
POLYMER BLENDS AND ALLOYS

Edited by
M. J. Folkes and P.S. Hope



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Contributors

Dr P.T. Alder	Courtaulds Films, Cheney Manor, Swindon, Wiltshire SN2 2QF
Dr R.G.C. Arridge	H.H. Wills Physics Laboratory, University of Bristol, Royal Fort, Tyndall Avenue, Bristol BS8 1TL
Mr J.G. Bonner	BP Chemicals Limited, PO Box 21, Bo'ness Road, Grangemouth, Stirlingshire FK3 9XH
Mr C.S. Brown	National Physical Laboratory, Queen's Road, Teddington, Middlesex TW11 0LW
Mr J.E. Curry	Werner & Pfliederer Corporation, 663 E. Crescent Avenue, Ramsay, NJ 07446, USA
Dr M.J. Folkes	Department of Materials Technology, Brunel University, Uxbridge, Middlesex, UB8 3PH
Dr P.S. Hope	BP Chemicals Limited, PO Box 21, Bo'ness Road, Grangemouth, Stirlingshire FK3 9XH
Dr W.H. Lee	Department of Materials Technology, Brunel University, Uxbridge, Middlesex, UB8 3PH
Professor J. Lyngaae-Jørgensen	Technical University of Denmark, Instituttet for Kemiindustri, DTH Building 227, DK-2800 Lyngby, Denmark
Dr S.C. Steadman	PERA, Melton Mowbray, Leicestershire LE13 0PB
Dr D. Vesely	Department of Materials Technology, Brunel University, Uxbridge, Middlesex, UB8 3PH

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1 Introduction

P.S. HOPE and M.J. FOLKES

Mixing two or more polymers together to produce blends or alloys is a well-established strategy for achieving a specified portfolio of physical properties, without the need to synthesise specialised polymer systems. The subject is vast and has been the focus of much work, both theoretical and experimental. Much of the earlier work in this field was necessarily empirical and many of the blends produced were of academic rather than commercial interest.

The manner in which two (or more) polymers are compounded together is of vital importance in controlling the properties of blends. Moreover, particularly through detailed rheological studies, it is becoming apparent that processing can provide a wide range of blend microstructures. In an extreme, this is exemplified by the *in situ* formation of fibres resulting from the imposition of predetermined flow fields on blends, when in the solution or melt state. The microstructures produced in this case transform the blend into a true fibre composite; this parallels earlier work on the deformation of metal alloys. This type of processing–structure–property correlation opens up many new possibilities for innovative applications; for example, the production of stiff fibre composites and blends having anisotropic transport properties, such as novel membranes.

This book serves a dual purpose. On the one hand it provides an up-date on the more conventional activities in the field of polymer blends, with a focus on practical aspects of use to the technologist interested in the development of blends or the design of production processes. To this end chapters are included on the rheology, processing and compatibilisation of blends, along with practical introductions to techniques for studying microstructure, and for modelling and understanding their mechanical performance. Even more important, it will introduce workers in both industry and academia to some of the forward-looking possibilities which the informed processing of polymer blends can offer, including the use of liquid crystal polymers and the novel development of *in situ* fibre composites.

Starting with the important area of blend production, Curry, in chapter 2, addresses some practical aspects of polymer blend processing, concentrating mainly on describing the operating principles and performance characteristics of compounding equipment suitable for the preparation of blends and alloys. The main features of the many different commercially available compounds are presented, with reference to their historical development, and practical

studies of the mixing mechanisms which operate in such processes are reviewed. Consideration is also given to the fundamental mechanisms of polymer dispersion, which are primarily responsible for the final phase morphology of immiscible blends. Theoretical and model experimental approaches to the issues of droplet break-up and coalescence are discussed, and it is concluded that these fundamental studies currently cannot predict the outcome of commercial processes, far less be used to design them; however, they do lead to some general rules which are useful for the technologist involved in blend development. The formulation of these guidelines is followed by a study of the performance of five commonly used compounders, carried out on both immiscible blends of low density polyethylene and polystyrene, and similar blends in the presence of a compatibiliser. It is clear from this work that choice of compounder and operating conditions affects the phase morphology of the resulting blend or alloy, and moreover that simply increasing the specific mechanical energy input to the compounding processes does not guarantee production of finer morphologies.

