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Design of Adhesives Bonds: An Introduction

By Dr. David A. Dillard, Adhesive and Sealant Science Professor
Engineering Science and Mechanics Dept., Virginia Tech (Blacksburg, VA 24061 USA)

Preface:

This document is provided for informational purposes only and is meant to be a brief overview that may be useful for engineers considering the use of adhesives for designing purposes. The author, Virginia Tech, and The Adhesive and Sealant Council, Inc. assume no liability for the use of the information contained herein.   Portions of this document have been adapted for use in Shigley's *Mechanical Engineering Design* Textbook, 6th, 7th, and 8th (2008) editions, McGraw-Hill.

Introduction:

The use of polymeric adhesives to join components for structural, semi-structural, and non-structural applications has expanded greatly in recent years due to the unique advantages adhesives offer for certain assembly processes and the development of new adhesives with improved robustness and environmental acceptability. The increasing complexity of modern assembled structures and the diverse types of materials used have led to many joining applications that would not be possible with more conventional joining techniques. Adhesives are also being used either in conjunction with or to replace mechanical fasteners and welds. Reduced weight, sealing capabilities, reduced part count and assembly time, as well as improved fatigue and corrosion resistance, all combine to provide the designer with customizable opportunities for assembly.   Indeed, the fabrication of many modern vehicles, devices, and structures are dependent on the use of adhesives.

For well-designed joints assembled with proper processing procedures, adhesive usage can result in significant reductions in weight. Eliminating mechanical fasteners eliminates the weight of the fasteners, but also may permit the use of thinner gage materials because stress concentrations associated with the loaded holes are eliminated. Because of their viscoelastic nature, polymeric adhesives are able to dissipate energy, and can significantly reduce noise, vibration, and harshness (NVH) in modern automobiles, for example. These damping characteristics have many other beneficial applications, including earthquake resistance of buildings, stability of optical drives for computers, and the resistance to damage and cracking. Adhesives can be used to assemble heat sensitive materials, or components which might be damaged by drilling holes for mechanical fasteners. They can be used to join dissimilar materials or thin gage stock which cannot be joined through other means.

In spite of a number of attractive features associated with the use of adhesives, either alone or in combination with traditional fastening methods, design methods for adhesives have not been widely incorporated into engineering design courses. In part, this arises because of some of the complications associated with the various types of joints, and the difficulty in establishing design procedures that can be universally applied. Furthermore, the use of adhesive bonding often requires additional skills beyond what an individual educated in a single academic discipline may possess. An understanding of surface preparation, polymer processing, and mechanics are all important concepts for the design team. Because adhesive bonding is so important to the design and construction of efficient structures of the future, greater emphasis on developing these interdisciplinary skills is recommended for those who find themselves involved in designing adhesive joints and their manufacture.

Mechanics of Adhesion

Adhesives are substances that are used to join two or more components together through attractive forces acting across the interfaces. The components being joined are commonly referred to as *adherends* or *substrates*. To function as an adhesive, a polymer must be able to take on the characteristics of both a liquid and a solid and coalescing (in the case of waterborne latex adhesives)[1]. The ability to properly wet a given surface depends on two aspects: favorable thermodynamic surface energies that encourage intimate contact of the adhesive and substrates being bonded, and sufficient time and molecular mobility for the adhesive to conform to and wet the substrate. Increasing pressure, temperature, or time of bonding may accelerate this latter kinetic process. If the adhesive and adherend surfaces are incompatible thermodynamically, however, poor bonding will often result because of the difficulty of achieving intimate contact between adhesive and substrate.

Over the years, a number of mechanisms have been used to explain adhesion in its many forms. Current understanding of the matter is that secondary bonding forces between atoms in close proximity are able to account for much of adhesion we observe. These bonds are referred to as dispersion or van der Waal forces, and breaking these molecular attractions would require relatively small amounts of energy, typically on the order of several tens of mJ/m^2 [2]. Primary chemical bonds can exist in certain situations, and although inherently stronger and more durable, this mode of adhesion is less widespread . Molecular inter-diffusion can also occur between two miscible polymers; a good example of this is rubber cement applied to two surfaces then brought together to allow inter-diffusion to occur. In some situations, electrical double layers can develop across the bond plane,

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[1] An apparent exception to this two stage process are pressure sensitive adhesives that remain relatively soft. Under light pressure conditions, the soft adhesive is able to flow to fill surface asperities, wetting the substrate. Once it has wet-out the adherend, a significant amount of energy is required to remove the adhesive. This is especially true for relatively rapid withdrawal, where the adhesive molecules do not have sufficient time to move, making the adhesive act more like a solid.

[2] For comparison, the surface energy of water is 72 mJ/m^2, so work of adhesion values involving secondary bond attractions are typically smaller than this.

leading to electrostatic attraction[3]. Frequently, enhanced bond strength can result from mechanically roughening the surface of substrates through abrasion or grit blasting. While commonly thought to enhance mechanical interlocking of the adhesive within the crevices and pores of the surface, mechanical roughening can remove weakly bound surface layers and increase the available bond area as well.

Breaking the attractive forces between the atoms of the adhesive and the substrates gives rise to small energies known as the thermodynamic work of adhesion, that are often measured in tens of mJ/m^2. On the other hand, when real adhesive joints are mechanically broken, fracture energies of several kJ/m^2 are often measured. These latter energies are referred to as practical adhesion, and are typically several orders of magnitude larger than the thermodynamic surface energies. This significant multiplication of energies is associated with the dissipation of energy in the adhesive, and sometimes the adherends, through viscoelastic or plastic deformation processes. These practical adhesion energies are quite dependent on rate of loading and temperature, and can often depend on adhesive and adherend thickness as well. For characterizing adhesive performance, fracture energies are often measured in such a way that plastic deformation of the adherends does not occur, as it can significantly overestimate the adhesive toughness. On the other hand, this enhanced energy dissipation in the adherends can be an important factor in practical adhesive joints. For example, in an automobile, passenger safety depends on substantial energy dissipation in the crush zones achieved because the adhesive bonds force the metallic components to deform in such a way that the metal dissipates large amounts of plastic energy.

