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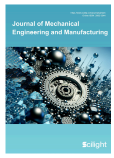

Communication

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Laser Welding of Morphologically Dissimilar Thermoplastic Structures

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Abstract: This work explores a disruptive solution for joining morphologically dissimilar thermoplastic structures (MDTS). The industry uses thermoset adhesives to bond these materials. This approach presents some intrinsic drawbacks (e.g., low automation, lengthy, with low flexibility, prone to human error, may require heat to cure, releases harmful residues/fumes, and may preclude recyclability). This work investigates the potential of an adhesive-free concept based on laser transmission welding for joining morphologically dissimilar thermoplastic structures composed of non-cellular and cellular thermoplastics by controlling the heat input to the foamed thermoplastic and the heat transfer to the non-cellular counterpart. The joint quality was evaluated by performing lap shear testing and scanning electron microscopy to assess joint morphology, and then comparing the results with those of the adhesive-bonded version. Considering the exploratory nature of this work, promising results were achieved, with the best welded joints reaching approximately 74% of the strength of the traditional adhesive solution, establishing a basis for future research to optimize the process.

Keywords: laser welding; thermoplastics; dissimilar structures; joining techniques

1. Introduction

In 2022, nearly 62 million passenger cars were produced worldwide [1]. Many interior car components consist of morphologically dissimilar thermoplastic structures, in which cellular materials (foamed plastics) are adhesively bonded to non-cellular thermoplastic components (usually injection molded thermoplastic panels). Protective equipment, packaging and casing, electronics, and the aeronautical and furniture industries also have products that bond these materials.

The industry uses adhesives (thermosets) to bond these materials, which presents some intrinsic drawbacks. This is a manual or low-automated procedure, which is lengthy and prone to human error. Usually, at the industry scale, it resorts to post-curing heating. This can be associated with emissions that can harm humans and the environment [2,3]. In addition, the dissimilarity between the bonded materials and the binding agent can preclude the recyclability of these structures at the end of their life. Concern about ecological practices is increasing, driving demand for new sustainable approaches.

Plastic welding, particularly laser welding, is still a rapidly developing field of research and development due to the increasing demand for lightweight materials and environmentally friendly technology [4]. Laser welding has gained significant attention as a promising technique for joining thermoplastics due to its precision, efficiency, and versatility [5,6]. Its potential for joining thermoplastics, particularly rigid non-cellular ones, has been explored using the laser transmission welding (LTW) technique [7,8].

In LTW, a laser beam is irradiated onto an overlap joint, passing through a laser-transparent part and being absorbed by the laser-absorbing part, leading to a rise in temperature at the interface and melting of the plastics [9]. LTW focuses on thermoplastics since thermosets cannot be re-fused. Nevertheless, LTW is often used for welding elastomers (such as polyolefin elastomers) and molded fibers [10]. Thus, it is not only a thermoplastic welding process showing potential to weld other types of polymers [9]. The thermoplastics chosen for LTW should ensure laser transmission and absorption [11,12]. Since LTW relies on the thermo-optical relationship between the laser beam and the target material, the target material should not be highly reflective [13]. The portion of the laser beam that is not reflected enters the material. The laser light absorbed into the material propagates and gradually transfers its energy through heat [14,15]. The heat generated in the material can eventually lead to material modifications, melting, or vaporization, as needed for laser welding or cutting [16].

The polymer parts used in the LTW assembly must have different thermo-optical properties: one must be laser-transparent or translucent, and the other must be laser-absorbing (opaque) to the laser radiation (at that specific wavelength) [17,18]. Pereira et al. [8] demonstrated the importance of having a transmissive part with high transmittance to infrared radiation and another with high absorbance to infrared radiation to achieve a successful joint between two PA6 parts in an overlap configuration (PA6 natural and dyed). Nevertheless, it is possible to join two theoretically transmissive materials by exploring all the process parameters. Fernandes et al. [7] demonstrated the importance of the clamping pressure applied between the two parts during welding. Although the achieved strength was lower than that of the base material, no additives, masking agents, or surface modifications were employed. There are a few other examples of welding transparent polymers by employing a thin absorbing interlayer or other appropriate absorbing medium at the interface [9,19,20].

