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Introduction

1.1 The *Art* of Adhesive Bonding

In a broader sense, the word *art* means any developed action based on knowledge, training, perception, imagination, and intuition as on the initiative to perform it. This description also applies to adhesive bonding, since the development of a safe and high-quality bond also requires similar attributes such as appropriate knowledge, creativity, experience, and innovative strength. It is therefore permissible and appropriate to apply the term *art of adhesive bonding* to the creation of a safe and high-quality adhesive bond (Figure 1.1).

The classic joining technologies such as screwing, riveting, and welding are used today in numerous applications in industry and trade. However, there are some side effects, such as weakening of the materials involved, uneven stress distribution, and a high probability of corrosion, which the user has to accept. In contrast, adhesive-bonding technology, which can be used to join almost all different engineering materials, offers considerable advantages. Thus, in the early phase of component development, the designer enjoys the design freedom desired through the use of adhesive-bonding technology. And later, after the development of the bonding system has been completed, engineers in the manufacturing plant can easily implement it in existing production processes for individual and series production. The use of adhesives to join materials is characterized by the fact that identical or different substrates are joined over a large area by an organic material (the adhesive), and the resulting system (the bonded joint) is capable of transferring the acting forces from one substrate to the other. A special feature here is that the bond cannot be detached without destroying it.

1.2 Adhesives

Adhesives are nonmetallic organic materials with sufficient internal strength (cohesion) that are capable of bonding materials through intermolecular interactions occurring at substrate surfaces (adhesion) and transferring forces from one material to another.

Adhesive Bonding in Five Steps: Achieving Safe and High-Quality Bonds, First Edition. Jürgen Klingen.

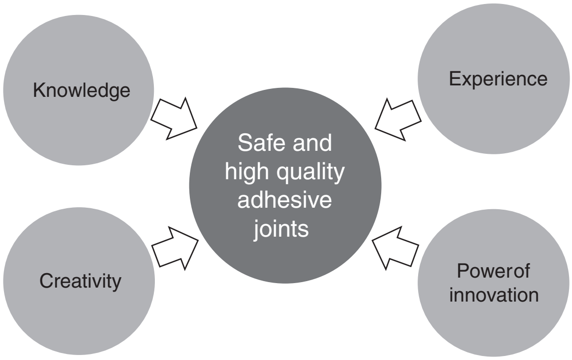

Figure 1.1 The creation of safe and high-quality adhesive joints through knowledge, creativity, experience, and innovation.

Two basic requirements must be met for a functioning adhesive, which are accomplished by appropriate adjustment of the chemical composition and physical properties:

- *good adhesion* – provided by sufficient molecular interactions with the material surfaces.
  During the bonding process, the adhesive must behave like a liquid, with a relatively low viscosity and the ability to wet the surface of the substrate to establish intermolecular interactions. This allows the molecules of the adhesive to approach the nanometer-scale molecular regions of the substrates.
- *good cohesion* – provided by sufficient molecular interactions within the cured adhesive layer.
  In application, the cured adhesive layer must behave like a strong solid with low-molecular flexibility. This is necessary for the transfer of tensile, shear, and peel forces from one substrate to another and to resist environmental influences. Therefore, for good cohesion, the adhesive chemistry must be adjusted to allow molecular interactions within the adhesive layer.

1.3 Adhesive Bonds

An adhesive bond is a two-dimensional connection of similar or dissimilar materials with the help of an organic material that adheres well to the surface of the two substrates to be joined. After the bonding has been prepared and the bonded component is in use, the task of the adhesive bond is to transfer forces from one substrate to the other.

In industry and craft usually, the following materials are used for the creation of an adhesive bond:

- metals,
- plastic materials,
- glasses, and
- wood.

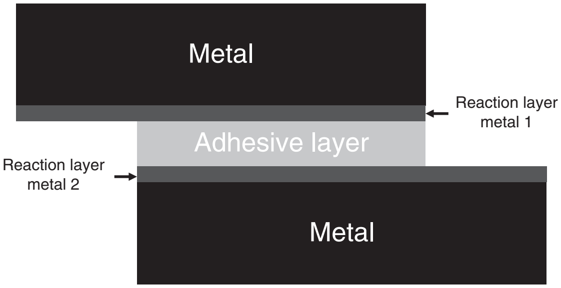

Figure 1.2 Structure of an adhesive bond with metal substrates, in which the adhesive is applied directly to the reaction layer.

