Lasers in Manufacturing Conference 2021

Laser microdrilling of thin aluminum sheets for metal-composite adhesion promotion

Ares, Félix[a*]; Coto, Ivette[a]; Delgado, Tamara[a]; Gontad, Francisco[a]; Mera, Laura[a]; Romero, Pablo[a]; Vidal, Sara[a]; Massé, Pascal[b]; Otero, Nerea[a]

[a]AIMEN, Polígono Industrial de Cataboi SUR-PPI-2 (Sector) 2, Parcela 3. 36418, Pontevedra, Spain
[b]Rescoll, Société de Recherche, 8 Allée Geoffroy Saint Hilaire, 33615 PESSAC CEDEX

Abstract

Thin (200 µm) aluminum sheets were drilled using a 1070 nm, CW fiber laser to improve hybrid metal-composite adhesion. The laser beam was guided by a BEO D35 laser cutting head. Micro holes of several diameters (40 – 220 µm) were generated with different spacing among them. The aluminum sheets were later coated with an adhesion promotion spray and thermoformed with a thin (200 µm) Carbon Fiber Reinforced Polymer (PA66) tape. InterLaminar Shear Strength (ILSS) and Single Lap Joint (SLJ) tests were performed on the following thermoformed samples: 1) Drilled, uncoated samples, 2) Non-drilled, coated samples, 3) Drilled, coated samples. The results show that samples that were neither coated nor drilled lack the necessary adhesion for the tests. Additionally, a significant adhesion improvement for the drilled, coated aluminum samples is accomplished, reaching up to 100% higher apparent interlaminar shear strength than plain, coated samples. Finally, the pattern that provided the best ILSS values was replicated with a ns pulsed fiber laser, resulting in an equally strong bonding, while increasing productivity tenfold.

Keywords: Micro drilling; Hybrid joining; Laser functionalization;

1. Introduction

The transport sector is under constant pressure to produce innovative lightweight structural solutions that improve vehicle fuel consumption. Single-material structural components in vehicles can be replaced, advantageously, by layered integrated multi- material systems. When properly selected and designed, these

* Corresponding author. Tel.: +34 986 344 000; fax: +34 986 337 302.
E-mail address: felix.ares@aimen.es.

layered composite-metal hybrid materials enable a significant weight reduction and consequently lower CO_2 emissions. Besides the benefits in weight and stiffness, the transition from an all-metal or composite bulk to a multi-layer hybrid metal/composite has already been shown to provide advances in crashworthiness, impact, strength, acoustic and vibrational performance in automotive and aerospace components and assemblies [1], while lowering material costs when compared with the bulk composite. However, their use has been limited by process scalability, which is directly affected by the joining process of the metal sheet with the composite material.

Despite intensive research and low-volume production, advanced continuous fiber polymer composites still lack truly high-volume applications in the automotive sector. Beyond their relatively high material costs, production presents significant technological and automation challenges, and sophisticated solutions that ensure competitive material processing are still missing. In contrast, sheet metal processing has long been the foundation for high product quality and process repeatability, and is the current baseline reference for volume and cost in high-volume production. By offering the possibility of integrating composites into sheet metal-like manufacturing systems, 2.5D or 3D hot-forming of layered 2D metal / composite hybrid tailored blanks, can potentially realize short process chains and cycle times, to reduce time-consuming manual process steps and material costs, for sustainable composite-metal hybridization in high-volume manufacturing of complex multi-functional structures. However, the bonding between composite and metal is no trivial matter, and has been object of research for the recent decades, such as mechanical fasteners or adhesive bonding, which are currently the most widespread solutions [2,3]. These options, however, present significant disadvantages, such as a heterogeneous distribution of stress in case of mechanical fasteners, or long curing times, tendency to environmental degradation and difficulty to ascertain durability in case of adhesive bonding [4].

In this work, laser drilling of thin aluminum sheets and the application of an anticorrosive, adhesion promoter sol-gel coating is studied as an alternative to the more common adhesive bonding between metal and composite.

