Thermoplastics

Properties and Design

A Collective Work Produced by

Imperial Chemical Industries Limited,
Plastics Division

Edited by

R. M. Ogorkiewicz

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Foreword

That there is a growing use of plastics in applications that demand careful design is undeniable; that this growth rate is as high as the intrinsic nature of plastics warrants is questionable. A major cause of limited exploitation is lack of confidence, the confidence that designers need to have in the capabilities and limitations of plastics as a class of materials, in their interpretation of design data and in their selection of the most suitable type and grade.

A major source of design data is the raw material manufacturer and of recent years there has been a massive, and perhaps sometimes bewildering, output. Data alone, however, are not enough. They often inspire in the users only the unwarranted confidence of those blinded by science. We believe not only that a clear understanding of the properties of plastics is essential to ensure that design data are relevant, but also that this understanding must be backed up by knowledge of how to apply these data to resolve problems in a cost-effective manner.

This book sets out to provide an understanding of the principles underlying the properties of plastics, and also of the design problems associated with plastics in a way that will, I believe, appeal to designers and engineers. The many practical illustrations are taken largely from that range of plastics with which the authors are most familiar.

C. Vowles
Chairman, ICI Plastics Division

Preface

The object of this book is to provide a general understanding of the properties of thermoplastics, to show methods of characterizing them and to indicate how the data which are now becoming available can be used in the design of thermoplastics articles. Of the various properties considered in the book, the mechanical ones are given most attention, because they govern more frequently than others the more exacting applications of thermoplastics. Attention is further centred on the type of information which is available, or required, about the mechanical, as well as other, properties of thermoplastics, rather than the data themselves.

A comprehensive body of data on a representative range of thermoplastics has in fact already been published under the title *Engineering Properties of Thermoplastics*. This collective work was produced by much the same team as that which prepared the current book and I had the privilege of editing it, as well as contributing to it, as I have had of editing the present one. The reception accorded to it encouraged further work on the subject but it was not considered appropriate to produce a second book along the same lines as the first. Reasons for this included the fact that significant advances had taken place in the general understanding of the properties and applications of thermoplastics. Moreover, although a considerable amount of additional information has been produced, it was still not sufficiently complete to warrant the preparation of another book centred on data. It was decided, therefore, to cover, in more general terms, progress made over the whole field of work on the properties of thermoplastics related to design.

As a result, the present work consists of twelve chapters, the first two of which provide a broad background to the use of thermoplastics and a general introduction to their properties. The following nine chapters describe the current state of knowledge of the different facets of the mechanical and other characteristics of thermoplastics. Thus, they cover, one by one, deformational behaviour, long-term durability, short-term strength and impact behaviour, various factors affecting mechanical properties, electrical, thermal and various other physical and chemical properties as well as processing properties and methods. The last chapter describes the use of mechanical design data and presents a number of case studies.

The author, or authors, of each chapter are specialists in the subject or have been closely connected with it. Each chapter contains illustrations of the way in which the different properties of thermoplastics can be characterized or of the way in which data on them can be put to practical, design purposes. Each chapter also includes a list of references or a list of publications recommended for further reading.

London 1973

R. M. OGORKIEWICZ

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Introduction

by P. C. Powell

1.1 GENERAL

In contrast with the appreciation of ferrous metals, glass and wood as engineering materials, the appreciation of even the established plastics is less well developed. This book seeks to improve that appreciation by providing some knowledge of the structure and properties of plastics, and by discussing the presentation of design data and ways of using these data to predict the performance of plastics products in service. The purpose of this chapter is to present a broad review of the plastics scene, by discussing the general attributes of plastics, how these materials are processed into products, and where these products are used in engineering and other applications. It is hoped that this will provide some perspective to the detailed discussions presented later in the book.

1.1.1 Attributes and Forms

Many different types of plastics are used to make articles of many varied shapes which fulfil functional requirements in a cost-effective manner. There are four basic features which make plastics of direct interest to designers, engineers and students of materials.

(1) The basic physical properties of plastics can be exploited in a wide range of properly designed articles which have the stiffness, toughness and resilience to resist the loads and deformations imposed during normal use.

(2) Plastics can be made which exhibit a variety of particular properties depending on the type of molecular structure in the material. These properties include transparency, low dielectric loss, low permeability to vapours and extreme chemical inertness.

(3) The shape possibilities for plastics articles are extremely wide, ranging from textile fibres (which are outside the scope of this book) through films and coatings to the three-dimensional articles, often of complicated shape, with which this book is mainly concerned.

