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Laser joining improvement and prediction of the quality of the joint of metal-composite samples using a control and supervision system for temperature and clamping force

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Abstract

Joining of multi-material parts is a growing need for development components with enhances properties. Laser conduction joining is a promising alternative but still a relatively unexplored technique for joining dissimilar metal-composite materials. As a thermal joining method, the achieved temperature is one of the most influent parameters on the strength of the joint and mainly depends on laser power, speed, material and geometry of the part, meanwhile the clamping force guarantees the heat conduction from the metallic specimen to the composite material. For this reason, the supervision and control of these parameters are especially relevant to ensure the quality of the joint. This paper is focused on the development of a control and supervision system of these parameters for the improvement of the process and the prediction of the joint quality. The system has been evaluated through on purpose production of defective joints for the validation of the reliability of the process with different metal-composite combinations.

Keywords: process control; process supervision; composite-metal laser joining; multi-material laser joining; quality prediction;

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1. Introduction

Driving by increasing strict limitation on fuel consumption and emission, automotive industry demands novel materials for weight reduction as composites (especially glass and carbon fiber reinforced polymers) which have strongly gained popularity as construction material during last years [Isenstadt et al., 2016].

However lightness cannot be obtained at the expense of other properties (mechanical, cost, quality…) and each type of material (metals and composites) can contribute with its unique properties to create components with enhanced performance. In consequence, there is a need for a strategic redefinition of material mixture for a more economical and ecological application of lightweight materials [Staeves, 2013].

The potential of manufacturing metal-composites components is accompanied by a main challenge: The joining of the material partners. Laser joining is presented as a promising alternative to commonly used joining methods, able to join complex geometries and avoiding the introduction of additional weight to the final component (screws or bolts) as well as removing the use of chemicals with environmental issues (adhesive joining).

First studies for laser joining of metal-composite parts were carried out by [Katayama et al., 2006] who proposed a new Laser-Assisted Metal and Plastic (LAMP) joining method, obtaining promising results over 304 Stainless Steel samples in combination with polyamide (PA) and polyethylene terephthalate (PET).

This initial research was carried out by laser transmission joining (laser energy is applied directly at the interface of the two parts when the upper layer is transparent to the laser wavelength). However the industry requires composites with colorants and high glass fiber content, so laser conduction joining/direct joining (which applies the energy to the upper part and the energy travels by heat conduction through it into the joining zone) is gaining relevance.

Both approach have been demonstrated the suitability of laser joining on a wide range of metallic-composite combinations as polycarbonate (PC), PA6, PA66-GF30 to Aluminum (AW-5182) [Amenda et al., 2013], Methylmethacrylate Acrylonitrile Butadiene Styrene (MABS), polypropylene (PP), PC to Steel [Rauschenberger et al., 2015] or Titanium and PET [Chan and Smith, 2016] by laser transmission joining, and PA6-GF30 to low alloy steel (HC420LA) [Rodriguez-Vidal et al., 2016] or CFRP to aluminum alloy by laser conduction joining, however it is still a challenging task because of lack of knowledge about materials interaction and tools for reliability improvement.

The creation of cavities on the metallic part where melted polymer can be introduced has proved to be one of the most important strategies for optimize mechanical interlocks [Jung et al., 2013], so different technologies for metal structuring as laser [Holtkampet al., 2009], machining [Cenigaonaindia et al., 2012], NRX (developed by Nucap) or Coniperf (developed by Andritz) have been tested during last years. Also the influence of other specific pre-treatments for strength improvement as anodizing [Zhang et al., 2016], or UV-ozone and plasma [Arai et al., 2014] have been analyzed and proved to be a potential alternative for adhesion promotion between materials.

Constant laser power and force have been applied for the previous tests, without taking into account the thermal and followability properties of the materials, therefore no control systems have been developed until now for dissimilar joining of composite-metal components.

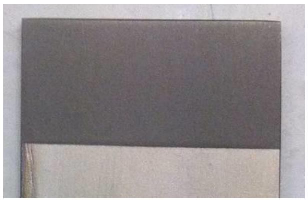
The focus of this research is on the implementation of both temperature and force control and supervision system which ensures optimal parameters during joining process on the one hand, and the prediction of the quality of the joint based on the evolution of the parameters on the other. The validation of this system has been carried out by the intentionally production of defective joints, improving the repeatability of the process and corroborating the capability of the systems to detect non-optimal joints.

