Industrieverband Klebstoffe e.V.

Adhesives in the Circular Economy

How adhesive technology makes products more durable and conserves resources

Summary

A key element of the EU Commission's Green Deal is the Circular Economy Action Plan (CEAP), which outlines the transition from a linear to a circular economy. Unfortunately, the term "*circular economy*" is often reduced to the topic of *recycling* – both in the public opinion and in political discussion. But the concept of a circular economy, as specified in the Action Plan, is much more comprehensive: it requires a holistic approach to the life cycle of products which also takes their resource efficiency into account. In keeping with this holistic view, both the EU Waste Framework Directive with its five-step waste hierarchy and the EU Commission's categorization system with its nine **R-strategies** provide the guideline for the circular economy and therefore establishes a link between eco-design and the circular economy.

Circular economy encompasses much more than just the single aspect of recycling. The core element of the transformation towards a circular economy are the so-called R-strategies: R0-Refuse, R1-Rethink, R2-Reduce, R3-Reuse, R4-Repair, R5-Refurbish, R6-Remanufacture, R7-Repurpose and R8-Recycle. R-strategies are among the most effective design strategies within the framework of the circular economy. The order of strategies listed above reflects the order of priority. Within the strategy element **Reduce** - lightweight design and construction, the goal is to achieve the same functionality in the long term with significantly less material and is undoubtedly the most effective strategy for material and resource efficiency. The strategy elements **Rethink** and **Reduce/Repair** are aimed at improving the longevity of products through a longer service life or through the repair/ replacement of products. The elements **Reuse**, **Refurbish** and **Remanufacture** are intended to significantly optimize the resource efficiency of products.

Modern products, in the form we know and use them in an industrial, craft or private environment, are hardly conceivable today without the use of adhesive bonding technology. Nevertheless, the advantages of adhesive bonding as a joining technique in the context of the EU's Circular Economy Action Plan are not generally known.

As a matter of fact, adhesive bonding is often the only joining technique capable of reliably combining (high-performance) materials in a way that offers long-term resistance – without impairing their unique and product-relevant properties. This makes adhesive bonding one of the most important technologies and thus an enabler of lightweight construction. Adhesive bonding allows the targeted improvement of the product's longevity and thus constitutes a key technology for circular economy. In fact, it especially tends to the needs of those strategy elements that are higher up in the hierarchy of R-strategies and therefore have a higher priority.

Adhesive bonding often allows products to be easily repaired – a simple method of extending their useful life. From a simple product repair to recycling processes which disassemble the product, there are many possibilities for separating the bonded joints. DIN/TS 54405:2020-12 "Construction adhesives – Guideline for the separation and recycling of adhesives and substrates from bonded joints" provides the user, and especially the product designer, with a guideline for separating bonded joints

with the aim of reusing components and products. In principle, the separated materials of bonded products are also available for reuse – provided there is an appropriate recycling process. This requires, however, that the end-of-life concept of bonded products is already made an integral part of product development – as early as in the product design and planning phase. Raw material and adhesive producers, adhesive users, product manufacturers, end consumers and recyclers – all players and part of the adhesive bonding system, thus shaping the value cycle of bonded products along their respective life cycles.

In the future, the intelligent eco-design of adhesive bonded products will therefore combine the following requirements: safety, technological performance, resource efficiency and long-term durability, including reparability and recyclability, combined with the social requirements of a more sustainable circular economy. In this area of conflicting priorities, adhesive bonding offers the required technological and ecological capabilities, thus underlining its claim to be the leading joining technique of the 21st century.

1 Introduction

Whether in industrial, craft or private environments, adhesive bonding is used in the manufacturing and processing of a wide variety of products. Without the use of adhesive bonding technology, modern products – in the form we know and use them today – are hardly conceivable from a technological, economic and also ecological point of view.

To meet the various requirements that products need to fulfil today, different materials are often combined in a specialised manner, each material with its specific properties. The key task of any type of joining technique is to preserve these essential material properties in the product and during its use, beyond providing a reliable and long-lasting bond. Compared to all other joining techniques, adhesive bonding has the unique ability to join not only the same but also different materials in a way that is both durable and safe, while retaining the product-relevant material properties of the parts to be joined. Additionally, the possibility to integrate supplementary functions into the bonded product that go beyond mere joining. These include, for example, heat and soundproofing, vibration damping, sealing, insulation and conductive bonding. Only the preservation of the material properties makes it possible to meet the increasing product requirements such as weight reduction, miniaturization, functional extension, design optimization and others, and to enable innovative product designs that explicitly meet those requirements.[1] In the 21st century, these designs will necessarily need to be based on multi-material composites using the so-called differential construction method. This is because a single material alone is usually unable to meet the ever-increasing and ever more complex product requirements.[2]

2 Adhesive bonding technology in the context of circular economy

Although the joining of different materials offers numerous benefits, mono-materials are often considered to be more advantageous from an ecological point of view. Joined products are often suspected as a hinderance to implement the Circular Economy Action Plan under the Green Deal. One of the main reasons for this incorrect assessment is the misinterpretation that the necessary separation of the bond is considered too difficult.

