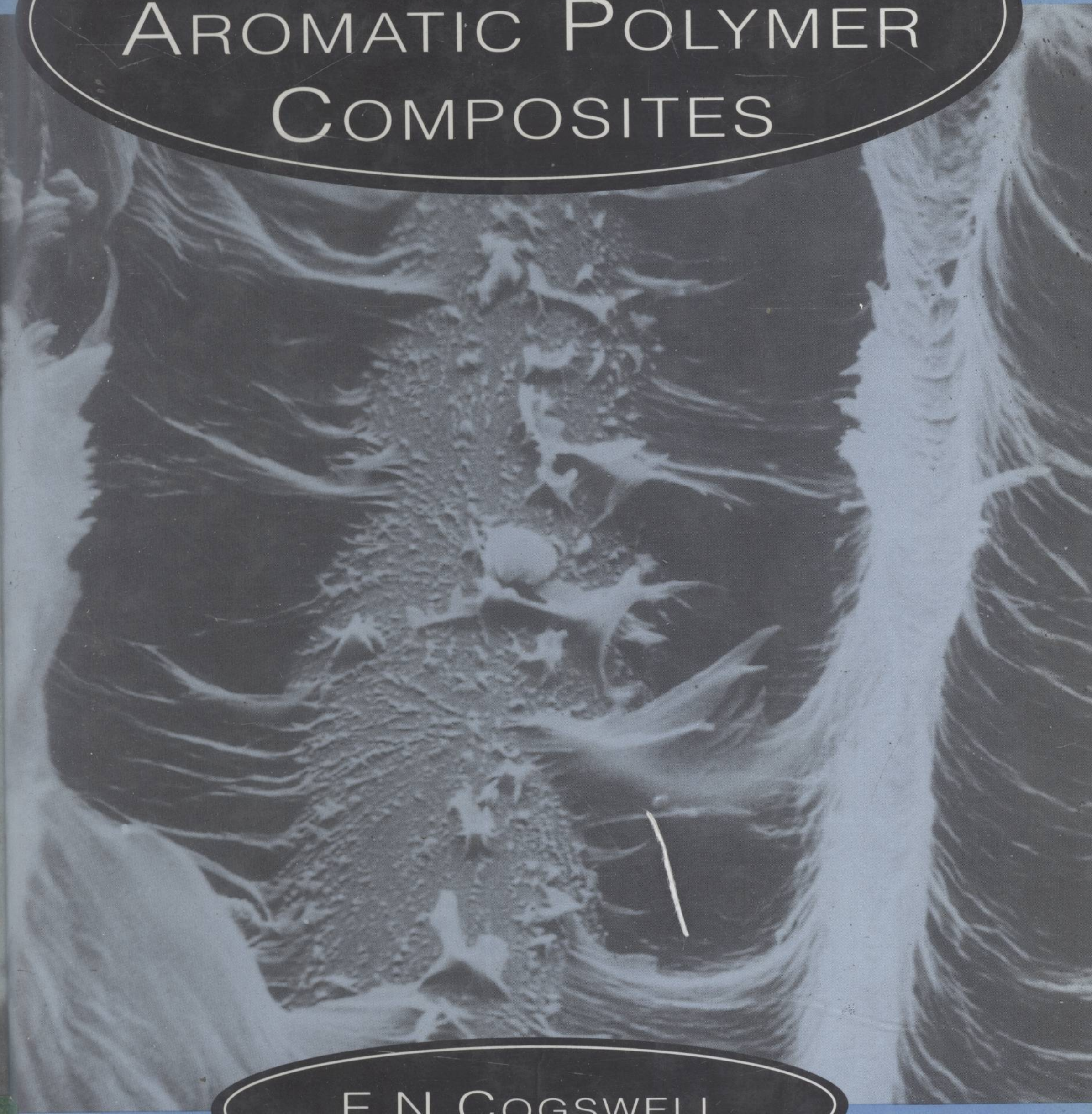
Thermoplastic Aromatic Polymer Composites



F N Cogswell

Thermoplastic Aromatic Polymer Composites

a study of the structure, processing and properties of carbon fibre reinforced polyetheretherketone and related materials

