Plastics Product Design Engineering Handbook

SECOND EDITION

Sidney Levy
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Plastics Product Design Engineering HANDBOOK

Second Edition

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Preface to the Second Edition

This new edition of the text has been expanded to include topics related to computer usage in the design of plastics products. In Chapter 5 the subject of finite element analysis is introduced as a new powerful tool which is rapidly gaining acceptance as a means of evaluating structures made of plastics materials. Reference is made to several of the widely used programs that can be used in this design approach.

There is a completely new Chapter 10 added on computer-assisted design and computer-assisted manufacturing. This fits with the greatly increased use of the CAD/CAM approach to plastics product design. Especially in the molded plastics parts, with emphasis on injection molding, the computer-assisted design techniques are the preferred methods for doing product design. The advantages in time, accuracy, and predictability of performance are substantial and, with increasingly sophisticated software and better data, the computer-assisted methods will be even more effective.

In the revised Chapter 11 there is material added to call attention to the importance of material and process interaction when using the computer-assisted design methods. At present this is an area where the lack of data poses a limitation to the application of CAD/CAM.

Many of the minor typos and errors which crept into the text of the first edition have been corrected and the problems reworked to correct numerical errors.

We wish to thank Scott Collins for his valuable assistance in obtaining the CAD/CAM chapter by Greg P. Terek which adds a great deal to the scope of the text. My coauthor J. Harry DuBois was incapacitated by a stroke during the revision of the book and we hope for his rapid recovery. We hope that the text will continue to be valuable to all those engaged in the interesting, if somewhat complex, activity of plastics product design.

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Preface to the First Edition

This is the first book directed to the solution of the problems of the plastics product designer that treats the subject from fundamentals to specifics with the applicable mathematics. Material economy developments necessitate a most rigorous approach to product design since materials costs have risen greatly and the user performance expectations have enlarged tremendously.

Plastics are materials that behave in a complex manner when subjected to physical and environmental stresses. The intuitive design approaches used by many designers to overcome the lack of knowledge of the performance characteristics of these materials has led to a combination of over-design and product failures. The approach here is to review the fundamentals of material structures and provide a background for an analytic design procedure for plastics products. This is carried out in the area of structural loads, cyclical loads, electrical field exposure, environmental exposure, and the other types of in-use exposure to which plastics components may be exposed.

Using the approach developed from the fundamentals, the text describes the design of plastics products in a variety of different fields and illustrates this with specific examples with solutions. Some examples are computer assisted to illustrate the method of arriving at a safe, effective, and economical design. The interplay of the various elements in the design such as aesthetics, customer acceptance, environmental influences, and the effects of the manufacturing processes on design and product performance is examined and a procedure given for making trade-offs for maximum utility and economy.

The need and use of product and material testing as part of the design process is covered. The relationship between the level of risk involved in the product use and the testing philosophy is explored so that an economical level of testing is arrived at consistent with successful usage. The role of the design engineer in the total product development process is also part of the discussion since it affects the specific responsibility of the designer in his job.

The authors believe that the text will aid in the design process and in the training of design engineers to work with plastics. Plastics are the most versatile of the engineering materials and we feel that a better understanding of the strength and the limitations of the materials will lead to highly successful and economical applications for the plastics.

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Introduction

Plastics have become increasingly important in the products used in our society, ranging from housing to packaging, transportation, business machines and especially in medicine and health products. Designing plastic parts for this wide range of uses has become a major activity for designers, architects, engineers, and others who are concerned with product development.

Because plastics are unique materials with a broad range of properties they are adaptable to a variety of uses. The uniqueness of plastics stems from their physical characteristics which are as different from metals, glasses, and ceramics as these materials are different from each other. One major concern is the design of structures to take loads. Metals as well as the other materials are assumed to respond elastically and to recover completely their original shape after the load is removed. Based on this simple fact, extensive literature on applied mechanics of materials has been developed to enable designers to predict accurately the performance of structures under load. Many engineers depend on such texts as Timoshenko's *Strength of Materials* as a guide to the performance of structures. Using this as a guide, generations of engineers have designed economical and safe structural parts. Unfortunately, these design principles must be modified when designing with plastics since they do not respond elastically to stress and undergo permanent deformation with sustained loading. Plastics also have a low stiffness compared with other materials; they cover a range of stiffness of six orders of magnitude and exhibit a high dependency of physical properties on temperature. It is obvious therefore that the structural design of plastics parts requires a different design approach.

