

Materials Forming, Machining and Tribology

Series editor

J. Paulo Davim, Aveiro, Portugal

More information about this series at <http://www.springer.com/series/11181>

Ahad Kh Janahmadov · Maksim Javadov

Fractal Approach to Tribology of Elastomers

 Springer

Ahad Kh Janahmadov
National Aviation Academy
Baku, Azerbaijan

Maksim Javadov
Baku, Azerbaijan

ISSN 2195-0911 ISSN 2195-092X (electronic)
Materials Forming, Machining and Tribology
ISBN 978-3-319-93860-8 ISBN 978-3-319-93861-5 (eBook)
<https://doi.org/10.1007/978-3-319-93861-5>

Library of Congress Control Number: 2018945911

Translation from the Russian language edition: *Фрактальные Подходы в Трибологии Эластомеров* by Ahad Kh Janahmadov and Maksim Javadov, © APOSTROFF Publishing House 2016. All Rights Reserved.

© Springer International Publishing AG 2019

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, express or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Printed on acid-free paper

This Springer imprint is published by the registered company Springer International Publishing AG part of Springer Nature
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

About the Book

This book summarizes the results of years of research on the problem of strength and fracture of polymers and elastomers. It sets out the modern approach to the strength theory from the standpoint of fractals, the kinetic and thermodynamic theories, as well as the meso-mechanic destruction.

The dimension reduction method is applied to model the friction processes in elastomers subjected to the complex dynamic loading. Finally, it analyzes a relation between the fracture mechanism and the relation phenomena, and provides new experimental data on the sealing nodes in accordance with their specific working conditions where the effect of self-sealing is observed.

The book is intended for researchers, graduate students, and engineers specializing in the field of tribology, and also for senior students of technical colleges.

Contents

1	About Theoretical Strength of Materials	1
1.1	Theoretical Strength of Solids	2
1.2	The Relationship Between Elastic Modulus and Theoretical Strength	5
1.3	The Concept of Phonon Destruction	6
1.4	The Phonon Theory of Destruction of Polymer Chain	8
1.5	The Relationship Between Mechanical and Thermal Properties of Solids	11
1.6	Some Types of Cracks	13
1.7	Nonlinear Fracture Mechanics and Fracture Criteria	17
1.8	The Griffith Theory of Fracture of Solids	19
	Literature	22
2	General Laws of Friction and Wear of Polymers	25
2.1	The Nature and Properties of Elastomer Friction	26
2.2	Principles of Failure of Elastomers	27
2.3	Thermodynamics of Failure and Criticism of Griffith Theory	29
2.4	The General Form of Phenomenological Theory	33
2.5	Statistical Theory of Fatigue Fracture	35
2.6	The Mechanism of Fatigue Failure of Elastomers	38
2.7	The Principles of Scaling and Generalized Variables	40
2.8	The Transition to Dimensionless Parameters. π -Theorem	42
2.9	The Stress-Relaxation in Elastomers and Self-sealing Effect	44
2.10	The Reasons of Absence of Self-sealing Effect in Elastomers	45
	Literature	46
3	Fractal Kinetics of Fracture	49
3.1	The Concept of Fractal. Fractal Dimension	49
3.2	Fractals of Condensed Matter Physics	52
3.3	Fractal Properties of Hierarchical Structure of Potential Relief	55

