

SESSION C:

PRODUCTION TECHNOLOGIES, CAE AND MANAGEMENT

Energy efficiency and carbon footprint of welded, adhesive and hybrid joining processes in the context of circular economy

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ARTICLE INFO

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DOI: <https://doi.org/10.46793/ET26.C07M>

PAGES: C53 – C59

ABSTRACT

This paper presents a systematic comparative analysis of energy efficiency and carbon footprint of welded, adhesive, and hybrid (weld-bonding) joining processes for metallic components, within the framework of the circular economy and Extended Producer Responsibility (EPR). With global welding energy consumption estimated at over 400 TWh annually, the identification of lower-energy joining alternatives is a critical step toward industrial decarbonization aligned with Paris Agreement targets and EU climate neutrality goals for 2050. The study integrates quantitative energy balances, Life Cycle Assessment (LCA) data, and experimental results on surface preparation effects on adhesive joint performance. Results demonstrate that adhesive bonding requires up to 6000× less direct process energy than MIG/MAG welding for equivalent joints, and generates 3-50× lower CO₂ emissions per meter of joint. Hybrid joining reduces energy consumption by approximately 30% compared to pure spot welding while improving fatigue strength by 60-70%. The circular economy implications of each technology - including reparability, disassembly, and end-of-life recyclability - are examined, and a conceptual decision framework for joining technology selection is proposed, based on lifecycle performance indicators and EPR compliance.

KEYWORDS

Energy efficiency, Carbon footprint, Welding, Adhesive bonding, Hybrid joints, Circular economy

1. INTRODUCTION

The joining of metallic components is a foundational operation in modern manufacturing, with the choice of technology directly influencing mechanical performance, economic viability, and environmental sustainability. Welding, long the dominant joining method in heavy industry, automotive, and aerospace sectors, is increasingly challenged by structural adhesive bonding and hybrid joining techniques - particularly under the mounting pressure of tighter CO₂ reduction mandates, mass-optimization targets, and circular economy legislation [1, 2].

According to the International Institute of Welding (IIW), global energy consumption in welding processes is estimated at over 400 TWh per year, representing a significant share of total industrial energy use [3]. In the context of the Paris Agreement and the European Union's target of climate neutrality by 2050, the identification and adoption of energy-efficient joining technologies has become an industrial and regulatory imperative [4].

Structural adhesive bonding of metallic structures, though established since the mid-20th century, has undergone a significant renaissance in recent decades, driven by advances in high-performance epoxy and acrylic adhesive formulations and progress in surface preparation science [5, 6]. Research compiled in [7, 8] demonstrates that surface preparation methods - including mechanical abrasion, laser cleaning, and laser texturing - exert a decisive influence on adhesive joint strength, with the optimal method depending on the adherend material and adhesive system combination.

The hybrid weld-bonding approach, which combines resistance spot welding or seam welding with a continuous structural adhesive, emerged primarily from the automotive industry's need to increase body-in-white stiffness while simultaneously reducing mass and weld point count [9, 10]. This concept has demonstrated synergistic effects exceeding the sum of individual contributions, particularly with respect to fatigue strength and vibration damping [11].

Within the evolving legislative landscape of Extended Producer Responsibility (EPR) - which holds manufacturers accountable for the full lifecycle of their products, including end-of-consumer-use stages - the choice of joining technology is no longer purely a question of technical performance and production cost. It has become a strategic decision with lifecycle-wide implications for resource efficiency, repairability, disassembly, and material quality at end of life [12].

The objective of this paper is to provide a structured comparison of welded, adhesive, and hybrid joining processes across four dimensions: (i) direct process energy consumption and CO₂ emissions, (ii) thermal effects and their consequences for material integrity, (iii) stress distribution and mechanical performance, and (iv) circular economy and EPR compliance metrics - including durability, repairability, disassembly, and recyclability.

2. ENERGY CONSUMPTION AND CARBON FOOTPRINT

2.1. Welding Processes

Fusion welding processes require significant local heat input to melt the base material, with or without filler material. The Heat Input (HI) is defined as the energy deposited per unit weld length:

$$HI = \eta \cdot \frac{U \cdot I}{v} \quad (1)$$

where η is the arc-to-workpiece energy transfer efficiency ($\eta = 0.60 - 0.95$), U is the arc voltage [V], I is the welding current [A], and v is the travel speed [mm/s]. Process efficiency varies widely: MIG/MAG welding achieves 75-85%, GTAW (TIG) 50-70%, SMAW 60-75%, laser beam welding 30-50%, and electron beam welding 85-95%. Characteristic heat input values for steel range from 0.05-0.5 kJ/mm for laser welding (HAZ width 2-5 mm) to 0.8–2.5 kJ/mm for MIG/MAG (HAZ width 10-20 mm).

