FATIGUE BEHAVIOUR OF LASER WELDED THERMO-PLASTIC COMPOSITES

Pierre Boutet, Catherine Peyrac, André Galtier

CETIM, 52 avenue Félix Louat, Senlis, France 60300

pierre.boutet@cetim.fr

Abstract : Since the end of the twentieth century, composite materials are of ever growing interest for companies in many sectors of industry. Among these, transport industry (particularly ground transport) is a real great actor of this change because of the competition in the performance raising and in the decreasing of polluting emissions that involves a drastic reduction of masses and inertias in movement. In addition, European instructions concerning recycling force companies to replace the use of thermosetting matrixes, which cannot be smelted, with the use of thermoplastic ones. Mastering appropriate assembly techniques allowing matching well the companies Safety Quality Delivery Costs (SQDC) requirements is thus necessary for this kind of materials.
Among all existing assembly techniques, transmission laser welding offers great perspectives. While it is well known and mastered when used on polymer materials, few studies have been performed on laser transmission welding applied to continuous fibers reinforced polymers, which are mainly used on structural parts. Taking into account the specificities of composite materials compared to classical polymers, the present work deals with the fatigue behaviour of such assemblies. The studied base material is a stratified polyamide 6.6 reinforced with 40% continuous glass fibers.
Some pure tensile fatigue tests (R = 0,1) have been carried out, and the influence of different parameters (width of the seam, number of passes, feedback of the laser beam, …) has been studied. Some sections and fractures observations have also been performed in the welded zones in order to understand the mechanisms involved in the damage process. The obtained testing results have been grouped in some Wöhler curves and discussed. The specificities of the welding process due to the composite materials heterogeneities are also approached and their influences on the weld quality are highlighted. In conclusion, some perspectives in research continuation are thus proposed.

1 INTRODUCTION

Known for their specific physical and mechanical properties, i.e. brought back to their density, composite materials have been the centre of growing interest in various industry areas since the end of the 20th century [1]. The transport sector can be found amongst the concerned areas, especially the land transport with 23% of the composite global market in 2005 [2]. The continuing search for performance and pollution control requires a dramatic decrease of the masses and inertia at stake. What is more, due to the European directives on recycling, the industrial partners tend to abandon the thermosetting infusible matrixes to use thermoplastic matrixes instead [3]. Structural parts made from composite material with a thermoplastic matrix (CTP) can therefore be more easily found for example in the automobile industry and industrialists must have assembly techniques that match their cost, quality, reliability and lead time requirements.

A well known and used permanent joining technique on polymer material is welding [4-5]. Amongst various welding techniques used to date, laser transmission welding helps to respond to the industry's pace and flexibility requirements [6]. However, very few studies have been carried out on such assembling of composite materials and especially on continous-fiber composite materials that are typical of the structure components. By considering the specific features with regard to the usual polymers, this study is therefore carried out on the fatigue behaviour of assemblies joined by laser transmission welding. Results are presented and discussed, and research perspectives are offered.

2 STUDIED MATERIAL AND METHODS

2.1 Material

This study has been carried out on a material with a 66 polyamide matrix (PA 6-6), reinforced with 40% of continuous fibreglass. The plates used to manufacture specimens are made from 5-ply unidirectional laminated materials obtained via warm pressing of prepreg procedure. Since the study leans towards the industry sector, this material is a very good compromise between cost and quality. The PA 6-6 matrix is largely used in the entire industry, especially the transport sector, and features very good physical and mechanical characteristics [7]. Fibreglass is by all means the most commonly manufactured and used reinforcement, and is thus a cheap product [8]. Continuous fibres therefore bring good performance at a reasonable cost. This alliance gives the final CTP a mechanical tensile strength of 762 MPa and a Young's modulus of elasticity of 34.7 GPa (see figure 2).

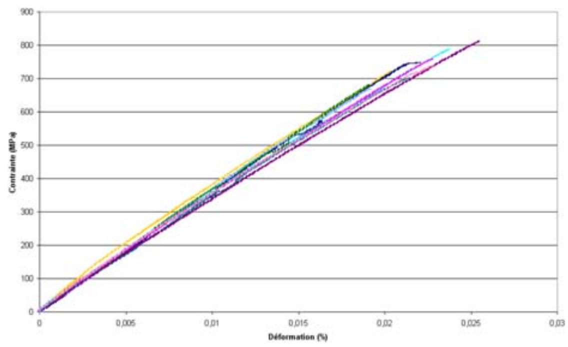

Figure 1: Tensile curve of the PA 6-6 – Continuous fibreglass [9].