Of course, it is technically possible to undo any connection.[3,4] For adhesive bonding, DIN/TS 54405 was published in 2020 as a guideline for separating bonded joints.[5] The technical effort required for this can be optimized if the future separation of bonded joints (e.g., for a recycling process) is already considered in the product design phase.

To determine the recyclability of joined products, it is necessary to take a holistic view of products. The assessment must take the environmental impacts as well as the reduction in the use of natural resources during the entire life cycle of the product into account. These effects must be considered and assessed neither separately from each other nor linearly over the individual life cycle phases of the product. Instead, the entire product life cycle, i.e., the sum of all life cycle phases, must be taken into account.[6,7]

3 Adhesive bonding technology in the context of the EU Waste Framework Directive and resource efficiency

For this holistic approach, the EU Waste Framework Directive with its five-step waste hierarchy provides the guideline and the legislative basis (Closed Substance Cycle Waste Management Act – KrWG) (see fig. 1). The hierarchy comprises the following five steps: 1. **Prevention**[8,9,10], 2. **Preparation for reuse**[11,12], 3. **Recycling**[13,14], 4. **Recovery**[15,16], 5. **Disposal**[17,18]. They are divided into the three overriding hierarchical priorities **prevention of waste**, **recovery of waste** and **disposal of waste**.

