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Daining Fang
Jinxi Liu

压电与铁电体的断裂力学

Fracture Mechanics of Piezoelectric and Ferroelectric Solids

清华大学出版社 Springer

内 容 简 介

本书是关于压电/铁电材料断裂力学的专著，从理论分析、数值计算和实验观察三个方面比较全面、系统地阐述了压电/铁电材料的电致断裂问题，强调静态、动态和界面断裂问题的力学提法以及力电耦合效应所导致的电致断裂的物理本质。本书的主要特色是：从晶体学的角度简要介绍了压电/铁电材料的基本特征；详细描述了压电材料的基本方程以及与断裂问题相关的一般解；以图的形式提供了大量的数值结果；给出了主题词和作者索引；用简洁的语言解释了复杂的电致断裂问题。本书可帮助固体力学、材料科学、应用物理和机械工程领域的读者很容易地抓住问题的物理本质并把握压电/铁电材料断裂力学的研究现状。

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Daining Fang
Jinxi Liu

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Foreword

Mechanical-electrical coupling and anisotropy of piezoelectric/ferroelectric solids complicate studies of their damage and fracture. Therefore, the solution of fracture mechanics problems for such materials is challenging. It has become an important subject in solid mechanics and materials physics to understand the physical mechanisms of fracture of piezoelectric/ferroelectric solids and improve the fracture resistance of such materials. This book discusses the characteristics and engineering background of piezoelectric/ferroelectric solids, the electromechanical coupling fracture behavior and failure modes from a systematic point of view, which combines solid mechanics and material physics. The establishment of fracture criteria is the embodiment of the research findings and theoretical system formed in recent years, which not only enriches the subject of studies in solid mechanics, but also underlies important academic values. This book is featured with the subject of "How Electromechanical Coupling Effect Influences Fracture Behavior of Piezoelectric/Ferroelectric Materials", and addresses clear physical concepts and prudent mathematic mechanics, leverages theoretical approaches, experimental technology and actual materials as a valuable reference for postgraduates and researchers in solid mechanics and materials physics.

The authors of the book, Professors Daining Fang and Jinxi Liu are both young scholars with high academic accomplishments as well as solid and profound foundation in the mechanic theories of intelligent materials and expertise in materials physics. Their work has focused on theories and experimental research in deformation and fracture of piezoelectric/ferroelectric materials and ferromagnetic materials, where they made a series of important innovations with significant impact both at home and abroad. Based on their years of research and studies of relevant literature in China and abroad, they have systematically interpreted the fundamental theories and research approaches as applied to fracture of piezoelectric/ferroelectric solids in the form of a monograph with unique and rich content, wide coverage of literature, step-by-step discussion, clean and prudent structure and high academic standards. It is an excellent academic book and I hereby would highly recommend it to the readers.

Kezhi Huang
At Tsinghua University

Preface

Rapid changes in the information technology have led to the development of mature technology for MEMS (microelectromechanical systems), microelectronics and packaging, sensing, actuation and the intelligent structure of control since the end of the 20^{th} century. As a result, new scientific problems in multi-field coupling of functional materials and micro information structural mechanics are proposed. For stress, strain and strong interaction between heat and electromagnetic phenomena, mechanical rules become extremely important to the design of the above MEMS, microelectronics and intelligent structures. Therefore, the reliability of these devices is attracting increasing attention. Fragility of piezoelectric/ferroelectric ceramics and defect formation during their preparation, such as voids and cracks, generally lead to the loss of expected functions and even damage of piezoelectric/ferroelectric components or piezoelectric/ferroelectric intelligent structures in terms of the single or synergic functions of mechanical and electric loading. Such challenges urge us to understand the physical mechanisms of fracture of piezoelectric/ferroelectric materials in order to provide theoretical basis for the reliability analysis and life cycle prediction of piezoelectric/ferroelectric materials. The science of fracture mechanics of piezoelectric/ferroelectric solids has undergone significant development since the end of 1980s. In the second half of last century, researchers in mechanics, physics and materials both in China and abroad made wide and in-depth investigations, which resulted in major breakthroughs. Although there are still disputes on some problems, it is possible to say that the theoretical framework of fracture mechanics of piezoelectric/ferroelectric solids has been well established.