Frederic Neil Cogswell

BUTTERWORTH
HEINEMANN

Butterworth-Heinemann Ltd
Linacre House, Jordan Hill, Oxford OX2 8DP

PART OF REED INTERNATIONAL BOOKS

OXFORD LONDON BOSTON
MUNICH NEW DELHI SINGAPORE SYDNEY
TOKYO TORONTO WELLINGTON

First published 1992

British Library Cataloguing in Publication Data
Cogswell, Frederic Neil
Thermoplastic aromatic polymer composites:
A study of the structure, processing and
properties of carbon fibre reinforced
polyetheretherketone and related materials.
I. Title.
668.9

ISBN 0 7506 1086 7

Library of Congress Cataloguing in Publication Data
Cogswell, F. N.
Thermoplastic aromatic polymer composites: a study of the
structure, processing, and properties of carbon fibre reinforced
polyetheretherketone and related materials/Frederic Neil Cogswell.
p. cm.
Includes bibliographical references and index.
ISBN 0 7506 1086 7
1. Polymeric composites. I. Title.
TA418.9.C6C54 1992
620.1'92–dc20 91-28715
CIP

Composition by Genesis Typesetting, Laser Quay, Rochester, Kent
Printed and bound in Great Britain by Redwood Press Limited, Melksham, Wiltshire

Foreword

At a SAMPE Conference in 1980 I lamented the lack of long fibre reinforced thermoplastic composites compared with thermosets. I said 'I believe that reinforced thermoplastics have a brighter future in the long run because the physical properties of the plastic arise from a more stringent chemistry, namely that necessary to produce linear polymerization, and hence should lead to better controlled and more reproducible physical properties'. At that time, Neil Cogswell was working on his magnificent invention which revolutionalized the field of thermo-formable composite materials by finding a commercially viable method for introducing long fibres into a high-performance thermoplastic resin.

The basic idea was very simple, as in so many inventions. The unique step was that of applying the force to the fibres in the direction in which they are strong so as to force the fibres into the resin and to coat them while preserving fibre alignment. Because the fibres are forced into the resin by applying the force along the direction in which they can sustain maximum force, they are individually wetted, the void content is kept to a minimum, and in addition the fibres can be uniformly distributed without the formation of islands of resin.

Thermoplastic composite materials of course embrace a wide field. But this book considers in detail only the material made possible by Cogswell's invention, namely carbon fibre reinforced polyetheretherketone at about 60% of volume reinforcement. Because the matrix of the resin is highly controlled, practically void-free, highly crystalline and a thermoformable plastic, many of the inherent properties of reinforced plastics and the methods of forming and manufacturing these can be demonstrated with this system. That is what this book is about and it gives me great pleasure, and indeed pride, to be able to write a foreword to it. The book covers all the difficult as well as the easy parts of composites engineering, dealing well with processing science and manufacturing technology, durability, temperature sensitivity, and environmental resistance. Neil Cogswell also recognizes that the performance of a structural material will outlast the usefulness of the structure. The issue of reclaiming high value materials is a significant one. This book deals, in an interesting way, with how thermoplastic structural materials can be re-cycled.

It is a book pointing the way to the future and I heartily recommend it to all those interested in composite materials.

Anthony Kelly
Vice-Chancellor University of Surrey

Preface

This book is designed to review our understanding of the field of thermoplastic composite materials through a detailed study of one member of that family – carbon fibre reinforced polyetheretherketone.

No prior knowledge of the field is required in order to read these chapters. The opening chapter is intended to lead the newcomer into the field. There follow detailed discussions: of the ingredients of these designed materials, of how they are made into composites, and, of their microstructure. Chapter 5 addresses the way in which such materials can be converted into structures. This is followed by a series of short reviews of the performance of carbon fibre reinforced polyetheretherketone and a discussion of the application of such materials in service. The final chapter considers the directions of research in this field and attempts to project their likely influence on the development of new businesses.

The work concludes with a number of appendices, and author and subject indexes.

Neil Cogswell

Acknowledgements

I am grateful to Mike Eades, Director of the ICI Thermoplastic Composites Business, and David Clark, Laboratory Director of the ICI Wilton Materials Research Centre, for their permission to publish this work.