2. Materials and experimental procedure

2.1. Test materials

Materials used in this work are steel (DC01) and aluminum (AlMg3) of 2 and 5mm thickness respectively in combination with glass fiber reinforced polyamide (PA6-47%GF) of 2mm thickness. The dimensions are 25mm width, 100mm length and 12.5mm overlap and have been joined into lap configuration (Figure 1b).

In order to create micro-cavities where melted material can be introduced and increment the mechanical interlock between materials, both metallic samples were micro-structured using sandblasting technology (see Figure 1a). The obtained surface roughness by means of this method is Rz=17,84mm ± 1,96mm (X direction), Rz=24,17mm ± 1,07mm (Y direction) for DC01 samples, and Rz=24,57mm ± 3,01mm (X direction), Rz=28,68mm ± 5,09mm (Y direction) for AlMg3 samples.



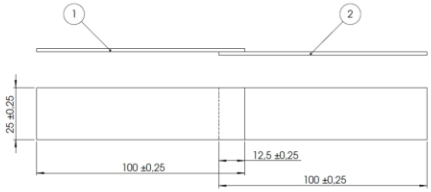


Fig. 1. (a) Sandblasted specimen; (b) Specimens configuration

2.2. Experimental setup and procedure

The laser joining has been performed using a diode laser of 3.1kW of power, model DL031Q from ROFIN coupled to a fiber optic cable with an output lens assembly that focuses the laser beam with a spot diameter of 10.2 mm and mounted on a 6 axis Fanuc S10 robot system (see Figure 2a).

Also a LASCON pyrometer from Dr.Mergenthaler able to measure temperatures between 140°C-600°C with a maximum rate of 10kHz has been focused with the laser beam. A temperature control has been implemented which enables to manage the laser power depending on the difference between the measured temperature and the set point (SP), in order to obtain a constant temperature along the joining process.

For clamping the specimens, a specific device suitable for laser joining of flat samples with included force control has been developed. The device is composed by the following elements: a transparent quartz glass window to enable the joining both by transparency and by conduction; a centering pocket for the exact positioning of the specimens; a pneumatic cylinder to open/close the clamping device capable to exert a controlled force up to 800N; a load cell to measure this force; and a proportional valve that modifies the air quantity introduced in the cylinder controlled by a PID. By this way, depending on the measures of the load cell and comparing it with the desired set point, the optimal air pressure is calculated in order to obtain a constant force (see Figure 2b).

Specific software for the acquisition, supervision, analysis and visualization of the data has been developed under Labview environment from National instruments. Through the graphical user interface, both temperature and clamping force set points are configured, the material combination is selected, as well as the type of supervision that will be applied to the joint (see Figure 2c):

- By level: An upper and lower limit is fixed around an optimal constant value for a good quality joint.
- By patterns: An upper and lower limit is fixed around a pattern curve along the time that will match with an optimal joint.

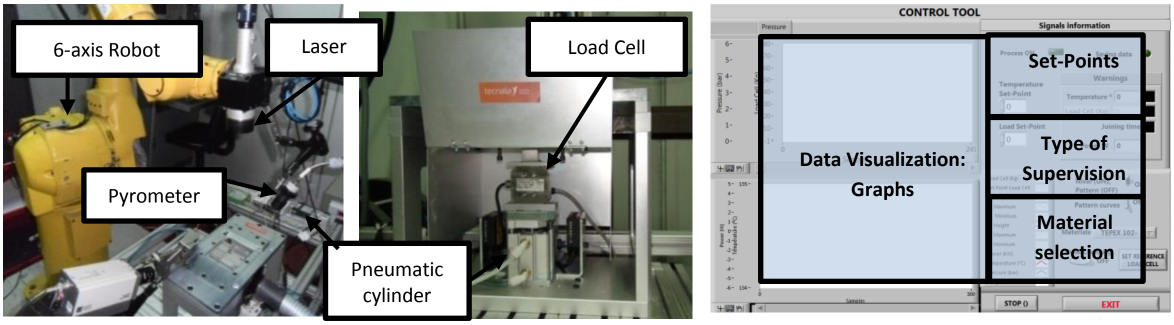


Fig. 2. (a) Laser system with temperature control; (b) Clamping system with pressure control; (c) Software interface

The system automatically configures the optimal process window depending on the material selection and type of supervision. Finally it generates a report with an estimation of possible defects in the joint based on the analysis of the supervised parameters. The optimal process parameters were previously obtained and saved in a configuration file based on the experimentation and knowledge of the properties of the materials.

