Thermal and Joule effect debonding techniques: Evaluation of mechanical strength and LCA analysis of bonded joints

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Abstract. Bonded joints play a crucial role in various engineering applications, particularly in aerospace, automotive, and structural industries, where they provide lightweight and high-strength connections. However, their permanent nature poses challenges when disassembly is required for maintenance, repair, or recycling. Efficient debonding techniques are essential to enable disassembly while minimizing damage to the substrates, preserving material integrity, and reducing environmental impact. Among the available methods, thermal debonding and Joule heating represent promising approaches, as they allow for localized heating, weakening the adhesive without excessive degradation of the substrate. These techniques leverage controlled temperature increases to reduce the adhesive's strength, facilitating joint separation. The effectiveness of these methods depends on several factors, including adhesive type, substrate material, and process parameters such as temperature, heating rate, and exposure duration. A comprehensive evaluation of these debonding strategies is essential to identify those that ensure structural integrity, ease of disassembly, and sustainability. This study focuses on thermal and Joule heating debonding techniques applied to aluminium substrates. The selected methods demonstrated a reduction of at least 75% in tensile shear stress at failure, enabling easy hand disassembly. Furthermore, the environmental sustainability of these solutions was assessed through a Life Cycle Assessment (LCA) to identify the techniques with the lowest environmental impact.

Introduction

The responsible use of natural resources and environmental protection have become imperative across the Western world. In particular, the European Union has placed environmental sustainability at the core of its policies through the 2019 "Green Deal," which addresses various aspects such as climate change, resource management, pollution, and circular economy principles [1], [2]. The EU's environmental policy is based on four fundamental principles: precaution (avoiding potentially harmful actions in the absence of scientific certainty), prevention (anticipating and mitigating environmental damage), pollution control at the source (direct intervention on the problem), and the "polluter pays" principle (assigning remediation costs to those responsible) [3]. Consequently, the recycling and reuse of materials, particularly those that are poor in nature, have become a priority for many nations, especially those lacking significant raw material reserves or recognizing that recycling generally leads to both economic savings and a reduction in environmental pollution [4].

This philosophy is also applicable to adhesive bonding, where research efforts continue to focus on recyclability [5], [6]. Although adhesive bonding provides an effective solution for joining materials, it presents challenges when disassembly is required during a product's lifecycle. As the industrial sector shifts away from the extractive model of "take, make, dispose" -which results in a continuous loss of valuable materials due to the abundance and low cost of natural resources-toward embracing circular economy principles, it becomes crucial to integrate debonding techniques at the design stage. These techniques enable the transformation of waste generated in one phase of a product's lifecycle into resources for another, thus promoting sustainability. To enhance the product lifecycle, greater attention must be given to debonding technologies, tools, and techniques during the design phase. The primary goal of debonding is to recover as many components as possible from an assembly without causing damage to the parts, the environment, or personnel, while minimizing or eliminating adhesive residues from surfaces and avoiding the use of excessively expensive tools or technologies [7].

Debonding techniques are classified based on the applied energy and the detachment mechanism. One of the most employed methods is mechanical separation, which exploits critical stresses such as peel stress and cleavage. However, this approach is generally ineffective for structural adhesives, as it tends to damage the substrates and leaves adhesive residues [8]. Conversely, thermal debonding utilizes temperature increases to reduce adhesive strength, with subsequent removal of residues through mechanical abrasion [9]. A hybrid variant is thermo-mechanical debonding, which combines heat and applied load and requires an understanding of the mechanical properties of materials as a function of temperature. An example of this is thermal-peel debonding, where the adhesive is heated beyond its glass transition temperature, making it more ductile and facilitating its removal [10].

This paper focuses on two specific debonding techniques, thermal debonding and Joule-effect debonding, to assess the recyclability potential of bonded joints. The evaluations were conducted through lap shear strength tests and Life Cycle Assessment (LCA) analyses to determine the environmental sustainability of the proposed debonding solutions.