Compatibilisation, that is to say modification of normally immiscible blends to give alloys with improved end-use performance, is an important factor in almost all commercial blends, and has been the subject of an enormous amount of experimental investigation, much of which remains proprietary. The reasons for compatibilising blends, and the strategies which can be employed, are dealt with in some detail by Bonner and Hope in chapter 3. The main methods of achieving compatibility are via addition of block and graft copolymers, or functional/reactive polymers, and *in situ* grafting or polymerisation (reactive blending). Which approach to employ will depend very specifically on the blend system under consideration, the technology available and (not least) the cost. For the convenience of the user the literature is reviewed in two parts; blend systems where separate compatibilisers are added, and those where compatibility is achieved by using reactive blending technology. Particular attention is paid to the most extensively researched systems (polyethylene/polystyrene blends, and blends containing polyamides). Future trends in which compatibilisation holds the key to commercial success are also identified. These include engineering polymer blends, aimed at very high performance applications such as aerospace products, superior performance commodity polymers, in which improved performance (e.g. thermal or permeation resistance) are imparted by addition of engineering polymers, and polymer recycling, for which compatibilisation may offer a more cost-effective alternative to separation technology.

In chapter 4 the rheology of polymer blends is explored by Lyngaae-Jørgensen, with particular regard to its role in the development of phase morphology during the production and processing of immiscible blends. The main rheological functions are introduced, followed by a summary of the rheological behaviour of miscible blends, blends exhibiting phase transitions during flow and immiscible blends. For immiscible blends in particular it is

clear that the rheology can be extremely complex, and that although recognisable and useful rheometric data can be obtained, unusual relationships, e.g. between viscosity and composition, are commonplace. Interpretation of these complex functions demands a 'microrheological' approach, taking into account the phase structure and the interfacial characteristics of the component polymers. Theoretical approaches to the issues of droplet break-up and coalescence during flow, introduced in chapter 2, are presented in more detail, including extension to include non-steady-state flow, and are illustrated by a case study for structure development during simple shear flow.

Chapter 4 also addresses the more complex flows which occur in extrusion and moulding processes. Experimental studies of extrusion and batch mixing processes have shown that most of the significant morphology development occurs very early in the process, mainly in the melting and softening stages. Prediction of the behaviour of polymer blends in all stages of an extrusion process—typically solids feeding and flow, melting, mixing, melt flow and solidification—is the subject of much current research but a total simulation is unlikely to be achieved in the foreseeable future, if ever. For this reason a more pragmatic approach based on dimensional analysis is advocated, which revolves around characterising the process in terms of dimensionless droplet break-up time, component viscosity ratio and capillarity number. Using this approach it is possible to identify some practical and quantitative guidelines for predicting the development of blend morphology during compounding processes.

As well as influencing—and being influenced by—rheology, as discussed above, the microstructure of polymer blends, and in particular their phase morphology, plays a major role in determining end-use performance. It is therefore important for those who are developing new blends, and indeed for technologists working with existing blends, to have available methods for studying phase structure and other microstructural features. In chapter 5, Vesely provides a practical guide to techniques for studying blend microstructure. The focus is mainly on microscopy, which in its various forms (light microscopy, scanning and transmission electron microscopy) provides the most useful and direct tool for observation of phase morphology. Details of operating principles and techniques are described, and practical advice is given on the application of a range of microscopy methods to polymer blends. Thermal analysis methods are also extensively used, particularly for measuring glass transition temperatures and characterising melting/crystallisation behaviour, and their application to blends is outlined. Other techniques (light scattering, neutron and X-ray scattering, and spectroscopy) are also briefly described. It is clear that in many cases combinations of measurement techniques are required to get a sufficiently useful picture of microstructure.

