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Adhesive bonding technology in the area of tension between circular economy and life cycle assessment – A study by Fraunhofer IFAM
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The challenge for adhesive bonding technology: The European Green Deal

A new action plan for the circular economy
- Biodiversity for 2030
- TBD with the Commissioner-designate

Preserving Europe’s natural heritage
- Sustainable transport
- Achievement of climate neutrality
- Clean, reliable and affordable energy

A Europe without pollution
- From the farm to the fork
- The transformation of agriculture and rural areas

Towards a modernised and simplified CAP
- "Farm-to-fork" strategy
- Vision for integrated rural areas
- Africa-Europe Alliance

Financing the transition
- European Investment Bank/Bank as European Climate Bank
- Investment plan for a sustainable Europe
- Green funding strategy
- Integration of climate change and sustainability into the MFF

Leave no one behind (just transition)
- Instrument for Just Transition, including the Just Transition Fund
- Mainstreaming of transition in the MFF

Proposal on CAP reform

Source: Fraunhofer IFAM
The circular economy action plan

Challenge for adhesive bonding technology:
European Green Deal and circular economy
The circular economy action plan

Central value chains:

- Electronics and ICT
- Batteries and vehicles
- Packaging
- Plastics
- Textiles
- Construction and buildings
- Food, water and nutrients

Energy efficiency → Reduction of greenhouse gas emissions ← Material/resource efficiency

Resource conservation

Climate neutrality
The circular economy action plan: examples of references to adhesive bonding technology

Generally speaking, **all** joining technologies are affected.

- **Reduce**
- **Replace**
- **Reuse**
- **Return**
- **Renew**

Low material and energy consumption: "Controlled longevity"

Renewable raw materials: Raw materials from waste

De-joining: Sorting by type

Source: Industrieverband Klebstoffe e.V.
All joining technologies are affected

- **Material fit joints**
  - Welded joints
  - Adhesively bonded joints
  - Soldered joint

- **Positive fit joints**
  - Clinched joint
  - Seamed joint
  - Bolted joint
  - Hook-and-loop

- **Force fit joints**
  - Elastic fit: Screwed and riveted joints
  - Field fit: Magnestism/Gravety
  - Frictional fit: Press-fit joints

- **Combined techniques (Hybrid joints)**
  - Bonding and spot-welding
  - Bonding and clinching
  - Bonding and folding
  - Bonding and reveting

Source: Fraunhofer IFAM
Increasing product requirements - the role of materials

• The requirements for products are constantly changing.
• Increasing product requirements are implemented through materials.

Materials are at the centre of meeting more complex requirements.
The number of materials to meet these requirements will continue to increase.
One of the central tasks of joining technology is to maintain the properties of the material in the joint.
New product requirements - the role of joining technology "Adhesive Bonding"

Adhesive bonding technology makes it possible to join all materials securely and with long-term durability while retaining their properties, thereby achieving the desired product characteristics and integrating additional functions into the adhesively bonded product that go beyond mere joining.

**Adhesive bonding technology** has the potential to become the No. 1 joining technology of the 21st century!
Facts and figures (as of 2018)

- 1,137,000 tonnes per year of adhesively bonding and sealing materials
- 1,055 m² adhesive tapes
- Turnover: approx. 4 billion €
- Indirectly generated value added: approx. 450 billion €
Adhesives under general suspicion

- Intensive use of adhesive making any disassembly step complex and dangerous;

removable, fastening systems in the assembly of priority parts. On the other hand, the worst scenario for reparability sees the use of non-removable fastening systems such as glues.

However, there is an apparent trend towards the increased use of adhesives, glues and of glass parts, which make more difficult to disassemble parts (Greenpeace 2017). According to some commonly available tools. The appliance shall be designed so that no gluing or welding fastening technique is encountered for any of the dismantling operations leading to the removal of these components. Within two weeks of a request made by

From 1 January 2019, manufacturers shall ensure that welding or firm gluing is not used as joining or sealing technique for the following types of components, when

No fastening technique using welding or gluing, other than through the use of adhesive tapes, is encountered in the sequence of dismantling operations leading to the extraction of the targeted

schwierig wird. Vor allem die Akkus sind immer schwerer zu wechseln, weil die Hersteller sie im Inneren der Geräte immer fester verkleben. Hier besteht auch die Gefahr, sie bei der Reparatur zu beschädigen - so dass die Akkus Feuer fangen.

