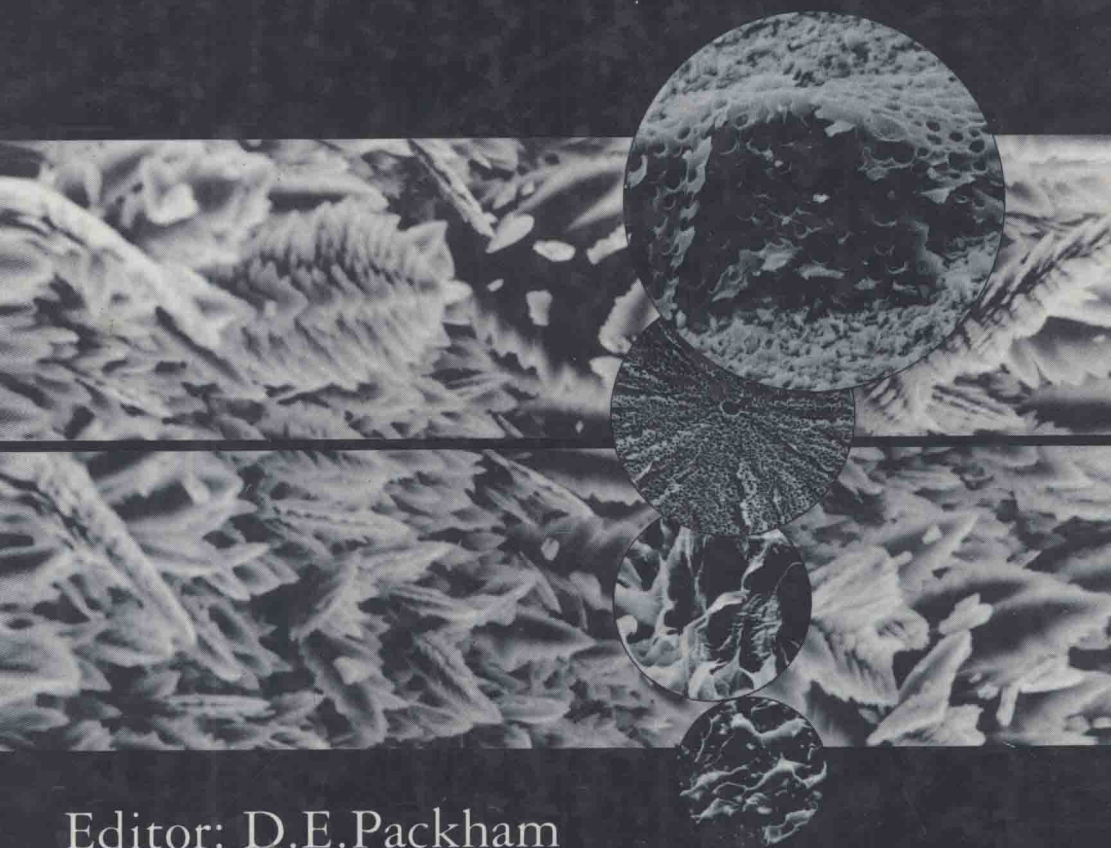


# Handbook of Adhesion



Editor: D.E.Packham

POLYMER SCIENCE & TECHNOLOGY SERIES

POLYMER SCIENCE AND TECHNOLOGY SERIES

SERIES EDITORS: DR D M BREWIS AND PROFESSOR D BRIGGS

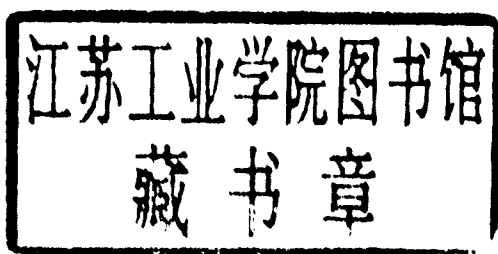
---

# HANDBOOK OF ADHESION

---

EDITOR:  
D E PACKHAM

SCHOOL OF MATERIALS SCIENCE  
UNIVERSITY OF BATH



**Longman Scientific & Technical**  
Longman Group UK Ltd  
Longman House, Burnt Mill, Harlow  
Essex CM20 2JE, England  
*and Associated Companies throughout the world*