Chapters 6 and 7 are concerned with the end-use performance of polymer blends. Arridge (chapter 6) tackles theoretical aspects of polymer blends and alloys and explains, in some mathematical detail, the theory which exists for

predicting the mechanical properties of composites and blends from component properties. For real blends and alloys this rigorous approach is essentially limited to the prediction of small strain behaviour (e.g. elastic constants) using linear viscoelastic representations. After general introductions to continuum mechanics, viscoelasticity and methods of representing structural anisotropy, predictive equations applicable to blends and alloys are presented and limitations to their use are discussed. The approach taken to predicting the properties of inhomogeneous (phase separated) blends is to treat them as composite materials, for which the properties of the composite phases can be combined using mixing rules of varying complexity. This provides a sound basis for understanding mechanical performance and will serve as a guide to further study for those involved in developing new materials.

Toughened polymers represent a large and rapidly evolving application area for polymer blends, particularly for engineering resins, where the requirements in terms of specific mechanical performance, sometimes at light product weights and at high operating temperatures, are exceptionally demanding. Established high-performance systems are repeatedly modified and improved largely by innovations in synthesis and compounding to produce more effective blends and alloys. In chapter 7 Lee provides a comprehensive survey of the toughening methods available for use in thermoplastics and thermosets. For thermoplastics, where toughening is achieved predominantly by incorporation of rubbery inclusions, the compatibilisation methods introduced in chapter 3 are revisited, but with emphasis on the more recent advances related to toughened polymers. More attention is paid in this chapter to toughening methods for the novel thermoset resins, including epoxy, cyanate ester and bismaleimide resins, developed in recent years as matrices for fibre-reinforced aerospace composites. The different processing technology associated with thermosets demands different toughening strategies. These include not only the introduction of rubbery inclusions but also incorporation of thermoplastic or rigid particulate fillers, and the use of semi-interpenetrating networks. The diverse mechanisms by which toughening can be achieved are reviewed, and related to specific material systems. These include shear yielding, crazing and voiding of the matrix polymer, cavitation, tearing and ductile drawing of rubber particles and other soft inclusions, and crack-pinning mechanisms. The role of particle size distribution and the influence of processing on toughness are also discussed.

Chapters 8 and 9 describe two of the new developments in polymer blends which offer potentially exciting future opportunities for commercial materials. Brown and Alder (chapter 8) present a review of work to date on the development of blends containing liquid crystal polymers (LCPs). The unusual flow and subsequent mechanical property behaviour of LCPs, which under suitable conditions can exist as structurally ordered fluids, makes them interesting materials in their own right. Commercial interest is growing in

their use in blends, although their high cost currently inhibits exploitation. One significant feature of blends containing thermotropic LCPs is their ability in some cases to significantly alter the rheology of the blend, often giving reductions in viscosity. Although the mechanisms by which LCP addition modifies flow behaviour are not well understood, a variety of effects have been observed in processing blends containing LCPs, some of which may prove to be of practical interest (for example reductions in melt temperature, melt pressure and extruder torque). A second feature of LCP blends is their ability to form a fibrillar structure during processing, giving a self-reinforcing effect, although poor interface adhesion and difficulty in controlling phase morphology have so far prevented realisation of potential. However, the study of blends containing LCPs is in its infancy and could offer exciting future possibilities.

The field of fibre-forming blends, and *in situ* composites, is itself an emerging technology, ultimately offering the potential to manufacture high performance composites via less expensive production routes than those currently used. In chapter 9 Steadman describes these complex systems, in which fibre-forming polymers are introduced to host matrices and then oriented to give reinforced structures. Methods of achieving this include *in situ* crystallisation or polymerisation of the fibre-forming polymer and the use of thermotropic LCP blends. Clearly the technology depends for its success on understanding numerous factors; for example how to control and achieve the desired blend morphology, including the effective use of compatibilisers, the response of the fibre-forming phase to elongational (orienting) flows during forming and the ability to control the placement of orientation-inducing flows in complex geometries. After a review of the field, a detailed study is presented using high density polyethylene as the fibre-forming phase and a polystyrene–polybutadiene–polystyrene (SBS) block copolymer as the matrix. Blends produced on a co-rotating twin-screw extruder and subsequently ram extruded or uniaxially drawn at a range of temperatures produced composites containing polyethylene fibrils with stiffnesses equivalent to E-glass fibres. This highly promising result points the way to an exciting future if the technology can be harnessed for use with other thermoplastic matrices.