In preparing the text I have received considerable assistance from my colleagues. My particular thanks are due to John Barnes who was a diligent and challenging scientific critic. The following corrected, or made material additions to, the work in draft form: David Blundell, Chris Booth, Mark Cirino, Robin Chivers, Liz Colbourn, Gerald Cuff, Mark Davies, David Groves, David Hodge, Tony Jackson, David Kemmish, Duncan Laidler, David Leach, Peter Meakin, Peter Mills, Roy Moore, David Parker, Judith Peacock, Steve Ragan, Ian Robinson, Paul Schmitz, Tony Smiley, Philip Staniland, Dave Stocks, Alan Titterton, Roger Turner, Phil Willcocks and Nabil Zahlan. I have tried to reflect their expertise, any errors that remain are my own.

My daughter Frederica read the chapters with the eyes of a scientist, but not one familiar with the field. She purged the text of jargon and pointed out where simplification or amplification were necessary.

The word processing was carried out with meticulous care and unfailing good humour by Margaret Tarry with contributions from Fiona Hack and Heather Dobson.

By her encouragement and forbearance during the long hours of writing, my wife Valerie reinforced the respect and esteem that is the basis of my love for her.

Neil Cogswell

As Materials Scientists, my colleagues and I have been encouraged, by ICI, to explore what things might be. This book is respectfully dedicated to our associates of the Engineering, Marketing and Management disciplines who actually make them happen.

Contents

Foreword ix
Professor A. Kelly, CBE FEng FRS

Preface x

Acknowledgements xi

1 An introduction to thermoplastic composite materials 1
1.1 Towards designed materials 1
1.2 Why thermoplastic structural composites? 5
1.3 Composite science 8
References 9

2 Components of a thermoplastic structural composite 11
2.1 Thermoplastic matrix resins 11
2.1.1 Chain extendable resins 13
2.1.2 Amorphous thermoplastics 14
2.1.3 Orientable polymer matrices 15
2.1.4 Semi-crystalline thermoplastic polymers 17
2.1.5 Polymer blends and compounds 18
2.1.6 The 'Victrex' range of aromatic polymers 19
2.1.7 Polyetheretherketone 21
2.2 Reinforcing fibres 31
2.2.1 Organic polymeric fibres 32
2.2.2 Inorganic filaments 33
2.2.3 Carbon fibres 34
2.2.4 High strength carbon fibres 35
2.3 Interfaces and interphases 37
2.3.1 Wetting of the fibre by the resin 38
2.3.2 Chemical bonding 40
2.3.3 Mechanical interlocking 41
2.3.4 Crystalline interactions 42
2.4 Thermoplastic structural composite materials 43
References 45

3 Product forms 51
3.1 Impregnation after shaping 51
3.1.1 *In-situ* polymerization 52
3.1.2 Linear chain thermosetting 'prepregs' 52
3.1.3 Film stacking 53

3.1.4 Partially impregnated tows 54
3.1.5 Cowoven and commingled products 54
3.1.6 Powder coating 56
3.1.7 General observations or impregnation after shaping 57
3.2 Preimpregnation processes 58
3.2.1 Solution impregnation 58
3.2.2 Chain extension processes 61
3.2.3 Melt impregnation 62
3.2.4 The integration of impregnation technologies 64
3.3 A comparison of product forms 64
3.4 A selection of product forms in carbon fibre/PEEK 71
References 73

4 The microstructure of Aromatic Polymer Composites 78
4.1 Voids 78
4.2 Organization of the fibres 80
4.2.1 Fibre distribution 80
4.2.2 Fibre straightness 83
4.3 Morphology of the matrix 88
4.3.1 The amorphous phase 88
4.3.2 Crystallization and crystallinity 89
4.4 Internal stresses in the composite 97
4.5 Quality in composites: the control of microstructure 101
References 101

5 Processing science and manufacturing technology 107
5.1 Processing science 107
5.1.1 Chemical change 108
5.1.2 Thermophysical properties 111
5.1.3 Rheology 114
5.1.4 The analysis of processing operations 123
5.2 Manufacturing technology 124
5.2.1 Consolidation 125
5.2.2 Continuous consolidation 128
5.2.3 Tape placement 130
5.2.4 Continuous forming 132
5.2.5 Stamping 134
5.2.6 Diaphragm forming 136
5.2.7 Incremental processing 139
5.2.8 Machining 140
5.3 Assembly technologies 141
5.3.1 Fasteners 142
5.3.2 Adhesive bonding 143
5.3.3 Solvent bonding 143
5.3.4 Fusion bonding 144
5.3.5 Interlayer bonding 145

