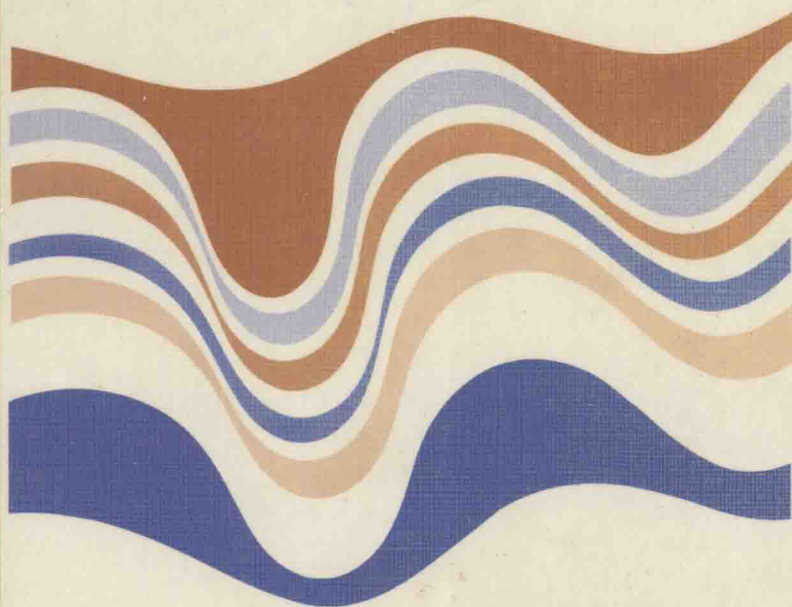


Mechanical Properties of Reinforced Thermoplastics

Editors

D.W. Clegg and A. A. Collyer



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MECHANICAL PROPERTIES OF REINFORCED THERMOPLASTICS

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MECHANICAL PROPERTIES OF REINFORCED THERMOPLASTICS

Preface

The reinforcement of materials such as mud and clay by hair, straw and vegetable fibres has been long established in man's history, enabling him to improve his buildings and extend his engineering abilities. With the advent of modern synthetic polymers it was rapidly realised that the addition of fibres, flakes and particulate materials to polymer matrices could improve mechanical properties significantly. Fibres and flakes are the most effective and have enabled several polymers with limited properties to compete with long-established metallic materials, resulting in cost, weight and processing economies. This is increasingly apparent in the selection of materials for aerospace and road vehicle applications as well as in a multitude of domestic products.

Reinforced plastics, both thermosets and thermoplastics, are used in increasingly harsh environments involving elevated temperatures and aggressive conditions. Fibre reinforcement of thermoplastics dominates, and a pattern of increasing replacement of fibre reinforced thermosets by reinforced thermoplastics is emerging. This trend is encouraged by the development of continuous fibre reinforced grades of the newer high-temperature engineering thermoplastics such as polyether ether ketone.

The first part of this book reviews the mechanical properties and theories of short fibre reinforcement. The principal reinforcements are reviewed and a separate chapter is devoted to the uses of natural fibres as reinforcements for thermoplastics. This is an interesting and commercially important area, especially for Third World countries

where these fibres are grown but are facing severe competition from synthetic fibres in traditional applications such as ropes and matting. Subsequent chapters cover the exciting developments in continuous fibre reinforcement of thermoplastics and the requirements, theories and technologies involved in the bonding between reinforcements and matrices.

The second part of the book concerns the interrelationship between constitution, morphology, rheology and processing characteristics of reinforced thermoplastics. It covers the most recent developments and discusses techniques used to study the materials.

In addition, a chapter is devoted to designing with short fibre reinforced thermoplastics and the influence of fibre orientation on design is explained.

The work as a whole shows the importance of many varied disciplines to the understanding and development of reinforced thermoplastics, and will be of interest to materials scientists, engineers and technologists in industry, research laboratories and academic institutions. It is a worthwhile introduction to the subject for students as well as providing an up-to-date review of recent innovations in the field.

Finally, we would like to thank Mr J. Evans for drawing many of the diagrams, Mr M. Morris for supplying Fig.1.2 and Dr A. Norcliffe for helpful discussions on mathematical theories. Other acknowledgements are given at appropriate places in the text.

