

Proceeding Paper

Mechanical Characterization of Metal–Polymer Joints Fabricated via Thermal Direct Bonding Technique [†]

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Abstract: In recent years, thermoplastic polymers and composites have seen increasing application across various industrial sectors to develop lightweight structures. These materials have gained popularity in the market due to advancements in additive manufacturing. Thermal direct joining serves as an effective solution for integrating such thermoplastic materials into existing or de-novo metal structures. This method enables the creation of lightweight and virtually reversible joints, which foster end-of-life recyclability, thus aligning with the principles of a circular economy. However, these joints are still affected by a low strength, which is mostly related to the poor polymer–metal interaction. The use of surface treatments that promote mechanical interlocking of the polymer within surface asperities in the mating metallic adherend can be an effective strategy to enhance the strength, as well as to improve the toughness and damage tolerance of the joints. In this work, a laser treatment was used to modify the surface texture of an aluminum sheet prior to thermal bonding with 3D-printed polylactic acid (PLA). Different surface textures were analyzed by modifying the main process parameters. Roughness and wettability measurements were performed to identify the most effective processing condition. Finally, mechanical tests were performed to verify the improvement in joint resistance obtained by interface modification.

Keywords: thermal direct joining; polymers; surface treatments; green joints



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1. Introduction

In the last decade, there has been a growing need to limit CO₂ emissions and mitigate climatic issues [1]. In different industrial fields, e.g., transportation and robotics, a valid strategy is to employ the so-called structural *lightweighting*, whereby advanced truss structures and lattice geometries have been put forward to ensure reduced weight without compromising structural performance [2,3]. However, the simplest approach to reach this goal is the use of lightweight materials, e.g., polymers or composites, to replace traditional ones, e.g., metals.

The introduction of these materials leads to the need to study new joining techniques that are compatible with a variety of materials without increasing the weight of the joint. Traditional techniques, such as the use of bolts or rivets, do not guarantee the structural integrity of the joined materials and, moreover, contribute to a weight increase, which

offsets the sought weight reduction achieved through the use of lightweight materials. A valid alternative is the introduction of adhesive bonded joints. In this context, the use of structural adhesives, typically of the thermosetting type, and the consequent environmental issues related to the production and disposal of these adhesives represent a strong impulse for developing or improving alternative joining techniques. An emerging technique that offers good versatility in combination with a lightweight and green approach is direct thermal joining [4–6]. This approach could be easily employed for joining thermoplastic polymers with metals by exploiting the polymer itself as an adhesive. In particular, by heating the metallic parts and bringing together the hot metal with a thermoplastic polymer, this latter will be melted and will bond to the metal. By holding parts in the right position until the polymer solidifies (even through the application of a weight), it is possible to obtain a green, light, and fast joint. The metal counterpart could be heated using different approaches, e.g., laser source, induction, friction, etc. [6]. The most critical point related to this joining technique is the need to guarantee an adequate bond. A valid approach is the employment of surface treatments for improving the interaction between metallic and polymeric substrates. Various studies have demonstrated that surface treatments allow for improved joint strength. This aspect has been deeply analyzed for adhesive bonding joints, and the importance of a proper surface preparation for improving fracture toughness is well known [7–9]. Surface preparation is also crucial for the thermal direct joining method and several studies in recent years have demonstrated that metal surface preparation leads to significant improvement in joint strength [10–12]. For example, Chu et al. [13] evaluated the influence of laser treatment for improving interaction between SU304 steel and PET bonded through laser joining. In particular, the authors employed a laser source for the realization of micro-pits on metal surfaces. After that, the capability of the polymer to penetrate the micro-pits was evaluated both numerically and experimentally. It was demonstrated that, by developing a proper pit geometry (in terms of width and depth), it is possible to allow the flow of the polymer into the metallic substrates, thus ensuring a mechanical interlocking. Krausel et al. [14] evaluated the influence of sand-blasting treatment for improving shear strength in single-lap joints (SLJs) realized using 22MnB5 steel and PA6 substrates. The thermal direct joint was obtained using induction as a heating source. Mechanical tests demonstrated that the sand-blasting treatment allows shear strength improvement higher than 45%. Zhang et al. [15] analyzed the influence of laser micro-patterning on SLJ strength. Samples were realized using AISI 304 steel substrate and a carbon fiber-reinforced polyamide (PA66-CF), bonded through a laser source. The authors realized a square micro mesh on a metallic substrate and evaluated also the influence of mesh spacing on shear strength. Mechanical tests demonstrated that the micro mesh significantly improves joint strength (up to 374%) thanks to the mechanical interlocking.