This is also true in other areas such as thermal design, environmental design, and geometric design of parts where the unique properties of plastics require a different design approach. This book is intended to show how plastics are different from other engineering materials, and to develop the relationships necessary to design intelligently with these materials. The book proceeds from a basic understanding of how the physical structure of these materials differs from other materials and describes how these differences affect their performance under various stresses. It also describes how to use this information in the design of products.

The results of processing the plastic materials affect their performance profoundly. The basic information of plastics structures is given to enable the designer to predict the performance of his product within the limitations of the processing. The unique effects of the environment on plastics are examined so that the designer can design a product for a lifetime exposed to the "use" environment.

The text is divided into four sections. The early chapters cover the physical structure and molecular configuration of the polymer materials which are the basic materials of plastics. It shows how the microstructure of the materials leads to the observed physical and chemical properties and develops the basic relationships between the response of the materials and the applied stresses.

The next section is concerned with developing the mathematical relationships and formulas to describe the response of plastics members to static and dynamic loads. Specific design situations are analyzed and the methods of problem solving developed. Because of the complex nature of the materials, solutions are frequently not possible. The use of graphical solutions, curve-fitting techniques, and computer-assisted design techniques are explored.

The Second Edition has added a section to Chapter 5 describing the finite element concept and how it can be applied to the design of plastics structures. The limitation of the program for the nonlinear elastic response of polymer-based materials is pointed out and several useful finite element programs are suggested for design use.

The new Chapter 10 has been added to cover the use of computer-assisted methods used in design. It also includes the use of the computers in manufacturing since data from the product design can be used to generate the tooling required for production. The new chapter reflects the widespread and increasing use of the computer in the development of new products—especially in the plastics field.

The section that follows covers the geometrical considerations in design, with particular emphasis on the methods of improving the effective stiffness of plastics structures and of compensating for the nonlinear stress-strain behavior of the materials. The manufacturing processes impose additional restrictions on design and the way in which these affect the design process is described. The processes for manufacture allow freedom in design as well. They permit the extension of functional design concepts to a degree not possible with other materials by the combination of functions in one part which, in other materials, might require several parts.

The interaction between the product and process becomes an important factor in the use of computer-assisted design and manufacturing. The material added to the new Chapter 11 shows how the product-process interaction affects computer-assisted design and how the limitations can be compensated for while adequate software is developed to include these factors in the computer-assisted design procedure.

The next section covers the effect of the end-use environment on product performance so as to permit the design of a product for a reasonable lifetime with realistic economics. Included is the design engineer's involvement in testing and evaluating, as well as a definition of the specific function of the part, to prevent its abuse. The involvement of the product designer is such that his responsibility extends to having the product serve the end-user effectively, and the text indicates the extent and means whereby he can do this.

This book is written at a time when the nature of plastics products and the applications of plastics have been drastically altered. Plastics are no longer inexpensive materials to be substituted for other materials with little regard for their efficient usage. The energy and materials shortages in the raw materials to make plastics preclude any such possibility. Plastics products must be efficiently designed using rational methods of determining part sizes to meet the anticipated loads and other stresses. In addition, the environment of the design process has changed. The legal strictures on design for safe use, the environmental pressure caused by the existence of large numbers of plastics products such as packages, and the direct legal responsibility of the designer for the safety and utility of a product creates additional problems for the plastics product designer. It is hoped that this text will provide a tool for the efficient use of plastics materials in the design of safe, economical products. The use of functional design concepts that employ the unique properties of plastics materials can make possible a large variety of new and successful areas of application. The concluding chapter projects some of these areas.

This book is the outgrowth of lecture courses in plastics product design, a number of articles on specific areas of plastics engineering design, many years of combined experience of the authors in bringing plastics products to the market, and thirty years' experience with texts on plastics and the editing of journals. The authors hope that it will be helpful to designers in utilizing plastics and polymer-based materials, those complex and interesting materials that nature used long before man to create the interesting and beautiful forms of nature, including man himself.