2. Experimental method

200 µm thick plain, uncoated aluminum sheets were thermoformed with 200 µm PA66 composite tape, without any success, evidencing the need for mechanical interlocks or adhesive addition to achieve a successful bond between the materials.

To generate mechanical interlocks, a single-mode CW, 1070 nm wavelength fiber laser of maximum average power of 400 W was used to drill holes with an entrance diameter range between 40 to 220 µm on the aluminum sheets. As an adhesion promoter, an anticorrosive coating sol-gel developed by RESCOLL was applied to the drilled sheets and blank aluminum for reference.

The holes in the aluminum sheets were generated by a single laser pulse of 0,2 ms duration, at 400 W maximum power and cutting gas at 7 bar. The holes diameter was varied by placing the aluminum sheet at different distances from the focal plane, separating the material up to 1 mm from it. The distance between drilled holes was controlled by the ratio between the moving speed of the samples and the laser modulation frequency. For productivity purposes, the highest speed possible was used, 100 mm/s, and the frequency was adjusted to achieve the desired separation. The distance between the aluminum sheet and the focal plane, along with the separation between drilled holes are summarized in Table 1.

Table 1. Drilling parameters

Sample number	Distance to focal plane (mm)	Distance between holes (mm)
Combination #1	0	1
Combination #2	0.3	1
Combination #3	0.3	2
Combination #4	0.8	1
Combination #5	0.8	2

An S Neox 3D optical profiler was used to measure the entrance and exit diameters of the holes. In addition, samples were cut and analyzed by means of optical microscopy, allowing to measure the Heat Affected Zone (HAZ) of the aluminum and the hole shape. The same process was applied to thermoformed samples, to evaluate if the holes were completely filled by the polymer matrix of the Carbon Fiber Reinforced Polymer (CFRP).

For the Single Lap Joint (SLJ) tests, 75x25 mm^2 coated aluminum samples were used, with a 25x25 mm^2 area in one of the borders drilled. This area was then thermoformed with a single sample 25x75 mm^2 of PA66, as schematized in Fig 1, and tested.

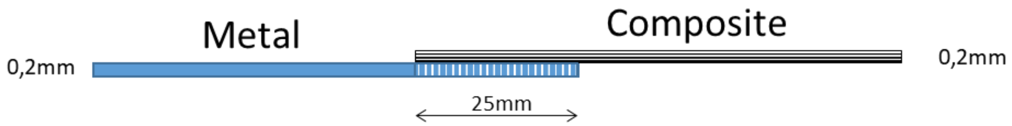


Fig. 1. SLJ tests preparation.

SLJ tests were performed on coated, non-drilled aluminum and all combinations shown in Table 1, both with coated aluminum and non-coated aluminum.

For ILSS tests, the 200 µm aluminum sheets were layered with 200 µm thick PA66 composite, to form samples of 23 intertwined layers (12 aluminum +11 PA66) with 50 x 16 mm^2 dimensions, as schematized in Fig 2. These samples were then thermoformed at 260 °C for 2 minutes, forming a solid block.

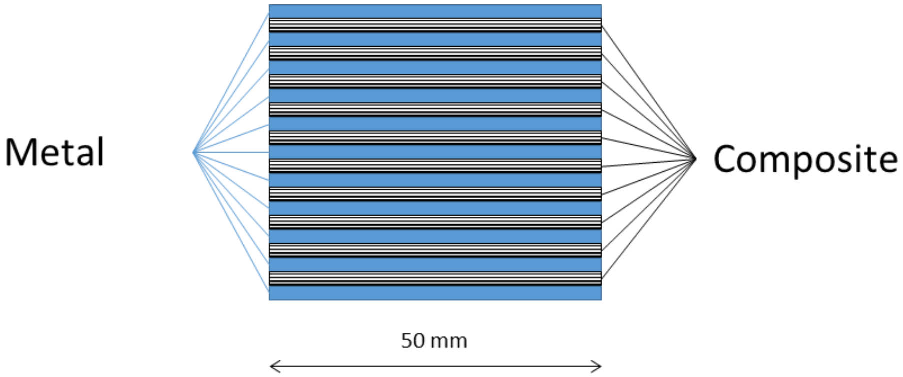


Fig. 2. ILSS tests preparation.

