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Laser hybrid joining of plastic and metal components for lightweight assemblies

J. Rauschenberger[a]*, A. Cenigaonaindia[a,b], J. Keseberg[a], U. Gubler[a], F. Liébana[b]

[a]LEISTER Technologies AG, Galileostr. 10, 6056 Kägiswil, Switzerland
[b]Tecnalia Research and Innovation, Parque Tecnológico de Bizkaia, 48170 Zamudio, Spain

Abstract

Plastic-metal hybrids are replacing all-metal structures in the automotive, aerospace and other industries at an accelerated rate. The trend towards lightweight construction increasingly demands the usage of polymer components in drive trains, car bodies, gaskets and other applications. However, laser joining of polymers to metals presents significantly greater challenges compared with standard welding processes.

We present recent advances in laser hybrid joining processes. Firstly, several metal pre-structuring methods, including selective laser melting (SLM) are characterized and their ability to provide undercut structures in the metal assessed. Secondly, process parameter ranges for hybrid joining of metals (steel, stainless steel) and polymers (MABS, PA6.6-GF35, PC, PP) are given. Both transmission and direct laser joining processes are employed. Lap-shear test results are shown that demonstrate that joint strengths exceeding the base material strength (cohesive failure) can be reached routinely with metal-polymer joining. Weathering test series prove that such joints are able to withstand environmental influences typical in targeted fields of application. The obtained results pave the way toward implementing metal-polymer joints in manufacturing processes.

Keywords: Laser hybrid joining, polymer metal joining, plastic metal joining, metal surface texturing, selective laser melting

* Corresponding author. *Tel.:* +41-41-662-7-537.
E-mail address: jens.rauschenberger@leister.com.

1. Introduction

Current industrial necessities are demanding new innovative manufacturing solutions in order to extend the use of polymer-polymer based composites in product manufacturing, and to substitute all-metal parts by new innovative products with improved characteristics [1, 2]. These potential applications can be clearly seen in several relevant industry sectors. For example, the automotive industry currently produces polymer components such as door modules, seat adjustments, instrument-panels and bumper cross-beams [3, 4], other sectors such as the aeronautic industry seek to join directly fiber-reinforced thermoplastic polymers (FRTP) materials with aluminum and titanium metals to reduce weight in the manufactured structures [5]. The electronics and white good industries seek to increase polymeric parts in order to add new functionalities or reduce manufacturing costs [6]. FRTP materials can provide most of the desired properties, such as improved high-strength/lightweight ratio, better corrosion resistance, and lower manufacturing cost, as well as environmental considerations including lower raw material and energy consumption throughout the entire product life cycle. However, different factors still limit the complete substitution of all-metal components by plastic materials, especially when high mechanical forces with variable direction and timescales are present. In these situations, the use of hybrid metal-polymer structures turns out to be a reasonable solution to achieve the required goals. On the one hand, metallic components withstand high loads, and on the other hand the polymeric part provides processing flexibility, low cost and desired mechanical characteristics [7, 8, 9].

Current industrial technologies for joining dissimilar materials have shown several manufacturing limitations [10]. For example, adhesive bonding frequently applies environmentally harmful or health-endangering chemicals and requires long curing periods which elevate energy consumption and manufacturing cost. Mechanical joins, such as rivets, bolts or screws, besides their simplicity introduce stress concentration areas with stress peaks around bore holes and considerably increase component weight. Other mass production technologies, extensively used in the industry, such as the over-injection molding processes require expensive molding or tooling and have low flexibility when product design changes or product repairs are necessary [11].

Laser technology has shown a great potential to directly produce hybrid polymer-metal bonds, avoiding several of the major limitations of traditional hybrid manufacturing technologies. Thanks to the ability to apply the laser energy with high accuracy onto components with complex geometries and directly attach the entire contact area between the dissimilar materials, it is possible to eliminate external additives or chemicals, as well as to avoid undesired heavy mechanical elements, such as screws or bolts [12, 13].

