

Contents

Preface *xv*

Author Biography *xvii*

1 Introduction *1*

- 1.1 The *Art* of Adhesive Bonding *1*
- 1.2 Adhesives *1*
- 1.3 Adhesive Bonds *2*
 - 1.3.1 Metal Bonds *3*
 - 1.3.2 Plastic Bonds *4*
 - 1.3.3 Glass Bonds *4*
 - 1.3.4 Wood Bonds *5*
- 1.4 Adhesive Bonding in Industry and Craft *6*
- 1.5 An Example for Adhesive Bonding in Nature *7*

2 History of Adhesive-Bonding Technology *9*

- 2.1 First Adhesives *9*
- 2.2 Adhesive-Bonding Technology: 1845–1930 *10*
- 2.3 Adhesive-Bonding Technology: 1930–1960 *14*
- 2.4 Adhesive-Bonding Technology from 1960 Until Today *18*
- References *20*

3 Wetting, Adhesion, and Cohesion *21*

- 3.1 Introduction *21*
- 3.2 Wetting of Surfaces *21*
 - 3.2.1 Young's Equation and Surface Tension *21*
 - 3.2.2 Surface Tension of Liquids *23*
 - 3.2.3 Surface Energy of Solids *23*
 - 3.2.4 Determination of the Critical Surface Tension *24*
 - 3.2.5 Polar and Dispersive Interactions *24*
- 3.3 Adhesion to Surfaces *26*
 - 3.3.1 Intermolecular Interactions *26*

| | | |
|----------|---|-----------|
| 3.3.2 | Summary Adhesion | 28 |
| 3.4 | Cohesion of Adhesive Layers | 29 |
| 3.4.1 | Summary Wetting, Adhesion, and Cohesion | 29 |
| | References | 30 |
| 4 | Adhesive Bonding in Industry and Craft | 31 |
| 4.1 | Introduction | 31 |
| 4.1.1 | Role of Adhesive Bonding in Production Today | 31 |
| 4.1.2 | Limitations of Adhesive Bonding | 32 |
| 4.2 | The Performance of Standard Adhesives Today | 32 |
| 4.2.1 | Vespa is Held by a 1 cm ² Adhesive Layer | 32 |
| 4.3 | Advantages and Disadvantages of Adhesive Bonding | 33 |
| 4.4 | Structural and Elastic Bonding | 36 |
| 4.4.1 | Structural Bonding | 38 |
| 4.4.1.1 | Limits of Structural Bonding | 39 |
| 4.4.2 | Elastic Bonding | 39 |
| 4.4.2.1 | Elastic Bonding for Heavier Loads | 39 |
| 4.5 | Selected Adhesive Systems used in Industry and Craft | 40 |
| 4.5.1 | “High-Speed” Cyanoacrylate Adhesives for Small Bonding Areas | 41 |
| 4.5.2 | “Easy-to-Use” Hotmelt Adhesives for Rapid Further Processing | 41 |
| 4.5.3 | “All-Purpose” Adhesives for Numerous Applications | 42 |
| 4.5.4 | The “All-Rounders” for Structural Applications | 43 |
| 4.5.5 | “User-Friendly” Conformable High-Performance PSA Foam Tapes | 44 |
| 4.5.6 | PSA Tapes for “Quick Connect and Disconnect” | 46 |
| 4.5.6.1 | High-Strength Fasteners | 46 |
| 4.5.6.2 | Hook-and-Loop Fasteners | 46 |
| 4.5.7 | “The Strong PSA Tape” for All Cases | 47 |
| | References | 48 |
| 5 | The 5 Steps for Achieving Safe and High-Quality Bonds (Overview) | 49 |
| 5.1 | Introduction | 49 |
| 5.2 | Requirements for the <i>Special Process</i> | 49 |
| 5.3 | Quality Standards | 50 |
| 5.4 | The 5-Step Project Management System | 51 |
| 5.4.1 | Introduction | 51 |
| 5.4.1.1 | Process Map | 52 |
| 5.4.2 | Planning, Concept, and Feasibility (Part 1) | 52 |
| 5.4.3 | Development and Launch (Part 2) | 53 |
| 5.5 | Gate Reviews | 53 |
| 5.5.1 | The Gatekeeper | 54 |
| 5.5.2 | Color Coding | 54 |
| 5.6 | Quality Requirements According to DIN 2304 | 55 |
| 5.6.1 | Part 1 – Classification of Adhesive Components into Safety Classes | 55 |
| 5.6.2 | Part 2 – Assignment of the Responsible Supervisors (SIC) | 57 |