The laser beam describes a rectangular path of 18mm width, 6 mm length for a specific number of repetitions, covering the entire overlapped area, at a speed of 50mm/s. The mechanical properties of the joint were analyzed by single lap shear tests. The results are represented by the failure force (load (kN) at which the joint breaks into two separate parts) divided by the overlapped area (12.5 × 25 mm).

3. Results and discussion

Knowing the interaction between materials and the optimal process parameters, some defects have been generated artificially by using inadvisable process setting. The performance of the system has been evaluated with the following criteria:

- The controlled parameters are maintaining around the selected set point during the joining.
- The quality results described on the generated report match with the visual inspection of the specimens and the results of the lap shear tests.

3.1. PA6+47%GF 2mm thickness with Steel (DC01) 2mm thickness

The used composite has got a high percentage of glass fibers and black colorants, so laser conduction joining should be applied. The temperature range for PA6 is wide (220°C (melting point) to 421°C (degradation point)), however, based on experimental data, not all the range of temperatures are suitable for an improved strength of the joint. The applied supervision strategy is based on levels.

Based on the guidelines, the control and supervision system has been tested under different process parameters in order to intentionally produce defects in the joint:

- Speed=50mm/s, Clamping force SP=50kg, Temperature SP=360ºC, Nº of repetitions=5, → Based on experimental data, this configuration is considered optimal for an improved strength of the joint (Two joints under same process parameters).
- Speed=50mm/s, Clamping force SP=50kg, Temperature SP=300ºC, Nº of repetitions=5, → Lower temperature in order to produce a defect related with reduced melted material.
- Speed=50mm/s, Clamping force SP=80kg, Temperature SP=300ºC, Nº of repetitions=5, → Lower temperature and higher clamping force in order to compare the influence of the clamping force.
- Speed=50mm/s, Clamping force SP=50kg, Temperature SP=430ºC, Nº of repetitions=5, → Higher temperature in order to produce burns or bubbles.

3.1.1. Results of quality control and supervision system

Figure 3 shows the obtained evolution of the temperature (left axis) and the calculated laser power (right axis) for each case. The red lines represent the limits in which the quality of the joint is expected to be acceptable. The legend of each curve includes the obtained strength for the corresponding joint:

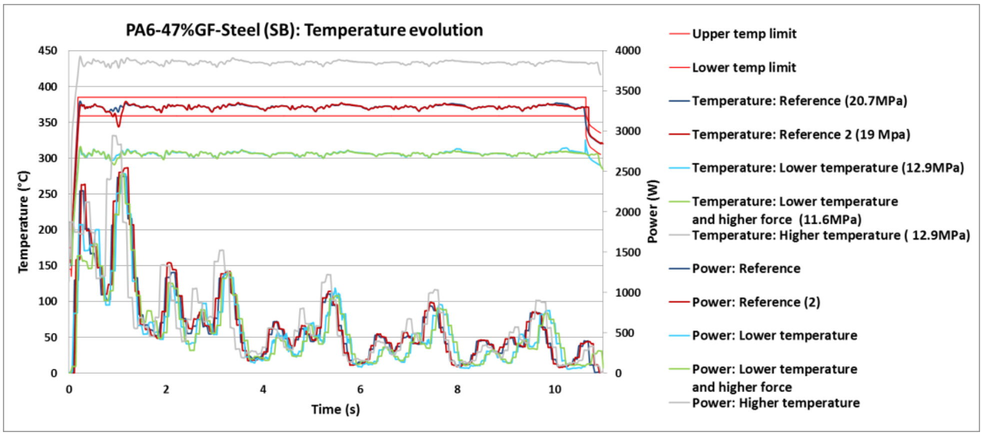


Fig. 3. Temperature and laser power evolution for PA6+47%GF-DC01.