Experimental details

The debonding analysis was conducted by evaluating disassembly techniques that could be easily applied in a short time, that required low energy consumption and that could be operated manually without the use of tools or instruments, preserving the integrity of the substrate. The essential condition was that the strength of the joint created with the selected adhesive remained unchanged or varied only slightly from a standard joint, even with design modifications to facilitate subsequent disassembly. The debonding techniques investigated in this study are summarised in Figure 1 and were performed on single-lap joints with a bonding area of 25 x 12.5 mm, following the guidelines of ASTM D1002 [11]. All substrates were made of 6061 T6 aluminium alloy with a thickness of 1.6 mm. Additionally, to perform Joule heating-based disassembly, it was necessary to introduce an electrically and thermally conductive element at the adhesive layer during the bonding process. Specifically, two materials were employed in this experimental campaign: a 304 stainless steel mesh consisting of 0.05 mm diameter wires with a 0.1 mm mesh opening and a carbon fibre tape with a thickness of 0.1 mm, cut to match the width of the overlap area. Their selection was also motivated by the ease with which they can be incorporated into the bonded joint during the bonding process. The adhesive selected for this study was 3M™ DP490, a two-component thixotropic structural epoxy resin prepared with a 2:1 mixing ratio.

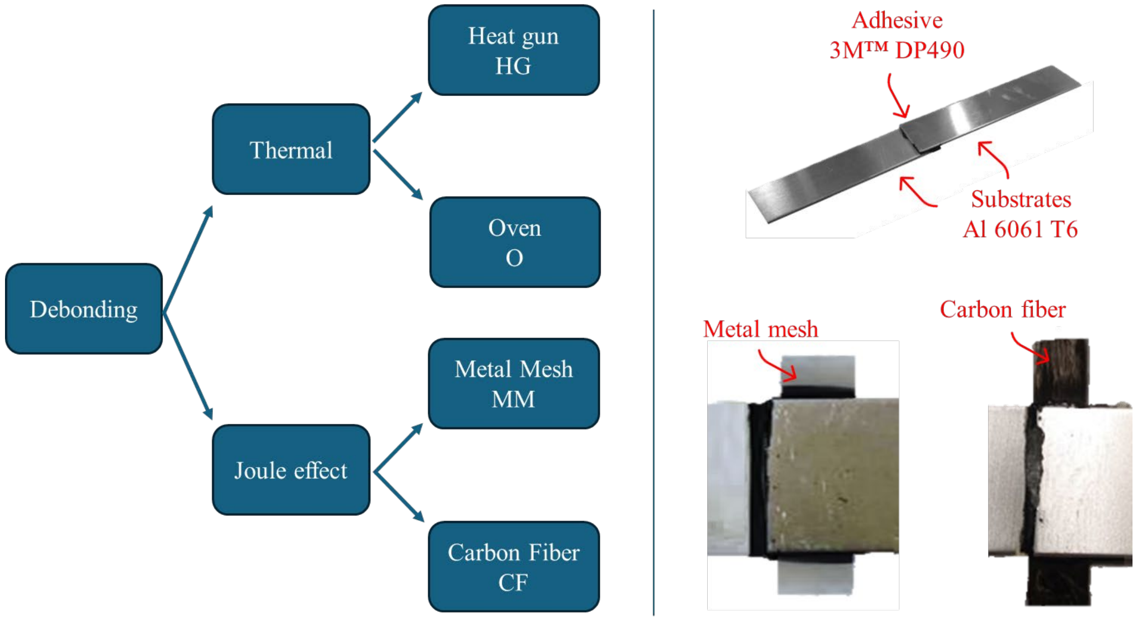


Figure 1 - The debonding techniques analysed in this study: summary diagram and joint structure.

Adhesive bonding. Prior to bonding, all substrates were degreased using acetone-soaked absorbent paper, followed by manual abrasion with 3M™ Scotch Brite™ MX-SR to increase surface roughness and promote mechanical interlocking with the resin. After a second acetone cleaning to remove any surface residues, the overlap area of the joint was delineated using masking tape to ensure precise area identification and proper adhesive application. Additionally, all elements to be incorporated into the bonding area (metal mesh and carbon fibre tape) were cleaned with acetone.

The two adhesives were then overlapped after inserting carbon fibre tape or wire mesh where necessary, and pressure was applied to eject the excess adhesive. The latter was subsequently removed to shape the fillet, thereby preventing stress concentrations at the extremities of the bonded area. Immediately after, the joint was loaded with appropriately sized weights to maintain correct alignment between the parts and apply the necessary pressure to assist curing. To achieve complete hardening, the joints were left at room temperature for 24 hours, followed by a post-curing treatment in an oven at 80°C for 1 hour.

