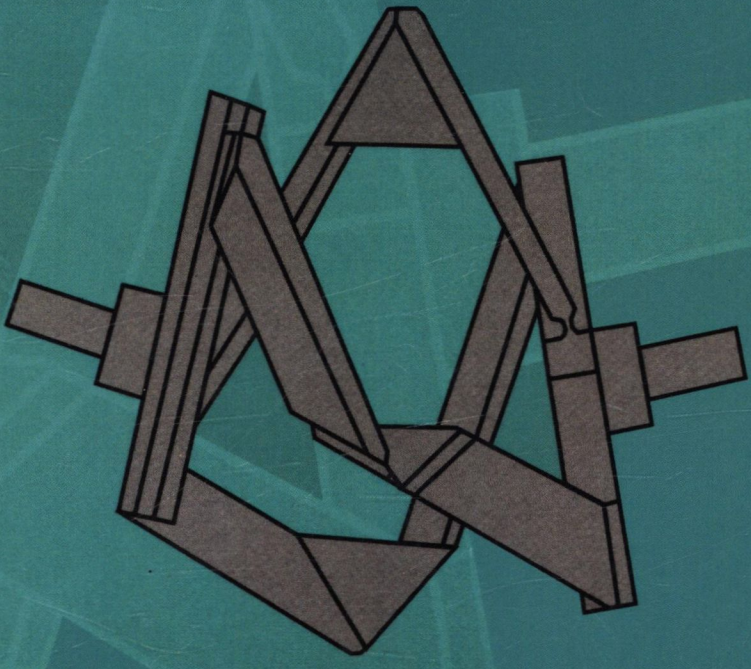
Engineering with Polymers

Peter C. Powell and
A. Jan Ingen Housz



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Engineering with Polymers

SECOND EDITION

Peter C. Powell and A. Jan Ingen Housz

Plastics and rubber materials, or polymers, are increasingly the first choice of engineers where reliable cost-effective performance and safety are essential. Already the volume of polymers used in the Western economy well exceeds that of metals. Today's engineers must therefore have a thorough grounding in the properties and applications of polymeric materials: the first edition of this book in 1983 was one of the first general textbooks on engineering with polymers. This is a new, substantially revised and enlarged edition.

The first chapters explain what polymers are, how they behave and how articles are made from them. Next, the authors show how the standard engineering techniques of stress analysis, structures, fluid mechanics and heat transfer and design can be adopted or adapted to cover plastics and rubber materials. The penultimate chapter deals with interactions between processing and properties. The final new chapter describes a variety of approaches to design of plastics products ranging from practical advice to the use or further development of theoretical principles backed up by examples and case-studies. An important feature of the book is the many problems which readers can use to test and develop their understanding; full answers to these problems are provided.

Peter C. Powell is Professor of Engineering Design with Plastics and Director of Education of the Faculty of Mechanical Engineering at the University of Twente, Enschede, the Netherlands. He is a committed and enthusiastic teacher. His main research interests are in design with plastics and fibre reinforced polymer composites, and in education and training strategies.

Jan Ingen Housz retired recently as a Senior Lecturer in the Faculty of Mechanical Engineering at the University of Twente. He has been active in spreading knowledge of engineering with polymers in industry and has chaired working groups on standardization and design of plastics structures.

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The cover picture shows an impression of a one-piece universal joint coupling between two axles based on twelve integral hinges as functional elements, compare problem 4 in section 10.2 (courtesy Philips C.C.P.).

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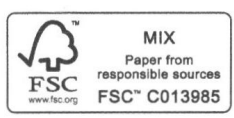

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Engineering with Polymers

Preface to second edition

In the 15 years since the appearance of the first edition of *Engineering with Polymers* there have been many changes relevant to the objectives stated in that preface. These changes include:

1. A substantial increase in the amount of teaching of polymers within the university engineering curriculum up to about graduate level, particularly in mechanical engineering courses, with reference to the teaching of materials behaviour, mechanics of polymers and polymer–fibre composites, design of polymer-based products, and (perhaps to a lesser extent) teaching of polymer melt fluid mechanics and heat transfer and the design of polymer melt processing machinery.
2. An increasing recognition of the contribution which solid-body mechanics can make to the design of cost-effective products within specialist courses in polymer technology up to about graduate level.
3. The number of books on polymers has perhaps doubled over the past 15 years, running now to some 3000 or so, many of them being extremely specialist in narrow areas and properly so. The number of titles aiming to provide an overview relevant to the general needs of engineering students remains much smaller, just a few.