2.2 Specimens and welding conditions

The fatigue tests specimens manufactured from initial composite plates were obtained through laser welding process (figure 2). This assembly process means that one of the parts must be transparent to the incident laser beam (of a given wave length) and that the other part must absorb the beam in order to relay its energy in the form of heat energy transmitted via contact to the first item. However, due to various reasons, it was important that the two parts of the assemble in this study be of the same material. First of all, the main reason is to keep the industrial application as a goal, and to limit the number of unknown parameters since few studies have been published on this subject so far. There are indeed various methods to render a transparent material absorbent. The chosen technological solution for these works is to colour the bulk material with carbon black. The mechanical properties of the resulting materials have been controlled and no manifest difference has been noted between that and the original material.

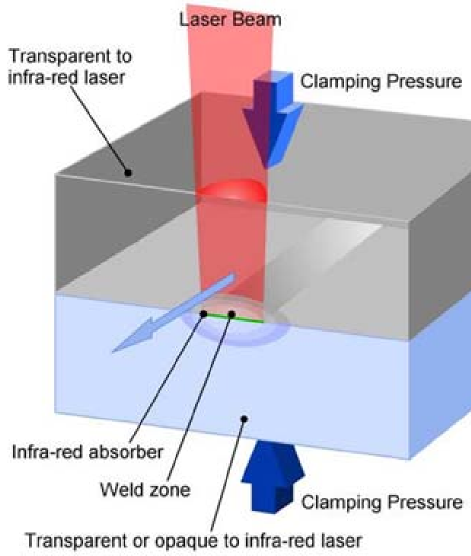

Figure 2: illustration of laser transmission welding [source Barkston Plastics]

Figure 3 shows the various configurations of the test specimen. Two different geometries of specimen are tested and different welding parameters have been set up. Figure 3-b therefore shows the "standard" geometry of the test specimens: they are single overlap shear test specimens manufactured from 5-ply sheets of raw materials (transparent and absorbent), i.e. a thickness of 1,4 mm. The heels allow to position the welded area within the plane of symmetry of the test configuration. The specimen geometry shown on figure 3-a, larger than the others, offers an alternative to this geometry in order to study the effects of linked edge on a similar welding, at the beginning and end of the weld seam. Finally, the figure 3-c presents the same geometry as the figure 3-b but has a larger welding seam, i.e. 15 mm (some 10 mm width weld seams have also been tested in order to get a better understanding of the influence of this width factor).

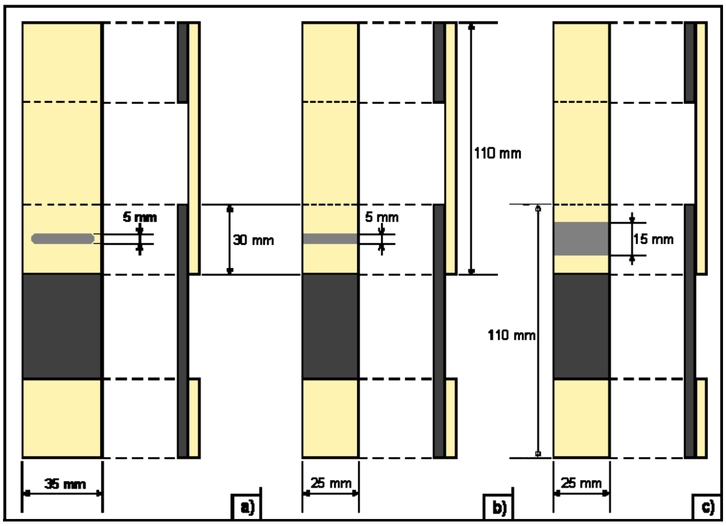

Figure 3: drawing of the shear test specimens. 3.a) test specimens with beginning and end of weld seam. 3.b) standard test specimens. 3.c) test specimens with a large weld seam.

The weld seams in all these test specimens have been made with a 940 nm wavelength diode laser, with an overriding temperature control system and a speed of 0.3 meter per minute. Several test specimens were therefore realized in order to compare some different processes parameters and highlight the influence of the parameters described below.