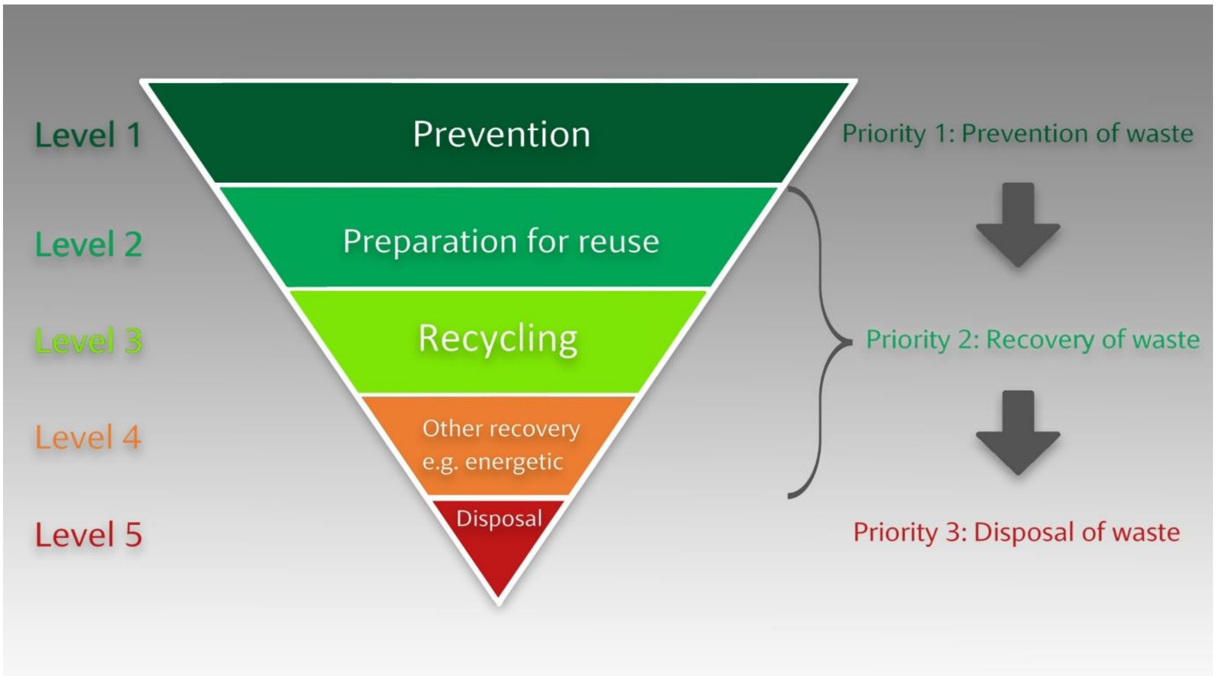

Fig. 1: EU Waste Hierarchy

The five-step waste hierarchy establishes a link between eco-design and the circular economy. The main goal of the circular economy is to enable an increase in resource efficiency by keeping materials and products in the economic cycle for as long as possible. This closed-loop circulation of materials objective is to reduce both the consumption of natural resources and the generation of waste. However, resource efficiency encompasses not only material efficiency but also energy efficiency. As already mentioned, lightweight construction is the key technology for making products energy-efficient during their entire life cycle.

4 Adhesive bonding and R-strategies

4.1 General information on R-strategies

Core elements of the transformation towards a circular economy are the so-called **R-strategies**[19,20,21] **R0-Refuse**, **R1-Rethink**, **R2-Reduce**, **R3-Reuse**, **R4-Repair**, **R5-Refurbish**, **R6-Remanufacture**, **R7-Repurpose** and **R8-Recycle**. They directly or indirectly increase resource efficiency and help reduce negative environmental impacts along the entire value chain, for example by significantly reducing CO_2 emissions. They not only count among the most effective design strategies in the framework of circular economy, but also establish its priorities.

R0-Refuse (make products redundant) is a higher-level strategy and deals with product or use design. The following explanations (chapters 4.2 - 4.5) refer to the strategy elements R1 to R8.

4.2 R1-Rethink

Improving the longevity of products to keep raw materials within the economic cycle is one of the most effective, resource-efficient eco-design strategies. Simply, **R1-Rethink**, is the use of a product over a longer period of time.

Here a few examples: The useful life of bonded products can be extended by the long-term durability of the bonded joints. The service life of cars is constantly increasing.[22] Rail vehicles run for up to 40 years. For an ICE train (German InterCity Express fast train) with an annual mileage of about 500,000 kilometers, this means a total mileage of 20 million kilometers for its projected lifetime. Aircraft fly 30 years or more, but need to be regularly maintained. [23,24]

The leading edges of rotor blades on wind turbines are exposed to high abrasive loads during operation due to the high circumferential speeds of up to 390 km/h. This causes massive damage to the laminate, especially in the area of the leading edge, making repairs necessary after just a few years. [25] The repair must be carried out as quickly as possible in order to minimize not only the turbulences resulting from the damage and thus the deterioration of the aerodynamics, but ultimately also the loss of generated energy. However, especially on offshore turbines, repairs are not only very time- and cost-consuming due to poor accessibility, but also not feasible in some weather conditions. For this reason, a protective layer is bonded to the leading edge already during rotor blade production. This layer guarantees a permanently smooth surface even under extreme offshore conditions, which cannot be achieved with other joining methods. The use of screws or rivets on the rotor blades is out of the question for two reasons: damage to the laminate on application and, for uneven surfaces caused by screw or rivet heads leading to inefficiencies and ultimately reduced energy yield. Furthermore, the connection between the edge protection and the rotor blades are subjected to additional mechanical loads resulting in the loss of long-term durability of the rotor blades. By contrast, the adhesive application described above not only ensures the projected energy yield over the planned service life, but also prevents the release of microplastics into the environment that would otherwise result from laminate damage.

Meanwhile, the durability of adhesively bonded structures has been sufficiently proven. From a holistic point of view, adhesive bonding thus enables building and design principles that feature significantly improved life cycle assessments (LCAs).

Extension of the product life cycle is achieved by improving the products' aging resistance. Optimized methods of surface treatment are, among others, used for this purpose. These improve the adhesion between the surfaces of the parts to be joined and the respective adhesive – an essential factor to ensure long-term resistance.[26,27,28,29]

Additionally, as adhesives are a non-conductive joining material, contact corrosion in metal bonding is avoided and thus the service life of the product extended.

Knowledge of the optimized properties need already to be considered in the eco-design phase.

4.3 R2-Reduce

Lightweight construction, i.e., achieving the same functionality with less material over the long term, is undoubtedly one of the most effective eco-design strategies for avoiding waste and saving energy during the product's service life.[30] Due to its potential to maintain the material properties, adhesive bonding must be considered one of the most important joining techniques for lightweight construction. It is also a key technology for the circular economy:

- Most, if not all materials can be joined by means of adhesive bonding. Especially modern high-performance materials used in lightweight construction.
- Adhesive bonding makes an important contribution to structural lightweight construction by enabling purposeful structures, e.g., reinforcing ribs, consequently saving material.
- Adhesive bonding provides a durable and reliable bond of different materials used in components to fulfill the specific requirements. This makes it a material-saving technique in multi-material lightweight construction.