Beyond the direct arc energy, welding processes impose additional energy demands for the production of shielding gases (Ar, CO₂, He), pre-heating and post-weld heat treatment (PWHT) for hardenable steels, cooling systems for equipment, and post-weld mechanical operations such as grinding, straightening, and surface treatment.

2.2. Adhesive Bonding Processes

In contrast to fusion welding, adhesive bonding requires no melting of the base material. Total process energy can be expressed as:

$$E_{total} = E_{surface\ preparation} + E_{application} + E_{curing} \quad (2)$$

where: E_{total} is the total energy, $E_{surface\ preparation}$ is the surface preparation energy, $E_{application}$ is the adhesive application energy, and E_{curing} is the curing energy.

Surface preparation energy depends strongly on method: mechanical abrasion (abrasive paper) requires 5-20 kJ/m², atmospheric plasma treatment 10-50 kJ/m², laser cleaning 50-200 kJ/m², and laser texturing 100-500 kJ/m². Adhesive application energy is negligible for manual dispensing; robotic two-component mixing systems consume 0.1-0.5 kW during operation. Curing energy: room-temperature-curing epoxy systems require no external energy (cure time 30 min to 48 h), thermally-activated adhesives require heating at 80–180 °C for 20-60 min (50-200 kJ/m²), and UV-curing systems are the most energy-efficient at 5-20 kJ/m² over 10-60 seconds of exposure.

A representative comparative calculation for joining two 2 mm steel plates over a 100 cm² bond area illustrates the magnitude of the difference: MIG/MAG welding a 400 mm seam with $HI = 1.5$ kJ/mm requires approximately 600 kJ total, while room-temperature-curing structural epoxy bonding of the same joint requires less than 0.1 kJ - a factor of approximately 6000.

2.3. Hybrid Weld-Bonding

Hybrid joining optimizes energy efficiency through strategic combination of the two technologies. Weld-bonding combines resistance spot welding with a continuous structural adhesive applied prior to welding. The adhesive fills the gap between adherends, while spot welds provide immediate handling strength during adhesive cure. This sequence - adhesive application, assembly, spot welding, curing - adds process steps relative to pure welding, but eliminates the need for increased weld point density. In automotive applications, replacing pure spot welding with weld-bonding (4 spot welds/dm² plus continuous structural adhesive vs. 8 spot welds/dm²) reduces energy consumption from 120-180 kJ/m² to 100-140 kJ/m² - an approximate reduction of 30%. The performance gains of weld-bonding exceed the sum of individual contributions. The adhesive layer reduces peak stresses around weld spots by 40-60% (as confirmed by FEM analyses), while weld spots arrest crack propagation through the adhesive. Additionally, the viscoelastic adhesive provides vibration damping, and the sealed weld spots are protected from moisture ingress, eliminating corrosion-fatigue interaction.

2.4. Life Cycle Carbon Footprint

Complete environmental impact assessment requires Life Cycle Assessment (LCA) that encompasses upstream energy production, ancillary materials, and waste treatment. LCA studies in the automotive sector report that MIG/MAG welding generates 3.5-5 kg CO₂ per meter of joint, room-temperature-curing adhesive bonding generates 0.1-0.3 kg CO₂/m, and thermally-cured adhesive systems generate 0.5-1.2 kg CO₂/m of joint. This indicates that adhesive bonding carries a carbon footprint 3-50× lower than conventional welding - a finding of direct relevance in the context of industrial decarbonization and emerging carbon pricing mechanisms.

3. THERMAL EFFECTS AND HEAT AFFECTED ZONE

3.1. HAZ Formation in Welding

Local melting during welding generates intense thermal gradients leading to the formation of the Heat Affected Zone (HAZ) - a region in which the base material undergoes thermally induced microstructural changes without reaching melting temperature [13]. HAZ width is a function of heat input, material thermal conductivity, and joint geometry.