| | | |
|----------|--|-----------|
| 5.6.3 | Part 3 – Proof of Applied Load < Load-Bearing Capacity of the Adhesive Layer | 57 |
| 5.6.3.1 | Measurements | 57 |
| 5.6.3.2 | Component Testing | 58 |
| 5.6.3.3 | Documented Experience | 58 |
| 5.6.3.4 | Combinations of 1–3 | 58 |
| | References | 58 |
| 6 | Planning (Step 1) – Preparing the Plan and the Project Contract | 59 |
| 6.1 | Introduction | 59 |
| 6.2 | The Project Plan and Contract | 59 |
| 6.3 | Roles of Project-Relevant People | 60 |
| 6.3.1 | Project Sponsor (Client) | 60 |
| 6.3.2 | Project Manager (Planner) | 61 |
| 6.3.3 | Project Champion (Advocate) | 61 |
| 6.3.4 | Supervisor In Charge (SIC) | 61 |
| 6.3.5 | Operating Staff | 62 |
| | Reference | 62 |
| 7 | Concept (Step 2a) – Substrates, their Surfaces, and their Treatment | 63 |
| 7.1 | Introduction to Chapters 7 and 8 | 63 |
| 7.2 | Substrates and their Surfaces | 64 |
| 7.2.1 | Introduction | 64 |
| 7.2.1.1 | Metals | 64 |
| 7.2.1.2 | Plastic Materials | 65 |
| 7.2.1.3 | Glasses | 66 |
| 7.2.1.4 | Wood | 66 |
| 7.2.2 | Ferrous Materials | 67 |
| 7.2.2.1 | Introduction | 67 |
| 7.2.2.2 | Mechanical Properties of Ferrous Materials | 68 |
| 7.2.2.3 | Classification of Steel | 69 |
| 7.2.2.4 | Surface Improvement of Steel | 71 |
| 7.2.3 | Aluminum and their Alloys | 74 |
| 7.2.3.1 | Introduction | 74 |
| 7.2.3.2 | Properties of Aluminum | 74 |
| 7.2.3.3 | Applications of Aluminum | 75 |
| 7.2.3.4 | Surface Improvement of Aluminum | 75 |
| 7.2.4 | Plastic Materials | 76 |
| 7.2.4.1 | Introduction | 76 |
| 7.2.4.2 | Properties | 76 |
| 7.2.4.3 | Chemistry of Plastic Materials | 78 |
| 7.2.4.4 | Thermomechanical Properties of Plastic Materials | 80 |
| 7.2.4.5 | Viscoelastic Properties of Plastic Materials | 82 |

