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Jean-Denis Béguin, Valentin Gazagne, Yannick Balcaen, Joël Alexis, Eric Andrieu

Laser Welding of Titanium Alloys with an Yb: YAG Disk Source

J.D.Beguin[1,a*], V.Gazagne[1,b] Y.Balcaen[1,c], J.Alexis[1,d], and E.Andrieu [2,e]

[1]Université de Toulouse, LGP, ENIT/INPT, 47 Avenue d'Azereix, 65016 Tarbes, France

[2]Université de Toulouse, Institut CARNOT CIRIMAT, UPS/CNRS/INPT, ENSIACET, 4 allée Emile Monso, 31030 Toulouse, France

[a]jean-denis.beguin@enit.fr, [b]valentin.gazagne@enit.fr [c]yannick.balcaen@enit.fr, [d]joël.alexis@enit.fr, [e]eric.andrieu@ensiacet.fr

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Abstract. In this paper, the laser welding of thin titanium sheet in a butt joint configuration are investigated using a continuous Yb: YAG disk source, with high beam quality and a particular fiber configuration, enable to provide a broad range of beam diameters with different intensity distribution. The thermal efficiency of the laser process is discussed as a function of the fiber type. The weldability results for the CP Ti grade 2 and the Ti-6Al-4V titanium alloy are expressed in terms of full penetration, and correct bead geometry (NF L06-395-2000). Full penetration welds are easily achieved with the core fiber, but the outer fiber produces welds with limited geometric defects. Butt joints microstructure consists of an acicular α phase in the fusion zone for CP Ti, and a martensitic α' phase for the Ti-6Al-4V alloy. Tensile test results confirm a similar or slightly higher joint strength for the full penetration welds, compared with the parent metal.

Introduction

Laser welding is a rapid and accurate process to join thin metal sheet with minimal heat input and low thermal distortions. It is a satisfactory candidate to replace riveting in order to reduce weight and cost in aerospace applications [1]. Recent innovations in laser process have led to the development of new laser source design with high beam quality: Among these new developments, we can notice the emergence of the Yb: YAG disk and fiber laser sources to produce deep penetration welds at high welding speed [2].
However, titanium alloys are noted for being difficult to weld, because of its high reactivity with oxygen, its rapid grain growth above β-transus, easier to overcome with laser welding [3]. In addition, the rapid cooling rate in the weld bead, can lead to the formation of very complex microstructure, varying from acicular α phase to martensite α' in the fusion zone (FZ) [4]. As a consequence, the final properties of the welds depend on the microstructure morphology and the geometrical defects of the fusion zone. The purpose of this present study is to determine the welding efficiency of the process, a "weldability domain" and the generated microstructure for both CP Ti and Ti-6Al-4V.

Experimental Method

Commercially pure titanium (CP ASTM grade 2) sheets (0.8 mm thick) and Ti-6Al-4V (ASTM grade 5) sheets (0.9 mm thick) were used as the base material. The microstructure of the base metal consists on a fine recrystallized α phase grains for the CP Ti and a classic annealed microstructure for the Ti-6Al-4V titanium alloy, composed of equiaxed α nodules surrounded by thin β phase. The titanium sheets were cut by laser processing to ensure a precise gap for a butt joint configuration welding. Before welding, titanium plates were mechanically polished with a P600 emery paper, to eliminate superficial oxides, water rinsed and cleaned by acetone. Alignment and clamping of butt joints require a precise fixture, to maintain a low gap and a controlled laser focus position relative to the joint (Fig. 1a). A trailing shield and a gas chamber were used to protect the top and root of the weld. After welding, butt joints were cut by laser processing from traverse section for microstructural characterisation and tensile tests (Fig. 1b and 1c).

