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Laser beam welding and straightening of Titanium T-joints for aircraft structures

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Abstract

This work deals with the development of laser beam welded (LBW) fuselage structures made of Titanium alloys. State of the art disk and fiber lasers have been employed to weld T-joints between Titanium Grade 2 sheets and Ti-6Al-4V Grade 5 stringers. Both skin sheet and stringers had a thickness of 0.8 mm. Optimum LBW parameters and process window have been determined for both laser sources with 400 and 500 microns spot size, respectively. Full penetration welds and minimum underfills (less than 80 µm) have been achieved without the addition of filler metal.
Due to the reduced thickness and stiffness of the skin, LBW led to significant distortion in samples with multiple welded stringers. A subsequent laser straightening (LS) process has been applied in order to reverse welding induced distortions. The results show the feasibility of manufacturing these aircraft structures based on T-joints between Titanium alloys. The work is completed with the analysis of ongoing developments to ensure required quality standards in large 3D HLFC structures, including seam tracking and process monitoring.

Keywords: laser beam welding (LBW); laser straightening (LS); titanium alloys; T-joints; aircraft structures

1. Introduction

The continuous growth of air transport worldwide makes necessary to improve its environmental impact in order to reduce CO_2 footprint. Reduction of fuel consumption and air pollutant emissions can be achieved by both reducing weight of fuselage structures and optimizing their aerodynamic performance. In this sense

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the introduction of high strength lightweight Titanium alloys, the replacement of conventional riveting joints as well as the implementation of advanced aerodynamic concepts like Hybrid Laminar Flow Control (HLFC) at the leading edges can decisively contribute to develop greener aircrafts (Abbas, 2012). HLFC concept is based on suctioning air through microperforated skin which generates an enlargement of laminar flow regime in the leading edges of aircraft structures (wings, tail,…) reducing fuel consumption (Schrauf, 2005).

Different manufacturing strategies of HLFC structures have been investigated so far in dedicated programs (Schultz, 2014). These research programs concluded that one suitable strategy to manufacture HLFC structures requires the welding of Ti-6Al-4V stringers to microperforated Ti Grade 2 (cp-Ti) sheet in T-joint configuration (Schrauf, 2005). The stringers are required in order to stiffen the structure due to the reduced thickness and low rigidity of microperforated sheets and additionally provide division between internal chambers to ensure suitable air suction.

Due to unique characteristics of laser beam welding (LBW) technology which is able to accurately focus concentrated heat source into workpieces, it entails a promising alternative for the development of HLFC and lightweight fuselage structures based on titanium alloys. Moreover, LBW is associated to fast welding speeds and low heat inputs which minimize residual stresses and distortion in welded parts. This is essential in thin components due to their low stiffness. In this sense, Engler et al., (Engler, 1999) was pioneer in the investigation of the manufacturing of titanium HLFC structures by CO_2 laser welding and straightening. Recently, some researchers (Reitemeyer, 2013) (Schult, 2014) have tested this concept in stainless steel structures employing state of the art disk laser source. In these works it was concluded that LBW and LS technologies can be successfully combined to manufacture real size aircraft HLFC components. The application of LS process after welding was able to compensate angular distortion along welding seam induced by LBW process.

However, LBW of thin titanium components entails some challenges. On one side, the overall weld quality greatly depends on process parameters (Kashaev, 2016) (Fomin, 2017) such as welding speed or laser power. In this sense, it is relatively easy to have lack of penetration and internal porosity defects in butt and T-joint configurations. On the other hand, due to the high reactivity of titanium alloys with atmospheric gases, superficial oxidation can be an important defect that can impair mechanical performance of these welds (Buddery, 2011) (Tsay, 2006) (Li, 2005). In order to avoid superficial oxidation sound cleaning procedures and effective shielding conditions must be ensured during welding. Formation of titanium oxides in the welds can be easily detected by simple visual inspection of surface coloration. ANSI AWS D17.1:2001 specifies discoloration acceptance criteria of welds for aerospace applications.