5.4 Rework, repair and reclaim 147
5.5 Quality in processing 148
References 150

6 Dimensional stability 160
6.1 Intumescence 160
6.2 Thermal expansion 161
6.3 Stiffness 163
6.3.1 Stiffness characterization of uniaxial laminates 164
6.3.2 Stiffness of multi-angle laminates 166
6.3.3 Creep resistance 167
6.4 Dimensional stability and morphological integrity 167
References 168

7 The strength of thermoplastic composites 171
7.1 Compression strength 171
7.2 The tensile strengths of uniaxial laminates 172
7.3 The tensile strengths of cross-plied laminates 173
7.4 Shear strengths 175
7.5 Technological tests 175
References 176

8 Durability 179
8.1 Fracture mechanics 179
8.1.1 Crack propagation in uniaxial laminates 180
8.1.2 Interlaminar crack propagation in different modes 181
8.2 Impact loading 183
8.3 Damage tolerance 185
8.4 Fatigue performance 186
8.5 Wear resistance 187
References 189

9 Temperature sensitivity 195
9.1 The effect of temperature on stiffness 196
9.2 The influence of temperature on strength 197
9.3 Toughness and temperature 198
9.4 Fire resistance 199
References 199

10 Environmental resistance 202
10.1 Ageing: time, temperature, air and stress 202
10.2 Permeability of gases 203
10.3 Water resistance 204
10.4 Exposure to aviation fluids 205
10.4.1 Methylene chloride 206
10.4.2 Paint strippers 206
10.4.3 Hydraulic fluids 207
10.4.4 Jet fuel 207

10.5 The space environment 208
10.6 Bio-sensitivity 209
References 210

11 The applications of thermoplastic structural composites 213
11.1 Medical uses 213
11.2 Satellites and launch vehicles 214
11.3 Aircraft structures 216
11.4 Marine applications 217
11.5 Automotive engineering 217
11.6 Industrial machinery 218
References 220

12 Future developments in thermoplastic structural composites 222
12.1 New thermoplastic composites 222
12.2 Thermoplastic design strategies 224
12.3 Processing technology 225
12.4 Resource management 226
12.5 Added function 227
12.6 Envoy 228

Appendices
1 Description of laminates 229
2 The importance of shear properties in the matrix 231
3 Mixtures of rods and coils 233
4 The description of molecular weight and its significance 235
5 Estimation of effective chain diameter 236
6 Radius of gyration of a molecule 238
7 Some issues in solution impregnation 239
8 Thermophysical properties of carbon fibre reinforced polyetheretherketone containing 61 per cent by volume of high strength carbon fibre 241
9 Flow mechanisms in discontinuous aligned product forms and in crimped fibre systems 242
10 A comparison of axial and transverse intraply shear viscosities for thermoplastic composites 244
11 Transverse squeezing flow 246
12 Platen pressing of carbon fibre/PEEK laminates 249
13 Bagging materials for thermoplastic composites 250
14 Thermal expansion transverse to the fibre direction 251
15 Influence of resin rich interlayers on shear compliance 253
16 Stiffness characteristics of carbon fibre/PEEK composites – a review 254
17 Strengths of carbon fibre/PEEK laminates 257
18 Fracture toughness data on carbon fibre/PEEK composites at 23°C 259

Subject index 263

Author index 269

1 An introduction to thermoplastic composite materials

1.1 Towards designed materials

The history of mankind can be written in terms of his use of materials. In the first place such materials were provided by nature; wood and stone are still abundant and can be both aesthetically pleasing and extremely serviceable. A second stage was to fashion those materials for a purpose: for example by hardening wood in a fire, or chipping flints to provide sharp edges. The discovery that nature also provided metals expanded the technological horizon of our ancestors and initiated a search for new and improved materials: it is no accident that, in a great many of our universities today, the disciplines of metallurgy and materials science are strongly coupled. However, in the last fifty years, following the chemical discoveries of nylon and polyethylene, the emphasis for new materials research has progressively moved towards non-metallic materials and especially the family of polymeric materials known as plastics. Simple plastics have limitations as structural materials, and it is with structural materials that man builds his world. In order to overcome these limitations recourse has been made to the expedient of reinforcing those resins with fibres to provide a family of composite materials, which, since the development of carbon fibres, have been able to compete with metals as structural materials. In this family technologists bring together the skills of diverse scientific disciplines to provide materials whose properties can be tailored to a specific need. Such structural composite materials are the heralds of the Age of Designed Materials.