den können. Es müsse daher Schluss sein mit der weit verbreiteten „Klebeorgie“, so ihre Überzeugung. Nötig sei eine neue Architek-
Non-detachable joining technologies - a possible misunderstanding, also for the circular economy

Materials and joining technologies are equally necessary for functional and safety-compliant product design.

detachable → non-detachable
in the common and technical interpretation of terms
Non-detachable joining technologies - a possible misunderstanding, also for the circular economy

**Detachable:**

"Detachable" joining must "hold" in use in the same way as "non-detachable" or "conditionally detachable" joining, i.e. be permanent, strong and secure. They are not allowed to disconnect uncontrollably, but should be able to be loosened after use.

A "detachable" connection in the technical sense allows the joining parts to be separated without damaging the joining parts and the joining element. The same joining elements and the same parts to be joined can basically be reused to restore the connection.

**Non-detachable:**

Commonly, "non-detachable" is understood to mean that the joining "holds" and cannot be detached during use. But, according to conventional understanding, the joint cannot be loosened even after use! Once joined - joined forever and ever!

However, a "non-detachable" joining can be detached in a technical sense. As a rule, however, only if the joining parts or joining elements and/or the joined components are destroyed or damaged in the process. Then the same joining part and/or the same joining element cannot be used to restore the connection.

However, "disconnecting", i.e. "loosening" a "non-detachable" connection for recycling purposes by damaging one or both connecting parts is possible.
Challenges of adhesive bonding technology in connection with "circular economy" and "eco-design"
Challenges of adhesive bonding technology in connection with "circular economy" and "eco-design"

Holistic view of adhesive bonding technology:

Adhesive bonding technology in the area of conflict between circular economy and eco-balance effectiveness: both must be considered!
Energy consumption and material efficiency/resource efficiency: the meaning of the terms

Material efficiency = \( \frac{\text{Bonus goods Product output} - \text{Onus Material input}}{\text{Effort goods Material input} + \text{Onus Product output}} \)

Energy???

The term "material efficiency" can be transformed into the term "resource efficiency".
Energy consumption and material efficiency/resource efficiency: the meaning of the terms

- **Ecodesign Directive**: Separation between material, resource and energy efficiency.
- **BUT**: Nomination of “energy”, “material” and “other resources”.

  Consideration of both "material" and "energy" as "resources".

Source: Art. 11 Ökodesign-RL. Erwägungsgrund Nr. 10 und 13 Ökodesign-RL; Franz Reimer / Susanne Tölle, Ressourceneffizienz als Problembezug, ZUR 2013, S. 589 – 598
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**Resource efficiency** = \[
\text{Bonus goods Product output} - (\text{Onus resource input - recycling share})
\]

\[
\frac{\text{Effort goods Material input} + \text{Onus Product output}}{\text{Effort goods Material input}: \text{raw materials, (scarce) resources}}
\]

undesirable materials, waste, emissions, energy consumption in the product life cycle phase

circular economy efficient material share minus energy input for recycling
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Resource efficiency_{\text{product life cycle phase}} = \frac{\text{Bonus goods Product output} - (\text{Onus resource input} - \text{recycling share})}{\text{Effort goods Material input + Onus Product output}}

- **Products received** (incl. additive functions)
- undesirable materials, waste, emissions, energy consumption in the product life cycle phase
- circular economy efficient material share minus energy input for recycling

Effort Goods Material input:
raw materials, (scarce) resources

Resource efficiency also takes into account the factor „energy“.
Resource efficiency is then considered for each of the following product cycle stages:

- Production
- Utilization
- Disposal ("end of life")

As a first rough qualitative estimate, the summary of the individual phases of the product life cycle, i.e. the consideration of the resource efficiency of all product life cycle stages together, can serve as a fundamental qualitative decision-making basis for the (further) development of an (adhesively bonded) product. For this purpose, the entirety of the product life cycle - and not the individual phases of the product life cycle in isolation - must be considered and evaluated. One instrument for holistic product life cycle consideration and assessment is the life cycle assessment (LCA).

