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Procedia CIRP 74 (2018) 506–510

www.elsevier.com/locate/procedia

10th CIRP Conference on Photonic Technologies [LANE 2018]

Influence of temperature and clamping force on the strength of the joint over different composite-metal combinations joined by laser

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Abstract

Vehicle weight in automobile industry is a strict limitation which can be overcome with novel material combinations. Laser conduction joining is an arising alternative but it still poses challenges for joining dissimilar metal-composite materials. Up to now, main research lines have been developed using constant process parameters (laser power and clamping force), so, the behavior of these composite-metal joints under different process parameters, and the control of the process itself, are unknown areas of investigation so far. This paper is focused on the implementation of closed-loop control systems for temperature and clamping force. Tests at different set-points have been carried out for different composite-metal combinations, and the strength of the joints has been assessed by single lap shear tests. The optimal joining process parameters have been found for each material combination.

Keywords: Laser joining; Lasr bonding; Metal-composite joining; Quality assurance; Process control

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1. Introduction

The European Commission imposes a CO_2 emission target of 95g/km on year 2020, for new manufactured passenger vehicles fleet [1]. The replacement of some steel components by lightweight materials helps to fulfill these requirements [2]. New components must be lighter but strong enough to overcome the demanding needs of the automotive industry, e.g. safety, which favors the combination of metal and composite parts. Therefore, new joining techniques between dissimilar materials are required.

Current joining technologies have shown some limitations [3]: Adhesives require long curing periods and present environmental restrictions; Mechanical joints introduce stressed areas at the joints and considerably increase the weight of the components; Mass production technologies such as over-injection molding processes require expensive tooling and have low flexibility in design changes. Laser technology represents a potential alternative, but still faces several challenges to be considered an effective solution [4].

First studies of laser joining metal-composite parts were carried out by Katayama et al. [5]. In this initial study, no pre-treatment was used and laser transmission joining was applied (since the plastic parts material was transparent to the laser radiation). The development of composite materials, with glass/carbon fibers and colorants, forced to develop a few years later the laser conduction joining [6]. In this case, the heat is transmitted through the bulk metal material up to the joining interface by heat conduction.

Further research was focused on the improvement of the joint strength, with the creation of mechanical interlocks between the composite and the metal parts. In this context, different surface texturing methods applied to the metallic parts were studied (milling, laser…), to create cavities where the melted plastic would penetrate [7,8].

It is clear that the surface roughness of the metallic part is relevant, but also the process parameters must be optimized to generate functional multi-material joints. Benyounis et al. [9] studied the effect of the laser power, speed and focal position on the heat input, and therefore in the quality of the joint.

10.1016/j.procir.2018.08.134

Lambiase and Genna [10] measured the temperature evolution using thermocouples attached to AISI304-PC sheets and determined a very small process window for an improved strength of the joint.

All the experiments were carried out using constant laser power, and showed the relevance of the temperature of the part on the strength of the joint. In these cases, the temperature of the whole metallic part was increased with the time and an edge effect could be produced, which could translate into non-homogenous joints with burnt or weakened joined areas.

Also, in all the experiments described above, fixed clamping force between the composite and metal part was applied. It is known that while the plastic material is melted, a force is needed to guarantee the heat conduction and the adhesion between the plastic and the metallic parts. However, the relevance and requirements of the clamping force has not been studied in detail until now.

The present laser joining research study is thus focused on the evaluation of the influence of temperature and clamping force on the strength of the resulting joints, over different metal-composite combinations. With this objective in mind, different control systems have been implemented in our laser facilities, which enable to obtain desired temperature and clamping force during the whole joining process.

2. Materials and experimental procedure

2.1. Materials and specimens

Materials used in this work were steel (DC01) and aluminum (AlMg3) as metallic samples, in combination with glass fiber (GF) reinforced polyamide (PA6-47%GF) and reinforced polypropylene (PP+47%GF). The samples dimension was 25mm of width, 100mm in length, with different thicknesses, and were joined into lap configuration according to EN1465, with an overlap of 12.5mm (Fig 1).

