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Adhesive Bonding Technology in the 21st Century

Synergy of Technological and Ecological Potentials

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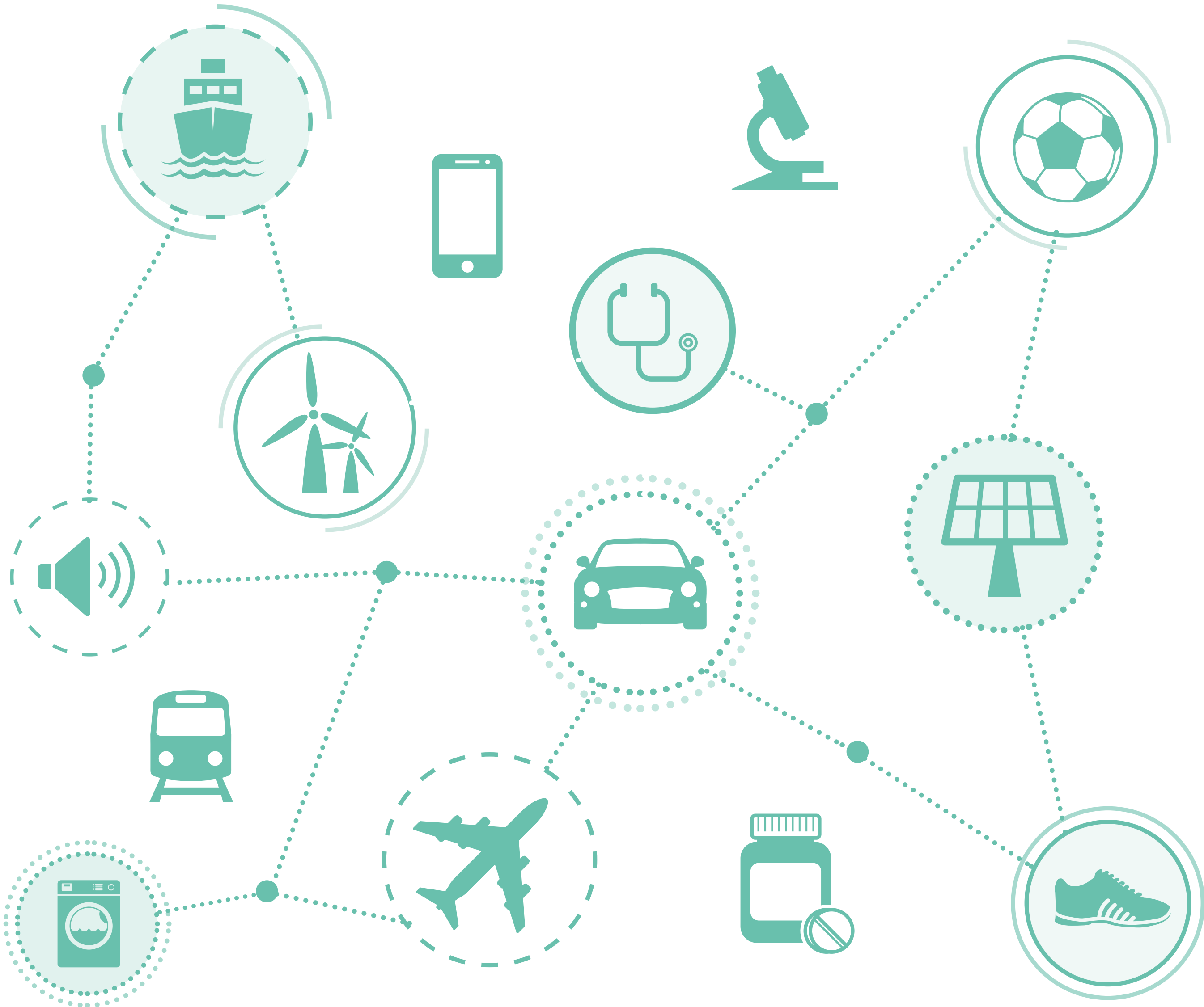

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Foreword

This book, Adhesive Bonding Technology in the 21st Century – Synergy of Technological and Ecological Potentials, by Prof. Dr Bernd Mayer and Prof. Dr Andreas Groß of Fraunhofer IFAM, Bremen, Germany, was commissioned by FEICA, the Association of the European adhesive and sealant (A&S) industry, to give an overview of the industry's various aspects. FEICA requested the above-mentioned experts to author the book on the occasion of the association's 50-year anniversary.

Stakeholders in the adhesives and sealants industry are well-served by the treatment of A&S technology in the Fraunhofer IFAM book. Fraunhofer IFAM / Division Adhesive Bonding Technology and Surfaces with its approximately 400 employees is the world's leading independent research and development institution and has more than five decades of experience in the areas mentioned (see https://www.fraunhofer.de/en.html). Fraunhofer IFAM fully covers adhesive bonding technology and its related areas and is active in the automotive, aviation, maritime, energy technology, medical technology, packaging and construction sectors, among others. In addition to basic research and development activities, the focus is on application-oriented service (from short-term advice to long-term planning and implementation projects), specific applications of the technology (e.g. in the packaging sector) and consultation and development (e.g. in the polymer chemical formulation of adhesives). Application-oriented examples of adhesive bonding technology activities at Fraunhofer IFAM include lightweight construction and sustainable production.

The Institute also specialises in extra-occupational training and, with its ISO 17024 accredited Training Centre for Adhesive Bonding Technology (www.bremen-bonding.com), has successfully offered a wide range of personnel-certifying courses worldwide for over 25 years, across hierarchies from the executive to the technical decision-making level. The knowledge generator thus becomes the knowledge transmitter at the same time.

It should be noted, too, that the authors of this book are recognised experts in the field of adhesives and sealants safety standards, e.g. the DIN, CEN and ISO quality assurance standards considered in the book. At the same time, both are editors of the Fraunhofer IFAM study 'Circular economy and adhesive bonding technology' published in 2020.

Adhesive Bonding Technology in the 21st Century is intended for a broad audience of industry stakeholders. The objective is to provide a comprehensive view of the adhesive and sealant industry in terms of its applications, technologies, innovations and trends.

The book is divided into five Chapters.

Chapter 1 sets the stage for what follows by presenting the key position adhesives bonding technology occupies compared to that of other joining technologies, like welding: various combinations of materials can be joined; material properties of the joined parts are usually not changed; new construction methods can be pursued; and the adhesive can introduce additionally new properties into the conjoined product.

Chapter 2, in turn, explores the many areas of application of adhesives and sealants in everyday life (e.g. tiles, flooring and carpeting; small appliances like irons; and paper bags) and in industry (e.g. aircraft, automobile and truck, and rail vehicle manufacturing; shipbuilding; wind turbine construction; medicine; and household products, including major appliances).

Chapter 3 considers adhesive and sealant economic importance. In the past the A&S industry has made significant contributions to the European economy in terms of euros contributed to the economy, number of employees in the industry, and market share. Reasonable Indications are that the industry's economic significance will grow in the future.

Chapter 4, then, the core of the book, takes a comprehensive look at adhesive bonding with respect to product safety law and circular economy potential. The first half of the chapter is concerned with adhesive bonding safety. Here much of the discussion centers on quality standards, notably, specifying ISO standard 9001 on error prevention in terms of adhesive and sealant applications, e.g. in DIN, EN and ISO standards. In this regard, the importance of verifiable personnel qualified through proper personnel-certifying training is highlighted. The second half of the chapter deals with the ecological potential of adhesives and sealants. In this case, adhesive bonding technology is considered as aligned with the goals of the circular economy in terms of, for example, lightweight construction, repair and recycling, disassembly and digitalisation.

Chapter 5 concludes the book with a view toward the future in terms of longevity. The term 'controlled longevity' is introduced to describe the synergy of a holistic approach in which adhesively bonded products serve as long as possible in a safe utilisation period and then, at the end of their product life, facilitate an effective circular economy.

In short, the adhesive bonding technology has become the joining technology of today. On the occasion of 50 years of FEICA, the voice of the A&S industry in Europe, Fraunhofer IFAM's Adhesive Bonding Technology in the 21st Century, gives an overview of the adhesives and sealants industry in terms of what it has so far accomplished and of what it promises for the future.

Adhesives and sealants: invisible but everywhere!

Kristel Ons

FEICA Secretary General

Guido Cami

FEICA President
AVISA Vice President
Industrie Chimiche Forestali President / CEO

An Introductory Note by the Authors

This publication 'Adhesive bonding technology in the 21st century - synergy of technological and ecological potentials' considers both the safety of products and ecobalance effectiveness including recycability are key, equally important elements for the future development of adhesive bonding and sealing technology. Equal importance means that each element must be considered without detriment to the other. The combination of safety and ecobalance effectiveness including recyclability results in the concept of 'controlled longevity' of adhesively bonded and sealed products. This 'controlled longevity' will significantly determine the development of adhesive bonding and sealing technology in the future. Safety and recyclability should be integrated into product development from the start. This means adhesively bonded and sealed products are to be thought of holistically from the very beginning across the product life cycle phases 'manufacture' and 'utilisation' up to the product life cycle phase 'end of life'.

In the future, the number of materials needed to meet changing requirements will continue to increase. Due to the growing complexity of product requirements, these products will also have to be multi-material composites. Beyond pure joining, joining technology therefore has the further central task of maintaining the material properties needed to meet the requirements. This represents a fundamental challenge for joining technology.

This is precisely where adhesive bonding technology plays a key role: With the help of adhesive bonding technology, the same or various materials can be safely joined with long-term stability. At the same time, the material properties required to meet the requirements are retained. Both aspects together make new and safe construction methods possible.

Through these construction methods, adhesive bonding and sealing are integral components for. e.g., lightweight construction, the energy transition and e-mobility, and thus support the circular economy and ecobalance effectiveness. Here it is noteworthy that adhesive bonding technology is probably the most widespread method of repair, even of products not originally adhesively bonded. Like products joined with any other joining technique, adhesively bonded products can also be detached; this is why adhesive bonding does not rule out disassembly and thus, in principle, recycling. On the contrary, due to the adhesive properties, adhesive bonding offers concrete starting points for disassembly. Recyclability is then ultimately determined by the recycling properties of the separated materials.

'Controlled longevity', the inseparable joining of product safety on the one hand and ecobalance effectiveness on the other, thus leads to a sustainable synergism. This synergism significantly secures and expands the areas of application for the adhesive bonding and sealing necessary in the 21st century.

Bremen, 5 September 2022

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Introduction

Whether high in the sky, on the face of the earth or deep within, on the surface of the water or even below, adhesive bonding technology almost always comes into play in the use of tangible products.

The reason for the astonishingly wide range of adhesive and sealant applications is that, in the context of joining technologies, only adhesive bonding technology has the potential to join identical or dissimilar materials with complete retention of their properties as well as with long-term stability and safety. This preservation of material properties during joining makes it possible for the products to meet constantly changing requirements such as weight reduction, miniaturisation, functionalisation expansion and design optimisation. In this way innovative construction products meeting certain requirements are possible for a product. So the technological and ecological potential of adhesive bonding technology makes it the number one joining technology in the 21st century. This century requires development of a wide variety of materials to meet rising demands. These materials are economically, technically and ecologically usable only with a joining technology that preserves their properties. Material development and joining technology are therefore inseparable.

Sealants are materials with adhesive properties used primarily to fill or seal gaps or joints between two surfaces or to seal an adhesively bonded joint itself. In the context of this publication, sealants are not always mentioned as a separate category but are included in adhesive bonding technology.

1

New product requirements - the role of materials, joining technologies and adhesive bonding technology

It is the materials that decisively determine the properties of a product. Materials and their properties are therefore the fundamental prerequisites for fulfilling a product requirement profile. Future requirement profiles arise from the major fields of energy, climate and environmental protection, resource conservation, mobility, health, safety or communication. These profiles are a driving force of materials science and development. Without materials development, continuous progress in the fields of mechanical engineering, transportation, the aviation industry, or the chemical industry, for example, would be inconceivable.[1] It is therefore not without reason that current studies show the direct or indirect dependence of a large number of technical innovations on the materials.[2]

In order to meet the constantly changing demands on products, the variety of materials for the manufacture of products is increasing as a result of material development. However, even today the requirements to be met are usually so complex that a single material - even with its specific properties - is not able to meet all these requirements on its own. Therefore, these new materials develop their innovative power only when joined with other materials, including more conventional ones. Consequently, products in the future will also have to be multi-component materials, i.e. composite systems consisting of different types of materials that fulfil requirements.[4] Here too, however, without exception materials develop their application-relevant effectiveness under two conditions:

- Their properties contribute in an unimpaired way to the fulfilment of the requirement profile
- The materials are securely *joined* in the product, in the part or in the component with the same or other materials with long-term stability

Consequently, requirements-oriented material development must always be combined with joining technology that is appropriate for the material. Only when material and joining technology fit together in the sense described do innovations become possible at all. These innovations then fulfil the complex requirements for products in technological, economic and ecological terms.

The challenge for joining technology in this context is also that, in general, the greater extent to which a material is developed, the more sensitive it becomes. A joining technology that is appropriate for the material must take this sensitivity into account. 'Material-compatible joining technology' in this context actually means 'material-*property*-compatible joining technology' (see Figure 1): The properties of the materials must be maintained despite the application of a joining technology in order to then fulfil the required profile of requirements in a long-term stable and safe manner.