(4) Finally, plastics can be readily made into products of complicated shape with repeatable dimensions, using efficient mass production techniques which can result in low unit labour changes.

It is a direct consequence of these attributes and forms that there has been a considerable emphasis on the use of plastics to replace existing materials.

More than twenty different plastics are manufactured in commercial quantities. They may be divided into two distinct and important groups: thermoplastics and thermosetting materials. Thermoplastics, which include acrylic, ABS (acrylonitrile butadiene styrene), nylon, polyethylene, polystyrene and PVC (polyvinyl chloride), account for about three-quarters of the annual production of plastics in the U.K. Thermoplastics are normally more flexible and creep rather more than the thermoset materials. Thermoplastics melt to become viscous liquids each time they are heated, and solidify on cooling: in theory this cycle of softening and hardening can be repeated indefinitely. The stability of the thermoplastic in the molten state confers versatility in a wide range of processing operations and the economics of using rework can be considerable. In contrast, a thermosetting material can only be heated and shaped once, during which process it becomes hard, rigid, insoluble and infusible: it cannot subsequently be reworked and the limited stability of the softened material before curing imposes restrictions on the associated processing techniques. Typical thermosetting materials include phenolics, epoxides and unsaturated polyesters.

1.1.2 Plastics and Engineering

Engineering and engineered applications probably account for as much as a quarter of the current annual production of thermoplastics in the U.K. The range of these applications is wide.

Long runs of pipework are extruded from PVC and from the polyolefins (polyethylene and polypropylene in particular); the largest high-density polyethylene pipes are 1·5 m diameter with 52 mm walls. Liquid storage tanks are being manufactured from acrylic, PVC and polyolefin sheet; one of the largest unsupported tanks, welded from polypropylene sheet, holds 45 m^3 and weighs about 2 tonnes empty. Large tanks can also be produced in one piece by other manufacturing methods. Gears range in size from the minute injection-moulded polyacetal precision components used in wrist watches through gears 225 mm pitch circle diameter, 350 mm facewidth and transmitting 50 HP, also injection moulded but in nylon, to the huge 4·25 m diameter, 95 mm facewidth gears monomer cast in nylon. Many motorway bridge bearings, each carrying loads as great as 1000 tonnes, are formed from stainless steel plates which slide over PTFE pads to accommodate movement due to thermal expansion.

There are also load-bearing products engineered from materials, some of which are not usually thought of as 'engineering plastics'. These applications include bottle crates, vegetable trays and other stacking containers injection-moulded from polyolefins; mechanical-handling pallets vacuum-formed from polystyrene and ABS or moulded from polyolefins; and chairs made by a variety of techniques from polypropylene, PVC, ABS, polystyrene, acrylic and polyethylene.

Applications involving critical performance requirements need not, of course, be confined to the realms of mechanical engineering. The use of low-density polyethylene as a dielectric for transatlantic submarine telecommunications cables, and of slot liners made from polyester film to provide electrical insulation and mechanical protection at high running temperatures in the stators of electric motors, are but two examples taken from electrical engineering. However, this book is mainly concerned with thermoplastics in mechanical engineering.

1.1.3 Elements of Design

There are many possible interpretations of the umbrella term 'design'. Certainly one of the tasks of the designer is to ensure that an article will adequately meet service requirements at an acceptable overall cost, and to achieve this the designer must know—from a proper design brief—its purpose. Such a task requires a knowledge and recognition of the strong interactions between such factors as economies, manufacture of raw materials into finished product, properties of materials in end-product form and appropriate selection of materials.

In the early days of the thermoplastics industry the emphasis was on ways of making articles, and factors such as the selection of material and the detailing of product dimensions were almost always relegated to the province of previous experience of similar plastics products and design problems. For many items such an approach is still appropriate today, and the designer draws upon an accumulated wealth of experience: there is after all no need to be erudite for its own sake. Increasingly, however, economic pressures concerning plant investments and product costs dictate a more calculated approach. There is mounting pressure to get the design 'right first time', thus reducing the crippling waste of unnecessary development time, especially in applications where substantial loads have to be carried and where it is essential to use the minimum amount of material commensurate with satisfactory performance.

At this stage a detailed discussion of ways of designing articles is inappropriate. It is more relevant to review the present state of the art in the plastics industry at large, so that the detailed properties of plastics and associated design procedures, to be discussed in the body of this book, can be seen in perspective.