Debonding. Two strategies were adopted for debonding: the first involved thermal detachment using hot air (via an AEG HG 600V heat gun or a Memmert UF260plus oven), while the second relied on Joule heating by using a metal mesh strip or a carbon fibre tape as conductors.

For detachment using the heat gun, the device was held above the overlap area of the joint at 10-20 cm. Throughout the heating process, the joint temperature was continuously monitored via a thermocouple to ensure it remained within the 130-200°C range. For the oven tests, the temperature was set to 180°C for 20 minutes to ensure that the joint reached a temperature consistent with the range used for the heat gun application. Joule heating-based debonding tests were conducted by connecting a DC power supply (IPSXP™ KPS1203D) to the metal mesh or carbon fibre tape, while the temperature was monitored using a thermocouple.

Table 1 lists the main parameters employed in the four different test cases, which were derived from preliminary experiments conducted in advance.

Table 1 - Parameters set for the debonding processes performed

Joint type	*t [min]*	*T [°C]*	*V [V]*	*I [A]*
Heat gun	5	< 200	-	-
Oven	20	180	-	-
Metal mesh	10	130	3.3-4.0	10.3
Carbon fibre	0.5	< 200	16	8.38

Mechanical testing. The reduction in mechanical resistance was quantified through lap-shear strength tests. To evaluate the impact of the adopted debonding solutions, tests were performed on two batches of specimens: one tested immediately after bonding and the other after undergoing the debonding process.

To ensure uniform initial conditions of the samples before mechanical testing, all joints were conditioned for 24 hours in a WEISS WK3 340 climatic chamber at a temperature of 23°C and a relative humidity of 50%. Subsequently, tensile tests were performed under standard laboratory conditions (T = 23 ± 2°C, RH = 40 ± 5%) using an Instron 8802 servo-hydraulic testing machine equipped with a 50 kN load cell.

To prevent specimen slippage during crosshead movement and, if necessary, ensure proper load alignment, each specimen was equipped with gripping tabs (25 mm × 25 mm). The specimens were then secured in the hydraulic grips of the testing machine, and the test was conducted at a crosshead displacement rate of 1.3 mm/min until joint failure, following ASTM D1002 guidelines [11]. Data acquisition was managed via Bluehill® software. The mean values of the maximum failure load, F, and the corresponding standard deviation were determined by testing three replicates for each joint series (N = 3).

Life Cycle Assessment. Environmental sustainability was assessed through a Life Cycle Assessment (LCA) conducted using SimaPro 9.6.0 (Analyst), in accordance with EN ISO 14040 and 14044 standards [12], [13]. The functional unit was defined as ten single-lap adhesive joints, each exhibiting a stress reduction of at least 75%. This number was selected to maximize the operational efficiency of the debonding equipment.

The system boundaries included the production and end-of-life phases, while the use, maintenance, and transport stages were excluded, assuming they were identical across all joint configurations. A cradle-to-cradle approach was applied to all scenarios involving material recovery after debonding, encompassing both production and reuse phases. An exception was made for the no-debonding (ND) scenario, modelled with a cradle-to-grave perspective. In this case, the system covered extraction, manufacturing and final disposal at waste collection facilities with no recycling stage. Including this scenario enabled direct comparison with debonding-enabled configurations, highlighting the environmental advantages of reuse.

The Life Cycle Inventory (LCI) was developed through a comprehensive input-output analysis of all processes within the defined system boundaries. Wherever possible, primary data measured in the laboratory were employed. When unavailable, secondary data were sourced from literature or from SimaPro's internal databases, with priority given to the Ecoinvent 3.9.1 database (allocation, cut-off by classification) [14]. Material and consumable masses (including aluminium substrates, DP490 adhesive, stainless steel mesh, carbon fiber tape, acetone, blotting paper, and abrasives) were measured using laboratory precision scales. Energy consumption during disassembly was recorded with a power meter Ketotek KTEM02. Since the adhesive was not available in Ecoinvent, a custom inventory was created based on its material safety data sheet [15], considering only substances exceeding 2% by mass. Similarly, carbon fibre tape was modelled following a literature-based process, including PAN (polyacrylonitrile) precursor synthesis from acrylonitrile, followed by stabilization and carbonization steps [16].