It is against this background that adhesive bonding technology occupies for four main reasons a key position compared to that of more conventional joining technologies such as welding, soldering, screwing or riveting (see Figure 2):

1. With the adhesive bonding joining technology, it is possible to securely join almost all combinations of the same or different materials with long-term stability and thus to realise material combinations that meet the product requirements

2. The material properties of the parts to be joined are not unacceptably changed by adhesive bonding. As a rule, they even remain unchanged: The adhesive bonding process, even with heat-curing adhesives and sealants, is relatively low-heat compared to welding or soldering,[5] which affect the material properties. There is, furthermore, no damage to the parts to be joined due to perforation as with riveting or screwing.

Fig. 1: Meeting increasing requirements through materials[3]

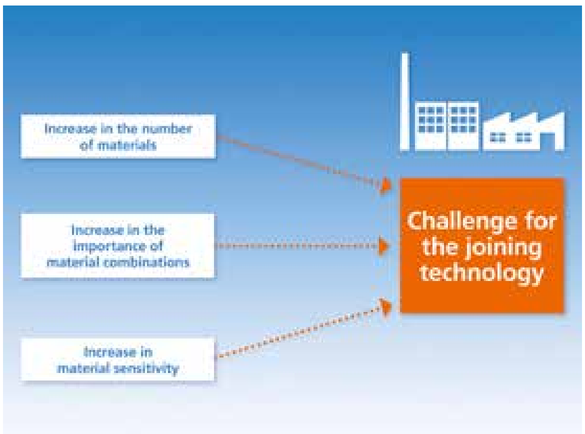


Fig. 2: Consequence of material developments: the challenge for the joining technology

The stress distribution influencing the load is almost uniform in adhesively bonded joints.

3. Material combination and simultaneous preservation of the material properties make it possible to optimally use the specific material properties for the respective component relevant to the requirements. This opens up possibilities for new construction methods (e.g. lightweight construction and miniaturisation).

4. Additional properties can be specifically integrated into the component via the adhesive. These properties go beyond the main function of pure joining and can be relevant for the circular economy.

The joining technology 'adhesive bonding' itself is initially defined quite simply as the 'joining of two materials (parts to be joined) with an adhesive'. The adhesive is a non-metallic material that joins two parts by means of adhesion (surface adhesion of the adhesive or sealant molecules to the surface of the part to be joined) and cohesion (internal strength of the adhesive or sealant itself).[6]
However, adhesive bonding clearly goes beyond the mere joining of materials because an adhesively bonded joint fulfils two main functions: 'force transmission' to transfer loads and 'deformation compensation' to compensate for different dynamics of the joined parts. These functions then lead to the main properties of an adhesively bonded joint: its strength and its deformation capacity.

In addition, adhesive bonding technology offers a number of other advantages compared to other joining technologies (see Figure 4).

An adhesive and a sealant may be able to compensate for joint tolerances and also seal an adhesively bonded joint against liquids and possibly also against gases. Elastic adhesives and sealants enable sound insulation and vibration damping. When bonding metals, the adhesive and sealant in the adhesively bonded joint can act as corrosion protection, as many are based on organic polymers that are non-conductive. These adhesives and sealants can be electrically insulating. Metal powders (usually silver powder) are added to other adhesives. The adhesives modified in this way then have very good conductivity and are used, for example, in microelectronics for the transmission of electric current. Still others are specially modified for the transmission of heat and consequently have a high thermal conductivity.

Modern adhesives and sealants are developed, among other reasons, to either transmit or filter out light of the desired wavelengths in the adhesively bonded joint. Adhesive bonding also offers a high degree of design freedom. This applies, too, to the design of surfaces in the joint area. Furthermore, joining thin, small and sometimes intricately shaped components is possible. An adhesively bonded joint can be designed in such a way that it remains hidden from the viewer's eye and does not interfere with the design of the overall product.
Like any technology, adhesive bonding naturally has limitations. There is a risk of joint failure if these limiting factors are not known to the designer or are not considered by the user. These factors are, in detail:

- Adhesives and sealants and thus adhesively bonded joints and gaskets can withstand only limited thermal stress
- The long-term stability of adhesively bonded joints is influenced by ageing processes (degradation)
- When an adhesively bonded joint is produced, the time until handling strength is reached varies from a few seconds to many hours. Fixing may be necessary.
- The loosening of any adhesively bonded joint is possible in principle. However, as with riveted or welded joints, this may require effort.

Fig. 3: Reasons for the key position of adhesive bonding technology

Fig. 4: Possible functions of an adhesive in an adhesively bonded joint


Hydrogen
H2

2

Areas of application of adhesives and sealants

2.1 Adhesive bonding in everyday life

Without most people being aware of it, adhesive bonding technology has long been a part of human life (see Figure 5): tiles, parquet, carpeting - all surely adhesively bonded. Adhesive bonding technology has long since developed into a (future) technology applicable everywhere. Adhesives can be used to join the parts of everyday objects as well as in highly complicated special products. And yet adhesives are often underestimated because of one of their very advantages: Adhesives (and sealants) are often not visible to the consumer.

It is hard to imagine how many times adhesives are used in everyday objects. In Europe, 4.7 million tonnes of adhesives and sealants were produced in 2020 (see Chapter 3).The European adhesive and sealant market is forecast to grow to €22.2 billion by 2026, at a compound annual growth rate (CAGR) of 3.6% for 2021-26.[8]

In everyday life, we are surrounded by many different adhesives and adhesive bonding technology applications. Some examples are given in Figure 6. Medical plasters, for example, are perceived as 'everyday products'; everyone needs them now and then. Their main purpose is to cover a wound and protect it from infection. To do this, they have to adhesively bond to the skin, but they also have to be painlessly removable. At the same time, they should adjust to the patient's movements, withstand water and absorb wound fluid or blood. Finally, they must not require any expert knowledge to be used – children must be able to attach them safely to a wound. These are many requirements for a seemingly simple product. Fingernails are also adhesively bonded. UV-curing acrylic adhesives, instant adhesives or self-adhesive nail foils are used. Adhesive bonding is also used in a conventional iron to ensure that its plastic covering is not damaged and deformed by the hot soleplate during the ironing process. If necessary, a heat shield is built into every iron and adhesively bonded in place. The silicone adhesive continues to adhere at service temperatures of up to 200 degrees Celsius. Adhesive bonding is also a joining technology that has been used in shoe manufacturing for a long time.

Nowadays there are hardly any areas in everyday life where the joining technology adhesive bonding is not used. This is not fundamentally different in everyday professional life. Various examples of industrial adhesive bonding are considered in the following chapter.

Fig. 5: Parquet adhesive bonding[7]

Fig. 6: Adhesive bonding technology in everyday life - adhesively bonded fingernails,[9] plaster, iron,[10] adhesively bonded shoes,[11] medical plasters

2.2 Industrial adhesive bonding

Aircraft manufacturing

Adhesives are not found just in everyday life. In industry, too, it is no longer possible to imagine production without them. One example of this is the aircraft industry (see Figure 7). In order to reduce operating costs per passenger and aircraft and to lower fuel consumption, so-called composite materials are used. These are materials consisting of layers of glass fibre reinforced plastic and aluminium that are joined together with high-performance adhesives. These high-performance adhesives have, for example, the necessary vibration resistance and are suitable for sudden temperature changes and the varying expansion of the substrates.

Fig. 7: Adhesive bonding technology - an indispensable part of modern aircraft construction[12]

Vehicle manufacturing

Nowadays, between 15 and 20 kg of adhesive and sealant are used in a passenger car (see Figure 8).

A typical application is the adhesive bonding of car windshields (see Figure 8, right), which has long been state-of-the-art in automotive engineering. Unlike in the past, today the pane is no longer inserted but is adhesively bonded with elastic polyurethane adhesive. Since the adhesive, which also performs a sealing function, can transfer forces in the adhesively bonded joint, the pane becomes a structural element for the entire car body. The advantage is that the adhesively bonded joint between the pane and the body increases the torsional stiffness of the vehicle by 15 - 20% compared to that of the inserted pane. This in turn makes it possible to use thinner, i.e. lighter, sheet metal and to reduce the weight of the vehicle.

In automotive body construction, adhesive bonding is also used: Spot-weld adhesive bonding is now state-of-the-art there. The advantage of spot-weld adhesive bonding is that it combines force transmission and immediate fixation. The adhesive bonding

Fig. 8: Adhesive bonding technology - an indispensable part of modern automotive engineering [13]: Adhesive bonding of car windshields is state-of-the-art[14] (left).

Fig. 9: Hybrid joining (spot-welding adhesive bonding) in car body construction: increasing crash stability means increasing occupant safety[15, 16]

is responsible for the high force transmission. Spot welds enable immediate fixation but allow only a punctiform transmission of force. With exclusively spot-welded joining, the force transmission is therefore concentrated at a few points and a small area. In contrast, adhesively bonded joints enable force transmission over the entire joint. So in many modern vehicles, the adhesive is even significantly responsible for crash safety and thus for the survival of the occupants in an accident (see Figure 9). Adhesive bonding is also increasingly used in commercial vehicle construction. Figure 10 shows the example of a truck. The exterior elements of the driver's cab are made of glass fibre reinforced plastic (GFRP) and are adhesively bonded to the metal body.

Fig. 10: Adhesive bonding technology in commercial vehicle construction: The GFRP outer elements of the driver's cab are adhesively bonded (left image). The red lines illustrate the adhesively bonded seams (right image).[17]

Rail vehicle manufacturing

Rail vehicle construction is now also an important area of adhesive bonding technology application (see Figures 11 and 13). In the case of rail vehicles, the increase in requirements consists in, among many other factors, the increase in speed and in transport comfort. To achieve these, the vehicles must become lighter and at the same time be able to withstand higher loads.

The adhesive bonding technology development in rail vehicles continues to progress. Adhesive bonding technology enables modern design, design being an important selling argument in rail vehicle construction.

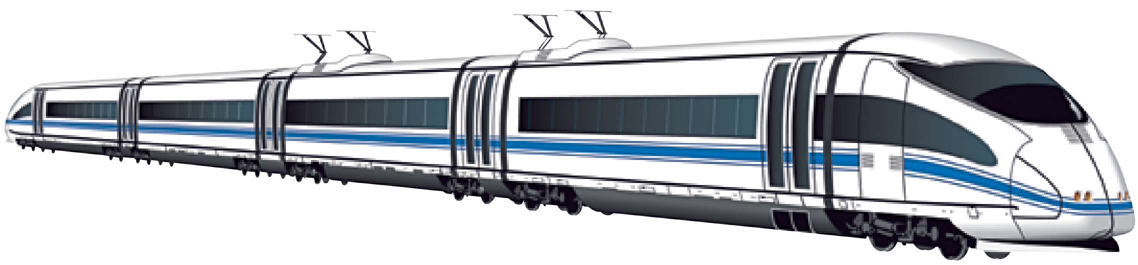
An example of a modern streamlined design without open edges and visible joints is the innovative Coradia iLint (see Figure 12).[19] It is powered by hydrogen-oxygen fuel cells and is greenhouse gas emission-free in the product life cycle phase ‚utilisation', as only water vapour and water condensate are emitted into the environment. Beyond the use of adhesive bonding technology in the fuel cells (see 4.3.6), adhesive bonding is used in all areas of final assembly of the Coradia iLint inside and outside the car bodies - whether front and side windows, front coverings, floors, step rails or insulating mats. Elastic polyurethane adhesives, water-based dispersion adhesives and dimensionally stable methyl methacrylate-based adhesives perform a variety of other functions in addition to providing reliable adhesion. For example, they transfer static and dynamic loads, ensure tolerance compensation and compensate for thermal expansion. In terms of even further benefits, they provide permanent protection against moisture penetration and contribute to the longevity of the vehicles.

Fig. 11: Adhesive bonding technology enables modern design.[18]

Fig. 12: Hydrogen train Coradia iLint[20]

Adhesive bonding technology in rail vehicle construction has taken on such a scope that, on the initiative of the German Federal Railway Authority (EBA), a standard (DIN 6701[21]) (see caption Figure 13 and Chapter 4.2) for quality assurance of the organisation and implementation of adhesive bonding processes in rail vehicle construction was developed and introduced in 2006. Although it is a national standard, in the meantime (as of 31 May 2022) more than 1,000 companies worldwide work according to this standard and are certified according to it.[22]

Fig. 13: Rail vehicle construction, example ICE[23] - The adhesive bonding technology has in the meantime reached such a state that a quality assurance standard (DIN 6701 / from 09/2022: EN 17460) has been introduced analogous to that for welding.



Shipbuilding

Fig. 14: Shipbuilding - The polycarbonate passenger window panes and the rows of seats (picture in the middle and one on the right) are adhesively bonded in place.[24]

As early as 2000, the Lürssen shipyard in Lemwerder (Germany) constructed high-speed ferries (see Figure 14) for an Indonesian customer, ferries which travel at a speed of 40 knots (> 70 km/h), unprecedented in this sector. In heavy seas, these ferries are exposed to violent shocks. The rows of seats are therefore adhesively bonded to the decks with moisture-curing, rubber-elastic adhesives. Unlike the bonding of a punctured joint like that of rivets or screws, the adhesive bonding prevents the seats from tearing out. In addition, the adhesive has a vibration-damping effect, which in turn increases passenger comfort. About a tonne of weight was also saved by making the passenger deck windows out of polycarbonate instead of glass. The plastic panes were also adhesively bonded with polyurethane adhesives. Over the product life of a ship, the multi-material lightweight construction realised by adhesive bonding technology dramatically reduces fuel consumption and eventually the CO_2 footprint.