In this way, the laser joining technology firstly developed at the Joining and Welding Research Institute of Osaka University [14] demonstrated the potential for achieving several polymer-metal hybrids between stainless steel and different thermoplastics such as PET, PA6 or PP [15-18]. Generally, the process typology is divided in two categories: laser transmission joining (LTJ) and laser conduction joining (LCJ), depending on the polymer optical transmission properties and metal heat conduction capacity. In LTJ, the polymeric composite must be highly transparent at the applied laser wavelength, so that the joining area can be directly targeted and heated by applying the laser radiation through the polymer composite, avoiding any plastic material damage. In the LCJ method the laser targets the non-transparent partner, typically the metallic component, and the heat is transmitted through the bulk material up to the joining surface by heat conduction. In this case the process efficiency is highly dependent on the metal thickness and heat conduction characteristics [19, 20].

Another relevant research area of direct hybrid bonding processes is the characterization of the factors affecting adhesion mechanisms in direct metal-polymer joining in order to develop strategies to improve the mechanical performance and determine the durability of the produced hybrids. In this direction, some authors identified the existence of mechanical adhesion (anchor effect), as well as other secondary unions, such as chemical bonding and Van der Waals forces. The first adhesion mechanism is directly influenced by the metal surface structure, such as grooves or surface roughness. An important part of current research work is focused on improving the joining resistance by enhancing the surface roughness and structure characteristics. The second mechanism is related to the influence of physical and chemical material characteristics, such as polymer-metal compatibility or the influence of environmental factors such as temperature and humidity on the join strength [14, 21].

The present work deals with both problems. Firstly, different texture types were applied with the aim of improving the metal surface characteristics and increasing the mechanical adhesion of different polymer-metal hybrids. Secondly, successfully attached material combinations were exposed to climatic factors in order to analyze their influence on the join durability / reliability.

2. Experimental Procedure

2.1. Test materials

In order to carry out the experimental trials and analyze the feasibility of laser joining processes, four polymeric materials (reinforced and naturals) were selected: Methyl methacrylate acrylonitrile butadiene styrene (MABS), polyamide 6.6-GF35 (PA 6.6-GF35), polypropylene (PP) and polycarbonate (PC). The polymeric test samples were produced by injection molding and basically are rectangular flat sheets of 80mm x 30mm with a variable thickness that covers a range between 1mm and 4mm, as described in Figure 1.

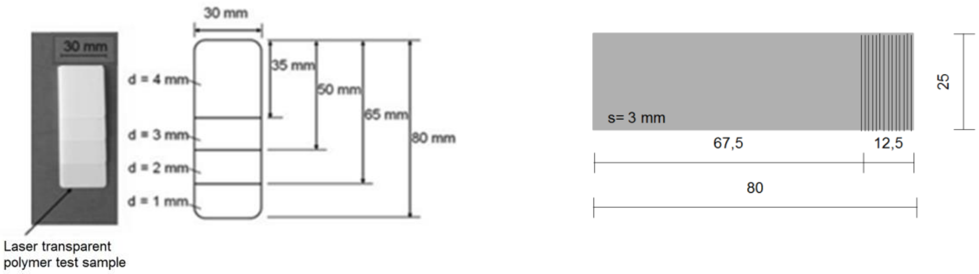

Figure 1. (a) Laser transparent polymeric test sample, (b) Schematic of the metal test sample.

Two of the metallic test samples are rectangular flat sheets of $80x25x3mm^3$ and were made of low-alloyed steel 1.0301 with the designation C10 and stainless steel 1.4401 with the composition X5CrNiMo17-12-2. These samples were surface-textured, using the NRX surface structuring technology and the selective laser melting method, with the aim of enhancing their surface adhesion properties. A third stainless steel (1.4306) sample of $80x25x1mm^3$ was textured using the ConiPerf metal punching technology. All the material combinations were joined with the polymers in an overlapping configuration, with a contact area of $25x12.5mm^2$ as shown in Figure 1.

2.2. Texturing process

The metal surface texture and geometries were modified using three different surface structuring technologies: The NRX and ConiPerf commercial structuring technologies, and the selective laser melting (SLM) method.

The NRX technology, developed by Nucap Industries [22], uses a specially tailored roller tool with tiny chisels machined on the surface. When the roller is moved and pressed against a metallic component, it produces hooks on the material surface that can improve the adhesion resistance in material direct bonding processes. The technology is able to treat large metal sheets at 5m/s producing homogeneously distributed and shaped hooks with a Velcro type structure. In this case, the texture was of 0.7mm height (Figure 2a).