*copublished in the United States with*  
*John Wiley & Sons, Inc., 605 Third Avenue, New York, NY 10158*

© Longman Group UK Limited 1992 except:  
Coupling agents – application *and* Durability of coatings in water by P Walker; High temperature adhesives; Polyimide adhesives; Polyphenylquinoxalines *and* Polybenzimidazoles by S J Shaw; Sealant joint design *and* Selection of joint sealants by J C Beech; Underwater adhesives by M R Bowditch; Wedge test by B M Parker; Wood adhesives – basic principles by D F G Rodwell; Wood composites – adhesives by B H Paxton: © Crown copyright 1992. Published by permission of the Controller of HMSO.  
Standards for adhesives and adhesion by G R Durnall: © British Crown copyright 1992/MOD reproduced with the permission of the Controller of the Britannic Majesty's Stationery Office.

Creep; Engineering advantages; Fatigue; Honeycomb structure; Joint assembly *and* Stresses in joints by R D Adams: © R D Adams

All rights reserved; no part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, or otherwise without either the prior written permission of the Publishers or a licence permitting restricted copying in the United Kingdom issued by the Copyright Licensing Agency Ltd, 90 Tottenham Court Road, London W1P 9HE

*First published 1992*

0 582 04423.5

**British Library Cataloguing in Publication Data**  
A British Library CIP record is available for this book

**Library of Congress Cataloging-in-Publication Data**  
Handbook of adhesion / editor, D.E. Packham.

p. cm. — (Polymer science and technology series)

Includes bibliographical references and index.

ISBN 0-470-21870-3

1. Adhesives. 2. Adhesion. I. Packham, D. E. (David Ernest),  
1030— . II. Series.

TP968.H34 1992

668'.3—dc20

92-15139

CIP

Typeset by 6JJ in 10/12 $\frac{1}{2}$  pt Times

Produced by Longman Group (FE) Limited  
Printed in Great Britain by The Bath Press, Avon

## Foreword

---

Good adhesion is vital to a number of important technologies. These include adhesive bonding, lamination, metallization, printing, painting, coating and composite production. All these technologies are growing, in some cases rapidly, aided by the introduction of new materials and processes, and by a better understanding of the background science.

Adhesion is a multidisciplinary subject embracing surface science, chemistry, physics, materials science and mechanical engineering. A very large and diverse technical literature on adhesion exists. This includes a substantial number of books on various aspects of adhesion. However, the *Handbook of Adhesion* differs from other books in the wide range of technologies covered and in its format. About two hundred articles are arranged in alphabetical order; extensive cross-referencing enables the reader to study all the complementary subject material. Each article contains a select bibliography.

The *Handbook of Adhesion* is edited by Dr D E Packham who is a senior lecturer at Bath University. Dr Packham has worked for many years on various aspects of adhesion. He has drawn together a highly experienced team of scientists and engineers to cover the diverse range of topics.

The *Handbook of Adhesion* is part of the new series 'Polymer Science and Technology'.

D M BREWIS  
Institute of Surface Science  
and Technology  
University of Technology  
Loughborough  
Leicestershire LE11 3TU

D BRIGGS  
ICI Wilton Research Centre  
PO Box 90  
Wilton  
Middlesbrough  
Cleveland TS6 8JE

## Preface

---

There is a long and valuable tradition of members of academic staff of universities acting as authors and editors of reference works written for the benefit of the general public as a whole or of sections of it with specialized interests. This is one way in which a university repays its debt to the society which sustains it. Thus when asked by the Series Editors if I would act as editor for the *Handbook of Adhesion*, I agreed to do so. It was not without some misgivings that I gave my agreement. I was somewhat overawed at the prospect of commissioning some 200 articles from over 50 authors in industry and higher education, and then relating the articles to one another in a single book with consistent style. In practice the job was lightened by the enormous support given me by the publisher's staff, particularly Dr Michael Rodgers and Dr Paula Turner, and also by the series editors, Professor David Briggs and Dr Derek Brewis. I would also like to thank the individual authors themselves for their patience with my editorial idiosyncrasies. In an attempt to keep the style of the book it has sometimes been necessary to modify articles in a way that individual authors would not have chosen. I must emphasize that the responsibility for the final form of the text, including the errors, is mine.