The author of the book has been engaged in the study of deformation and fracture mechanisms of piezoelectric/ferroelectric materials for over ten years and, as a result, gained significant experience and made distinct achievements in this area. This book attempts to give a systematic discussion on the fracture mechanics of piezoelectric/ferroelectric materials based on the research done by the author in combination with references to research done both at home and abroad. It explores some basic problems in mechanics of piezoelectric/ferroelectric solids under the topic of "How Electromechanical Coupling Effect Influences Fracture Behavior of Piezoelectric/Ferroelectric Materials". There are 13 chapters in the book, of which the first four chapters introduce applications of piezoelectric/ferroelectric materials, experimental methods and findings related to piezoelectric/ferroelectric fracture, characteristics of electromechanical coupling and basic formulas of piezoelectrics. The fifth chapter discusses the general resolutions of electromechanical coupling formula of piezoelectric materials. The last eight chapters discuss fracture behavior of piezoelectric/ferroelectric materials, covering the nature of tip-field, interfacial fracture, dynamic fracture, non-linear fracture, electromechanical coupling numerical methods, electrically induced fatigue crack extension, electrode induced, electroelastic field concentration, and mechatronic coupling fracture criteria.

The main purpose of the book is to induce new thinking that would benefit future developments in this field. Therefore, this book attempts to describe fracture mechanics of piezoelectric/ferroelectric materials from several perspectives not only addressing theoretical analysis of fracture, but also the findings of numerical simulations and experiments. Electromechanical coupling effects and anisotropic fracture features of piezoelectric/ferroelectric solids complicate the study of the fracture characteristics. Therefore, it is challenging to solve the problems in electromechanical coupling fracture mechanics. The authors attempt to cover theories and experiments, principles and applications, and present critique and new thoughts at the same time. This book is not only a complete and systematic treatise, but it also relates theory to practice in order to reflect the latest progress in this field.

Although the literature cited by the authors covers wide-ranging field, it is far from exhaustive. Owing to the abundance and complicated nature of the literature on this subject, it is inevitable that some studies are not included in this book and we regret if we missed to cite some achievements in this field. The authors sincerely hope that the publication of the book shall facilitate the applications of piezoelectric/ferroelectric materials and the development of new functional materials in China. At the same time, it shall also serve as a high level reference book for teachers, graduates and professional technicians conducting research in solid mechanics, materials science, dielectric physics, mechanical and electrical engineering. Due to the limited theoretical capability and practical experience of the authors, there may be errors and inappropriateness in the book and the authors sincerely hope to receive corrections and critiques from specialists and readers.

The studies conducted by the authors themselves and described in this book have been awarded sponsorship as Key Project of "9th Five-Year-Plan", Outstanding Youth Funding, Innovative Collective Project and International Cooperation Project under National Natural Science Foundation of China (NSFC) as well as the sponsorship for key project of Ministry of Education of China (MEC) and Doctorate Fund Projects of MEC. The authors are deeply grateful for such sponsorships, without which it would be difficult to complete such studies. The book also contains achievements made by the team members of the authors in post-doctorate/graduate programs over the last 12 years. The authors would like to thank their team members for their diligence, talents, contributions and cooperation in these studies. In their research, the authors have been cooperating with Professor A.K. Soh from Hong Kong University, Professor C.T. Sun from Prudent University of USA, Professor J.Y. Li from Washington University. The author of this book has benefited tremendously from their profound expertise and extends his sincere gratitude to them. The author also sincerely thanks his dear colleagues, Huang Kezhi and Yang Wei, who are also Academicians of Chinese Academy of Sciences, for their encouragement, assistance and support over many years. Finally, the author is especially grateful to Mr. Mao Guanzhong, Mr. Wei Weiyi, Mr. He Huijing and Ms. Zhao Xiaofang for their great support in typing the manuscript, amending the graphs and charts, and setting up the literature index.

