

PLASTICS ENGINEERING

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PREFACE

This book presents in a single volume the basic essentials of the properties and processing behaviour of plastics. The approach taken and terminology used has been deliberately chosen to conform with the conventional engineering approach to the properties and behaviour of materials. It was considered that a book on the engineering aspects of plastics was necessary because there is currently a drive to attract engineers into the plastics industry and although engineers and designers are turning with more confidence to plastics there is still an underlying fear that plastics are difficult materials to work with. Their performance characteristics fall off as temperature increases and they are brittle at low temperatures. Their mechanical properties are time dependent and in the molten state they are non-Newtonian fluids. All this presents a gloomy picture and unfortunately most texts tend to analyse plastics using a level of chemistry and mathematical complexity which is beyond most engineers and designers. The purpose of this text is to remove some of the fears, by dealing with plastics in much the same way as traditional materials. The major part of this is to illustrate how quantitative design of plastic components can be carried out using simple techniques and how apparently complex moulding operations can be analysed without difficulty.

Many of the techniques illustrated have been deliberately simplified and so they will only give approximate solutions but generally the degree of accuracy can be estimated and for most practical purposes it will probably be acceptable. Once the engineer/designer has realised that there are proven design procedures for plastics which are not beyond their capabilities then these materials will be more readily accepted for consideration alongside established materials such as woods and metals. On these terms plastics can expect to be used in many new applications because their potential is limited only by the ingenuity of the user.

This book is intended primarily for students in the various fields of engineering but it is felt that students in other

disciplines will welcome and benefit from the engineering approach. Since the book has been written as a general introduction to the quantitative aspects of the properties and processing of plastics, the depth of coverage is not as great as may be found in other texts on the physics, chemistry and stress analysis of viscoelastic materials. This has been done deliberately because it is felt that once the material described here has been studied and understood the reader will be in a better position to decide if he requires the more detailed viscoelastic analysis provided by the advanced texts.

In this book no prior knowledge of plastics is assumed. Chapter 1 provides a brief introduction to the structure of plastics and it provides an insight to the way in which their unique structure affects their performance. There is a resume of the main types of plastics which are available. Chapter 2 deals with the mechanical properties of unreinforced and reinforced plastics under the general heading of deformation. The time dependent behaviour of the materials is introduced and simple design procedures are illustrated. Chapter 3 continues the discussion on properties but concentrates on fracture as caused by creep, fatigue and impact. The concepts of fracture mechanics are also introduced for reinforced and unreinforced plastics.

Chapter 4 describes in general terms the processing methods which can be used for plastics and wherever possible the quantitative aspects are stressed. In most cases a simple Newtonian model of each of the processes is developed so that the approach taken to the analysis of plastics processing is not concealed by mathematical complexity. Chapter 5 deals with the aspects of the flow behaviour of polymer melts which are relevant to the processing methods. The models are developed for both Newtonian and Non-Newtonian (Power Law) fluids so that the results can be directly compared.

Throughout the book there are worked examples to illustrate the use of the theory and at the end of each chapter there are problems to be solved by the reader. These are seen as an important part of the book because in solving the problems the reader is encouraged to develop the subject material beyond the level covered in the text. Answers are given for all the questions.

R.J. CRAWFORD

1

Structure of plastics

1.1 Introduction

It would be difficult to visualise our modern world without plastics. Today they are an integral part of everyones lifestyle with applications varying from commonplace articles to sophisticated scientific and medical instruments. Nowadays designers and engineers readily turn to plastics because they offer combinations of properties not available in any other materials. Plastics offer advantages such as lightness, resilience, resistance to corrosion, colour fastness, transparency, ease of processing etc, and although they also have their limitations, their exploitation is limited only by the ingenuity of the designer.