As can be observed, all cases present similar behavior: The temperature set point is reached almost instantly and it is maintained constant during the joining process by adjusting the laser power. The two reference cases, are maintaining into the process window. Reference 2 suffers a small deviation which produces a momentary output of the limits, but recovers quickly. The other cases are clearly out of the process window. In any case, a very repetitive process is observed, with a practically identical evolution of the temperature and a minimum deviation of the set point.

Figure 4 shows the obtained evolution of the clamping force (left axis) and the calculated air pressure (right axis) for each case.

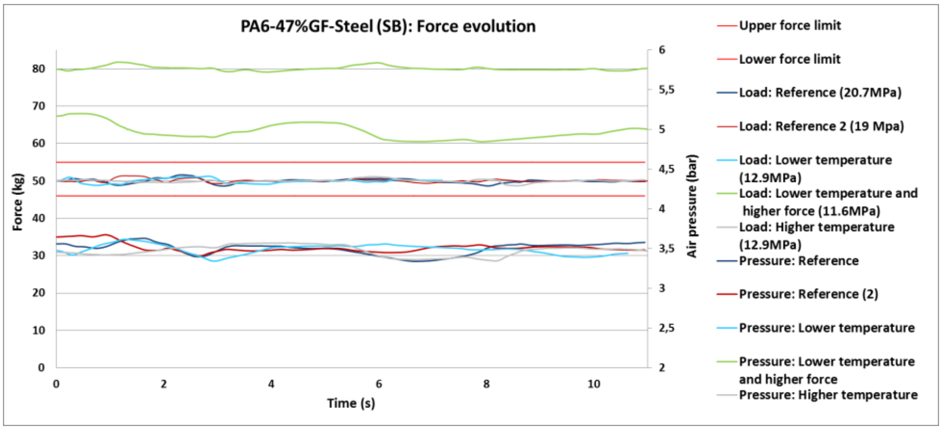


Fig. 4. Clamping force and air pressure evolution for PA6+47%GF- DC01.

It can be observed that in all cases the clamping force is maintained almost constant around the set point, by adjusting the air pressure of the pneumatic cylinder. It must be highlighted that minimum change into the air pressure (0.1bar) translates into bigger changes into the clamping force which could difficult a fine adjustment of the control system. However, the maximum obtained error regarding set point is ±2Kg.

All cases are maintaining into their process window, except the case of higher clamping force set point which is clearly out of the fixed limits.

Table 1 summarizes the obtained strength for each case and the generated reports that compile the evolution of each process parameter, the percentage of time into their process window and predicts possible defects that could be presented into the joint:

Table 1. (a) Quality report of non-defective PA6+47%GF- DC01 joint; (b) Quality report of non-defective joint 2 PA6+47%GF- DC01 joint; (c) Quality report of reduced temperature PA6+47%GF- DC01 joint; (d) Quality report of reduced temperature and increased force PA6+47%GF- DC0 joint 1; (e) Quality report of increased temperature PA6+47%GF- DC01 joint; (f) Visual inspection of the joints: (f1)non-defective joint; (f2) reduced temperature joint

(a)Non-defective joint 1: 20.7MPa

QUALITY CONTROL FOR DISSIMILAR JOINING

Material combination: PA6+47%GF-Steel

PARAMETERS (High *Level / Low Level*)

PROCESS PARAMETERS	SIGNAL	OK (%)	WARNING (%)	AVERAGE
	Temperature (ºC)	99,7	0 / 0 ,3	360
	Clamping force (Kg)	100	0 / 0	50
	Time (s)	100	0 / 0	10,9

OK: WARNING:

DETECTED DEFECTS

DESCRIPTION

NO DEFECTS RELATED WITH BAD MANAGEMENT OF FORCE
NO DEFECTS RELATED WITH BAD MANAGEMENT OF TEMPERATURE
NO DEFECTS RELATED WITH TOTAL CYCLE TIME

EVOLUTION OF THE PROCESS

FORCE EVOLUTION

TEMPERATURE EVOLUTION

OVER: OK: UNDER:

(b)Non-defective joint 2: 19 MPa

QUALITY CONTROL FOR DISSIMILAR JOINING

Material combination: PA6+47%GF-Steel

PARAMETERS (High *Level / Low Level*)