Four types of test specimens have thus been welded based on the figure 3-b geometry:

- Series NA("non asservie" or *without feedback*): the overriding control system is deactivated and the beam strength is set to 40W;
- Series A ("Asservie" or *with feedback*): the welding is controlled, with a target set to 160°C at the surface;
- Series 2P ("2 passes"): welded with the same conditions as the series A, but with two passes on the same weld seam.
- Series 3P ("3 passes"): welded with the same conditions as the series A, but with three passes on the same weld seam.

The figure 3-a geometry has been used to weld the DF Series ("Debut et fin de cordon" – Weld seam start and end) with the same conditions as the A series so as to isolate the effects of the weld seam tips.

The figure 3-c produced two series of test specimens, as mentioned before:

- Series CM ("Cordon moyen", or medium weld seam width), assembled with a 10 millimeters wide weld seam made by three successive passes with a controlled beam, with the same parameters as the series A (diameter: approximately 5mm), with a recoverage rate of 50% between each pass.
- Series CL ("Cordon large", or large weld seam width), assembled with a 15 millimeters large weld seam, made with the same method as the one used for the series CM.

3 TESTING

Some tests have been carried out on a MTS hydraulic fatigue machine. The tests helped to estimate the endurance limit of the test specimens at 2.106 cycles. The imposed load was sinusoidal, with a 0.1 ratio and a 8Hz frequency. Tests were performed in strength control and the real applied stress is calculated after testing by observation of rupture facies by SEM (scanning electron microscope). Indeed, these observations allow determining the real welded area.

4 RESULTS AND DISCUSSIONS

The results of fatigue tests are presented and analysed in this section. They are categorized to highlight the influence of parameters that have been tested in this works. The whole results shown below have been post treated with the fatigue software ESOPE. It is worth noting that the simplifying hypotheses made in this paper are quite strong.

4.1 SEM observation and assumptions to estimate the applied stress

For all fatigue results, it may be interesting to consider the applied load that can be immediately used for a design project, for example for a weld seam resistance per unit of length. However, it is important to understand the origin of the differences in the specimen behaviour of the series and to compare the specific resistance of each type of joint. These results were therefore analysed, based on the observation of the fracture facies of the weld seams.

The analysis is based on the study of welding breaking profiles since the attempt to characterize the joints using different non destructive techniques (NDT) proved to be unsuccessful. Presently, these are not suited to our test specimens, first because of their geometry and their dimensions, and also because of the inherent heterogeneity of the raw material. The observations have therefore been made from the SEM images in order to have a good depth of field and quality for the analysis. Figure 4 illustrates the fracture surface of two samples by SEM.

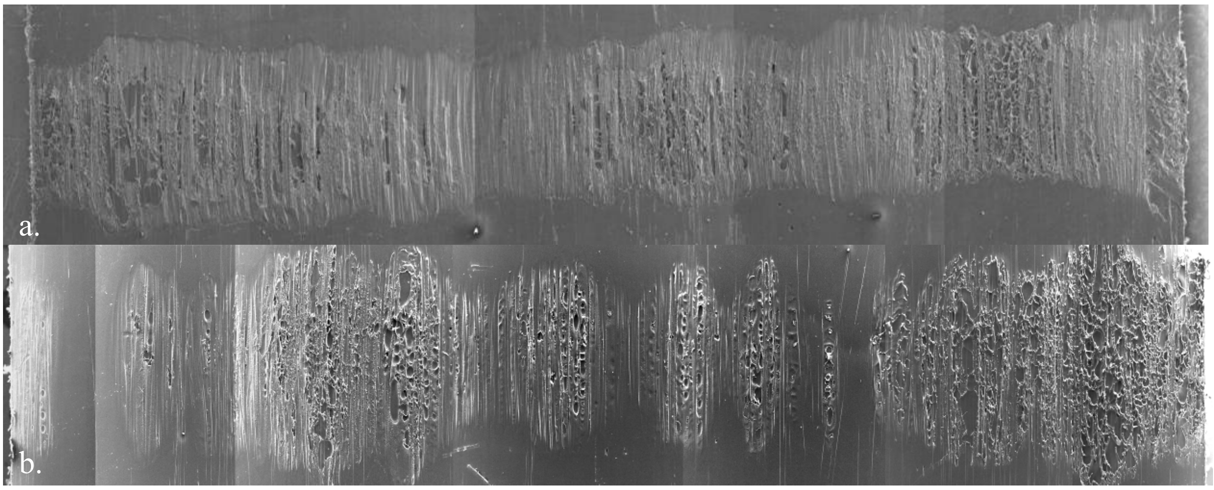

Figure 4: Broken welds that have been restored from SEM images:
4.a) Series of NA test specimens 4.b) Series of A test specimens