3.4	Kinetics of Fracture from the Point of Theory of Fractals	61
3.5	Analysis of Relationship Between the Fractal Dimension of Dissipative Structure of Pre-destruction Zone, and the Mechanical Properties and the Critical Deformation States of Metals and Alloys	73
3.6	Diagnosis of Contact Interaction of Solids Using Fractal Analysis Method	84
3.6.1	The Emergence of Fractal Structures During Evolution of Complex Systems	85
3.6.2	The Dependence of Contour Pressure Roughness at Elastic and Plastic Contacts	88
3.6.3	The Calculation of Fractal Dimension of the Supporting Surface Curve for the Ultimate Value of Penetration	92
3.6.4	The Calculation of Power Spectrum of Profile Roughness and the Diagnosis of Contact Modes of Metallic Bodies	94
	Literature	97
4	Modern Problems of Frictional Contacts of Elastomers	101
4.1	Efficient Linear Viscoelastic Characteristics of Nonhomogenous Elastic (Composites) and Viscoelastic Bodies	101
4.2	Derivation of Expressions of New Efficient Moduli	103
4.3	Analytical Solution of the Problem of Loading Viscoelastic Half-Space	105
4.4	Building Approximate Solutions with Effective Time Moduli	107
4.5	Modification of Efficient Hashin–Shtrikman Moduli for the Two-Component Isotropic Composite	113
4.6	Derivation of Expressions of Effective Hashin–Shtrikman Moduli of Reuss Type	114
4.7	Models of Averaging Effective Characteristics of the Two-Component Elastic Composite	118
4.7.1	Model of Iterative Conversion of Efficiency Characteristics	119
4.7.2	Model of Averaging Effective Characteristics	121
4.8	The Problem of Loading Double-Layer Shell	123
4.9	The Problem of Loading Triple-Layer Plates	126
4.10	Nanotribological Processes During Electric Discharge in Discrete Ohmic Contacts of “Polymer–Metal” Pairs	129
4.10.1	Electrical Currents in Surface and Subsurface Layers of Polymer Lining	131
4.10.2	Electrical Rift in Discrete Ohmic Contacts of Metal–Polymer Pairs of Tribosystems	134

4.10.3	Local Fracturing of Polymer Films in Ohmic Contacts of Tribo-Coupling	137
4.11	The Frictional Interaction in Electric and Thermal Fields of Metal-Polymer Frictional Pairs	139
4.11.1	Electrical Conductivity of Surface Lining of Polymer Lining	139
4.11.2	The Contact-Impulse Interaction of Frictional Pairs with Different Energy Levels of Materials	143
4.11.3	Selection of Materials of Electrodes and Their Behavior at the Transition Phase of the First Kind	148
4.11.4	The General Laws of Electrodynamic Characteristics of the Micro-protrusion Contact Spots at Their Frictional Interaction	149
4.11.5	The Phenomena of Electrical Explosion and Hear Discharge at the Frictional Interaction in Metal-Polymer Pairs	153
4.11.6	The Phenomena of Thermal Explosion at Frictional Interaction of Metal-Polymer Pairs	158
4.12	Fractal Analysis of Disperse-Filled Elastomeric Composites	160
4.12.1	Molecular Modeling of Mesoscopic Polymeric Composite Systems	168
4.12.2	Fractal Analysis of Structure and Properties of Interphase Layers in Disperse-Filled Elastomeric Composites: The Significant Nanoeffect of Strengthening Elastomers by Nanoparticles	174
	Literature	179
5	Dimension Reduction as Modeling Method for Elastomers Under Complex Dynamic Loading	185
5.1	Contact Mechanics and Physics of Friction	185
5.1.1	The Depth of Indentation as Steady Controlling Parameter of Contact Configuration	186
5.1.2	The Surface Gradient and the Size of Micro-contact as the Main Surface Parameters	190
5.1.3	Examples of the Generalized Friction Laws	192
5.2	Meso-mechanical Nature of Friction and Numerical Modeling in Tribology	195
5.2.1	Tribology in the Era of Information Technologies	195
5.2.2	Mesoscopic Nature of Friction	196
5.2.3	Method of Dimensionality Reduction	198
5.3	Dimensionality Reduction for Modeling Friction Process in Elastomers	200
5.3.1	Main Principles of Dimensionality Reduction	200

5.3.2	Precise Mapping Based on Dimensionality Reduction of Axisymmetric Contact Problems with and Without Adhesion	225
5.4	Dimensionality Reduction for Modeling Friction of Elastomers	239
5.4.1	Modeling Friction of Elastomers Under Complex Dynamic Loading	239
5.4.2	Modeling Friction of Elastomers at Contact with Rough Surface	256
	Literature	275
6	General Problems of Sealing Units and Their Classifications	283
6.1	The Primary Mechanism of Sealing Units	283
6.1.1	Classifications of Sealants	288
6.1.2	Leakage of Sealing Components	291
6.2	Major Groups and Design Types of Rubber Sealants	296
6.2.1	Group of Sealants	309
6.3	Synthesis of Sealing Downhole Packers	310
6.4	Destructive Influence of Two-Phase Fluids on Cuffs of Screw Pumps	320
	Literature	326
7	Stress–Strain State of Sealants of Complex Shapes	327
7.1	Strain Characteristics of Casing Sealant	327
7.2	Creeping in Casing Sealant	331
7.3	Strain Characteristics of Casing Sealant of Complex Shape	338
7.4	Examining Stress–Strain State of Sealing Element of Casing	344
7.5	Determination of Sealing Ability of Sealant	348
7.6	Ensuring Effectiveness of Sealant	354
7.7	Effectiveness of Radial Sealant in Hydraulic Cylinder	360
7.8	Influence of Geometric Shape of Sealant on Self-sealing	364
	Literature	368
8	Sealing Properties of Elastic Element	371
8.1	Conditions of Self-sealing	371
8.2	Impact of Wicking on Self-sealing	378
8.3	Determination of Optimal Gap Between Elastic Element and Operational Casing	381
8.4	Determination of Forces Applied to Elastic Element	383
8.5	Assessment of Impact Rate of Load to Elastic Element	384
8.6	Impact of Sealant Shape on Stress Relaxation in Contact Zone	391
8.7	Impact of Axial Force Rate on Sealing Process	395
	Literature	400
	Conclusion	401