Although several studies have demonstrated the feasibility of LTW for rigid thermoplastics and, in some cases, transparent polymer combinations, these works primarily focus on morphologically similar materials with relatively homogeneous thermal behavior and contact conditions. In contrast, cellular thermoplastics introduce additional challenges associated with their low density, reduced thermal conductivity, and susceptibility to collapse or degradation under localized heating. Consequently, process windows established for conventional thermoplastics cannot be directly transferred to foam-based structures. Furthermore, most previous studies prioritize maximizing weld strength at the expense of preserving foam morphology, which is critical for applications involving cushioning, tactile response, or lightweight structures.

However, regarding the welding of polymeric foams, to the best of our knowledge, only one work in the literature has addressed this challenge. In this rare example, Hopmann and Kreimeier [21] employed the LTW method to join absorbing and laser-transparent closed-cell polypropylene (PP) foams, assessing LTW suitability for foamed components as an alternative to contactless welding methods due to the fragile foam structure. Transmittance and intensity profile measurements of the transparent specimen showed that the transmission of the foamed test specimens is lower than that of compact specimens, which is not impactful for the present study, since the foamed part is the absorbent one. In the same study, Hopmann and Kreimeier [21] highlighted that a possible post-expansion of the enclosed gas during the welding process must be taken into account, as once the surrounding material is melted, the gas can expand due to the increased temperature, leading to defects during solidification. Although the parameters and joint must be adjusted due to the material morphology, this is still a morphologically similar joining. In the literature, welding has never been applied to morphologically dissimilar thermoplastics, which, if successfully achieved, would have massive potential in many key industries.

Therefore, this work investigates, for the first time, the feasibility of laser transmission welding for joining morphologically dissimilar thermoplastic structures composed of non-cellular and cellular polymers. Unlike conventional LTW configurations involving homogeneous or morphologically similar materials, the present approach must accommodate substantially different thermal conductivities, densities, and heat sensitivities between the joined materials. The scientific contribution of this work lies in establishing the initial process feasibility and identifying how laser energy input affects interfacial joining and foam degradation mechanisms. To achieve this, a process-scanning window was explored to define acceptable limits for heat input while balancing joint performance and preservation of foam morphology. Joint quality was evaluated through lap shear testing and SEM observations.

2. Materials and Methods

This work employs materials used in the manufacturing of automotive interior door panels and dashboards, specifically polypropylene (PP) and PP foam. Both are widely used in the automotive industry for interior components and in the commodities market. Natural PP and dark PP foam were supplied in 2.5 mm and 2 mm thick sheets, respectively. The non-cellular PP is a high-crystallinity polyolefin with a density of 905 kg/m^3, while the PP foam has a density of 45 kg/m^3.

Specimens were welded according to the dimensions and lap-joint configuration shown in Figure 1. The laser beam directly irradiates the natural PP (top layer). A single pass was produced with the SISMA SWA-300 pulsed Nd:YAG laser system (1064 nm wavelength). The welding procedure was conducted following a preliminary analysis, aiming to establish the energy thresholds that enable melting of the materials and, conversely, excessive energy input that leads to material degradation. The selected parameter ranges were defined to balance two competing requirements: generating sufficient interfacial melting to promote bonding while avoiding excessive thermal degradation or foam structure collapse. Preliminary trials demonstrated that excessive energy input rapidly induced localized foam collapse and degradation, thereby constraining the upper processing limits. It was confirmed that the energy required to initiate the degradation or decomposition of cellular material is considerably lower than that of non-cellular material. Based on these, a constant beam diameter of 2 mm was defined. Lower diameters would lead to excessive energy densities, even for low energy inputs. The scanning speed was set to 8 mm/s. The parts to be welded are positioned in a jig that ensures uniform, homogeneous contact between them, which is essential for the LTW process. Mechanical clamping was applied using a fixed jig configuration to maintain intimate and uniform contact between the parts during welding. Although the setup did not allow direct quantification of the applied pressure, the same clamping condition (50% of foam deformation) was maintained throughout all experiments to ensure process consistency.