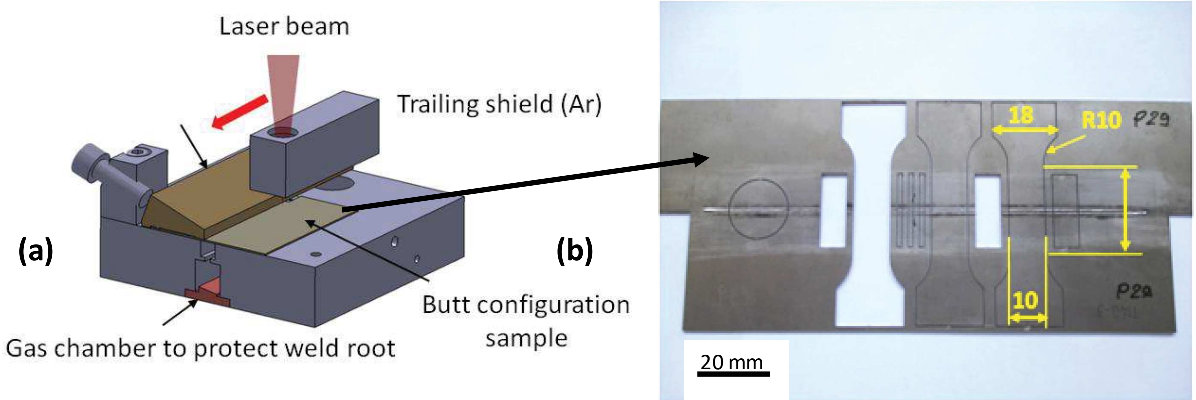

Figure 1: Experimental set-up, (a) Laser welding fixture, (b) localization of metallographic and tensile test sample.

Titanium sheets were welded using an Yb: YAG laser disk system, with a maximum continuous power of 3 kW, an emission wavelength of 1030 nm and a beam parameter product (BPP) of 8 mrad. Low BPP values imply high focusability of the laser beam [2]. The laser beam is delivered by a core fiber (diameter 100 µm) or a coaxial outer fiber (diameter 400 µm). An optical device controls the beam guidance between the inner core or outer fiber. The intensity distribution, measured by a beam profiler is very different for the core fiber and the coaxial fiber (Fig. 2). The core fiber displays a Gauss-like intensity distribution at the focus point, while the coaxial fiber displays a circular top-hat shaped intensity distribution.

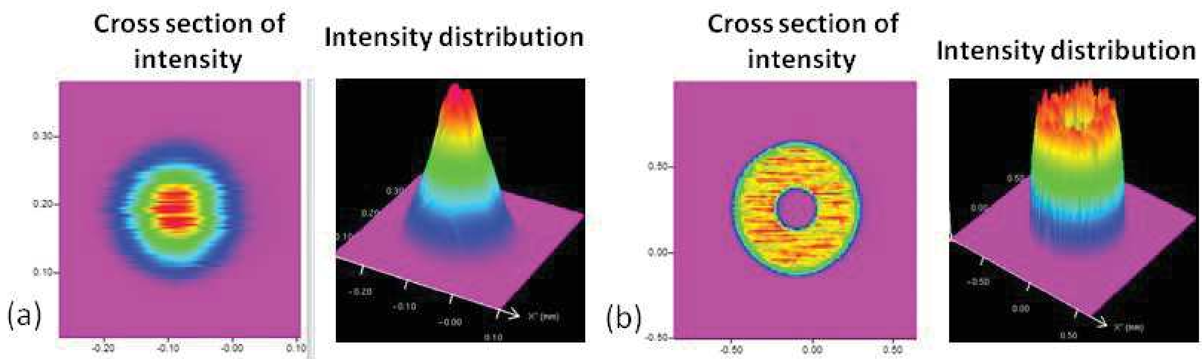

Figure 2: Intensity distributions at the focal point with (a) the 100 µm core fiber (500 W, Φ=150 µm), (b) the 400 µm outer fiber (500 W, Φ=150 µm) measured with a Primes Focus monitor device.