For reference purposes, ILSS Samples were also manufactured with blank, coated aluminum sheets, as well as with non-coated, drilled aluminum with combinations #1, #3 and #5.

Finally, the best drilling combination was replicated with a 200 W, ns pulsed fibre laser: a redENERGY SPI EP Z 200 laser system.

3. Results

The entrance and exit diameters of each sample was measured by the S-Neox optical profilometer, as shown in Fig 3, and the results are collected in Table 2.

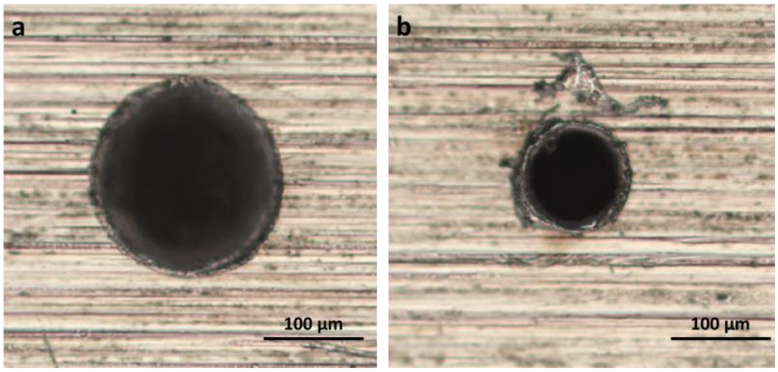


Fig. 3. (a) Entrance beam hole in combinations #4 and #5, (b) Exit beam hole in combinations #4 and #5.

Table 2. Holes diameters

Sample number	Entrance diameter (µm)	Exit diameter (µm)
Combination #1	40-60	40-60
Combinations #2,3	90-110	70-90
Combinations #4,5	180-220	100-140

After the evaluation of the entrance and exit diameter, one of each sample was cut and the holes profile was analyzed, as well as the HAZ, as presented in Fig 4.

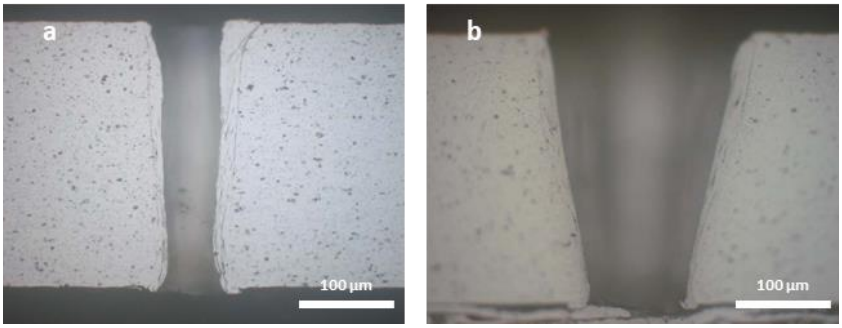


Fig. 4. (a) Hole profile of combination #1 drilled aluminum sheets; (b) Hole profile of combination #4 and #5 drilled aluminum sheets.

As it can be seen, Combination #1 holes are practically straight (measured inclination is 2-4 degrees), while Combinations #4 and #5 have a steeper inclination (10-20 ° depending on the hole), resulting in the exit diameter being smaller than the entrance one. The HAZ can also be appreciated on the walls, as non ejected molten aluminum, varying its depth between 5 to 20 µm.

