Adhesion Technology Recap: Current and Emerging Areas

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Contents

Abstract

This chapter gives a brief description of the subjects and chapters that are included in this second edition of the handbook and the most important changes in relation to the first edition. The handbook is organized in ten parts: theory of

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adhesion, surface treatment, adhesive and sealant materials, testing of adhesive properties, joint design, durability, manufacture, quality control, applications, and emerging areas. A total of 58 chapters are presented covering all aspects of adhesion and adhesives. In addition to the information contained in each chapter, an extensive list of references is given (approximately 4000 references).

60.1 Theory of Adhesion

In ▶ Chap. 2, “Theories of Fundamental Adhesion” by Packham, the historical development and current status of the four classical theories of adhesion (mechanical theory, adsorption theory, electrostatic theory, and diffusion theory) are reviewed. The role of weak boundary layers is also discussed with emphasis on the importance of careful investigation of the locus of failure of an adhesive bond. Next, Brogly in ▶ Chap. 3, “Forces Involved in Adhesion” describes the main forces responsible for adhesion, from strong covalent bonds to weak van der Waals forces, also considering specific interactions such as acid-base or capillary forces. ▶ Chapter 4, “Wetting of Solids” by Shanahan and Possart considers thermodynamic aspects of wetting, which involves intimate contact between the two phases and the environment. A short overview of the relevant processes and parameters in the spreading of liquids on substrates is presented in ▶ Chap. 5, “Spreading of Liquids on Substrates” by Reiter. In a simplified view, the dynamics of these processes can be understood as being controlled by the balance of driving forces and resistance due to dissipative processes. Finally, in ▶ Chap. 6, “Thermodynamics of Adhesion,” Possart and Shanahan show that wetting data may be used to estimate the thermodynamic, or Dupré, energy of adhesion, provided certain assumptions are made and suitable models constructed for, in particular, interfacial tensions.

60.2 Surface Treatments

The use of surface treatments to optimize adhesion has been well-established. In ▶ Chap. 7, “General Introduction to Surface Treatments,” Critchlow considers the main treatment methods for metals and polymers in terms of how such processes are carried out and their influence on surface physical and chemical properties. Consideration has been given to a range of treatments from simple degrease options to the more highly complex multistage processes. Davies, in ▶ Chap. 8, “Surface Treatments of Selected Materials,” discusses high-performance surface treatments for several metals and other materials. Surface treatment of aluminum and other metals is used to illustrate how proper surface preparations meet these requirements. ▶ Chapter 9, “Surface Characterization and Its Role in Adhesion Science and Technology” by Watts reviews a variety of methods of surface characterization that have been found to be useful in the study of adhesion. The methods considered can conveniently be considered in three groups: surface topography, surface free energy of a material, and surface-specific chemical analysis. Next, Watts in

▶ Chap. 10, "Use of Surface Analysis Methods to Probe the Interfacial Chemistry of Adhesion" explores the manner in which the surface analysis methods of X-ray photoelectron spectroscopy (XPS) and time-of-flight secondary ion mass spectrometry (ToF-SIMS) can be used to extract information regarding the interfacial chemistry of adhesion from polymer/metal systems such as adhesive joints. The last chapter of this section, ▶ Chap. 11, "Organosilanes: Adhesion Promoters and Primers" by Abel, describes organosilanes from their genesis to their chemistry. The necessary interactions that such molecules have to develop on materials in order to fulfil their main role as adhesion promoters are explained. The use of silanes as primers particularly where the user aims to improve adhesion or protect from corrosion is also considered. Some other organic or nonorganic adhesion promoters are also discussed.