In the vehicle construction sector, lightweight design is critical. Adhesive bonding enables, among others, structural window bonding, bonding of reinforcement profiles, bonding inside the car body, and the bonding of thinner metal sheets in order to realize material savings in production. This, in turn, leads to significant energy savings in the use phase. The use of thinner metal sheets is only achieved by adhesive bonding: the surface-to-surface bonding of the components ensures the comparatively uniform transmission of force between the joining partners. This effect is further enhanced using modern high-strength and ultra-high strength steels. Adhesive bonding is the only low-temperature technique capable of joining such materials in a way that is appropriate to their material properties.[31],[32] Thanks to adhesive bonding, lightweight materials are also used, in rail vehicle construction. Adhesive bonding reduces the energy consumption and thus the specific CO_2-equivalent emissions per passenger or ton kilometer in the ecologically so important use phase of the product life cycle.[33]

Apart from lightweight construction, miniaturization is a highly effective way of saving resources. Simply put: the smaller the product, the lower the material consumption. Adhesives are indispensable in miniaturization (e.g., in electronics manufacturing), because there is a need for ever smaller dimensions to satisfy continuously rising functional requirements. For this area of application, special adhesives have been developed that are ideally suited to bond a wide variety of materials in the smallest of spaces – quickly, reliably and with long-term stability.[34,35] If traditional soldering (the joining technique used in the past) were used for these small dimensions, there would be a risk of damaging the components by the high temperatures of the molten solder. Adhesive bonding in miniaturization allows, however, much more than just the material-specific, high-precision joining of miniature components.[36] Today's sophisticated adhesives fix coils in place, seal housings and can also be used as chip encapsulants. Moreover, adhesives shorten production processes due to extremely fast curing times and can also be reliably dosed in quantities of a few tenths of a milligram. Additionally, adhesives are also used in high-reliability chip encapsulation. Only with the help of adhesives as a suitable potting compound can the fine structures on chips and wires be protected from mechanical stresses (vibrations, temperature fluctuations) and environmental influences (moisture, corrosion) in a way capable of extending their service life. With other joining techniques, this can only be achieved with significantly greater effort or not at all.[37,38]

4.4 R3-Reuse, R4-Repair, R5-Refurbish, R6-Remanufacture

Adhesive-based product design that makes use of the so-called differential construction method allows the bonding of several components that can also be de-bonded. It offers the additional feature of reparability. Adhesive bonding is already the most frequently used repair method, even for previously unbonded products. Thanks to repair bonding, products have a longer useful life, thus keeping the raw materials in the cycle for longer. In many cases, adhesive bonding and repair provide an optimum system. Without adhesive bonding, many repairs in the private, craft and industrial sector would be unthinkable. A common example, also in the private sector, is the repair bonding of furniture (parts) that becomes necessary after long and intensive use.

In the case of safety-relevant components, adhesive bonding is implemented in accordance with detailed repair instructions. This involves, in particular, fiber-reinforced composites that are used in aircraft construction or with wind turbines. In the event of damage, e.g., due to rockfall or hail, only part of the material is cut out and a cut-to-size repair patch glued in place. After repair, the components can withstand the same loads and stresses as before the damage. The same has been true for more than one hundred years in the field of structural timber engineering, where damage can also be repaired through bonding.

in order to repair damaged parts, the disassembly of the product giving access to the parts must be industrially feasible. Disassembly processes need to be a key priority when developing and testing new products. These contribute to extending the product life cycle while at the same time helping to recover the materials that can no longer be used. Whether microelectronics or large structures in the building industry: Future product designs need to be compatible with the circular economy and will therefore have to include the aspect of disassembly.

For several decades now, the windshields of cars and other means of transportation have been glued in place, and subsequently also the other window parts including glass panes. The removal of these panes for the purpose of repair or replacement has already been considered in the design phase and is done by cutting the elastic, thick adhesive joint out with a cutting wire. The remaining adhesive is removed, usually with a vibrating spatula, and finally the new pane can be glued in place. The defective pane can now be included in the glass recycling process. This repair is carried out in all car repair shops according to specified procedures. The same applies to the repair of minor damage to windshields (e.g., caused by stone chips). Light-curing adhesives have been specially developed for this purpose.