It follows then that there has been emerging an increasing number of students with an improved elementary understanding of polymer properties and processing and the relevance of this knowledge to the design of products to be made from polymers. Many of these graduates have already begun to make a substantial contribution to the more successful use of polymers as their careers develop. This will doubtless continue. The meaningful questions these graduates raise, and the value of their mechanical engineering background skills, contribute directly to the expansion of the use of polymers within the polymer and polymer-using industries. It is hoped that the first edition of this book, and similar titles, have made some modest contribution towards these positive developments.

With such expansion of activity and publications, the question naturally arises: why a second edition of *Engineering with Polymers*?

We recognize that the academic scene continues to change and develop. Within the mechanical engineering curriculum we recognize that polymers were being introduced in a usable way much earlier than 15 years ago. It is encouraging that there is now scope for the incorporation within the engineering syllabus of more material and in different ways compared with 15 years ago. In particular the increasing emphasis on design activities and learning-by-doing provide new challenges. The then rather new feature in the first edition of introducing additional learning material through the solving of problems has become much more widely accepted.

Our new edition naturally builds on the old edition. Large parts of the first edition remain, with some amendments to correct mistakes, to bring up-to-date, and to include a few more problems which experience has suggested will enhance the building of understanding. In retaining the overview of polymer engineering, we recognize that much of the basics was rightly stated.

The bringing up-to-date is particularly noticeable in Chapter 9, where the influence of processing on properties and product behaviour has been substantially revised in the light of recent research. Chapter 7 on fibre–polymer composites has been considerably extended, in recognition that the mechanics appeals strongly to mechanical engineers as a natural extension to the well-known conventional solid-body mechanics for isotropic materials, and the concepts pervade much of the behaviour of manufactured polymer products, whether composites or just polymers with a measure of molecular orientation.

We see the first nine chapters as providing a minimum literacy in polymer background for a mechanical engineer. Chapter 10 is a completely new addition to the book. In this chapter we introduce various tools for the designer. Some of these are substantially practical. Some of them introduce more advanced material relevant to specific issues, on the basis that if readers can follow them, they can develop a similar level of reasoning in other topics: to cover all possible developments in this depth is impossible in one modest volume. We have had to make a selection. Some of the chapter provides material which suggests how it may be used in the design context, starting with incomplete design requirements and using the information in the rest of the book to suggest what sorts of questions need to be asked and what answers are needed before going on to any design calculations and reaching conclusions of practical interest.

We are well aware that there has been an explosion in the use of computers, both in academia and in industry; this development makes a substantial contribution to product design in polymers as well as in most other technologies. We have, however, resisted a temptation to cast this book in the form of numerical modelling of engineering with polymers. We are reluctant to put the emphasis on the use of numerical methods before the basic physical

principles are understood. What we have tried to do is to present a coherent account of the physics and engineering of polymers: we hope that the theoretical analysis is clear and provides a framework which can be used to solve simple problems within the scope of the book. We are convinced that computers can then be used to make more detailed investigations of the phenomena described in each chapter of this book and to solve engineering problems with polymers. We are also convinced by our colleagues who do so, that others can successfully translate the principles into numerical techniques far better than we can.

The first edition was written by Peter Powell as sole author, although he enjoyed support from a large number of colleagues and constructive critics during that time and afterwards. He has since gained further experience in teaching the subject material of the book within the UK (especially at Imperial College, London, at the Manchester Metropolitan University and as Director of the UK Integrated Graduate Development Scheme in Polymer Engineering at Manchester) and also outside the UK in continental Europe, North Africa, and North and South America.

During the past 10 years Peter Powell has enjoyed increasing interaction with the University of Twente, where Jan Ingen Housz had developed courses on the same subjects from his position on the mainland of Europe; at first by giving invited lectures on short courses at Twente. In 1991 Peter Powell moved to Twente to develop full-time a new Chair in Engineering Design in Plastics within the Mechanical Engineering department at Twente, and from September 1991 they collaborated not least in the preparation of this second edition. This collaboration, together with exposure to and direct involvement with the Dutch approach to design teaching, project-centred learning and polymer engineering education, has indeed been most stimulating and fruitful.

We both acknowledge our indebtedness to many colleagues (in particular Remko Akkerman, Durk van Dijk, Kaspar Jansen and Peter Reed) who have suggested analysis and examples and to many students who have worked through early versions and who have always courteously suggested revisions and corrections which have made for greater clarity. From them we have learned much.

