Contents

Preface *xi*

1 Benefits, Limitations, and Applications of Adhesive Bonding *1*
1.1 Definition of Basic Concepts *2*
1.2 Historical Context on Adhesive Bonding *3*
1.3 Benefits and Limitations of Adhesive Bonding *4*
1.4 Examples of Current Applications of Adhesive Bonding *8*
1.4.1 Transportation *8*
1.4.1.1 Aeronautical Industry *8*
1.4.1.2 Road Transport and Rail Industry *11*
1.4.1.3 Naval Industry *13*
1.4.2 Civil Engineering *15*
1.4.2.1 Tiling *15*
1.4.2.2 Floor and Wall Covering *15*
1.4.2.3 Anchoring Systems *15*
1.4.2.4 Building Facades *16*
1.4.2.5 Wooden Construction *17*
1.4.3 Labelling and Packaging Industry *18*
1.4.3.1 Labelling of Consumable Products *18*
1.4.3.2 Packaging *18*
1.4.4 Medical Applications and Devices *19*
1.4.5 Electronic Devices *23*
1.4.6 Sport Equipment *23*
1.4.7 Footwear *24*

2 Principles of Adhesion *27*
2.1 Forces Associated with Adhesion *28*
2.2 Surface Roughness *31*
2.3 Wettability *32*
2.4 Adhesion and Cohesion Work *35*
2.5 Spreading *36*

2.6 Adhesion Theories *37*
2.6.1 Adsorption Theory *37*
2.6.2 Mechanical Theory *38*
2.6.3 Diffusion Theory *41*
2.6.4 Electrostatic Theory *41*
2.7 Defects and Weak Spots in Adhesive Joints *42*

3 Surface Preparation *45*
3.1 Objectives of Surface Preparation *45*
3.2 Classes of Substrate Materials *47*
3.2.1 Metals *47*
3.2.2 Polymers *47*
3.2.3 Composites *48*
3.2.4 Other Materials *49*
3.3 Surface Preparation Processes *49*
3.3.1 Passive Processes *51*
3.3.1.1 Passive Chemical Processes *51*
3.3.1.2 Passive Mechanical Processes *55*
3.3.2 Active Processes *59*
3.3.2.1 Active Chemical Processes *59*
3.3.2.2 Physical–Chemical Processes *62*
3.3.3 Primers and Adhesion Promoters *65*
3.4 Conservation of the Post-treatment Surface *67*

4 Main Families of Adhesives and Adhesive Selection *69*
4.1 Typical Composition of a Modern Adhesive *69*
4.2 Methods for Adhesive Classification *70*
4.2.1 Molecular Structure *70*
4.2.1.1 Thermosets *71*
4.2.1.2 Thermoplastics *71*
4.2.1.3 Elastomers *72*
4.2.1.4 Hybrid Materials *72*
4.2.2 Physical Form *74*
4.2.3 Mechanical Properties *74*
4.2.4 Hardening and Implementation Method *75*
4.2.4.1 Hardening by Chemical Reaction *75*
4.2.4.2 Hardening via Physical Processes *76*
4.2.4.3 Pressure-Sensitive Adhesives *76*
4.2.5 Chemical Composition *77*
4.3 Main Structural Adhesives *77*
4.3.1 Epoxy Adhesives *77*
4.3.2 Polyurethane Adhesives *78*
4.3.3 Acrylic Adhesives *79*
4.3.4 Phenolic Adhesives *80*
4.3.5 Aromatic Adhesives *81*

4.4 Main Non-structural Adhesives *81*
4.4.1 Elastomeric Adhesives *81*
4.4.2 Polyester Adhesives *82*
4.4.3 Hot Melt Adhesives *82*
4.4.4 Inorganic Adhesives *83*
4.5 How to Select an Adhesive *83*
4.5.1 Case Study: Adhesive Selection for the Automotive Industry *84*
4.6 How to Test and Characterise an Adhesive *88*
4.6.1 Mechanical Testing *88*
4.6.1.1 Strength Tests *89*
4.6.1.2 Fracture Tests *93*
4.6.1.3 Testing Under Severe Environmental and Loading Conditions *98*
4.7 Mechanical Properties of Adhesives *102*

5 Manufacture *107*
5.1 Adhesive Storage *107*
5.1.1 Storage Time *108*
5.1.2 Humidity *109*
5.1.3 Temperature *109*
5.1.4 Light and UV Radiation *110*
5.2 Adhesive Metering and Mixing *110*
5.2.1 Adhesive Metering *111*
5.2.2 Adhesive Mixing *111*
5.3 Adhesive Forms and Application *114*
5.3.1 Liquid Adhesives *114*
5.3.2 Paste Adhesives *115*
5.3.3 Film Adhesives *116*
5.3.4 Tapes *117*
5.4 Joint Assembly and Fixturing *117*
5.4.1 Moulds and Fixtures *117*
5.4.2 Adhesive Thickness Control *119*
5.4.3 Joint Assembly *119*
5.5 Adhesive Hardening *120*
5.5.1 Heat Curing Processes *121*
5.5.2 Evaporation-Based Processes *125*
5.6 Finishing Steps *126*