The term "plastic" refers to a family of materials which includes nylon, polyethylene and PTFE just as zinc, aluminium and steel fall within the family of "metals". This is an important point because just as it is widely accepted that zinc has quite different properties from steel, similarly nylon has quite different properties from PTFE. Few designers would simply specify "metal" as the material for a particular component so it would be equally unsatisfactory just to recommend "plastic". This analogy can be taken still further because in the same way that there are different grades of steel there are also different grades of, for example, polypropylene. In both cases the good designer will recognise this and select the most appropriate material and grade on the basis of processability, toughness, rigidity, etc.

It is usual to think that plastics are a relatively recent development but in fact, as part of the larger family called "polymers", they are a basic ingredient of plant and animal life. Polymers are materials which consist of very long chain-like molecules (typical molecular weights can be in the region of 300,000). Natural materials such as silk, shellac, bitumen, rubber and cellulose have this type of structure. However, it was not until the 19th century that attempts were made to develop a synthetic polymeric material and the first success was based on cellulose. This was a material called "Parkesine", after its

inventor Alexander Parkes, and although it was not a commercial success it was a start and eventually led to the development of "Celluloid". This material was an important break-through because it became established as a good replacement for natural materials which were in short supply - for example, ivory for billiard balls.

During the early twentieth century there was considerable interest in these new synthetic materials. Phenol-formaldehyde ("Bakelite") was introduced in 1905 and about the time of the second World War materials such as nylon, polyethylene and acrylic ("Perspex") appeared on the scene. Unfortunately many of the early applications for plastics earned them a reputation as being cheap substitutes. It has taken them a long time to overcome this image but nowadays the special properties of plastics are being appreciated which is establishing them as important materials in their own right. The ever increasing use of plastics in all kinds of applications means that it is essential for designers and engineers to become familiar with the range of plastics available and the types of performance characteristics to be expected so that they can be used to the best advantage.

Experience has shown that one of the things which puts people, particularly students, off plastics is their complex structure. Fortunately, however, in order to use plastics effectively it is not necessary to have a detailed knowledge of their chemical structure. All that is required is a general awareness of their internal structure in order to appreciate the differences between the various types and grades of plastics. For this reason the following sections give a brief summary of the structure of plastics without getting involved in complex polymer chemistry. In this way it will be seen that the unique molecular structure of plastics which has such a major influence on the flow behaviour of the molten plastic and the viscoelastic behaviour of the solid plastics, can be explained in simple terms.

1.2 Polymeric Materials

Synthetic large molecules are made by joining together thousands of small molecular units known as *monomers*. The process of joining the monomers together is called *polymerisation* and the number of these units in the long molecule is known as the *degree of polymerisation*. The names of many polymers consists of the name of the monomer with the suffix "poly-". For example, the polymers polypropylene and polystyrene are produced from propylene and styrene respectively.

The words "polymers" and "plastics" are often taken as synonymous but in fact there is a distinction. The polymer is the pure material which results from the process of polymerisation and is usually taken as the family name for materials which have long chain-like molecules and this includes rubber. Pure polymers are seldom used on their own and it is when additives are present that the term plastic is applied. Polymers contain additives for a number of reasons. In some cases impurities are present as a result of the polymerisation process and it may be uneconomic to remove these to get the pure polymer. In other cases additives such as stabilisers, lubricants, fillers, pigments, etc are added to enhance the properties of the material. By tradition the term *plastics* excludes rubber.

There are two important classes of plastics:

(a) Thermoplastic materials

In a thermoplastic material the long chain-like molecules are held together by relatively weak Van der Waals forces. A useful image of the structure is a mass of randomly distributed long strands of sticky wool. When the material is heated the intermolecular forces are weakened so that it becomes soft and flexible and eventually, at high temperatures, it is a viscous melt. When the material is allowed to cool it solidifies again. This cycle of softening by heat and solidifying when cooled can be repeated more or less indefinitely and is a definite advantage in that it is the basis of most processing methods for these materials. It does have its drawbacks, however, because it means that the properties of thermoplastics are heat sensitive. A useful analogy which is often used to describe these materials is that like candle wax they can be repeatedly softened by heat and will solidify when cooled.