PROCESS PARAMETERS	SIGNAL	OK (%)	WARNING (%)	AVERAGE
	Temperature (ºC)	97,8	0,7 / 1,5	360
	Clamping force (Kg)	100	0 / 0	50
	Time (s)	99,5	0,5 / 0	11

OK: WARNING:

DETECTED DEFECTS

DESCRIPTION

NO DEFECTS RELATED WITH BAD MANAGEMENT OF FORCE
NO DEFECTS RELATED WITH BAD MANAGEMENT OF TEMPERATURE
NO DEFECTS RELATED WITH TOTAL CYCLE TIME

EVOLUTION OF THE PROCESS

FORCE EVOLUTION

TEMPERATURE EVOLUTION

OVER: OK: UNDER:

(c) Reduced temperature SP: 12.9MPa

QUALITY CONTROL FOR DISSIMILAR JOINING

Material combination: PA6+47%GF-Steel

PARAMETERS (High *Level / Low Level*)

PROCESS PARAMETERS	SIGNAL	OK (%)	WARNING (%)	AVERAGE
	Temperature (ºC)	0,6	0 / 99,4	301
	Clamping force (kg)	100	0 / 0	50
	Time (s)	100	0/ 0	10,9

OK: WARNING:

DETECTED DEFECTS

DESCRIPTION

NO DEFECTS RELATED WITH BAD MANAGEMENT OF FORCE
TOO LOW TEMPERATURE SETPOINT, LACK OF MELTED MATERIAL
NO DEFECTS RELATED WITH TOTAL CYCLE TIME
POSSIBLE REDUCED STRENGHT BECAUSE OF TEMPERATURE REASONS

EVOLUTION OF THE PROCESS

FORCE EVOLUTION

TEMPERATURE EVOLUTION

OVER: OK: UNDER:

(d) Reduced temperature and increased force SP: 11.6 MPa

QUALITY CONTROL FOR DISSIMILAR JOINING

Material combination: PA6+47%GF-Steel

PARAMETERS (High *Level / Low Level*)

PROCESS PARAMETERS	SIGNAL	OK (%)	WARNING (%)	AVERAGE
	Temperature (ºC)	0,6	0 / 99,4	302
	Clamping force (kg)	0	100 / 0	80
	Time (s)	96,9	3,1/ 0	11,3

OK: WARNING:

DETECTED DEFECTS

DESCRIPTION

TOO HIGH FORCE SETPOINT, POSSIBLE WEAKENING OF MATERIAL
TOO LOW TEMPERATURE SETPOINT, LACK OF MELTED MATERIAL
NO DEFECTS RELATED WITH TOTAL CYCLE TIME
POSSIBLE REDUCED STRENGHT BECAUSE OF TEMPERATURE AND FORCE REASONS

EVOLUTION OF THE PROCESS

FORCE EVOLUTION

TEMPERATURE EVOLUTION

OVER: OK: UNDER:

(e) Increased temperature SP: 12.9 MPa

QUALITY CONTROL FOR DISSIMILAR JOINING

Material combination: PA6+47%GF-Steel

PARAMETERS (High *Level / Low Level*)

PROCESS PARAMETERS	SIGNAL	OK (%)	WARNING (%)	AVERAGE
	Temperature (ºC)	0,5	0 / 99,5	431
	Clamping force (kg)	100	0 / 0	50
	Time (s)	97,4	2,6/ 0	11,2

OK: WARNING:

DETECTED DEFECTS

DESCRIPTION

NO DEFECTS RELATED WITH BAD MANAGEMENT OF FORCE
TOO HIGH TEMPERATURE SETPOINT, NON OPTIMAL PROCESS PARAMETEF
NO DEFECTS RELATED WITH TOTAL CYCLE TIME
POSSIBLE REDUCED STRENGHT BECAUSE OF TEMPERATURE REASONS

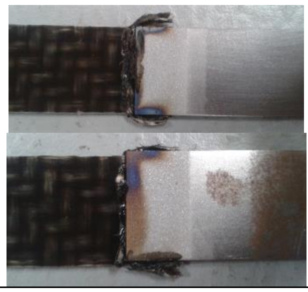
EVOLUTION OF THE PROCESS

FORCE EVOLUTION

TEMPERATURE EVOLUTION

OVER: OK: UNDER:

(f1) non-defective joint
(f2)reduced temperature joint



The reference cases show a value of 99.7% and 97.8% respectively of maintenance of the temperature into its process window. 100% is not achieved because of the implemented supervision strategy based on limits without taking into account the response time of the process at the start and end of the joining process. In the second case, also the additional deviation of the temperature in a certain instant is detected.