By the first author
At Beijing Tsinghua Park

Contents

Chapter 1 Introduction

Abstract This chapter summarizes briefly the research background, development history and future trend of fracture mechanics of piezoelectric/ferroelectric materials. In Section 1.3, the structure and arrangement of the present book are introduced.

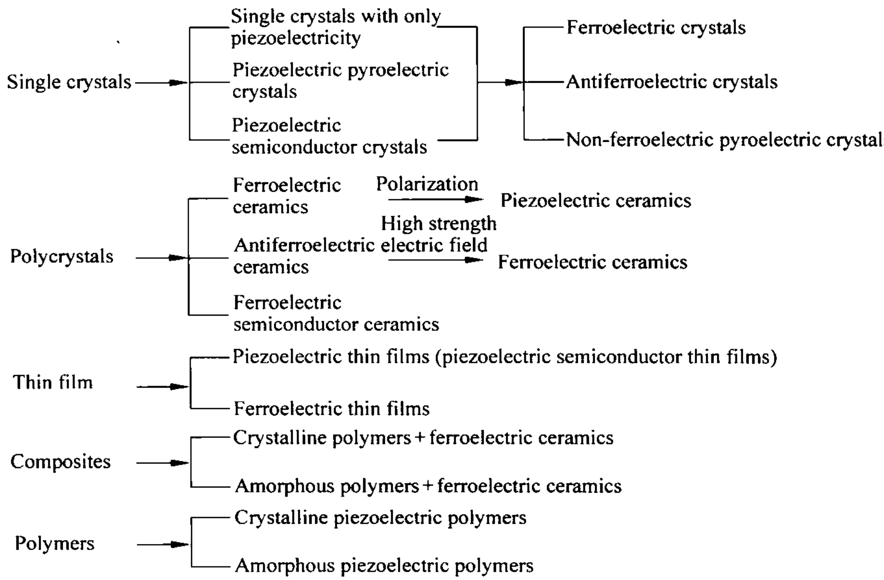
Keywords piezoelectric/ferroelectric material; fracture mechanics

1.1 Background of the research on fracture mechanics of piezoelectric/ferroelectric materials

Piezoelelctric/ferroelectric materials fall into the category of functional materials due to their piezoelectric effect which enables the conversion between mechanical energy and electrical energy. The piezoelectric effect includes direct piezoelectric effect and inverse piezoelectric effect. The former refers to the physical phenomenon of the occurrence of an electric field within a piezoelectric/ferroelectric solid when it is subjected to mechanical load. This phenomenon was discovered by the brothers P. Curie and J. Curie in a quartz crystal in 1880. The second effect refers to the mechanical behavior of mechanical deformation taking place in a piezoelectric/ferroelectric solid when it is under the effect of an electric field. In 1881, G. Lippmann suggested the existence of this mechanical behavior by using energy conservation and electricity conservation, and it was experimentally verified by the Curie brothers several months later. The discovery of the piezoelectric effect generated keen interest among scientists. A great amount of research work has been done in the macroscopic and microscopic theories of piezoelectrics/ferroelectrics. The development of various piezoelectric/ferroelectric materials and their application in modern science and technology field, and abundant research results have been achieved (Zhang and Wang, 2001).

According to the crystal structure or composition of the materials, piezoelectric/ferroelectric materials can be classified into single crystals, polycrystals, thin films, composites and polymers. These five types of piezoelectric/ferroelectric materials can be sub-classified as follows (Sun and Zhang, 1984):

Whether a material possesses piezoelectricity or not usually depends on the structural form of its crystal. Generally speaking, centrosymmetric crystals do not possess piezoelectricity, while the crystals devoid of centers of symmetry possess piezoelectricity. Polarization will occur in some crystals having no



centers of symmetry due to the variation in temperature. This phenomenon is called pyroelectric effect and the corresponding materials are termed pyroelectric materials. The pyroelectric effect is caused by the spontaneous polarization in crystals. Piezoelectric materials do not necessarily all possess pyroelectric effect, but all the materials possessing pyroelectric effect must be piezoelectric materials. In pyroelectric materials, some materials not only have spontaneous polarization within certain temperature range, but their spontaneous polarization can also be reversed due to an externally applied electric field. This type of materials is termed ferroelectric materials. Piezoelectric, pyroelectric and ferroelectric materials are all dielectric materials and their relationships are shown in Fig. 1.1. It should be