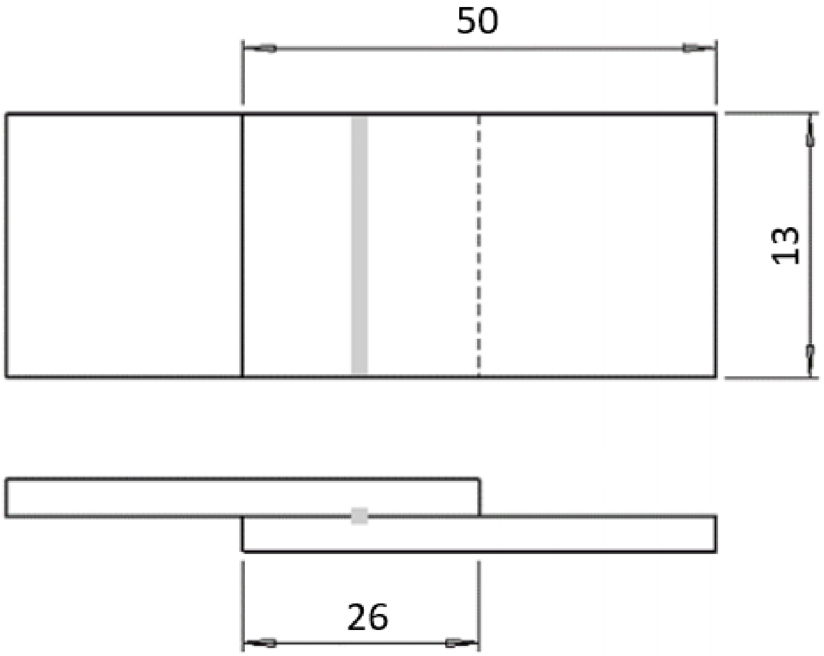

Figure 1. General dimensions of the welded specimens (mm): top layer corresponds to a 2.5 mm thick natural PP directly irradiated by the laser beam, and the bottom layer corresponds to a 2 mm thick PP foam.

For the other parameters (pulse power, pulse width, and laser spot overlapping), a Design of Experiments (DoE) methodology was implemented following the Taguchi method. After establishing the parameter ranges, an L9 orthogonal array with three factors and nine parameter sets was generated. Power, pulse width, and spot overlap were selected because they govern heat input and energy density. Table 1 lists all parameter sets to be used for the welding experiments and their associated energy levels. These were established based on a preliminary trial that helped define the process window limits. In the present work, the process window corresponds to the range of energy inputs capable of promoting interfacial joining without inducing excessive foam collapse or thermal degradation. Five replicas were produced for each set. ANOVA was then performed to assess the statistical significance of each parameter.

The energy values presented in Table 1 correspond to the pulse energy output reported by the laser system. Theoretically, pulse energy is expected to be the product of the pulse duration and the selected percentage of the machine's peak power (12 kW). Although the manufacturer does not disclose the equipment's internal methodology for determining or measuring pulse energy, the machine-reported values are consistent with the expected theoretical trend and were therefore adopted for comparative analysis between parameter sets.

Table 1. Set of laser welding parameters.

Set #	Power (%)	Pulse Duration (ms)	Overlap (%)	Energy (J)
1	8	7	60	7.6
2	8	8	65	8.7
3	8	9	70	9.8
4	10	7	65	8.6
5	10	8	70	9.8
6	10	9	60	11.0
7	12	7	70	9.5
8	12	8	60	10.8
9	12	9	65	12.2

Lap shear testing was performed to assess joint quality using the Shimadzu AGS-X-10 kN universal testing machine. Testing was performed at 1 mm/min, using spacers between the samples and the grips to minimize bending moments around the joint. Joint failure is expected at the interface or within the foam due to its lower strength. To assess weld quality, the mechanical performance of welded joints was compared with that of conventionally bonded samples, produced with a polyolefin adhesive by an automotive supplier under industrial conditions.

Additionally, since the PP foam is typically covered by an aesthetic layer in door panels and dashboards, usually a TPO membrane, samples consisting of PP foam covered with a TPO membrane were welded to PP using the parameters that yielded stronger joints. This allowed us to determine whether the outer layer is affected by the heat.

In addition, samples were analyzed using a Hitachi TM4000 Plus SEM to examine joint morphology. Specimens were mounted on carbon tape and observed under a 15 kV accelerating voltage using a backscattered electron (BSE) detector.