1.2 PLASTICS TECHNOLOGY: EARLY HISTORY AND DEVELOPMENT

1.2.1 Adaptation

It is a feature of the very early days of plastics that the first plastics were closely related to naturally occurring materials, that the delay between chemical discovery and commercial exploitation was great, and that machinery was adapted from existing equipment designed for other classes of materials.

The first thermoplastic, cellulose nitrate, was a horny material produced by digesting wood fibres, paper or rags with nitric acid, and the first items made from this were exhibited in 1862. The chief disadvantage of this material, developed in a plasticized form as 'Celluloid', was its highly inflammable nature. More than half a century was to elapse before a non-flammable variant, cellulose acetate, came into commercial production.

The extrusion process for making spaghetti was known in Italy before 1800: as a discontinuous process it was developed in 1872 to make continuous lengths of rod, bar or sheet from 'Celluloid'. Injection moulding (based on the pressure die casting of metals) was introduced in a crude form in 1878, but both processes were left substantially undeveloped for half a century.

1.2.2 Thermosets

The earliest plastic of real interest to the engineer was the thermosetting resin phenolformaldehyde (PF), introduced as 'Bakelite' in 1907. Uses of PF, processed by compression moulding, were at first restricted to the electrical industry, for making items such as switch bases, terminal blocks, fuse boxes, plugs and sockets. In contrast to the dark opaque colours of PF, aminoplastics based on urea-formaldehyde (UF) introduced in the late 1920s and melamine-formaldehyde (MF) in the early 1930s, offered translucency and a wide range of colours. However, these materials are outside the scope of the book.

1.2.3 Synthesis and Development of Thermoplastics

The modern thermoplastics industry dates from the 1920s when the first processing machinery specifically designed to make articles from thermoplastics on a mass-production scale anticipated the commercial production of materials synthesized from chemical feedstocks rather than from naturally occurring substances.

The first commercial injection moulding machines designed for thermoplastics used injection rams actuated by compressed air. The early 1930s saw the use of pre-plasticization units (in which the plastic was melted before being fed to the injection cylinder) and by the end of the decade shot weights of over a kilogramme had been achieved, using hydraulically operated rams. Machines of more modest capacity were by then already capable of fully automatic operation. In the mid-thirties the early extruders designed for thermoplastics came on to the market.

PVC was in commercial production by the end of the 1920s and in a plasticized form it was replacing rubber for insulating electric cables as early as 1932. Unplasticized PVC, available in 1937, was hard, stiff and tough, and its good chemical resistance was exploited in chemical plant.

The 1930s saw the commercial introduction of three other important thermoplastics: polymethylmethacrylate (acrylic), polystyrene, and low-density polyethylene, the first two having natural outstanding transparency. Acrylic first became available in the form of clear, stiff, hard cast sheet which could be readily shaped and which was tougher and safer than glass: it rapidly replaced glass interlayered with cellulose nitrate in aircraft canopies. Acrylic moulding powders also became available in the mid-thirties, albeit in limited quantities. Although polystyrene was cheap, stiff, crystal clear and extremely easy to process, it made an unpromising start because of its extreme brittleness but in a modified form it was later to become an important material. The first polyethylene plant came on stream in 1939. This tough, resilient material found immediate application as an insulant for high-frequency low-voltage cables in radar, and its low-loss properties were later exploited in high-performance transatlantic submarine cables.

Further important materials to be introduced in the 1940s were nylon, ABS and PTFE (polytetrafluoroethylene). The high strength, stiffness and abrasion resistance of nylon were exploited in injection moulded gears and other components which replaced high-quality metal ones in light machinery. The tough ABS materials were introduced in the late 1940s and a toughened, and therefore much improved, 'impact resistant' polystyrene at the beginning of the 1950s. These materials owed much to the earlier synthesis of general purpose rubbers deriving from butadiene and styrene; and the development of the synthetic rubbers stemmed from the need to find a material which was more elastic than plasticized PVC, which was originally used as a natural rubber replacement. PTFE entered commercial production at the end of the 1940s. It is a soft flexible material, chemically inert, an excellent electrical insulator, has outstanding non-stick characteristics and can withstand continuous temperatures in the range −250°C to +250°C.

1.3 THE PRESENT RANGE OF MATERIALS AND LIKELY DEVELOPMENTS

1.3.1 The Scale of Operations

In the first twenty years or so of the thermoplastics industry, raw materials derived mainly from coal or from agricultural sources. However, 1950 saw the birth of the modern petrochemical industry, which quickly began to produce in large quantities, and at attractive prices, the basic materials from which most plastics are now made. This was one of the two factors responsible for a tremendous increase in the growth rate of the industry. The other factor was that, at about the same time, understanding of the relationship between molecular structure and the behaviour of plastics became clearer, and recognition of the potential importance of newly developed molecular structures led to rapid commercialization.