For low-alloy steel, MIG/MAG welding typically produces a HAZ of 10-20 mm width [14]; austenitic stainless steel (X5CrNi18-10), due to lower thermal conductivity, generates HAZ of 8-15 mm with pronounced thermal distortion [15]; Al alloys (e.g. EN AW 5754), owing to high conductivity and low melting point (630-650 °C), produce the widest HAZ at 15-30 mm and are most susceptible to dimensional distortion requiring post-weld correction [16].

Microstructural changes in the HAZ depend on temperature and cooling rate. In steels, the region adjacent to the fusion line undergoes overheating and austenitic grain growth, which - following transformation to ferrite - results in a coarse-grained structure with reduced strength and toughness [17]. Further consequences include normalization in the inter-critical zone (A₃-A₁), and partial austenitization at lower temperatures. Cooling rate governs the final microstructure: slow cooling produces ferritic-pearlitic structure; rapid cooling may generate martensite with increased hardness but reduced toughness and susceptibility to hydrogen embrittlement [18]. Tensile strength in the HAZ is typically reduced to 80-95% of base material values, while hardness may range from 70% to 150% depending on the degree of hardenability [19]. Residual tensile stresses in the weld direction can reach 300-500 MPa in low-alloy steels (70-80% of yield strength), significantly affecting fatigue performance and susceptibility to stress corrosion cracking [20].

3.2. Absence of Thermal Effects in Adhesive Bonding

The fundamental advantage of adhesive bonding lies in the complete absence of base material melting, thereby eliminating HAZ formation and all associated microstructural consequences. Adherend temperature during bonding is governed solely by curing conditions. Room-temperature-curing systems do not raise adherend temperature beyond 20-30 °C - insufficient for any metallurgical transformation. Thermally cured adhesives at 80-180 °C produce uniform, moderate heating far below the critical A₁ temperature (723 °C for steel), leaving base material properties fully intact.

The elimination of HAZ yields several practical benefits: residual stresses of thermal origin are removed (improving fatigue life and stress corrosion resistance); mechanical properties are preserved throughout the entire adherend volume (critical for precipitation-hardened alloys); and thermal distortion is essentially eliminated, reducing or eliminating the need for post-assembly dimensional correction. Residual stresses in adhesive joints arise solely from polymer shrinkage during cure (typically 2-5% volumetric contraction for epoxy systems), generating local interface stresses of only 5-15 MPa - negligible compared to welding residual stresses.

4. STRESS DISTRIBUTION AND MECHANICAL PERFORMANCE

4.1. Stress Concentration in Welded Joints

Welded joints are inherently characterized by geometric and microstructural discontinuities acting as stress concentrators. Sources include geometric notches (weld toe, root notch, surface irregularities), microstructural interfaces between base material, HAZ, and fusion zone, and internal defects (porosity, inclusions, incomplete penetration). The stress concentration factor α_k ranges from 1.5-2.5 for optimally executed joints to above 4-8 for joints with significant defects. More than 70% of fatigue failures in welded structures initiate in the HAZ/fusion zone interface region, where geometrical, microstructural, and residual stress effects combine.

4.2. Load Transfer in Adhesive Joints

Adhesive joints distribute load over a large bonded area rather than concentrating it through a small cross-section. For a single-lap joint of bonded area A under shear force F, the nominal shear stress is: $\tau = F/A$.

However, shear and peel stress concentrations occur at joint edges - the 'edge effect' analytically described in [21 and 22]. FEM analyses confirm that edge stress concentration factors $\alpha_k = 2-4$ are achievable depending on geometry and adherend stiffness, with the critical failure mode being peel stress (mode I opening) at joint edges. Design strategies to mitigate edge stress concentration include optimized overlap length ($L_{opt} = 15-25 \times t_{adherend}$), tapered adherend edges (reducing peel stress by 30-50%), and spew fillet formation (improving strength by 15-25%).

4.3. Fatigue Performance Comparison

For welded steel joints under axial tensile loading, fatigue limit at $N = 10^7$ cycles is typically $\Delta\sigma \approx 80\text{--}120$ MPa ($R = 0.1$), representing a reduction factor of approximately 0.25–0.30 relative to static strength. For adhesive joints (high-performance structural epoxy), static shear strength is $\tau_{static} \approx 25\text{--}35$ MPa with fatigue limit at $N = 10^6$ cycles of $\Delta\tau \approx 6\text{--}10$ MPa ($R = 0.1$). Experimental data in [7] for SikaFast 580 on X5CrNi18-10 stainless steel yielded a fatigue strength of $\Delta\tau = 6.24$ MPa at 10^6 cycles.