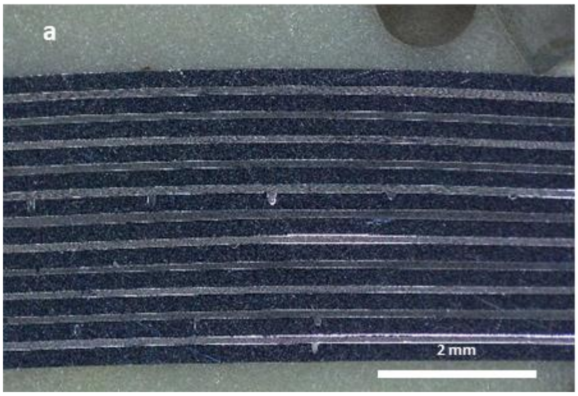
After drilling the aluminum, the sheets were sprayed with the coating developed at RESCOLL. It was observed that sheets drilled with #1 combination had the holes completely blocked by the coating, thus removing the anchorage points generated for the polymer matrix. Combinations #2 and #3 had less than 35% blocked holes, while Combinations # 4 and #5 had less than 20%. Combination #1 drilled sheets were discarded from the ILSS tests, but uncoated samples were still analyzed.

SLJ tests were conducted as previously described, and the results are gathered in Table 3.

Table 3. SLJ results.

Sample number	Non coated aluminum (MPa)	Coated aluminum (MPa)
Combination #1	1.16 ± 0.11	-
Combination #2	0.5 ± 0.21	1.57 ± 0.40
Combination #3	1 ± 0.28	1.47 ± 0.15
Combination #4	0.76 ± 0.67	1.47 ± 0.22
Combination #5	1.22 ± 0.05	1.53 ± 0.28
Non-drilled aluminum	-	1.04 ± 0.34

Once coated, 12 aluminum sheets were laid up alternately with 11 CFRP layers and thermoformed, generating a 23-layer block, as shown in Fig 5 (a). Each CFRP layer was placed with a 90 ° difference compared to the previous one. Some of these blocks were cut and analyzed, to evaluate if the holes were properly filled by the polymer within the CFRP, and the others were used for ILSS tests. Fig 5 (b) shows a microscopy image of a hole completely filled by the polymer.



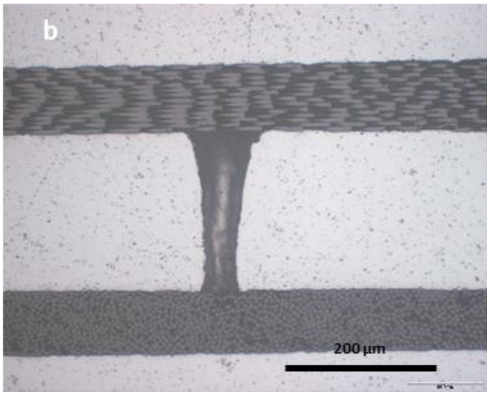


Fig. 5. (a) 12+11 layer block; (b) hole completely filled by the polymer matrix within the CFRP.

In addition, other 23-layer blocks were manufactured for comparison purposes. These samples were either not coated or drilled. All of them were used for ILSS tests. The results for the blocks manufactured with drilled aluminum are summarized in Table 4.

Table 4. ILSS results.

Sample number	Non coated aluminum (MPa)	Coated aluminum (MPa)
Combination #1	8.21 ± 0.83	-
Combination #2	-	40.36 ± 1.42
Combination #3	9.80 ± 0.86	31.55 ± 3.77
Combination #4	-	31.89 ± 3.92
Combination #5	7.18 ± 0.70	34.28 ± 2.12
Non-drilled aluminum	-	15.10 ± 3.70

As a reference, monolithic CFRP of the same thickness has an apparent ILSS of 47.29 ± 4.12 MPa.

Taking into consideration these results, the drilling combination that provided the best ILSS values, combination #2, was chosen to be reproduced by a ns pulsed fiber laser, in order to increase productivity. With the CW laser system used so far, at 100 mm/s, and a separation of 1 mm between drilled holes, it takes around 3 minutes to drill a 100 x 100 mm^2 area.

Several tests were performed with the SPI EP Z 200 laser to reproduce the combination #2 drilling. However, it was noticed that the drilled holes had significantly lower conicity, being the exit and entrance diameters more similar to each other than in the previous cases. Also, a 100-pulses burst at 4.16 MHz, 200 W average power and 8 ns pulse duration, generated an 80-90 µm entrance diameter hole on the aluminum sheet and a 70-80 µm exit diameter hole, which was one of the most similar shapes achievable to that of combination #2 (Fig 6).