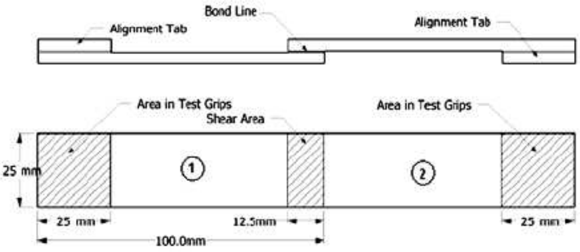

Fig. 1. Samples configuration.

Then, metal specimens were micro-structured using sandblasting technology. The obtained surface roughness by means of this method was:

- Rz=17.84μm ± 1.96μm (X direction), Rz=24.17μm ± 1.07μm (Y direction) for DC01
- Rz=24.57μm ± 3.01μm (X direction), Rz=28.68μm ± 5.09μm (Y direction) for AlMg3.

Where Rz is the average of the maximum height of the profile over all cut-off lengths.

2.2. Experimental and setup procedure

The laser joining operation was performed using a diode laser of 3.1kW of power, model DL031Q from ROFIN. It was coupled to a fibre optic cable with an output lens assembly, that focuses the laser beam with a spot diameter of 10.2 mm. The laser equipment was mounted on a 6 axis Fanuc S10 robot system, which allows the repeatability of the laser beam path with a positioning accuracy of 0.2 mm (see Fig. 2).

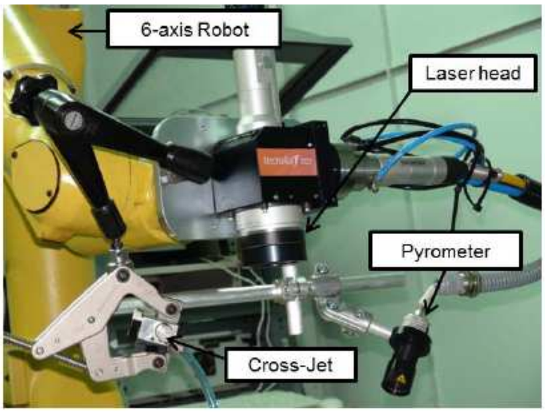

Fig. 2. Overall setup for hybrid composite-metal joining.

Temperature at the upper side of the metallic samples was measured with a LASCON pyrometer from Dr.Mergenthaler, with a temperature range from 140°C to 600°C, at a sampling rate of 1 kHz, focused with the laser beam. A temperature closed-loop control was implemented, to manage the laser power depending on the difference between the measured temperature and the target temperature (SP), in order to obtain a constant temperature value during the whole joining process.

For clamping the composite-metal specimens, a specific device was developed, which included a force control system (see Fig. 3).

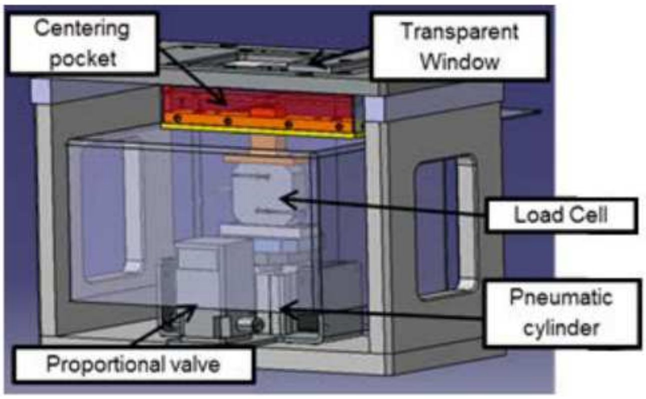

Fig. 3. Clamping device with force control system.

The clamping device was composed of the following elements: a transparent quartz glass for applying pressure while the laser is radiating; a centering socket for the repetitive positioning of the specimens; a pneumatic cylinder to open/close the clamping device, able to exert a force up to 800N and a load cell to measure this force; a proportional valve to adjust the air quantity introduced in the pneumatic cylinder and a PI controller, configured under LabVIEW environment, from National Instruments, to manage the proportional valve, providing a constant clamping force.