Hybrid weld-bonding joints demonstrate exceptional fatigue performance: fatigue limit at 10^6 cycles reaches $\Delta\sigma = 75\text{--}95$ MPa, compared to $\Delta\sigma = 45\text{--}55$ MPa for pure spot welding and $\Delta\sigma = 30\text{--}40$ MPa for pure adhesive bonding - improvements of 60–70% and 100–140%, respectively. This synergy is mechanistically explained by: (i) stress redistribution - the adhesive layer reduces peak stresses around weld spots by 40–60% (FEM); (ii) crack arrest - weld spots impede crack propagation through the adhesive, while adhesive prevents microcrack initiation from HAZ; (iii) damping - the viscoelastic adhesive absorbs cyclic energy; and (iv) corrosion protection - the adhesive seals weld spots from moisture ingress, eliminating corrosion-fatigue interaction.

5. SURFACE PREPARATION AND DISSIMILAR MATERIAL JOINING

5.1. Surface Preparation Effects

Experimental research reported in [7, 8] demonstrates the critical influence of surface preparation on adhesive joint performance. For X5CrNi18.10 stainless steel bonded with SikaFast 580, mechanical abrasion with P180 abrasive paper yielded the best results - a 20.8% increase in joint strength relative to unprepared specimens - with predominantly cohesive failure mode, $R_a = 0.45$ μm surface roughness, and controlled oxide layer chemistry. Laser cleaning proved optimal for the same material with SikaPower 880 adhesive, yielding a 17.47% strength increase. For EN AW 5754 Al alloy with SikaFast 580, P180 abrasion again provided the best performance ($R_a = 1.75$ μm , predominantly cohesive failure). Laser cleaning similarly proved best for EN AW 5754 with SikaPower 880.

Laser texturing, despite achieving near-zero contact angles ($<10^\circ$) and elevated oxygen content, did not improve joint strength relative to mechanical preparations. Microstructural examination revealed a redeposited layer with reduced chemical reactivity and mechanical stability. This finding has direct energy efficiency implications: the higher energy cost of laser texturing (100–500 kJ/m² vs. 5–20 kJ/m² for abrasive paper) does not translate into improved performance for the material-adhesive combinations studied.

5.2. Dissimilar Material Joining

Dissimilar material welding (e.g. steel-aluminium) is severely constrained by large melting point differentials (870 °C for Fe-Al), formation of brittle intermetallic phases (FeAl, Fe₂Al₅, FeAl₃) with hardness exceeding 1000 HV, and differential thermal expansion coefficients generating residual stresses near yield strength at the interface. Intermetallic layer thickness above 10 μm leads to drastic joint strength reduction. Adhesive bonding inherently eliminates all three constraints: no metallic melting means no intermetallic phase formation; the relatively low adhesive modulus ($E = 2\text{--}10$ GPa vs. 70–210 GPa for metals) accommodates differential thermal expansion; the adhesive layer provides electrical isolation, preventing galvanic corrosion; and the same joining process applies to any material combination.

6. CIRCULAR ECONOMY AND EPR FRAMEWORK

6.1. Conceptual Framework

Extended Producer Responsibility (EPR), as synthesized by the OECD, defines an approach whereby producers bear environmental and economic responsibilities for their products throughout the entire lifecycle, including the post-consumer phase, with the aim of improving resource efficiency and supporting circular material flows [12]. The choice of joining technology - whether a structure is to be realized by welding, adhesive bonding, or a hybrid joint (e.g. weld-bonding) - ceases to be a purely technical question of load-bearing capacity and production cost, and becomes a strategic decision with implications for the entire product lifecycle. From the standpoint of EPR and circularity, the key evaluation criteria are: durability, repairability, disassembly, recyclability, and secondary material quality.

Welded joints typically impede selective disassembly and component reuse, but allow relatively clean metal streams during recycling. Adhesive joints can improve fatigue resistance and reduce mass (thereby lowering emissions during the use phase), but may simultaneously hinder material separation and lead to waste contamination. Hybrid joints represent a compromise - they enhance structural performance and safety, but further complicate deconstruction and material recovery processes. Within this framework, joining technology selection determines lifecycle performance across all circular economy metrics. A conceptual framework linking these principles with the design and manufacture of metal structures, and highlighting the impact of joining technologies on lifecycle performance indicators and EPR compliance costs, is presented in Figure 1.