At this stage it is helpful to distinguish between two classes of thermoplastics: the low-priced high-tonnage materials (PVC, polyethylene, polystyrene and polypropylene), sometimes called the commodity plastics, and the higher-priced lower-tonnage speciality materials such as acrylic, ABS, PTFE, nylon, polycarbonate, polyacetal, PPO (polyphenylene oxide), polysulphones and thermoplastic polyesters. With the exception of acrylic and ABS, the speciality materials have been developed to offer either a higher modulus or a higher working temperature range, or both, together with other desirable combinations of properties, compared with those afforded by many of the commodity plastics; these attributes usually being achieved at the expense of a higher cost imposed not least by the more humble scale of operations. Such materials have come to be termed 'engineering plastics' but the limitation of this term is that it implies that only the specialist materials are useful within the engineering context, which, as has been mentioned in section 1.1.2, is demonstrably untrue.

1.3.2 The High-Tonnage Materials

At present the U.K. uses more PVC than any other plastic: over 350,000 tonnes in 1971. Compounds can be formulated from PVC and a variety of additives, including plasticizers where appropriate, to cover a remarkably wide range of properties and to be suitable for injection moulding, extrusion, compression moulding and calendering. By virtue of its low cost and the range of grades available, PVC is the most versatile of all plastics. Applications of the unplasticized material (which is self-extinguishing) range from roofing sheet and vandal-proof glazing to pipe fittings, while cable insulation and shoe soling are examples of the use of the more flexible plasticized grades.

Of the 290,000 tonnes of low-density polyethylene used in the U.K. in 1971, much went into applications which exploited toughness, flexibility and chemical resistance to varying degrees. More than 50% of the material is extruded into film, 15% is injection moulded, and about 10% is blow-moulded into bottles and containers. In addition, low-density polyethylene is used in, for example, electrical applications, extruded pipe and rotationally moulded large containers and furniture.

Polystyrene accounted for more than 150,000 tonnes of the plastics used in the U.K. in 1971. There are three basic types: general purpose (G.P.) polystyrene (a rather brittle material), toughened polystyrene and expanded polystyrene. The G.P. type is widely used for toys and the packaging of cosmetics. Toughened polystyrene is used in refrigerator liners, containers for dairy products and housings for domestic electrical equipment, and the expanded form finds application in protective packaging and as a thermal insulating medium.

Polypropylene was introduced in 1959 and its combination of strength, fatigue resistance, stiffness, excellent electrical insulation and temperature and chemical resistance at a low price ensured a phenomenal growth to almost 100,000 tonnes per annum in the U.K. within 12 years. Extruded pipe and sheet are widely used in chemical plant, injection moulded applications (which account for about 50% of the market) include stacking containers and chair shells, and a large number of moulded components are used in cars. Recent developments in its use for twines, fibres, film yarn, carpet backing and face piles have already accounted for 30% of the use of polypropylene, a share which is likely to increase.

High-density polyethylene, introduced in 1954, is much stiffer and stronger than low-density polyethylene, and some of its properties are comparable with those of polypropylene. In 18 years the annual U.K. market has grown to about 60,000 tonnes. About half of the U.K. usage is in blow-moulded containers ranging from small bottles to large tanks, and about 30% in injection moulded items such as dustbins and bottle crates. Sheet and very large pipes are also extruded from high-density polyethylene and currently a rapid growth area is in the use of this material for the replacement of tissue and wrapping paper.

1.3.3 The Specialist Materials

We are concerned here only with a broad picture rather than with an exhaustive treatment. Attention is therefore confined to some of the commercially important materials.

Historically, acrylic is one of the oldest speciality thermoplastics, followed by nylon, ABS and PTFE, all of which were in commercial production by the end of the 1940s. Since then acrylic sheet has almost completely replaced glass for illuminated signs and lighting fittings, and acrylic moulding powders are now the preferred materials for rear-lamp housings for vehicles.

Nylon materials offer good stiffness, strength, toughness and abrasion resistance, but they do absorb moisture which affects their dimensional stability and stiffness. Reinforcement of nylon with glass fibres is widely practised and this increases stiffness and strength, widens the working temperature range and improves the dimensional stability. Normally processed by injection moulding, typical applications include gears, bushes, cams, bearing and housings for power tools and domestic equipment.