In some cases has been observed a slightly deviation in the total cycle time, that has not got influence in the strength of the joint.

The reference cases have been provided a similar strength around 20MPa and the supervision software has concluded that no defects have been detected. On the other cases, the software has alert of a possible strength reduction because of temperature and force reasons, which corresponds with the obtained strength of around 12MPa.

The visual inspection of the specimens does not present any relevant information regarding the quality of the joint, however the developed software has shown its effectiveness on detecting parameters out of their process windows and their relationship with possible defects, predicting in all the tested cases the presence of a joint with reduced strength.

3.2. PA6+47%GF 2mm thickness with Aluminum (AlMg3) 5mm thickness

Aluminum presents a high reflectivity of the laser beam (94%), so very low percentage of laser energy will be absorbed and therefore surface treatment for energy absorption improvement is advisable. This also translates into higher temperature SP at the upper part, to obtain a suitable temperature at the interface. The high reflectivity will produce unstable evolution of the temperature and slow response until reach the desired set point, for this reason, a supervision system based on patterns has been applied.

Based on the guidelines, the control and supervision system has been tested under different process parameters in order to intentionally produce defects in the joint:

- Speed=50mm/s, Clamping force SP=30kg, Temperature SP=430ºC, Nº of repetitions=3, Sandblasting both sides → Based on experimental data, this configuration is considered optimal for an improved strength of the joint (Reference).
- Speed=50mm/s, Clamping force SP=50kg, Temperature SP=430ºC, Nº of repetitions=3, Sandblasting both sides → Higher pressure in order to produce weakening of material.
- Speed=50mm/s, Clamping force SP=30kg, Temperature SP=430ºC, Nº of repetitions=5, Sandblasting both sides → Higher Nº of repetitions to produce a defect related with excess of cycle time.
- Speed=50mm/s, Clamping force SP=30kg, Temperature SP=410ºC, Nº of repetitions=3, Sandblasting both sides → Lower temperature to produce reduced melted material.
- Speed=50mm/s, Clamping force SP=30kg, Temperature SP=430ºC, Nº of repetitions=3, Sandblasting only at the interface → No treatment in order to produce reduced energy absorption.

3.2.1. Results of quality control and supervision system

Figure 5 shows the obtained evolution of the clamping force (left axis) and the calculated air pressure (right axis) for each case.

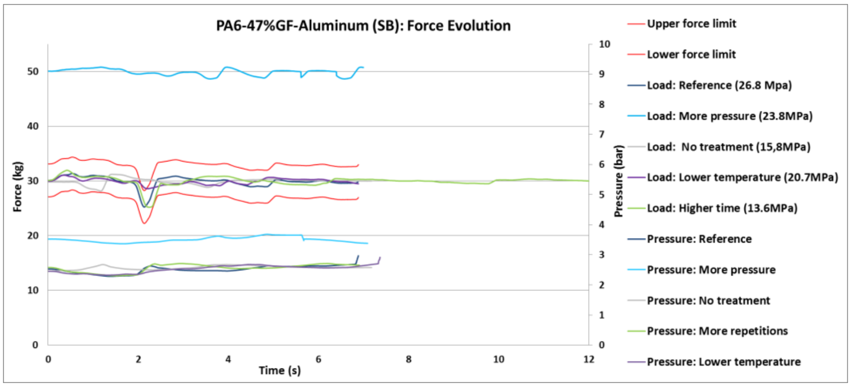


Fig. 5. Clamping force and air pressure evolution for PA6+47%GF- AlMg3.

The implemented control system enables the maintenance of the clamping force almost constant around the set point. However, in this case the maximum obtained error is slightly higher than in the previous case (±2kg vs ±4kg), specially at the start of the process when the temperature is not yet stabilized.