Holistic view → production + utilization + disposal ("end of life")
Energy consumption and material efficiency/resource efficiency: the importance of the holistic approach (Life cycle assessment - LCA)

Life cycle assessment (LCA):
- Early ecological assessment of adhesively bonded products possible
- Awareness of holistic considerations of adhesively bonded products, which has long been anchored at the technical level
  Projection onto the ecological level
- DIN EN ISO 14040 → comprehensive, no product-specific rules as the basis for concrete life cycle-based modelling
- Method → feasible, accurate, comprehensible, meaningful, robust
- Data → Quality, accuracy, timeliness, availability
  → FAIR: findable, accessible, interoperable, reuseable
- Footprint-initiatives (EU) → mostly only one environmental impact
- Harmonisation approach (EU) → Product Environmental Footprint – PEF → comparative statements
- Environmental Product Declarations – EPDs → Focus adhesive/direct product comparison
- Adhesive → not the focus Environmental considerations of adhesively bonded products
  → low adhesive content
  → Focus on the adhesively bonded product
- Adhesive data sheets → additional information on the ordered adhesive failure mechanism
- In future → Even stronger networking of adhesive manufacturers/adhesive users/recyclers
- R&D and adhesive industry → Potential for the development of appropriate circular economy and life cycle assessment solutions
- Performance of adhesive bonding technology and adhesive bonding development → already proven today
Adhesive bonding technology and resource efficiency

• Adhesive bonding is a key technology for lightweight construction.
• Adhesive bonding can increase the longevity of products. Examples: Food packaging, vehicle
  • The development of alternative energy sources is inconceivable without adhesively bonding.
• Electromobility is inconceivable without adhesive bonding.

• Adhesive bonding is an integral part of the energy transition.

Through adhesive bonding, the overall ecological balance of adhesively bonded products
is generally positive.
Energy consumption and material efficiency/resource efficiency: the importance of materials
Energy consumption and material efficiency/resource efficiency: the importance of materials

Specific CO₂ equivalent emissions per passenger or tonne-kilometre of rail transport

Source: Studie Öko-Institut e.V., Treibhausgasemissionen durch die Schieneninfrastruktur und Schienenfahrzeuge in Deutschland (FKZ 363 01 244), 2013
Energy consumption and material efficiency/resource efficiency: the importance of materials

The product properties are largely determined by the material properties.

RegioShuttle - lightweight construction made of steel and GFRP

Source: Stadler Rail AG, Bussnang, Switzerland
Energy consumption and material efficiency/resource efficiency: the importance of joining technology

Task of joining technology: Enabling optimum use of material properties

Lightweight construction in rail vehicle construction

Source: Fotolia
energy consumption and material efficiency/resource efficiency: the importance of joining technology „Adhesive Bonding“

RegioShuttle - Using GFRP outdoors: lightweight construction through adhesive bonding technology
Energy consumption and material efficiency/resource efficiency: the importance of the holistic approach (Life cycle assessment - LCA)

Resource efficiency_{product life cycle phase} = Bonus goods Product output - (Onus resource input - recycling share)

Effort goods Material input + Onus Product output

Products received (incl. additive functions) - undesired materials, waste, emissions, energy consumption in the product life cycle phase - circular economy efficient material share minus energy input for recycling

Effort Goods Material input: raw materials, (scarce) resources

waste, emissions
Strategies for adhesive bonding technology to support circular economy and eco-design/eco-balance effectiveness

The adhesive bonding technology supports the circular economy and eco-design/eco-balance effectiveness.

Holistic life cycle consideration incl. "end of life" scenarios: "controlled longevity".

Realisation: „controlled longevity“

In terms of the "controlled longevity" of adhesively bonded products, cohesive adhesive failure is favoured for their separation.

Source: Fraunhofer IFAM
Strategies for adhesive bonding technology to support circular economy and eco-design/eco-balance effectiveness

Adhesive bonding technology does not contradict the circular economy and eco-design/eco-balance effectiveness:

- For reasons of product safety, technical adhesively bonded joints are designed for high resistance, durability for reasons of product safety.
- Disassembly necessary for the circular economy → Separation of different materials and their reuse at the highest possible value-added stage

**Target:**
Conceptual design of adhesively bonded products in the direction of „controlled longevity“:

Control of product integrity + Control of material separation

(utility) + (end of life)

Product safety + Circular economy
Strategies for adhesive bonding technology to support circular economy and eco-design/eco-balance effectiveness

- Dismantling strategies should be based on local triggers.
- Users, repairers and recyclers must be informed about the dismantling option provided by the adhesive manufacturer (recycling, repair).

