# High Temperature Deformation and Fracture of Materials

# 材料的高温变形与断裂

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Science Press
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科学出版社
北京

# 内 容 简 介

本书内容分两篇共25章。上篇为高温变形篇，包括金属与合金蠕变的宏观规律、蠕变位错亚结构、纯金属蠕变、固溶体合金蠕变、第二相粒子强化合金蠕变、扩散蠕变、超塑性以及多轴蠕变等内容，重点论述蠕变过程中位错与各种晶体缺陷的交互作用、蠕变微观机制以及蠕变物理模型和理论。下篇为高温断裂篇，包括蠕变空洞形核和长大、蠕变裂纹扩展、蠕变损伤与断裂的评价与预测、高温低周疲劳断裂、蠕变疲劳交互作用以及材料的高温环境损伤等内容，从微观、宏观和唯象三个层次论述了高温断裂理论及其工程应用。

本书可作为高等院校材料学科研究生教学参考书，也可供材料、固体物理和力学专业教师及科研人员参考。

**图书在版编目(CIP) 数据**

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材料的高温变形与断裂＝High Temperature Deformation and Fracture of Materials：英文/张俊善著. —北京：科学出版社，2010
ISBN 978-7-03-027540-0

Ⅰ. 材… Ⅱ. 张… Ⅲ. ①材料-高温变形-研究-英文 ②材料-断裂-研究-英文 Ⅳ. TB303

中国版本图书馆 CIP 数据核字（2010）第084363号

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责任编辑：姚庆爽/责任校对：刘小梅
责任印制：赵 博/封面设计：耕者设计工作室

科学出版社 出版
北京东黄城根北街16号
邮政编码：100717
http://www.sciencep.com

中国科学院印刷厂 印刷
科学出版社发行 各地新华书店经销
*
2010年7月第 一 版 开本：B5（720×1000）
2010年7月第一次印刷 印张：24
印数：1—1 500 字数：483 800

**定价：88.00 元**

**(如有印装质量问题，我社负责调换)**

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# Preface

Many structural components used in the industrial facilities for energy resources, petrochemical, aeronautical and aerospace engineering are operating at high temperatures. For instance, the vapor temperature in a thermal power station is about 600 ℃; the temperatures for hydrogen production and ethylene-cracking are as high as 950 ℃ and 1050 ℃, respectively; and the working temperatures of turbine blades in an aircraft exceed 1000 ℃. High temperature strength is therefore the major concern of these materials.

High temperature strength is defined as the resistance of a material to high temperature deformation and fracture. The definition of high temperature is the temperatures at which the atomic diffusion is fast enough to affect significantly the plastic deformation and fracture behaviors of materials. Usually, for metallic alloys the temperatures considered are higher than one half of their melting points ($T_m$). Atomic diffusion is a time-dependent process; hence the deformation and fracture of materials at high temperatures are related to the duration of loading. Therefore, time-dependent parameters, the strain rate and the fracture life, must be introduced in describing the high temperature strain-stress behavior of materials. In the description of the room temperature mechanical behaviors of metallic alloys, the duration of loading plays rather a less important role. In addition, the chemical or electrochemical reaction kinetics can be very fast at high temperatures. The description, in order to be reliable, has to be made by taking the high temperature environmental properties of materials into consideration.

High temperature deformation and fracture is truly an interdisciplinary subject. The many theories developed for high temperature deformation and fracture are mainly based on dislocation and diffusion, but every stage of their development resorts to the fundamental principles of solid state physics, physical metallurgy, elastic-plastic mechanics, fracture mechanics and damage mechanics, and so forth. High temperature deformation and fracture has long been one of the most active research topics in materials science and engineering. Since the 1970s, remarkable progress has been achieved in developing the relevant microscopic models and theories. In the mean time, research and development activity has also been extensively carried out on new high temperature materials such as intermetallic compounds, ceramics, polymers and composite materials, and ample experimental data have been documented. The idea of writing this book grew out of an attempt for a systematic survey of the research results obtained in the high temperature deformation and fracture community during the past four decades.

In this book, we describe the general macroscopic behaviors of high temperature deformation and fracture shown by various materials, and introduce the mechanisms proposed at two microscopic length scales, i. e. , the atomic and the dislocation levels. Emphasis is placed on the models and/or theories that bridge the microscopic mechanisms and the general macroscopic properties successfully.