The display screens of mobile phones can usually be replaced with the help of repair kits. Repair instructions are available on the internet for every type of phone so that skilled users can carry out many repairs on their own. This also includes loosening the respective adhesive bond.

In principle, the examples given above can be transferred to almost all other areas of adhesive applications such as shipbuilding, the optical and acoustics industry, medicine, medical technology, dental health, household appliances, the footwear and sporting goods industry and many more.

The technology of adhesive bonding offers a wide range of possibilities for debonding the joints. DIN/TS 54405 provides the user with a guideline for separating bonded joints. In the future, adhesive bonding will therefore be a key technology for ensuring that both the products and the materials used for their manufacture are reparable and reusable.[5]

4.5 R8-Recycle

The intelligent eco-design of products ensures high material and energy efficiency as well as a long product life, while at the same time reducing the amount of waste. But even the most innovative design and the best optimized manufacture process combined with the use of products over time cannot prevent the products or product components from becoming waste in the long term – even with the longest possible and most resource-efficient life cycle. After a certain time of service, the cost and effort involved in strategy elements R3 to R6 becomes so high that their realization makes no sense – neither economically nor ecologically – due to the additional consumption of material and energy.

The task now is to recover as many of the resources contained in the products as possible. The hierarchy is the following:

- Material recovery (material recycling)
- Energy recovery (incineration)
- Disposal (landfill)

In material recycling, there is a distinction made between mechanical and chemical recycling.

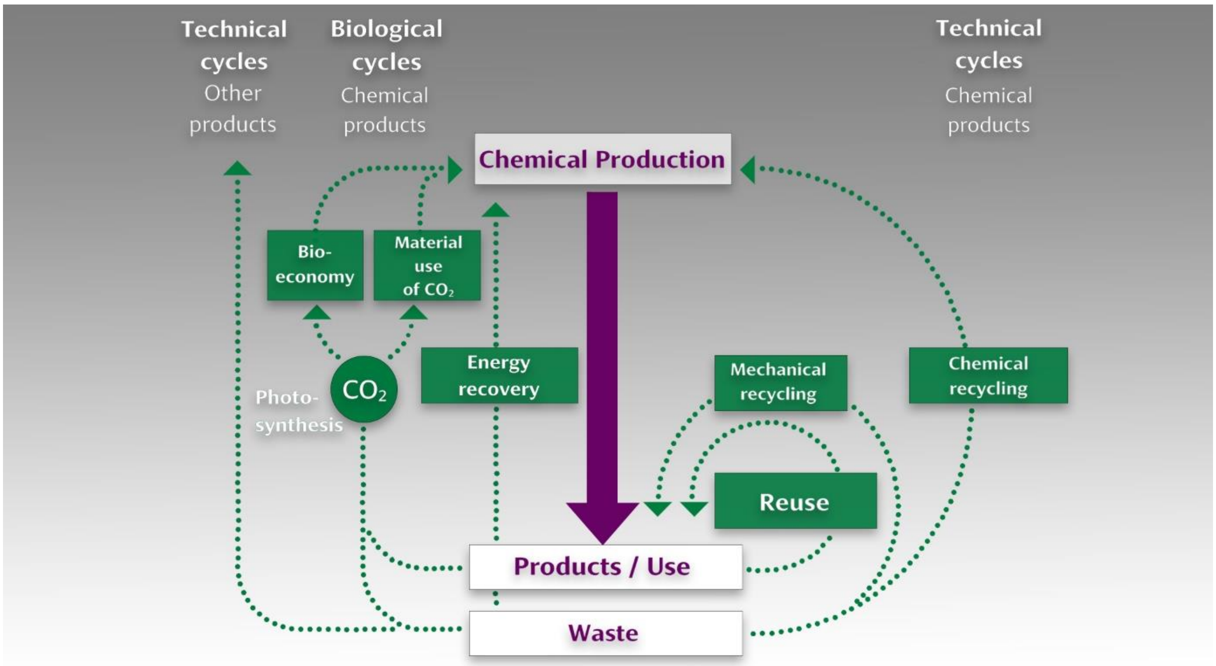

Fig. 2: Circular economy and recycling

For mechanical recycling (see fig. 2), the target materials, i.e., the materials that are to be returned to the cycle and which there are established recycling processes, are separated as carefully as possible from all other materials in the product. Separating the target materials from the non-recyclable materials should ideally be executed in the most ecologically sound manner throughout the entire process of material recovery, including the procedures of collection, sorting and actual recycling. As a rule, this works particularly well if the separation process is started as early as possible, e.g., by the separate collection of waste. Separating the materials contained in a product is now a key task in all recycling processes because, as stated above, almost all products of daily life consist of a combination of very different materials. Likewise, a wide variety of joining techniques are used today to join the materials, with adhesive bonding becoming increasingly important due to the advantages described in the introduction. But no matter which joining technique is used: Already when designing the joint, its separation at the end of the product life cycle must be considered. This requires precise knowledge of the recycling process for the designed products since process-specific separation and sorting procedures have been integrated into each recycling process.