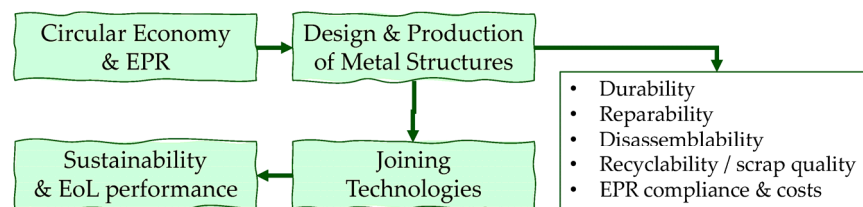


Figure 1: Conceptual framework linking circular economy and extended producer responsibility (EPR) [12]

6.2. Lifecycle Circular Economy Assessment

Welded joints generally impede selective disassembly and component reuse, as their separation requires cutting operations. The resulting metal streams are relatively clean and fully recyclable. However, welded designs are not conducive to Design for Disassembly (DfD) principles.

Adhesive joints can improve fatigue resistance and reduce structural mass - thereby indirectly reducing emissions during the use phase - but pose significant challenges for material separation at end of life. Since most structural adhesives are based on thermoset systems that do not soften under the application of heat, non-destructive disassembly is not practicable.

Hybrid joints combining welding and bonding represent a compromise between structural performance and manufacturing efficiency, while simultaneously further complicating disassembly and material recovery relative to either individual technology. Research aimed at overcoming the limitations of adhesive joints at end of life encompasses several promising directions: thermally-activated adhesives that lose load-bearing capacity above 200 °C, chemically-activated systems, dynamically covalent adhesives with reversible bond breaking, and bio-degradable formulations designed for short-lifecycle products.

6.3. EPR Cost Implications

Under EPR frameworks, producers bear financial responsibility for end-of-life management costs. Joints that complicate disassembly - such as structural adhesives - may impose higher EPR compliance costs, while designs enabling clean metal recovery at end of life can reduce these costs. Carbon pricing mechanisms additionally penalize energy-intensive processes such as conventional welding. The comprehensive evaluation framework for joining technology selection must therefore integrate: initial capital and operating costs, process energy and CO₂ emissions (direct and LCA), mechanical performance requirements, EPR compliance costs, and projected carbon price impact over product lifecycle.

7. TECHNOLOGY COMPARISON SUMMARY

The preceding analysis across energy consumption, thermal effects, mechanical performance, and circular economy metrics enables a structured comparison of the three joining technologies. Table 1 summarizes the key parameters, quantifying the trade-offs between welded, adhesive, and hybrid joints across the dimensions examined in this paper.

The data presented in Table 1 confirm that no single joining technology demonstrates unconditional superiority across all evaluated parameters. Each method exhibits a distinct performance profile that reflects its underlying physical mechanisms and process characteristics. Welding (MIG/MAG) registers the highest direct energy consumption and CO₂ emissions per unit length, alongside significant heat-affected zone widths and residual stresses. However, it retains a clear advantage in end-of-life disassembly and recycling potential, as well as lower EPR compliance risk - factors of increasing regulatory relevance in the context of the European Union's evolving product responsibility frameworks.

Table 1: Comparative overview of welded, adhesive, and hybrid joining processes

Parameter	Welding (MIG/MAG)	Adhesive Bonding	Hybrid	Best
Direct energy [kJ/m]	800–2500	0.1–200	100–140	Adhesive
CO ₂ emission [kg/m]	3.5–5.0	0.1–1.2	~1.5–2.5	Adhesive
HAZ width [mm]	10–20 (steel)	None	Reduced	Adhesive
Residual stress [MPa]	300–500	5–15	Intermediate	Adhesive
Stress concentration α_k	1.5–8	1.1–4	~1.3–2.5	Adhesive
Fatigue limit [MPa]	80–120	6–10 (τ MPa)	75–95	Hybrid
Dissimilar materials	Limited	Excellent	Good	Adhesive
Disassembly/recycling	Moderate	Difficult	Difficult	Welding
EPR compliance risk	Low	Moderate–High	Moderate	Welding

Adhesive bonding presents the most favorable environmental profile in terms of energy input and carbon footprint, while also enabling the joining of dissimilar materials with minimal thermal disturbance. These characteristics make it particularly well-suited for lightweight multi-material assemblies in automotive and aerospace applications. Nevertheless, the inherent difficulty of disassembly and the limited recyclability of cured polymer adhesives represent significant constraints from a circular economy perspective, particularly as Extended Producer Responsibility legislation continues to tighten across EU member states.