In this context, this work deals with the development of LBW fuselage structures made of titanium alloys. State of the art disk and fiber lasers have been employed to weld T-joints between 0.8 mm thickness Titanium Grade 2 sheets and Ti-6Al-4V Grade 5 stringers. The investigation is focused on the feasibility analysis to achieve sound welds which can meet acceptance criteria which are in force for aerospace applications while avoiding LBW induced distortion in real components. Current investigations have been performed in non microperforated sheets, but with an aimed future transference to microperforated sheets.

2. Experimental procedure

2.1. Laser beam welding (LBW)

LBW trials of T-joints between commercially pure titanium (cp-Ti, Grade 2) sheet and Ti-6Al-4V (Grade 5) stringers were completed using two state of the art disk and fiber lasers. Both skin sheet and stringers had a thickness of 0.8 mm. The edge of Ti-6Al-4V stringers was milled before welding in order to ensure a good surface matching and cleaned. Welds were completed without adding filler metal.

Beam characteristics of both lasers are included in next table. On one hand, 5 kW continuous wave disk laser Trudisk 5002 (6C) from Trumpf company together with an optical head Trumpf - BEO D70 mounted on a Gantry KUKA RLP60-60 robot was employed. On the other hand, an alternative welding setup consisting of 8 kW continuous wave ytterbium fiber laser (YLS-8000-S2-Y12) from IPG Photonics Corporation, Precitec - YW52 optical head and 6-axis KUKA KR30HA robot was disposed. Experimental welding trials were carried out in both systems in order to obtain LBW process window and compare them.

Table 1. Main characteristics of laser equipment.

Characteristic	YLS-8000-S2-Y12	Trudisk 5002(6C)
Laser source	Fiber	Disk
Maximum power (kW)	8	5
Diameter of laser beam delivery fiber (µm)	400	400
Collimation lens (mm)	120	200
Focal lens (mm)	300	200
Focal spot diameter µm)	500	400
Center wavelength (nm)	1070	1030
Beam parameter product (BPP) (mm · mrad)	7.4	8

Optimization of LBW parameters and shielding system was performed using 50 mm height straight Ti-6Al-4V stringers. This optimization was based on the metallographic observations of weld cross-sections and visual inspection. T-joints with different welding parameters (laser power (P) and offset (a) from stringer-skin interface) were welded in both laser systems. Welding speed (v) was fixed at 3.5 m/min. Main welding trials were performed at 25º incidence angle (α). This incidence angle was defined as the minimum one to avoid physical interference between laser welding head with 200 mm focal lens and skin. Every weld was performed at focal position, i.e., without defocusing (F=0). A scheme of welding configuration is shown in Fig 1a.

Cross-sections of welds were analyzed by optical microscopy (Olympus GX51) after cutting, mounting, grinding, polishing and etching with Kroll's reagent (3% HF, 6%HNO_3, 91% distilled water). Dimensions of weld pool and heat affected zone (HAZ) and welding defects such as excessive underfills, lack of fusion at the root, insufficient penetration into skin or internal porosity were examined by metallographic inspection. The following weld quality acceptance criteria were defined: full consolidation of stringer-skin interface (full penetration of stringer), face underfills below 80 µm (< 10% workpiece thickness) and weld penetration into skin above 160 µm (> 20% sheet thickness). Additionally, acceptance criteria of welds for aerospace applications according to ANSI AWS D17.1:2001 "Specification for Fusion Welding for Aerospace Applications" were applied. This standard also states acceptable colors of titanium welds. Bright silver, silver, straw, bronze or brown colors are acceptable ones, whereas violet, green, blue, gray or white are not allowed.

Due to the high reactivity of titanium alloys with oxygen and nitrogen which can decrease tensile ductility of welds (Buddery, 2011) (Tsay, 2006) (Li, 2005), it is mandatory to ensure a good shielding during welding. This was achieved by assembling a local shielding device to the laser welding head. The shielding device was composed by a front nozzle and two back nozzles which provided dynamic shielding while welding. Additionally, skin component was placed on a support plate with machined groove that was filled with argon to provide extra shielding from underneath. This combined shielding from three sides of the weld enabled (Fig 1c) the achievement of bright silver welds in the front (face), back (root) and under the skin.