In this work, the thermal direct joining method was employed to bond an aluminum substrate with a polymeric 3D-printed adherend. A laser treatment was selected to modify the morphology and wettability of the metal. Surface analysis was carried out through roughness measurements and wettability measurements using the sessile drop technique. Finally, a tailored surface treatment was employed for fabrication of single-lap joints (SLJs), and mechanical testing was carried out to determine the corresponding shear strength.

2. Materials and Methods

2.1. Materials

Hybrid joints with dissimilar adherends were fabricated combining aluminum alloy and polymer substrates. We selected AA6016 aluminum since it is widespread in different industrial applications (e.g., automotive). The main mechanical properties are summarized

in Table 1. Regarding the polymer, 3D-printed polylactic acid (PLA) was selected. The mechanical properties extracted from the datasheet are summarized in Table 1.

Table 1. Mechanical properties of the adherends.

	AA6016	PLA
Young modulus [GPa]	71	1.96
Yield strength [MPa]	220	
Ultimate strength [MPa]	280	32
Elongation at break [%]	12	32.8

To promote material interaction, the aluminum substrate was modified through a laser surface treatment. A laser marker machine, Compactmark G8 (Lasit, Torre Annunziata, Italy), was employed for surface treatment. The machine is equipped with a Yb-fiber source and has a maximum power of 100 W and a maximum scanning speed equal to 3000 mm/s. In addition, the laser frequency ($1/\lambda$) and pulse duration (τ) can be adjusted, as schematically shown in Figure 1a. The laser parameters were modified to identify the best combination for improving surface wettability. In this work, only the laser power and scanning speed were modified through experiments, while pulse duration and pulse frequency were excluded from the analysis and set constant, as explained below.

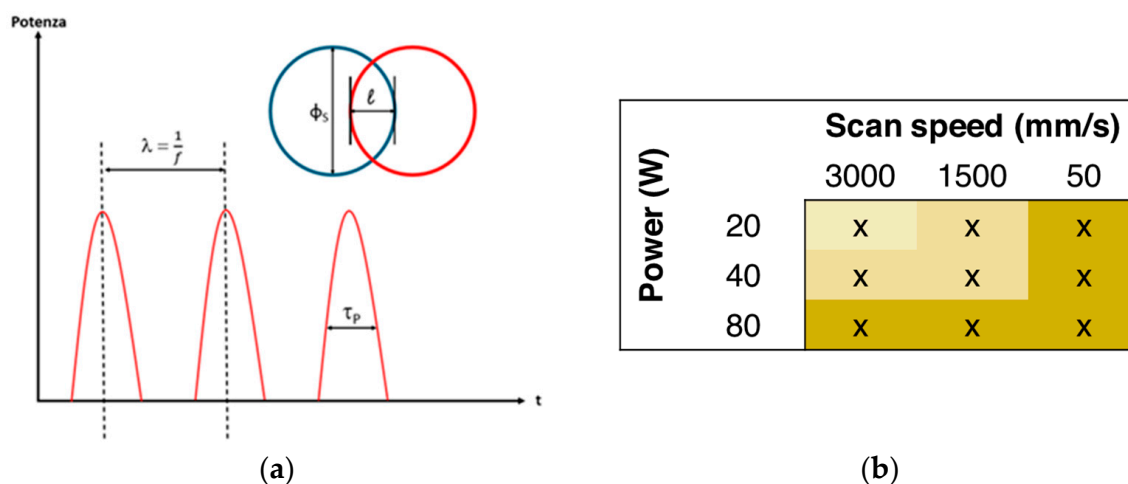


Figure 1. (a) Laser working principle, (b) surface treatment experimental plan.