Hybrid joining emerges as an intermediate solution that partially reconciles the conflicting requirements of mechanical performance and sustainability. By combining adhesive bonding with mechanical fastening or welding, hybrid joints achieve fatigue performance superior to either constituent method alone, while moderating the energy and emissions penalties associated with pure welding processes. The stress concentration factor and residual stress levels are reduced relative to welding, and dissimilar material compatibility is retained from the adhesive component. However, hybrid joints share the end-of-life disassembly challenges of adhesive bonding, limiting their circularity potential.

The matrix given in Table 2 summarizes the relative advantages of each joining technology with respect to sustainability, mechanical performance, and circular economy requirements.

Table 2: Comparative decision matrix for welded, adhesive, and hybrid joining processes

Criterion	Welding	Adhesive Bonding	Hybrid Joining
Energy Efficiency	★	★★★★★	★★★★★
Carbon Footprint	★	★★★★★	★★★★★
Fatigue Performance	★★★★★	★★	★★★★★
Dissimilar Material Joining	★★	★★★★★	★★★★★
Recyclability / End-of-Life Recovery	★★★★★	★★	★★

Rating scale: ★ = poor performance, ★★★★★ = excellent performance.

Table 2 presents a rating comparison of all three joining technologies. Adhesive bonding scores highest in energy efficiency, carbon footprint, and dissimilar material joining, making it the best choice when environmental performance is the priority. Welding scores highest in recyclability and end-of-life recovery, as metal separation and reprocessing are well-established processes. Hybrid joining performs best in fatigue resistance, which is important in automotive and industrial structures subjected to cyclic loading.

The choice of joining technology depends on the requirements of each specific application. When recyclability and end-of-life recovery are the main concern, welding is the most suitable option. When the goal is to reduce weight, join different materials, and lower emissions, adhesive bonding is preferred. When high mechanical performance under dynamic loading is required and moderate environmental impact is acceptable, hybrid joining offers the best balance.

The numerical ranges in Table 1 vary depending on material type, joint geometry, and process conditions, and should be treated as approximate values. The ratings in Table 2 agree with findings reported in the literature, though actual performance may differ based on specific material combinations, production scale, and applicable regulations.

8. CONCLUSIONS

This paper has presented a multi-dimensional comparative analysis of welded, adhesive, and hybrid joining processes from the perspectives of energy efficiency, carbon footprint, thermal and mechanical performance, and circular economy compliance. Key conclusions are:

- Adhesive bonding demonstrates clear superiority in energy efficiency - requiring 3-6000× less direct process energy than arc welding - and generates 3-50× lower CO₂ emissions per unit joint length as determined by LCA studies.
- The complete elimination of HAZ in adhesive bonding preserves base material integrity, eliminates thermally-induced residual stresses and distortion, and enables effective dissimilar material joining - advantages unattainable in fusion welding.
- Welding retains its essential position in applications requiring extreme joint strength, hermeticity, service temperatures above 200 °C, and where established industry standards and certifications are mandatory.
- Hybrid weld-bonding represents the optimum solution for mass manufacturing contexts. Fatigue strength improvements of 60-70% over pure welding, 30% energy reduction, and 20-30% stiffness gains demonstrate the synergistic potential of the combined approach.
- Surface preparation remains critical for adhesive joint performance. Mechanical abrasion (P180) is optimal for both X5CrNi18-10 and EN AW 5754 with SikaFast 580, while laser cleaning is superior with SikaPower 880. Laser texturing does not improve joint strength due to redeposited layer formation, making it energetically unjustified.
- From a circular economy and EPR perspective, the development of reversible and bio-based adhesive systems is an active research priority that may resolve the end-of-life limitations of adhesive and hybrid joining.

The energy transition and industrial decarbonization agenda strengthen the case for low-energy joining processes. However, final technology selection must holistically balance energy efficiency, mechanical performance, economic viability, EPR compliance, and end-of-life environmental impact through a lifecycle assessment approach.

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