This book, then, represents the fruits of fifty to sixty authors drawn from universities and industry. Such an authorship is unexceptional: there are hundreds of books resulting from collaboration like this in many areas of pure science, applied science and engineering.

In the past decade in the United Kingdom there has been an enormous emphasis on the importance of universities' collaborating with industry and serving its needs. This emphasis has been backed up by Government financial policies designed to make universities change their ways. Many of the practices of industry have been introduced into universities with the result that increasingly the performance of academics is being judged in terms of the *cash* they can bring in from research contracts and the *income* they can raise by selling of their services in the market place. It is ironical that the hard canons of market forces being imposed on

universities will mean that collaborative ventures, such as this book, will become things of the past: they are bound to fail the market criterion of cost effectiveness.

The changes being urged on universities represent much more than a trimming of the sails to the winds of political change. They represent a determined effort radically to change their fundamental values, or in the more percussive language used recently by the leader of a powerful pressure group, 'to break the academic mould'. If this happens, books of this sort will be among the lesser casualties of the breaking of the academic mould.

D E PACKHAM  
UNIVERSITY OF BATH  
JANUARY, 1992

*Publisher's Note*

While every effort has been made to trace the owners of copyright material, in a few cases this has proved impossible and we take this opportunity to offer our apologies to any copyright holders whose rights we may have unwittingly infringed.

## Introduction

---

### *Scope of the Handbook*

The *Handbook of Adhesion* is intended as a book of reference in the field of adhesion. Adhesion is a phenomenon of interest in diverse scientific disciplines and of importance in a wide range of technologies. Therefore the scope of this *Handbook* includes the background science (physics, chemistry and materials science) and engineering and aspects of adhesion relevant to the use of adhesives, sealants and mastics, paints and coatings, printing and composite materials.

### *Intended readership*

The book will be of value to professional people of many different backgrounds who need to have an understanding of various facets of adhesion. These will include those working in research, development or design, as well as others involved with marketing or technical service. This book is intended as a reference work for all those needing a quick, but authoritative, discussion of topics in the field of adhesion, broadly interpreted. It is intended for scientists and engineers qualified at national certificate or degree level. The aim has been to write it so that a detailed knowledge of individual science and engineering disciplines is not required.

### *Length of articles*

The *Handbook* has been designed so that it is easy to retrieve the information required, whether this is confined to a single point or it is more extensive. Thus articles are arranged alphabetically and it has been editorial policy for each article to be, as far as possible, intelligible on its own, and to limit its length to around three pages which can be quickly assimilated. Many enquirers will want more extensive information than a single article can provide. For this reason there is copious cross-referencing to related articles elsewhere in the *Handbook*, and a

comprehensive index. **Cross-references** are shown by giving titles to articles in **bold**.

### *Literature references*

The literature references at the end of the articles are intended to give further information to the *general* enquirer, so, where possible, they list authoritative reviews, monographs or text books, rather than original research papers. Those who need access to original papers should easily find the reference through these secondary sources. The article on **Literature on adhesion** and the associated selected bibliography in **Appendix 3** give broad guidelines on the book and periodical literature in the field.

### *Broader study*

As well as providing an answer to a specific query, the *Handbook* can be used for a discursive study of topics in adhesion, even as a starting point for an extended research project. Use might be made of the **Classified list of articles** (p. xxiii) where articles on related topics are grouped together and arranged, where appropriate, in a logical sequence for reading.