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Chapter 1

An Introduction to Fibre Reinforced Thermoplastics

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1.1. INTRODUCTION

When considering materials for load-bearing applications, designers are increasingly examining the advantages of using plastics materials, both thermosets and thermoplastics, instead of traditionally accepted materials and, in particular, metals. Thermoplastics have three main advantages, their low specific gravities, their low energy requirements for manufacture and their low costs of fabrication, particularly by the injection moulding route.

The strength-to-weight and stiffness-to-weight ratios of various materials are shown in Table 1.1.^{1,2} The thermoplastics have higher strength-to-weight ratios than aluminium and steel, but lower stiffness-to-weight ratios, giving rise to increased buckling under load. Therefore, when designing with thermoplastics, the design is influenced more by stiffness than by strength.

When energy costs are high, the amount of energy required to produce unit volume of material is an important consideration. It can be seen from Table 1.2³ that the energy required to produce a cubic metre of thermoplastics is less in general than that required for metal production. Environmentalists will approve of this.

The third point of comparison, namely fabrication, sees another advantage offered by thermoplastics materials. They can be made rapidly and reproducibly into complex shapes by injection moulding,

TABLE 1.1
Comparison of the Mechanical Properties of Several Types of Engineering Materials^{1,2}

<i>Material</i>	<i>Specific gravity</i> (g cm^{-3})	<i>Modulus</i> (GN m^{-2})	<i>Specific modulus</i> (MN m kg^{-1})	<i>Strength</i> (MN m^{-2})	<i>Specific strength</i> ($\text{kN m}^{-1} \text{kg}^{-1}$)
Aluminium	2.7	71	26	80	30
Brass (70Cu/30Zn)	8.5	100	12	550	65
Mild steel	7.86	210	27	460	59
Polyamide 66	1.14	3	2.6	80	70
Polycarbonate	1.24	2.3	1.9	60	48
Polyamide 66/30% glass	1.38	8	5.8	160	116

TABLE 1.2
Energy Requirements for the Production of Different Materials
(After Sheldon³)

<i>Material</i>	<i>Energy</i>	
	(MJ kg ⁻¹)	(KJ m ³ /10)
Bottle glass	18	41
Low-density polyethylene	69	64
High-density polyethylene	70	67
Polypropylene	73	68
Polyvinyl chloride	53	69
Polystyrene	80	84
Polyurethane	130	100
Polypropylene/30% glass fibre	90	100
Polyester/30% glass fibre	90	150
Phenoplast	150	200
Steel	45	350
Aluminium	>200	>540
Brass	95	600

which is not labour intensive and lends itself well to microprocessor control.

The importance of thermoplastics has increased since the advent of the newer, high-temperature engineering thermoplastics; various polyamides, polysulphone (Union Carbide Ltd), polyether sulphone (ICI), polyether ether ketone (ICI), polyether imide (General Electric) and polyimide (DuPont). All but the last can be injection moulded. Table 1.3⁴⁻⁹ shows typical properties of some of these materials. These mechanical properties compare well with those of aluminium, even at elevated temperatures (200°C), resulting in a number of the materials being used where traditionally a metal would have been chosen. Often this has led to an improvement in design of the part.

One example of this is in the use of polyether sulphone for printed circuit boards. This material can be soldered with no distortion, and the production of the parts by injection moulding is rapid and cheap. The new improvement offered by the use of this material is that of three-dimensional printed circuit boards.¹⁰

TABLE 1.3
Properties of Various High-temperature Engineering Thermoplastics Compared with Aluminium⁴⁻⁹

<i>Property</i>	<i>Unit</i>	<i>Polysulphone</i>	<i>Polyether sulphone</i>	<i>Polyether ether ketone</i>	<i>Polyether imide</i>	<i>Polyimide</i>	<i>Aluminium</i>
Specific gravity	g cm^{-3}	1.24	1.37	1.32	1.27	1.36	2.7
Tensile modulus	GN m^{-2}	2.5	2.44	1.1	3.0	1.43	71
Tensile strength at yield (20°C)	MN m^{-2}	70	80	91	105	72-86	80
Flexural strength (20°C)	MN m^{-2}	106	129	—	200	—	—
Notched Izod impact	J m^{-1}	69	84	—	50	80	—