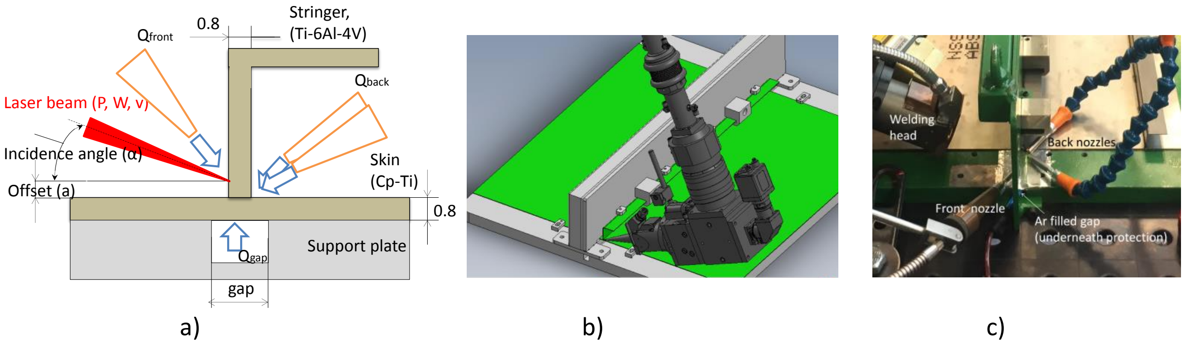


Fig. 1. (a) scheme of welding configuration; (b) clamping system and (c) shielding system configuration

After initial LBW process development, 100 mm and 500 mm length panel demonstrators were welded. Both demonstrators with straight and L-shape stringers (18 mm height by 19.5 mm) were manufactured. L-shape stringers were welded using a special clamping system which ensured good contact between skin and stringer and perpendicularity to the skin (Fig 1b).

The welding system in the disk laser facility was completed by a low wave infrared (LWIR) camera (NIT – New Infrared Technologies) that was introduced to monitor the IR radiation emitted from the root (back side of the weld) and TH6i welding seam tracking system (Scansonic). These systems were implemented in the welding of 500 mm length panel demonstrator after an initial fitting and optimization of monitoring and seam tracking parameters.

Additionally, laser straightening process (LS) was developed in the fiber laser system. Details of LS process development are given elsewhere (Froend, 2017).

3. Results and discussion

3.1. LBW process development

A first round of LBW trials was completed in both LBW systems in order to determine optimum parameters for the T-joint configuration. Since the energy input is a critical parameter which determines welding penetration, distortion and overall welding quality, initial LBW process development was focused on the optimization of this parameter. In LBW, heat input is closely related to line energy (L_E) which can be directly calculated from laser power (P) and welding speed (v).

$$L_E = \frac{P}{v} \quad (1)$$

Welding speed determines interaction time between laser beam and workpiece. Slow welding speeds are usually associated with higher porosity levels in butt and T-joints of Ti-6Al-4V (Kashaev, 2016) (Fomin, 2017) due to longer exposure times to laser radiation. Having this into account the selected welding speed was 3.5 m/min. This value ensured a good comprise between lack of porosity in welds and seam tracking and monitoring performance. For this reason, welding speed was kept constant and the influence of energy input was determined by changing laser power (P).

Due the low thickness of workpieces and absence of filler metal, this joint configuration was very sensitive to laser beam incidence angle (α in Fig 1a). This is shown in Fig 2 which compares the cross-sections and microstructural features of two welds performed at the same energy input (12 kJ/m) with the fiber laser, but different incidence angles. It is shown that the lowest incidence angle of 15º (Fig 2a) leads to full stringer penetration with reduced underfills and good weld penetration. On the contrary, lack of penetration at root is evident in the weld performed at 25º (Fig 2b). Moreover, an increase of energy input up to 13.7 kJ/m at this incidence angle did not avoid lack of penetration defect, but gave rise to deep underfills, internal porosity and higher heat affection of skin. Three welds of Fig 2 were carried out without offset by pointing the laser beam directly to the intersection point between stringer and skin interfaces (a=0).