The experiment plan is summarized in Figure 1b: both laser power and speed were modified in order to cover the entire range available; the laser frequency was modified in function of the selected scanning speed, thus ensuring a spot overlap equal to 50%; and the pulse duration was fixed equal to 350 ns. In addition to the described treatment, it was chosen to evaluate the influence of so-called “cleaning”, i.e., a laser treatment carried out at very low power values and high scanning speed. In fact, previous studies demonstrated that this treatment could improve surface wettability [11,12]. More specifically, it was chosen to introduce cleaning both before and after the laser treatment. Consequently, the experimental plan reported in Figure 1b was executed three times, thus leading to three different configurations: (i) L treatment, which refers to a surface treated only by laser; (ii) C+L treatment, which refers to a treatment carried out on a cleaned surface; and (iii) L+C treatment, i.e., a cleaning treatment carried out after laser treatment.

The influence of laser treatment was evaluated through roughness analysis and contact angle measurements. The optical profilometer UP300 (Rtec, San Jose, CA, USA) was employed for analyzing surface texture. Surface profiles were analyzed to acquire the roughness parameters, i.e., R_a , which is the average value between peaks and valleys

on a surface, and R_z , which measures the difference between the five highest peaks and lowest valleys.

In addition, surface wettability was analyzed through contact angle measurements using a semi-automatic machine, Kruss DSA30E (Kruss scientific, Hamburg, Germany). A 2 μ L-glycerol drop was employed for measuring surface wettability. The contact angle measurement was carried out after drop stabilization, i.e., at 60 s. At least three different measurements were made for each surface treatment.

2.2. Joint Fabrication

Single-lap joints (SLJs) were obtained through the thermal direct joining technique. The joint geometry and dimensions are reported in Figure 2a. The metallic substrate was firstly heated using a hot plate to about 300 °C. After that, the metallic substrate was clamped as shown in Figure 2b such that the overlap area as well as the substrate alignment could be controlled. After that, a weight equal to 4 kg, which corresponds to a 0.128 Mpa pressure on the bonded area, was applied to the overlap area until the assembly cooled down to room temperature. The pressure was ensured also into the cooling down process to avoid joint misalignment or damage due to polymer shrinkage. During the process, the temperature was monitored using a thermocouple.

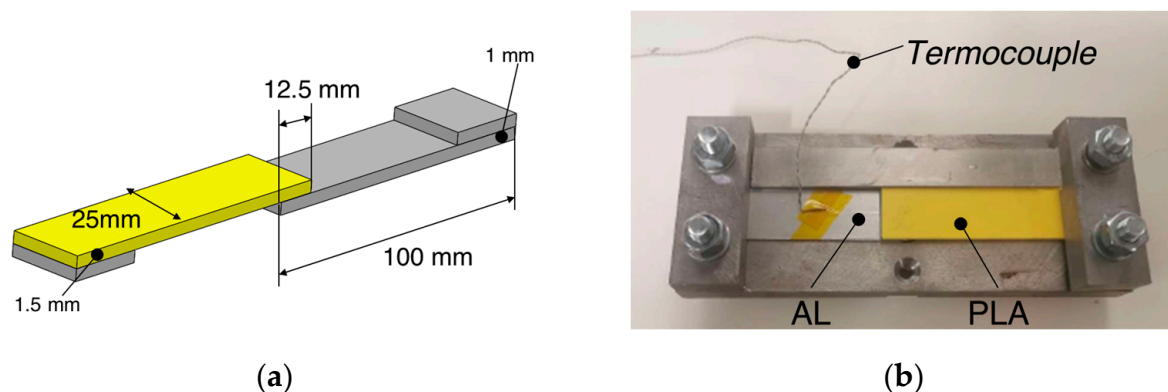


Figure 2. (a) Single-lap joint geometry, (b) clamping and alignment tool employed for joint fabrication.

Mechanical tests were carried out using an electromechanical testing machine equipped with a 5 kN loading cell, and a crosshead speed equal to 2 mm/min was employed (ASTM D1002 [16]).

3. Results

3.1. Surface Analysis

The treated surfaces were analyzed to identify the best combination of the laser parameters. In Figure 3, the roughness measurements are reported.

The roughness measurements demonstrated that laser treatment could affect the surface texture significantly. In particular, by using a low scanning speed combined with high laser power, it was possible to reach a roughness value 17.5 times higher than the as-received (AR) surface. However, by increasing the scanning speed, it seems that the laser power does not affect significantly the roughness value, and its variation is negligible. Regarding the cleaning treatment, it seems that it does not influence the surface characteristics in both configurations, i.e., before or after the laser treatment itself. Similarly, the contact angle measurements are reported in Figure 4.