Source: Fraunhofer IFAM
Detachable adhesively bonded joints

Disconnection of an adhesively bonded joint via a trigger that does not occur in the product life cycle phase "utilisation".

Universal but non-specific triggers:
- mechanical load
- heat/cold
- water
- solvents

Adhesives with specific triggers:
- light of specific wavelength, if applicable
- Applied electrical voltage
- Heating with microwaves/high frequency fields
- photodegradable primer layer

Source: Fraunhofer IFAM
Detachable adhesively bonded joints

Detaching adhesively bonded joints with the main function of load transfer
• E-FAST method
• Electrochemical separation
• Separation with superheated steam

Detaching adhesively bonded joints without the main function of load transfer
• Large stirring reactors
• Water-soluble / swellable adhesives (if necessary + enzymes, encapsulated active substances)

Need for research!
Non-detachable adhesively bonded joints

State of the art: Even non-detachable adhesively bonded joints can be separated.
- Mixture of various end-of-life products → Shredding with subsequent separation of the fragments
  - Low quality of the recyclate
- High number of similar products → Disassembly line for automated disassembly and sorting by type
  - Extreme solution, only useful for a few products

Targeted debonding is a prerequisite for repair, deconstruction and recycling.
Disassembly processes

Disconnecting the adhesively bonded joint does not always have to make sense:

Exclusion criteria debonding:

- High resource consumption
- Use of hazardous components in the adhesive or in the dissolving process
- Safety reduction of the adhesively bonded joint

Recycling of the adhesive itself has no ecological impact: the focus is on recovering the adhesively bonded parts

Source: Fraunhofer IFAM
Disassembly processes

**Disassembly enabler:** Design measures and disassembly aids are crucial

<table>
<thead>
<tr>
<th>Disassembly option</th>
<th>Type of components</th>
<th>Comment</th>
</tr>
</thead>
</table>
| Chop up           | • Wide range of different component geometries  
|                   | • Small component dimensions  
|                   | • High quantities         | Suitable for series production, in use |
| Mechanical detachment of the adhesively bonded joint | • Large component dimensions  
|                   | • High dead weight of the single-material components | Need for research: automation in large-scale production |
| Detaching by heat input |                | Stand-alone disassembly tool, but can also be combined with mechanical loosening |
| Disassembly through media influence |                | Can also be combined with mechanical detachment |

Adhesive bonding provides a starting point for detaching the material bond.

Independent of this, a distinction must be made between **recyclability** (in the sense of the basic possibility of recycling) and **recycling implementation** (in the sense of actual recycling).
Product design that is compatible with the circular economy

Disassembly-friendly design

Consideration of the product life cycle phase "End of Life" (disposal) in development

- Product safety + effectiveness of the circular economy →
  In-depth understanding of the load cases at hand and how to handle them appropriately with adhesives (e.g. accessibility of the adhesively bonded joint for splitting reagents/radiation).
- Constructive elements to control disassembly
- Targeted introduction of peeling forces in disassembly (avoid peeling forces in the product life cycle phase "utilisation")

Disassembly triggers are integrated in the product design suitable for disassembly, but are definitely ineffective during the product life cycle phase "utilisation".
Product design that is compatible with the circular economy

Product design

Adhesive bonding technology can be seen as an "enabler" of lightweight construction:

• Adhesive bonding technology for targeted structures, e.g. adhesively bonded stiffening elements such as ribs

• Multi-material construction through adhesive bonding technology of different lightweight materials

• Differential construction → Repair capability → Design adaptations

Individualisation of products according to customer requirements can be carried out without setting up a completely new product line in the existing process chain
Product design that is compatible with the circular economy

Design and adhesive application
- Avoiding "over-engineering" by defining realistic requirement profiles (specifications).
- Optimising the ageing resistance.
- Using the application technology, which is matched to the adhesive and product requirements, to avoid oversizing of adhesively bonded surfaces and joints.