It is however important to note that the distribution of stress inside the welded area is three-dimensional, as it is for bonded joints, and non-homogeneous across the joint width. The use of the $\sigma = F/S$ formula to convert force in stress is therefore only a first estimate that does not reflect reality [11]. This conversion is even less representative of reality since the joint width is not constant in the welded zone as we can see in figure 4. Moreover, it should be specified that porosities also have an influence on the local stress level, which is not taken into account is this study, and that their rate is neither considered. Actually, this conversion step is mostly done to compare all different series of specimen with each others. Consequently, this is thus a mean to weight the loading strength in order to estimate the influence of the tested parameters without being disturbed by the difference of effective area, varying from one series to another.

The porosities can in fact be found irrespective of the test specimen series and their origin could not be determined. Several assumptions have been brought forward, e.g. a withdrawal of material during the cooling period, a degassing of the material or humidity initially present in the material (polyamide is known for its hydrophilic properties). It seems however that it is not linked to a material burning since spots of browning typical of this phenomenon were never seen, but an energy contribution that took place too quickly can however be considered. The observation of these porosities on two extreme test specimens showed that their rate is usually between 10% and 20% of the total area.

4.2 Results presentation and assumption

All fatigue results are both presented with the applied strength (kN) as a function of the number of cycles and with the calculated applied stress (MPa) as a function of number of cycles.

As presented previously, data are analysed with a Fatigue software. First of all, for a 50% survival probability level, a mean fitting curve is obtained considering a linear regression as $\log N = \log C - m.\log \sigma$ with the fatigue data (only the failed fatigue tested samples are considered); m is the slope of the curve in a log-log plotting.

Indeed, for some specimen series the data available were sometimes too poor to draw an SN curve, but taking into account the comportment similarities with other series it has been decided to set the slope of curves in such cases (figure 7.b: series CM). Because of this hypothesis, we can thus get an idea of the fatigue strength and compare it with that of the other series. However, as this approximation does not allow us to get an idea of the scatter in the results, an additional error shall be made in the position of the curve. This scatter, known to be great in the fatigue phenomenon, is in our case varying from 50% to more than 100%. It is thus good to take care about it when observing the results

4.3 Consequence of the number of passes

Figure 5 presents the fatigue results and fitting Basquin curves for the specimen series A, 2P and 3P corresponding to different number of passes (see § 2.2).
The difference between the curves of series A and 2P or 3P shows that it is important to get a continuous weld seam during the welding process. The overall aspect of a series A weld seam can clearly be seen on figure 4.b. However, series 2P and 3P, welded with the same parameters as the previous one, show a profile similar to that shown in figure 4.a. Continuous passes therefore enabled a better remelt of the material and better quality welds. As it has been previously said, the aim of the conversion of the load in stress was to weight the applied strength with the effective surface. Thus what can be observed on the figure 5.b is that even with the fatigue curves showing the stress, discontinuous welds are weaker than continuous one – this has also been seen in series A. It is therefore safer to make several passes in a material which is difficult to weld if a continuous weld cannot be guaranteed with a single one.

However, the results show a saturation of the phenomenon since a clear difference between series 2P and 3P cannot be observed.