3. Results

The mechanical tests performed on the adhesively bonded samples revealed failure through the foam, with a strength of 1.32 MPa. For the welded specimens, joint strength was higher at lower energy inputs, with parameter set #1 yielding the highest average strength of 0.98 ± 0.14 MPa. (Figure 2). This represents 74.2% of the reference strength. Although the value achieved is lower than that of the adhesively bonded specimen, the obtained strength demonstrates the feasibility of welding morphologically dissimilar thermoplastic structures and provides a promising basis for future optimization. Therefore, given the application and the exploratory nature of the current work, the values obtained offer a positive outlook for future optimizations and provide initial insights.

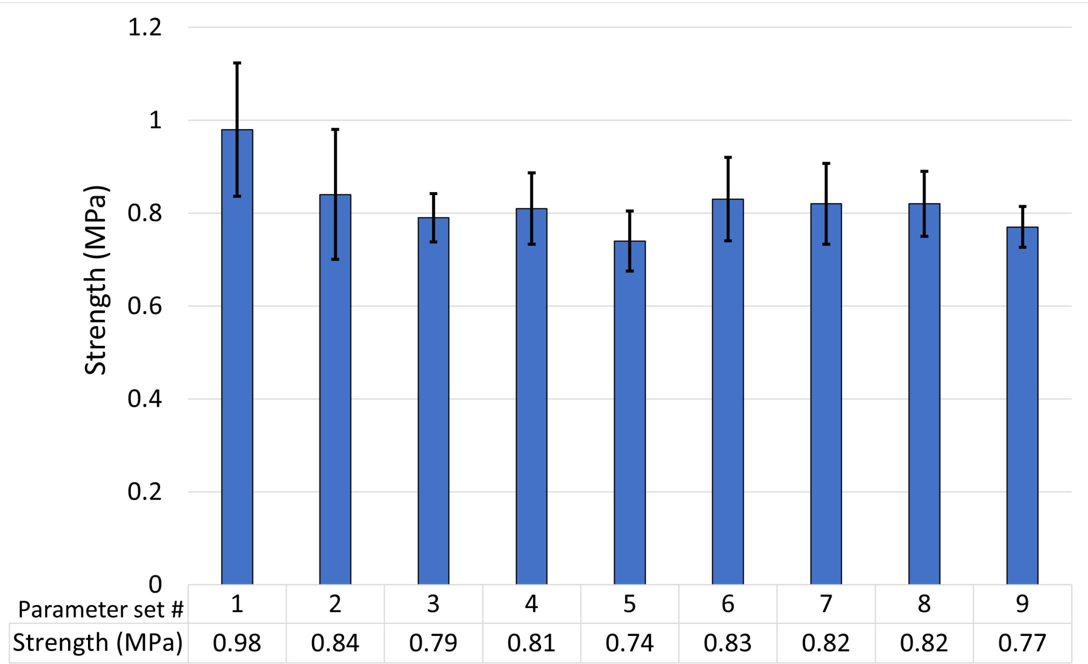

Figure 2. Lap shear strength of welded morphologically dissimilar thermoplastic structures (PP/PP foam MDTS) produced under different processing conditions: (1) 0.98 ± 0.14 MPa; (2) 0.84 ± 0.14 MPa; (3) 0.79 ± 0.52 MPa; (4) 0.81 ± 0.08 MPa; (5) 0.74 ± 0.06 MPa; (6) 0.83 ± 0.09 MPa; (7) 0.82 ± 0.09 MPa; (8) 0.82 ± 0.07 MPa; (9) 0.77 ± 0.04 MPa.

Figures 3 and 4 present the main effects and the interaction plots, respectively. The *p*-values for laser power, pulse width, and laser spot overlap were below the critical alpha value, specifically 0.046, 0.046, and 0.025, respectively, confirming their statistically significant influence on weld joint strength within the explored process window. Among the investigated parameters, overlapping exhibited the lowest *p*-value, suggesting a comparatively stronger influence on heat accumulation and interfacial thermal conditions.