Experimental parameters are listed in the following table 1. In order to study the effect of welding parameters on the full penetration and bead geometry, a wide process parameter range was investigated. The laser was focussed 0.3 mm below the specimen surface, to enable a better process stability and reduce porosities and spatters of the welds [5].

Table 1:Experimental parameters and metallographic responses.

Welding parameters	Values	Responses (NF-LF06-395)
Power [W]	500-2500 (5 levels)	Weld penetration
Speed [m/min]	1-8 (5 levels)	Weld geometry
Focal Spot diameter [µm]	120-750 (5 levels)	
Argon gas flow [l/min]	10-40 (4 levels)	

Results and Discussion

Influence of the fiber type on the process efficiency. The process efficiency was investigated on CP Ti grade 2 thin sheets. The process efficiency is relative to weld seam cross section and the energy delivered to the workpiece [6]. Figure 3 exhibits the effect of the focal diameter on FZ area according to the core or outer fiber. It can be seen that welds generated with the core fiber for smaller (120 µm) or bigger focal diameter (305 µm) require greater input energy to obtain large melted areas than intermediate focal diameters (175 µm and 240 µm). In the opposite, for the outer fiber, smaller focal diameters provide better melting efficiency, with higher melted zone area (Fig. 3b). This suggests that heat exchanges on CP Ti grade 2 thin sheets are probably different for the core or the outer fiber.

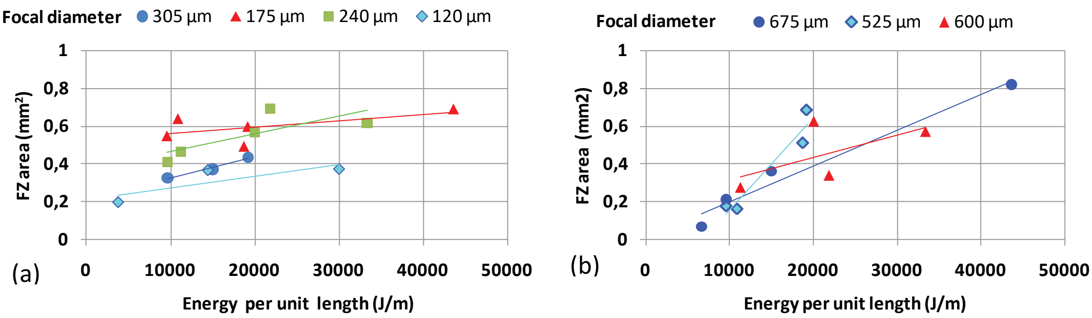

Figure 3: Fusion zone area as a function of energy per unit length for different focal diameters, (a) with the core fiber, (b) with the outer fiber.

In order to understand the heat exchanges phenomena, we focused on the melted zone which is strongly dependent on the thermal efficiency of the process. This term corresponds to the ratio of the necessary power to melt the material to the total incident power [6]. It is strongly depends on the dimensionless Peclet number written as follow:

$$Pe = \frac{Vr}{\alpha} \quad (1)$$

Where, r is the beam radius, V the welding velocity and α the thermal diffusivity of the material, ($9.6x10^{-6}$ $m^2.s$ for CP Ti grade 2). This number corresponds to the ratio of the thermal transport by convection and conduction. As a consequence, for a Peclet number less than 1, the heat exchanges will be dominated by heat conduction phenomena, on the other hand, the heat convection phenomena will be dominant. Figure 4 illustrates the influence of the Peclet number on the process efficiency. For a Peclet number less than 1, the FZ area are smaller compared to HAZ area, on the contrary, FZ area are greater than HAZ for a Peclet number greater than 1.