Acknowledgments

The authors gratefully acknowledge the assistance and encouragement of Professor Herman Mark, Professor A. G. H. Dietz and Harry S. Katz for their helpful suggestions and review of the manuscript. Permission to reproduce data from many important texts by leading authors is greatly appreciated. We also thank the many material and machinery makers who supplied illustrations for this book. Charlotte A. Levy has been a tremendous help in typing and preparing the copy.

Contents

Chapter 1

Polymer Structure and Physical Properties

Each material that we come in contact with has its own special properties. Some are hard while others are soft. Some things are heavy and others are light. Some materials feel warm while others feel cold. These subjective properties are related to the intrinsic physical properties of material which can be defined and measured on an appropriate scale. Some of these properties are listed in Table 1-1.

The properties are related to the atomic and molecular structure of the materials. For example, we could compare iron, glass, salt, and polyethylene plastics. They represent a metallic crystalline solid, a vitrified amorphous ceramic, a nonmetallic crystalline solid, and an amorphous high polymer. Figures 1-1, 1-2, 1-3, and 1-4 show the structures in schematic form for each of these materials.

Metallic crystalline solids such as iron, nickel, or aluminum are hard stable materials. They conduct electricity and heat. They range in density from 2 g/cc up to the most dense solids known. Objects made from metallic crystalline materials respond to forces or loads applied in an elastic manner, that is, they deform in proportion to the applied force and recover to their original dimension when the distorting force is removed. When the applied force exceeds a characteristic value, the elastic limit, the material flows and the part deforms permanently. After the deformation, however, the part still behaves elastically at loads below the elastic limit.

The ductility, the extent of permanent deformation possible, varies widely between different metals and when the ductile limit is exceeded, the material becomes brittle and breaks.

Glassy materials exhibit widely different properties. They conduct heat well but are electrical nonconductors. They are generally transparent to light and other electromagnetic radiation. Their initial

Table 1-1. Physical Properties of Various Materials.

	Steel	Copper	Polyethylene	Phenolic	Glass
Specific gravity	7.8	8.9	0.92	1.3	2.5
Thermal conductivity (Btu/hr/sq ft/°F/in.)	27	200	0.19	0.3	0.7
Thermal expansion (in./in./°C)	8.2	9.8	120	15	5.1
Specific heat	0.1	0.1	0.5	0.4	0.2
Modulus of elasticity	30×10^6	17×10^6	0.15×10^6	10^6	10×10^6
Hardness (Rockwell)	C40	C15	R50	M110	C90
Electrical resistivity	19	2.03	10^{23}	10^{17}	10^{21}

response to applied load is an elastic deformation with complete recovery if the load is applied for relatively short periods of time (hours or days). Under sustained load, they deform permanently even at loads well below the elastic limit. The rate of cold flow or creep is temperature and time dependent as with most materials.

Glassy materials are brittle; they can be deformed elastically by small amounts, generally under 1% and they fracture when the limit is exceeded. They are very sensitive to shock (high rate loading) and are generally considered poor structural materials despite their high strength. While the physical properties of metals are affected by the processes used in their manufacture, glassy materials are much more

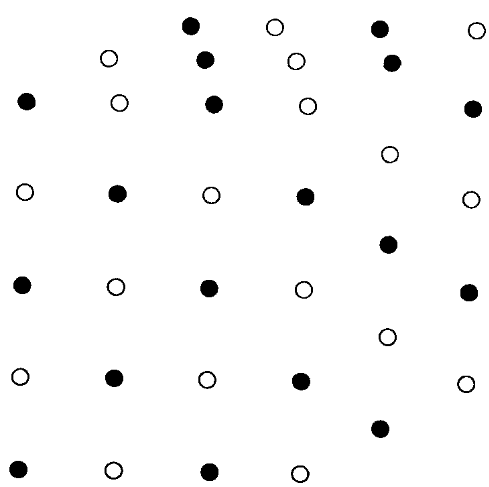

Fig. 1-1. General crystalline structure of an ionic solid-like substance.

