Adhesion and Adhesives Technology

An Introduction

2nd Edition

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This book is dedicated to my wife, Janice,
and to my children, Nick and Amanda

Preface

Adhesion science is a multidisciplinary field, which encompasses aspects of engineering as well as physical and organic chemistry. The breadth of the field is possibly the reason that there have been so few books on the subject written by a single author. The books in this area have tended to be handbooks, treatises, or other compilations by multiple authors. I have attempted to provide a broad view of the field, but with a consistent style, that leads the reader from one step to another in the understanding of the science. The second edition also includes problems for the student to work in order to help build on the information presented in the text.

The text assumes that the reader has little or no knowledge of the science of adhesion. The bulk of the book is written with the supposition that the reader has had a course in college level calculus as well as college level organic and physical chemistry. The book has also been written in such a fashion that even a person that has a meager knowledge of these subjects can learn something about adhesion science from reading this book. That is, the emphasis is on *understanding* the science rather than a complete and detailed exposition on any part of it. An attempt has been made to describe as much as possible in words and examples rather than in detailed mathematical derivations. That mathematics has been included in those sections where more detail seemed necessary. Each section or chapter starts with a simple view of the subject area, starting at the same point an entry-level textbook would begin. Each section or chapter then builds to a point at which more detail is available for the reader who is or wants to be a practitioner of the art and science of adhesion. Many sections also includes helpful practical suggestions about how measurements can be made, how surfaces can be modified, or how adhesives can be formulated to lead to a useful result. The second edition includes a number of new topics in the chemistry of adhesives. The wish of the author is to produce a well-rounded introductory view of each of the fields, which form adhesion science no matter what the technical background of the reader may be. As science progresses, our understanding of natural phenomena changes. This book also includes news aspects of the understanding of adhesion science, in particular the connection between fundamental adhesion and the practical adhesive bond strengths of adhesive bonds is expanded upon.

I would like to acknowledge some of the people at 3M who have assisted me either by reviewing this manuscript or by providing support to pursue my study of the science of adhesion. These people include Sam Smith, Bill Schultz, Dave Wangsness, Ted Valentine, Brian Smillie, Dick Hartshorn, Don Theissen, George Allen, Tom Savereide, Morgan Tamsky, Larry Clemens, Rich Newell, and Mike Engel. Without their friendship and support, it is doubtful that I would have had the opportunity to build the base of expertise necessary to prepare a book this book. I would also like to acknowledge the late Prof. Bob Kooser at Knox College who inspired me to pursue a career in physical chemistry.

Al Pocius

Contents

1 Introduction

1.1 Introduction and Chapter Objectives

Adhesive bonding is a method by which materials can be joined to generate assemblies. Adhesive bonding is an alternative to more traditional mechanical methods of joining materials, such as nails, rivets, screws, etc. Adhesive bonding is not a new joining method. Use of adhesives is described in ancient Egypt [1] and in the Bible [2]. Bommarito [3] describes recipes for adhesives that were formulated during the Middles Ages. One such recipe shows that people in the middle ages had an appreciation for the generation of composite materials as well as the use of drying oils:

"Very Strong, Very Good Glue"

"Take clay roof tiles and grind them to a fine powder using a flour grinder. Add a similar amount of iron rust, also ground to a fine powder. Add live lime in an amount equivalent to the clay and iron rust and incorporate the mixture with linseed oil. Use immediately to glue what you want as this glue is better when used fresh than otherwise."

A major step in adhesive technology took place in the early 1900s with the advent of synthetically prepared adhesives. Thus, widespread use of adhesives as a joining medium is a relatively recent phenomenon.

All joining methods have their advantages and disadvantages and adhesive bonding is not an exception. This introductory chapter explores some of the positive and negative features of adhesive bonding as a joining method. Exploring these features sets the stage for many of the chapters to follow. The objectives of this chapter are

- to acquaint the reader with the basic definitions used in adhesion science
- to provide the reader with a basis for understanding the advantages and disadvantages of using adhesive bonding
- to discuss the place of adhesive technology in our economy and to provide examples of where adhesives are utilized
- to describe sources of information about adhesion and adhesives for those who are becoming practitioners of the art and science of adhesive bonding.