Figure 6 shows the obtained evolution of the temperature (left axis) and the calculated laser power (right axis) for each case:

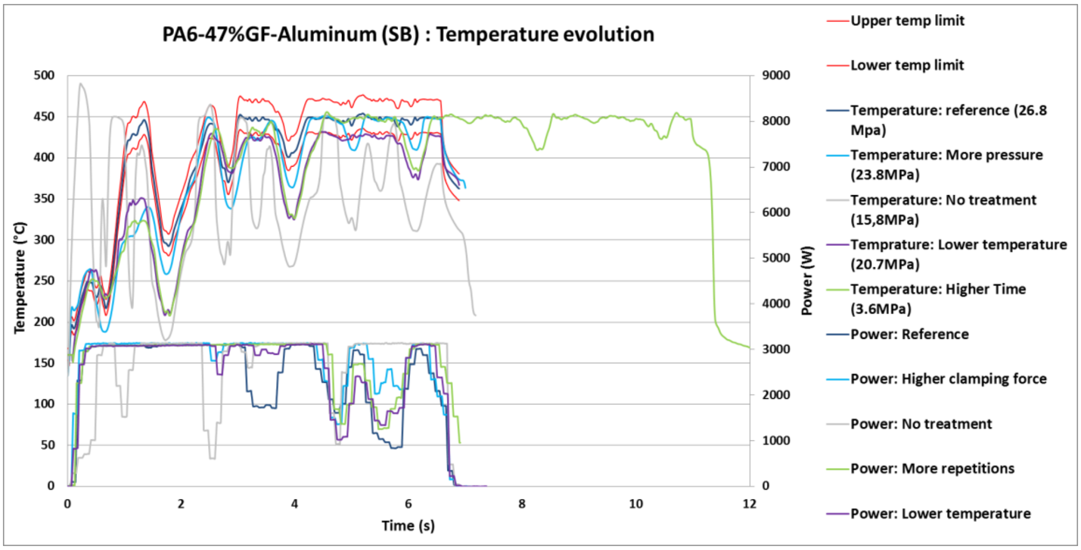


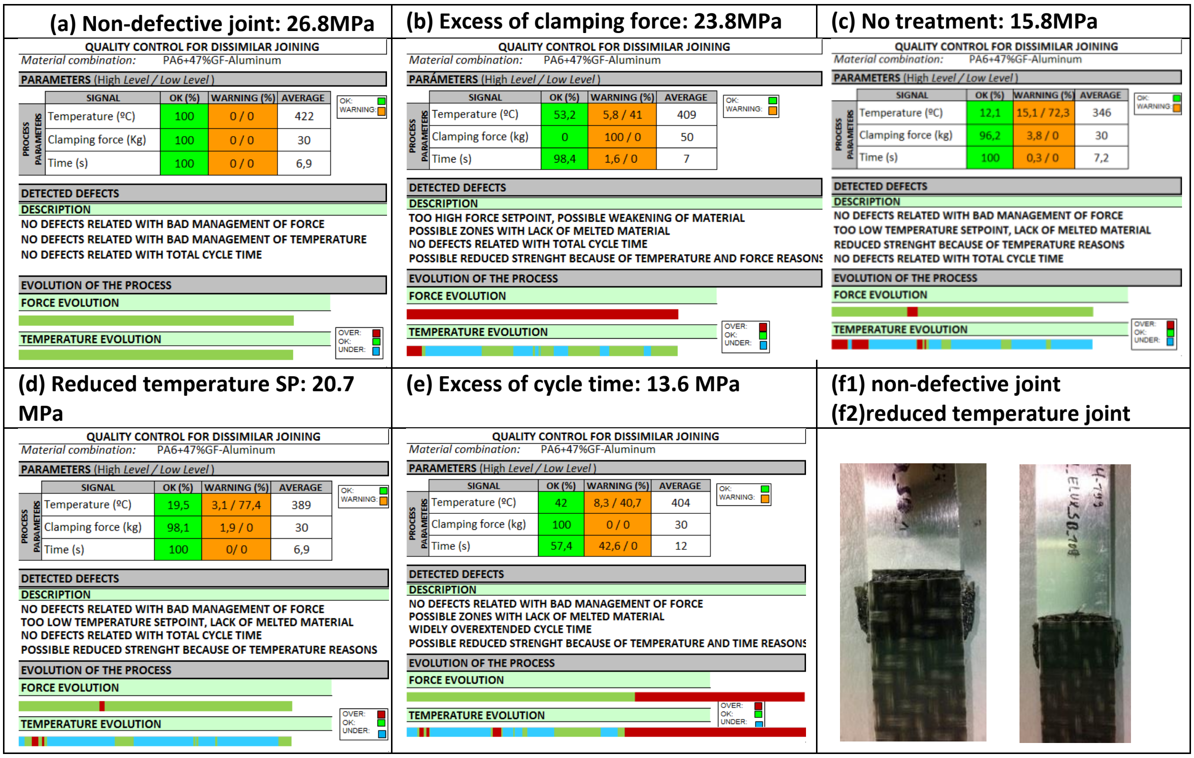
Fig. 6. Temperature and laser power evolution for PA6+47%GF- AlMg3.

