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Introduction

Composite materials are available in many forms and are produced using a variety of manufacturing methods. A range of fibre types is used – primarily carbon and glass – and these can be combined with a variety of polymer matrices. This book concentrates on 'long' fibre composites, including fibres from a few centimetres in length (i.e. excluding injection moulding compounds). So the processing methods of interest include compression moulding of thermoplastic or thermoset moulding compounds; resin transfer moulding based on dry fibre preforms; forming and consolidation of thermoset prepreg and thermoplastic sheets; and forming of new material forms including composite/metal laminates and polymer/polymer (self-reinforced) composites.

Whatever the material form or manufacturing process, there is one common step: forming of initially planar material into a three dimensional shape. This is the focus of 'Composite Forming Technologies'. The book includes descriptions of industrial forming processes, case studies and applications, and methods used to simulate composite forming. This description is intended for manufacturers of polymer composite components, end-users and designers, researchers in the fields of structural materials and manufacturing, and materials suppliers. Whilst the bulk of the text is devoted to modelling tools, the intention is to provide useful guidance and to inform the reader of the current status and limitations of both research and commercial tools. It is hoped that this will form essential reading for the users of such modelling tools, whilst encouraging others to 'take the plunge' and adopt a simulation approach to manufacturing process design.

This text may be considered broadly in two halves, with Chapters 1–7 covering the fundamental aspects of modelling and simulation, and Chapters 8–13 describing practical aspects including manufacturing technologies and modern practices in composites design. The first chapter provides a comprehensive introduction to the range of deformation mechanisms that can occur during forming for a range of materials, along with appropriate test methods and representative data. Chapter 2 describes fundamental constitutive models as required for composite forming, including the bases for commercial kinematic (draping) and mechanical (forming) simulations. The latter topic is continued in Chapter 3, including a detailed description of finite element simulation techniques for forming of dry fabric preforms. The methodology here can be considered similar to that used for sheet metal forming, albeit with a more complex material model. Chapter 4 continues the modelling theme, with a description of 'virtual testing', whereby materials input data for forming simulation are predicted from the material structure. This topic is of particular interest, as it may offer the opportunity to select materials that are fit-for-forming, or even to design new materials with a specific component in mind. Chapter 5 details the use of modern simulation techniques for composite forming within an optimisation scheme, with the aim of selecting materials and process parameters to eliminate such defects as wrinkling or undesirable fibre orientations. Chapter 6 describes the methodology and current status of simulation tools for compression moulding, including applications to sheet moulding compound (SMC) and glass mat thermoplastic (GMT). The following chapter completes the initial treatment of simulation and modelling, with a description of composite distortion – notably the common phenomenon of 'spring-in' – caused by manufacturing induced stresses.

The second half of the book begins with four chapters describing forming technologies for a range of materials. This begins with a relatively new family of materials – composite/metal hybrids – which have recently found applications in the aerospace sector (notably as fuselage panels for the Airbus A380). Another new family is covered next, referred to as 'self-reinforced polymers'. These materials include fibre and matrix from the same polymer material, addressing one of the current concerns for polymer composites – recycling. The next two chapters cover more conventional materials – thermoset prepreg and thermoplastic composite sheet. Prepreg forming technologies are described in detail, from the traditional hand lay-up and autoclave cure approach to current developments in automated tape placement and diaphragm forming. The thermoplastics chapter includes a detailed description of the range of material forms, along with their appropriate forming and consolidation techniques. Chapter 12 describes the current state-of-the-art in simulation software for composite forming within an industrial context, detailing the use of modern software tools to design the material lay-up, and describing how these tools can be integrated within the manufacturing environment. Finally Chapter 13 covers the issue of benchmarking of composite forming. This topic is particularly timely, drawing on current worldwide efforts to compare both formability characterisation tests and forming simulation tools for benchmark materials. It is hoped that this will lead to standardisation of formability testing – a key requirement for more widespread use of analysis tools – and guidelines on the accuracy of the range of simulation approaches that are currently available.

Contents

1
Composite forming mechanisms and materials characterisation

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1.1 Introduction

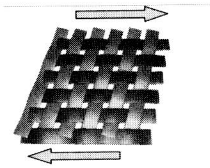
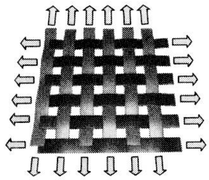
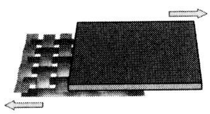
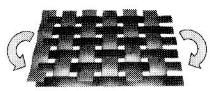
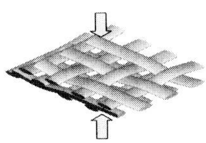
This chapter describes the primary deformation mechanisms that occur during composites forming. Experimental procedures to measure material behaviour are described, and typical material behaviour is discussed. The scope of this description is reasonably broad, and is relevant to a variety of manufacturing processes. While other materials will be mentioned, the focus here is on forming materials based on continuous, aligned reinforcing fibres. Specifically, materials of interest here include:

- Dry fabrics, formed to produce preforms for liquid composite moulding.
- Prepregs, comprising aligned fibres (unidirectional or interlaced as a textile) within a polymeric (thermoset or thermoplastic) matrix.

While other materials are also formed during composites processing, the above have received by far the most attention amongst the research community. The techniques described here can also be applied to polymer/polymer composites, although these materials present a number of challenges (see Chapter 9). Moulding compounds such as glass-mat thermoplastics (GMTs) and thermoset sheet moulding compounds (SMCs) are formed by a compression (flow) moulding process; here formability is usually characterised by rheometry (see Chapter 6).

Focusing on continuous, aligned fibre materials, a number of deformation mechanisms during forming can be identified (Table 1.1). The remainder of this chapter will focus on methods for characterising materials behaviour. Materials testing typically has a number of objectives. Often the primary motivation is simply to understand materials behaviour during forming, and in particular to rank materials in terms of formability. If this can be related to the material structure, then this understanding may facilitate design of new materials or optimisation of manufacturing process conditions. Another aim may be to obtain materials data for forming simulation. For the most advanced codes, this may

Table 1.1 Deformation mechanisms for continuous, aligned fibre based materials during forming

Mechanism	Schematic	Characteristics
Intra-ply shear		• Rotation of between parallel tows and at tow crossovers, followed by inter-tow compaction • Rate and temperature dependent for prepreg • Key deformation mode (along with bending) for biaxial reinforcements to form 3D shapes
Intra-ply tensile loading		• Extension parallel to tow direction(s) • For woven materials initial stiffness low until tows straighten; biaxial response governed by level of crimp and tow compressibility • Accounts for relatively small strains but represents primary source for energy dissipation during forming
Ply/tool or ply/ply shear		• Relative movement between individual layers and tools • Not generally possible to define single friction coefficient; behaviour is pressure and (for prepreg) rate and temperature dependent
Ply bending		• Bending of individual layers • Stiffness significantly lower than in-plane stiffness as fibres within tows can slide relative to each other; rate and temperature dependent for prepreg • Only mode required for forming of single curvature and critical requirement for double curvature
Compaction/ consolidation		• Thickness reduction resulting in increase in fibre volume fraction and (for prepreg) void reduction • For prepreg behaviour is rate and temperature dependent.