1.2 Basic Definitions

An assembly made by the use of an adhesive is called an *adhesive joint* or an *adhesive bond*. Solid materials in the adhesive joint, other than the adhesive, are known as the *adherends*. The phenomenon, which allows the adhesive to transfer a load from the adherend to the adhesive joint, is called *adhesion*. There is also the phenomenon of *abhesion*, which is the condition of having minimal adhesion. This property is important when an assembly is needed from which the adhesive can be removed on demand. Materials that exhibit abhesion are also known as *release materials* and they are used to make certain pressure-sensitive adhesive constructions. Pressure-sensitive adhesives are described in Chapter 9.

The actual strength of an adhesive joint is primarily determined by the mechanical properties of the adherends and the adhesive. The term we apply to the measured physical strength of an adhesive bond is *practical adhesion*. The primary purposes of this book are to describe the phenomenon of adhesion, to describe the chemistry and properties of adhesives, and to discuss the current understanding of the relationship between practical adhesion, adhesion, and the mechanisms of energy dissipation in the adhesive joint.

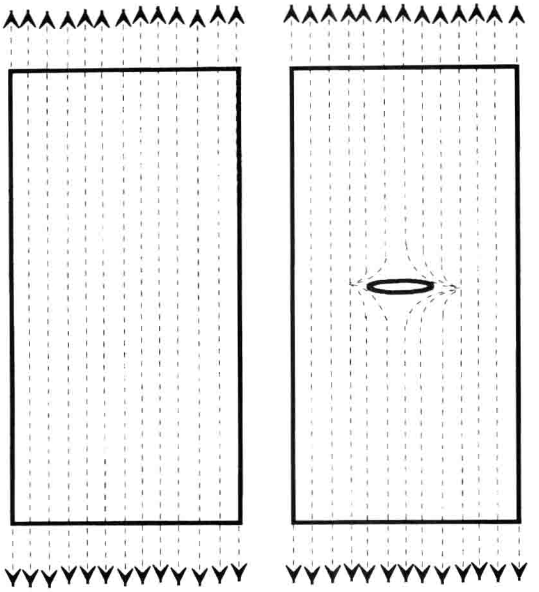
1.3 Advantages and Disadvantages of Adhesive Bonding

One major differentiation between an adhesive joint and a mechanically fastened joint is that in the second, a mechanical fastener must pierce the adherend in order to execute an assembly. When a mechanical fastener pierces an adherend, or if the adherend is pierced before the installation of a mechanical fastener, a hole is created in the adherend.

In Fig. 1.1 we see two examples of an adherend. In Fig. 1.1(a), the adherend is intact. If a load was applied to the adherend, the lines of force propagating through the adherend would be continuous. If instead, the adherend had a hole in it (such as depicted in Fig. 1.1(b)), the lines of force could not be continuous through the adherend and would have to go around the hole. Thus, at the edges of the hole, the force experienced by the material is much larger than the force experienced by the material remote from the hole. The edges of the hole not only have to support the force that is applied to those edges, but also must support the force that should have been supported by the material that would have been in the hole. As we will find in Sections 2.4 and 3.5.1 on fracture mechanics, this situation is known as a *stress concentration*. A stress concentration can cause a decrease in many physical properties of the adherend as well as those of the mechanical joint. In contrast, if an adhesive is used to generate an assembly, no hole is generated in the adherend. Therefore, the physical properties of the adherend are maintained after the assembly has been created.

The use of mechanical fasteners in a joint can lead to several problems that are not present when adhesives are used. First, the overall strength of the joint can be reduced. Second, the joint can experience early fatigue failure. Third, if either of the adherends is sensitive to shock, the act of applying the mechanical fastener could cause the assembly to fail.

Adhesive bonds, when executed in a properly designed adhesive joint, do not exhibit high stress concentrations, so the properties of the adherends can be fully utilized. However, adhesive joints do require a much larger area of contact between the adherends and the



(a) (b)

Figure 1.1 Diagram showing lines of force through a monolithic body (a) and a body containing an elliptical hole (b). The lines of force pass continuously through (a) but are unable to do so in (b). This results in a stress concentration at the edges of the elliptical hole.

adhesive in order to carry the same load as a mechanical fastener. Some of the criteria for the proper design of an adhesive joint are described in Chapters 3 and 11.