Finally, it is clear that a book of this nature cannot comprehensively cover a field which is enormous in terms of the breadth of science and technology and the diversity of materials systems employed, and which is growing rapidly. It does, however, pull together the key technology issues in sufficient depth to provide the newcomer with a grasp of their scope and significance and to point the way forward in some of the emerging new technologies. This will no doubt prompt the reader to enquire further in his or her area of interest; to assist in this the bibliography below contains a few of the excellent books published in the field in recent years. Utracki (1989) in particular contains recent and comprehensive summaries of patent literature and commercially available

blends. However, any amount of reading can do little more than provide the tools needed for the job; the way forward in this fertile area must then be left to the ingenuity of the blend developer.

Bibliography

- Paul, D.R. and Newman, S. (eds) (1978) *Polymer Blends*, Academic Press, New York.
Utracki, L.A. (1989) *Polymer Alloys and Blends: Thermodynamics and Rheology*, Hanser, Munich, Vienna, New York.
Walsh, D.J., Higgins, J.S. and Maconnachie, A. (eds) (1985) *Polymer Blends and Mixtures*, Martinus Nijhoff, Dordrecht.

2 Practical aspects of processing of blends

J.E. CURRY

2.1 Introduction

This chapter appears amid an environment of intensive investigation into the thermodynamics and flow behavior of polymer blends themselves and an enhanced understanding of the kinematic behavior of mixing devices. As in other fields, the digital computer has multiplied the detail with which physicists can explain the observed development of blend morphology and engineers can elucidate on the deformation and stress effects of their mixer design. An argument could be made to let the controversy settle before going to print. On the other hand, a consensus of identifying cause and effect has developed which should be published.

The objective of this chapter is to present the machinery, techniques and analysis of commercial polymer blending processes.

2.1.1 History

The development of modern compounders with their complicated gear trains, precision tooling, high tech metallurgy, and intricate process geometries can be traced [1, 2] through a history of personal rivalries, international cooperations, corporate cartels, military urgency and war reparations. What has evolved represents economic and marketing successes as well as reliable technical solutions.

The earliest compounders were developed as dough mixers in the food industry and coincidentally as mixers for viscous chemicals like rubber, gutta percha, masonry products, and soap. Mixers and extruders were originally developed to separately mix and then transport or shape viscous masses.

2.1.2 Mixers

Single-shaft (Figure 2.1). Plodders, paddle mixers, and ribbon blenders are used primarily for powder blending and, sometimes, in the jargon of plasticized polymers, for preparation of the 'dry mix', a plasticizer loaded polymer powder. The mixers may have close fitting rotors, heated barrel jackets, alternately pitched rotors and barrel pins to enhance mixing, as well as

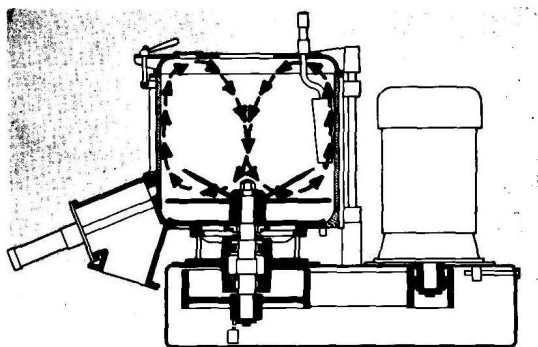
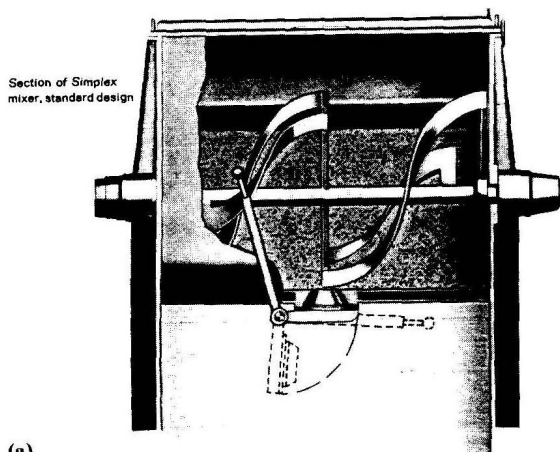