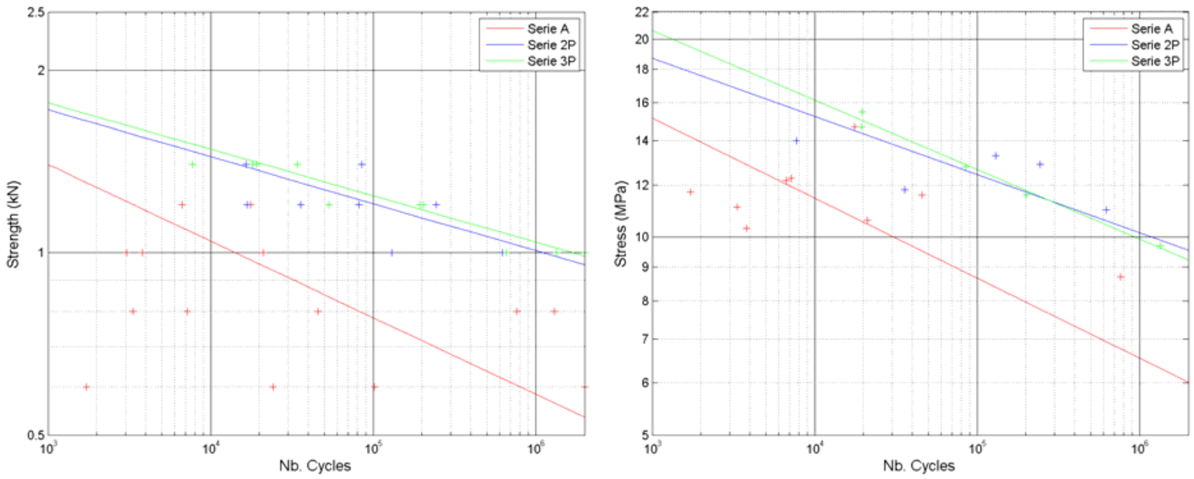

Figure 5: Comparison of the Basquin curves for the specimen series A, 2P and 3P
5.a) Ploted in strength 5.b) Ploted in stress

4.4 Influence of the weld seam extremities

Figure 6 presents the fatigue data and fitting Basquin curves for the specimen series A, DF corresponding to different weld seam edges (see §2.2).

The minimal difference that can be observed on the stress curve in this case is simply linked to a wider average area in the welds with a seam weld beginning and end. Once the stresses are shown, both curves are in the same scatter band. It is thus possible to consider that, in composite materials, the weld seam extremities do not alter its fatigue behaviour.

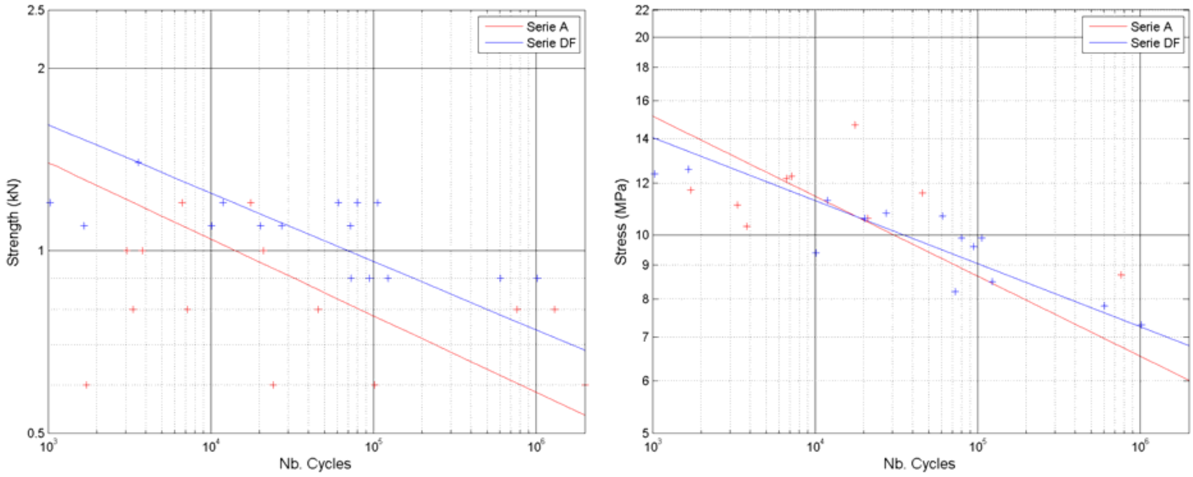

Figure 6: Comparison of the Basquin curves for the specimen series A and DF

6.a) Ploted in strength 6.b) Ploted in stress

4.5 Influence of the weld seam width

Figure 7 presents the fatigue data and fitting Basquin curves for the specimen series A, CM and CL corresponding to different weld seam width (see §2.2).