Fibre reinforced polymeric composite materials have three elements: the reinforcing fibre, the matrix resin and the interface between them. Consider a piece of composite material the size of a little finger with a volume of 10 millilitres. Such a piece of composite, based on 60% by volume of carbon fibres of diameter 7 micrometers, contains 160 kilometres of fibre, 4 millilitres of resin and 3½ square metres of interface – the distance from London to Birmingham, the volume of a thimble, and the area of a large dining table respectively. The reinforcing fibres are stiff, often with a modulus higher than that of steel, but because they are also slender – 7 microns is just visible to the naked eye – they feel silky to touch. It is only when they are stuck together with resin that their rigidity becomes apparent. It is the reinforcing fibre which largely determines the stiffness and strength of the composite. For optimum effect they are highly collimated so as to provide a high volume packing: hexagonal close packing would, in theory, allow 91% by volume of fibres to be achieved, but, in practice, most commercial structural composite materials utilize 60–65% by volume of fibres.

High collimation of the fibres provides the maximum possible reinforcing effect along the axis of the fibre. Transverse to that direction there is little effective reinforcement. This anisotropy of properties provides added freedom to the designer, who can now arrange the reinforcement in his materials according to the load paths in the structure that he is building. The matrix resin transfers stress between the fibres and stabilizes those fibres when the structure is subjected to compression loadings. It must provide this service when under attack by hostile environments. The resin is also the medium which determines the processes by which the composite material is shaped into a structure and, during that process, it protects the reinforcing fibres from damage by attrition. The stiffness and strength of the resin is usually low in comparison to that of the fibres – a factor of 100 between reinforcement and resin modulus is common – but the resin plays a vital role both in determining the serviceability and the processability of the material.

The third element in a composite material is the interface between the resin and the reinforcement. The physical constraints provided by a high loading of fine diameter fibres is often sufficient to affect the properties of the resin in the neighbourhood of the fibre. In addition the fibres themselves may have chemically activated surfaces or be coated to promote adhesion of the resin. Thus, instead of a simple interface between materials, it may be more correct to consider an interphase. In a system containing 60% by volume of reinforcing fibres 7 μm in diameter the mean thickness of resin coating on each fibre is 1 μm and any 'interphase' may extend through the whole of the matrix. The integrity of the interface plays a critical role in optimizing the service performance of the composite material, especially in respect of the resistance to hostile environments and in determining the toughness of a composite. The reinforcement, matrix and interface act together to achieve optimized serviceability.

There are several texts[1–10] that describe the science of fibre reinforced composite materials – their history, application and potential – as viewed from different perspectives. Particular emphasis is naturally placed upon their mechanical performance, which depends upon their laminar construction. The basic building block of composite structures is a simple lamina of collimated fibres typically ⅛ mm thick (Figure 1.1).

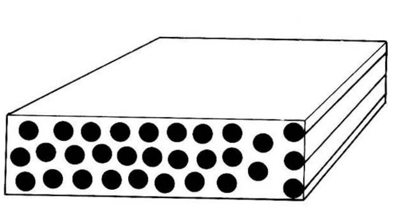


Figure 1.1 Basic building block: a lamina of collimated fibres

Along the fibre direction the theoretical stiffness of the composite lamina is given by:

$$\text{AXIAL STIFFNESS} = V_F E_F + V_M E_M$$

where V_F is the volume fraction of the reinforcing fibre
V_M is the volume fraction of the matrix resin
E_F is the modulus of the reinforcing fibre
E_M is the modulus of the matrix resin

Usually the modulus of the fibre is much greater than that of the resin, and a good approximation to the axial stiffness of the composite can be made by ignoring the resin component. Transverse to the fibre direction there is much less reinforcement. In this direction the fibres themselves may be significantly less stiff than along their axis, and since their cross-section has a very low aspect ratio, they will have little reinforcing effect but simply act as a filler. As a first approximation the transverse stiffness can be taken as:

$$\text{TRANSVERSE STIFFNESS} = E_M / V_M$$

In general, composite materials are not used as simple axial laminates, because structures have to accept a variety of loading patterns. To accommodate such loads, simple shell structures are usually laminated with the individual plies or laminae oriented in different directions (a description of such laminates is given in Appendix 1). A quasi-isotropic laminate is one in which the composite layers have been arranged so that, in the plane of the moulding, the properties are the same in any direction. High stiffness and strength are only part of the equation in the design of structures. Compared to metals, composite materials have a relatively low density: the single outstanding property of carbon fibre reinforced plastics is their stiffness per unit weight (Table 1.1).