All pre-bonding surface preparation steps were also accounted for in the LCI. These included degreasing with acetone-soaked paper, manual abrasion using 3M™ Scotch-Brite™ MX-SR pads, second acetone cleaning, masking of the bonding area, and acetone cleaning of the inserts. Quantitative data were collected for all materials used in these operations.

At the end-of-life stage, the aluminium substrate was assumed to be 99% reusable, while the DP490 adhesive and carbon fibre were treated as non-recyclable waste. The stainless-steel mesh was considered 80% reusable. Energy consumption for the debonding process varied by technique, ranging from 1.412 kWh (thermal oven) to 0.001 kWh (Joule-effect debonding with carbon fibre inserts).

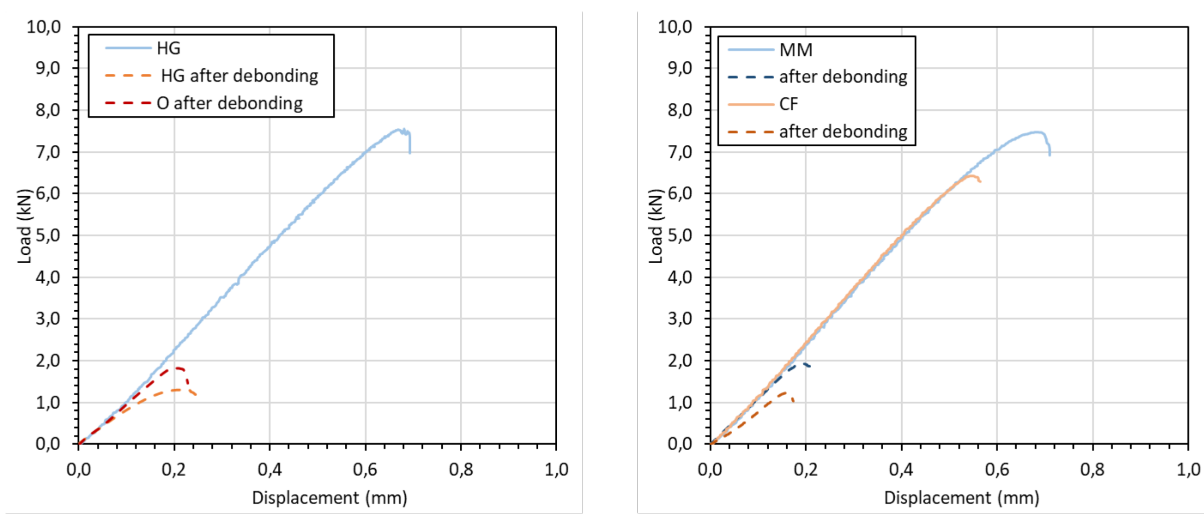
Environmental impact assessment was carried out using the ReCiPe 2016 Endpoint H method, considering all midpoints as defined by the methodology. Results were expressed in millipoints [mPt] and are directly comparable with values reported in the scientific literature [17].

Result and discussion

Mechanical results: Table 2 and Figure 2 present the shear strength values of the joints before and after debonding, following the previously described methods. The effectiveness of the process was assessed by determining the percentage reduction in strength.

Table 2 – Comparison of the mechanical shear strengths of bonded joints before and after the debonding operation.

DEBONDING TYPE	SHEAR STRENGTH [MPA]		DECREASE [%]
	Predebonding	Postdebonding	
HEAT GUN	24.3 ± 2.80	4.93 ± 1.64	-79.7%
OVEN	24.3 ± 2.80	5.93 ± 1.92	-75.5%
METAL MESH	25.5 ± 2.58	6.11 ± 2.11	-76.0%
CARBON FIBRE	19.0 ± 0.73	3.96 ± 0.87	-79.2%



a) b)

Figure 2 - Mechanical characteristic decreasing before and after debonding operation in cases of thermal (a) and Joule effect debonding (b).

