n_m$	Steady-state stress exponent of the matrix in a multi-phase material
$N$	Constant structure stress exponent and dislocation link length per unit volume
$\dot{N}$	Nucleation rate and rate of release of dislocation loops
$p$	Steady-state dislocation density stress exponent
$p'$	Inverse grain size stress exponent for superplasticity
<b>PLB</b>	Power law breakdown
<b>POM</b>	Polarized light optical microscopy
<b>PSB</b>	Persistent slip band
$q$	Dislocation spacing, $d$ , stress exponent
$Q_c$	Activation energy for creep (with $E$ or $G$ compensation)
$Q'_c$	Apparent activation energy for creep (no $E$ or $G$ compensation)
$Q_p$	Activation energy for dislocation pipe diffusion
$Q_{sd}$	Activation energy for lattice self-diffusion
$Q_v$	Formation energy for a vacancy
$Q^*$	Effective activation energies in composites where load transfer occurs
$r_r$	Recovery rate
$R_o$	Diffusion distance
$R_s$	Radius of solvent atoms
$s$	Structure
<b>SAED</b>	Selected area electron diffraction
<b>SESF</b>	Superlattice extrinsic stacking fault
<b>SISF</b>	Superlattice intrinsic stacking fault
<b>STZ</b>	Shear transformation zone
$t$	Time
$t_c$	Time for cavity coalescence on a grain boundary facet
$t_f$	Time to fracture (rupture)
$t_s$	Time to the onset of steady-state
$T$	Temperature
$T_d$	Dislocation line tension
$T_g$	Glass transition temperature
$T_m$	Melting temperature
$T_p$	Temperature of the peak yield strength

$T_x$	Onset crystallization temperature
<b>TEM</b>	Transmission electron microscopy
$T-T-T$	Time—temperature—transformation diagram
$v$	Dislocation glide velocity
$v_c$	Dislocation climb velocity
$v_{cr}$	Critical dislocation velocity at breakaway
$v_D$	Debye frequency
$v_p$	Jog climb velocity
$\bar{v}$	Average dislocation velocity
$\bar{v}_\ell$	Climb velocity of dislocation links of a Frank network
$V$	Activation volume
$w$	Width of a grain boundary
$\bar{x}_c$	Average dislocation climb distance
$\bar{x}_g$	Average dislocation slip length due to glide
<b>XRD</b>	X-ray diffraction
$\alpha$	Taylor equation constant
$\alpha_0$	Constant
$\alpha'$	Climb resistance parameter
$\alpha_{1-3}$	Constants
$\beta, \beta_{1-3}$	Constants
$\gamma$	Shear strain
$\gamma_0$	Characteristic strain of an STZ
$\gamma_A$	Anelastic unbowing strain
$\gamma_{gb}$	Interfacial energy of a grain boundary
$\gamma_m$	Surface energy of a metal
$\dot{\gamma}$	Shear creep rate
$\dot{\gamma}_{ss}$	Steady-state shear creep rate
$\delta$	Grain boundary thickness or lattice misfit
$\Delta a$	Activation area
$\Delta G$	Gibbs free energy
$\Delta V_c$	Activation volume for creep
$\Delta V_L$	Activation volume for lattice self-diffusion
$\epsilon$	Uniaxial strain
$\epsilon_0$	Instantaneous strain
$\dot{\epsilon}$	Strain rate
$\dot{\epsilon}_{min}$	Minimum creep rate
$\dot{\epsilon}_{ss}$	Steady-state uniaxial strain rate
$\bar{\epsilon}$	Effective uniaxial or von Mises strain
$\theta$	Misorientation angle across high-angle grain boundaries
$\theta_\lambda$	Misorientation angle across (low-angle) subgrain boundaries
$\theta_{\lambda ave}$	Average misorientation angle across (low-angle) subgrain boundaries
$\lambda$	Average subgrain size (usually measured as an average intercept)
$\lambda_s$	Cavity spacing
$\lambda_{ss}$	Average steady state subgrain size
$\nu$	Poisson's ratio
$\nu_0$	Attempt frequency (often Debye frequency)
$\rho$	Density of dislocations not associated with subgrain boundaries