6 Quality Control *127*
6.1 Quality Control of the Incoming Materials *128*
6.1.1 Control of Adhesive Quality *128*
6.1.1.1 Mechanical Properties *128*
6.1.1.2 Viscosity *128*
6.1.2 Control of Adherend Quality *129*
6.1.2.1 Mechanical Properties *129*
6.1.2.2 Wettability, Contact Angle, and Surface Energy *129*

6.1.2.3 Surface Roughness *131*
6.2 Quality Control of the Manufacturing Process *133*
6.3 Quality Control on Bonded Structures *137*
6.3.1 Types of Defects Present in Bonded Joints *137*
6.3.2 Destructive Tests *138*
6.3.2.1 Proof Tests *139*
6.3.2.2 Fractography Analysis *139*
6.3.3 Non-destructive Tests *141*
6.3.3.1 Visual Inspection *141*
6.3.3.2 Tap Test *142*
6.3.3.3 Ultrasonic Test *143*
6.3.3.4 Acoustic Emission Test *143*
6.3.3.5 Radiography Test *144*
6.3.3.6 Eddy Current Test *145*
6.3.3.7 Thermal Infrared Method *146*
6.3.3.8 Lamb Wave-Based Testing *146*
6.3.3.9 Electromechanical Impedance Spectroscopy *146*
6.3.3.10 Laser-Based Testing *149*

7 Environment, Health, and Safety *151*
7.1 Toxicity of Adhesives: Are Adhesives Really Toxic? *153*
7.2 General Precautions for Handling Adhesives *153*
7.2.1 Pictograms *154*
7.2.2 Training for Handling Adhesives *157*
7.2.3 Safety Eyewear *158*
7.2.4 Hand Protection – Gloves *158*
7.2.5 Safety Shoes *159*
7.2.6 Lab Coat *159*
7.2.7 Ventilation Systems *159*
7.3 Hazardous Characteristics of the Most Common Adhesives *160*
7.3.1 Structural Adhesives *160*
7.3.1.1 Epoxies *160*
7.3.1.2 Polyurethanes *161*
7.3.1.3 Acrylic Adhesives *161*
7.3.1.4 Phenolic Adhesives *161*
7.3.1.5 Aromatic Adhesives *161*
7.3.2 Non-structural Adhesives *162*
7.3.2.1 Synthetic Rubbers *162*
7.3.2.2 Polyesters *162*
7.3.2.3 Hot Melt Adhesives *162*
7.3.2.4 Inorganic Adhesives *162*
7.4 Surface Preparation Precautions *162*
7.5 Adhesive Application Precautions *164*
7.6 Environmental Protection *164*
7.6.1 Air *165*

7.6.2 Water *165*
7.6.3 Soil *166*

8 Design of Bonded Joints *167*
8.1 Main Loading Modes on Adhesive Joints *168*
8.2 Main Adhesive Joint Geometries *169*
8.3 Joint Strength Prediction Using Analytical Methods *171*
8.3.1 Determination of Stresses Acting on an Adhesive Joint *172*
8.3.2 Failure Criteria for Bonded Joints *175*
8.3.2.1 Failure in the Adhesive *176*
8.3.2.2 Failure in the Adherends *177*
8.4 Joint Strength Prediction Using Numerical Methods *180*
8.5 Parameters That Affect Joint Performance *183*
8.5.1 Effect of Adhesive Thickness *183*
8.5.2 Effect of Overlap Length *184*
8.5.2.1 Overlap Length and Adhesive Behaviour *185*
8.5.2.2 Overlap Length and Adherend Strength *186*
8.5.2.3 Overlap Length and Composite Adherends *187*
8.5.3 Effect of Temperature and Thermal Stresses *187*
8.6 Methods to Improve Joint Strength *189*
8.6.1 Adhesive Fillet *189*
8.6.2 Mixed Adhesive Joints *190*
8.6.3 Functionally Graded Joints *190*
8.6.4 Hybrid Joints *191*
8.7 Case Studies *192*
8.7.1 Case Study 1 – Effect of Adhesive Type on the Strength of Adhesive Joints *192*
8.7.2 Case Study 2 – Effect of Overlap Length and Adherend Type on the Strength of Adhesive Joints *194*
8.7.3 Case Study 3 – Effect of Adhesive Thickness on the Strength of Adhesive Joints *197*
8.7.4 Case Study 4 – Strength Prediction of Adhesive Joints with Composite Adherends *201*
8.7.5 Case Study 5 – Strength Prediction of an SLJ with Cohesive Zone Modelling *205*
8.7.6 Case Study 6 – Effect of Thermal Stresses on Adhesive Joints *208*

9 Durability of Adhesively Bonded Joints *213*
9.1 Environmental Effects *214*
9.1.1 Hygrothermal Ageing *214*
9.1.2 Temperature *220*
9.2 Loading Conditions *221*
9.2.1 Fatigue *221*
9.2.1.1 Total Fatigue Life (S–N) Approach *223*
9.2.1.2 Fatigue Crack Growth Approach *225*
9.2.2 Creep *229*

10 Case Studies *235*
10.1 Vehicle Construction *235*
10.2 Seat Fixation in Passenger Trains *237*
10.3 Aeronautical Applications *239*
10.4 Flexible Cooling Circuits *241*
10.5 Glass to Metal Bonding in Appliances *243*
10.6 Roof Coverings *245*
10.7 Shoe Manufacture *246*
10.8 Food Packaging *248*

Recommended Bibliography *251*
Referenced Bibliography *251*
Index *253*