### *How to use the Handbook*

Detailed instructions on use of the *Handbook* are given inside the front cover.

Remember **Cross-references** are shown by giving titles to articles in **bold**.



## *List of articles – alphabetical*

---

- Abrasion treatment* J F WATTS Removal of loose layers, roughening, improved adhesion
- Accelerated ageing* A MADDISON Shear and wedge tests, humidity, corrosive environments
- Acid–base interactions* K W ALLEN AND J R G EVANS Relation to work of adhesion, Drago equation
- Acids* D E PACKHAM Concept of acid–Brönsted–Lewis, conjugate bases–electron donor/acceptor
- Acoustic microscopy* M G SOMEKH Basis of technique; application to adhesion
- Acrylic adhesives* F R MARTIN Basic material, setting mechanism, applications, advantages, disadvantages
- Addition polymerization* J COMYN Initiation, propagation, termination; application to adhesives
- Adhesion* D E PACKHAM Etymology, usage – qualitative, quantitative, practical, theoretical, bonds at interface
- Adhesion–fundamental and practical* D E PACKHAM Relationship between joint strength and interfacial forces
- Adhesion in medicine* M E R SHANAHAN Macroscopic level (e.g. prostheses) and cellular level
- Adhesion under ultra-high vacuum* R G LINFORD Adhesion in ultra-high vacua oxide-free metals, cold welding, crystallographic effects
- Adhesive classification* B C COPE Classified by setting mode and chemical nature
- Adhesives for textile fibre bonding* A J G SAGAR Non-woven materials, flocking, tyres, belts and hose

- Adhesives in textile coating, laminating and printing* A J G SAGAR Types of adhesive for coated fabrics, seaming, carpets and pigment printing
- Adhesives in the textile industry* A J G SAGAR Applications and adhesive types
- Adsorption theory of adhesion* K W ALLEN Adsorption via primary or secondary bonds
- Aerospace applications* S TREDWELL Adhesives used: structures bonded
- Alkyl-2-cyanoacrylates* J GUTHRIE Monomer synthesis; polymerization
- Anaerobic adhesives* D P MELODY Chemical constitution, applications
- Animal glues and technical gelatins* C A FINCH Origin and uses
- Anodizing* A. MADDISON As a pretreatment: different electrolytes and uses
- Auger electron spectroscopy* J F WATTS Basis of technique, application to adhesion problems
- Autohesion* J COMYN Contact theory, diffusion theory, development of bond strength
- Automotive applications* A MADDISON Types of adhesive used, advantages
- Autophoretic primers* J L PROSSER Aqueous dispersions containing acids which deposit corrosion-resistant films
- Blister test* A J KINLOCH Use, theory, variations
- Cathodic disbondment* J F WATTS Failure of bonds to ferrous alloys in an aqueous environment
- Climbing drum peel test* K B ARMSTRONG Peeling of metal sheet, e.g. skin from honeycomb
- Coextrusion* R J ASHLEY Production of a laminate in a single process
- Compatibility* J COMYN Free energy of mixing; solubility parameter; diffusion; weak boundary layers
- Composite materials* D E PACKHAM General introduction— emphasis of crucial role of interfacial adhesion
- Condensation polymerization* J COMYN Application to adhesives
- Contact angle* J F PADDAY Young's equation; nature of the contact angle; roughness
- Contact angles and interfacial tension* D E PACKHAM Young's equation; work of adhesion, interfacial tension and surface energy