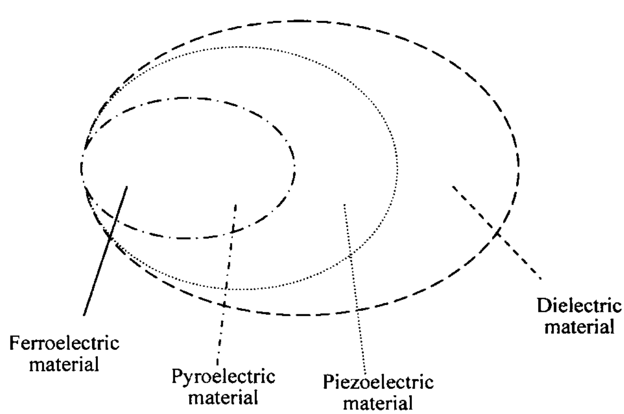


Figure 1.1 Relations among dielectric materials, piezoelectric materials, pyroelectric and ferroelectric materials

pointed out that the fracture mechanics of piezoelectric materials is different from that of ferroelectric materials. Although brittle ceramics are the main materials for both types, the former investigates the fracture problems of ideal cracks under electromechanical coupling effect on the basis of linear piezoelectric theory while the latter deals with the fracture of ferroelectric materials connected with domain switch, electric yield and constitutive nonlinearity.

At present, the piezoelectric/ferroelectric materials widely used in engineering are mainly piezoelectric/ferroelectric ceramics and piezoelectric/ferroelectric composites consisting of ferroelectric ceramics and polymers. Piezoelectric/ferroelectric ceramics are typical brittle materials with the characteristics of low fracture toughness and high flaw sensitivity. Therefore, when the devices and structures made of piezoelectric/ferroelectric ceramics are under electromechanical joint effect or separate effect, the concentration of stress field and strain field often caused by flaws, such as inclusion, pores, cracks, etc., which appear in the process of manufacture or in the process of use leads to failure in their designed function and even dielectric breakdown or fracture damage will take place, which restricts wider application of the piezoelectric/ferroelectric ceramics and further improvement in the performance of related devices. Therefore, in recent years, it has become an important research subject in the fields of solid state mechanics and materials physics to get a clear understanding and thorough grasp of the physical and mechanical mechanisms of the fracture of piezoelectric/ferroelectric materials, to make reliable analysis and prediction and present the corresponding toughening mechanisms.

1.2 Development course and trend

The piezoelectric/ferroelectric materials applied in modern technology, as pointed out in the above section, are mainly piezoelectric ceramics and ferroelectric ceramics. Hence, the fracture mechanics of piezoelectric/ferroelectric materials can be deemed as the fracture mechanics of piezoelectric/ferroelectric ceramics. The fracture mechanics of piezoelectric/ferroelectric materials involves materials science, dielectric physics, electricity and solid state mechanics, with a typical characteristic of an interdisciplinary subject. The research object is piezoelectric/ferroelectric solids with cracks and the purpose is to reveal the laws of crack growth, instability, cracking and microphysical mechanisms, to establish effective fracture criteria and seek the approach for material toughening so as to provide theoretical reference for reliability analysis and design of piezoelectric/ferroelectric devices.

Beginning with the research by Pak (1990, 1992), Sosa and Pak (1990), Sosa (1991), Suo *et al.* (1992), Wang (1992a) as well as Zhang and Hack (1992) in the early 1990s, the fracture mechanics of piezoelectric/ferroelectrics has become a focus of attention and a research field of interest. Prior to that, only Parton (1976), Deeg (1980), Parton and Kudryavtsev (1988) had made a theoretically exploratory