1.3.1 Metal Bonds

When bonding to metal, it should be noted that contact is not usually made with the bare metal. Provided that the substrates are cleaned and, if necessary, surface-treated, a – so-called – reaction layer remains, which has been created by the reactions of the metal surface with the environment. This layer usually consists of reaction products of the materials with gases in the air such as oxygen, carbon dioxide, or even water. If the adhesion of this layer to the base material of the substrate and additionally its cohesion is sufficient, the adhesive can be applied directly to this layer (Figure 1.2).

Compared to plastics and glasses, the surface structure of metals is relatively complex and consists of:

- base metal material,
- interface layer (2000–5000 nm) with modified physical and/or mechanical properties, caused by the forming process during the production of the material,
- reaction layer (1–50 nm) formed by chemical changes at the interface and representing the actual adhesion layer,
- adsorption layer (0.1–1 nm), with adhering *non-material* molecules such as water and gases, and
- impurity layer, with solid materials such as dust or liquid contaminants such as oils, greases, or moisture.

In any case, for good adhesion, both the adsorption layer and the contamination layer must be removed by suitable cleaning and/or surface treatment methods before the adhesive is applied to the material surface (Figure 1.3). As already discussed, bonding is then usually carried out on the reaction layer. Examples for this case are aluminum and copper. In a normal atmosphere, aluminum always has an up to 50 nm thick porous oxide layer (reaction layer) that forms spontaneously in air. This surface can be bonded directly if no extreme high demands are made on long-term resistance. If this is the case, as often in the aerospace industry, however, this oxide layer must be removed from aluminum components. In the case of copper, a resistant brown copper oxide layer forms after a few hours in air and adheres well to the substrate. After months, this layer transforms by reaction with the CO_2 in the air to green basic copper(II) carbonate, the so-called patina, which additionally contains sulfate and/or chloride anions. Adhesive bonds of good quality can be

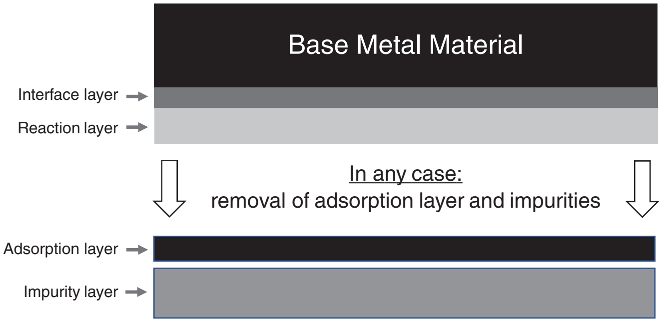

Figure 1.3 Detailed structure of a metal surface and removal of the adsorption layer/impurities to expose the reaction layer before bonding.

produced on both the brown copper oxide and the green copper carbonate layers. Therefore, the reaction layer does not have to be removed here either.

These are cases where, after cleaning the surfaces, adhesives can be applied directly to the reaction layer. However, this is not always the case. If the cohesion of the reaction layer is low and/or its adhesion to the base material is insufficient, it is necessary to remove the reaction layer from the surface as well. This is the case with low-alloyed or unalloyed steels, because the reaction layer (rust) does not adhere sufficiently to the base material. Another reason for such a measure may be the poor influence of the reaction layer on the aging resistance of the bond, as in the case of galvanized (zinc-coated) steel. Also, in this case, the reaction layer should also be removed from the surface before bonding. Zinc oxide initially forms on galvanized steel surfaces, which then reacts further with carbon dioxide in the air to form resistant zinc hydroxide/carbonate reaction layers. These layers bond very well with the base material even under the influence of temperature, but their hydrophilic (water-attracting) character leads to a negative influence on the quality of the bond, which is why they should be removed.

1.3.2 Plastic Bonds

As with metals, plastics are often not bonded to the pure material. In the case of softened plastics, for example, plasticizers can diffuse to the surface after some time, leading to a drop in strength and thus to failure of the bond. This effect occurs, for example, with polyvinylchloride (PVC) or ethylene-propylene-diene rubber (EPDM) materials and cannot be completely avoided by surface treatment. Therefore, when selecting materials for bonding, care should be taken to ensure that the parts to be bonded do not contain such substances or that these are crosslinked and thus chemically anchored in the polymer.

1.3.3 Glass Bonds

When bonding glass, the adhesive is usually not applied to the pure glass surface either, but finds a layer covered with OH groups generated by hydrolysis. These are created by so-called *glass corrosion*, in which the metal oxides contained in the glass are dissolved in water adsorbed on the surface. This increases the OH ion concentration on the glass surface and the pH value rises. Thus, glass corrosion has a considerable negative influence on the formation of adhesive forces on the glass surface and, especially in the case of glasses with a high alkali content, the surface energy is significantly reduced. For this reason, the surfaces of glass should be treated with suitable adhesion promoters, especially if the glass composites are required to have high resistance to aging.