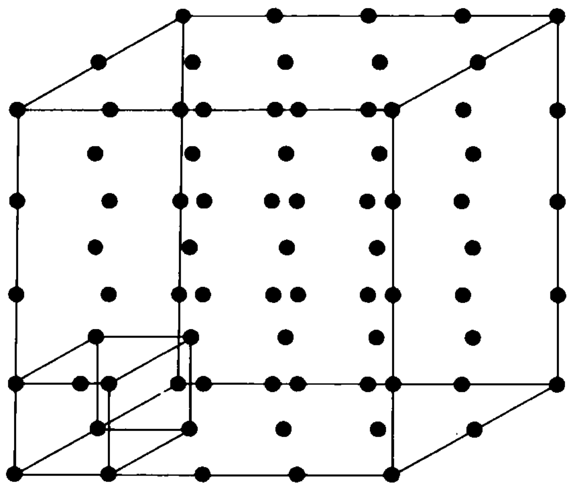

Fig. 1-2. Crystalline structure of a metallic item.

sensitive to processing effects. Stresses induced in glass objects during working can cause sudden failure even without external loading. These stresses are induced during cooling from the melt.

Nonmetallic (ionic) crystalline solids such as salt are nonconductors of electricity and fair conductors of heat. They vary widely in

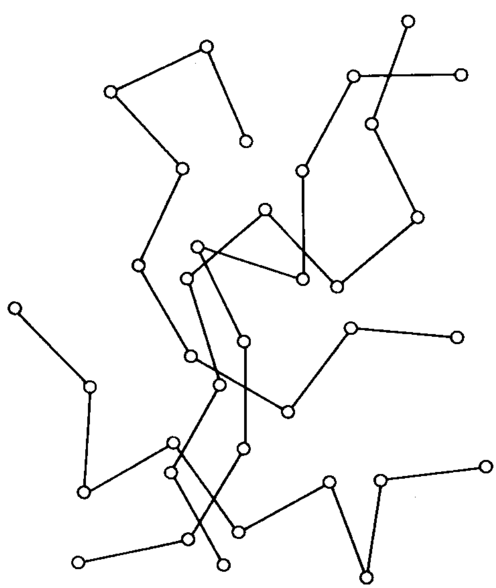

Fig. 1-3. Structure of a vitrified amorphous ceramic.

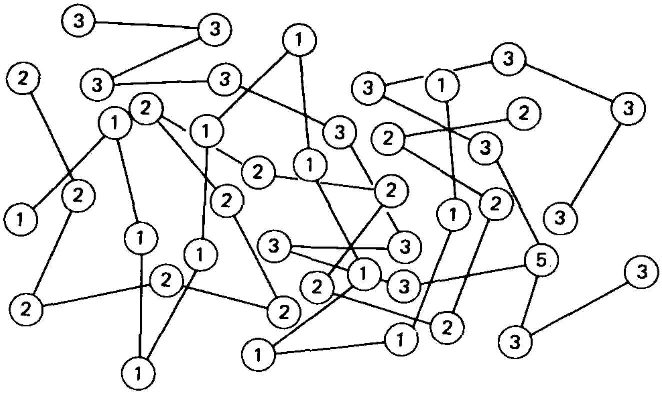

Fig. 1-4. Structure of an amorphous high polymer. Numerals facilitate following the individual chains.

density but are generally in the less extreme ranges from about 1.0–5.0. They differ from the metallic crystals in lacking free electrons which provide both electrical conductivity and high thermal conductivity. The crystalline solids deform elastically under applied forces and, depending on the type of crystal structure, can undergo brittle fracture or ductile deformation at force levels above the elaslic limit. They generally are hard materials with a high modulus of elasticity (force per unit of deformation). The ionic crystals are frequently transparent and often are colored. Polycrystalline ceramics such as densified alumina are strong materials although they do undergo brittle failure. They are frequently capable of absorbing large (high rate) shock loads. They exhibit a low order of deformation under sustained load and are among the most stable materials known, even at high temperatures.

Polymeric (plastics) materials such as polyethylene have a wide range of physical properties. Some are transparent and most pass electromagnetic radiation over a wide spectral range. The range of elastic modulus for plastics unreinforced by other materials is low, ranging from slightly over 1,000,000 psi down to 10 psi. Plastics are nonconductors of electricity and poor-to-fair conductors of heat. The structure of polymers combines some glassy structure, some non-metallic crystalline structure, and some amorphous structure and their response to applied forces is quite complex. For short duration (1/1000 seconds) loading, many plastics respond elastically or viscoelastically. This elastic response is damped, and the deformation