Peter C. Powell
A. Jan Ingen Housz

Enschede, August 1997

Preface to first edition

Products made from plastics and rubber materials are based on polymers, and contribute strongly to the national economy not least in terms of performance, reliability, cost-effectiveness and high added value. Among the many reasons why polymers are widely used, two stand out. First, polymers operating in a variety of environments have useful ranges of deformability and durability which can be exploited by careful design. Secondly, polymers can often readily, rapidly and at an acceptable (low) cost be transformed into usable products having complicated shapes and reproducible dimensions. Moreover the volume of polymers used in the Western economy already exceeds that of metals. It therefore follows that engineers come into contact with polymers in terms of designing, making or using products.

Unfortunately most engineers who graduated in the early 1980s or before still know little about polymers and are not therefore well equipped (from their education alone) to exploit them within the broad range of available materials. Universities, polytechnics and colleges are aware of the need for some polymer content within undergraduate engineering courses. Most of this teaching should be broadly based and devolve on existing portfolios of standard engineering skills rather than provide an advanced course for polymer specialists. A modest number already meet this need, the remainder seek to do so.

There appears to be no consensus of what might constitute a minimum useful knowledge of engineering with polymers within a mechanical engineering degree course. And, although there are some 200 titles on polymers, no one book seems to cover the field at the right level, although one or two provide useful guidance. Neither has there as yet emerged a preferred way of teaching this topic – not that this is at all surprising.

In the long term it would be very satisfactory if the main concepts of engineering with polymers pervaded undergraduate courses, taking their natural place alongside other established materials in illustrating the themes of engineering science, technology, design and practice. Achievement of this

on a national basis will take considerable time and effort. However, in many institutions it seems more practicable to offer a self-contained lecture course in polymer engineering to begin with. The success of such an approach can then be judged not least by the rate of pervasion of polymers into the degree course, probably via design and project work. Such an introductory lecture course has the advantage of requiring only modest resources.

The material in this book has been developed over many years and is a slightly extended version of a well supported 20 lecture course offered to final-year undergraduate students in the Mechanical Engineering Department at Imperial College, London. The book outlines and illustrates the main principles of engineering with polymers whilst recognizing the superficiality of a broad but shallow and largely descriptive approach and the intellectual rigour of advanced theoretical analysis. Furthermore, where practicable the book introduces skills which permit a simplified quantitative analysis of the behaviour of polymers during processing and in use.

Within the constraints of time and space, the coverage must inevitably be selective rather than comprehensive. It has been assumed that the student or engineer picking up this book is familiar with the basic principles of engineering. On mechanics of isotropic solids, this includes Hooke's law in two to three dimensions, plane stress, plane strain and constraint, transformation of axes for stress and strain, yield criteria and the basic concept of mode I linear elastic fracture mechanics. The simple micromechanics of unidirectionally aligned strong fibres in a weak flexible matrix are revised but briefly. On the transport side, the reader will be familiar with the isothermal developed one-dimensional laminar flow of incompressible Newtonian fluids within pipes and between parallel plates, and with steady and non-steady heat conduction within isotropic continua. This book recognizes that many students of engineering currently have little or no polymer background and respond without enthusiasm to a chemistry-based materials approach.

The contents of this book embrace four main themes. The first four chapters introduce the language, terminology and technology of polymers. After an introduction to the relevant polymer physics there is an account of the general properties of polymers and the need for compounds or recipes on which commercial plastics and rubber materials are based. The first section of the book ends with a description in engineering terms of the main methods used to make articles from polymers.

The second section, Chapters 5 and 6, gives an account of the stiffness, strength and fracture of nominally isotropic polymers, and describes how these properties can depend markedly on the duration or rate of loading, on temperature and on the nature of the environment. The design procedures for avoiding load-bearing failure are standard; the values of properties may seem strange – moduli in the range 10^6 to $10^9\,N/m^2$, design stresses of $10\,MN/m^2$ and fracture toughnesses of the order of $1\,MN/m^{3/2}$. Acceptable strains up to 1% are commonplace in plastics, and can frequently be more

than an order of magnitude higher in rubber. For reasons of space and with great regret, these two chapters do not discuss procedures for designing rubber components which operate under cyclic loading or at very large strain (where large strain non-linear elasticity is required).