- Contact angle measurement* J F PADDAY Techniques – where applicable; precautions needed to obtain reproducibility
- Conversion coating* A MADDISON Phosphate, chromate and alkali oxide treatments
- Corona discharge treatment* D BRIGGS Form of plasma treatment applied especially to polyolefins
- Coupling agents – application* P WALKER Use as adhesion promoters
- Coupling agents – chemical aspects* J COMYN Silanes, titanates, zirconates: reactions
- Creep* R D ADAMS Occurrence; protection against creep failure
- Critical surface tension* D E PACKHAM Measurement; typical values; relationship to surface energy
- Cyanoacrylate adhesives* J GUTHRIE Anionic polymerization, additives, applications, advantages and disadvantages
- Degreasing* J F WATTS Solvent, alkali and emulsion cleaners; efficiency
- Diffusion theory of adhesion* K W ALLEN Polymer–polymer autohesion, molecular-weight dependence
- Dispensing of adhesives* C WATSON Techniques used industrially for the application of adhesives to surfaces to be bonded
- Dispersion forces* K W ALLEN Nature of dispersion forces, ubiquity, energy–distance relationships; Lennard–Jones potential
- Displacement mechanisms* D M BREWIS displacement of organic contaminants from high-energy surfaces by adhesives
- Durability – fundamentals* A J KINLOCH Stability of interface in presence of water  $W_A$ , cf.  $W_{A/L}$
- Durability of coatings in water* P WALKER Deleterious effects water may have on adhesion
- Electrical adhesion* K KENDALL Adhesion in a strong electrical field; applications
- Electron microscopy* D E PACKHAM TEM and STEM applied to adhesion studies
- Electron probe microanalysis* B C COPE Basis of technique; examples in adhesion science

- Electrostatic theory of adhesion* K W ALLEN Outline of theory ; discussions of applicability
- Ellipsometry* R GREEF Theory, application to adhesion problems
- Emulsion and dispersion adhesives* G C PARKER Polyvinyl acetate and copolymers, setting, advantages and disadvantages
- Engineering advantages* R D ADAMS Advantages of adhesives in joining materials compared with mechanical fastenings
- Engineering design with adhesives* C WATSON Advantages of use of adhesives : specific examples of improved design
- Engineering surfaces of metals* J F WATTS Practical metallic surfaces are oxidized, contaminated and rough : pretreatments ; adhesion
- Epoxide adhesives* J COMYN Basic material, setting mechanism, applications
- Etch primers* J L PROSSER Chemical action : application to aluminium and steel
- Ethylene-vinyl acetate copolymers* D E PACKHAM Copolymer composition and properties ; hot melt and emulsion adhesives
- Extrusion coating* R J ASHLEY Techniques and materials used
- Fatigue* R D ADAMS Problem of service life, minimizing effects, susceptibility of different adhesives
- Fibre composites – introduction* B C COPE Fibre orientation, fibre-matrix interface ; surface treatment
- Fibre composites – joining* A J KINLOCH Thermoset matrices, peel-ply, abrasion ; thermoplastic matrices, corona discharge
- Fibre composites – matrices and fibres* B C COPE Scope of different fibre and matrix materials
- Fibre composites – processing techniques* B C COPE Comparison of processing methods
- Fibre-matrix adhesion – assessment techniques* F R JONES Direct and indirect test methods
- Fibre-matrix adhesion – carbon fibres* F R JONES Structure of carbon fibre ; effect of surface treatment
- Fibre-matrix adhesion – glass fibres* F R JONES Types of fibre ; surface treatment
- Filled polymers* J R G EVANS Types of filler ; choice of surface treatment

- Finite element analysis* A D CROCOMBE Principles and application to adhesive joints
- Flame-sprayed coatings* H REITER Principles, materials, applications
- Flame treatment* D BRIGGS Pretreatment of polymers, scope
- Footwear applications of adhesives* S ABBOTT Scope for adhesives; materials used
- Fourier transform infra-red spectroscopy – FTIR* B C COPE Basis; advantages; photoacoustic system
- FPL etch* D E PACKHAM Sulphochromatic treatment for Al; durability; topography
- Fracture mechanics* A J KINLOCH Basis; energy balance and stress intensity factor approaches
- Fracture mechanics test specimens* A J KINLOCH Test methods for flexible and rigid joints
- Friction–adhesion aspects* A D ROBERTS Influence of adhesion on friction; Schallamach waves
- Fusion welding by mechanical movement* M A GIRARDI Ultrasonic and friction welding
- Fusion welding – external heating* M A GIRARDI Hot plate, high-frequency and implant welding
- Glass transition temperature* D A TOD Property changes at  $T_g$ ; measurement; effect of molecular structure and moisture
- Good–Girifalco interaction parameter* D E PACKHAM Definition of  $\phi$ ; evaluation for ‘dispersion force’ interface; interfacial tension; solid surface energies
- Health and safety* D C WAIGHT Hazards associated with adhesives: sources of information
- High-temperature adhesives* S J SHAW Comparison of different types; recent developments
- High-temperature stability: principles* D E PACKHAM Molecular structure and thermal stability
- Honeycomb structure* R D ADAMS Structural use; materials; bonding
- Hot melt adhesives* D M BREWIS Basic composition, advantages and disadvantages, uses