In the same way, selective laser melting (SLM) was used to produce layer-by-layer a complex 3D structure geometry from a CAD file (Figure 2b). The technology uses a thin uniform layer of metal powder, which is applied and welded to the surface of a metal sample, according to a specific laser path programmed in the CAD drawing. Once the metal powder is welded and solidified, a new material layer is applied and welded onto the previously manufactured surface, thus increasing the material height. The generated metal surface texture protrudes by 1 mm over the base material surface (Figure 2b). Due to the manufacturing process, micro-structures are generated at the side walls of the protrusions which function as under-cuts for improving adhesion in the join.

Thirdly, perforations of approximately 1mm of diameter and with a triangular profile set off the metal surface were created using the ConiPerf technology developed by Andritz AG. This process is a mechanical punching process, that can be applied to plate thicknesses up to many times as thick as the openings are large (Figure 2c).

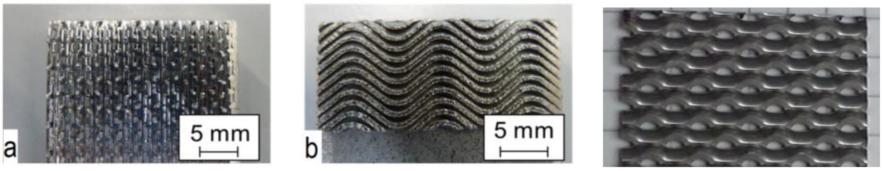

Figure 2. (a) Nucap NRX structure [22], (b) Selective laser melting structure, (c) Andritz ConiPerf structure.

2.3. Experimental setup and procedure

The laser transmission joining process was performed using a LEISTER NOVOLAS Basic AT laser welding system that can provide a maximum laser power of 600W at 940nm wavelength. The laser head generates a line beam focus of 20mm length and ~1mm width, thus providing a maximum laser intensity of 31W/mm^2. In order to carry out the trial weldings, a specific clamping device with a pneumatic cylinder was used, capable of exerting a constant force of 900N. This clamping allows for working in two different modes: one with a standard upper glass configuration and a second with a specially developed upper pressuring metal element with a square hole of 12.5x25mm^2 that lets the laser pass through and impinge directly on the components (Figure 3b).

The first setup (standard configuration) was applied to join metals with transparent polymers using the LTJ process, whereas the second configuration was mounted to join metals with polymer composites using the LCJ method. Additionally, an optical pyrometer was mounted next to the laser head, pointing at a fixed static position of the metal surface in order to get information on the processing temperature (Figure 3a).

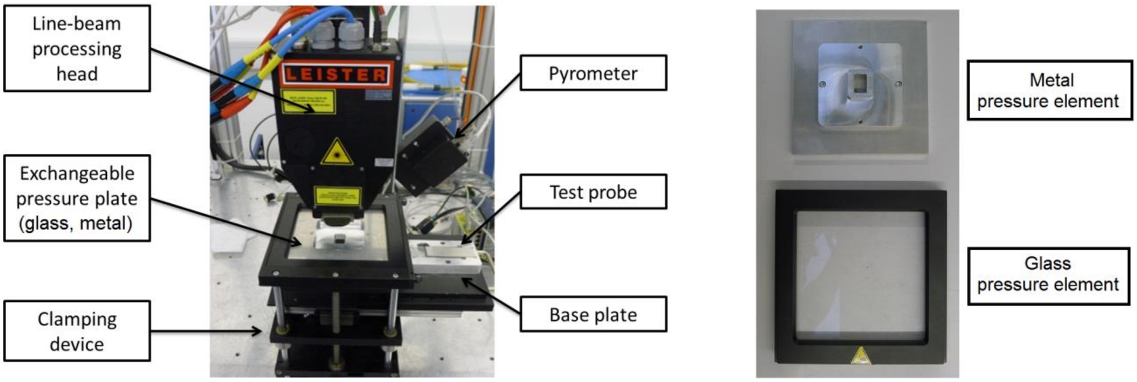

Figure 3. (a) Overall setup for hybrid polymer-metal joining, (b) Clamping pressure elements.

During the joining experiments, the laser path described a simple go-and-return trajectory of the line beam, with a linear displacement of 25mm of length, covering the entire width of the metal test sample (25mm), as shown in Figure 4 (black arrows).