This book has 25 chapters and is divided into two parts. Part I (chapters 1-12) is devoted to high temperature deformation. The contents cover topics about the macroscopic high temperature deformation behaviors of metals and alloys; the development of the substructures during creep; the creep of pure metals, solid solution alloys, particle strengthened alloys and intermetallic compounds; diffusion creep; superplasticity and the multiaxial creep behaviors. Part II (chapters 13-25) covers high temperature fracture, where the creep cavity nucleation and growth, the creep crack propagation, the evaluation and prediction for creep damage and fracture, the creep-fatigue interactions, and the high temperature environmental damage of materials are discussed.

The Chinese version of this book was intended to be a reference book for our graduate students and young researchers. The motivation for publishing this book is to facilitate young students and researchers to catch on quickly the basic ideas of high temperature strength theories and the recent progresses. Considering this we choose the most typical models proposed at each stage of the development of high temperature strength theories. We present the theoretical framework of these models, rather than making comprehensive comments on the huge amount of experimental data, whether they are supporting or contradicting the theories. A comprehensive bibliography has not been attempted in the Chinese version of this book, and the references quoted in the English version are out of the same consideration.

The publication of the Chinese version of this book was financially supported by a science publishing fund of Chinese Academy of Sciences and by a publishing fund of the Dalian government.

Prof. Shouyi Gao carefully reviewed the manuscript of the Chinese version of the book. I appreciate his valuable comments and suggestions on it. My thanks are also due to my colleagues who have deeply involved in the English translation work. A non-exhaustive list would certainly include Dr. Yingmin Wang, Dr. Hao Huang, Dr. Fumin Xu, Dr. Guoqing Chen, Dr. Xiaopeng Zhu, Dr. Aimin Wu, Dr. Honggang Dong, Dr. Xiao Ren, Prof. Liangming Peng and Prof. Qing Zhou. I acknowledge the assistance of Prof. Mingkai Lei, Prof. Yi Tan and Prof. Wenlong Zhou for the organization of the translation work. I am grateful to Dr. Weixing Chen at the University of Alberta of Canada, and Dr. Yuyuan Zhao at the University of Liverpool of the UK who revised Part I and Part II of the English version, respectively. Without the help of these colleagues and friends, the project would have never been finalized.

I thank my wife, Qide Nan, for her patience and encouragement while I am working on the book at weekends and holidays. Her faithful love was, and still is a great source of confidence.

Finally, I would like to point out that I am responsible for all the errors or deficiencies that should unavoidably remain in this book.

Jun-Shan ZHANG
Dalian

# Contents

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## Part I High Temperature Deformation

Part II High Temperature Fracture

# Part I

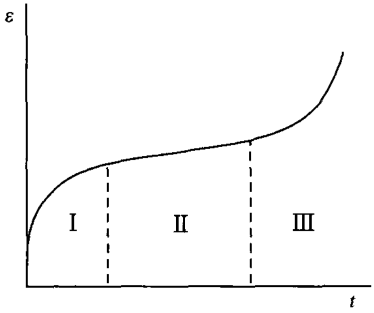
## High Temperature Deformation

# 1

# Creep Behavior of Materials

## 1.1 Creep Curve

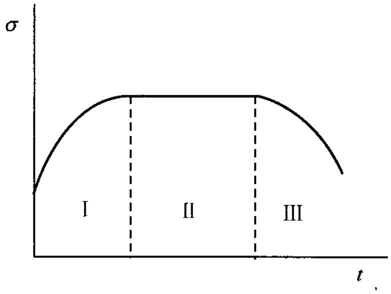
The time-dependent plastic deformation of materials under constant stress at elevated temperature is called creep. In creep test, a constant load or a constant stress is applied to the specimen and the change of strain is recorded as a function of time. Figure 1. 1 shows a typical creep curve schematically. As can be seen, there are three stages of creep. In the first stage, called primary creep, creep rate decreases with time. The second stage, called steady state creep or secondary creep, is characterized by a constant creep rate. In the third stage, called tertiary creep, creep rate increases with time, eventually leading to fracture.



*1. 1* Typical creep curve at constant stress.

This type of behavior can be explained by simultaneous occurrence of strain hardening and dynamic recovery at elevated temperature. At the beginning of creep, the deformation resistance is small and the strain rate is high. In primary creep, strain hardening causes the creep rate to decrease with strain. With increasing strain hardening, the rate of dynamic recovery is increased. The steady state creep will be reached when the strain hardening is balanced by the recovery softening. The tertiary creep, where creep rate increases (or flow stress decreases) with time, is primarily attributed to localized necking and also to the formation of creep cavities. Many commercial alloys, when tested in tensile creep, exhibit a large tertiary creep and no (or vary short) secondary stage is observed. In such a case the minimum creep rate is used to characterize creep properties. The absence of steady state creep is attributed to structural instability, for example particle coarsening and grain growth.