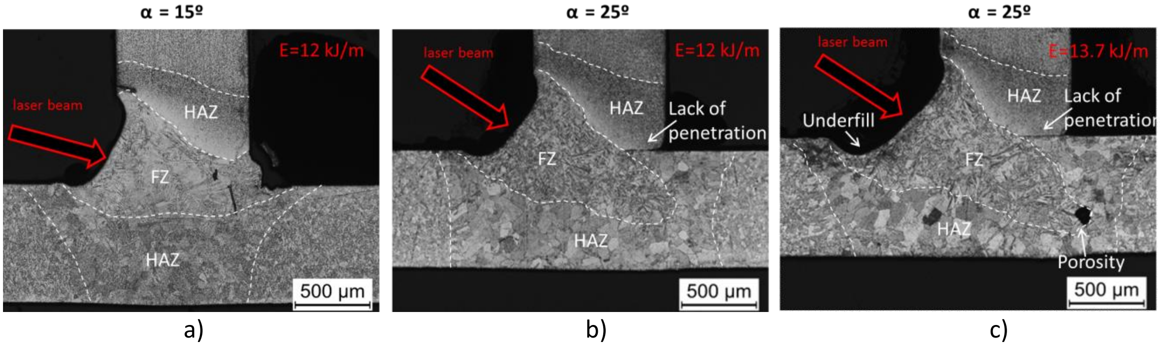


Fig. 2. Cross sections of LBW T-joints at different incidence angles and energy inputs.

An accessibility analysis was performed in order to check the feasibility of using low incidence angles in real fuselage structure designs. It was concluded that an incidence angle of 15º can lead to physical interference between welding head and workpiece if 200 mm focal lens are used. Moreover, aimed structures (leading edges of wings and tail) usually have an internal curvature which can further reduce accessibility. For this reason, it was decided to set incidence angle at 25º.

Fig 3 displays cross-sections of different welds that were performed with disk laser at different laser powers (P) and offsets (a), keeping the rest of parameters as detailed previously (v=3.5 m/min, α=25º, F=0). It is clearly shown that as the incidence point moves upwards, lack of fusion defect at the root becomes narrower. At 650 W, the laser power is not enough to achieve full penetration. However, at 750 and 800 W, the size of the underfills at skin and stringer is well above 80 µm. It was concluded that 700 W was the optimum laser power to meet defined acceptance weld quality criteria. For this optimum power, offsets above 0.4 mm gave rise to reduced welding penetration into skin, whereas at offsets lower than 0.3 mm non continuous and unstable penetration was observed in the root (backside) by visual inspection (Fig 4).