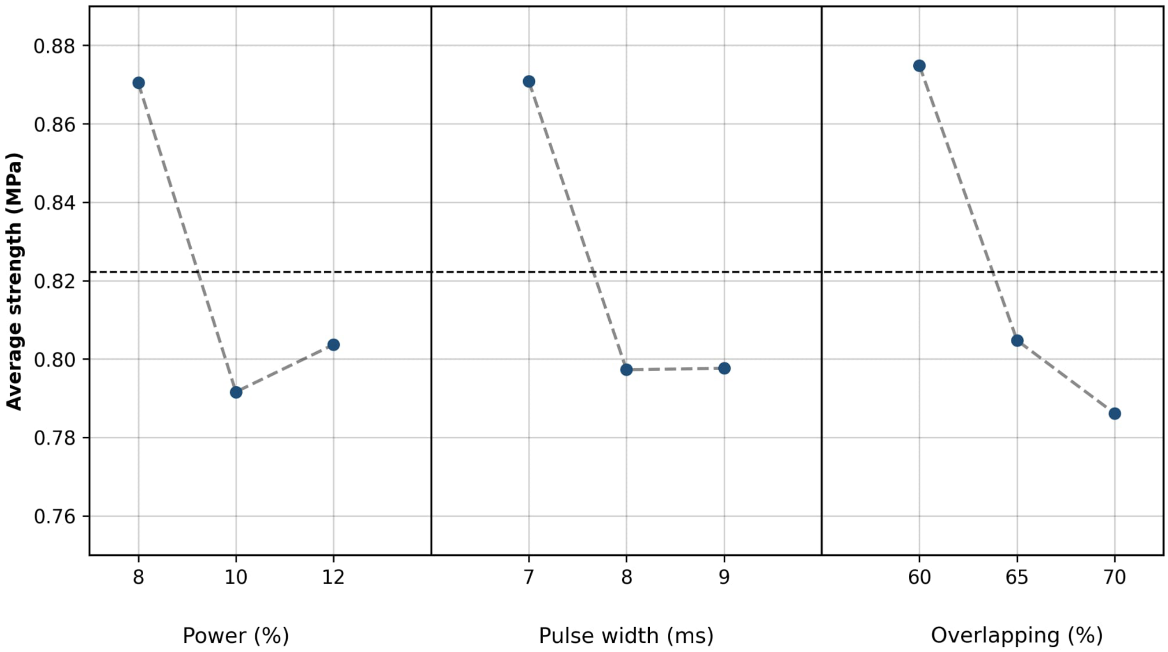

Figure 3. Main effect plot for joint strength depicting strength evolution with power, pulse width, and overlapping. The average strength of 0.822 MPa across all samples is also displayed.

