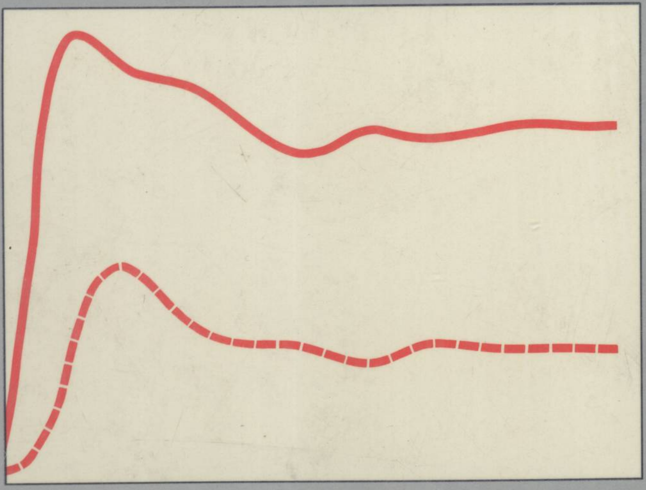
Brostow/Corneliussen

Failure of Plastics



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edited by
Witold Brostow
and
Roger D. Corneliussen

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Failure of Plastics

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We dedicate this book
to the memory
of a great scientist, humanitarian,
our teacher and friend

Paul John Flory

Witold Brostow and Roger D. Corneliussen

Figure on the front cover:

We show on the cover one item pertaining to computer simulation of competition between chain relaxation and crack propagation (cf. Section 10.4). The horizontal coordinate is time, beginning on the left with the moment of breaking a bond between two segments of a polymer chain. The vertical axis shows the distance between adjacent segments. The continuous line shows oscillations of a segment adjacent to the broken bond, the broken line similarly oscillations of the next segment. In the present case oscillations subside with time, and a new stable position is found. In some other simulations breaking of a series of neighboring bonds and crack propagation were observed. (From W. Brostow and D.P. Turner, *J. Rheology* 1986, **30**, August issue).

Foreword

The Society of Plastics Engineers is pleased to sponsor and endorse "Failure of Plastics". The subject matter is both of significant importance within the plastics industry and of great interest to users of plastics materials. The authors are highly respected and well known in SPE for their expertise in the subject. Dr. Roger Corneliussen has been affiliated with the SPE educational seminar program for many years and his presentation on "Failure Mechanism in Plastics" has been among the most popular and well attended programs.

SPE, through its Technical Volumes Committee, has long sponsored books on various aspects of plastics and polymers. Its involvement has ranged from identification of needed volumes to recruitment of authors. An ever-present ingredient, however, is review of the final manuscript to insure accuracy of the technical content.

This technical competence pervades all SPE activities, not only in publication of books but also in other areas such as technical conferences and educational programs. In addition, the Society publishes four periodicals – *Plastics Engineering, Polymer Engineering and Science, Journal of Vinyl Technology* and *Polymer Composites* – as well as conference proceedings and other selected publications, all of which are subject to the same rigorous technical review procedure.

The resource of some 25,000 practicing plastics engineers has made SPE the largest organization of its type in plastics worldwide. Further information is available from the Society at 14 Fairfield Drive, Brookfield Center, Connecticut 06805.

Robert D. Forger
Executive Director
Society of Plastics Engineers

Preface

Failure has been a serious problem in the use of materials since the beginning of recorded history. To a large extent, the development of materials science and engineering has resulted because of serious failures. This is no less true for the newer materials such as polymeric ones. Unfortunately, such failures will become even more important as the number of critical engineering applications of polymers increases. The problem is especially difficult: polymeric materials are sensitive to processing, and affected by the environment, time, and temperature often in an "unpredictable" manner.

The present book was organized with this situation in mind. Although at first we thought of writing the whole book ourselves, the breadth of this area made the task very difficult. Instead, we decided to invite experts to contribute. We are very pleased at the caliber of those who accepted the challenge. They come from three continents. We believe this volume will give the practicing engineer as well as the researcher insight into each of the pertinent areas. To a considerable extent, the result is a forum for presenting relatively new, consistent, and exciting approaches to the entire field of failure phenomena.