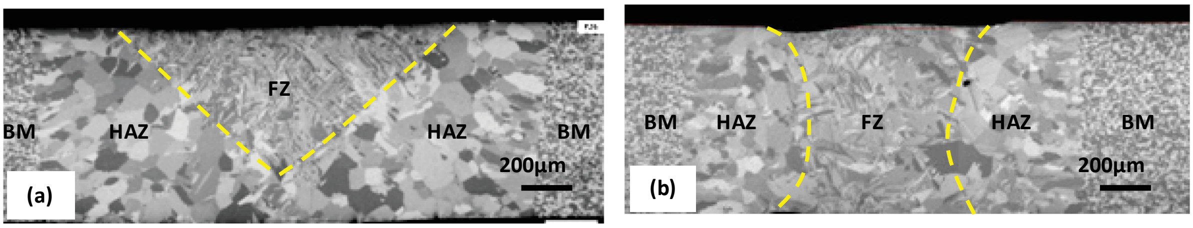

Figure 4: Relationship between thermal efficiency and Peclet number (Pe), (a) Pe=0.86, (b)Pe=3.52.

To improve the welding efficiency, heat conduction losses must be minimized, the Peclet number should be greater than 1. This can be achieved by adapting the welding speed and the focal diameter. In the above section, it is identified that in the case of the core fiber, an increase of the focal diameter at a maximum value of 300 µm will improve the thermal efficiency, while for the outer fiber it will be preferable to keep the focal diameter less than 600 µm, to assure a better thermal efficiency.

Welding process diagram on CP Ti grade 2. A process window to generate “full penetration” welds was investigated applying a wide range of process parameters (power, welding velocity, focal diameter) on the CP Ti grade 2 sheets. Welded joints were made under variable Ar flow rate, ranging from 10 to 40 $l.min^{-1}$. A weld coloration indicates an insufficient gas protection for a flow rate under 17 $l.min^{-1}$.

In order to normalise the effect of power, welding velocity, and focal diameter, the laser power density has been plotted as a function of interaction time. Among experimental results, not all the combination of process parameters led to correct welds (Fig. 5). Analysing the weld defects, such as incomplete penetration or cut through, two process boundaries has been highlighted. On one hand, the minimum power density to achieved full penetration should be approx. $5x10^5$ W/cm^2, on the other hand, the maximum interaction time could be approximately 7 ms. These two boundaries delimit three domains: a domain with an insufficient penetration, a domain with full penetration and a cut through domain. It’s seems more easily achieved with the core fiber than the outer fiber for both CP Ti and Ti-6Al-4V titanium alloy. The power density seems to be a determinant parameter for a full penetration. These results are in good agreement with the results obtained by Quintino et al. on a Ti-6Al-4V titanium alloy with a fiber laser [7].

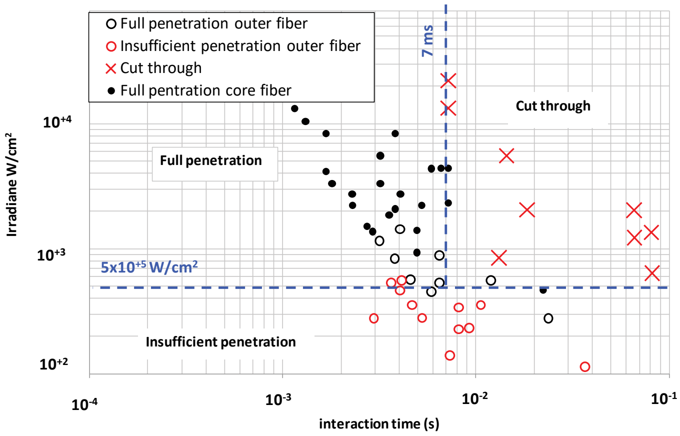

Figure 5: “Full penetration” window for a CP Ti grade 2.

Comparison of the Weld quality window of the CP Ti grade 2 and Ti-6Al-4V alloy. After determining a “full penetration” window for the welding process, the aim of the study was to determine a sound weld domain with a correct geometry according to the NF-L06-395-2000 standard (Fig. 6), for CP Ti and Ti-6Al-4V alloy. To evaluate the weld bead defects such as underfill, undercut and undesirable root profiles, butt joints were observed by optical microscopy after a metallographic cross section preparation. The results of weld defects examination are reported are plotted as a function of irradiance and interaction time for a CP Ti and a Ti-6Al-4V alloy (Fig. 6).