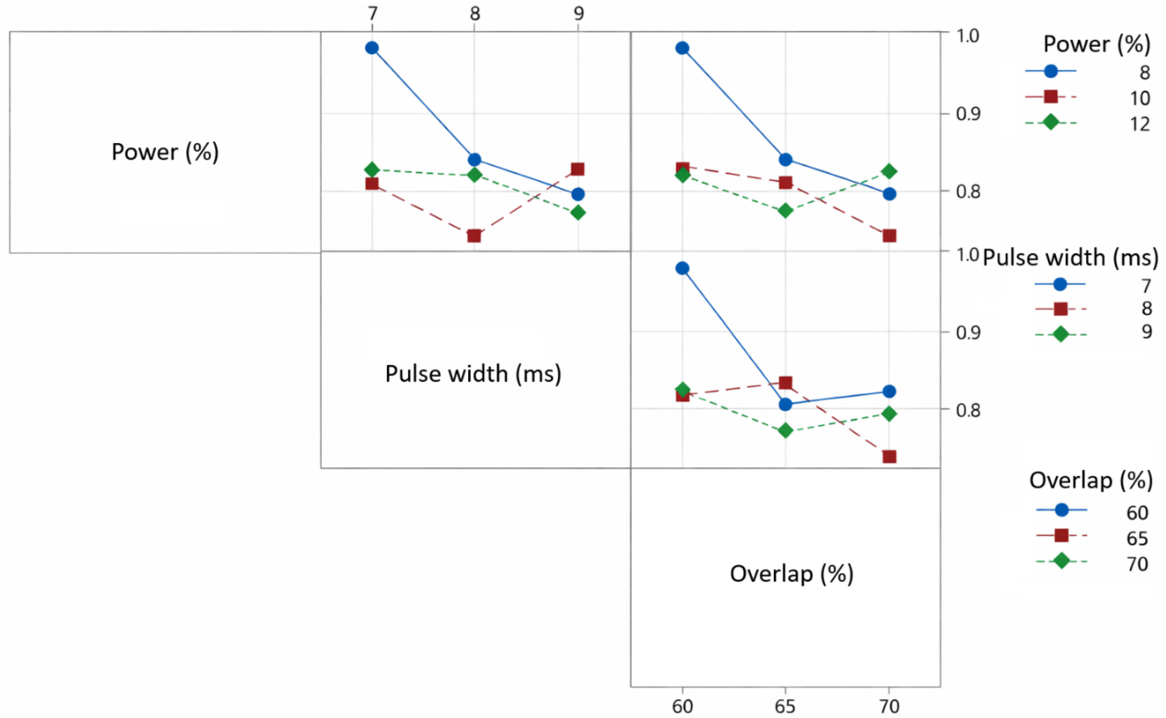

Figure 4. Interaction plot for joint strength depicting how joint strength (MPa) evolves with power, pulse width, and overlap relations.

Although the welded joints did not reach the strength of the adhesive-bonded reference, the achieved performance remains promising considering the absence of adhesives, the fundamentally dissimilar morphologies involved, and the exploratory nature of the process development. Overall, the best outcome was obtained with the least energetic parameter set. This is consistent with the current data, as the best mechanical properties for all two-parameter combinations correspond to the lower-energy settings. This conclusion is supported by both the main effects plot, which displays the effects of each parameter individually, and the interaction plot (Figure 4). These findings also corroborate the SEM observations described next.

The superior performance observed under lower energy input conditions is attributed to the foamed structure's high thermal sensitivity. Due to its low density and reduced thermal conductivity, the foam experiences localized heat accumulation, promoting premature cell collapse and thermal degradation when excessive energy is applied. Although higher energy inputs may increase local melting, they also reduce the foam's structural integrity and limit the formation of a mechanically stable interfacial region. Consequently, the process window for successful joining is relatively narrow and governed by the balance between interfacial melting and preservation of foam morphology.

Figure 5 shows the non-cellular PP surface after lap-shear testing, depicting residual portions of the foam structure at the welded interface. This highlights the joining between the two parts, showing that failure occurred through tearing in the heat-affected zone rather than pure delamination. The sample shown in Figure 5 was welded with parameter set #1, which yielded higher strength. Observations after lap shear testing indicated that higher strengths correspond to more foam on the non-cellular PP surface. Additionally, these observations support the mechanical results, as the strongest joints corresponded to conditions where partial foam remnants remained attached to the non-cellular PP after testing. This suggests that excessive energy input does not improve interfacial bonding but instead promotes foam degradation and weaker failure regions near the interface.