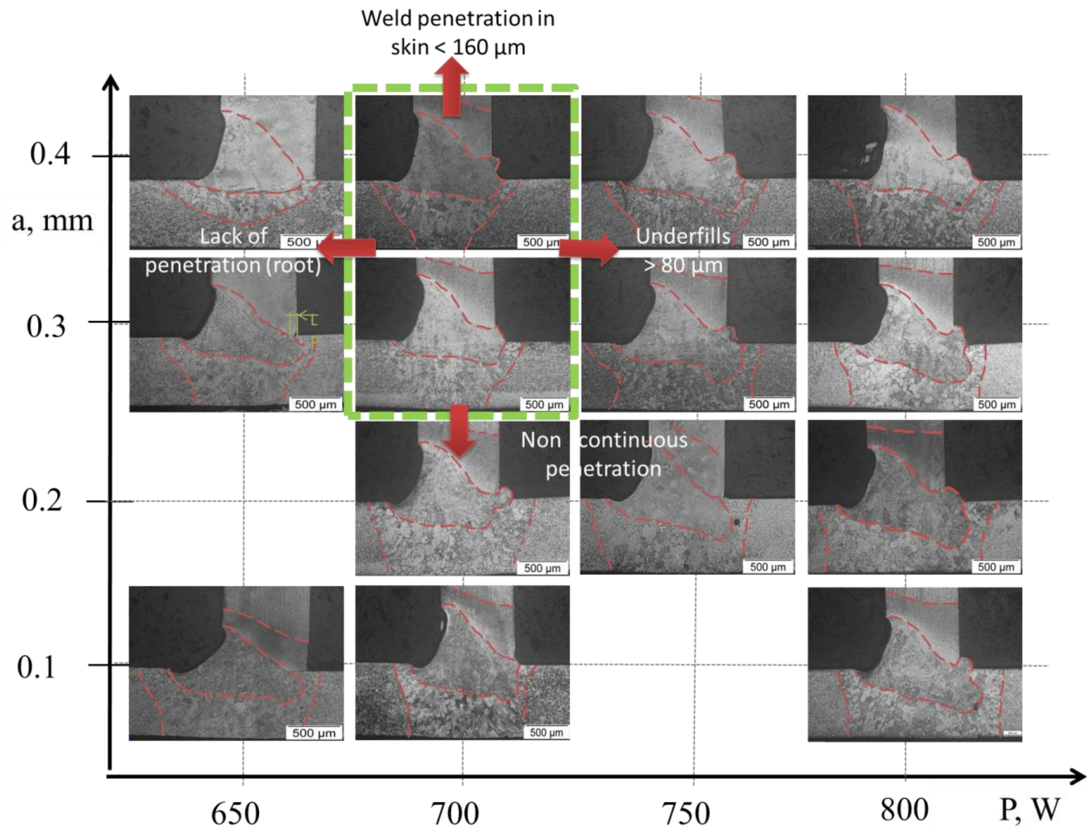


Fig.3. Cross sections of T-joints with different laser power (P) and offset (a) combinations obtained with disk laser.

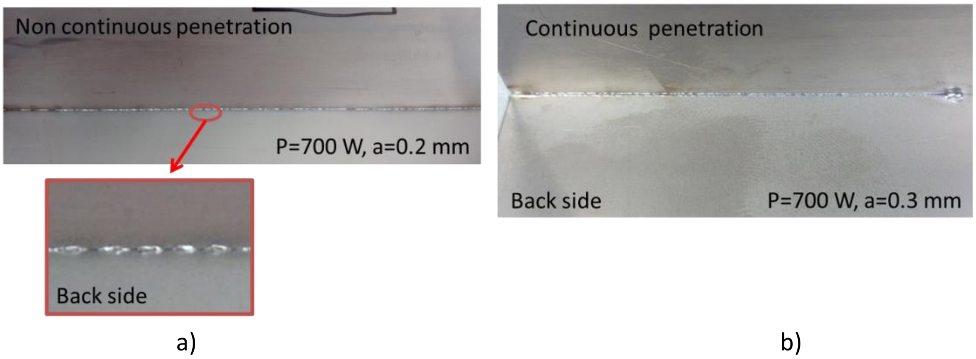


Fig.4. Magnification of back side of the T-joints showing a) non continuous penetration and b) continuous root penetration.

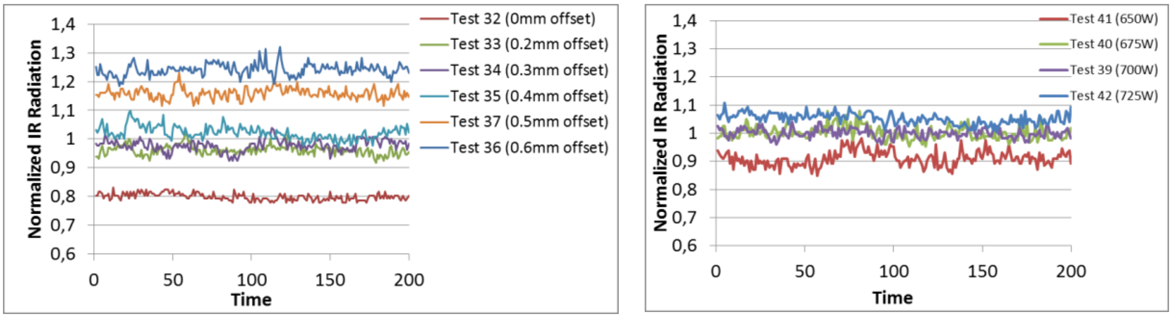
Similar LBW trials were completed in the fiber laser system. The results were comparable to the ones reported above for disk laser device. Optimum process parameters for fiber laser equipment was defined at

600-650 W and 0.2-0.3 offset. Out of this process window it was not possible to meet the weld quality requirements.