The large values of practical adhesion energies for high-quality modern adhesives provide significant resistance to debond growth.   Adhesive formulators have developed a number of toughening techniques that have been successfully incorporated into commercial adhesives, improving their resistance to impact and fatigue loading. This is one reason that properly designed adhesive joints utilizing tough adhesives can be more durable under sustained fatigue loading than joints assembled with mechanical fasteners, where stress concentrations surrounding holes or spot welds can lead to failure over repeated load cycles.

Types of Adhesives

There are a large number of adhesive types for various applications. They may be classified in a variety of ways depending on their chemistries (e.g. epoxies, polyurethanes, polyimides), their form (e.g. paste, liquid, film, pellets, tape), their type (e.g. hot melt, reactive hot melt, thermosetting, pressure sensitive, contact, etc.), or their load carrying capability (structural, semi-structural, or non-structural).

Structural adhesives refer to relatively strong adhesives that are normally used well below their glass transition temperature, an important property for polymeric materials, above which polymers are rubbery and below which they are glassy. Common examples of

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[3] To see an example of this, rapidly peel a pressure sensitive adhesive tape from glass in a dark room to which your eyes have become accustomed. You will likely see small blue sparks associated with electrical break-down of this charged double layer.

structural adhesives include epoxies, cyanoacrylates, and certain urethanes and acrylic adhesives. Such adhesives can carry significant stresses, and lend themselves to structural applications.

For many engineering applications, *semi-structural* (applications where failure would be less critical) and *non-structural* (applications of facades, etc. for aesthetic purposes) are also of significant interest to the design engineer, and provide cost-effective means required for assembly of finished products.   These include *contact adhesives* where a solution or emulsion containing an elastomeric adhesive is coated onto both adherends, the solvent is allowed to evaporate, and then the two adherends are brought into contact. Examples include rubber cement and adhesives used to bond laminates to countertops.

Pressure sensitive adhesives are very low modulus elastomers which deform easily under small pressures, permitting them to wet surfaces. When the substrate and adhesive are brought into intimate contact, van der Waals forces are sufficient to maintain the contact and can provide relatively durable bonds for lightly loaded applications. Pressure sensitive adhesives are normally purchased as tapes or labels for non-structural applications, although can also come as double-sided foam tapes which can be used in semi-structural applications. As the name implies, *hot melts* become liquid when heated, wetting the surfaces and then cooling into a solid polymer. These materials are increasing used in a wide array of engineering applications using more sophisticated versions of the glue guns widely used by consumers. *Anaerobic adhesives* cure within narrow spaces deprived of oxygen; such materials have been widely used in mechanical engineering applications to lock bolts or bearings in place. Cure in other adhesives may be induced by exposure to ultraviolet light or electron beams, or may be catalyzed by certain materials such as water which are ubiquitous on many surfaces.

Adhesives of various chemistries are available in many different forms as well. For structural applications, adhesives are available as pastes, liquids, films, and supported films. The latter are supported on loose knit or mat scrim cloth to improve the handling properties and also to offer some measure of thickness control. Many of these adhesives produce little or no out-gassing when cured, significantly reducing the likelihood of voids within the adhesive. It is important that these adhesives be kept dry, as absorbed moisture can create significant void problems.   Thermosetting structural adhesives are normally available in two-part forms that are mixed through carefully controlled stoichiometry into a product that cures within the desired time window. One-part forms are also available in which the resin and hardener (cross-linking agent) are already mixed together. These one-part forms must be kept at sufficiently low temperature that the reaction does not occur prematurely, sometimes utilizing latent cross-linking agents that are not active at low temperatures. One-part thermosetting adhesives often have limited *shelf life*, and often must be stored at low temperatures, but do offer very high performance capabilities. *Pot life* refers to the time after a two-part adhesive is mixed during which it is workable and will still make a satisfactory bond. Materials with too short of a pot life will harden too fast, and do not give the workers sufficient time to assemble the product. An excessively long pot life may delay the cure time and slow the assembly process.

Adhesives may be applied in a variety of ways depending on the form it comes in. Adhesives may be spread on a surface manually, or may be dispensed using a variety of sophisticated nozzles and robotic equipment that is currently available. Maintaining adherend cleanliness, providing proper jigs and fixturing during cure, and providing adequate cure conditions may all be important considerations for certain types of adhesives.

The *glass transition temperature (*T_g*)* is one of the most important properties of any polymer, and refers to the temperature vicinity in which the amorphous portion of the polymer transitions from a hard, glassy material to soft, rubbery material. Although specific temperatures are often quoted for the glass transition temperature, it is important to remember that this transition temperature is a rate dependent process[4]. For thermosetting structural adhesives, the glass transition temperature should normally be 50°C higher than the expected service temperature[5]. Unless there are significant exotherms associated with the cure process, the glass transition temperature of an adhesive seldom exceeds the cure temperature. High performance structural bonds often require an elevated temperature cure to provide a sufficiently high T_g in a reasonable cure time. One concern with such conditions, however, are the residual stresses which may develop with an assembled joint is cooled from the cure temperature to the service conditions.

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[4] For example, silly putty at room temperature will readily flow when pulled slowly, will bounce like a rubber ball when dropped on the floor, or can shatter in a brittle fashion when struck with a hammer.

[5] The glass transition temperature of epoxies and other adhesives can be significantly reduced by moisture absorption, a factor which should be considered when designing for humid applications.