As can be observed, in the case of no treatment at the upper part (gray curve), the temperature set point cannot be reached along the joining process in spite of the use of maximum laser power available. In the other cases, the temperature takes around 3 seconds to reach the set point and remains almost constant with some punctual decrease of the temperature at some positions. During the first 3 seconds, the laser power is operating at 100% and then is regulated according the difference between the measured temperature and the fixed set point.

The reference curve is maintaining between the limits, however the other curves are not completely into the limits during the joining process. The unstable evolution of the temperature confirms the suitability of use a supervision system based on pattern curves instead of constant level.

Table 2 summarizes the obtained strength for each case, and the reports generated by the supervision system:

Table 2. (a) Quality report of no-defective PA6+47%GF- AlMg3 joint; (b) (a) Quality report of excess of pressure PA6+47%GF- AlMg3 joint; (c) Quality report of no-surface treatment PA6+47%GF- AlMg3 joint; (d) Quality report of extended cycle time PA6+47%GF- AlMg3 joint; (e) Quality report of reduced temperature PA6+47%GF- AlMg3 joint; (f) Visual inspection of the joints: (f1)non-defective joint; (f2) reduced temperature joint



As well as in the previous case, the visual inspection of the specimens does not provide any relevant information regarding the quality of the joint.

Analyzing the output of the supervision system, a too high clamping force with a possible weakening of the material has been detected in the second case. However, the percentage of time of the temperature into its process window is only 53% in spite of the optimal configuration of the set point. The obtained strength is slightly reduced compared with reference (23.8MPa vs 26.8MPa).

The same behavior on the temperature evolution (out of its process window in spite of a good configuration of the set point) has been detected in the case of excess of cycle time. However in this case the obtained strength is poor compared with the reference (13.6MPa vs 26.8MPa).

Also the case of no treatment at the upper part provides poor strength (15.8MPa) that is detected by the supervision software, meanwhile lower temperature provides medium strength (20.7MPa). This behavior highlights that not all the tested parameters have got the same influence into the quality of the joint. This influence has not been taking into account into the developed software. For this reason, the software differentiates between a good quality and non-good quality joint but up to now it does not provide an estimation of the value of the strength depending on the relevance of the affected parameter.

Based on this information, it can be concluded that the joining process is less repetitive in comparison with the previous materials combination, i.e. the same parameters configuration does not provide the same evolution, and therefore could not provide the same strength of the joint. This behavior could be explained because of the high reflectivity factor of the aluminum, that makes difficult to obtain a repetitive process and highlights the need of an improved surface pre-treatment method.

4. Conclusions and further research

- The supervision system provides a report with truthful information about possible defects based on the analysis of main relevant parameters.
- Material combinations that can be controlled by levels are more repetitive than other combinations that are more unstable and pattern controls should be applied.
- The reliability of the quality control system and the generated report is based on a deep understanding of the behavior of the process and the interaction between materials and light. Thus, novel material combinations, different thicknesses and geometries will require new testing phase to find both the optimal parameters and the configuration of the supervision system.
- The developed supervision system is a probabilistic method that must be used as a guideline. It is not a deterministic method that guarantees the strength of the joint.
- Defective surface texturing cannot be detected by the implemented supervision system, therefore, additional control systems during this step of the process are advisable.

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