60.3 Adhesive and Sealant Materials

The first chapter ▶ "Classification of Adhesive and Sealant Materials" (Chap. 12) by Sancaktar classifies adhesive and sealant materials. For this purpose, various categories are considered depending on the polymer base, functionality in the polymer "backbone," physical forms, chemical families, functional types, and methods of application. Next, in ▶ Chap. 13, "Composition of Adhesives," Kim et al. give information about various ingredients that may appear in an adhesive or sealant: primary resins, hardeners, solvents, fillers, plasticizers, reinforcements, and various additives. In the third chapter of this section, Papon (▶ Chap. 14, "Adhesive Families") classifies adhesives and sealants in three broad groups. First, there are adhesives where the polymer is pre-existing (and must be placed beforehand in fluid form: solution, emulsion, or "melt" state). Second there are adhesives where the polymer is formed during the course of a reactive process (polymerization). Third, Papon describes the particular category of pressure-sensitive adhesives where the polymer exhibits viscoelastic properties able to develop adhesion during the bonding step. The basic concepts, formulations, and test methods for pressure-sensitive adhesives are presented in ▶ Chap. 15, "Pressure-Sensitive Adhesives (PSAs)" by Paul, stressing the importance of interfacial interactions, viscous loss, and extensibility. Selection of the correct adhesive for an application can be a daunting task due to the many types commercially available ranging from different chemistries through different forms to an almost continuum of material properties. Kellar in ▶ Chap. 16, "Selection of Adhesives" gives a logical approach to this task and selection criteria.

60.4 Testing of Adhesive Properties

The first chapter by Dillard ▶ "Physical Properties" (Chap. 17) addresses several relevant physical properties of adhesives, including viscosity, density, and stress-strain behavior, quantities that are often thought to be intrinsic properties of a material. The thermal properties of adhesives are described next by Comyn.

Consideration is given to the shelf life, the hardening process, the glass transition temperature, the thermal conductivity and thermal expansion, and the thermal breakdown of adhesives. In ▶ Chap. 19, “Failure Strength Tests,” da Silva et al. describe the major failure strength tests used to determine the intrinsic adhesive properties. Tensile, compressive, and shear tests are described with reference to the major international standards. Bulk and in situ (adhesive in a joint) tests are discussed and related. ▶ Chap. 20, “Fracture Tests” by Blackman considers first the fracture in a bulk adhesive specimen under mode I, i.e., tensile opening loading conditions. Mode II (in plane shear) and mixed-mode I/II testing of adhesive joints are also considered. There is often the need to measure the resistance to fracture in a joint with flexible substrates. One such test is the peel test, and some variants of the peel test are considered in that chapter. Goglio, in ▶ Chap. 21, “Impact Tests,” describes the main tests used to assess the impact strength of adhesives and joints. The main tests used in the experiments are pendulum, falling weight, and Hopkinson bar loading conditions or evolutions of these. The last chapter of this section by Dillard and Yamaguchi deals with ▶ Chap. 22, “Special Tests.” This chapter gives a brief description of special mechanical tests for various types of material and sample geometries, such as blister tests, tensile tests and shear tests for sealants/foam adhesives, indentation tests, scratch tests, tack tests, and tests for the evaluation of residual stresses.