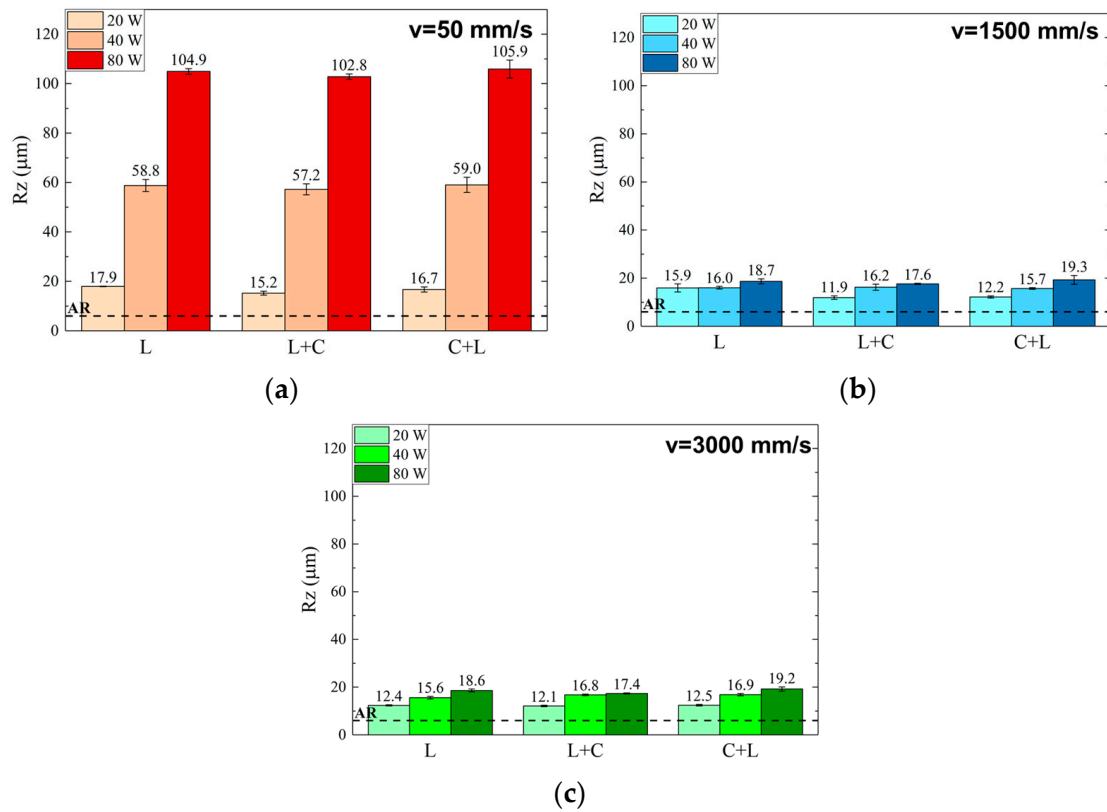


Figure 3. Roughness measurements carried out on laser-treated surfaces using a scanning speed equal to (a) 50 mm/s, (b) 1500 mm/s, and (c) 3000 mm/s. (L: laser, L+C: laser followed by cleaning; C+L: cleaning followed by laser).