$\rho_m$	Mobile dislocation density
$\rho_{ms}$	Mobile screw dislocation density
$\rho_{ss}$	Steady-state dislocation density not associated with subgrain walls
$\sigma$	Applied uniaxial stress
$\sigma_i$	Internal stress
$\sigma_o$	Single crystal yield strength
$\sigma'_o$	Annealed polycrystal yield strength
$\sigma''_o$	Sintering stress for a cavity
$\sigma_p$	Peierls stress
$\sigma_{ss}$	Uniaxial steady-state stress
$\sigma_T$	transition stress between five-power law and Harper–Dorn creep
$\sigma_{TH_s}$	Threshold stress for superplastic deformation
$\sigma_y  _{T, \dot{\epsilon}}$	Yield or flow stress at a reference temperature and strain rate
$\sigma_y^{0.002}$	0.2% offset yield stress
$\bar{\sigma}$	Effective uniaxial, or von Mises, stress
$\tau$	Shear stress
$\tau_b$	Breakaway stress of the dislocations from solute atmospheres
$\tau_c$	Critical stress for climb over a second phase particle
$\tau_d$	Detachment stress from a second phase particle
$\tau_j$	Stress to move screw dislocations with jogs
$\tau_{or}$	Orowan bowing stress
$\tau_B$	Shear stress necessary to eject dislocation from a subgrain boundary
$\tau_{BD}$	Maximum stress from a simple tilt boundary
$\tau_L$	Stress to move a dislocation through a boundary resulting from jog creation
$\tau_N$	Shear strength of a Frank Network
$(\tau/G)_t$	Normalized transition stress
$\phi(P)$	Frank network frequency distribution function
$\chi$	Stacking fault energy
$\chi'$	Primary creep constant
$\psi$	Angle between cavity surface and projected grain boundary surface
$\omega_m$	Maximum interaction energy between a solute atom and an edge dislocation
$\Omega$	Atomic volume
$\omega$	Fraction of grain boundary area cavitated

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# CHAPTER 1

# Fundamentals of Creep in Materials

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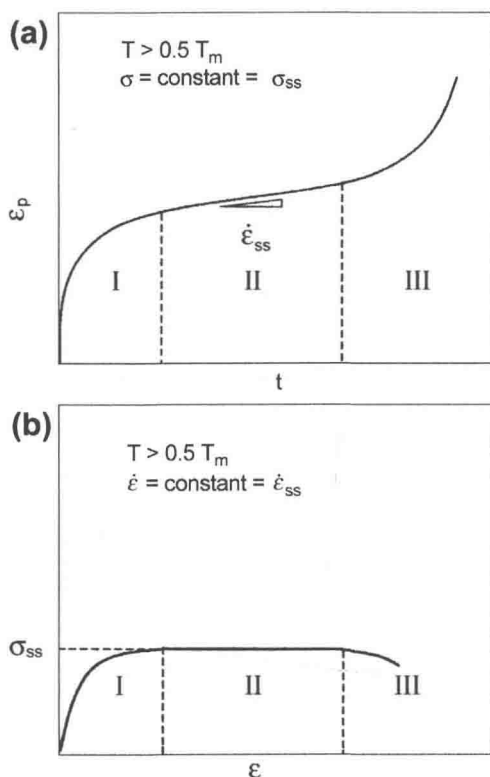
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## 1. INTRODUCTION

### 1.1 Description of Creep

Creep of materials is classically associated with time-dependent plasticity under a fixed stress at an elevated temperature, often greater than roughly  $0.5 T_m$ , where  $T_m$  is the absolute melting temperature. The plasticity under these conditions is described in Figure 1 for constant stress (a) and constant strain rate (b) conditions. Several aspects of the curve in Figure 1 require explanation. First, three regions are delineated: Stage I, or primary creep, which denotes that portion where (in (a)) the creep rate (plastic strain rate),  $\dot{\epsilon} = d\epsilon/dt$  is changing with increasing plastic strain or time. In Figure 1(a), the primary creep rate decreases with increasing strain, but with some types of creep, such as solute drag with “3–power creep,” an “inverted” primary occurs where the strain rate increases with strain. Analogously, in (b), under constant strain rate conditions, the metal hardens, resulting in increasing flow stresses. Often, in pure metals, the strain rate decreases or the stress increases to a value that is constant over a range of strain. The phenomenon is termed Stage II, secondary, or steady-state (SS) creep. Eventually, cavitation and/or cracking increases the apparent strain rate or decreases the flow stress. This regime is termed Stage III, or tertiary, creep and leads to fracture. Sometimes, Stage I leads directly to Stage III and an “inflection” is observed. Thus, care must sometimes be exercised in concluding a mechanical SS.