LBW process development in parallel laser systems (disk and fiber) demonstrated that the process window for this joint configuration is really narrow and requires very accurate control of laser power and focus point. This requirement can be critical for the industrial implementation of LBW in real aircraft structures. For this reason the performance of state of the art seam tracking system (TH6i from Scansonic) was checked in 500 x 500 mm panel demonstrators. This seam tracking system is composed by a triangulation sensor that performs a no-contact scan of the shape of the joint. It is a powerful system which receives and analyses signals coming from 3 parallel scans. This increases the joint detection capacity and reduces signal interpretation problems due to reflectivity or interference issues. By adjusting the joint detection criteria and laser scanning parameters (exposure time and laser power) joint detection capability of this system at the tested welding speed (3.5 m/min) was close to 95% which provides good seam tracking performance.

3.2. Welding process monitoring development

Since lack of fusion defect at the root can be critical for the structural and fatigue performance of welded aircraft structure (Kashaev, 2016), it was decided to develop a real time LBW process monitoring system that can automatically detect this defect. For this reason a LWIR camera was assembled to the welding head in order to capture the IR radiation emitted from the back side during the welding. A set of welding trials was performed in disk laser facility using different laser powers (P) and offsets (a). Fig 5a displays normalized IR emission captured by the camera at different offset configurations. It can be clearly observed that emission from welds performed out of the process window significantly differs from welds that met acceptance criteria. Welds with low offsets (e.g., 0 mm) are associated with lower normalized IR emission values, whereas both welds performed at 0.5 and 0.6 mm offsets emitted a IR radiation that was more than 15% higher that the nominal values for optimum parameters. Note that higher offsets than 0.4 mm brought about reduced weld penetration into skin. Non continuous penetration areas observed in the sample welded at 0.2 mm offset (Fig 4a) were correlated to normalized emission peak drops down to 0.92.



a) b)

Fig.5. Normalized IR emission values recorded from the backside during welding time at different offsets (a) and laser powers (b).

A comparable peak drop is observed in the sample welded at 0.3 mm which coincides with a localized point where the weld seam at the backside is not totally smooth. This irregularity was associated to a poor fitting between stringer and skin surfaces. It is worth noting that the clamping system must perform a uniform controlled load in order to avoid gaps between parts or waviness of stringer wall. Both issues will ruin weld quality due to the absence of filler metal.

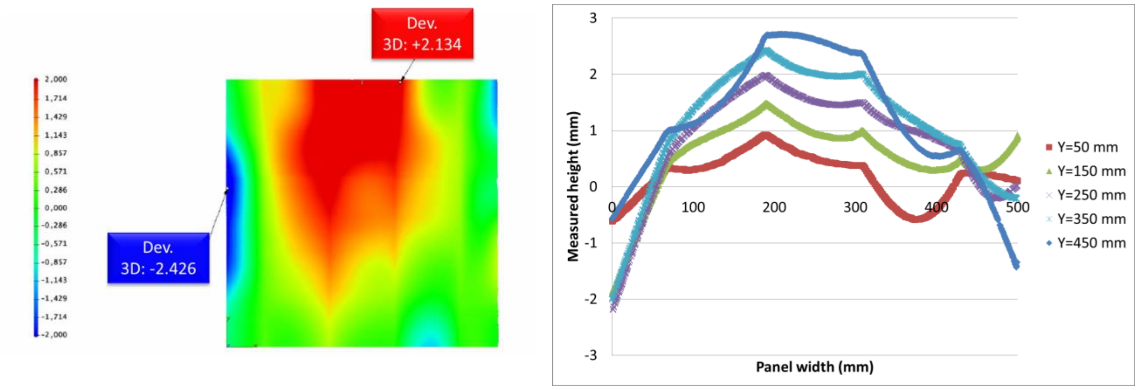
On the contrary, the sample welded at 0.4 mm offset displays a uniform normalized IR emission during the whole length of the weld. It was checked by visual inspection that the weld seam of this sample was perfectly smooth and continuous.

Similar results and behavior was observed in welds performed at different laser powers from 650 to 725 W at a constant offset of 0.4 mm (Fig 5b). In this case, three samples that were welded at P between 675 W and 725 W exhibited even and constant normalized IR emission values between 1 and 1.1. It was verified by visual inspection that the appearance of these three welds was also indicative of good and stable root penetration. On the contrary, the sample welded at 650 W presented clear lack of fusion defect at the root (Fig. 3). Note that normalized IR emission values of this sample fell down below 0.9.