60.5 Joint Design

This section starts with ▶ Chap. 23, “Constitutive Adhesive and Sealant Models” by Sancaktar. The chapter includes deformation theories and viscoelasticity with linearity and nonlinearity considerations, rubber elasticity, singularity methods, bulk adhesive as composite material, damage models, the effects of cure and processing conditions on the mechanical behavior, and the concept of the “interphase.” ▶ Chapter 24, “Analytical Approach” by Tong and Luo presents an analytical approach for determining stress and strength of adhesively bonded joints. Various closed-form solutions for adhesive stresses and edge bending moment for balanced single-lap joints are presented and compared. In ▶ Chap. 25, “Numerical Approach: Finite Element Analysis,” Ashcroft provides first a general background to the development and application of the finite element (FE) method. Then he discusses some of the practical aspects of FE modeling and gives applications of the FE method to adhesively bonded joints. FE analysis is currently the only technique that can comprehensively address the challenges of modeling bonded joints under realistic operating conditions. However, a reliable and robust method of using FE analysis to model failure in bonded joints is still to be developed. Öchsner, in ▶ Chap. 26, “Special Numerical Techniques to Joint Design,” introduces special numerical techniques to analyze adhesive joints. The first part covers special FE techniques which reduce the size of the computational models. The second part of this chapter introduces alternative approximation methods, the boundary element method and the finite difference method. In ▶ Chap. 27, “Design Rules and Methods to Improve Joint Strength,” da Silva et al. describe the main factors influencing joint strength. Methods are then proposed to improve the joint strength by using fillets, adherend profiling and other geometric solutions, and hybrid joining. Repair designs are also discussed. Finally, configurations are recommended for several types of joint. ▶ Chapter 28, "Design with Sealants" by Anderson describes the many factors to go into the design of reliable sealant joints. The various joint types are discussed and illustrated, and their critical dimensions and materials are described. Sato, in ▶ Chap. 29, "Design for Impact Loads," discusses design methods for adhesively bonded joints subjected to impact loading. Methodologies to treat the dynamic responses of structures are shown. Some examples of stress analysis are shown, where closed-form approaches and dynamic FE analyses are explained. The last chapter of this section ▶ "Vibration Damping of Adhesively Bonded Joints" (Chap. 30) by Adams et al. discusses the general concept of vibration damping in vibrating structures and how it can be used to limit vibration amplitudes. Simple equations for calculating the damping of a lap joint in tension and bending have been developed. As there is very little experimental data available, the damping of a variety of adhesively bonded single-lap joints has been measured by the authors.

60.6 Durability

In ▶ Chap. 31, "Effect of Water and Mechanical Stress on Durability," Ashcroft and Comyn discuss the effect that absorbed water has on the strength of adhesively bonded joints. The influence of adherend surface treatment, applied stress, and adhesive type on the environmental degradation of bonded joints is demonstrated. Methods of modeling the environmental degradation of adhesively bonded joints using coupled hygro-mechanical finite element (FE) analysis are then described. Chapter "Radiation and Vacuum" of the first edition has been substituted by ▶ "Adhesives in Space Environment" (Chap. 32) by Dagras et al. In the first part, a description of the different uses and needs related to adhesives on spacecraft is given. Then, the characteristics of space environment are explained. Once in orbit, the adhesive has to withstand constraints as particles radiations, UV, and atomic oxygen that are not present on Earth. Before spacecraft launch, the adhesives have to be validated and tested on ground with conditions as representative as possible of the space environment. Finally, the impact of this space environment on adhesives and the associated degradations are described. ▶ Chapter 33, "Fatigue Load Conditions" by Ashcroft discusses some of the main factors when considering fatigue, with particular reference to issues applicable to bonded joint. The main methods of characterizing and predicting the response of bonded joints to fatigue loading are described. Finally, there are sections on the special cases of creep-fatigue and impact fatigue. In ▶ Chap. 34, "Creep Load Conditions," Geiss considers viscoelastic models, superposition principles, experimental testing procedures, and predictive methods. In the last chapter of this section, ▶ "Durability of Nonstructural Adhesives" (Chap. 35) by Palmer, methods evaluating durability and test regimes, including exposure to elevated and reduced temperatures, UV radiation, moisture, saline solutions, stress, and fatigue, both individually and combined in cycles are considered.

60.7 Manufacture

The first subject in this section is ▶ “Storage of Adhesives” (Chap. 36) by Engeldinger and Lim. A major part of this chapter focuses on the shelf life and safety aspects. Adhesives are divided into four categories, solvent-based, water-based, hot-melt, and reactive adhesives. In ▶ Chap. 37, “Preparation for Bonding,” Lutz discusses each item of the process chain: the storage of adhesives, transfer to the application area, different metering and dispensing technologies, mixing equipment used, substrate preparation, and quality control. Proposals are made regarding education of personnel and how to create a safe working environment. In ▶ Chap. 38, “Equipment for Adhesive Bonding,” Peschka describes the equipment required for manual adhesive bonding processes. Automation and robotics are outlined with a special emphasis on parameters affecting accuracy. Accelerated curing using such devices as UV radiation and inductive heating is also treated. The last chapter of this section, ▶ “Environment and Safety” (Chap. 39) by van Halteren, deals with the different aspects of consumer, work, and environmental protection, including health and safety information, related to the use of adhesives in industrial and domestic areas.