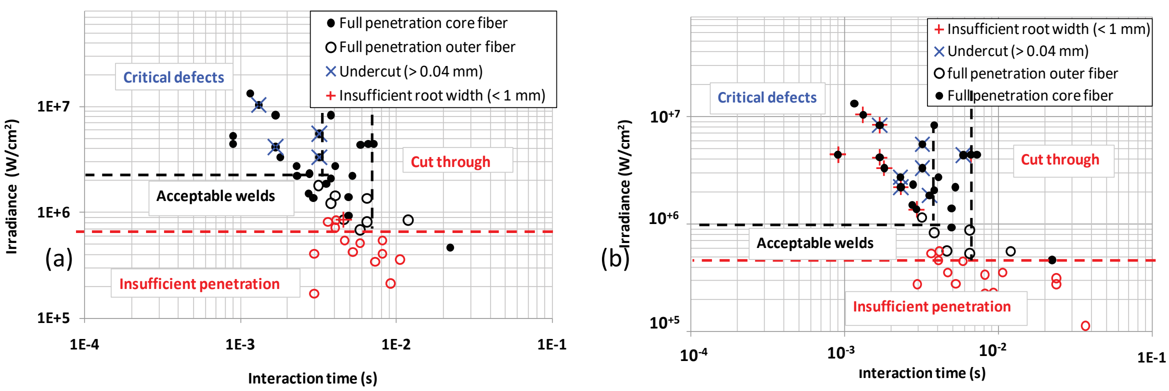

Figure 6: Relationship between weld full penetration, laser power density and interaction time, (a) CP grade 2 titanium, (b) Ti-6Al-4V titanium alloy

It can be noticed that the “acceptable weld” domain for CP Ti and Ti-6Al-4V are similar but significantly reduced. Correct welds can be produced with the outer fiber for a power density range from 5.10^5 W/cm^2 to 10^6 W/cm^2. Geometric imperfections appear with the core fiber for a power density higher than 10^6 W/cm^2. Undercut is the most detrimental defect present for titanium alloys. It is reported that the presences of imperfections such as underfill or undercut lead to stress concentration and can reduce mechanical properties of the weld [8]-[4]. Undercut defect appears at high power and low welding speed [3]. The root width depends on the weld depth/width aspect ratio. An increase of the aspect ratio leads to a decrease of the cross-sectional fusion area and therefore tends to reduce the root width.

Weld microstructures and mechanical properties. The thermal cycle during laser leads to a significant local change in the titanium microstructure. Three different zones are visible for each weld (Fig. 7): Base Metal (BM), Heat Affected Area (HAZ) and Fusion Area (FZ). The cooling rate in the FZ is high enough to form an acicular α phase for CP Ti and α’ martensite for Ti-6Al-4V alloy. In the HAZ region adjacent to the FZ, the microstructure consists on coarse α grains for CP Ti, and a mixture of α’, primary α and β phases for Ti-6Al-4V.