In a way similar to what has occurred in rail vehicle manufacturing, quality assurance of the organisation and implementation of adhesive bonding technology processes will also be standardised in shipbuilding in the future (see 4.2).[25]

Wind energy

Wind energy is a highly important development area for our future. To build increasingly efficient wind turbines (see figure 15), the rotor blades are completely adhesively bonded. The rotor blades of the turbines are made of glassfibre reinforced plastic, a material with comparatively high rigidity and comparatively low weight. According to conventional construction methods, the rotor blades are made of two half-shells, which are then joined completely by adhesive bonding technology. Depending on the size of the rotor blade, several hundred kilograms of epoxy resin adhesive are used for this.

Joining the rotor blade half-shells would be inconceivable without adhesive bonding technology. Welding would destroy rotor blade materials and spot mechanical joining techniques would lead to material damage in the rotor blade by the drilling of holes. The extreme mechanical loads alone occurring during operation at rotational speeds of up to 390 km/h[26] would have fatal consequences. For this reason, highly dynamic structural adhesives have been developed that can withstand these extreme loads. Consequently, adhesive bonding technology prevents material damage and thus makes it possible in the first place to construct these turbines for the production of regenerative energy.

Fig. 15: Wind turbines - The fibre reinforced plastic (FRP) rotor blades are adhesively bonded.

Optics

For optics and high-performance optics, adhesive bonding technology is an essential joining process (see figure 16). It enables the stress-free joining of the various optical elements. This absence of stress is often necessary, as it allows for an interference-free, unaffected beam path.

Fig. 16: Adhesive bonding technology in optics - interference-free, unaffected beam path.

Medical technology

An adhesively bonded endoscope is an example of the extensive use of adhesive bonding technology in different areas of medical technology (see figure 17). Endoscopes are manufactured for minimally invasive use. The tube diameter of an endoscope is approx. 2 mm. It is adhesively bonded with a UV-curing adhesive of adapted wavelength, which allows the light to pass through undisturbed during the examination.

The use of adhesive bonding technology in dental medicine (see Figure 18) is also standard. The oral flora places the highest demands on the long-term stability of an adhesively bonded joint. Radiation-curing adhesives are used that were developed precisely for this area of application.

Fig. 17: Adhesive bonding technology in medical technology - an adhesively bonded endoscope for minimally invasive use (tube diameter approx. 2 mm, UV-curing adhesive)

Fig. 18: Adhesive bonding technology in medicine - Use of adhesive bonding technology in the dental sector[27]

Medicine

Medical adhesives are used for implants, during operations and for wound closure (see figure 19). Besides fibrin adhesives[28], special cyanoacrylate adhesives (instant adhesives) and UV-curing systems[29] are also used as medical adhesives.[30]

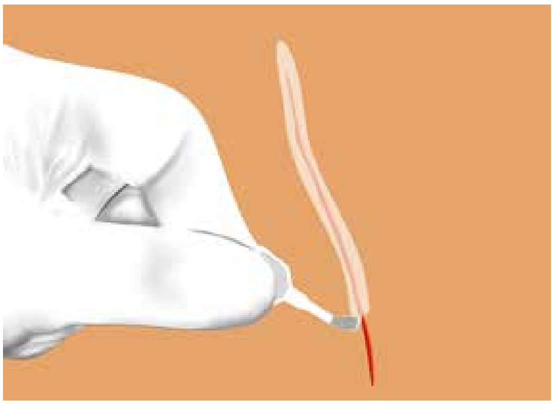


Fig. 19: Adhesive bonding in medicine[31]

Household appliance industry ('white goods')

In the household sector, too, adhesive bonding technology is used in many ways (see Figure 20).

One example is the cooking oven, where the ceramic hob (Figure 21, centre) and the glass panel and design parts of the extractor bonnet (Figure 21, left) are adhesively bonded. Figure 21, right, shows an oven where the control front, door and design parts are adhesively bonded with heat-resistant silicone adhesive and sealant that can withstand temperatures up to 250 degrees Celsius.

Fig. 20: Adhesive bonding of household products[32]

Fig. 21: Adhesive bonding technology in the household sector - adhesively bonded glass pane and design parts of the cooker bonnet[33] (left), adhesively bonded ceramic hob[34] (centre) and adhesively bonded door and design parts of the oven[35] (right)

Acoustics industry

The production of acoustic boxes is no longer conceivable without the use of adhesive bonding technology. The highest quality standards are achieved by adhesive bonding of loudspeaker membranes (see Figure 22).

Fig. 22: Adhesive bonding technology in the acoustics industry - adhesively bonded loudspeaker membranes[36]

Shoe industry

Adhesive bonding technology has also become indispensable in the production of shoes. It enables two-dimensional and tight joining of individual parts made of different materials (see Figure 23). Unlike in the stitching process, there is no puncturing of the materials, and the degree of water thightness is much higher than with traditionally produced shoes.

At the same time, adhesive bonding technology allows for shoe repair (see Figure 24), which is a simple and effective approach to sustainability: The product life of the shoe is significantly prolonged. In this way, shoe waste is significantly reduced and the environment is protected. Professional repair is no problem with adhesives: The shoemaker easily removes the worn soles and heels and reattaches new ones with a durable adhesive. The beneficial effect of such a cost-effective repair is the extended use phase of shoes leading to less resource consumption and a positive impact on the environment.

Fig. 23: Adhesive bonding technology in shoe manufacture - adhesively bonded laminate construction of a sports shoe

Fig. 24: Adhesive bonding technology in shoe repair[37]

Sports

A very memorable example, representative of the broad use of adhesive bonding technology in the field of sports, is the FIFA World Cup footballs. The original football was made of natural leather by sewing the individual leather parts together (see Figure 25, left). Even though since the 1986 World Cup the balls have no longer been made of leather but of plastic, the joining technology remained the same: Sewing continued.

'Team spirit' (see Figure 25, right), the ball of the 2006 FIFA World Cup, was the first World Cup ball whitout stitching. There were no more material damages due to holes for sewing and no more punctiform force transmissions, but instead there were adhesively bonded joints over the entire surface. 'Team spirit' was thus the first fully adhesively bonded football of a FIFA World Cup. The changes of the manufacturing process led, amongst other positive effects, to a lower water uptake in rain and a lighter ball allowing for better control.

Fig. 25: Adhesive bonding technology in sport - from the leather ball to the high-tech ball
Left: Ball of the 1954 World Cup: a ball consisting of 18 leather segments sewn together
Right: 'Team spirit' of the 2006 World Cup: the first fully adhesively bonded football

3

Adhesive bonding - economic significance of adhesives and sealants

The European adhesive and sealant industry represents about 2% of the total European chemical industry's turnover. In 2020, this specialty chemical sector contributed more than 15 billion euros to the EU economy and employed more than 45,000 people. The global market for adhesives and sealants reached a value of 50 billion euros in 2020, with Europe holding a share of almost 35%.

About 500 million euros were spent on research and innovation in 2020. Adhesive and sealant companies spent on average 2-3% of sales on R&D, which is higher on average than the chemical industry.[38]

Modern adhesive bonding technology has thus long been an integral part of innovative technology development in almost all areas.[39] Due to its technological potential, adhesive bonding makes economic contributions to the stabilisation and expansion of Europe as a business location.

The importance of the adhesive bonding technology in the European market is indicated in the following, which shows the growth of market share and tonnage for adhesives and sealants from 2020 to 2026, and compound annual growth rates (CAGRs) from 2021 to 2026:

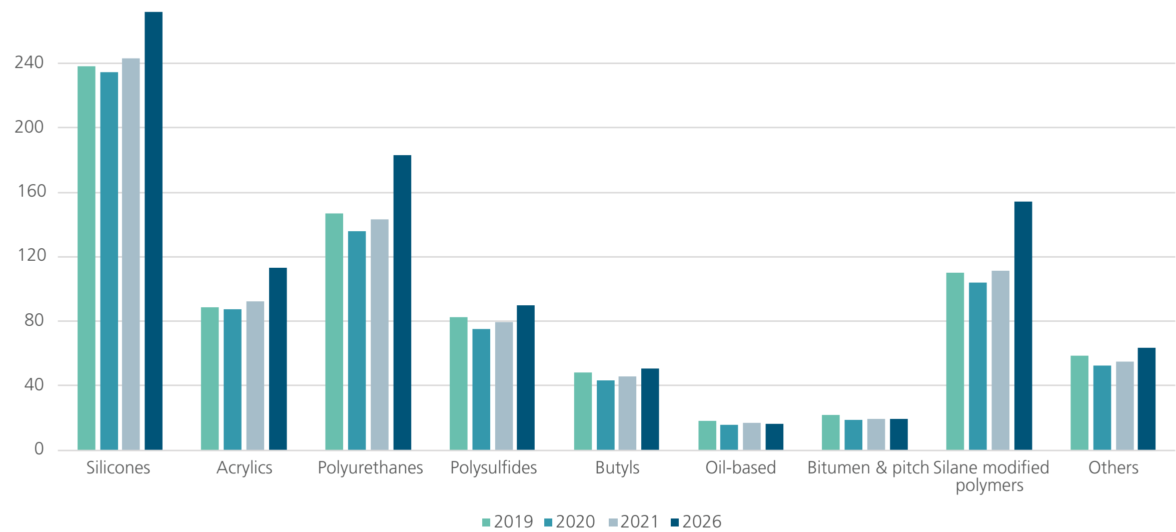
- Adhesives share of the market: nearly €11.6 billion (2020) → €13.9 billion (forecast for 2021) → close to €16.5 billion (growth by 2026)
- Adhesives tonnage: 3.9 million tonnes (2020) → 4.1 million tonnes (forecast for 2021) → 4.7 million tonnes (growth by 2026)

Fig. 26: Adhesive bonding - There is hardly an area where it is not used.

- CAGR for adhesives, 2021-2026: 3.5% for market share and 3.0% for tonnage
- Sealants share of the market: nearly €4.0 billion (2020) → close to €4.7 billion (forecast for 2021) → over €5.7 billion (growth by 2026)
- Sealants tonnage: 768,000 tonnes (2020) → 806,400 tonnes (forecast for 2021) → 962,400 tonnes (growth by 2026)
- CAGR for sealants, 2021-2026: 4.1% for market share and 3.6% for tonnage

As indicated, growth is stronger for sealants, albeit from a smaller base.

Fig. 27: **Europe sealants demand by product category ('000 tonnes) 20-19-2026**



Continued further development is expected in reactive polymer-based technology of adhesive and sealant (A&S) products with improved technical properties. Rapid progress is being made in curing technologies at the chemistry and process technology levels. This also includes adhesives that can conduct electricity. This trend is strongly linked with the development of electric vehicles with an improved battery life and faster charging. Progress is also being made in the ability to cure faster at lower temperatures as well as in thermal stability to gain production efficiencies.

Fossil-based raw materials will continuously be substituted by renewable raw materials that contribute to the circular economy.

Furthermore, especially in Western Europe, an additional eco-balance-relevant focus continues to be on the use of solvent-free products wherever possible and on continued high demand for safe, recyclable, sustainable A&S products where price and quality remain decisive. The general trend is toward adhesives and sealants that enable a more efficient production process with a lower CO_2 footprint.

It can be assumed that there are around 33,000 different adhesive and sealant products on the market in Europe, from which the most suitable can be selected for a wide variety of applications.

Only the so-called ‘all-purpose adhesive’ does not exist, nor does the ‘universal bolt’ or the ‘global rivet’.

4

Adhesive bonding technology: product safety law and circular economy capability

4.1 Preliminary remark

The space for design opportunities in industry and handicraft is subject to a continuous process of change due to constantly changing technical, social and legal conditions. This change also affects adhesive bonding in particular, as it is now an essential joining technology in almost all sectors and industries. For this reason, bonded joints must be 'safe' on the one hand, i.e. product integrity must be controlled during the product life cycle phase 'utilisation' (see 4.2). On the other hand, the subsequent product life cycle phase 'end of life' must also be considered (see 4.3). Both phases must be considered as equal and in no way in competition with each other.

4.2 Safe adhesive bonding: 'State of the art' and 'Special process'

4.2.1 Basic information on product safety

In principle, across materials, applications and technologies, the following applies in a legally binding manner: In order to be able to use a material, a product made from it or a process safely, work must be carried out according to the 'state of the art', especially in the case of products relevant to safety. The legally binding nature is based on the Product Safety Act[40], according to which a product - consequently also an adhesively bonded product - can be placed on the market only 'if it does not endanger the safety and health of persons when used as intended or in a foreseeable manner'.

If this safety verification cannot be provided with purely non-destructive methods and one hundred percent certainty at the same time, then, according to the internationally recognised and globally implemented ISO 9001, so-called 'special processes' are present in the underlying manufacturing processes.[41] These are processes in which non-destructive monitoring or measurement or non-destructive testing methods in production or on the product cannot verify the result to the full extent, i.e. not with one hundred percent certainty. This also applies to adhesive bonding technology and adhesively bonded products, and, therefore, adhesive bonding is also such a 'special process'.[42]

This term comes from ISO 9001, which requires the introduction of a quality management system (QMS) for all 'special processes'. Its core statement is simply that If there can be errors in a process or product that cannot be detected and verified with one hundred percent certainty by non-destructive means, then these errors must be avoided from the outset.