For the thermally debonded joints, the batch that did not undergo any debonding process showed an average shear strength of 24.3 MPa. In contrast, the joints modified with a metal mesh showed

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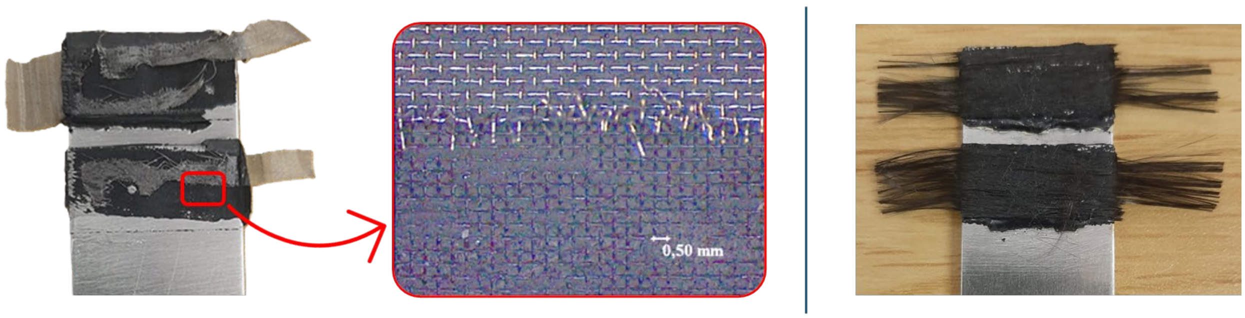
an increase in strength to 25.5 MPa, suggesting that the mesh helped to improve the anchorage of the adhesive through a mechanical interlocking effect (Fig. 3a). In particular, the adhesive penetrated the openings of the mesh, improving load distribution and reducing the tendency of the fracture to deadhesion phenomena. In contrast, joints containing carbon fibre showed a reduction in strength at 19.0 MPa, indicating that the addition of the carbon fibre tape hindered proper adhesion between the adhesive and the substrates. The analysis of the fracture surface revealed a distinct behaviour compared to the other two cases: the insufficient resin impregnation of the carbon fibres led to a premature detachment of the adhesive, resulting in a predominantly deadhesive failure mode (Fig. 3b). In addition, the transverse orientation of the fibres with respect to the loading direction negatively affected the performance of the joint, reducing the effectiveness of the adhesive bond.



a) b)

Figure 3 - Fracture surfaces typically manifested with Joule effect debonding: Metal Mesh MM (a) and Carbon Fibre CF (b)

The debonding tests confirmed that all the applied techniques led to a significant reduction in shear strength, with decreases exceeding 75%. The paint remover, applied under the previously described conditions, resulted in the greatest reduction, with a 75.5% decrease in strength. Similarly, heat treatment in an oven at 180°C for 20 minutes proved highly effective, achieving a comparable 75.5% reduction in just 5 minutes. For the joints with metal mesh and carbon fibre, debonding was particularly effective, with strength reductions of 76.0% and 79.2%, respectively. It was also observed that in cases where manual disassembly was performed, bending or cleavage forces were often applied, altering the joint's behaviour compared to standard loading conditions. These findings suggest that the incorporation of a metal mesh not only enhances the mechanical strength of the joint but also facilitates controlled debonding. In contrast, while carbon fibre provides a reasonable level of strength, it proves less effective both in terms of adhesion and controlled removal.

LCA results. Concerning the environmental sustainability analysis, Table 3 presents the main midpoints values for all analysed cases, together with the final score, obtained from the sum of all contributions. Data show that the scenario without debonding (ND) is the most impactful, with the highest overall score, since, in this mode, no reuse of the joint takes place. As expected, in the cases where debonding was performed, the millipoint scores were significantly lower, with the lowest values recorded in the Joule effect debonding scenarios: precisely 7.93 for metal mesh and 7.28 for carbon fibre.

Table 3 – Distribution of the main midpoints for the five cases analysed: joints with no debonding (NG), with debonding by hot gun (HG) and oven (O) and with debonding by Joule effect through metal mesh (MM) and carbon fibre (CF).

Characterization factors	***ND***	***HG***	***O***	***MM***	***CF***
GWP, HH	30.12	6.84	11.21	3.25	3.02
PMFP	41.64	4.30	7.20	1.93	1.75
HTPc	21.73	1.04	1.62	0.57	0.53
HTPnc	11.45	2.49	3.61	1.57	1.49
FFP	0.73	0.38	0.57	0.21	0.21
Others	2.94	0.71	1.19	0.40	0.28
Total	108.59	15.76	25.40	7.93	7.28

Regarding the global warming potential and impact on human health (GWP-HH), the case without debonding (ND) showed the highest value (30.12), while the configurations with debonding showed a significant reduction, with the lowest value of 3.02 for the carbon fibre debonding. A similar trend was also observed in the PMFP, where the ND case reached a value of 41.64, significantly higher than the other scenarios, confirming a higher environmental impact.