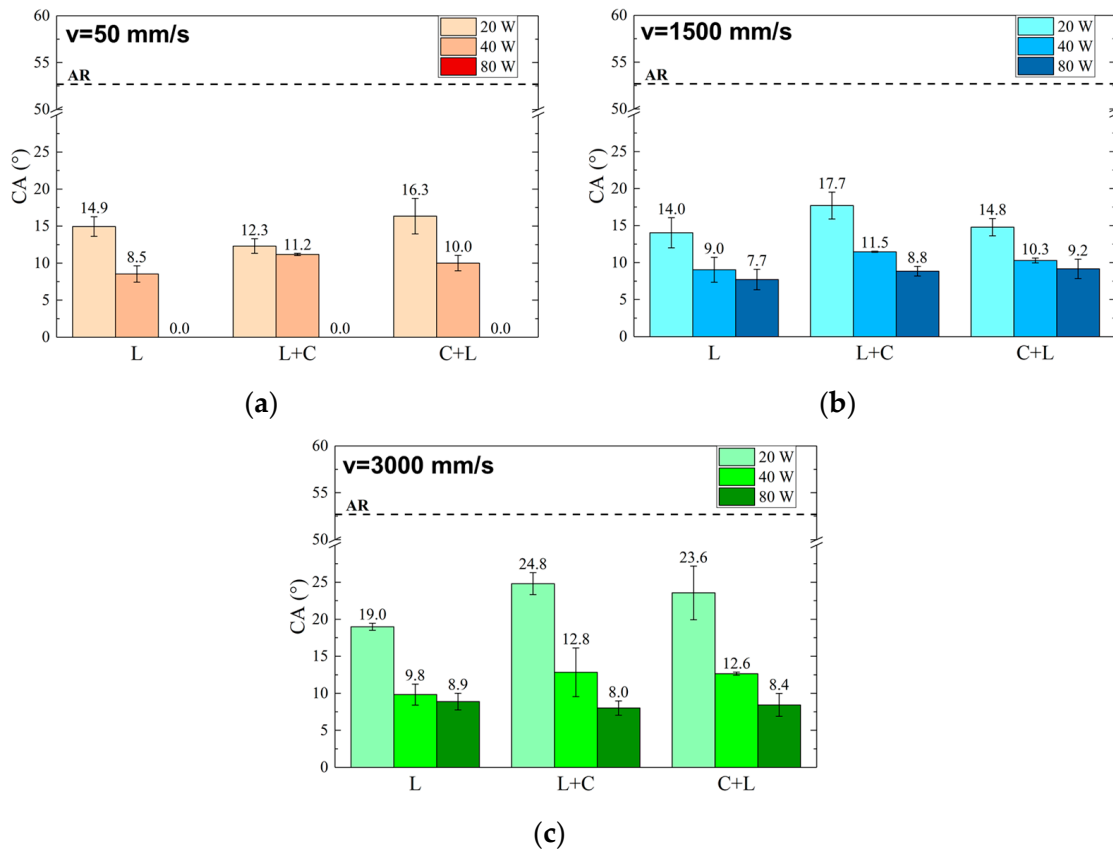


Figure 4. Contact angle measurements carried out on laser-treated surfaces using a scanning speed equal to (a) 50 mm/s, (b) 1500 mm/s, and (c) 3000 mm/s.

Contact angle measurements demonstrated the capability of the laser-treated surface to improve surface wettability. All analyzed surfaces demonstrated a reduction of the contact angle values. As observed for the roughness analysis, the lowest scanning speed allowed the lowest contact angles, i.e., the highest wettability. In particular, the combination of high power and low speed led to full wettability, i.e., a contact angle of zero. This value corresponds to the highest roughness value, thus demonstrating that an optimum surface condition can be obtained by a proper combination of the laser processing parameters. Also in this case, the cleaning treatment influence was negligible, thus the increase in the time requested for cleaning treatment did not correspond to an improvement in roughness/wettability.

Starting with these results, further investigations were carried out around the “optimum solution” extracted from the above analysis, i.e., 80 W and 50 mm/s. After a few iterations, it was found that turning the laser power to 90 W while keeping the scan speed equal to 50 mm/s provided the highest roughness and wettability. These parameters were employed in the surface treatment of AA6016 substrates employed for SLJ fabrication.

3.2. Mechanical Testing

Laser-treated substrates were employed for SLJ fabrication. The shear strength of the samples was compared with the value obtained on AR samples. The results are reported in Figure 5.