1.3.4 Wood Bonds

Due to its pronounced pore structure, which offers the possibility of mechanical anchoring of the adhesive film in the structure, wood is a grateful substrate for bonding. In addition, the chemical structures of the main constituents of the wood matrix (cellulose and lignin), which to a large extent contain hydroxyl and other polar functional groups, result in numerous opportunities for the formation of hydrogen bonds and even covalent chemical bonds in the adhesive layer. However, the behavior of the adhesive at the boundary layer is strongly influenced by the wood density, which depends on the wood species, but within the wood species also on whether it is early or late wood. Since wood in practice always has a residual moisture content of 6–15%, the adhesive used must have a certain compatibility with water and water vapor, both during application and in continuous use.

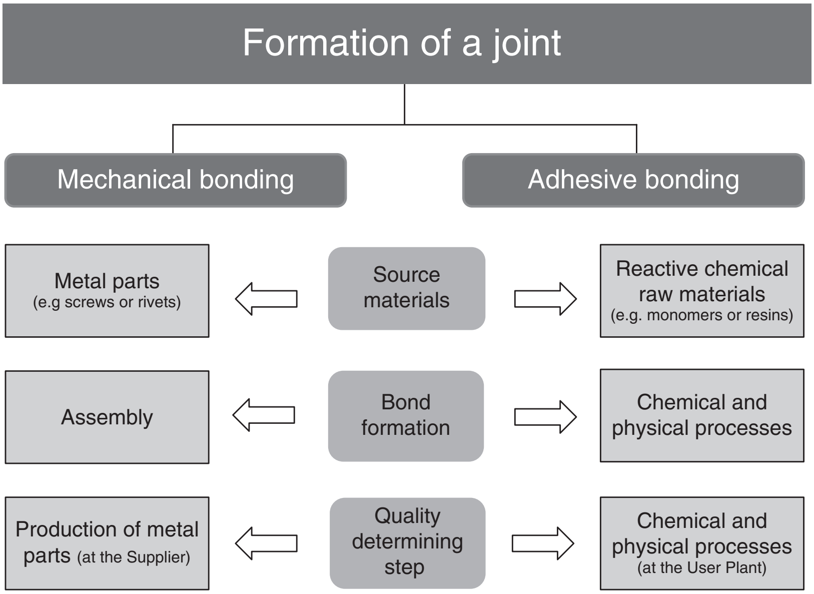

Figure 1.4 Formation of a joint by using the classical methods and adhesive bonding.

1.4 Adhesive Bonding in Industry and Craft

The production of high-quality bonded components in industry and crafts makes high demands, which applies to both the manufacturing process and the environment in which the parts are produced. A key difference from traditional joining techniques such as screwing or riveting, where the joining process has no or little influence on the quality of the joint, is that in adhesive bonding adhesion and cohesion are built up in the manufacturing process. Thus, the process parameters during the manufacture of bonded components are of extreme importance for the quality of the final bond (Figure 1.4).

The mechanism for adhesion formation on material surfaces and the chemical and physical processes that occur when loads are applied to the bond are not fully understood and are still the subject of current and future research. Therefore, the exact calculation of adhesion forces at the beginning and after loading is not possible. This is often seen as a disadvantage of the adhesive-bonding technique. However, it is very well possible to manufacture bonded components with good reliability if appropriate planning is carried out, taking into account existing experience, and extensive proof of the robustness of the bonded joint is provided by investigations on laboratory samples and prototypes.

Figure 1.5 Mussels adhesive bonded to a wooden pile in the North Sea near Domburg, the Netherlands. Source: Dr. Jürgen Klingen, Aboso-Consulting.

1.5 An Example for Adhesive Bonding in Nature

There are also excellent bonded joints in nature that have been optimized by evolution over long periods of time. One example is the bonding of mussels to different surfaces by means of an adhesive made of proteins, whereby this adhesive is produced by the mussels themselves with the help of their specialized glands. This enables the mussels to adhere to materials such as wood, metal, glass, and coral, and to withstand strong impacts from salt water (Figure 1.5). Due to the unique combination of properties, this adhesive is of interest to adhesive researchers and is a candidate for medical adhesive applications, particularly in surgery and regenerative medicine. For example, such biocompatible adhesives could enable the rapid treatment of complicated bone fractures instead of fixing them with screws, nails, or plates. Also, this adhesive developed by nature might be able to quickly close skin wounds and other injuries.