The third section recognizes the growing importance of materials such as fibre-reinforced plastics and rubbers that have properties which can vary dramatically according to the direction in which they are measured. Chapter 7 outlines the intriguing properties of panels of these materials and introduces elementary design methods for avoiding failure. The analysis here inevitably looks more complicated than that used for isotropic polymers but, beneath the disguise of some algebraic manipulations, the principles are but a modest extension of well known theory. Beyond fibre-reinforced systems, this chapter provides a basis for the exploitation of molecular orientation of unreinforced polymers in plastics packaging, and helps to develop an understanding of the causes of some faults in plastic products arising during manufacture.

The final section, Chapters 8 and 9, describes the thermal and flow properties of polymer melts relevant to the main melt processing methods. This leads to the development of simple fluid mechanics and heat transfer, to predict relationships between pressure and output rate, and energy requirements, both important in sizing equipment to achieve cost-effective production. An account is also given of the common effects of processing on the properties of polymeric articles.

Students welcome opportunities to test their understanding of the principles of a subject, not least where these relate to examination practice or professional practice. Problems are an integral part of this book, not just tacked on to the end of each chapter. Some of the early problems in each group are simple algebraic ones included to give a 'feel' for the orders of magnitude of those quantities such as forces, pressures, deformations, deflections, flow rates and cooling times commonly encountered in designing with polymers. Others involve modest development of the material in the text to provide additional insight into problems which arise in polymer engineering and technology. There is a rather larger number of problems here than could reasonably be associated with most 20 lecture courses.

A further selection of problems could have been devised for solution using computing or numerical techniques, for example in designing with composites where the level of algebra is fairly trivial but where repeated manual calculations are extremely tedious and error-prone. This approach relies on the basic principles, however, and the line has been drawn there. Those who wish to explore the application of modern methods of calculation would find ample opportunities when engineering with polymers.

There are of course many ways of approaching the teaching of the topics mentioned in this book. The self-contained single lecture course represents one proven approach within which a reasonably self-consistent body of

material can be covered; this presents challenges recognized by both the teacher and the student. There is of course the attendant risk in this tidy approach that the subject of engineering with polymers is seen to be compartmentalized and set aside from other topics on which it depends or to which it can contribute. Design studies and project work can show this rather too clearly – and do provide opportunities for integrating the main themes of engineering. Another proven approach has the objective of integrating polymers within the engineering curriculum, throughout the degree course. Provided the polymer aspects of the syllabus are actually covered, this has much to commend it. Some members of staff teaching topics such as mechanics of materials or fluid mechanics have a well developed background in such established materials as steel, concrete, water and air, and may feel, understandably, less confident about teaching aspects of engineering with polymers, even though they realize that the threshold of essential polymer knowledge in their field is often quite modest.

However, whatever the style of teaching, I hope that my colleagues in academia, who have an important role in polymer engineering, will find here a useful source of material which they can adapt or develop to meet their perceptions of local needs.

The scope of engineering with polymers is vast. This book is small, and it is apparent that its contents reflect a wish to integrate polymer topics within several standard engineering techniques, especially mechanics of solids and fluid mechanics. It would have been possible to provide other slants embracing such important aspects as machinery operation, manufacturing systems and control, but these have not been pursued. The emphasis has been on the principles which should be of lasting value. Current practice and technology change rapidly – practical details including costings can be readily grasped and developed for specific industries when the reader needs them, and for these reasons are excluded. But, even where topics have been included as central to the principles of engineering with polymers, limitations of space and teaching time have dictated worthy omissions. These include the behaviour of rubber and fibre–polymer composites under cyclic loading, designing rubber products which operate at large strains, joints and load transfer into polymer structures, thermal stresses and interactions between heat and momentum transfer.

I would like to thank Professor Arthur Birley of Loughborough University and Professor Graham Ellison of Bristol University for their helpful advice and comments on drafts of this book and for encouraging me to complete the project. Dr Roger Fenner kindly commented on Chapter 8. I am grateful to Professor Gordon Williams of Imperial College for stimulating and fruitful discussions on the teaching of engineering with polymers to mechanical engineering students in both undergraduate and postgraduate courses, and for the opportunity to develop these ideas into their present form. I would like to thank successive years of students at Imperial College

and elsewhere who have responded generously with helpful feedback. I am indebted to Mrs Liz Hall who so efficiently transformed my manuscripts into a magnificent typescript; her courtesy, sense of humour and impeccable professionalism provided a source of inspiration and encouragement which I greatly value.

Peter C. Powell
Bristol 1983

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