3.3. Analysis of welding distortions

A 500 x 500 mm flat panel demonstrator with 4 L-shape stringers was welded in order to validate shielding system, welding monitoring and seam tracking system in representative part and analyze welding induced distortions. Stringers were 500 mm long and had 18 x 19.5 mm shape. They were welded leaving a span distance of 120 mm. The panel was welded employing previously determined optimum parameters (P=700 W, a=0.4 mm, α=25º). Fig 6a represents color map of Z-component of distortion obtained by contactless laser scanning 3D measuring system. The flatness error induced by welding distortion was 4.5 mm.

As it is observed in Fig 6a, highest positive distortion data are concentrated in the middle of the panel (X between 200 and 300 mm) close to the point where the weld of each stringer ends ,i.e., Y=500 mm. That means that both distortion shape and values are not homogeneous along panel length (Fig 6b). Moreover, there were some clear concavities between stringers which led to conclusion that there was a waviness induced by welding distortion. This waviness between stringers was not observed in a second shorter panel (100 mm long) demonstrator that was welded reducing the span distance between stringers to 70 mm. In this case “Zeppelin” effect was observed due to the angular distortions induced by LBW of T-joints (Fig 7). In this second demonstrator the as welded distortions were effectively reduced by applying laser straightening (LS) process with fiber laser. Both experimental LS procedure and straightening results together with physical laser forming mechanism are explained in detail in a recent paper (Froend, 2017).



a) b)

Fig.6. a) Color map of Z component distortion of 500 x 500 mm panel demonstrator. X direction (horizontal) is perpendicular to stringers and Y direction (vertical) is parallel to them. b) Z component distortion curves along panel width (X direction) at different Y sections.

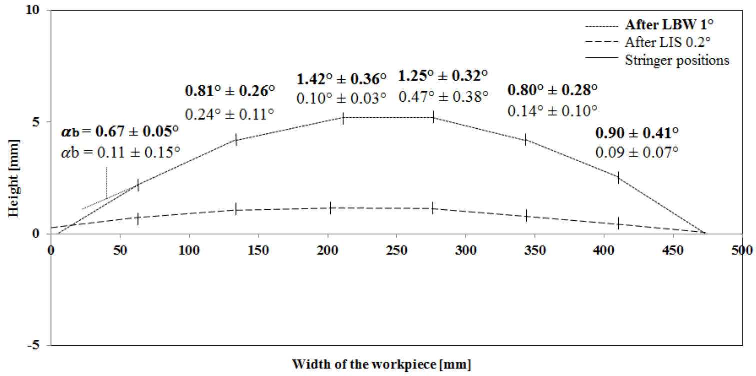


Fig.7. Z component distortion and angular distortion between stringers in 500 x 100 mm demonstrator panel in as welded condition and after LS.

4. Conclusion

- LBW is an enabling technology of lightweight aircraft structures based on titanium alloys and T-joints and can effectively contribute to the development and implementation of advanced aerodynamic concepts like HLFC.

- LBW of T-joint configuration (0.8 mm workpiece thickness) is extremely sensitive to variations in incidence angle, incidence point (offset from stringer and skin interface) and laser power. Sound and approved welds can only be obtained within a very narrow process parameter window (± 25 W laser power and ±0.1 mm offset). This small process window was comparable in disk and fiber laser equipment with slightly different laser beam characteristics.

- Regarding the T-joint configuration, a dynamic shielding must be provided from the front side, backside and under the skin in order to avoid the formation of harmful oxides in the weld and HAZ.

- A seam penetration monitoring system has been developed which can effectively distinguish between welds carried out within the process window and out of it leading to lack of fusion defect at the root or reduced penetration into the skin. This monitoring system can be applied in real time and is able to detect local defects or instabilities due to poor fitting of workpieces or laser beam deviations from the joint. These deviations can be avoided using state of the art seam tracking system.

- LBW of panel demonstrators induced distortions leading to a loss of flatness. Span distance between stringer of 120 mm gave rise to concavities and waviness in the skin which produced an uneven distortion distribution. More even distortions were obtained by reducing the span distance between stringers to 70 mm, which allowed the effective reduction of as-weld distortions by subsequent LS process.

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