An attempt has been made to make the chapters as uniform as possible from the point of view of symbols, terminology and units in particular. Each of us was frustrated many times perusing proceedings of conferences, even exciting ones, when the same quantity was discussed under different names by different authors, with no connections between contributions. Here, our authors have mutually read the contributions made before submitting the final versions of their respective chapters. Referees have also paid attention to possible repetitions, introduction of cross references, and uniformity. At the same time, we wanted to preserve the intent of individual writers. A delicate task of reviewing the entire volume, taking into account these factors, has been performed by David P. Turner of Drexel University. It is thanks to these efforts that we have a volume with much more coherence than the average collective work.

In addition to those named above, we would like to thank Mr. Joachim Spencker, the Publisher, and also Dr. Edmund H. Immergut, Consulting Editor for Hanser, for their initiative, as well as for their cheerfully given help and advice. Working with them and with our large international team of authors and experts has been a rare pleasure.

Failure, to some extent, is the dark side of engineering. We hope this book will help the polymer community deal successfully with these problems in a positive and satisfying manner. Putting together what we already know ought to lead to a coherent view of failure. Such a view would greatly aid the prevention of future unpredictable failures of polymeric materials.

Witold Brostow and Roger D. Corneliussen
Philadelphia, January 1986

Acknowledgments

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List of Important Symbols

The quantities listed here are those recommended by international learned unions and/or used by the majority of the authors.

a	area
$a_i \ (i=1, 2, \ldots, N)$	constants
$a(t)$	acceleration
a_T	shift factor
e_s	surface energy
f	frequency
h	height; depth; the Planck constant
k	the Boltzmann constant
l	length
l_{max}	length at maximum deflection
l_0	original length
l_f	final length
m	mass
n	refractive index
n^*	number of defects
$\bar{r}$	stress vector; polar coordinate
r	degree of polymerization; radius
s	specific shear strength; cluster size
t	time
t^*, t_R, t_i, etc.	relaxation time
v	specific volume; velocity
v_c	craze velocity
v^*	characteristic volume
w	work; weight
W_v	wear volume
x, y, z	Cartesian coordinates
A	area
A_i	coefficients
B_i	coefficients
C_i	coefficients
$D(t)$	tensile creep compliance
D_m^*	maximum value of dynamic relaxation
E	the Young modulus = modulus of elasticity
$E(t)$	tensile stress relaxation modulus
F	force
F^+	maximum relaxation rate
G	the Gibbs function; names "free energy" or "free enthalpy" should not be used
G_{I_i}	interfacial fracture energy
G_s	shear modulus
G_s'	storage modulus
G_s''	loss modulus
H	enthalpy
H'	hardness; yield pressure
I_R	intermittant relaxation
J	Joule (unit)
J	J-integral
J_0	dielectric constant at limiting frequency

$J(t)$	shear compliance
K	degree Kelvin
K_c	critical stress intensity factor
K_{Ic}	plane strain fracture toughness
K_I	stress intensity factor
K_t	stress concentration factor
L	load
L_i	contour length of *i*-th polymer segment
L_e	end-to-end distance of a segment
L_σ	stress transfer length
N_A	the Avogadro number
P	pressure
R	gas constant
S	entropy
T	thermodynamic (=absolute) temperature
T_g	glass transition temperature
U	energy
V	volume
W	toughness; wear
α	isobaric expansivity (also called cubic or thermal expansion coefficient; the first name given is recommended)
α'	relaxation parameter
α^*	geometric factor; material constant
β	polarizability
β'	coefficient
γ	shear strain
$\tan \delta$	loss tangent
$\tan \delta_{max}$	maximum loss tangent
γ	surface tension
ε	linear strain = relative elongation = engineering strain
ε_a	engineering strain of the amorphous region
ε_i	permittivity
ε'	permittivity
ε''	dielectric loss factor
ε^*	complex permittivity
ε_0	permittivity of vacuum = electric constant
ε_r	relative permittivity
η	viscosity
κ_T	isothermal compressibility
λ	wavelength; uniaxial deformation
μ	dipole moment; friction coefficient
$\mu(t)$	absorbed energy
ν	the Poisson ratio
ρ	mass density (not number density)
ρ_{cl}	cross-link density
σ	engineering stress
σ_0	initial stress at time $t=0$
σ_t	true stress
τ	shear stress
ω	circular frequency

Contents