The laser beam described a rectangular path of 18mm of width and 5 mm in length, covering the entire overlapped area. The path was repeated 3 times at a speed of 50mm/s, resulting in a cycle time of 6.5 seconds.

The joint strength was analyzed by single lap shear tests, carried out by uni-axial MTS 407 at 5mm/min.

3. Results and discussion

3.1. Influence of the temperature

Three different material combinations were laser joined using a clamping force of 50kg, under different temperature set-points, to evaluate their influence on the joint strength:

Table 1. Material combinations and thermal behavior.

Metal – Composite (Thickness)	Melting Temp	Degrade Temp
DC01 (2mm) - PP+47%GF(2mm)	163 ºC	375 ºC
DC01(2mm) - PA6+47%Gf (2mm)	220 ºC	421 ºC
AlMg3(5mm)- PA6+47%Gf (2mm)	220 ºC	421 ºC

A wide range of temperature set-points between 220°C and 430°C was tested, to ensure that all the thermoplastic materials were melted (lower range) and degraded (the upper range).

Fig. 4 and Fig. 5 shows the performance of the implemented control system for different material combinations (Green: Temperature set-point; Red: measured Temperature; Black: Power (%)). As it can be observed, the laser power is continuously adapting to the joining requirements.

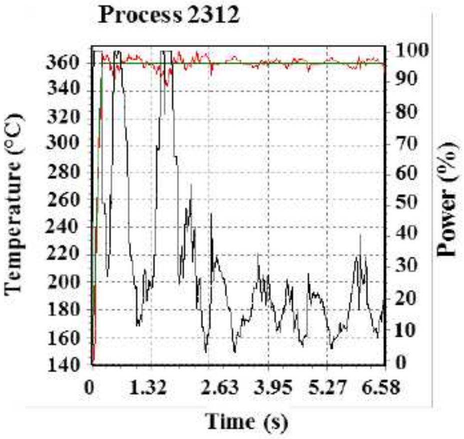

Fig. 4. Temperature control for PA6+47%GF (2mm)-DC01 (2mm)

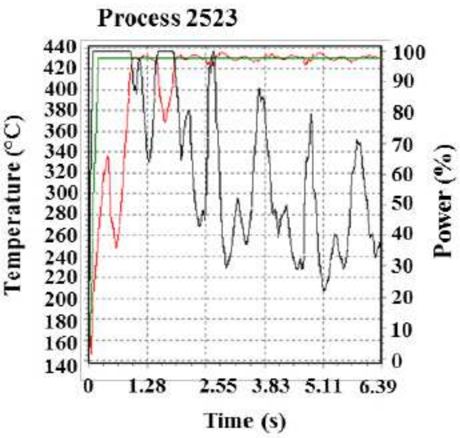

Fig. 5. Temperature control for PA6+47%GF (2mm)-AlMg3 (5mm).

For each material configuration, the average joint strength was assessed. Fig. 6 summarizes the test results, including the standard deviation.

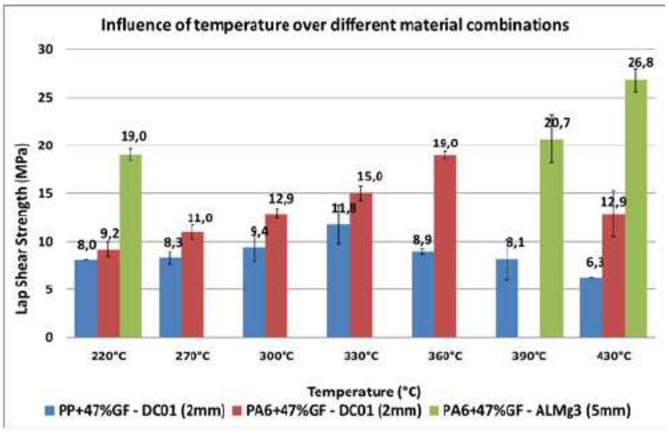

Fig. 6. Influence of temperature over different material combinations.