| | | |
|----------|---|------------|
| 7.2.4.6 | Plastic Materials Used in Industry and Craft | 85 |
| 7.2.5 | Glass | 93 |
| 7.2.5.1 | Introduction | 93 |
| 7.2.5.2 | Classification of Glass | 94 |
| 7.2.5.3 | Manufacture of Glass | 94 |
| 7.2.6 | Wood | 95 |
| 7.2.6.1 | Introduction | 95 |
| 7.2.6.2 | Properties of Wood | 95 |
| 7.2.6.3 | Wood Surfaces | 96 |
| 7.3 | Surface Cleaning and Treatment | 96 |
| 7.3.1 | Introduction | 96 |
| 7.3.1.1 | Importance of Surface Treatment | 97 |
| 7.3.2 | Surface Characteristics | 100 |
| 7.3.2.1 | Metals | 100 |
| 7.3.2.2 | Plastics | 102 |
| 7.3.2.3 | Glasses | 105 |
| 7.3.3 | Surface Cleaning | 105 |
| 7.3.3.1 | Cleaning with Organic Solvents | 105 |
| 7.3.3.2 | Cleaning with Aqueous Systems | 108 |
| 7.3.3.3 | Cleaning of Metal Surfaces | 108 |
| 7.3.3.4 | Cleaning of Plastic Surfaces | 109 |
| 7.3.3.5 | Cleaning and Degreasing Processes | 109 |
| 7.3.4 | Surface Treatment | 110 |
| 7.3.4.1 | Mechanical Surface Treatment | 111 |
| 7.3.4.2 | Chemical Surface Treatment | 115 |
| 7.3.4.3 | Physical Surface Treatment | 118 |
| 7.3.4.4 | Summary: Physical Surface Treatment Methods | 125 |
| | References | 127 |
| 8 | Concept (Step 2b) – Adhesives, their Selection, and Definition of Concepts | 129 |
| 8.1 | Introduction | 129 |
| 8.2 | Adhesives for Industry and Craft | 129 |
| 8.2.1 | Introduction | 129 |
| 8.2.1.1 | Adhesive Classification by Curing Mechanism | 130 |
| 8.2.1.2 | Adhesive Classification by Number of Components | 132 |
| 8.2.2 | 1K Adhesive Systems | 132 |
| 8.2.2.1 | Cyanoacrylate Adhesives | 133 |
| 8.2.2.2 | 1K PU Adhesives | 137 |
| 8.2.2.3 | 1K Silicone Adhesives (RTV-1) | 143 |
| 8.2.2.4 | Hotmelt Adhesives | 146 |
| 8.2.2.5 | Photoinitiated Adhesives | 155 |
| 8.2.2.6 | Anaerobic Adhesives | 161 |
| 8.2.2.7 | 1K Epoxy Adhesive | 164 |
| 8.2.2.8 | Solvent-Borne and Dispersion Adhesives | 169 |

- 8.2.2.9 Pressure-Sensitive Adhesives (PSAs) 174
- 8.2.3 2K Adhesive Systems 189
 - 8.2.3.1 Introduction 189
 - 8.2.3.2 Curing and Processing of 2K Adhesives 190
 - 8.2.3.3 Applications of 2K Adhesives 190
- 8.2.4 2K Epoxy Adhesives 190
 - 8.2.4.1 Overview 190
 - 8.2.4.2 Chemistry and Composition 190
 - 8.2.4.3 Curing/Processing 191
 - 8.2.4.4 Properties 192
 - 8.2.4.5 Applications 192
- 8.2.5 2K Acrylate Adhesives 193
 - 8.2.5.1 Overview 193
 - 8.2.5.2 Chemistry/Composition 193
 - 8.2.5.3 Processing 193
 - 8.2.5.4 Properties 194
 - 8.2.5.5 Applications 194
- 8.2.6 2K PU Adhesives 195
 - 8.2.6.1 Overview 195
 - 8.2.6.2 Curing/Processing 195
 - 8.2.6.3 Properties/Applications 196
- 8.3 Adhesive Bonding on Metal, Plastic, Glass, and Wood Surfaces 196
 - 8.3.1 Adhesive Bonding on Metals 196
 - 8.3.1.1 Adhesive Bonding on Steel Surfaces 197
 - 8.3.1.2 Bonding on Steel Sheet 197
 - 8.3.1.3 Bonding on Oily Steel Sheet 198
 - 8.3.1.4 Bonding on Galvanized Steel 199
 - 8.3.1.5 Surface Treatment of Galvanized Steel 200
 - 8.3.1.6 Bonding on Stainless Steel 200
 - 8.3.1.7 Surface Treatment of Stainless Steel 201
 - 8.3.1.8 Bonding on Aluminum Surfaces 202
 - 8.3.1.9 Surface Treatment of Aluminum 202
 - 8.3.1.10 Surface Treatment for Long-term Aging-resistant Bonds 203
 - 8.3.2 Adhesive Bonding on Plastic Materials 204
 - 8.3.2.1 Role of Diffusion and Solubility Characteristics 205
 - 8.3.2.2 Bonding on Recycled Plastic 205
 - 8.3.2.3 Long-term Resistance of Plastic Bonds 206
 - 8.3.3 Adhesive Bonding on Glass 207
 - 8.3.3.1 Selection of Adhesive for Glass Bonding 207
 - 8.3.3.2 Glass Bonds with Long-term Resistance 208
 - 8.3.3.3 Surface Treatment of Glass 208
 - 8.3.3.4 Adhesives for Glass Bonding 210
 - 8.3.4 Adhesive Bonding on Wood 210
 - 8.3.4.1 Requirements for Wood Bonding 211
 - 8.3.4.2 PVAC Dispersions (White Glue) 212