- Humidity* J COMYN Relative humidity, laboratory control of humidity
- Hydrogen bonding* D BRIGGS Nature and occurrence of hydrogen bonding, work of adhesion, examples where important
- Impact resistance* A MADDISON Impact behaviour of different adhesives; effects of pretreatment
- Industrial applications of adhesives* C WATSON Scope of adhesives; bonding cylindrical components
- Inelastic electron tunnelling spectroscopy* J COMYN Basis of technique – its potential in the study of adhesion
- Infra-red spectroscopy of surfaces* J COMYN ATR and MIR; photoacoustic spectroscopy
- Internal stress* K KENDALL Origin; effect on adhesion measurement; reduction of internal stresses
- Joint assembly* R D ADAMS Types of assembly methods, used industrially
- Joint design – cylindrical joints* C WATSON Factors affecting joint performance; specimen calculation
- Joint design – general* C WATSON Flat and cylindrical joints; good and bad practice
- Laminating* R J ASHLEY Use of aqueous-based, solvent-based and hot melt adhesives
- Literature on adhesion* D E PACKHAM Guide to textbooks, reference books and journals
- Locus of failure* D M BREWIS Cohesive and interfacial failure; experimental investigation
- Mechanical theory of adhesion* K W ALLEN Macro- and micro-interlocking; influence on adhesion
- Microfibrous surfaces* D E PACKHAM Examples of preparation Fe, Cu, Zn. Use as substrates in adhesion–energy dissipation
- Microstructure of joints* D E PACKHAM Microstructural features of adhesive and substrate and their effect on adhesion
- Napkin ring test* D E PACKHAM Calculation of shear stress: refinements
- Non-destructive testing of adhesively bonded surfaces* G J CURTIS Acoustic wave techniques, resonance and pulse echo testers

- Optical microscopy* B C COPE Resolution; phase contrast; Nomanski differential inference contrast
- Packaging industry* R J ASHLEY Adhesives used, service requirements
- Paint constitution and adhesion* J L PROSSER Binder, pigment, adhesion mechanism
- Paint primers* J L PROSSER Function; make-up
- Paint service properties and adhesion* J L PROSSER Internal stress; testing; weathering
- Peel tests* D E PACKHAM Peel force and peel energy; factors affecting peel energy; angle variation
- Phenolic adhesives* S TREDWELL Resoles, novolaks; modifications; uses
- Plasma pretreatment* D BRIGGS Plasma for noble gases, reactive gases; plasma polymerization
- Plastisols* J PRITCHARD Function, manufacture and use
- Polar forces* K W ALLEN Nature of Keesom and Debye forces, attraction constants; Lennard-Jones potential
- Polybenzimidazoles* S J SHAW Structure: use as high-temperature adhesive
- Polyether ether ketone* D A TODD High-temperature stability; use as matrix for fibre composites
- Polyimide adhesives* S J SHAW Condensation and thermoplastic polyimides, imide prepolymers; high-temperature stability
- Polyphenylquinoxalines* S J SHAW Chemical constitution: use as high-temperature adhesive
- Polyurethane adhesives* G PARKER Solvent-free and solvent-based systems, toxicology
- Polyvinyl alcohol in adhesives* C A FINCH Production and uses
- Power adhesion* K KENDALL Adhesion between fine powder particles: practical consequences
- Pressure-sensitive adhesives* D W AUBREY Nature of pressure sensitive adhesion, materials used
- Pressure-sensitive adhesives—adhesion properties* D W AUBREY Shear and peel strengths; tack tests
- Pretreatment of aluminium* D M BREWIS Chromic acid etch, chromic acid anodizing, phosphoric acid anodizing; relative bond durability