For the most part, adhesives are polymeric materials that exhibit viscoelastic properties. Materials that display viscoelasticity have both a viscous character as well as an elastic character. These terms are described in more detail in Chapters 2 and 5. Polymer-based adhesives absorb mechanical energy applied to the joint and dissipate that energy as heat. Hence, fatigue failures are delayed in comparison to mechanical fastening. For example, Schliekelmann [4] describes the increase of fatigue life for joints made by a combination of mechanical fastening and adhesive bonding. Table 1.1 shows this data. The increase in fatigue life of the combination joint is obvious. The viscoelastic properties of adhesives and the role they play in the adhesive bonding and debonding process are discussed in Chapters 2, 5, 6 and 9.

Finally, many adhesives do not require input of mechanical energy to effect an assembly. Hence, shock-sensitive materials can be easily made into an assembly. For example, one would not consider joining of dynamite sticks with nails. However, dynamite sticks can be easily joined by pressure-sensitive adhesive-backed tape.

Table 1.1 Comparison of Fatigue Life of Joints (Aluminum Adherends, 4 cm lap and 1mm Adherend Thickness)

Sample	Fatigue life (cycles)
Riveted	211,000
Riveted and sealed (using an elastomeric sealant)	42,000
Riveted and adhesively bonded using a 2-part epoxy	>1,500,000

The primary disadvantage of adhesive bonding is that it relies on adhesion for the transfer of load through the assembly. Adhesion is a surface physico-chemical phenomenon that is discussed in Chapters 4 and 6. Since adhesion is a surface phenomenon, it follows that the physical properties of the adhesive joint depend strongly on the character of the surface of the adherend and how the adhesive interacts with that surface. Thus, an adherend with an improper surface could lead to lower joint strengths than might be predicted from the mechanical properties of the adhesive and the adherend. Surface problems are even more important when one tries to generate adhesive bonds that are durable in adverse environments. The need for a proper surface, and the fact that it is not always available, are disadvantages of adhesive bonding in comparison to mechanical fasteners, which are not affected by the state of the surface of the members of a joint. Practical methods by which one can generate surfaces that are amenable to adhesive bonding are discussed in Chapter 7.

Adhesives display several other advantages over mechanical fastening. One of these advantages is the reason for the widespread use of adhesives in the aerospace industry, specifically the ability of adhesives to not only form a joint, but also to seal the assembly in one step. Mechanical fastening often requires separate sealing steps to create a pressurizable assembly. Adhesives also allow galvanically dissimilar materials to adhere to one another without accelerating corrosion. For example, the mechanical joining of steel and aluminum would be a disaster in the making. Aluminum would act as an anode to steel and corrode rapidly in corrosive environments. Since most polymeric adhesives are non-ionic and electrical insulators, a properly effected adhesive bond would electrically separate the members of the galvanic couple while still joining them structurally.

However, mechanical fastening does have a number of advantages over adhesive bonding. Once a mechanical fastener is applied, one certainly knows that it is there. Adhesives, by their nature, are internal to the joint. In most cases, it is not easy to determine (without destructive testing) whether the adhesive was properly applied. This lack of non-destructive quality control has led to entire studies on methods by which adhesive bonds can be inspected in a non-destructive fashion. One other advantage of mechanical fasteners over adhesive bonding is that the engineering of mechanically fastened assemblies is part of many schools' curricula. However, there is a paucity of courses on the engineering of adhesively bonded structures. Thus, there may be a certain lack of confidence in the use of adhesives among engineers and designers. It is hoped that this book will increase

Table 1.2 Comparison of Welding versus Adhesive Bonding in Terms of Their Production Characteristics

Welding	Adhesive bonding
Little or no substrate preparation is necessary	Adherend surface preparation is often necessary
Post-heat treatment is sometimes necessary	Post-cure is often advantageous
Welding equipment is expensive, heavy and power intensive	Equipment is only sometimes necessary and may be as simple as an oven
Wires, rods and welding tips are inexpensive (except for aluminum)	Adhesives are moderately expensive, depending upon type
Production rate can be rapid	Production rate can be rapid but is heavily dependent upon the adhesive
Non-destructive tests are applicable but are expensive	Non-destructive tests are available but are not predictive of bond strength
Welder must remove heat sensitive and/or flammable materials away from the welding operation	No need to remove heat sensitive materials from the bonding area, dependent upon cure conditions

Table 1.3 Comparison of Welded Joints versus Adhesive Bonds

Welded joint	Adhesive bond
Permanent	Permanent (with proper surface preparation)
Local stress points	Predominantly uniform stress distribution
Joints often have to be "dressed" for aesthetics	No surface markings
Useful only for identical materials	Dissimilar materials are easily joined
High temperature resistance	Low to moderate temperature resistance
Poor fatigue resistance	Excellent fatigue resistance

confidence in the use of adhesives and potentially lay the groundwork for an engineering curriculum in this area.