60.8 Quality Control

This section starts with ▶ Chap. 40, “Quality Control of Raw Materials” by Wakabayashi. The main components of adhesives are first described, and then quality control procedures are discussed such as chemistry, impurity content, molecular weight, viscosity, density, and quality control of raw materials in storage. Next, in ▶ Chap. 41, “Processing Quality Control” by Haraga, the processing quality control of adhesively bonded joints in actual production lines is discussed. Topics such as control of environmental conditions and materials, inspection of surface treatment of adherends, adhesive selection for easy process control, and education and training of operators are treated. In ▶ Chap. 42, “Nondestructive Testing” by Adams, the types of defect encountered in adhesive joints and the nondestructive testing techniques available to detect them are reviewed. Several techniques are available for void detection, the most commonly used being ultrasonics and different types of bond tester. The detection of poor cohesive properties is more difficult but can be achieved with ultrasonic or dielectric measurements. The last chapter of this section, ▶ “Techniques for Post-fracture Analysis” (Chap. 43), was rewritten by Créac’hcadec. This chapter presents three types of measurement systems: microscopy, compositional analysis, and mechanical observations. A table sums up an exhaustive list of the major observation devices. Then, the main methods are detailed with macroscopic and mesoscopic observations, microscopic observation, physico-chemico analysis, and mechanical observations.

60.9 Applications

The first application treated is the "Aeronautical Industry" by Hart-Smith. The following topics are treated: basic needs, adhesive characteristics, surface preparation, design of adhesive joints, durability, defects, thermal effects, quality control, composite structures, repairs, and examples of use. ▶ Chapter 45, "Aerospace Industry" was extensively revised by Pérès and Larnac. The chapter introduces some of the specific bonding-related issues that face those responsible for bonding operations in space applications such as extremely high mechanical loads over a short time, with the launcher and its payloads subjected to gravity magnified by about 20, followed by exposure to extremely high temperatures over a very long period, with the observation and telecom satellites under zero gravity. Dilger and Frauenhofer updated ▶ Chap. 46, "Automotive Industry." Typical applications for automobiles are shown. Additionally, suitable adhesive properties and surface treatments are discussed. ▶ Chapter 47, "Adhesive Bonding for Railway Application" is next treated by Suzuki. It is shown that adhesives are an indispensable joining technology for railway industries. Adhesives are used for the fabrication of almost all rail cars. For example, in the steel main structure of conventional rolling stock, adhesives are applied for bonding decorated aluminum sheets of wall and ceiling to frames, bonding of floor covering to the floor plate, and fixing heat insulating material to the inside of the carriages. ▶ Chapter 48, "Marine Industry" by Davies describes the use of adhesive bonding to assemble structures in the marine industry. The marine environment is extremely aggressive, and this has resulted in widespread use of fiber-reinforced composite materials. Adhesive bonding is a lightweight and corrosion-resistant means of joining these materials. Three industrial applications are used to illustrate the use of adhesive bonding, small pleasure boats, high-performance racing yachts, and bonded structures in the offshore industry. In the well-revised chapter ▶ "Civil Construction" (Chap. 49), Böhm et al. describe adhesive bonding applications in the civil construction sector, specific requirements, and adherends. The execution of bonding and properties of adhesive bonded civil constructions are also treated. Jung and Kim, in ▶ Chap. 50, "Electrical Industry," explain the mechanisms underlying the electrical conduction in adhesive joints, and the thermal and mechanical parameters that should be measured are introduced. In terms of the evaluation of the reliability of adhesives in electronics, the basic test procedures, including several specific test methods and analysis techniques, are explained. ▶ Chapter 51, "Shoe Industry" by Martín-Martínez constitutes one of the very few reviews in the existing literature on shoe bonding and gives an updated overview of the upper to sole bonding by means of adhesives. The surface preparation of rubber soles and both the formulations of polyurethane and polychloroprene adhesives are described. The preparation of adhesive joints and adhesion tests are also revised. Another chapter was added to this section on ▶ "Oil Industry" (Chap. 52) by de Barros et al. due to the increase adhesives application that field, especially for repairs. The main advantage by using adhesive bonding is to avoid the fire risk concerning the traditional weld process. Adhesives also feature protection against corrosion which is a main concern in offshore installations. This chapter shows that the use of composites has become a real alternative to structural repairs in situ as these materials become more and more reliable.