In this way, the Product Safety Act[40] links its legally binding requirement of non-destructivesafety verification for 'special processes' and products manufactured with these processes with the above-mentioned ISO 9001 core statement of - as far as possible without exception - error prevention. And this is so from the beginning of a product development phase until the end of product use.

Now, 'special processes' are actually nothing unusual. On the contrary, we are virtually surrounded by 'special processes' in our professional and private lives. Not only welding and adhesive bonding but all joining technologies, in fact almost all manufacturing and processing procedures in industry and handicraft, cannot be verified one hundred percent non-destructively and are therefore - like adhesive bonding - 'special processes'.

Fig. 28: Quality management system for avoiding errors that occur

4.2.2 Technology-specific realisation of ISO 9001 through standards

As shown, adhesive bonding technology is irreplaceable for European industry and for our everyday lives, and the economic significance of the value generated by adhesive bonding technology is very high (see Chapter 3). Nevertheless, neither the technological performance potential nor the image of adhesive bonding technology has yet achieved the status it deserves among the general public. The reasons for this are complex and can be illustrated by two examples.

1. Adhesive bonding is used for handicraft work with wood and paper, for example. From this it is deduced that adhesive bonding technology is 'child's play'. The adhesive bonding system successfully used for handicrafts is transferred to professional applications; this usually turns out to be a fallacy. However, the fallacy is not due to the 'adhesive' and certainly not to the 'adhesive bonding technology', but to the 'adhesive bonder', i.e. the person carrying out the work. The 'adhesive bonder' has abstracted incorrectly due to a lack of adhesive bonding competence and has come to the wrong conclusions.
2. Adhesive bonding technology is often not considered a genuine technology until the intended joining technology proves to be productively unfeasible. It is not uncommon for adhesive technology to save the day, but to do so without proper attention having been given to all the following elements:
   - The testing of the adhesive bondability of the joining part materials
   - The design of the surfaces of the joining parts for adhesion
   - The determination of the compatibility of the adhesive solidification mechanism with the joining part materials and production edge conditions
   - The tailoring of the constructive design of the joint to adhesive bonding.

Failure is pre-programmed if the basic technological requirements necessary for a successful adhesively bonded joint are not met, the adhesive bonding cannot work.

However, both examples - and the list could be extended almost indefinitely - have one thing in common: For the assessment of the failure that is usually inevitable under these conditions, the guilt is assigned to the 'adhesive' or the 'adhesive bonding technology'. This false and unreflected attribution of guilt shapes the image of adhesive bonding technology. It damages the necessary basis for future applications of the technology: trust.

Such a result is not specific to adhesive bonding. As a general rule, it's better to avoid things one doesn't trust.

4.2.3 Standards for quality assurance: welding

In the history of joining technologies, there is an outstanding example of precisely this: The number one joining technology of the 19th century in metal construction was the 'special process' of riveting.[43] It was trusted, and that is why the riveting technique was used.[44] It is not without reason that the most famous, purely riveted exhibit that still exists today is the Eiffel Tower in Paris.

The 'special process' of welding was viewed very critically when it was introduced in metal construction at the end of the 19th century and beginning of the 20th. Although welding technology had superior potential compared to riveting technology, its use was inhibited by its lack of a positive image. The reason was quite simple: Riveting technology, although a 'special process', was trusted precisely because of the positive experiences with it, which welding technology at the time still lacked.

However, it is indisputable that the image of welding technology - even in the popular view - has turned around completely in the course of the 20th century and that welding technology has developed into the number one joining technology of the 20th century.[45,46,47] One of the main reasons for this is that the 'special process' of welding is trusted precisely because of the positive experience gained through its use. Such an experience is necessary in order for a technology - which was originally 'new' – to be used in an industrial context on a broad scale.[48]

Building trust is the basis of this image change. This, of course, includes continuous research and development to improve the technology. However, welders built trust at the same time at an early stage by designing and implementing quality assurance measures and regulations for the use of their technology (see Figure 29).[49]
As a result, application errors were increasingly avoided. The results were increasing safety in the application and, ultimately, the necessary trust in the technology.
All welding ISO and CEN QS standards[50, 51, 52, 53, 54] listed in Figure 29 as such regulations have the function of specifying ISO 9001 and its core idea of error prevention in terms of welding technology. That is, they merely supplement an existing ISO 9001 quality management system in a technology-specific manner. For this purpose,

Fig. 29: Examples of welding regulations for quality assurance

the QA standards for welding technology listed in Figure 29 as examples have the three strategic core elements of classification, personnel and verification. In the welding context, these sets of rules correspond to the 'state of the art', are internationally accepted, and fulfil the requirement of the Product Safety Act to manufacture according to this 'state of the art'.

4.2.4 Adhesive bonding technology quality standards

The undeniable success of welding technology has been transferred to the 'special process' of adhesive bonding.[55] And adhesive bonding technology is clearly on the right path insofar as ISO 9001-specifying regulations have been or are being published - analogous to those for welding technology (see Figure 30).[56, 57, 58, 59, 60, 61, 62] The function of the regulations is also to concretise the ISO 9001 core idea of error prevention in terms of adhesive bonding[63] so that the user companies can continue to bond safely. The goal is to create in the use

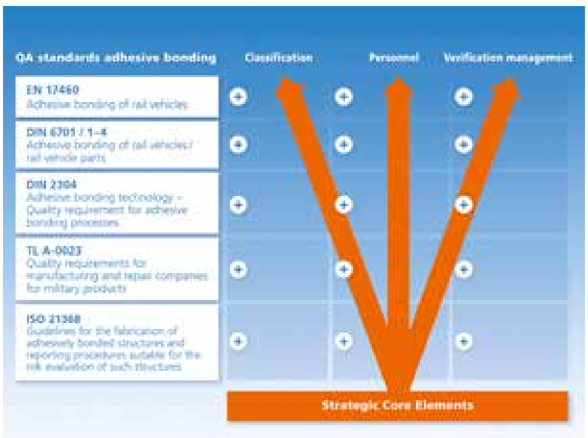


Fig. 30: Examples of adhesive bonding technology regulations for quality assurance

of adhesive bonding even more trust, which is ultimately the basis for realising innovations that are undoubtedly necessary for the future.[64]

Today's adhesives and sealants are high-tech products. When used properly, they usually enable zero-error production. Nevertheless, adhesive bonding errors still occur, more than 90% of which are due to application errors. It is precisely this contradiction that the above-mentioned adhesive bonding technology quality assurance standards address. If the main reason for adhesive bonding errors is not *adhesive* errors but adhesive *application* errors, improvements must be made in the area of application. Consequently, these standards are purely user standards. Their aim is to organise adhesive bonding technology application processes in such a way that the entirety of the adhesive bonding process is 'under control' by the user. They apply to all adhesives and sealants, regardless of their solidification mechanisms and their mechanical-technological properties in the joint. They apply for all material combinations and for all batch sizes in production.[65]

The standards are compatible with each other in terms of content and structure and contain the three strategic core elements already mentioned in connection with welding technology: classification, personnel and verification.[66]

Core element 1 - Classification of adhesively bonded joints

For the classification of the adhesively bonded joint according to safety requirements, the regulations and standards consider only one question: *What happens if the adhesively bonded joint fails?* The classification of the adhesively bonded joint is done only with regard to potential effects regarding joint failure and is therefore an analysis of the damage sequence. All adhesively bonded joints must be classified by the adhesive user, not by the adhesive manufacturer, into the following safety classes:

- Class 1: indirect or immediate danger to life and limb
- Class 2: possible danger to life and limb, major environmental damage
- Class 3: probably no personal injury or major environmental damage, maximum loss of comfort or performance
- Class 4: definitely no personal injury or environmental damage, maximum loss of comfort or performance

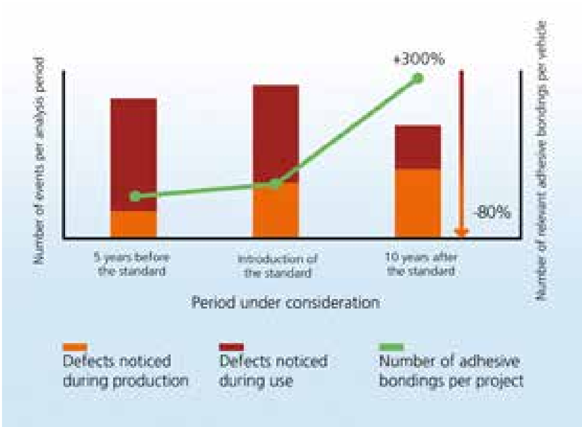


Fig. 31: Long-term study on the impact of the introduction of DIN 6701[71]

Sealants are included in this classification if they have an influence on the safety of adhesively bonded joints.

Core element 2 - Adhesive bonding personnel (ABC)
The Adhesive Bonding Personnel (ABP) comprises employees with *verifiable* adhesive bonding qulification[67]. The adhesive bonding supervisory personnel (Adhesive Bonding Coordinator - ABC) is responsible for adhesive bonding technology and all related activities in the company. The ABC is the central point of contact in the company for all quality-influencing factors of the entirety of the 'special process' of adhesive bonding and for the verifiable adhesive bonding competence of the entire Adhesive Bonding Personnel.

Core element 3 - Verification : actual load is always less than the maximum load capacity
The adhesively bonded joint must be dimensioned *with the assistance of the Adhesive Bonding Coordinator ABC* in such a way that its real loading is always less than the maximum loading capacity over the entirety of the product life. This must be documented in a comprehensible manner. The verification itself can be carried out in the following ways: 1) dimensioning, 2) component testing, 3) documented experience or 4) a combination of 1- 3.

Figure 31[68] illustrates the success of the introduction and implementation of QA standards using the example of DIN 6701 in rail vehicle construction. The implementation of adhesive bonding technology was examined as part of a long-term study over 15 years.[69] As Figure 31 shows, the number of significant, in this sense load-transmitting, adhesively bonded joints was rather low before the introduction of the standard (left bar). In addition, adhesive bonding errors were for the most part noticed only in the product life cycle phase 'utilisation', i.e. by the customer. This situation did not change fundamentally in the five following years (middle bar). A change occurred only with the introduction and implementation of the standard, the decisive change parameter. Ten years after the introduction of the standard, the number of load-transmitting, structural, adhesively bonded joints increased by 300% (right bar) compared to the initial situation. At the same time - despite a significant increase in the number of adhesively bonded joints compared to the number at the time before the introduction of the standard - the occurrence of adhesive bonding errors decreased by 80%. In addition, the detection of adhesive bonding errors changed completely. The few adhesive bonding errors that occurred were now mostly identified and corrected by the manufacturer.

Consequently, it can be stated for the QA standards: based on an existing QMS, these regulations define the aforementioned 'state of the art' for the professional organisation and implementation of adhesive bonding technology processes, which are obligatory in product safety law. They specify both the requirements for the quality-compliant execution of adhesively bonded joints and the general organisational, contractual and production-related principles for the fabrication of these joints[70]. This enables the user to design the entire adhesive bonding process and the life cycle of adhesively bonded products in a robust and reproducible manner, i.e. 'under control' in the standards sense. Through more qualified adhesive and sealant applications, the application areas of the key technology of adhesive bonding are further developed in a more qualified manner and thus the image of adhesive bonding, which in some areas is still in need of improvement, is sustainably improved.[71]

4.2.5 Personnel qualification in adhesive bonding technology with certificate: core element of quality assurance

The central element in the implementation of the quality assurance and Adhesive Bonding Standards described in 4.2.4 is undoubtedly the deployment of qualified adhesive bonding personnel. Here, too, adhesive bonding technology is similar to welding technology. For the latter, the use of verifiably qualified personnel has represented the 'state of the art' worldwide for decades. Similarly, in adhesive bonding technology, the European Federation for Welding, Joining and Cutting (EWF) Personnel Qualification System (see Figure 32), which is harmonised throughout Europe and recognised and used worldwide by the industry, was successfully implemented in 1994. In adhesive bonding technology, too, industry and handicraft are increasingly realising

Target group	Welding technology	Adhesive bonding technology
Decision-making level	**Welding Engineer (IWE)** DVS®-IIW/EWF 1170 (IAB 252r1-11)	**Adhesive Bonding Engineer (EAE)** DVS®-/EWF 3309 and EWF 6602
Technical management and supervision level	**Welding Specialist (IWS), Welding Practitioner (IWP)** DVS®-IIW/EWF 1170 (IAB 252r1-11)	**Adhesive Bonding Specialist (EAS)** DVS®-/EWF 3301 and EWF 6602
Performing level	**Welder (IW)** DVS®-IIW/EWF 1170 (IAB 252r1-11)	**Adhesive Bonder (EAB)** DVS®-/EWF 3305 and EWF 515

Fig. 32: Personnel qualification systems in welding and adhesive bonding technology

that the professional use of this technology in a company requires verifiable qualification of personnel, both technologically and economically.