The HTPc and HTPnc, which quantify carcinogenic and non-carcinogenic human toxicity respectively, show a marked difference between the ND case and the other scenarios. For the HTPc, the ND value (21.73) is about 20 times higher than for the Joule effect debonding cases, while for the HTPnc, although the difference is smaller, it is still significant (11.45 for ND versus values between 2.49 and 1.49 in the other scenarios). Fossil fuel consumption (FFP) follows a similar trend: the ND case has the highest value (0.73), while a significant reduction is observed in the other scenarios, with values close to zero.

Taken as a whole, the analysis shows that the scenarios in which electricity was applied in the joint are the most sustainable, with the lowest overall environmental impact. These results suggest that the strategies adopted in these cases can contribute significantly to the reduction of emissions and associated negative effects. On the contrary, cases where hot gun or oven was used scored less favourably, negatively influenced by the GWP-HH category due to higher electricity consumption. However, it is important to emphasise that, even in these scenarios, the scores in the various categories were always lower than in the case without debonding (ND).

Table 4 presents the values assumed by the different endpoint categories for the five analysed cases.

Table 4 – Endpoints for joints with no debonding (NG), with debonding by hot gun (HG) and oven (O) and with debonding by Joule effect through metal mesh (MM) and carbon fibre (CF).

Endpoint	***ND***	***HG***	***O***	***MM***	***CF***
Human health	105.33	14.86	23.98	7.46	6.84
Ecosystems	2.50	0.52	0.84	0.26	0.23
Resources	0.76	0.38	0.58	0.21	0.21
Total	108.59	15.76	25.40	7.93	7.28

As observed, regardless of the specific debonding scenario examined, the most influential endpoint is human health. This result is primarily due to the significant electricity consumption required by all the considered methods, as well as the substrate cleaning procedures during the bonding phase.

When analysing the behaviour of the different joint configurations, the control series (ND) exhibits the highest impact across all evaluated endpoints. Notably, its effect on human health is significantly greater than that of the other series. Additionally, in terms of ecosystem and resource impacts, this joint type shows higher values, although the difference is less pronounced compared to the human health category.

The series in which an oven or a hot gun was used show an intermediate influence, with a relevant impact but significantly lower than the ND joint, especially regarding human health. The most favourable results were obtained in both Joule-heating-based debonding cases, which recorded the lowest values across all impact categories analysed.

Conclusion

This study investigated the efficiency and environmental sustainability of thermal and Joule-effect debonding techniques applied to bonded aluminium joints. The results demonstrated that all tested debonding methods significantly reduced the shear strength of the joints by at least 75%, allowing for efficient manual disassembly without compromising substrate integrity.

From a mechanical perspective, the introduction of a metal mesh within the bonded joint not only facilitated Joule heating but also improved initial shear strength due to mechanical interlocking. Conversely, the inclusion of a carbon fibre tape slightly reduced the initial bond strength, likely due to inadequate adhesion between the adhesive and carbon fibres. Nevertheless, both conductive materials enabled effective Joule heating-based debonding, confirming their suitability for sustainable disassembly.

The Life Cycle Assessment results revealed that the most environmentally sustainable debonding methods were those utilizing Joule heating, particularly with carbon fibre and metal mesh conductors. These techniques exhibited the lowest overall environmental impact, as indicated by significantly reduced values in global warming potential, human health impact, and fossil fuel consumption. Traditional thermal methods, such as heat gun and oven heating, while effective, were associated with higher energy consumption and environmental burdens. However, it is important to note that the environmental impact values associated with oven heating are higher than those of other debonding techniques. This can be attributed, at least in part, to the limited number of samples (10) considered in the analysis for this method. A larger sample size would likely provide a more representative evaluation, potentially influencing the midpoint and endpoint impact on values.

Overall, the findings support the adoption of Joule heating-based debonding as a viable, sustainable alternative to traditional thermal debonding techniques. Implementing such approaches in industrial applications could enhance material recyclability, reduce environmental impact, and facilitate the transition toward a circular economy. Future research should explore the scalability of these methods in different adhesive-substrate combinations and assess their applicability in real-world manufacturing and recycling scenarios. Moreover, further investigation should focus on the topic of rebonding, particularly identifying the most effective resin removal methodologies after disassembly and evaluating the performance of re-bonded joints.

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