Examples of thermoplastics are polyethylene, polyvinyl chloride, polystyrene, nylon, cellulose acetate, acetal polycarbonate, polymethyl methacrylate and polypropylene.

(b) Thermosetting materials

A thermosetting material is produced by a chemical reaction which has two stages. The first stage results in the formation of long chain-like molecules similar to those present in thermoplastics, but still capable of further reaction. The second stage of the reaction takes place during moulding, usually under the application of heat and pressure. The resultant moulding will be rigid when cooled but a close network structure has been set up within the material. During the second stage the long molecular chains have been interlinked by strong bonds so that the material cannot be softened again by the application of heat. If excess heat is applied to these materials they will char and degrade. This type of behaviour is analogous to boiling an egg. Once the egg has cooled and is hard, it cannot be softened again by the application of heat.

Since the cross-linking of the molecules is by strong chemical bonds thermosetting materials are characteristically quite rigid materials and their mechanical properties are not heat sensitive. Examples of thermosets are phenol formaldehyde, melamine formaldehyde, urea formaldehyde, epoxies and some polyesters.

1.3 Structure of Long Molecules

As mentioned several times already, polymeric materials consist of long chain-like molecules. Their unique structural configuration affects many of their properties and it is useful to consider in more detail the nature of the chains and how they are built up. The simplest polymer to consider for this purpose is polyethylene. During the polymerisation of the monomer ethylene,

the double bond (see fig. 1.1) is opened out enabling the carbon single bonds to link up with neighbouring units to form a long chain of CH_2 groups as shown in fig. 1.2. This is a schematic representation and conceals the fact that the atoms are joined to each other at an angle as shown in fig. 1.3.

In all the groups along the chain the bond angle is fixed. It is determined by considering a carbon atom at the centre of a regular tetrahedron and the four covalent bonds are in the directions of the four corners of the tetrahedron. This sets the bond angle at $109^\circ 28'$ as shown in fig. 1.4 and this is called the tetrahedral angle.

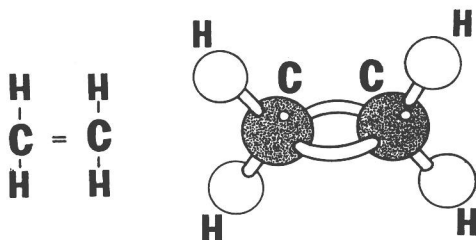


Fig.11 ETHYLENE MONOMER

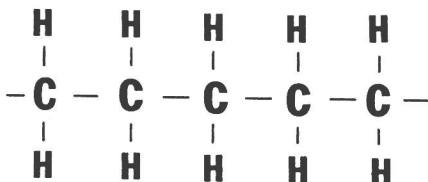


Fig.12 POLYETHYLENE MOLECULE

For a typical molecular weight of 300,000 there are about 21,000 carbon atoms along the backbone of the chain. Since the length of the C-C bond is $0.154 \times 10^{-9}\text{m}$ the dimensions of an extended zig-zag chain would be about 2700 nm long and 0.3 nm diameter. This gives an idea of the long thread like nature of the molecules. It must be remembered, however, that in any particular polymer, not all molecular chains have the same length. The length of each chain depends on a series of random events during the polymerisation process. One chain may grow rapidly in a region with an abundant supply of monomer whereas other chains stop growing prematurely as the supply of monomer dries up. This means that a particular sample of synthetic polymer will not have a unique value for its molecular weight. Instead statistical methods are used to determine an average molecular weight and the molecular weight distribution.