Graded adhesively bonded joints
- For graded adhesively bonded joints: Breakage of the adhesively bonded joint systematically on one side.
- Already implemented for double-sided adhesive tapes with different adhesion on both sides.
- Transfer to liquid adhesives → Need for research
Adhesive bonding technology and repair

Adhesive bonding - probably the most frequently used repair method

Adhesive bonding is more than the question: How do I get the adhesively bonded parts separated again for recycling?

Design of adhesives in the non-industrial sector (private, handicraft, industry):

- Robust application
- Low susceptibility to errors
- Safety requirements mostly low

Adhesive bonding technology for repairing safety-relevant components:

- Elaborated repair instructions (e.g. aircraft construction, wind energy)
Adhesive bonding technology and recycling

- The detachability of an adhesively bonded joint must already be taken into account in the product design.

Distinction for recycling between:

- **purely adhesively bonded joints**
  - The more similar the products to be recycled, the more targeted the recycling.
  - Debonding usually: combination of local heat and mechanical loading

- **Hybrid joints**
  - Additional joining technologies, e.g. as assembly aid, crack stopper.
  - But: Preventing targeted disassembly

In the future, research is needed into how adhesive bonding technology can dispense with supporting assembly aids or similar.
Digitalisation in the effectiveness of the circular economy in adhesive bonding technology – Digital tools and data

Digital tools

- Assistance to overcome existing information deficits for adhesive bonding technology
- Simulation to reduce the experimental effort through validated models
- Long-term monitoring of adhesively bonded joints using Structural Health Monitoring - SHM
  - SHM: continuous or periodic method for monitoring structures (Source: DGZfP)
  - Permanent integration of sensors into the structure to be monitored
- Digital Twin
  - Storage of e.g. information on disassembly and recycling
  - Prerequisite for the development of suitable models: understanding of complex interrelationships between adhesion and cohesion, joining part properties, moisture and mechanical load, permanent load,…
Digitalisation in the effectiveness of the circular economy in adhesive bonding technology – Digital tools and data

Data

- Linking the development of adhesively bonded products that are compatible with the circular economy with digitalisation (data)

  • Development of a common language for data exchange
  • Common language: technical as well as regulatory → Standardised ontologies

  ![Diagram](image)

  **Target:**
  Provision of reliable, comparable and verifiable information for (adhesively bonded) products

  **„Translator“:**
  impartial communication of material-, regulation- and data-based information between stakeholders in the sustainable development process
Integration of upstream and downstream manufacturing steps in process chain modelling and optimisation

- In the future, digital tools as well as material- and process-related data will allow a holistic view and long-term stability of adhesion to achieve maximum identification in terms of material, cost and energy efficiency.

- Future sustainable developments of adhesively bonded products and adhesive bonding technology production will include ageing and separating modelling.
Digitalisation in the effectiveness of the circular economy in adhesive bonding technology – Digital tools and data

Outlook with regard to digitalisation in the effectiveness of the circular economy in adhesive bonding technology

• In the 21st century, materials will become visible via their material presence or spatial arrangement, additionally in joining with their (meta-) data with the inclusion of "end of life" scenarios.
• In the future, materials will be inextricably linked to data across all product lifecycle phases.

economic value of these connections > material value

Source: Fraunhofer IFAM
The potential of adhesive bonding technology as the joining technology of the 21st century.
Summary:
Adhesively bonding is part of the solution to eco-design and circular economy

The use of adhesive bonding supports and enables the implementation of a comprehensive circular economy and thus has positive effects on the life cycle assessment.

In the future, adhesively bonded products will have to be considered across all phases of their product life cycle.

Adhesive bonding technology and eco-design do not contradict each other.

Adhesive bonding technology and repair, adhesive bonding technology and recycling and also adhesive bonding technology and resource efficiency do not represent a contradiction either.

Digital systems support decisions in the use of adhesive bonding technology.

The "adhesive" itself can also contribute to resource efficiency.

Adhesive bonding technology supports the circular economy and eco-design.
Download free of charge

German: https://www.ifam.fraunhofer.de/de/Presse/Kreislaufwirtschaft-Klebtechnik.html