If the material is tensioned at a constant strain rate and the change of flow stress is recorded as a function of strain, then another type of deformation curve is obtained as shown in Fig. 1. 2. The constant strain rate deformation can also be divided into three stages. The flow stress increases with strain in the first stage; remains constant in the second stage and decreases in the third stage until fracture.



1. 2 Typical deformation curve at constant strain rate.

The two types of creep test, constant-load (or constant-stress) and constant-strain-rate creep, correspond to two engineering applications of materials at high temperature: long term services of components at constant load and hot processing at constant deformation rate, such as rolling, drawing and forging.

## 1. 2 Stress and Temperature Dependence of Creep Rate

### 1. 2. 1 Stress Dependence of Creep Rate

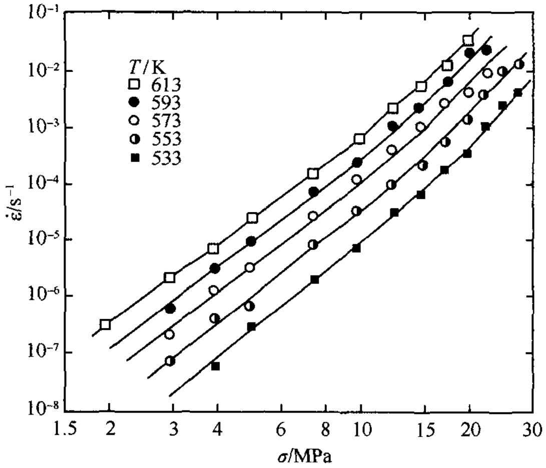
Extensive phenomenological creep studies on polycrystalline metals indicate that the relationship between the steady state creep rate, $\dot{\varepsilon}$, and the applied stress, $\sigma$, is described by the power law:

$$\dot{\varepsilon} = A_1 \sigma^n \qquad (1.1)$$

where $A_1$ is a constant associated with temperature and material, and $n$ is the stress exponent of creep rate. (From now on, the term "creep rate" will indicate steady state, or minimum, creep rate if there is no special notation). The value of $n$ can be determined from the slope of $\log\dot{\varepsilon} \sim \log\sigma$ plot of experimental data at constant temperature. The value of $n$ for pure metals in the intermediate stress range is usually equal to 5 (In the low-stress range diffusional creep takes place and it will be discussed in Chapter 9). An example of this plot for pure aluminium is shown in Fig. 1. 3[1]. It can also be seen from the figure that the liner relationship between $\log\dot{\varepsilon}$ and $\log\sigma$ (power law creep) in the intermediate stress range breaks down in the high stress range. This phenomenon is called power law breakdown (PLB). The stress dependence of creep rate in the PLB range can be described by

$$\dot{\varepsilon} = A_2 \exp(B\sigma) \tag{1.2}$$

where $A_2$ and $B$ are constants related to material and temperature.



1.3 Stress dependence of creep rate for pure aluminum [1].

The stress dependence of creep rate in the intermediate and high stress ranges can be described by the following unified equation[2]

$$\dot{\varepsilon} = A_3 (\sinh \alpha\sigma)^n \tag{1.3}$$

This equation reduces to Eq. (1.1) at lower stress and to Eq. (1.2) at higher stress. It should be noted that Eqs. (1.1) and (1.2) represent different creep mechanisms. Therefore, Eq. (1.3) does not have a physical meaning although it is convenient for mathematical treatment of creep over a wide range of stress.

### 1.2.2 Temperature Dependence of Creep Rate

The creep rate can be described by an Arrhenius equation,

$$\dot{\varepsilon} = A_4 \exp\left(-\frac{Q_c}{RT}\right) \tag{1.4}$$

where $Q_c$ is the activation energy for creep, $A_4$ is a constant for a given stress, $R$ is the gas constant and $T$ is the absolute temperature. This equation indicates that creep is a thermally activated process. Figure 1.4 shows $\log\dot{\varepsilon} \sim 1/T$ plots of the creep data within the range of power law creep in Fig. 1.1[1]. The activation energy for creep for a given stress can be determined from the slope of the straight line for the stress in Fig. 1.4. The almost identical slopes of the lines for different stresses indicate that the activation energy for creep is independent of stress in certain stress range.

Since the dislocation substructure in the steady-state creep stage depends on the modulus-normalized stress but not on temperature, the activation ener-