Table 1.1 Comparative weights of panels with same bending stiffness

Material	*Modulus* GN/m^2	*Relative thickness*	*Specific gravity*	*Relative weight*
Metal				
Steel	210	1	7.8	7.8
Aluminium	73	1.4	2.7	3.8
Aircraft grade composite				
Quasi-isotropic	40	1.7	1.6	2.7
Uniaxial	120	1.2	1.6	1.9
Space grade composite				
Uniaxial	300	0.9	1.6	1.4

The low density of composite materials increases the thickness of a panel. This further increases the stiffness, allowing composites to achieve 30% weight-saving in comparison to aluminium structures of the same flexural stiffness. There are still the through thickness properties of the laminate to be considered. In general, structures are not designed to carry loads in this direction but adventitious loads may occur, and the design of composite structures should also take account of those through thickness properties. This is one of the areas where we shall see that thermoplastic composites have demonstrated exceptional advantage.

A further major structural advantage of composite materials is that they have proved themselves to be exceptionally resistant to fatigue in comparison with metals. In addition, because it is possible to design the material at the point of manufacture, it is possible to tailor in certain features, such as dielectric properties, to achieve highly specific effects: one of the earliest and most successful uses of glass fibre reinforced plastics has been in the provision of radomes in aircraft[11]. A further service advantage is resistance to corrosion, where polymeric materials have an excellent record.

As well as their advantages in service, the introduction of polymeric composite materials can significantly reduce the total part count in building a structure. This leads to economies of manufacture. There is one area where composite materials have yet to attain their full potential. At this time the field of structural design is, in practice, largely based on a metals history, i.e. design practice is to assume isotropic materials. At the present time many of the structures that are built from composite materials are based upon modified 'metal' designs, but there are notable exceptions where the principle of anisotropy is a cornerstone. The theory of anisotropic design is established[12] but it has only become so during the last twenty years. It will be of great significance to the future of designed materials to see how those who have been schooled in anisotropic design apply those principles in practice.

As well as the bulk properties of materials, there is a growing opportunity to tailor the surface of a material. At this time such tailoring in composite materials tends to be at the interface between fibre and resin or a surface modification to functionalize two surfaces in order to facilitate joining them together. Ultimately that principle of surface modification will also be expressed as a way of adding service function to the exterior of a structure.

Our present generation of reinforced plastics is only making relatively limited use of the composite concept. Fibres can carry messages as well as loads; the incorporation of piezo-electric elements in a structure can make it responsive; the notion of combining 1 kg of computer for every 10 kg of structure would provide memory and adaptive learning ability; the principle of 'smart' materials is, of necessity, a composite concept. The present generation of composite materials offers significant advantages to the designer of today; the designer of tomorrow has the opportunity to tailor those materials to the needs of the function he seeks to achieve.

From this introduction it is necessary to refine the objectives of this work. It is my belief that, provided the broad picture is retained in view, the study in depth of a narrow part of the field of the science of materials can lead to the proposition of general principles whose validity can subsequently be tested. Thus I seek to provide that study in depth within a narrow field. This study provides a self-consistent body of data from which the relation between different functions of the material can be established. The organization of this work, which necessarily encompasses a wide range of scientific disciplines, should then provide a picture against which other systems may be compared and contrasted. Lastly, it is desirable that the subject matter of the detailed study should be both timely and of lasting value. These considerations lead to the selection of thermoplastic structural composites and, in particular, their paradigm – carbon fibre reinforced polyetheretherketone – as the theme.