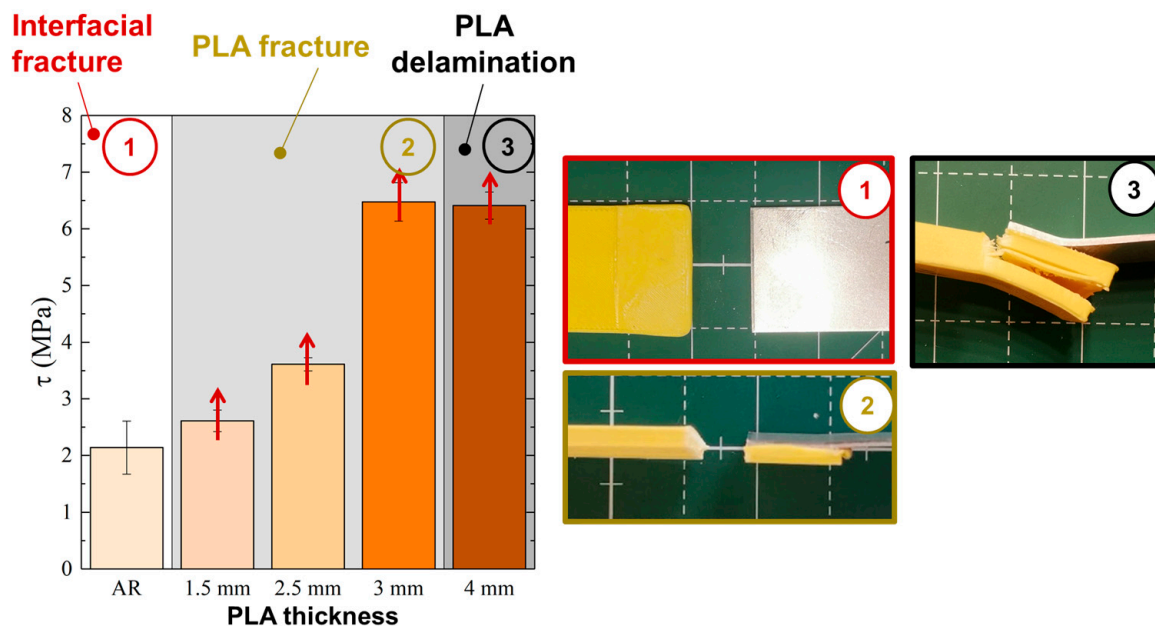


Figure 5. Shear strength and fracture surfaces of SLJs obtained using thermal direct bonding assisted by laser treatment of the metallic adherend.

The SLJ fabricated using the AR substrates exhibited an interfacial fracture with a shear strength equal to 2.14 MPa. Sample failure occurred in a sudden fashion, resembling a brittle behavior. On the other hand, the laser-treated sample failure occurred within the PLA substrate, which suggests that the limiting factor was the PLA strength rather than the joint strength (arrows in the figure indicate that the effective shear stress value is higher than test-end condition).

To mitigate this issue, the PLA substrate thickness was increased, with the goal of reducing the peel stresses that were believed to have contributed to premature PLA failure. Therefore, further experimental tests were carried out by increasing the substrate thickness—up to 4 mm. However, in all analyzed configurations, joint failure still occurred within the

PLA, but there was a progressive increase in the applied load which led to bending and the plasticity of the aluminum adherend.

These results indicate that the interfacial strength of laser-treated joints is significantly higher compared to the as-received condition. However, the tests were unable to provide a reliable estimate of the joints' shear strength due to the complex failure mechanisms observed. Despite the adjustment of PLA thickness, the joints continued to fail within the PLA adherend. Additionally, the yielding of the aluminum adherent contributed to joint rotation, which altered the load path, introducing significant bending, further complicating the interpretation of the results.

4. Conclusions

In this study, we evaluated the influence of laser treatment on improving the shear strength of joints obtained through the thermal direct method. AA6016 aluminum substrate and a PLA substrate were selected for the fabrication of a hybrid joint. Aluminum substrates were treated to improve interaction with polymeric substrates. A laser treatment was selected, and laser parameter variation influence was evaluated. The results of the surface analysis demonstrate that laser treatment offered the possibility to modify surface characteristics significantly. In particular, a combination of a laser scan speed equal to 50 mm/s with a laser power equal to 80 W led to full wettability of the surface, i.e., a contact angle equal to 0 and a roughness value over 17x higher than the AR surface. A further optimization process led to the identification of an optimum laser parameters combination, i.e., 50 mm/s and 90 W. These latter were employed as the surface treatment for AA6016 substrates of SLJ samples. Shear tests were carried out to evaluate the influence of laser treatment on joint strength. All SLJ samples with laser-treated substrates exhibited PLA substrate failure that prevented the isolation and measurement of the joint strength under shear conditions. Nevertheless, the results demonstrate the potential of laser treatment to significantly improve the mechanical behavior of joints. However, the joint geometry employed in this work did not prove suitable for accurately assessing the interfacial strength due to the combined effects of PLA fracture and aluminum plasticity. Therefore, a redesign of the joint geometry is required to eliminate these failure modes and enable a more reliable evaluation of joint strength. Further studies are ongoing to explore alternative geometries and loading conditions.

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