Figure 2.1 Single-shaft mixers used for feedstock blending. (a) Low intensity ribbon blender, simplex model (courtesy of Werner & Pfleiderer Corporation). (b) High intensity blender model MA (courtesy of T.K. Fielder).

ingenious dump and opening mechanisms to allow complete emptying and access for cleaning. These mixers are not normally used for plasticating processes.

A second class of single-shaft mixers is the intensity blender which is distinguished by its rugged design and high shaft speed with tip speeds in excess of 40 m s^{-1} . In addition to mixing, subtle morphology changes can be effected by the so-called thermokinetic action. These changes include blend sintering and powder densification.

Multishaft. Deficiencies of single-shaft mixers include an inability to generate high mechanical stress fields throughout a large portion of the mix volume and a tendency of plasticated mixes to stick to the rotor.

From the 1840s onward, generations of mills, cutters and multishaft mixers were invented in the industrial centers of the time; the US, England, and industrialized states of current Germany. These devices melted, mixed, stuffed and coated rubber, doughs, sausages, ceramics and the other viscous masses of the day on a commodity scale for the first time.

In the early 20th century a highly successful class of internal mixers was developed which survives and has spawned a continuously operating counterpart. In 1916, F.H. Banbury of Werner & Pfleiderer (Saginaw, Mich.) was granted a patent for a counter-rotating batch mixer whose shafts rotate at different speeds and whose charge is contained by a ram (Figure 2.2). The rotor design which caused flows to circulate through the chamber was an adaptation

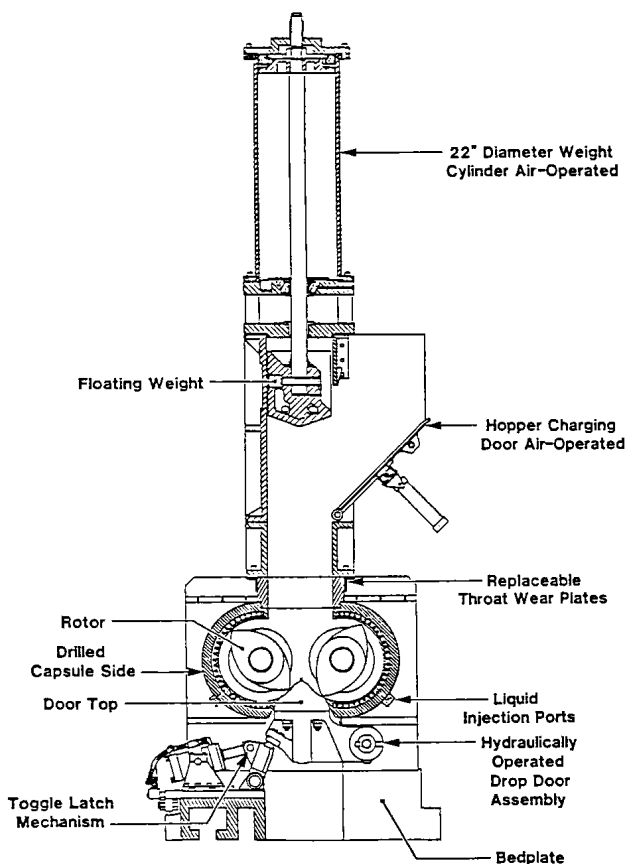


Figure 2.2 Plasticating multi-shaft batch mixer after the Banbury Patent, Model F270 (courtesy of Farrel Corporation).