Tables 1.2 and 1.3 show a compilation of comparisons of a well-known joining method, welding, to adhesive bonding as compiled by Lees [5]. The features of adhesive bonding versus welding further highlight the advantages and disadvantages of the former versus the latter.

1.4 Uses of Adhesive Bonding in Modern Industry

For thousands of years, adhesive bonding has been used in the production of veneered furniture. Many examples of veneered furniture from Egyptian and Roman times are found in museums. Adhesives were also used for the generation of wooden musical instruments. In more recent times, adhesives are still used in the generation of veneered wood. In addition, adhesives are used in a far wider array of applications than could have been imagined by our ancestors. The primary boost in the use of adhesives came with the advent of synthetic polymeric materials with improved mechanical properties.

There are many types of adhesives, both organic and inorganic. The inorganic adhesives are familiar to most people and include materials such as Portland cement and solder. The chemistry and physical properties of these adhesives are not discussed in this book although the sections on mechanical properties and surfaces for organic materials apply just as well to these adhesives. Rather, the adhesives discussed in this book are those that are based entirely or primarily on organic materials. The chemistry and physical properties of these polymer-based adhesives are discussed in Chapters 8–11.

Since these adhesives are organic in nature, they normally have a lower specific gravity than either the inorganic adhesives mentioned above or most adherends. Thus, assemblies produced with polymer-based adhesives weigh less than those produced with inorganic adhesives or with metallic fasteners, a major advantage in the aerospace industry where lightweight structures are of paramount importance.

Despite the fact that the use of adhesives is not part of many engineering curricula, there are many examples of the use of adhesive bonding in industry. The aerospace industry uses adhesive bonding to great advantage in the construction of many components. Figure 1.2 is

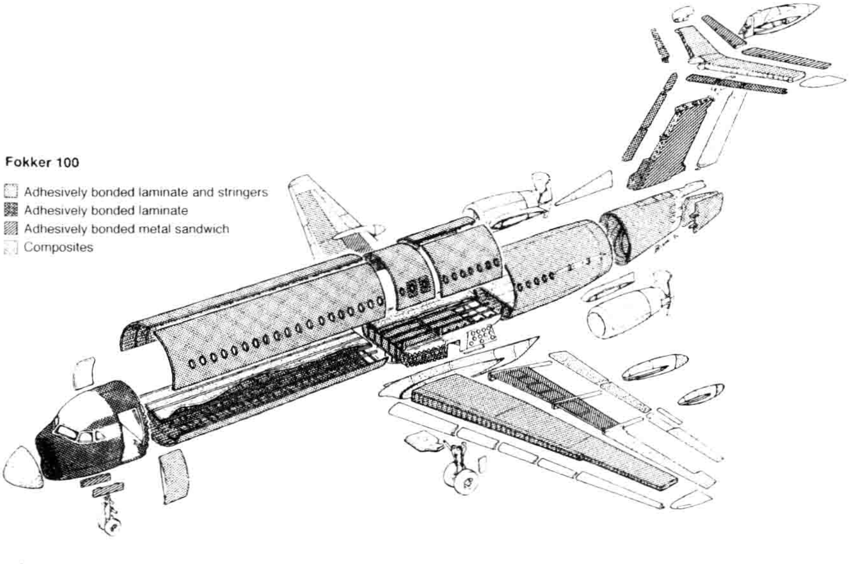


Figure 1.2 Diagram of a Fokker F-100 aircraft showing the sections of the aircraft that are adhesively bonded. Note that a substantial amount of the fuselage is constructed using structural adhesives. (Diagram courtesy of the Fokker Aircraft Company, The Netherlands, reprinted with permission.)