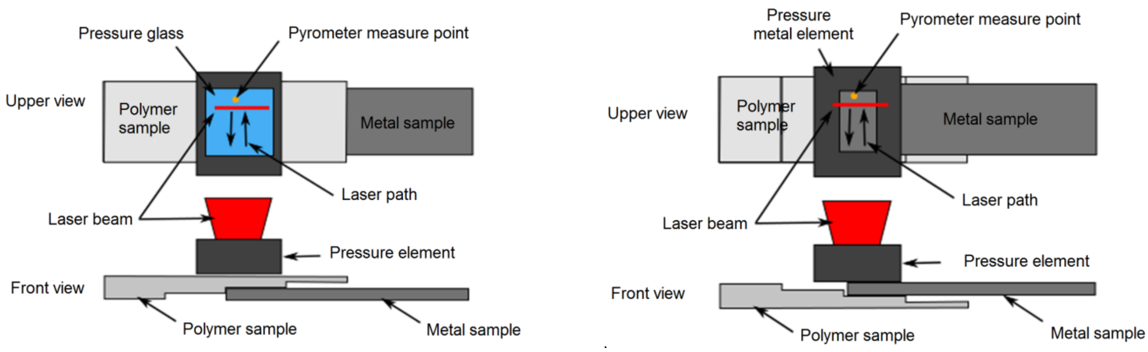

Figure 4. (a) Machine setup for LTJ, and (b) LCJ methods.

The test materials were divided in two groups, according to the difficulties of applying the laser joining process. The first group includes PP, PA6.6-GF35 and MABS thermoplastic polymers, which have shown high laser energy transmission at 940nm wavelength and as a consequence were applicable to the laser transmission joining process (Figure 4 left). Although PC also shows good laser transmission properties, it was excluded from the LTJ process due to the difficulties of obtaining good joins without suffering burns or material degradation. All test trials performed with PC resulted in burning or degrading around the texture protrusions prior to obtaining any acceptable joins of the hybrid compound. In particular for the NRX texturized metal samples, a homogenous thermal field was impossible to obtain in the LTJ configuration. The direct laser heating of the metallic hooks in the NRX texture produces sparks due to the excessive heating of the metal peaks, which always resulted in polymer damage or burn around the laser heated hooks.

Thus, the LTJ technique was applied to attach MABS, PP, and PA6.6-GF35 with all five metal types, while the LCJ method was applied to produce hybrids between PC and four of the textured metal types.

The joining tests were performed applying a constant laser power of 500W to the laser path in all welding experiments. The objective of the programmed heating strategy was to produce a uniform temperature field at the joining area. In all performed bonding experiments, the return speed always was set 1.5-times faster than the go movement speed in order to avoid any excessive heating of the materials interface and the consequential polymer damage during the laser return movement.

The study of the influence of climate exposure was performed after joining all test samples using the parameters of

Table 1. The produced hybrid compounds were exposed for 24h to a humidity and temperature cycle (Figure 5) in a climate chamber in order to study the influence of water absorption and temperature in the material combinations and surface structures. Finally, all the joined hybrid bonds were shear stress tested and the results were analyzed against previous experiments without climate exposure.

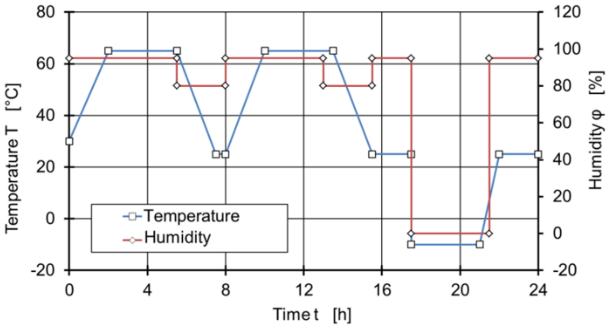

Figure 5. Temperature and humidity climate exposure cycle.

3. Results

With the aim of establishing the most suitable laser energy input *E* for producing optimal hybrid compounds, the laser velocity was varied during both LTJ and LCJ experiments. The found optimal processing parameters and the obtained average shear stress values for the 2mm thickness polymer section (Figure 1) are described in

Table 1.

Figure 6. Shear stress tests of polymer metal hybrids.

The mechanical properties of the compounds were evaluated performing shear stress tests, as depicted in Figure 6. For each successful bonding parameter, four test repetitions were performed in order to reduce the error and study the dispersion of the mechanical data.

All tests, except for PA6.6-GF35 with NRX- and ConiPerf-structure combinations, resulted in cohesive failure, i.e. the failure occurred in the base polymer material, not at the join.