In the case of PP+47%GF-DC01, the above graph (blue columns) shows a clear inflection point at 330ºC, achieving a maximum shear strength of 11.8 MPa. For the PA6+47%GF-DC01 samples (red columns), a similar behavior was observed at 360°C, obtaining a maximum value of 19 MPa. PP presents a lower melting point than PA6, which explains its lower set-point.

The chemical compatibility can explain these different strength values: PA6 has higher surface free energy than PP (45.4 vs 30.2 mJ/m2). This can be translated into higher wetting out, which then maximizes the contact area and the attraction forces.

Regarding PA6+47%GF-AlMg3 samples, a maximum strength of 26.8MPa was obtained at 430°C. Aluminum has higher specific heat than steel (880 J/ (kg*K) vs 460 J/ (kg*K)) and higher reflectivity index (94% vs 76%). This can be translated into higher laser power requirements and/or lower temperatures reached at the metal-composite interface, which then explains the higher set-point for the aluminum samples.

It has been demonstrated that temperature has a great influence on the resulting joint strength, and that process temperatures near the plastic degradation point usually provides higher joint strength. The higher the temperature, the lower the viscosity of the plastic material, which then enables the melted material to fill the surface cavities previously produced on the metallic samples.

Regarding the joint failure mode, an adhesive failure has been observed on plastic-steel samples, while the plastic-aluminum samples present a cohesive failure mode, revealing a great amount of GF (see Fig. 7).

Fig. 7. Failure mode (a) PA6+47%GF-DC01; (b) PA6+47%GF-AlMg3.

As explained above, the PA6-AlMg3 combination presented the highest joint strength. However, similar results to the PA6-DC01 samples were expected, as both use the same plastic material. The main difference between them was the thickness of the metallic part. For this reason, new joints with 2mm aluminum plates were carried out, under the same process parameters. The obtained joint strength was 13MPa (similar to steel).

In this case, the temperature reached at the interface was lower compared to the aluminum samples of 5mm, which can explain the reduced strength. Also, the higher thermal conductivity (205 W/ (m*h)) could have an impact: the increase of the thickness of the metal sample increases the time to dissipate the heat and slows down the cooling rate. To corroborate this theory, a new control strategy with variable set-point was implemented, including a short period at optimal set-point combined with a period at low temperature to obtain a slowed cooling.

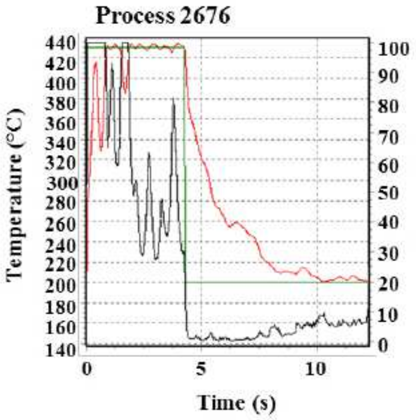

Fig. 8. Control of temperature with variable temperature SP.

Three temperature profiles were tested on the 2mm AlMg3 samples, with the aim of matching the results of the 5mm AlMg3:

- 2 repetitions at 430ºC + 3 repetitions at 200 ºC.
- 2 repetitions at 430ºC + 4 repetitions at 200 ºC.
- 2 repetitions at 430ºC + 6 repetitions at 160 ºC.

Fig. 9 summarizes the results: The last temperature profile matches the strength of the 5mm aluminum samples (27.9 MPa vs 26.8MPa), validating the proposed theory. However, not every temperature profile is valid. Furthermore, it could even be counterproductive. Therefore, it would be necessary to find out the optimal profile for each material combination.