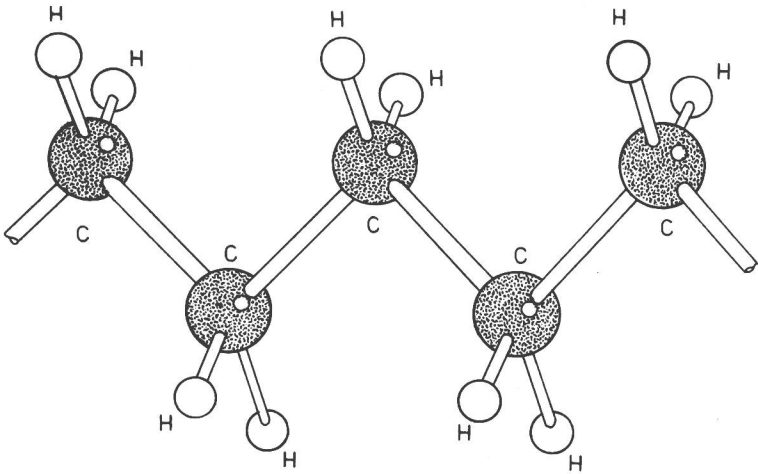


Fig. 13. POLYETHYLENE MOLECULE

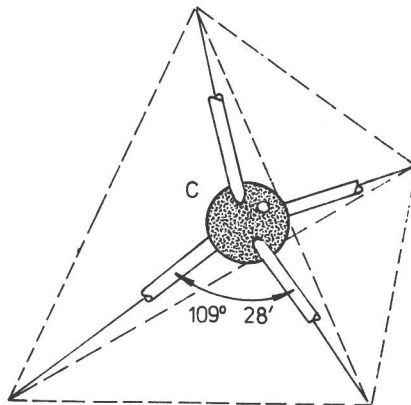


Fig. 14. TETRAHEDRAL ANGLE

1.4 Conformation of the Molecular Chain

The picture presented so far of the polyethylene chain being of a linear zig-zag geometry is an idealised one. The conformation of a molecular chain is in fact random provided that the bond tetrahedral angle remains fixed. This is best illustrated by considering a piece of wire with one bend at an angle of $109^{\circ}28'$ as shown in figure 1.5a.

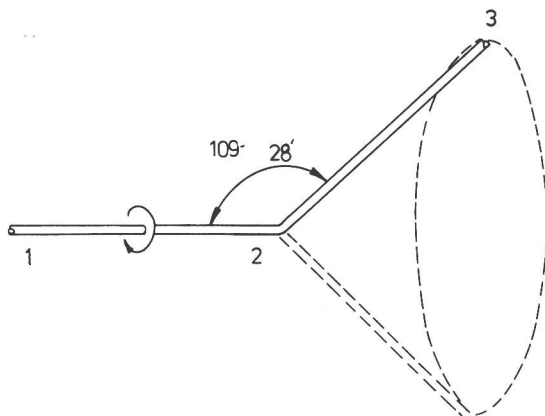


Fig. 1.5 (a).

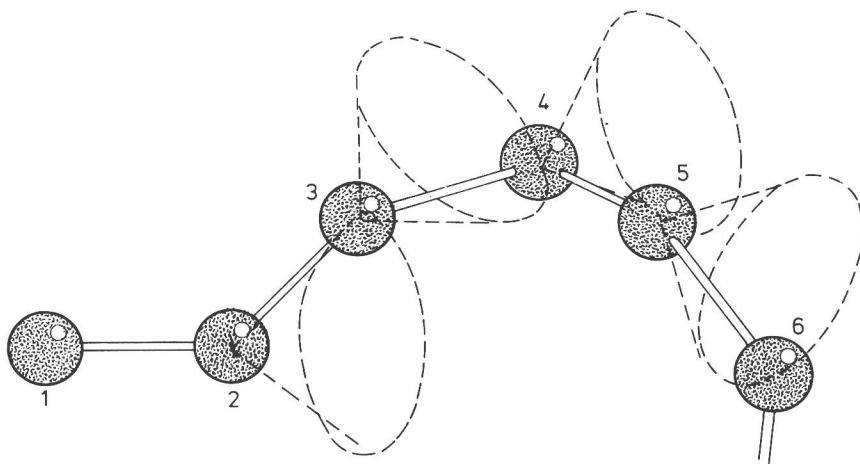


Fig. 1.5 (b) RANDOM CONFORMATION OF CARBON BACKBONE
ON MOLECULAR CHAIN