Table 1. Processing parameters and average shear stress values.

	PA6.6-GF35				**MABS**				**PC**				**PP**			
	V_{go} (mm/s)	**V_{return} (mm/s)**	**E (kJ)**	**Shear Stress (kN)**	**V_{go} (mm/s)**	**V_{return} (mm/s)**	**E (kJ)**	**Shear Stress (kN)**	**V_{go} (mm/s)**	**V_{return} (mm/s)**	**E (kJ)**	**Shear Stress (kN)**	**V_{go} (mm/s)**	**V_{return} (mm/s)**	**E (kJ)**	**Shear Stress (kN)**
SS_ SLM	5	7.5	4.2	6.5	8.5	12	2.5	2.5	2	3	10.4	3.8	15	22	1.4	1.5
S_ SLM	5	7.5	4.2	4.6	8	12	2.6	2.4	2	2.5	11.6	3.7	9.5	14	2.2	1.4
SS_ NRX	5	7.5	4.2	3.7	7.5	11	2.9	1.9	2.5	3.5	8.3	3.4	5	7.5	4.2	1.4
S_ NRX	6	9	3.5	1.5	4	6	5.2	2.3	2	3	10	3	10	15	2.1	1.4
SS_ coniperf	5	7.5	4.2	2.7									8	12	2.6	1.6

E(kJ): Laser input energy during joining process

P(W): Laser power

V_{go}(mm/s): Laser line beam go speed

V_{return}(mm/s): Laser line beam return speed

L(mm): Laser line beam movement/displacement length

SS: Stainless Steel

S: Steel

SLM: Selective Laser Melting-textured metal

NRX: NRX-textured metal

coniperf: ConiPerf-textured metal

Feeding speed and laser power, resp. energy are related as follows:

$$E(kJ) = P(W)x\left(\frac{L(mm)}{V_{go}(\frac{mm}{s})} + \frac{L(mm)}{V_{return}(\frac{mm}{s})}\right)/1000 \quad (1)$$

$$E(kJ) = 500x\left(\frac{25}{V_{go}(\frac{mm}{s})} + \frac{25}{V_{return}(\frac{mm}{s})}\right)/1000 = 12.5x\left(\frac{1}{V_{go}(\frac{mm}{s})} + \frac{1}{V_{return}(\frac{mm}{s})}\right) \quad (2)$$

The following diagram shows the mechanical test results without weathering exposure:

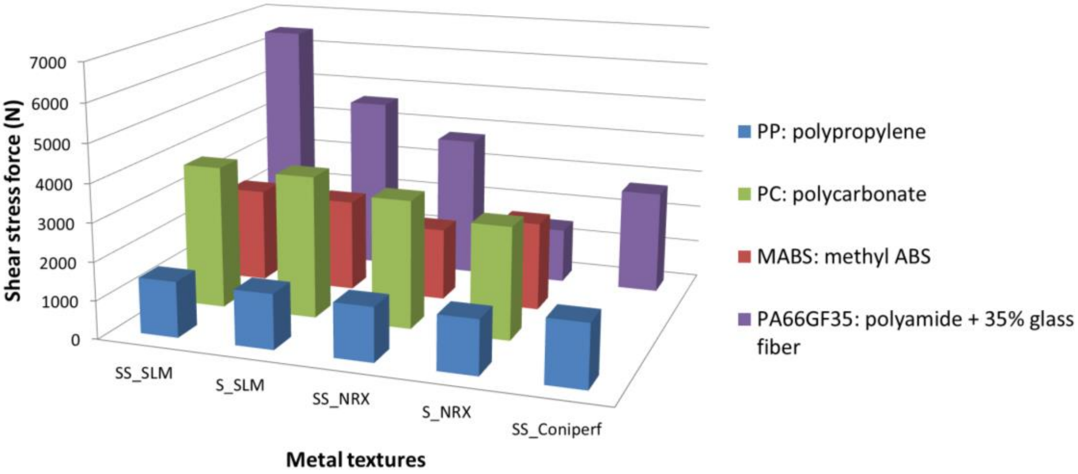

Figure 7. Average shear stress test results.

On average the best mechanical results (6.5kN) were achieved with the selective laser melting textures in the material combination stainless steel combined with PA6.6-GF35. The weakest average resistance (approx. 1.4kN) was obtained combining PP with the rest of the metals and structures. Polycarbonate (3.5kN) and MABS (2.3kN) both showed medium resistance values in shear stress experiments, although PC withstood higher shear stress loads.