The curve showing the stress results reveals that, in this case, it is impossible to consider proportionality between the width of the joint and the accepted stress. It is worth noting that the same phenomenon can be observed on bonded joints. Indeed it is possible to note a limit width beyond which there would not be any increase in term of performance.

However, it is rather hard to interpret the figure 7.b. Indeed, the sca tter of series A is such that it is possible to consider that the three curves meet inside their respective dispersion. It is nevertheless possible to consider the fact that series CM and CL offer a better fatigue strength due to the edge effects, which are less important compared to series A.

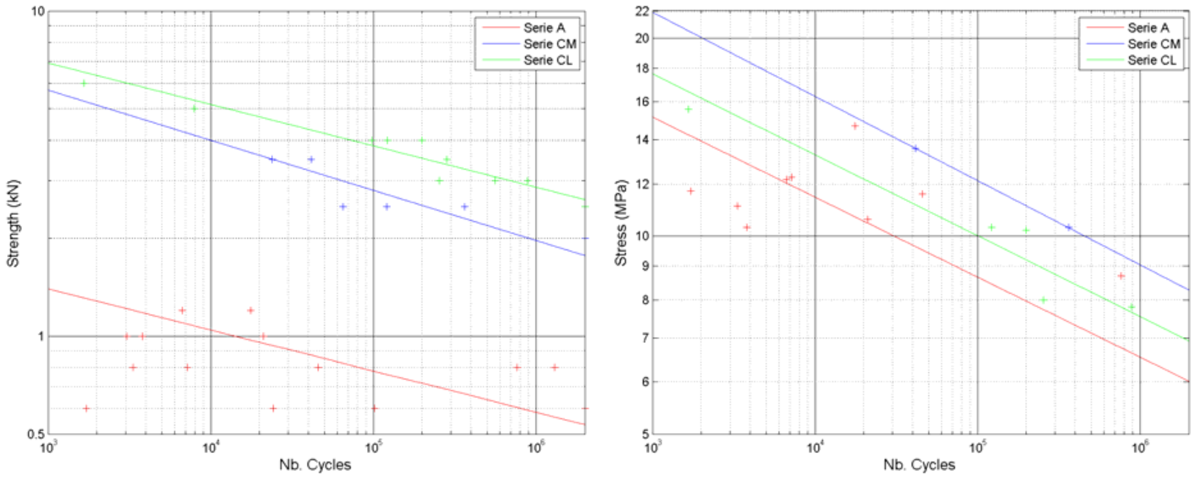

Figure 7: Comparison of the Basquin curves for the specimen series A, CM and CL

7.a) Ploted in strength 7.b) Ploted in stress

4.6 Influence of the process control

Figure 8 illustrates the fatigue data and fitting Basquin curves for the specimen series A and NA corresponding different weld control with or without feeback control (see §2.2).

The comparison of the results from both series makes it possible to more clearly see the influence of the welding process. Indeed, when the laser is driven with a certain temperature (series A), the strength factor is managed by the control system on the one hand. On the other hand, this factor can vary during the process. However, when it is driven with a certain strength (series NA), it remains set to the value programmed by the operator. It is difficult to make sure that the energy delivered at the interface during the process is the same in both cases. As a consequence, if most curves show similar inclines, the series NA - which is the only one to have been welded with no temperature control – shows a gentler slope, which gives it a higher strength limit. This difference highlights the importance of the welding parameters on the assembly. Series A would therefore have had different characteristics if its welding process had been performed with a higher controlled temperature or a slower speed. The perfect solution would probably be to think in terms of energy received by the surface per unit of time so as to have a better control of the process. Even if it seems obvious, it is in fact much more complicated in our case since the material and consequently its optical and thermal properties are by nature heterogeneous. Digital simulations can however help to develop the process.