1.2 Why thermoplastic structural composites?

In 1990 thermoplastic composites represented about 3% of the total market for polymer matrix structural composites. The greater part of organic matrix composites presently in service are based on crosslinkable thermosetting resins. Of these, epoxy resins are the most prolific representatives. When carbon fibres were first introduced, there were several attempts[13–17] to develop composite materials based on thermoplastic polymers such as the polysulphone family. By creating low viscosity polymer solutions, the reinforcing fibres could be impregnated with such resins[18]. However, it proved extremely difficult to eliminate residual solvents from such materials[19,20], and their retention caused problems, including blistering of the moulding and a reduction in properties, particularly at high temperature. Further, the use of solution technology betrayed a sensitivity of those amorphous polymers to attack by chemical reagents. Since composites were of particular interest to the aerospace industry, where hydraulic fluids, aviation fuels and the use of paint strippers are widely encountered, soluble materials were placed at a severe disadvantage. Not all thermoplastic composites were made by solution processing: it was possible to interleave layers of reinforcing fibres and resin films and then, in a protracted moulding operation, wet out the fibres in a high-pressure moulding process[21–3]. Such film stacked composites gained a small niche in the market place but, for the most part, the field of structural composite materials was ceded to ccrosslinkable thermosetting resins. Because of the convenience with which epoxy resin systems could be hand layed up into structures, thermosetting composite materials became established as excellent prototyping materials and were gradually translated into full scale production.

By 1980, three problems had become evident with epoxy composite materials: their brittleness, their sensitivity to water, and the slow manufacturing technology. Although it was possible to improve either the toughness or the water resistance of epoxy composite materials, a common experience was that an improvement in one property usually led to a falling off in the other. The introduction of preimpregnated carbon fibre reinforced polyetheretherketone, a high temperature semi-crystalline polymer, in continuous tape form[24] simultaneously offered a solution to the problems of toughness and environmental resistance, with the added bonus of potentially developing high rate processing: thermoplastic materials were translated into a major platform for research and product development. These material forms are now becoming qualified products. They extend the range of applications established for their thermosetting cousins in particular into that segment of industrial activity that requires high rate automated fabrication.

Thermoplastic matrix materials derive their properties from their long chain entangled molecules. The entanglement of the chains provides the matrix with strength and effectively acts as a temporary crosslink. Because the chains are not fixed by their chemical structure, they have the ability to slip past one another when subjected to intense local stress; thus, whereas a crosslinked polymer has no alternative but to be strong or to break in a brittle fashion, a linear chain polymer has the ability to dissipate energy locally by chain slippage. This ability confers the property of toughness on the composite. Some linear chain polymers also have the ability to pack tightly together in a semi-crystalline network. This network also provides an effective physical crosslink in the system, enhancing strength. The crystalline structure further provides resistance to attack by hostile reagents. When a linear chain, thermoplastic, polymer is melted the chains may move freely with respect to one another, so that the composite can be formed into shape. In contrast to their thermosetting cousins, with long chain thermoplastic materials this shaping process is a purely physical one, depending on heat transfer, geometry and the forces applied. The absence of chemistry, the necessary companion of thermosetting processing, means that thermoplastic polymers can be fabricated into structures rapidly and with a high level of quality assurance: all the chemistry has been carried out by those people whose business is chemistry, leaving the fabricator free to concentrate wholly upon his art of making shapes.

The potential for rapid processing with thermoplastic structural composites is of particular significance. With high performance thermosetting resins the cure cycle is usually several hours long: with thermoplastics the absence of chemistry means that structures can be formed in minutes, or even seconds. The protracted nature of thermoset processing is not necessarily a constraint in industries, such as aerospace, where the required rate of production may be less than one a day and each individual structural component must be optimally tailored to shape. In such circumstances the advantages of low capital expenditure on tooling may justify the use of slow, labour intensive, fabrication processes. Such a vision, however, unnecessarily limits the horizon of structural composite materials. For the first twenty years of their life it was widely believed that carbon fibre reinforced plastics would make the transition from specialist aerospace materials to general industrial products: considerable investment in carbon fibre capacity testifies to that belief, but, except in the area of high performance sporting goods and short fibre moulding compounds, the penetration has been disappointingly small. The difficulty in achieving that translation has been the requirement for appropriate mass production technology for high performance structural composites. Thermoplastic structural composites offer the potential for mass production, which may provide the key to the metamorphosis of high performance composite materials into high quality mass production materials for the general industrial designer.

The thermoplastic family of materials is particularly broad in respect of the service it can offer. There are a wide range of resins: elastomeric materials such as polyurethanes, general purpose resins such as polypropylene, engineering plastics