Introduction

The physics and mechanics of polymers widely use the ideas and methods from solid- and liquid-state physics, thermodynamics, and statistical physics. For example, solid-state physics and polymer physics are both focused on the relationship between the physical properties and the structures of materials.

Solid-state physics observes two ultimate conditions: *super-state* for different classes of crystals (superconductivity, ferromagnetism, and superplasticity for metals, ferroelectric state of dielectrics); *super-fluidity* for quantum liquids (helium). In the same way, polymers have their own super state, which is called the *highly elastic state*. The highly elastic state is explained not only by the structure of polymer molecules, but also by the internal rotation, the well-known property of simple molecules from molecular physics. The theory of high elasticity is built on the application of conformational statistics of macro-molecules, which is a study of statistical physics as part of polymer physics. The relaxation and thermal properties of fluxed polymers and liquids are mainly similar across many aspects (vitrification, rheology). And the crystalline polymers have a structure similar to solids, however, besides the crystalline phase within volume they also have the amorphous phase in the interphase layers. Based on the electrical properties, polymers are dielectrics and they are characterized by the electret state; from their magnetic properties, we can say that polymers are diamagnetic, and from their optical properties that they have the profound birefringence at the molecular orientation. At the same time, all polymers have unique mechanical properties, among which the highly elastic properties take the most important role. In the solid state, polymers are close, in terms of mechanical properties, to those solids that are studied in the mechanics of deformable solids. In the highly elastic state, as well as in the viscous-fluid state, the mechanics and rheology of polymers are successfully supplemented and developed.

Approximately for every 10 years, the physics and mechanics undergo radical changes creating new branches within science: polymer biophysics, rigid-chain polymer physics, relaxation spectrometry of polymers, phonon destruction of polymers, and so on.

Hence, there is a necessity at every stage of development of the physics and mechanics of polymers to generalize scientific results with respect to fractals, kinetic and thermodynamic theory, and meso-mechanics of destruction.

Finding frictional force between the rough solid surface with a given topology, and elastomer is still a complex and not fully resolved problem. Its complexity is primarily defined by the fractal relief of the contact surfaces. In order to correctly calculate friction, the fractal approach at the nanometric and macroscopic levels is required with respect to surface roughness, as well as the wide range of the elastomer relaxation time differing up to nine orders of magnitude, which determines the multiscale of problem in time.

The hierarchically organized memory is used to solve the problem of multiscale in time, which plays an important role in the friction of elastomers. The combination of the dimensionality reduction method with the hierarchical memory allows creating an effective numerical method for calculating friction between the rough surface with arbitrary topology and elastomer with arbitrary linear rheology. The verified results show an applicability of the method for solving a number of actual tribology problems.

As a result of theoretical and empirical studies, as well as numerical calculations, the authors analyzed the mechanics and mechanism of elastomers in the mobile and stationary hydraulic systems. The book explains the mechanical behavior of various elastomers, their deformability, and strength under complex dynamic loads, which are characteristic to oil and gas equipment. The authors also partially used the results from work done with support of Science Foundation at State Oil Company of Azerbaijan Republic (SOCAR).

The authors would like to thank reviewers, Prof. S. G. Chulkin and D. G. Agalarov, for valuable comments, O. A. Dyshin (Ph.D.) for helping to prepare individual chapters, as well as N. Z. Askerova and A. M. Denzieva for assisting in publication of this monograph.

The authors hope that this work will have a positive contribution in solving problems of tribology of elastomers, and would be grateful for any comments from readers.