60.10 Emerging Areas

▶ Chapter 53, "Molecular Dynamics Simulation and Molecular Orbital Method" by Zhao et al., various simulation methods pertaining to adhesion technology are introduced, such as molecular dynamics, quantum mechanics, the molecular orbital method, and the density functional theory. Some examples are proposed investigating adhesion issues using various simulation methods. ▶ Chapter 54, "Bioadhesives" was rewritten by Richter. It gives an overview about natural adhesives and biological adhesives leading to bioinspired applications. Biological and microbiological adhesives have an enormous potential for industrial applications. The most prominent ones are constructional, packaging, and medical applications. Gorb, in ▶ Chap. 55, "Biological Fibrillar Adhesives: Functional Principles and Biomimetic Applications," reviews functional principles of biological systems in various animal groups such as insects, spiders, and geckos with an emphasis on insects and discusses their biomimetic potential. Data on ultrastructure and mechanics of materials of adhesive pads, movements during contact formation and breakage, the role of the fluid in the contact between the pad and substrate are presented. ▶ Chapter 56, "Adhesives with Nanoparticles" are discussed by Taylor. This chapter outlines the principal types of nanoparticles and the methods that may be used to disperse the particles in a polymer matrix. It discusses how nanoparticles can alter the mechanical properties (stiffness and fracture), electrical properties (conductivity), and the functional properties (permeability, glass transition temperature) of thermoset polymers. In ▶ Chap. 57, "Adhesive Dentistry," Nicholson describes the principal uses of adhesives in clinical dentistry, covering both the materials and the clinical techniques involved. The two types of tooth-colored material, namely, the composite resin and the glass-ionomer cement, are described, together with their current variations. Surface pretreatment is critical for the success of these systems, and the current state of the understanding of this aspect of the subject is described. ▶ Chapter 58, "Adhesion in Medicine" is covered by Chivers. Adhesives technology has two main applications in medicine as considered in this chapter, for internal fixation of tissues usually after surgery and for use on the skin, primarily to hold dressings in place. The last chapter by Sato concerns ▶ "Recycling and Environmental Aspects" (Chap. 59). Adhesively bonded adherends should be often separated before they can be recycled. For this purpose, dismantlable adhesives, which can be separated with stimulations (softening of adhesive, expansion force due to blowing agents or thermally expandable microcapsules, chemical degradation, and electrochemical reaction), have been developed recently. These adhesives can be applied to adherend recycling or product reworking.

60.11 Conclusions

The preparation of this second edition has been an interesting experience for the editors. The review process gave a deeper insight into the various aspects of adhesion from basics to applications. Authors come from every background (chemistry, physics, mechanics) and work in either academia or industry, proving that adhesion is a truly multidisciplinary and widely applied subject. The editors would like to thank the authors for their patience with the preparation of this handbook. Finally, the editors especially thank Dr. Christoph Baumann, Ms. Tina Shelton, and Ms. Monika Garg, Springer editors, who helped enormously toward the success of this handbook.