Charpy notched impact	kJ m^{-2}	—	—	54	10.0	—	—
Rockwell hardness	Class	M69	M88	—	M109	—	B70
Glass transition temperature	$^{\circ}\text{C}$	190	225	143	230	—	—
Melting point	$^{\circ}\text{C}$	—	—	334	—	—	660
Heat deflection temperature (1.85 MN m^{-2})	$^{\circ}\text{C}$	173	203	135-160	200	360	—
Vicat softening point (1 kg)	$^{\circ}\text{C}$	—	226	—	219	—	—
Upper service temperature	$^{\circ}\text{C}$	171	180	260	170	315	100

If thermoplastics are so good, why have they not completely replaced metals? One of the main reasons is their poor high-temperature capability. If there were three main improvements to make to thermoplastics, they would be to stiffness, strength and creep resistance at elevated temperatures. It is instructive to consider how modifications can be made to achieve this end.

1.2. METHODS OF IMPROVING THE MECHANICAL PROPERTIES OF THERMOPLASTICS

There are several methods of achieving improved mechanical properties; in describing them it is hoped to place in context the role of fibre reinforced thermoplastics.

1.2.1. Molecular Architecture

Manipulation of the molecular architecture of a polymer necessarily means developing a new material and the industrial process by which it can be manufactured in bulk. This is extremely speculative and costly, and new thermoplastics, unless markedly different from existing ones, have a limited potential for penetrating the market.

This has not always been true and it is useful to examine how the different architectures developed over the years influence stiffness and give higher temperature capabilities. Figure 1.1(a) shows the molecular configuration of high-density polyethylene (HDPE). It has poor mechanical properties and cannot be used at high temperatures; as such it is unsuitable for engineering applications. The molecule has a flexible backbone chain that can extend and rotate into many conformations with relative ease, giving a low melting temperature, T_m , and a low stiffness.

A better material from a load-bearing viewpoint, polystyrene, is shown in Fig. 1.1(b). Here, the aromatic sidegroups restrict the movement of the backbone chain, giving a far more rigid material. As it happens, polystyrene is very brittle and not suited to engineering applications in unmodified form.

The secret of a higher-temperature capability and stiffness lies partly in the ease of movement of the backbone chain. In polyphenylene oxide (PPO), Fig. 1.1(c), the aromatic rings are in the backbone structure, giving a greatly restricted movement. Unfortunately, the restriction is too much, and PPO is an intractable material, although its mechanical

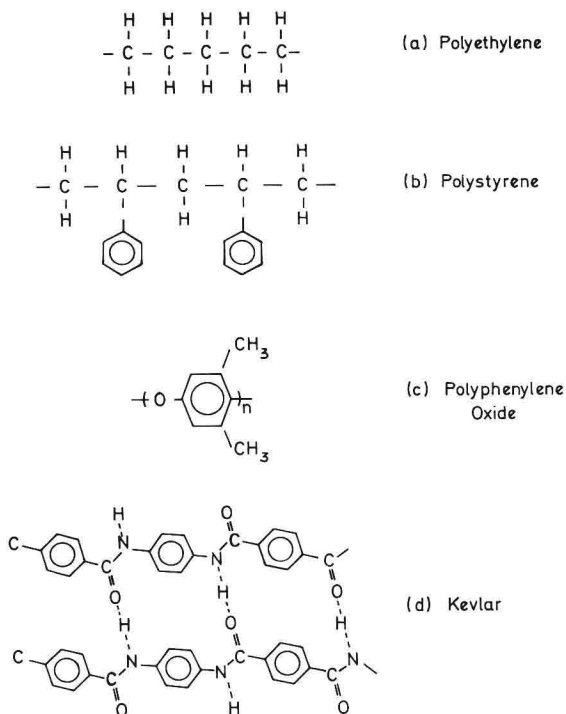


Fig. 1.1. Molecular architecture of some thermoplastics.

properties are desirable. PPO is usually modified by incorporating a graft copolymerisation with PS. This is available as 'Noryl' (General Electric Plastics).¹¹

Figure 1.1(d) shows the aromatic polyamide structure of Kevlar 49, another intractable material. This is used as a reinforcing fibre in thermoplastics matrices, and is included for that reason. Often, intractable materials decompose before they melt.

In this section, so far, the high-temperature and stiffness characteristics have been related only to the overall structure; these desirable characteristics can be achieved by replacing the carbon-carbon bonds by stronger ones, such as silicon-oxygen. Eventually this would lead to a discussion of ceramic materials, many of which are used as reinforcements. Further discussion of molecular architecture is given by Hearle¹² and Mascia.¹³