| | | |
|---------|--|-----|
| 8.3.4.3 | Hotmelt Adhesives | 212 |
| 8.3.4.4 | Formaldehyde Resin Dispersions | 213 |
| 8.3.4.5 | Post-curing PVAC Dispersions | 213 |
| 8.3.4.6 | Moisture-curing 1K PU Adhesives | 213 |
| 8.3.4.7 | Bonding Wood to Other Materials | 213 |
| 8.4 | Loads on Adhesive Bonds | 214 |
| 8.4.1 | Introduction | 214 |
| 8.4.2 | Long-term Behavior of Adhesive Bonds | 214 |
| 8.4.3 | Mechanical Loads | 215 |
| 8.4.3.1 | External Loads | 215 |
| 8.4.3.2 | Internal Loads | 215 |
| 8.4.4 | Environmental Loads | 219 |
| 8.4.4.1 | Temperature Changes | 219 |
| 8.4.4.2 | Water Diffusion | 220 |
| 8.4.4.3 | Corrosive Media Impact | 220 |
| 8.5 | Adhesive Specification | 222 |
| 8.5.1 | Introduction | 222 |
| 8.5.2 | Definition of Substrates | 223 |
| 8.5.3 | Determination of Loads on the Joint | 223 |
| 8.5.4 | Definition of Adhesive Requirements | 224 |
| 8.5.5 | Definition of Surface Treatment Method | 225 |
| 8.5.6 | Definition of Manufacturing Process | 226 |
| 8.5.7 | Adhesive Specification | 228 |
| 8.5.8 | Some Practical Guidelines for Adhesive Selection | 229 |
| 8.6 | Definition of Concepts | 230 |
| | References | 231 |

9 Feasibility (Step 3) – Demonstrating Feasibility and Validation of the Preferred Concept 235

| | | |
|---------|--|-----|
| 9.1 | Introduction | 235 |
| 9.2 | Production of Bonded Joints in the Laboratory | 236 |
| 9.2.1 | Preparations Before Starting Work in the Laboratory | 236 |
| 9.2.1.1 | Provision of Personal Protective Equipment | 237 |
| 9.2.1.2 | Preparation of the Workplace | 239 |
| 9.2.1.3 | Preparation of the Adhesive | 241 |
| 9.2.2 | Execution of the Work for the Production of a Bonded Joint in the Laboratory | 241 |
| 9.2.2.1 | Surface Treatment | 241 |
| 9.2.2.2 | Bonded Joints with 1K Adhesives | 244 |
| 9.2.2.3 | Bonded Joints with 2K Adhesives | 256 |
| 9.3 | Test Methods for Adhesive Bonds | 263 |
| 9.3.1 | Introduction | 263 |
| 9.3.1.1 | Technological and Physical Tests | 263 |
| 9.3.2 | Technological Test Methods for Adhesive Bonds | 264 |
| 9.3.2.1 | Shear Test | 265 |