The EWF personnel qualification system (see Figure 32) covers the entire adhesive bonding technology and links theory with practical exercises (see Figure 33). It goes without saying that occupational health and safety is an important topic in personnel qualifications. The personnel qualifications are product-, company- and industry-neutral as well as cross-hierarchical because the system covers in equal measure all the following:

- the technical decision-making level (European Adhesive Engineer - EAE)[72]
- the technical management or supervision level (European Adhesive Specialist - EAS)[73]
- the execution level (European Adhesive Bonder - EAB)[74]

All this ensures that adhesive bonding technology can be implemented holistically and professionally in the areas of work and responsibility, from the idea to the finished product.

In order to guarantee product, company and industry neutrality, EWF personnel qualifications are carried out exclusively by ISO/IEC 17024[76] accredited training institutions, as is the case with welding technology.[77, 78] This ISO/IEC 17024 accreditation represents an internationally objective quality feature and strictly separates training, examination and certification. The EWF diplomas or certificates are thus internationally comparable and recognised. Actually, courses with more than 23,000 participants have been held worldwide since 1994, and the trend is rising.

Any organisational measures related to process ultimately fulfil their purpose only if the personnel know not only what is to be done but also how, when and where something is to be placed in the daily work context and carried out independently. The aim of personnel qualification is, therefore, in the sense of 'Qualified Market Development – QME', to place adhesive bonding technology knowledge on a solid basis and to enable companies to independently use and implement this joining technology in a professional manner that complies with standards.[79]

Fig. 33: EWF personnel qualification in theory and practice[75]

4.3 The ecological potential of adhesive bonding technology

4.3.1 Adhesive bonding technology in the context of the circular economy and life cycle assessment effectiveness

Regardless of its unique joining technology potential, adhesive bonding technology unfortunately finds itself in the common and therefore also in the political view exposed to the challenge of being a joining technology that contradicts the EU action plan for the circular economy (European Green Deal) and the EU Waste Framework Directive fixed therein. One of the main reasons for this clearly incorrect assessment is that the term 'non-detachable' in joining technology is, especially in an ecological context, completely misunderstood in both popular and political assessments.[80]

Every joint, even one technically classified as 'non-detachable', can in principle also be detached again.[81] For 'detachable'[82] as well as for 'non-detachable'[83] joining technologies, it is the material structure of the joining partner materials that determines the basic circular economy capability and not the joining technology used.

In addition, the topic of 'circular economy capability' is commonly, and unfortunately often politically, focused on the topic of 'recycling' and in this way reduced. The EU Waste Framework Directive comprises five stages: 1) 'Prevention'[84, 85, 86, 87], 'Preparation for re-use'[88, 89, 90], 'Recycling'[91, 92, 93], 'Other recovery'[94, 95, 96] and 5), 'Waste disposal'[97]. Thus, two leves are legally superordinate to recycling.[98]
2) before Preparation
3) before Recycling
4) before Other recovery

The so-called 'R-strategies'[99, 100, 101] serve as the core framework of the transformation towards a circular economy. They support the definitely more comprehensive claim of a circular economy, which requires the holistic consideration of a product in terms of a life cycle assessment (LCA / DIN EN ISO 14040 – 14044) (see Chapter 4.3.9).[102, 103, 104, 105, 106] During the entirety of a product's life cycle, the environmental impacts, the reduction of the utilisation of natural resources and the reduction of waste produced must not be considered and assessed separately from each other or linearly in individual life cycle phases. On the contrary, the entirety of the product's life, i.e. the sum of all product life cycle phases, must be taken into account.[107, 108]

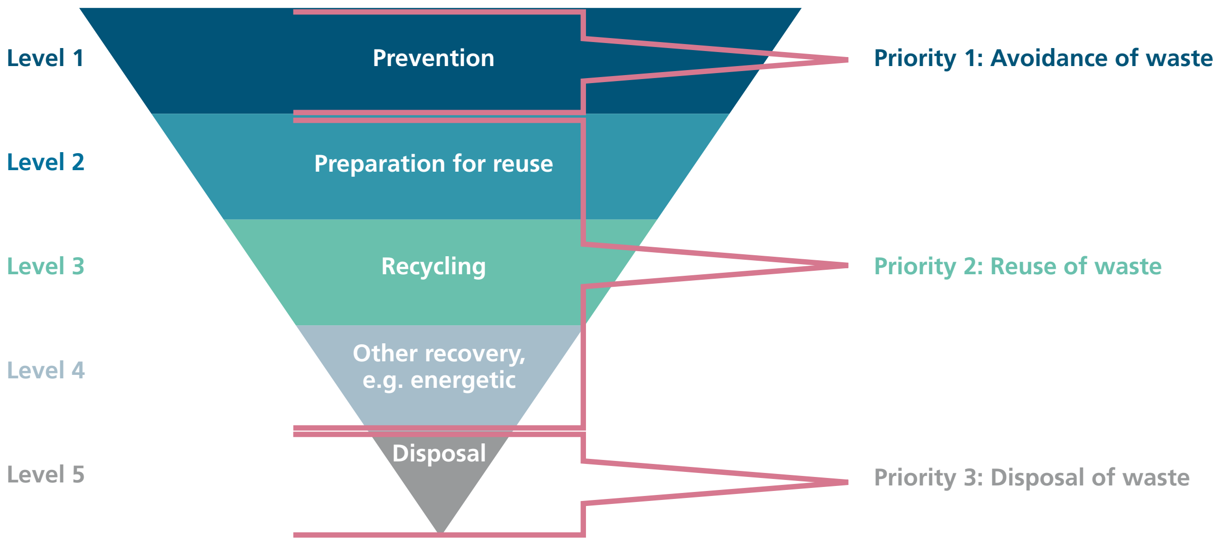


Fig. 34: EU waste hierarchy

Fig. 35: Adhesive bonding in shipbuilding for lightweight constructions[114]

Fig. 36: Adhesive bonding technology also makes agricultural machinery lighter.[116]

4.3.2 Adhesive bonding technology and lightweight construction

There are two most effective design strategies, then, for avoiding waste. The first is lightweight construction, i.e. achieving the same or better function with less material over the long term (reducing the amount of raw materials used in production). The second is the improvement of the longevity of products through repair, refurbishing, remanufacture and repurposing (keeping raw materials within the economic system).[109] Lightweight construction is therefore more than just reducing the weight of a product. Consistent lightweight construction also increases material or resource efficiency in all phases of the product life cycle.

In this context, adhesive bonding technology is one of the most important 'enablers' of lightweight construction due to its potential to preserve material properties in the joining of lightweight materials. Adhesive bonding technology is also a key technology for the circular economy:

- The adhesively bonded realisation of specific structures, e.g. stiffening elements such as ribs, contributes to constructive leightweight design in a material-saving way
- Through the long-term stable and secure joining of different materials that are used in the component according to the specific requirements, adhesive bonding in multi-material construction can also make material lightweight construction possible

In the lightweight transport sector, the use of adhesive bonding technology (e.g. adhesive bonding for car windshields, stiffening profiles, and the vehicle body) enables the use of thinner sheets to save material and energy in the use phase. It has been state-of-the-art for more than 20 years that car windscreens are adhesively bonded and thus become a torsion-stiffening and weight-reducing structural element.

In the case of vehicles, the key lightweight construction technology of adhesive bonding offers the possibility of using new structural materials with lower density and weight. It also allows, in particular, a reduction of sheet thicknesses in conventional steel construction due to the technology's two-dimensional force transmission. Through partial, stiffness-increasing doubling, adhesive bonding leads here to a reduction in material and thus in weight through the use of thinner sheets.

In principle, even thinner sheets can be used for modern high-strength and ultra-high-strength steels.[110] Melting during welding destroys the strength-determining, inner structure of the steel. Consequently, such sheets can be used in means of transport only if they are joined, i.e. adhesively bonded, in a manner appropriate to the material.[111] Reducing the thickness of the sheet metal primarily saves a lot of material and energy resources for the construction of the vehicle. Then, secondarily, due to its lower weight, less energy is needed for operating the vehicle, the result being less greenhouse gas emsissions from the combustible engine.

In rail vehicle manufacturing, the product life cycle phase 'utilisation', i.e. driving operation, is the determining factor with regard to energy need and emission reduction compared to the product life cycle phases 'manufacturing' and 'end of life'. The use of lightweight construction materials, realised with adhesive bonding technology, reduces energy consumption and thus the specific CO_2-equivalent emissions per passenger or tonne-kilometre.[112]

Lightweight construction and adhesive bonding, furthermore, already have a long tradition in aircraft construction. From the fuselage to the wings, from the engines to the interior, adhesives are used to create joints that preserve material properties and are stable and secure in the long term. Further innovations will come in this field. In the future, these advantages of adhesive bonding will also become evident in shipbuilding and inland waterway construction. The results of a study[113] by the German Maritime Centre (DMZ) make it clear that the increased use of adhesive bonding technology as an important enabler technology for lightweight construction, and the associated weight savings and reduction of resources will improve the eco profile of this sector in the future.

The reduction of weight plays an important role in agricultural machinery construction, too. This is because welded steel has mostly been used in the construction of machines up to now. A research project[115] from 2019 now shows that steel can also be reliably joined with adhesives, with a reduction of the wall thickness and a lightening of the components. With adhesively bonded component samples made of high-strength steels that are not suitable for welding, it was also possible to demonstrate high strength under dynamic loads.

Adhesive bonding technology has thus long been an indispensable factor for the realisation of lightweight construction through multi-material design enabling a lower ecological footprint. At the same time, as shown in Chapter 4.3.7, adhesive bonding does not prevent the disassembly of products. On the contrary, adhesive bonding offers promising possibilities for detaching the joints.[117] Therefore, in the future, adhesive bonding technology will be a key to ensuring a longer use phase, repairability and, eventually, the recyclability of products.

Various studies[118] show that the grey energy for the primary production of wood is about half that for structural steel (S275J2), whereby most of the energy is used for drying.[119] In addition, in terms of mass, wood is significantly more efficient than concrete and can indeed compete with structural steel.[118] In order to profitably implement the ecological and mechanical advantages of wood as a material in modern construction, two limitations must be overcome. First, the limitation regarding the dimensions of the wood must be surpassed. Raw wood, as a direct product of trees, is available only in limited cross-sectional sizes and lengths. It is only through adhesive bonding technology that various wood materials[120, 121] can be produced in almost any dimensions.[122] Such dimentions are prerequisite for the use of wood in structures, from multi-storey housing[123] to high-rise buildings,[124] as a substitute for less sustainable materials (see Figure 37). The second limitation to be

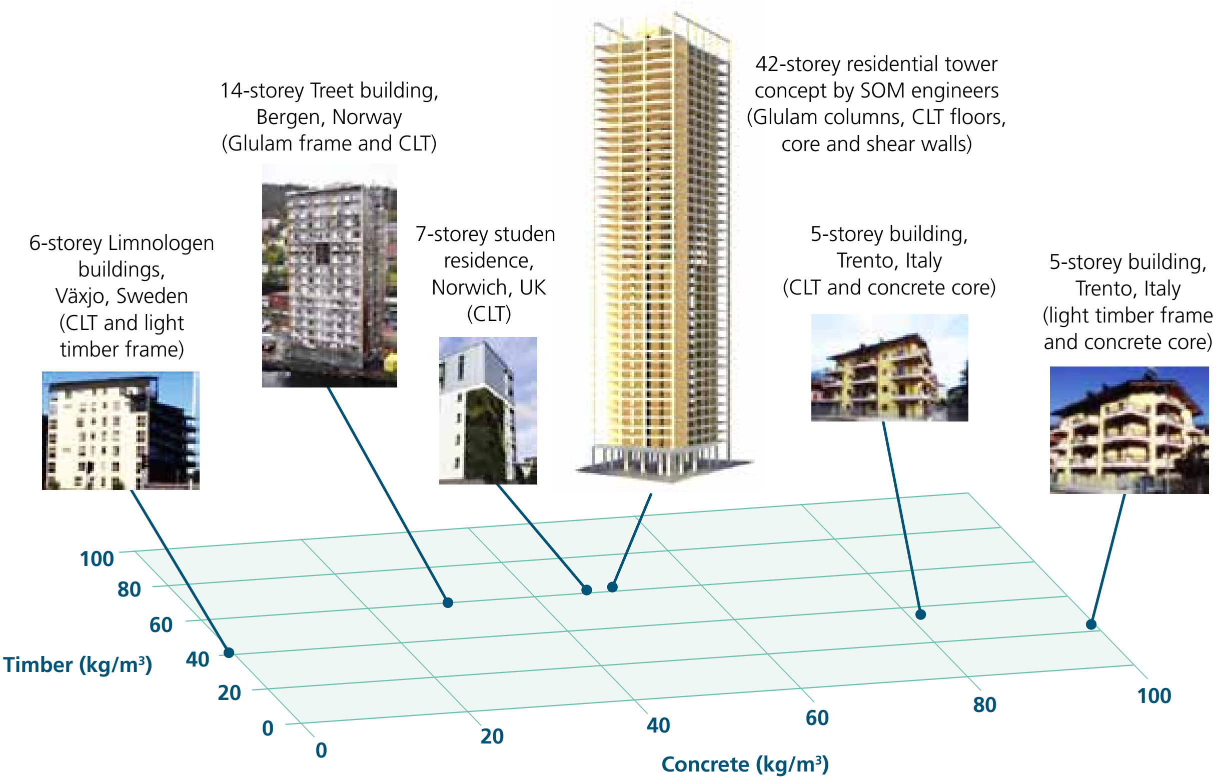


Fig. 37: Material consumption, expressed as mass, in multi-storey timber buildings. The horizontal axes show the mass of wood or concrete used per m³ of the respective building. The size of the images indicates the height of each of the six case study buildings studied[1]