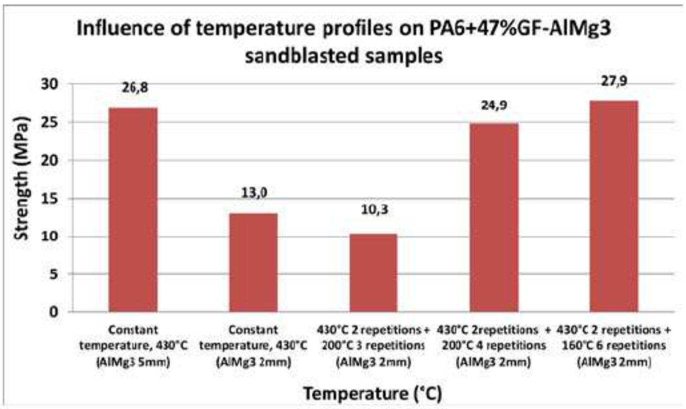

Fig. 9. Influence of the temperature profiles on the joint shear strength.

3.2. Influence of Clamping Force

Different clamping force set-points were tested with the PA6+47%GF (2mm)-DC01 (2mm) samples. The specimens were laser joined at 300 ºC, with a rectangular path and 3 repetitions at a speed of50mm/s.

Fig. 10 summarizes the obtained joint shear strength. As it can be observed, the clamping force does not have a relevant influence on the joint strength and a wide range of values provides similar results. The composite material is manufactured using long fibers, which cannot be introduced into the created cavities of the metallic samples (only the thermoplastic matrix can fill the cavities). To ensure an adequate heat transmission, it is necessary a pressure which can guarantee the close contact between the metal and the plastic parts. On the other side, very high clamping forces could restrain the flow of the thermoplastic material, thus, a compromise must be found.

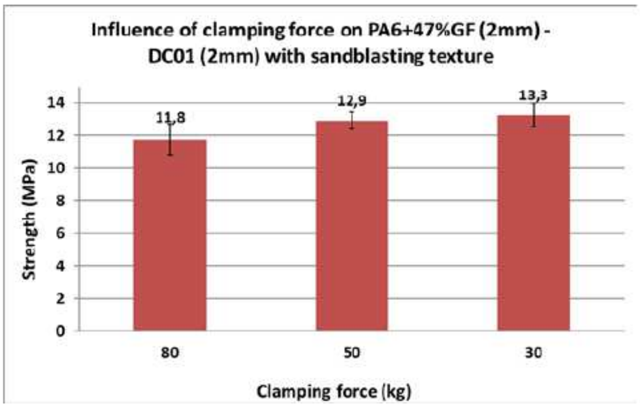

Fig. 10. Influence of the clamping force on the strength of the joint.

4. Conclusions

- The use of control systems for temperature and clamping force, instead of using a fixed laser power and an on-off clamping device, aims to obtain reliable information about their influence on the strength of the joint, providing a more repetitive process less influenced by external variants.
- Temperature of the part is the most influential parameter in the strength of the joint. All the tested material combinations present an optimal temperature setting for improved strength. It is necessary to configure a set-point (on the upper side of the metallic part) higher than the plastic melting point, in order to obtain an optimal temperature at the interface, especially for the thicker metallic samples.
- The thickness of the samples is particularly relevant on the aluminum samples. Using temperature profiles (few repetitions at optimal set-point and various repetitions at low temperature) allows to slow down the cooling rate and to improve the joint strength. However, not every temperature profile is suitable, and specific tests must be done for each case, in order to find out the optimal profile of temperature.
- The clamping force has little relevance on the joint strength for materials with long glass fibers. A close contact between parts, and therefore pressure, is a requirement for adequate heat transmission between the parts. However, higher forces could impede the flow of the thermoplastic matrix into the cavities and slightly reduce the joint strength.
- Any change on the combination, thickness or geometry of the parts requires new testing trials for establishing the optimal parameters. Further research on simulation tools for the estimation of the optimal process parameters is necessary.

Acknowledgements

The research leading to these results has received funding from the European Union’s Horizon 2020 programme under grant agreement Nº 677625 within FlexHyJoin project.

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