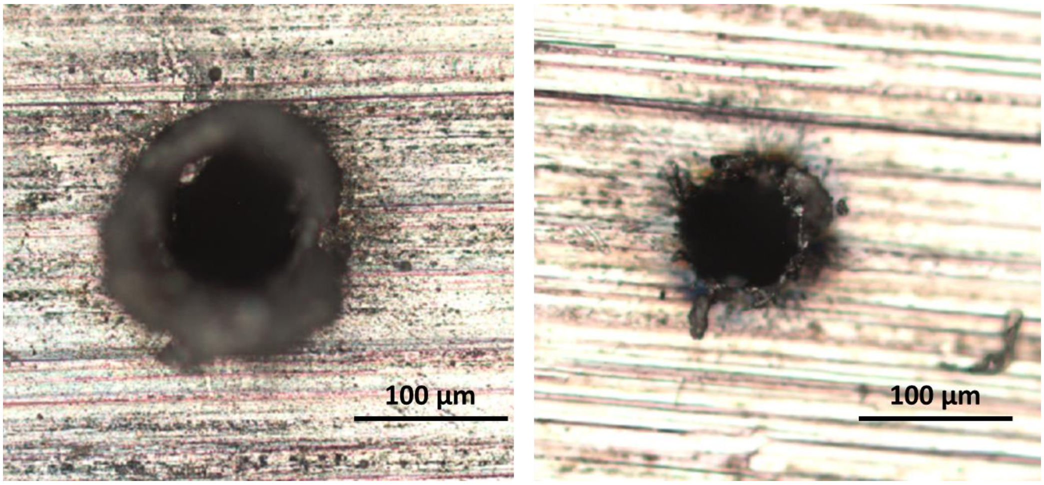


Fig. 6. (a) Entrance hole diameter of ns pulsed laser generated holes, (b) Exit hole diameter of ns pulsed laser generated holes.

Drilled sheets with 80-90 µm entrance diameter holes separated 1 mm from each other in a reticular matrix were manufactured with the ns pulsed laser and then coated and prepared for ILSS testing. The value obtained was 39.28 ± 1.43 MPa, very close to that of combination #2 with the CW laser system. The productivity was drastically increased with the ns pulsed laser, requiring less than 15 seconds to drill a 100 x 100 mm^2 aluminum area.

4. Conclusions

Laser drilling has proven to be a successful way of enhancing adhesion between thin sheets of aluminum and PA66. Furthermore, the combination of a sol-gel anticorrosive and adhesion promoter coating with laser microdrilling provides excellent results, achieving similar apparent interlaminar shear strength as the monolithic CFRP.

Depending on the separation between drilled holes, it is possible to process an area of 10 cm^2 under 2 minutes. This value can be improved tenfold by using a high-power nanosecond pulsed fiber laser and a galvanometer scan head to guide the laser beam at high speeds.

Acknowledgements

This work has been supported by the European Union's H2020-EU.2.1.5.1. - Technologies for Factories of the Future programme under grant agreement No 768710 – Lay2Form and the Factories of the Future Public Private Partnership.

References

[1] BOTELHO, E. C. at al, A review on the development and properties of continuous fiber/epoxy/aluminum hybrid composites for aircraft structures. Mat. Res. [online]. 2006, vol.9, n.3 [cited 2017-01-11], pp.247-256.

[2] F. Balle, G. Wagner and D. Eifle // J. Adv. Eng. Mater. 11 (2009) 1.

[3] W.S. Kim, I.I. Yun, J.J. Lee and H.T. Jung, Evaluation of mechanical interlock effect on adhesion strength of polymer–metal interfaces using micro-patterned surface topography // Int. J. Adhes. Adhes. 30 (2010) 408.

[4] Paul Kah, Raimo Suoranta, Jukka Martikainen, Carl Magnus, Techniques for joining dissimilar materials: Metals and polymers. Reviews on Advanced Materials Science · April 2014