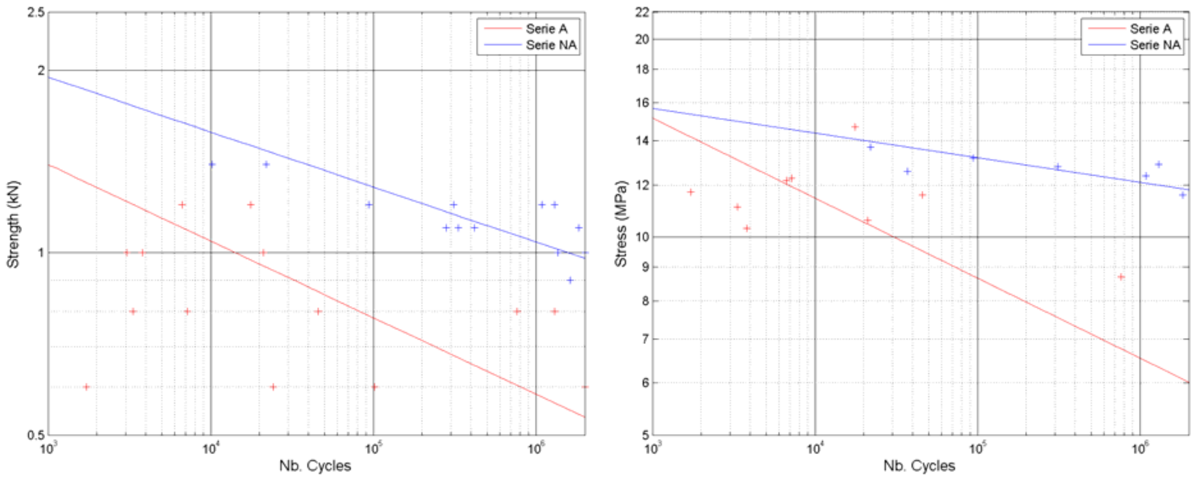

Figure 8: Comparison of the Basquin curves for the specimen series A and NA
8.a) Ploted in strength 8.b) Ploted in stress

4.5 Summary of the results

Figure 9 shows all the test results generated according to Basquin law, and table 1 resumes all the Basquin fitting parameters and fatigue strength at 2.10^6 cycles.

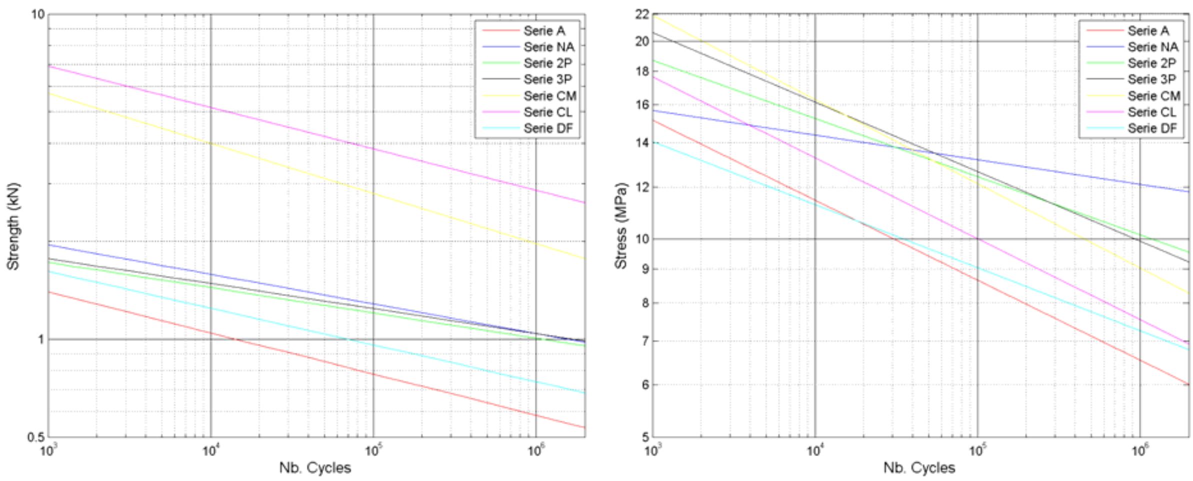

Figure 9: Comparison of the Basquin curves for all the specimen series
9.a) Ploted in strength 9.b) Ploted in stress

Table 1: Coefficients of the Basquin curve for all test specimen series and their strength limit at 2.10^6 cycles

Specimen series		**A**	**NA**	**2P**	**3P**	**CM**	**CL**	**DF**
Strength curves	m	7.9	11	12.9	13	6.5	7.9	8.8
	log(C)	9.6	14.3	13.9	14.3	18.3	22.2	11.2
	F_d (kN)	0.54	0.98	0.95	0.98	1.99	2.65	0.69
Stress curves	m	26,6	8,2	11,3	9,5	10,4	7,8	8,1
	log(C)	80,1	29,3	40,0	35,5	34,5	31,0	30,2
	σ_d (MPa)	11,80	6,02	9,55	9,23	6,79	8,27	6,92