If the requirements are known, appropriate solutions can be developed for all joining techniques – of course also for adhesive bonding. The possible separation processes for bonded joints are explained, for example, in DIN/TS 54405.[5]

One example that shows how the desired target materials can be recovered from bonded products on an industrial scale today is the recycling of a wide variety of paper products. These are subjected to mechanical treatment in an aqueous environment so that the cellulose fibers – i.e., the target material – enter the aqueous phase. Hydrophobic adhesive coatings are then separated mechanically from the cellulose suspension by screening.

The recycling of metal and glass products is conducted at sufficiently high temperatures or, to put it more precisely, at the melting temperature of the target material. Separation of the target material from impurities achievable with the help of technologies that are already used in the production of these materials from primary raw materials. To keep the yield as high as possible, sorting is commonly carried out before the recycling process proper so that as little foreign material as possible is introduced into the actual high-energy recycling process. Adhesive bonded structures are separated; residues from adhesive applications do not normally interfere with the recycling process due to the high temperatures involved.

In chemical recycling, various techniques are used to recover the hydrocarbons present in the materials. This is achieved by supplying energy in the form of high temperatures and pressures. Chemical recycling processes range from the solvolysis of homogeneous, unmixed waste over the pyrolysis of defined waste mixtures to the gasification of wide assortments of waste. The question of whether joined products – consisting, for example, of different plastic materials – need to be separated beforehand can only be answered if the specific chemical recycling process is known. Here, too, adhering residues of adhesive are not expected to cause problems due to the small quantities and their chemical composition.

Additionally, the residues of adhesive applications, obtained from sorting and recycling processes, can be recovered to a certain extent. In many recycling plants, their energy content is recovered by incineration. Due to the small quantities and heterogeneity of the substances used, material recycling of adhesive residues does not make sense – neither economically nor from an ecological point of view. However, most adhesives can be incinerated very effectively, so that the last step in waste recycling, i.e., landfill, is not relevant for adhesive applications.

5 Outlook: Controlled longevity

The technology of adhesive bonding has the potential to respond to new ecological requirements with technical innovations. In the future, the value chains of adhesively bonded products will need to be considered holistically and coherently over the life cycle phases of **manufacture**, **use** and **disposal**. This involves the end-of-life concept of adhesively bonded products becoming an integral part of product development as early as in the design and product planning phase. To achieve this goal, special attention must be paid to the strategies R1 to R6 (**Rethink**, **Reduce**, **Reuse**, **Repair**, **Refurbish** and **Remanufacture**). Raw material and adhesive producers, adhesive users, product manufacturers, end consumers and recyclers become an integral part of the adhesive bonding system along the value cycles of bonded products.

To ensure this holistic approach, the future development of adhesive bonded products must be carried out with special attention to waste hierarchy levels 1 (prevention of waste) and 2 (preparation for the reuse of waste, see fig. 1) in keeping with the goal of a controlled longevity. In this way, it is possible to link the control of product integrity during the life cycle phase **use** (which should be as long as possible) with the targeted separation of materials in the life cycle phase **disposal**. The separation of a bonded joint is then caused by at least one external trigger that does not occur during normal use of the bonded joint and therefore does not affect the safe use of the bonded product.

The controlled debonding of bonded joints is necessary to enable not only the disassembly and rebuilding but also the repair of structures and products. Controlled debonding thus helps to extend the useful life of products in keeping with strategy elements R2 to R6. However, both the user and the recycler of a bonded product must be aware of the disassembly option offered by the manufacturer; the same applies to repair processes. For example, the repair of windshields in means of transportation has long been state of the art. And the repair of mobile phone display screens can meanwhile also be completed by skilled users. The underlying separation mechanisms are transferable to other areas of adhesive bonding.

In the future, chemical recycling will be a useful and necessary complement to mechanical (material) recycling (see fig. 2). As a preferred alternative to a purely energy-based recovery, it opens up a future-oriented perspective, especially for bonded plastic products that may still have adhering paint or adhesive residues.

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