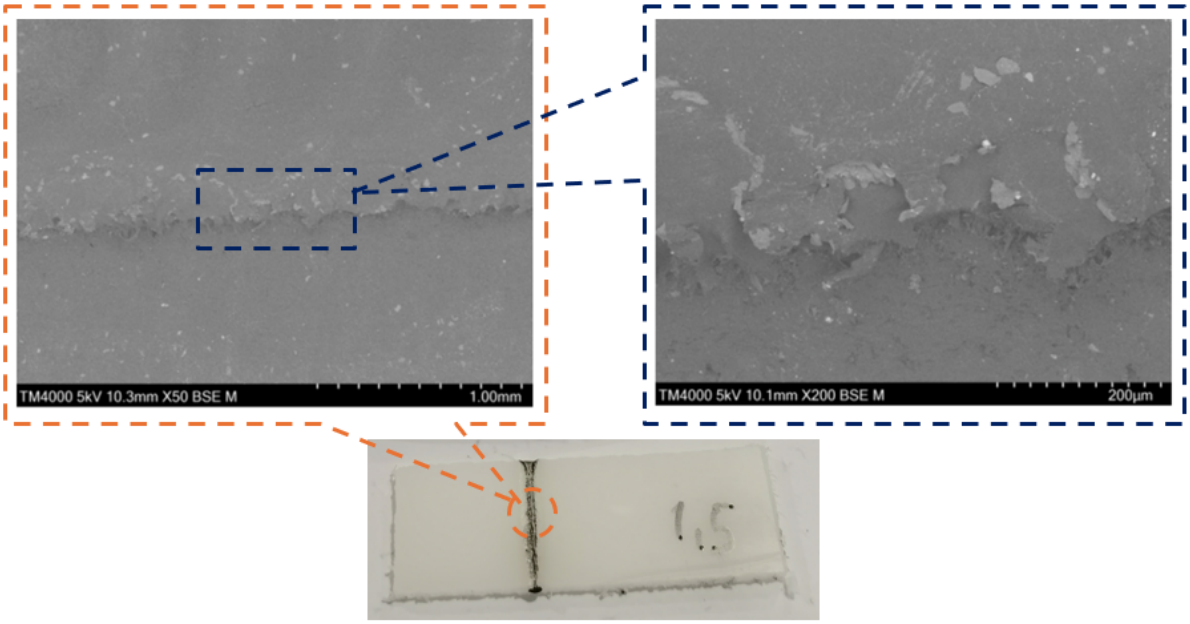

Figure 5. SEM micrograph of PP interface on the laser scanned region with parameter set#1, depicting residual foam after mechanical testing (50× and 200× magnifications).

After visual inspection, the TPO-covered foam still provides the desired aesthetic and tactile experience. It remains unaffected by the heat but shows a noticeable reduction in foam volume beneath due to cell collapse. In future work, the process parameters can be optimized, and the laser trajectory can be designed as a hidden part of the assembly if this is identified as an issue.

From an industrial perspective, the proposed process offers potential advantages regarding automation, cycle time reduction, process flexibility, and recyclability compared with conventional adhesive bonding. Since LTW is already implemented industrially for thermoplastic joining, adapting the process to morphologically dissimilar structures may facilitate integration into existing production environments. Nevertheless, additional optimization and robustness studies remain necessary before large-scale implementation.

4. Conclusions

This work addresses a relevant gap in the literature by proposing an adhesive-free methodology for welding morphologically dissimilar thermoplastic structures (MDTS). It enabled the joining of MDTS, demonstrating the method's potential for lower lead times as a flexible, easily automated process, while also eliminating potentially harmful elements and facilitating the recyclability of these structures. Laser transmission welding proved feasible, demonstrating outcomes that were previously unanticipated and not reported in the literature. It produced joints with mechanically meaningful strength for exploratory evaluation and potential low-load applications, while highlighting the need for further process optimization.

This work demonstrated, for the first time, the feasibility of laser transmission welding for joining morphologically dissimilar thermoplastic structures composed of non-cellular PP and PP foam. The best processing condition yielded a joint strength of 0.98 ± 0.14 MPa, corresponding to approximately 74% of the adhesive-bonded reference strength. The results showed that lower energy inputs favor joint quality by limiting foam collapse and thermal degradation while still promoting sufficient interfacial melting. These findings establish the initial process feasibility and provide insight into the relationship between laser energy input and preservation of foam morphology. Although the explored process window remains limited and further optimization is required, the proposed approach demonstrates strong potential as an adhesive-free, automatable, and recyclable joining solution.

Nevertheless, this work presents some limitations that should be acknowledged. The parameter window explored remains limited, and the influence of additional variables, such as clamping pressure, beam trajectory, and thermal field evolution, was not investigated quantitatively. Furthermore, the study focused on demonstrating process feasibility rather than achieving full process optimization. Future work should therefore include thermal monitoring, expanded process optimization, and long-term performance assessment of the welded structures.

Although this study focused on PP and PP foam, the proposed approach may potentially be extended to other thermoplastic systems involving cellular and non-cellular morphologies. However, the feasibility and process window will strongly depend on the thermo-optical and thermal properties of the selected materials. Overall, a previously unreported joining approach was successfully demonstrated, achieving mechanically meaningful joints despite severe thermal and morphological mismatches between the materials.

Author Contributions

Conceptualization, F.A.O.F; methodology, F.A.O.F. and C.A.; validation, F.A.O.F. and A.B.P.; formal analysis, F.A.O.F., A.B.P.; investigation, A.J.O.F., C.A., and F.A.O.F.; re-sources, F.A.O.F. and A.B.P.; data curation, C.A.; writing—original draft preparation, C.A., A.J.O.F., and F.A.O.F.; writing—review and editing, F.A.O.F., A.B.P.; visualization, C.A. and A.J.O.F.; supervision, F.A.O.F: and A.B.P.; project administration, F.A.O.F.; funding acquisition, F.A.O.F. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

Data is contained within the article and further requests can be made to the authors.

Conflicts of Interest

The authors declare no conflicts of interest.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

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