It is thus possible to set a hierarchy in the fatigue strength of the welded seams. It is as follows in a decreasing strength limit:

1. Series CL 2. Series CM 3. Series NA 4. Series 3P
5. Series 2P 6. Series DF 7. Series A

Table 2 partly helps to explain the results found in figure 9 by presenting the welds dimensional characteristics accordingly to the appropriate series.

Table 2: dimensional characteristics of the test specimens, per series.

Test material series	**A**	**NA**	**2P**	**3P**	**CM**	**CL**	**DF**
Average welded surface (mm²)	80.05	97.61	95.10	97.96	250.49	385.43	108.21
Standard deviation	1.64	0.67	1.07	6.15	2.42	3.14	1.57
Coefficient of variation	2.05%	0.69%	1.13%	6.28%	0.97%	0.82%	1.45%
Relative measured surface	0,82	1,00 (reference)	0,97	1,00	2,57	3,95	1,11

5 CONCLUSION

This work has been carried out as a prospective study, in order to get an idea of the fatigue behavior of laser transmission welded continuous fiber thermoplastic composites. Some assumptions have been made in order to compare the different specimen series, and some results have been presented.
Combining all the remarks presented previously, i.e. the process management and the energy delivered management at the interface on the one hand and the completion of several passes on the other hand, could eventually give the means to get rid of the properties of materials. It would require a first pass with a low energy beam in order to record the reaction of the material before performing the welding pass. In this case, the temperature feedback could be used as a mean to analyse the material's behaviour during the first pass, while a power feedback could be set up during the second one.

It is worth noting that the strong heterogeneity of continuous fiber composite materials seems to cause a significant scatter in the weld width along the specimens (figure 4). Consequently, in order to get a better welding quality, different solutions are proposed:

- the multi pass seams, that present a best aspect and mechanical properties than single pass ones.
- a better control of the amount of energy brought to the welding interface. Indeed, this quantity strongly depends on the absorption of the transparent plate, so that managing the laser beam intensity to take it into account could significantly improve the quality of the weld line.
- a better quality of the material is also of great importance. Indeed, the more the material is homogeneous, the more the weld line should be of regular width, independently of the welding process.

A way to improve the quality of the weld seams would also be to really understand the origin of the porosities, in order to decrease their quantity. Moreover we realized that NDT such as ultrasonic testing, radiography, infrared thermography, are not suitable for such material and geometry, which make it impossible to control the morphology of the welded zone without breaking it.
On the other hand, it is worth noting that in the results presented above, the NA specimen series (without feedback control) present a lower slope than all the other ones. The testing of other feedback parameters could thus lead to obtain a behaviour close to this one, maybe with a better fatigue limit.

Finally, a good way to continue this work would be to study the influence of the fiber orientation compared with the seam orientation, since an industrial application would never use this techniques on plates with straight weld lines orientated perpendicularly to unidirectional continuous fiber.

REFERENCES

[1] S. Mazumdar, 2005, *Global Composites Market 2004-2010*

[2] A. Lemasçon, 2007, *Panorama prospectif composites*

[3] J. P. Candoret, 2010, *Marché des composites thermoplastiques 2010-2014,* CETIM newswatch, Janvier 2010

[4] P. A. Atanasov, 1995, *Laser welding of plastics : theory and experiments*, Optical engineering, vol. 34, no10, pp. 2976-2980

[5] R. A. Grimm, 1995, *Welding processes for plastics, Advanced Materials and Processes*; Volume 147; Issue: 3 pp. 27-30

[6] P.A. Hilton, 2003,Transmission laser welding of plastics, First International Symposium on High-Power Laser Macroprocessing

[7] D. Glassock, *High Performance Polyamides Fulfill Demanding Requirements for Automotive Thermal Management Components*

[8] J. Renard, 2005, *Fundamentals of Fibre Reinforced Composite Materials*

[10] M. *Oumarou*, 2011, *Approche probabiliste du comportement à long terme d'assemblages structuraux réalisés en composites thermoplastiques*