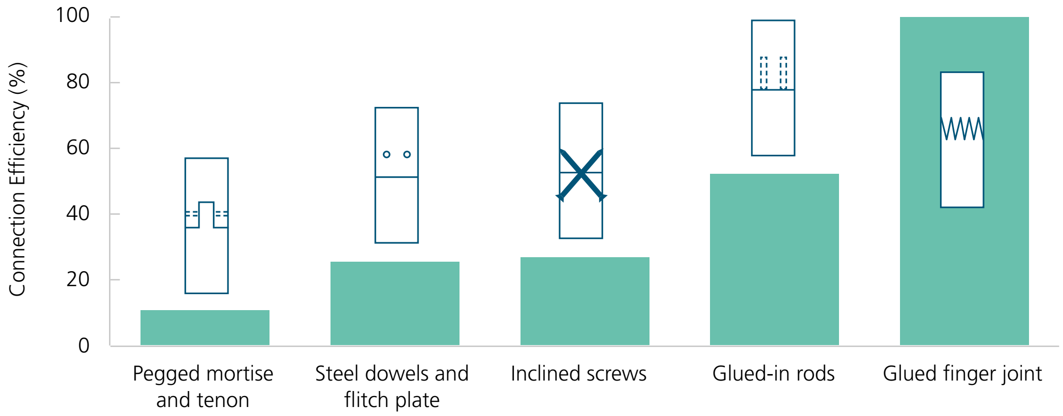


Fig. 38: Efficiency of joints between 100 mm times 200 mm timber members transmitting an axial tensile force - the efficiency of the joining is the ratio of the strength of the joint to the strength of the fasteners[118]

surpassed as regards the use of wood is that concerning the bonding technology. A decisive element for the performance of most timber structures is the joints between the load-bearing components.[125] When the efficiency of adhesively bonded joints is compared with that of a different joint type, the adhesively bonded joint is shown to have the highest efficiency (see Figure 38).[122] The decisive factor for the full economic and ecological development of CO_2-neutral construction with wood is, therefore, adhesive bonding technology, without which modern timber construction could not exist. Adhesive bonding technolocy can overcome both of the limitations regarding the use of wood in modern construction. It is only through adhesive bonding that modern timber engineering can be rethought and can reduce the use of unsustainable building materials, while being flexible enough to allow for repair.[126, 127]

4.3.3 Adhesive bonding technology and repair

The adhesive bonding technology design in the so-called differential construction method for a product consisting of several components that can basically be separated from each other again has further advantages in addition to the lightweight construction potential. One of these advantages is, for example, the ability to be repaired. Even today, adhesive bonding is the most frequently used repair method - even for non-adhesively bonded products. This means that a product can be used longer and thus raw materials can be kept in the economic system longer as a significant contribution to the conservation of resources. Consequently, adhesive bonding technology and repair do not represent a contradiction. On the contrary, many repairs in the private, handicraft and industrial sectors would be inconceivable without adhesive bonding.

For safety, adhesive bonding technology is used in accordance with detailed repair instructions. This includes, in particular, fibre composites, for example in aircraft construction or wind turbines. In the event of damage, e.g. due to stone impact or hail, part of the material is cut out and shafted, and then an exactly fitting repair patch is adhesively bonded. Afterwards, the components can bear the same load as before the damage. Basically, however, the question arises as to how products with adhesively bonded joints can be repaired. As a rule, separation must take place locally without damaging the rest of the product. Unless special separation mechanisms are built in, separation takes place mechanically, often at elevated temperatures. This is explained

Fig. 39: Adhesive bonding technology as a repair technique - also in the private sector[128]

Example 1: Repair of windscreens in means of transport

For several decades now, windscreens, and subsequently also other windows, have been adhesively bonded into cars and other means of transport ('state of the art'). Elastic thick-film adhesives are used for this purpose, which, among other things, compensate for tolerances of the car body. By joining the panes to the body in a load-transmitting manner, they become a structural, stiffness-increasing element of the entire vehicle. As a result, the car body becomes safer and at the same time considerable material can be saved. Sheet thicknesses can be reduced due to the gain in stiffness, and lighter construction can be used. The results are the saving of energy and pollutants in both the production and the operation of the vehicles.

The removal of the panes is already taken into account in the design and is done by cutting the 'thick' adhesively bonded joint with a cutting wire. After the windscreen is removed, the remaining adhesive can be removed, for example, with a vibrating spatula, so that the new windscreen can then be adhesively bonded in place. This repair can be carried out in all garages according to prescribed procedures. The same applies to the repair of minor damage to the windscreen. Special light-curing adhesives have been developed for this purpose; they penetrate particularly well into the fine cracks of the damaged area and can then cure there. This means that the windscreens need to be completely replaced only in the event of major damage. Thus considerable resources are saved.

Example 2: Repair of display screens on mobile phones

The display screens of mobile phones are also often damaged, so that they have to be replaced. If the manufacturer has not deliberately prevented replacement by choosing unsuitable designs or adhesives, the screens can usually be changed. Repair kits are available for this purpose that work in a way similar to that of car windscreens. However, additional heating, for example with a household hair dryer, is often required to detach the adhesively bonded joint. A repair is also possible by skilled laypersons, but the procedure is not yet as established as with car windscreens though it is nevertheless already common practice.

In mobile phones, too, the use of appropriate adhesively bonded joints to facilitate repair and recycling must be adequately planned for in the design phase of a product and accordingly build into the product. Adhesively bonded joints do not prevent repairability or recyclability. Specific technologies and innovations enable the easy removal of adhesively bonded batteries, screens and back covers. In particular, adhesives and sealants are available that can be removed, if necessary, by electromagnetic irradiation, i.e. thermal treatment, directed locally at the bonded surface. This does not affect the joined parts. Other solutions for debonding include chemical or mechanical techniques. These options should be considered when information on repairability or on the behaviour of adhesives and sealants in the product life cycle phase 'end of life' is provided.

The techniques described require repair of the products by professionals who have the appropriate skills, tools and knowledge. This ensures the quality of the product. It also ensures the proper and correct handling of both parts to be replaced and 'end of life' materials and products with regard to the principles of the circular economy.

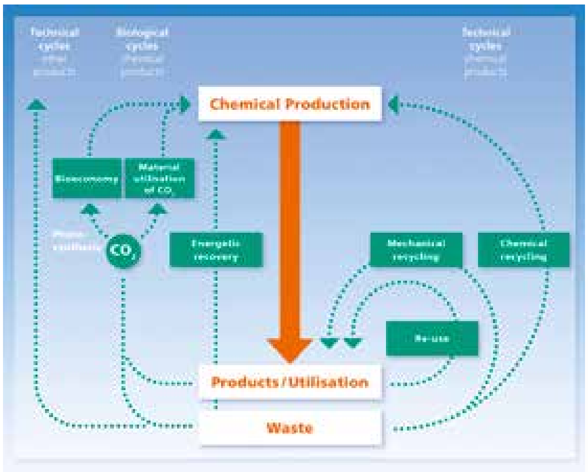


Fig. 40: Circular economy and recycling[129]

using the two examples given below. There are precise descriptions of how the repair is to be carried out and of which materials are to be used. The repair and its implementation in valid regulations are already considered in the design. Furthermore, personnel qualified in adhesive bonding technology are strongly advised.

4.3.4 Adhesive bonding technology and recycling

Adhesive bonding technology and recycling are not a contradiction either, because, from a technical point of view, all adhesively bonded parts can in principle be detached for recycling. As with repairability, the potential for development lies in taking debonding into account as early as the product design stage. As a rule, debonding involves a combination of local heat and mechanical stress, to which adhesively bonded joints react more sensitively and with significantly less durability. This form of debonding is mainly used for larger or more valuable items. In the case of a very heterogeneous mixture of different products, the separation of the materials will be possible only after shredding. In practice, when many small parts are adhesively bonded, often only built-in debonding mechanisms can be used (e.g. in the case of labels), as manual separation or detachment is not economical or practical (e.g. in the case of laminate flooring panels). The adhesives and sealants - as well as varnishes and various impurities - remain on the separated materials which is unproblematic in the case of thermally recyclable materials such as metal or glass. In suitable cases, the adhesive can also be removed afterwards. In a few other cases, separation is possible, e.g. after flotation. Specific examples are the removal of cementitious adhesives from insulating foam, or sealants with a density <1 g/cm^3 from glass surfaces. In the case of mechanical recycling of plastics, however, adhesive residues or sealant residues lead to a loss of quality. This, however, can be regarded as uncritical in the case of heterogeneous product mixtures, which always contain aged mixed plastics, including adhering adhesives, sealants and varnishes. Successful examples of raw material separation are the recycling of cars, mobile phones and soft packaging.

Even if plastics can be mechnically recycled initially, they will degrade in each mechanical recycling loop and will eventually have to undergo chemical recycling. Although chemical recycling processes are still in their infant stages of development, it isconceivable to recycle in the future plastics with all kinds of adhering adhesives, sealants, coatings or varnishes. Plastics would be treated as raw materials through chemical recycling by decomposition into low-molecular basic materials (see Figure 38). These basic materials are standard starting points of major chemical processes and thus make possible the use of existing production resources.

Example 1 - Recycling of cars:

These days, after the operating fluids have been removed, cars are first partially dismantled in order to separate the large plastic parts, the cables (since copper is considered a particularly valuable raw material that also interferes with the recycling of steel and aluminium) and the windows. Especially in the case of the panes, the adhesively bonded joints are also detached. The adhesive and sealant residues and plastic parts of the glass panes decompose thermally during glass recycling and therefore do not interfere.

If the number of cars with a high proportion of plastic in the body increases (e.g. because of planking of body frames with fibre composite plastic), it will be necessary to remove this plastic before further processing. In terms of lightweight construction and thus resource-saving vehicles in production and operation, the joining will primarily have to be by adhesive bonding. The disassembly here can be done in a way similar to that of the glass panes. This is limited by auxiliary fasteners (such as screws or rivets) needed in production or, in the event of a crash, as crack stoppers. In these cases, the parts would be torn off by a strong, specifically applied force. If the utilisation of these parts as spare parts is desired, the auxiliary fasteners must be removed beforehand with considerable effort (e.g. drilling).

The remaining bodywork, consisting largely of steel and aluminium, is shredded and then separated into fractions using long-established processes. Residues of adhesives, sealants and coatings remain on the metal but do not interfere due to the high temperatures involved in metal recycling. The major part of the adhesives, sealants and coatings found in the light (non-metal) fraction together with other plastics remaining in small proportions in the car body can, from today's perspective, be used only thermally for energy generation. In the future, however, using this residue as raw material by decomposing it together with other plastic waste into low-molecular basic materials is conceivable to utilise.

The illustration shows that cars can largely be disassembled into their components. This is only slightly affected by adhesively bonded joints. Adhesively bonded joints can already be separated to a large extent, but this separation should improve significantly if disassembly is taken into account already in the design of the vehicle (see Chapter 4.3.7).

Example 2 - Recycling mobile phones:

Mobile phones, including smartphones, are commonly considered to be unrepairable and only recyclable at low value chain levels. The reason often given for this is that the devices are highly adhesively bonded. It is possible for the manufacturer to make the reprocessing of these products difficult in this way. It is also possible to make their repairability difficult through the failure to provide spare parts. Neither of these situations, however, represents a technical necessity.

It should be noted that, for example, the adhesives and sealants used for embedded batteries often fulfil more than just the function of precisely positioning the batteries in the device. They also fulfil additional functions:

- Sealing, the keyword being *waterproofing*
- Thermal and electrical management as insulators or conductors
- Safety, for example, in terms of flame retardancy
- Design freedom
- Protection against dropping

The aspect of waterproofness in relation to functionality reaches the highest value, 66%, when users are asked which features are important when they buy a smartphone.[130]

Systematic disassembly and recycling of individual components, if automated. economically requires the collection of the devices. Apple developed a process by which iPhones could be completely dismantled, regardless of the joining technology used.[131] The disassembly robot was called Liam. This was coupled with a buy-back system when a new unit was purchased.[132] Already in 2018, the recycling robot Liam was replaced by the successor system Daisy. Daisy is able to recognise the different iPhones and dismantle 200 smartphones per hour.[133] In 2019, a second line was built to expand capacity, so that up to 2.4 million units can now be dismantled per year.[134] This is independent of whether the components are screwed, clipped or adhesively bonded.

However, there are also semi-automatic processes for the disassembly of mobile phones. These are partly aimed at recycling components, but also partly at repair in the professional sector. The iPhone X is to serve as an example of the disassembly procedure with a special tool set; instructions are available as a video.[135] Most disassembly instructions are aimed at repairing the phone for the highest possible level of recycling. There are repair instructions on the internet for almost every type of phone, so that even experienced laypersons can make many repairs on their own, including detaching the respective adhesively bonded joints. This shows that disassembly is possible, independently of whether the device, the individual components or only the materials are later reused.