| | | |
|---------|---|-----|
| 9.3.2.2 | Tensile Test | 267 |
| 9.3.2.3 | Peel Test | 268 |
| 9.3.2.4 | Cleavage Test | 270 |
| 9.3.2.5 | 3-Point Bending Test | 270 |
| 9.3.2.6 | Wedge Test | 270 |
| 9.3.3 | Aging Conditions for Adhesive Bonds | 272 |
| 9.3.3.1 | Immersion Test | 272 |
| 9.3.3.2 | Climate Test | 272 |
| 9.3.3.3 | Climate Change (VW PV 1200) | 272 |
| 9.3.3.4 | Salt-Spray Test | 273 |
| 9.3.3.5 | Climatic Corrosion Test (KKT Test) | 273 |
| 9.3.3.6 | Cataplasma Test | 274 |
| 9.3.3.7 | Outdoor Weathering Test | 274 |
| 9.3.3.8 | Fracture Surface Evaluation | 274 |
| 9.3.4 | Physical Test Methods | 275 |
| 9.3.4.1 | Differential Scanning Calorimetry (DSC) | 276 |
| 9.3.4.2 | Dynamic Mechanical Thermal Analysis (DMTA) | 276 |
| 9.3.4.3 | Thermo Gravimetric Analysis (TGA) | 279 |
| 9.3.4.4 | Fourier Transform Infrared Spectroscopy (FTIR) | 280 |
| 9.4 | Properties of Adhesive Bonds | 280 |
| 9.4.1 | Introduction | 280 |
| 9.4.1.1 | Structural Adhesive Bonds | 280 |
| 9.4.1.2 | Elastic Adhesive Bonds | 281 |
| 9.4.2 | Thermomechanical Properties of Adhesives | 281 |
| 9.4.2.1 | General Thermomechanical Properties of Adhesives | 281 |
| 9.4.2.2 | Thermomechanical Properties of PSAs | 284 |
| 9.4.3 | Shear Properties | 286 |
| 9.4.3.1 | Shear Modulus | 287 |
| 9.4.3.2 | Shear Stress–Strain Behavior | 287 |
| 9.4.4 | Creep and Flow | 289 |
| 9.4.4.1 | Creep | 289 |
| 9.4.4.2 | Flow | 289 |
| 9.4.4.3 | Influence of Creep on the Bonded Joint | 289 |
| 9.4.4.4 | Phases and Types of Creep Behavior in Adhesive Joints | 290 |
| 9.4.4.5 | Creep Curves | 292 |
| 9.4.4.6 | Stress Relaxation Curve | 294 |
| 9.5 | Designing Adhesive Bonds | 295 |
| 9.5.1 | Introduction | 295 |
| 9.5.2 | Provision of Sufficient Bonding Area | 297 |
| 9.5.2.1 | Introduction | 297 |
| 9.5.2.2 | Butt Joints | 297 |
| 9.5.2.3 | Single Lap Joints | 298 |
| 9.5.3 | Avoiding Stress Peaks | 304 |
| 9.5.3.1 | Peel Loads | 305 |
| 9.5.3.2 | Bending Loads | 306 |

| | | |
|-----------|--|------------|
| 9.5.3.3 | Cleavage Loads | 306 |
| 9.5.3.4 | Plastic Deformation of the Substrates | 307 |
| 9.5.4 | Dimensioning of Bonded Joints | 307 |
| 9.5.4.1 | Reduction Factors | 309 |
| 9.5.4.2 | Dimensioning of Elastic Adhesive Bonds | 310 |
| 9.5.4.3 | Dimensioning of Adhesive Bonds with Plastics | 312 |
| 9.5.4.4 | Concluding Remarks on the Structural Design and Dimensioning of Bonded Joints | 313 |
| 9.5.5 | Examples for Dimensioning of Adhesive Bonds | 313 |
| 9.5.5.1 | Example 1 – Joining Two Stainless-Steel Plates (Structural Bonding) | 313 |
| 9.5.5.2 | Example 2 – Bonding of a GFRP-Element for Interior Design (Elastic Bonding) | 315 |
| 9.5.5.3 | Example 3 – Bonding of a Glass Pane with an Aluminum Frame (Elastic Bonding) | 317 |
| | References | 319 |
| 10 | Development (Step 4) – Establishing a Robust Manufacturing Process Ready for Production | 321 |
| 10.1 | Introduction | 321 |
| 10.1.1 | Status of the Project | 321 |
| 10.1.1.1 | Objectives of the Development Step | 321 |
| 10.1.1.2 | Requirements for the Successful Completion of the Development Step | 323 |
| 10.2 | Adhesive-Bonding Manufacturing Process (Overview) | 323 |
| 10.2.1 | Process Objectives for the Production of a Bonded Joint | 325 |
| 10.3 | Processes for Adhesion Build-up | 326 |
| 10.3.1 | Adhesive Preparation | 326 |
| 10.3.1.1 | Storage/Tempering | 326 |
| 10.3.1.2 | Homogenization | 327 |
| 10.3.1.3 | Setting the Viscosity | 327 |
| 10.3.1.4 | Newtonian and Non-Newtonian Fluids | 328 |
| 10.3.1.5 | Viscosity of Adhesives | 329 |
| 10.3.1.6 | Thixotropy of Adhesives | 330 |
| 10.3.1.7 | Setting the Room Humidity | 330 |
| 10.3.2 | Adhesive Delivery and Application | 331 |
| 10.3.2.1 | Adhesive Delivery to the Surface | 331 |
| 10.3.2.2 | Adhesive Application to the Substrate | 336 |
| 10.3.2.3 | Bead Application | 338 |
| 10.3.2.4 | Spot Application | 338 |
| 10.3.2.5 | Screen-Printing Application | 338 |
| 10.3.2.6 | PSA Tape Lamination | 339 |
| 10.3.2.7 | Brushing, Troweling, and Squeegeeing | 339 |
| 10.3.2.8 | Spray Application | 339 |
| 10.3.2.9 | Roller Application | 340 |