The PA6.6-GF35 showed the largest shear stress variation depending on choice of material type combination and metal surface texture, ranging from 6.5kN for SLM-textured stainless steel of maximum average resistance to 1.5kN for NRX textured steel. The ConiPerf structure with PA6.6-GF35 provided 2.7kN of shear stress force, the lowest among all stainless steel samples. This behavior is explained by the fact that the join fails at the bonding interface. PP showed the lowest shear stress variation to choice of material and texture. The average maximum resistance was almost unchanged with texture or metal type variation. In case of PC and MABS combinations, a relatively regular mechanical performance was obtained with the different material and texture combinations, but the SLM texturing technology produced better results than the NRX.

Finally weathering test experiments were performed for the SLM and NRX textured test samples. Using the joining parameters of

Table 1 the following results were obtained:

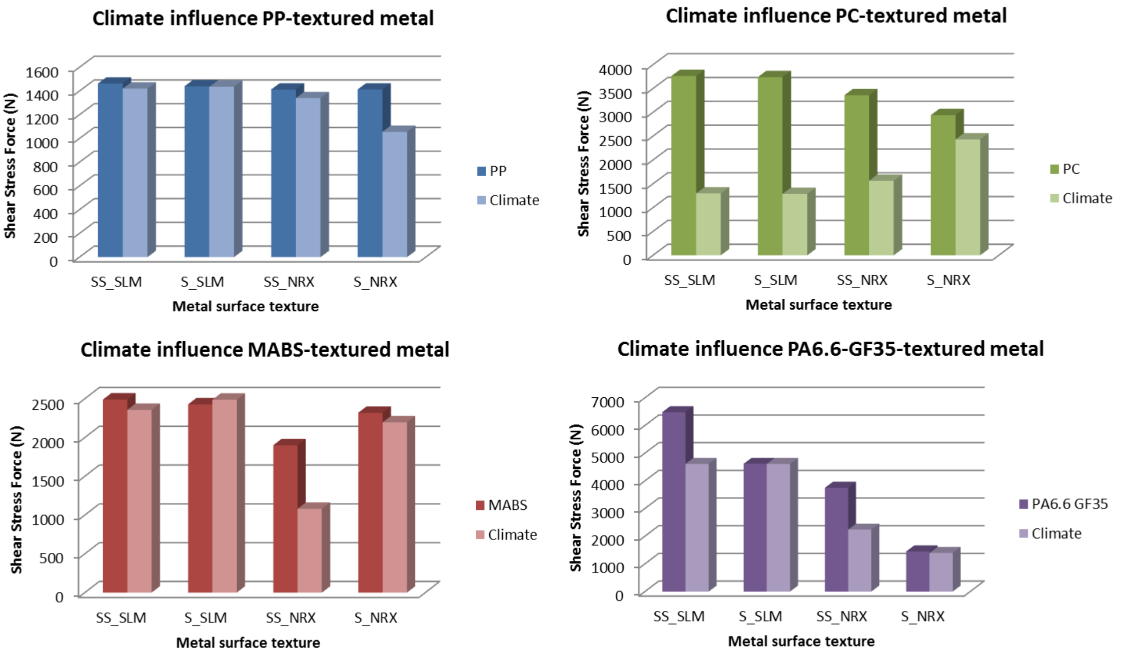

Figure 8. Influence of climate exposure on joining resistance.

PP and MABS materials showed almost no resistance reductions after temperature and humidity exposure, especially when joined with SLM structured metal. PC and PA6.6-GF35 materials showed on average worse shear stress performance, in particular PC material joined with SLM structured metal, which produced 30% of resistance reduction. After climate exposure, PA6.6-GF35 has the highest value of water absorption of 3.5% of the volume which likely explains the reduction in bond resistance, in particular for stainless steel (Figure 8).

4. Conclusions

In this paper, a novel experimental study on the applicability of selective laser melting and two mechanical surface structuring techniques as new approaches to laser joining of hybrid polymer-metal compounds was presented. The conducted experiments show that surface pre-treatment techniques are able to increase considerably the mechanical resistance of the produced hybrids. Moreover, it was demonstrated that the material type and weathering effects, such as temperature and humidity, are relevant and need to be studied in more detail in order to ensure the reliability and performance of the produced joins.

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