There are also more comprehensive manufacturer-independent concepts for recycling mobile phones.[136]

Example 3 - Recycling of flexible packaging:

Soft packaging, especially that known under the trade name Tetra Pak®, is often considered non-recyclable due to the laminated mixture of paper (approx. 75%), plastic (approx. 20% polyethylene) and aluminium (approx. 5%). Manual disassembly is practically impossible due to the thickness of the plastic and metal layers. Industrial processes have been developed, though, in which separation is very much possible and is also carried out to a high degree.[137]

4.3.5 Adhesive bonding technology, durability and resource efficiency

Adhesive bonding technology, durability and resource efficiency are not contradictory either because adhesive bonding can increase the longevity of products.

The range of applications for adhesives and sealants literally extends from A to Z. Products with adhesively bonded joints have proved that they can easily last for at least 15 years, sometimes more than 30. The long-term stability of adhesively bonded joints supports the useful life of these products. As a rule, you want a house to last a lifetime.[138] The lifespan of a car is increasing.[139] The average age of cars registered in Germany, for example, was 9.5 years on 1 January 2019, with 40% of cars older than 10 years.[140] In addition, the ability of a damaged windscreen to be repaired in order to extend the life of the product is state of the art and beyond question. (see Chapter 4.3.4).

A rail vehicle runs for up to 40 years. When the resource efficiency of the ICE is considered, for example, it should be noted that it has an annual mileage of approx. 500,000 km.[141] For its designed service life of 40 years, this means a total mileage of 20,000,000 km. The repairability is already predetermined in the design; furthermore, the vehicles are subject to regular predetermined maintenance to ensure their longevity.

Aircraft fly for up to 30 years. They are regularly monitored and repaired for a long life.[142] The longevity of these products has been verified.

The use of adhesive bonding technology contributes to increasing the longevity of products, i.e. the extension of the product life cycle phase 'utilisation'. This is also achieved through the development of adhesively bonded products with optimised ageing resistance. Among other things, optimised surface treatment processes are used for this purpose. These processes specifically adjust or improve the adhesion between the surfaces of the joined parts, and enhance the adhesive as an essential long-term resistance factor.[143, 144, 145, 146, 147, 148, 149] Knowledge of the optimised properties can then in turn be taken into account in the design.

In addition, adapted requirement profiles and optimised constructive designs and production specifications avoid resource-intensive 'over-engineering'. Optimising adhesive bonding technology, for example, through improved application that applies the exact amount of adhesive and sealant required and thus avoids time-consuming reworking can also contribute to increasing resource efficiency. Furthermore, adhesives lead to material savings, even in areas as diverse as food packaging (shelf life extension) and transport construction (lightweight construction) (see Chapter 4.3.2).

One of the main functions of soft packaging (see 4.3.4 / example 3) is to protect food as optimally as possible and thus extend its shelf life. Furthermore, that they are important for the modern distribution of food and are lighter in comparison to conventional can packaging

made of glass or metal and can therefore be transported more easily. It should be noted that these laminated multi-material composites have a much better carbon footprint and eco-balance-efficiency compared to the conventional packaging mentioned above (see also 4.3.4 - Recycling flexible packing).

Adhesive bonding thus enables building and construction principles with improved life cycle assessments in the holistic consideration of life cycles.

The development of alternative energy sources (see Chapter 4.3.5) is inconceivable without adhesive bonding (sealing of solar cells and joining of rotor blades in wind turbines). Just as inconceivable are electromobility (construction of magnetic cores for electric motors from electro-packaging sheets, sealing of battery cells, and thermal management of batteries with thermally conductive adhesives) and fuel cells (hermetic sealing and joining of bipolar plates).

The adhesive also contributes to resource efficiency. In terms of circular economy-friendly adhesive formulations, recyclates can be suitable raw materials for adhesives and sealants. Furthermore, bio-based adhesives are already used today in certain mass applications. However, because many necessary property profiles of synthetic adhesives cannot yet be realised for bio-based adhesives, the applicability of these adhesives is still limited. Nevertheless, adhesives are an ideal product group for the use of renewable raw materials. Moderate quantities are sufficient to make the raw material synthesis economically feasible and the ecological impact large enough. The development of renewable raw materials for widespread utilisation in adhesives and sealants is well underway, but there is still an enormous need for research to reach the level of use of fossil raw materials.

4.3.6 Adhesive bonding technology and energy transition

Adhesive bonding is an integral part of a successful energy transition because the development of alternative energy sources is inconceivable without adhesive bonding. Adhesive bonding is what makes modern systems for alternative energy production and their reliable large-scale energy generation possible in the first place (Figure 41). This begins with the sealing of solar cells as well as the construction of solar modules. Even for houses with a lightweight, flat or curved roof, for which the installation of a solar system was previously out of the question for reasons of weight and stability, adhesive solar films now make such roofs usable for energy. Adhesively bondable solar films are extremely light and flexible, and existing buildings can be quickly retrofitted with them for energy efficiency. Within a very short time, these films, which have a self-adhesive backing, can be attached to the existing roof surface. Though exposed to UV rays, heat, cold and moisture, the films will last for over 20 years. Furthermore, when the rotor blades of wind turbines are constructed, up to about 1 tonne of adhesive is needed to join the two half-shells of a rotor blade. Only adhesive bonding maintains the required material properties of the rotor blades so that these products are sufficiently light for optimised energy yield and durable for optimised longevity.

4.3.7 Adhesive bonding technology and e-mobility

Transport is the movement of people, animals, or material goods from place to place.[153, 154, 155] The European transport sector consists of more than 80% motorised private vehicles[156, 157], which are responsible for 26% of

Fig. 41: Adhesive bonding is an integral part of the energy transition[150] (left),[151] (centre),[152] (right)

all CO_2 emissions in the EU.[158] Consequently, transport policy represents a European field of action for reducing CO_2 emissions.[159] All the technologies used for this purpose for alternative energy generation, storage and conversion are directly dependent on the successful use of adhesive bonding.

Electromobility, for example, is not possible without adhesive bonding. Application of the technology begins with the construction of the magnetic cores for the electric motors from electro-packaging sheets, continues with the sealing of the battery cells and ends with the thermal management of the batteries with thermally conductive adhesives.[160] The same applies to fuel cells. Not only do these have to be hermetically sealed and mounted as modules, but the bipolar plates also have to be joined together. All this is done quite efficiently through electrically conductive adhesive bonding.[161] Sealing in particular is a challenge, independent of whether hydrogen or methanol is used as fuel, as both are highly permeable.

4.3.8 Adhesive bonding technology and disassembly

For the greatest possible product safety, technical adhesively bonded joints are designed for high durability. In many places, they are also overdimensioned for this safety reason. This is because in real life the actual use of products can deviate from the intended use and thus the loads that occur are difficult to predict. In addition, from an ecological point of view, the service life of a product should be as long as possible even if next-generation products are more energy efficient, for example. New production often requires a more significant input of energy and materials. The substitution of the still fully functional 'old product' with that of the newer generation does not lead to any ecological savings when viewed holistically.

In terms of the circular economy, however, disassembly is also necessary at a given point in time in order to separate different materials and reuse them at the highest possible value-added stage. This applies equally to all technologies joining different materials.

The detachment of an adhesively bonded joint is caused by an external 'trigger' that does not function in the normal use of the adhesively bonded product and therefore does not affect its safe use. If necessary, two triggers are combined to prevent unintentional detachment. This is shown schematically in Figure 42.

The most universally applicable but non-specific triggers are mechanical load and heat. These can be used to detach all adhesively bonded joints. Other triggers that usually do not require an adhesive and sealant adapted to them are water and other media such as solvents, whereby the detachment may also take a very long time. If necessary, superheated water in an autoclave or a steam pot can be very helpful here. However, there are also adhesives that use very specific triggers such as light with certain wavelengths, an applied electrical voltage, or heating with microwaves or high-frequency fields. The effectiveness of the individual triggers depends to a large extent on the composition of the adhesives.

Since the strength of an adhesively bonded joint can be controlled much better via the cohesive strength of the adhesive than the adhesion level on the joined parts, up to now the mechanical design of an adhesively bonded joint has had the goal of a cohesive fracture for safety reasons: The solidified adhesive is itself torm apart but continues to adhere to the previously joined parts.

Industrially feasible disassembly processes for the recovery of joined materials or the repair of adhesively bonded products are essential focal points of the development process and product testing. From microelec-

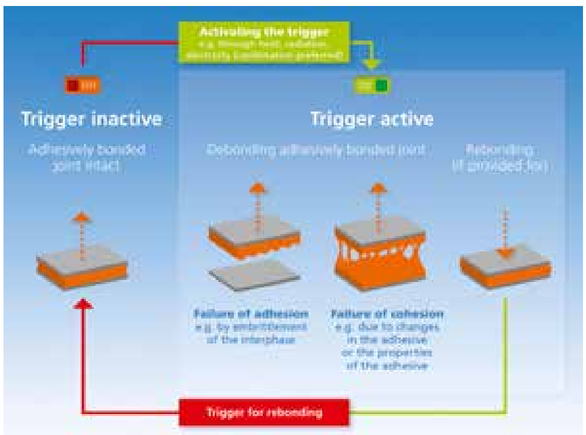


Fig. 42: Debonding due to a trigger leads to adhesive or cohesive detaching of the adhesively bonded joint. In rare cases, rebonding may occur due to another trigger.

tronics to large structures in the building industry, the requirements for both circular economy friendliness and eco-balanced product designs taking disassembly into account will be listed in future specifications.

Triggers for adhesive solution and design measures to improve the economic efficiency of disassembly processes are considered at an early stage of product development. Accessibility for disassembly influences the design and construction. Force-intensive processes are mechanised or supported by automatic machines or robots. Detaching by heat input is a disassembly option for adhesively bonded products, both in combination with mechanical detaching and independently. Disassembly through media influence is already being used successfully both in handicraft (e.g. removing wallpaper) and for mass-produced products (e.g. removing labels from deposit bottles).

When adhesively bonded joints are designed, the occurrence of peel stresses is generally avoided for the product life cycle 'utilisation'. The adhesive does not withstand these linearly occurring mechanical loads in the adhesively bonded joint designed for planar load transfer and shear stress. However, a design suitable for disassembly can be created in such a way that the peeling forces to be avoided in use can be introduced in a targeted manner during disassembly. An example of this is so-called explosive screws, which deliberately lead to the peeling separation of adhesively bonded parts. It is important to consider in such approaches that the load case that leads to the disassembly of the bonded parts cannot occur under any circumstances during the life cycle phase 'utilisation'.

Thus, adhesive bonding does not prevent the disassembly of products but offers promising possibilities for detaching the joints. For economic disassembly, however, the disassembly capability must be included in the planning specifications at an early stage of product development.

Whereas up to now the product life cycle phase 'utilisation' has been decisive for the design of a product, in the future the product life cycle phase 'end of life', i.e. the disassembly of the adhesively bonded joint and the circular economy capability of the materials used, must also be firmly integrated into the product life cycle phase 'development'. For this purpose, the 'dismantling-friendly' requirements, taking into account 'repair' and 'reuse', must be integrated from the outset into design guidelines for various material combinations and components of different sizes. This applies from microelectronics to large components in the building industry. In terms of product safety together with the circular economy, in order to achieve this integration of requirements in the design stage, an in-depth understanding of existing load cases in connection with adhesives is necessary.

Depending on which disassembly concept is pursued, accessibility of the adhesively bonded joint for cleavage reagents or radiation must be made possible during disassembly, for example, so that these approaches can be used. For this purpose, constructive elements are provided that control the initiation of disassembly. Structures are conceivable which, in a way similar to that of grease nipples for introducing lubricant into assemblies, introduce a fission reagent distributed over the adhesively bonded joint but are unactivated during the product life cycle phase 'utilisation'. Similar approaches could be pursued for radiation-induced disassembly approaches and integrated into the product design.

'Rebonding' after detaching, i.e. joining again using the same adhesive, is almost never possible. It might be possible, for example, with hotmelt adhesives. Since the state of the adhesive in each case is unknown, rebonding is not sensible with the usual technical products for the safety reasons mentioned above alone.

Furthermore, recycling the adhesive and sealant itself would hardly have an ecological impact as the amount of adhesive used is usually very small.

Fig. 43: Sustainable material development for imaginative adhesive bonding technology products with a lifelong integrated and (digitally) always available disassembly idea

4.3.9 Adhesive bonding technology and digitalisation

Digitalisation supports adhesive bonding technology decisions both for safer product design and for more sustainable effectiveness of the circular economy. Within the framework of a cross-life-cycle approach, digital tools and the availability of detailed material- and process-related data along the entirety of value chains or cycles will in the future allow developers of adhesively bonded joints to to optimise product safety and environmental friendliness regarding resources and cost efficiency.

When it comes to environmental properties in this context, Digital Product Passports (DPPs) could be introduced as a formula to communicate the environmental performance of products in accordance with already established sustainability or environmental metrics (e.g. Environmental Product Declarations - EPD based on EN 15804+A2, Product Environmental Footprint - PEF, EU Ecolabel) based on existing scientific evidence (Life Cycle Analysis - LCA). [162, 163, 164, 165, 166]

For the adhesive and sealant industry, a DPP would also be a way to communicate in an integrated way the industry's product characteristics (Declaration of Performance - DoP) or compliance with CEN standards, e.g. in accordance with the Construction Products Regulation (CPR) and its technical specifications. Furthermore, the DPP could also communicate and accompany the disassembly process and the ‚end-of-life' treatment in accordance with regional guidelines, as the DPP works with Global Positioning System (GPS) coordinates. Finally, the DPP would help to align product information in a digital way, especially for products with limited packaging space such as adhesives and sealants, transparency thereby being ensured.