| | | |
|-----------|--|------------|
| 10.3.2.10 | PSA Film Lamination | 340 |
| 10.4 | Processes for Cohesion Build-up | 340 |
| 10.4.1 | Adhesive Component Mixing | 341 |
| 10.4.1.1 | Mixing in Batch | 341 |
| 10.4.1.2 | Static Mixing | 342 |
| 10.4.1.3 | Quality of the Mixture | 342 |
| 10.4.1.4 | Process Technology of Static Mixing | 344 |
| 10.4.1.5 | Dynamic Mixers | 345 |
| 10.4.2 | Joining and Fixation of the Bond | 346 |
| 10.4.2.1 | Joining | 346 |
| 10.4.2.2 | Fixation | 346 |
| 10.4.3 | Curing of the Adhesive Layer | 346 |
| 10.4.3.1 | Physically Curing Systems | 347 |
| 10.4.3.2 | Chemically Curing Systems | 347 |
| | Reference | 348 |
| 11 | Start of Production (Step 5) | 349 |
| 11.1 | Work Done So Far | 349 |
| 12 | Contemporary Adhesive-Bonding Applications | 351 |
| 12.1 | Introduction | 351 |
| 12.1.1 | Adhesive Market Development | 351 |
| 12.1.2 | Customer Requirements for Adhesive Bonding | 352 |
| 12.2 | Adhesive Bonding in Lightweight Construction | 352 |
| 12.2.1 | Introduction | 352 |
| 12.2.2 | Lightweight Requirements in Transportation | 352 |
| 12.2.3 | Lightweight Bonding with Modern “Crash-Resistant” 2K Adhesives | 353 |
| 12.2.4 | Elastic Bonding in Truck Construction | 354 |
| 12.2.5 | Printable Adhesives | 355 |
| 12.3 | The Role of Adhesives in Modern Facade Construction | 355 |
| 12.3.1 | Structural Glazing with Silicone Adhesives | 356 |
| 12.3.2 | Structural Glazing with PSA Tapes | 356 |
| 12.4 | Adhesive Bonding on Low-Energy Plastics | 357 |
| 12.4.1 | Introduction | 357 |
| 12.4.2 | R&D for Bonding to Low-Energy Surfaces | 358 |
| 12.4.3 | Self-Adhesive Transfer Tapes | 358 |
| 12.4.4 | Structural Adhesives for Low-Energy Surfaces | 359 |
| 12.5 | Adhesive Bonding with Structural 2K Adhesives | 360 |
| 12.5.1 | Guinness World Record | 360 |
| 12.5.2 | Structural Bonding in Sports | 360 |
| 12.5.3 | Structural Bonding in Art | 361 |
| 12.5.4 | Bonding with 2K Acrylates in Advertising | 362 |
| 12.5.5 | Highly Transparent Bonding | 363 |
| 12.6 | Inductively Curing Adhesives | 363 |

| | | |
|--------|---|-----|
| 12.6.1 | Advantages of Inductively Curing Adhesives | 363 |
| 12.6.2 | User Benefits | 364 |
| 12.6.3 | Potential for Innovative Bonding Solutions | 365 |
| 12.7 | Adhesive Bonding with High-Performance Acrylic Foam Tapes | 366 |
| 12.7.1 | Characteristics and Properties | 366 |
| 12.7.2 | User Benefits | 366 |
| 12.7.3 | Acrylic Foam Tapes for Powder-Coating Processes | 366 |
| 12.7.4 | Flame-Retardant Acrylic Foam Tapes | 367 |
| 12.7.5 | Visually Demanding Applications | 367 |
| 12.7.6 | Bonding of Touchscreens | 368 |
| 12.8 | Closing Wounds with Hotmelt Adhesives | 369 |
| 12.8.1 | User Benefits | 369 |
| | References | 369 |

General References 371

Index 373