- Pretreatment of copper* D E PACKHAM Conventional and microfibrinous surfaces
- Pretreatment of fluorocarbon polymers* D M BREWIS Problems of these materials, chemical and plasma treatment
- Pretreatment of metals prior to bonding* D M BREWIS Survey of mechanical and chemical treatments
- Pretreatment of metals prior to painting* J L PROSSER Need for pretreatment; survey of common methods
- Pretreatments of polymers* D M BREWIS Effects of solvent, mechanical, oxidative and plasma treatment
- Pretreatments of polyolefins* D M BREWIS Polyolefins, scope and effects of different treatment types
- Pretreatment of steel* J F WATTS Abrasion, pickling and conversion coatings
- Pretreatment of titanium* D M BREWIS Survey of important types of pretreatment and comparison of bond durability
- Primary bonding at the interface* J F WATTS Examples in organic coatings, metallized plastics and adhesion promoters
- Primers for adhesive bonding* D M BREWIS Types of primers for metals and polymers
- Primers for sealants* G B LOWE Types for porous and non-porous surfaces
- Printing ink adhesion* G C BATTERSBY Assessment of adhesion, water-based inks, screen inks
- Radiation-cured adhesives* M R HADDON AND T J SMITH Electron beam and UV curing systems: advantages, disadvantages, uses
- Reaction setting adhesives* D M BREWIS One- and two-part adhesives; applications
- Release* D E PACKHAM Examples where low adhesion needed – internal and external release agents
- Repair methods* K B ARMSTRONG Methods for composites and honeycomb panels on large structures such as aircraft
- Rheological theory* D E PACKHAM Rheology and joint strength: the possibility of adhesive failure
- Roughness of surfaces* D E PACKHAM Characterization of roughness, effect on adhesion



- Rubber adhesion* A D ROBERTS Unvulcanized and vulcanized rubber: viscoelastic effects
- Rubber-based adhesives* J PRITCHARD Adhesives based on natural rubber, polychloroprene, butyl rubber, polyisobutylene and SBR compared
- Rubber fillers* J A LINDSAY Role of fillers, non-reinforcing and reinforcing fillers, adhesion aspects
- Rubber to metal bonding – applications* G LAKE Tyres; bearings; durability
- Rubber to metal bonding – basic techniques* P M LEWIS In- and post-vulcanization bonding
- Rubber to metal bonding – pretreatments* P M LEWIS Degreasing, mechanical cleaning, chemical cleaning
- Rubber to metal bonding – testing* J A LINDSAY Peel tests, tests in tension
- Scanning electron microscopy* B C COPE Mode of operation, examples of use
- Scratch test* D E PACKHAM Assessment of thin film adhesion
- Sealants* G B LOWE Chemical composition, use
- Sealants in double glazing* G B LOWE Types of materials, durability
- Sealant joint design* J C BEECH Design of butt and lap joints
- Secondary ion mass spectrometry* D BRIGGS Static, dynamic and imaging SIMS
- Selection of adhesives* D M BREWIS Selling time, initial performance, durability, cost
- Selection of joint sealants* J C BEECH Comparison and criteria for selection
- Shear tests* A D CROCOMBE Tests in tension and torsion
- Solvent-based adhesives* J PRITCHARD Aqueous and organic solvent-based adhesives; uses; advantages and disadvantages
- Solvent welding* M A GIRARDI Scope, advantages and disadvantages
- Standard for adhesives and adhesion* G R DURTNAL Discussion of scope and background to national standards
- Statistics* C CHATFIELD Data collection and analysis; quality control; reliability