The term “creep” as applied to plasticity of materials likely arose from the observation that at modest and constant stress, at or even below the macroscopic yield stress of the metal (at a “conventional” strain rate), plastic deformation occurs over time as described in Figure 1(a). This is in contrast



**Figure 1** Constant true stress and constant strain rate creep behavior in pure and Class M (or Class I) metals.

with the *general* observation, such as at ambient temperature, where a material deformed at, for example,  $0.1\text{--}0.3 T_m$ , shows very little plasticity under constant stress at or below the yield stress, again, at “conventional” or typical tensile testing strain rates (e.g.,  $10^{-4}\text{--}10^{-3} \text{ s}^{-1}$ ). (The latter observation is not always true as it has been observed that some primary creep is observed (e.g., a few percent strain, or so) over relatively short periods of time at stresses less than the yield stress (e.g., [1,2])).

We observe in Figure 2 that at the “typical” testing strain rate of about  $10^{-4} \text{ s}^{-1}$ , the yield stress is  $\sigma_{y1}$ . However, if we decrease the testing strain rate to, for example,  $10^{-7} \text{ s}^{-1}$ , the yield stress decreases significantly, as will be shown is common for metals and alloys at high temperatures. To a “first approximation,” we might consider the microstructure (created by dislocation microstructure evolution with plasticity) at just 0.002 plastic strain to be independent of  $\dot{\epsilon}$ . In this case, we might describe the change in yield



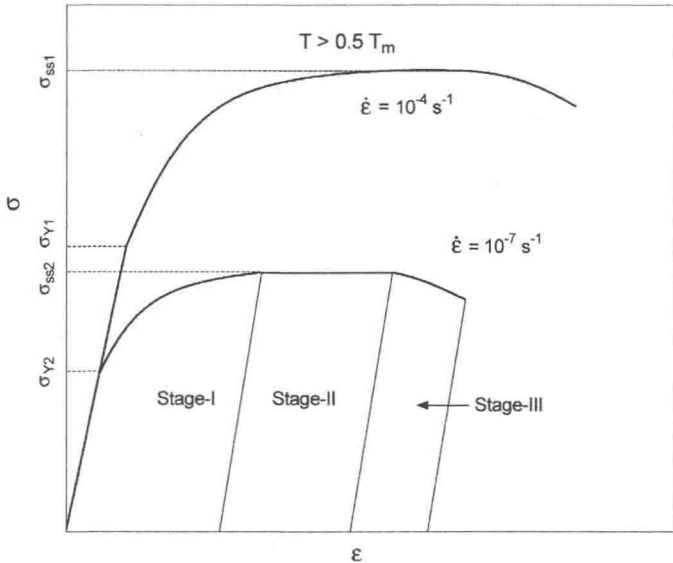


Figure 2 Creep behavior at two different constant strain rates.

stress to be the sole result of the  $\dot{\epsilon}$  change and predicted by the “constant structure” stress-sensitivity exponent,  $N$ , defined by.

$$N = \left[ \frac{\partial \ln \dot{\epsilon}}{\partial \ln \sigma} \right]_{T,s} \quad (1)$$

where  $T$  and  $s$  refer to temperature and the substructural features, respectively. Sometimes, the sensitivity of the creep rate to changes in stress is described by a constant structure strain-rate sensitivity exponent,  $m = 1/N$ . Generally,  $N$  is relatively high at lower temperatures [3] which implies that significant changes in the strain rate do not dramatically affect the flow stress. In pure fcc metals,  $N$  is typically between 50 and 250 [3]. At higher temperatures, the values may approach 10, or so [3–10].  $N$  is graphically described in Figure 3. The trends of  $N$  versus temperature for nickel are illustrated in Figure 4.

Another feature of the hypothetical behaviors in Figure 2 is that (at the identical temperature) not only is the yield stress at a strain rate of  $10^{-7} \text{ s}^{-1}$  lower than it is at  $10^{-4} \text{ s}^{-1}$ , but also the peak stress or, perhaps, SS stress, which is maintained over a substantial strain range, is *less* than the yield stress at a strain rate of  $10^{-4} \text{ s}^{-1}$ . (Whether SS occurs at, for example, ambient temperature has not been fully settled, as large strains are not easily achievable. Stage IV and/or recrystallization may preclude this SS [11–13].)