Digital twins enable the selection of optimally suited disassembly processes. Radio Frequency Identification (RFID) chips in adhesively bonded products make all data of the materials as well as adhesives and sealants available for disassembly. The highly experimental verification effort required for the process integration of adhesive bonding technology into a production process is reduced with the help of suitably calibrated digital material and component models. Verifiable and maintenance-cost-reducing lifetime predictions for the resource-saving replacement of wear parts significantly increase safety gains and longevity (Structural Health Monitoring/SHM).[167]

4.3.10 Adhesive bonding technology and ecological requirements

The use of adhesive bonding supports the implementation of a comprehensive circular economy and thus has positive effects on the life cycle assessment.
The *effectiveness of the circular economy* results from the fact that adhesively bonded joints can be detached again in a controlled manner after the product life cycle phase 'utilisation'. The *improvement of the life cycle assessment* in a holistic consideration of all product life cycle phases results from the unique abilities of adhesive bonding described above:

- Long-term stable and safe joining of the same or different materials
- Preservation of the material properties
- Integration of additional functions, e.g. effective assessment of the life cycle

It is precisely this unique ability of a joining technique that makes it possible to create successful construction methods and product designs that promote eco-balance.

This unique selling point of adhesive bonding technology supports the Ecodesign Directive. This directive takes a holistic view of a product life cycle with a focus on greenhouse gas emissions. The holistic approach must already be included in the adhesive bonding technology product planning and design phase, which influences 80% of the product impact. To connect (for the sake of eco-balance) energy consumption, material and resource efficiency, the Ecodesign Directive classifies material <u>and</u> energy as a resource.[168] This allows energy consumption and material efficiency to be transferred to resource efficiency, and adhesively bonded products

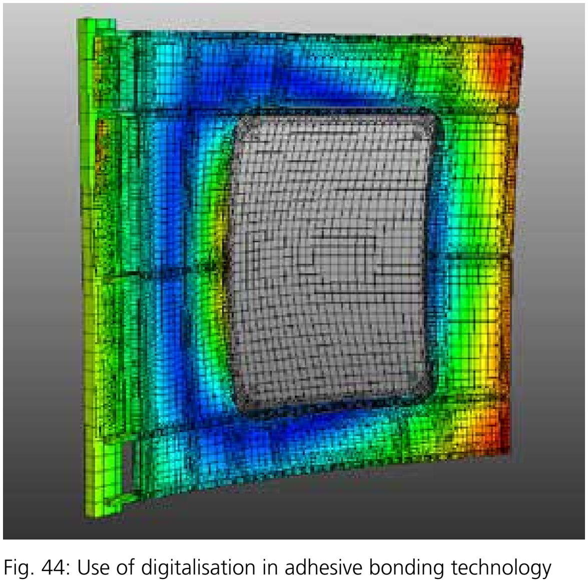


Fig. 44: Use of digitalisation in adhesive bonding technology applications

to be considered holistically. For example, in rail vehicle construction, where adhesive bonding technology is used comparatively widely, the driving operation, i.e. the product life cycle phase ‘utilisation’, is the determining environmental factor compared to the product life cycle phases ‘manufacture’ and ‘end of life’. The adhesive bonding technology use of lightweight materials reduces energy consumption and thus the specific CO_2 equivalent emissions per passenger or tonne kilometre. These reductions support this industrial sector, which is demanding from the point of view of safety and long-term durability, in a way that makes eco-balance effective.

Such life cycle assessments (LCA / DIN 14040 - 44) enable the holistic consideration of adhesively bonded products with regard to ecological improvements. They currently represent the most comprehensive assessment method for environmental impacts. An indispensable prerequisite for this is the quality, timeliness and availability of the underlying data: FAIR (*f*indable / *a*ccessible / *i*nteroperable / *r*eusable). The product-related harmonisation approach of the environmental footprint of products and services (‘Product Environmental Footprint - PEF’) initiated by the European Commission makes comparative environmental statements on functionally identical products comprehensible. This requires the timely definition of product group-specific PEF Category Rules (PEFCR) for end products manufactured using adhesive bonding technology. Due to its small share in the end product, a focus on the adhesive itself is definitely not advisable, as the positive effects that the adhesive enables as a construction material in the adhesively bonded end product would be disregarded. Nevertheless, extensive data sets are available in Model Environmental Product Declarations (Model EPDs) of adhesives and sealants, e.g. the FEICA Model EPDs for the construction sector.

5

Future perspective: ‘Controlled longevity’ - linking product safety and eco-balance effectiveness when adhesive bonding technology is used

In the future, all products will be considered holistically across all phases of their product life cycle, from both the perspective of their product safety and their circular economy or environmental balance effectiveness. For this holistic view, future developments of adhesively bonded products will take place in the sense of *controlled longevity*.[169] What is meant by this is that one has control over the integrity of the adhesively bonded joint over the specified, predictable period of the product life cycle phase 'utilisation' and can subsequently dispose of it in a controlled and ecologically targeted manner in the product cycle life phase 'end of life'.

Controlled longevity thus brings together the two aspects of 'product safety' and 'circular economy/eco-balance effectiveness'. So during the longest possible product life cycle phase 'utilisation', the adhesively bonded joints fulfil the legally required safety requirements. Then in the product life cycle phase 'end of life', these joints enable the effectiveness of the circular economy as stipulated in the EU Waste Framework Directive.[170]

In addition to ensuring normatively that the real loading of an adhesively bonded joint in the product life cycle phase 'utilisation' is always less than its maximum loading capacity, the holistic view also includes making the 'end of life' concept of adhesively bonded products an integral part of product development as early as the product planning and design phase. The new challenges resulting from product safety *and* circular economy concepts therefore will require even more intensive communication and cooperation in the future and thus even closer networking of all players along value chains. Raw material producers, adhesive and sealant manufacturers, adhesive and sealant formulators, adhesive and sealant users, product manufacturers, end customers and recyclers will jointly form future value creation cycles as part of the of the 'adhesive bonding' sytem along the life cycle of these products. The holistic consideration of adhesively bonded products with regard to ecological improvements along value chains or cycles is made possible by the life cycle assessment (LCA) (see Chapter 4.3.10) as currently the most comprehensive assessment method for environmental impacts.

Adhesive bonding technology and ecodesign are therefore not contradictory if product integrity and material separation are linked in terms of the *controlled longevity* described above. The detaching of an adhesively bonded joint is caused by at least one external trigger that does not occur in the normal use of the joint and therefore does not affect the legally required, verifiably safe use of the product. The targeted separation of materials after product use, which is effective of the circular economy, is a prerequisite for recycling, dismantling and repair.

From an ecological point of view, the 'Design for Environment' (DfE) based on FAIR data concepts (see Chapter 4.3.10) including maintenance, repair or renovation should be used. Here, the PEF (see Chapter 4.3.9) would offer the advantage of incorporating the data sets collected in the life cycle assessments and EPDs. Safety and technical data sheets of adhesives and sealants should be supplemented with information for the product life cycle phase 'end of life'. When assessing the circularity of an adhesively bonded product, the adhesive manufacturer should be involved as an advisor from the beginning, but the responsibility of the decision lies with the adhesive user. With regard to the challenges initiated by the circular economy, intensive communication and close networking of all the above-mentioned stakeholders in the 'adhesive bonding system' are imperative. The solution-oriented technical flexibility, readiness to adapt and innovative ability are undoubtedly available and have already been demonstrated in the past with many new requirements.

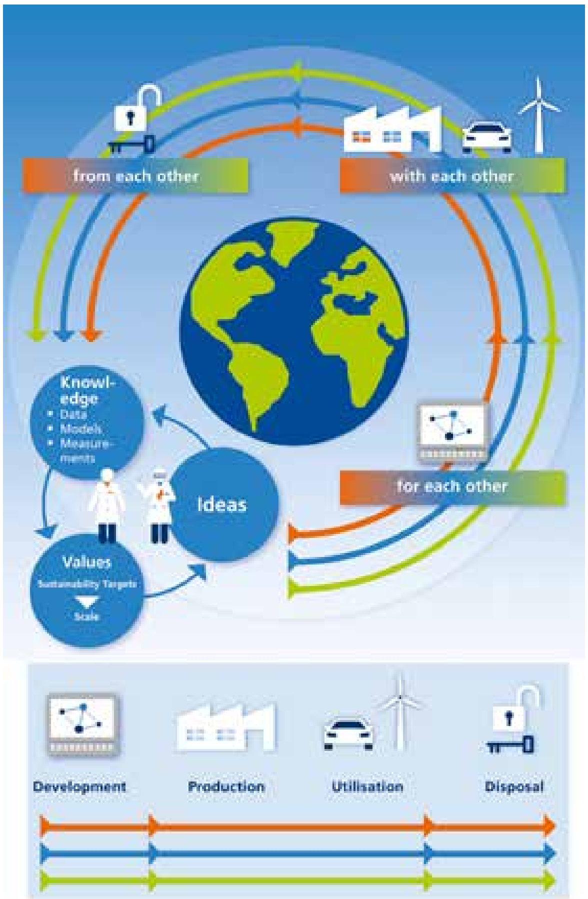


Fig. 45: All key stakeholders in the life cycle use information for holistic design, application and utilisation of adhesively bonded materials.

Disassembly processes of adhesively bonded products for raw material recovery or repair will be key focal points of the development process and product testing in the future. The requirements for disassembly should be listed in the future in requirement profiles for product designs that are compatible with the circular economy and have an impact on the ecological balance sheet. Triggers or constructive measures to improve the economic efficiency of disassembly processes should already be considered in this early phase of product development. In the case of a high number of variants, small dimensions and high quantities, dismantling (shredding), which enables sorting by material type, can be a variant of the disassembly prosess. Components of large dimensions with a high dead weight of sorted components favour the use of mechanical detaching of adhesively bonded joints. Accessibility for disassembly aids must be ensured by design. Force-intensive processes can be mechanised or supported by automatic machines or robots. In this context, however, the use of product-specific disassembly lines is largely untested. Detaching by heat input is a means of dismantling adhesively bonded products, both in combination with mechanical detaching and independently. Disassembly by media exposure is suitable in principle for aqueous, but especially for starch-based adhesive dispersions and is already being used successfully in handicraft (e.g. removal of wallpaper) as well as for mass-produced products (e.g. removal of labels from deposit bottles). Adhesive bonding technology has long been an indispensable factor relevant to eco-balance in the realisation of lightweight products through multi-material construction. In the future, adhesive bonding technology will also be a key to ensuring that products can be repaired and recycled. Accordingly, adhesive bonding does not prevent the disassembly of such products but offers a promising possibility for detaching the joined parts.

Continuous inventions and innovations by the players in the development of raw materials, adhesives and sealants, as well as adhesively bonded products, have already brought dynamic development in the past decades. In particular, numerous new groundbreaking solutions have been developed with regard to the constantly increasing regulatory requirements for certain substances (e.g. from the group of solvents, plasticisers, monomers and biocides). Industrial adhesive and sealant development has verifiably the potential to develop and offer technically suitable solutions within given legislative and ecological boundary conditions, to meet these new requirements with adequate industry-specific solutions and to arrive at optimised products. The ability of adhesive bonding technology to produce safe and

Fig. 46: Adhesive bonding technology - the joining technology of the 21st century

ecologically sound adhesively bonded joints has already been demonstrated many times by the players involved in the fields of research and development, the adhesive industry and adhesive application.

The view ‚from material to safe product' combines the aspects of safety and long-term stability with the requirements of a circular economy in the sense of product sustainability. In this area of conflict, adhesive bonding technology has the necessary technological and ecological performance capacity and thus offers the potential to become the leading joining technology of the 21st century.

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86 Gesetz zur Förderung der Kreislaufwirtschaft und Sicherung der umweltverträglichen Bewirtschaftung von Abfällen (Kreislaufwirtschaftsgesetz - KrWG), § 13, 24, 25

87 Measures to this end are to be taken before a substance, material or product has even become waste. In the case of products that cannot be made superfluous because their functions cannot be abandoned or the same functions cannot be offered with radically different products, they aim to promote product design that makes the respective product resource-efficient, durable, repairable, reusable or updatable and reduces the amount of waste. Examples of this are the reuse of products as well as the extension of their lifespan. In addition, the harmful effects of generated waste on the environment and human health should be reduced. The same applies to the content of harmful substances in materials and products, and also to waste products generated during the product life cycle phases 'development', 'utilisation' and 'end of life'. The regulations phase out waste landfilling. They strengthen the five-step waste hierarchy and oblige EU Member States to take specific measures and focus their waste strategy on prevention and recovery instead of landfilling and incineration.

88 Gesetz zur Förderung der Kreislaufwirtschaft und Sicherung der umweltverträglichen Bewirtschaftung von Abfällen (Kreislaufwirtschaftsgesetz - KrWG), § 3, Absatz 21

89 This is considered to be 'any recovery operation of testing, cleaning or repairing in which products or components of products that have become waste are prepared in such a way that they can be reused without further pre-treatment'.

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91 Gesetz zur Förderung der Kreislaufwirtschaft und Sicherung der umweltverträglichen Bewirtschaftung von Abfällen (Kreislaufwirtschaftsgesetz - KrWG), § 3, Absatz 25

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Notes

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