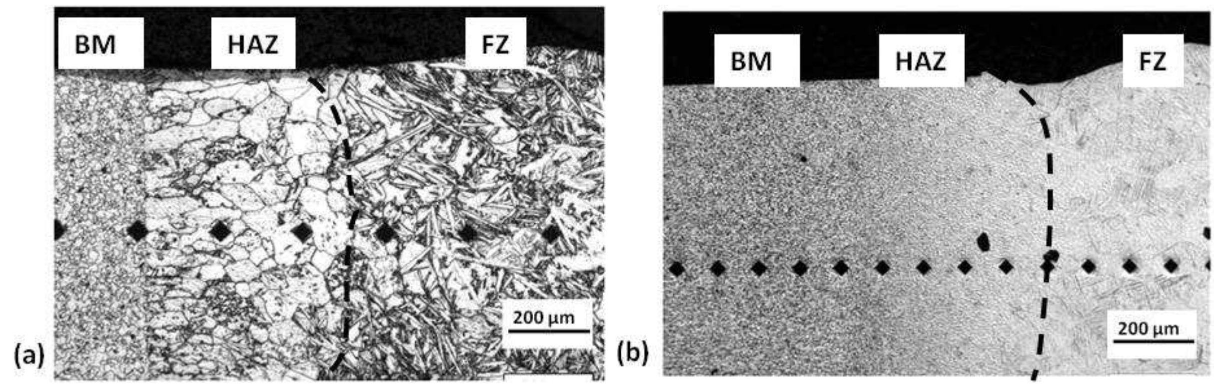

Figure 7 : Welds made at 1500 W, 4.5 m/min, diam. 370 µm (a) CP Ti grade 2, (b) Ti-6Al-4V alloy.

Full penetration welds were investigated under tensile test at room temperature with a constant cross head speed of 2 mm.min^{-1}. Laser welds joints have similar or slightly higher tensile strength with a reduced ductility. Tensile strength obtained in this study ranges from 445 to 471 MPa for the CP Ti, and 1017 to 1046 MPa for the Ti-6Al-4V alloy, indicating an increase of 5% and 3% respectively, compared with the base metal. The elongation at fracture decreases approximately 38% for CP Ti and 76% for Ti6Al4V alloy. These mechanical properties can be correlated to the formation of acicular microstructure in FZ for the CP Ti or Brittle α’ microstructure for the Ti-6Al-4V alloy. Similar results were observed with a conventional fiber and Nd: YAG laser source by A. Squilace et *al.* and X. Cao et *al.* [1]-[4].

Summary

(1) The thermal efficiency of the process is influenced by the heat conduction dissipation. To improve the welding efficiency conduction losses must be minimized by varying the focal diameter and the welding speed.
(2) Full penetration welds are more easily achieved with the core fiber than the outer fiber.
(3) The core fiber produces welds with more geometric defects than the outer fiber.
(4) Full penetration welds have similar or slightly higher joint strength. Undercut defect seem to have no influence on the tensile properties. A significant decrease in ductility can be attributed to the presence of acicular phase in FZ.

References

[1] A. Squilace, U. Sprisco, S. Ciliberto, A. Astarita, Effect of welding parameters on morphology and mechanical properties of Ti-6Al-4V laser beam welded butt joints, Journal of Materials Processing Metallurgy, 212 (2012) 427-436.

[2] R.S. Sharma, P. Molian, Weldability of advanced high strength steels using Yb: YAG disk laser, Journal of Materials Processing Technology, 211 (2011) 1888-1897.

[3] A. Costa, R. Miranda, L. Quintino, D. Yapp, Analysis of beam material interaction in welding of titanium with fiber lasers, Materials and manufacturing processes, 22 (2007) 798-803.

[4] X. Cao, M. Jahazi, Effect of welding speed on butt joint quality of Ti-6Al-AV alloy welded using a high-power Nd:YAG laser, Optics and Lasers in Engineering, 47 (2009) 1231-1241.

[5] A-M El-Batahgy, T. DebRoy, Nd-YAG Laser Beam and GTA welding of Ti-6Al-4V, International Journal of Engineering and Technical Research, 2 (2014) 43-50.

[6] A. Patschger, J. Bliedtner, J.P Bergmann, Approaches to increase process efficiency in laser micro welding, Physics Procedia, 41 (2013) 592-602.

[7] L. Quintino, A. Costa, R. Miranda, D. Yapp, V. Kumar, Welding with high power lasers-A preliminary study, Materials and design, 28 (2007) 1231-1237.

[8] N. Kashaev, D. Pugachev, V. Ventzke, Microstructure and mechanical performance of autogenously fiber laser beam welded Ti-6242 butt joints, Material Science & Engineering, A 694 (2017)110-120.