Materials and Design 47 (2013) 300–308

Contents lists available at SciVerse ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Fiber laser cutting of Ti6Al4V sheets for subsequent welding operations: Effect of cutting parameters on butt joints mechanical properties and strain behaviour

L.D. Scintilla, G. Palumbo, D. Sorgente, L. Tricarico *

Dipartimento di Meccanica, Matematica e Management (DMMM), Politecnico di Bari, Viale Japigia 182, 70126 Bari, Italy

ARTICLE INFO

Article history:
Received 8 October 2012
Accepted 6 December 2012
Available online 27 December 2012

Keywords:
Titanium alloy
Lasers
Cutting
Welding
Digital image correlation
Plastic behaviour

ABSTRACT

The effect of laser cutting parameters on the mechanical behavior of laser butt welded joints whose edges were obtained by laser cutting was investigated. The paper aims to demonstrate that new high power solid-state fiber lasers not only represent a valid and reliable alternative to the most established CO_2 and Nd:YAG laser sources, but also allow to obtain cuts having edges well suited for subsequent direct laser welding. First Ti6Al4V 1 mm thick sheets having edges machined by milling were laser welded. Once the optimal welding condition was determined, the mechanical characterization of sheets cut by fiber laser and then laser welded was performed. Comparative strain analysis performed by a digital image correlation technique highlighted the effect of the gap between the sheets resulting from the different cut edge quality. Experimental results showed that the correct selection of laser cutting parameters allows to obtain butt joints characterised by mechanical properties comparable with the ones obtained by milling. Cutting edge quality in the optimal range of gap values allows to obtain the best mechanical performances of the joint.

1. Introduction

During the last decades, with the escalating fuel prices and awareness of environmental changes more attention is focused in order to develop sustainable products [1]. Their constituent components and structures must be designed, developed and manufactured saving up materials and energy. The use of lightweight alloys is a viable choice in order to achieve sustainability requirements and in particular weight reduction and functional advantages of structures and vehicles that represent the most important goals of the engineering design and manufacturing [2–4]. If compared to the other light alloys, Titanium (Ti) alloys are most widely used for different technologically advanced sectors due to their superior performance characteristics, such as high strength to weight ratio, high corrosion resistance, high strength and stiffness at elevated temperatures, fatigue resistance. Examples are medical, aerospace, automotive, petrochemical, nuclear and power generation industry [5]. The increasingly stringent requirements during operation in these field are met by Ti and its alloys but the elevated raw material and machining costs make their use highly selective, in particular in automotive and aircraft industry. From one side, the high material cost is due to its production by the current Kroll process, which is still quite expensive; anyway, endeavours to reduce the cost of Ti have seen a number of potential alternative production technologies [6]. From the other side, Ti and its alloys cannot be easily manufactured and in a cost-effective way by conventional cutting methods. This is due to their poor thermal conductivity, low elastic modulus and high chemical affinity at elevated temperatures that adversely affect the tools life [7]. High quality components can be produced by forging and subsequent machining, whose costs can be up to 40% of the total costs of a final part [8]. In some cases finished components can have uneconomical buy-to-fly ratios [9].

In order to support the wider use of Ti alloys also in conventional industrial applications and thus reduce the costs associated with the material supply and manufacturing, two main strategies can be adopted.

The first strategy consists in reconsidering the design phase of Ti alloy components in order to optimize the material usage. The production of near-net shape components by a high integrity joining process could significantly reduce the material waste and increase the production rates [9]. Using Tailor welded blanks (TWBs), i.e. welding sheets having different characteristics into a single flat blank before the forming process, is possible to achieve the optimal material arrangement and weight reduction [10,11]. For example, with this manufacturing approach, automakers can add strength to parts where it is needed and reduce the overall weight and cost of a vehicle. TWBs application is expected to be one of the candidates to address also the problem of weight reduction for Ti alloys [12–14].

One of the three approaches for light-weighting illustrated by Mayyas et al. [1], i.e. to develop a design for energy efficiency, is based on the usage of optimized cross-sectional shapes of

* Corresponding author. Tel./fax: +39 080 5962778.
E-mail address: tricarico@poliba.it (L. Tricarico).

0261-3069/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.matdes.2012.12.014

Nomenclature

e_1	major strain	t	sheet thickness (m)
e_2	minor strain	UTS	ultimate tensile strength (N m^{-2})
E_f	elongation to fracture	v_C	cutting speed (m s^{-1})
p	assist gas pressure (Pa)	v_W	welding speed (m s^{-1})
P_L	laser power (W)	x_C	distance from the center of the weld bead in DL direction (m)
Q	heat input (J m^{-1})	YS	yield strength (N m^{-2})
Ra	roughness – arithmetic mean value (m)		
Rt	roughness – total height (m)		

structures. In this way better loading performances are achieved without weight increase using Tailor Welded Blanks/Tubes/Coils (TWB/T/C) technology to customize the blanks thickness and grade according to local performance criteria.

The second strategy consists in modifying the processes used for the Ti alloys components manufacturing and to use advanced processes rather than mechanical cutting methods. Laser cutting is especially indicated because there is no mechanical contact between the workpiece and the cutting tool [15] and the effectiveness of thermal processes depends on the thermal properties of the material to be machined. In this context, laser beam cutting represents a promising process in machining Ti alloy parts. Most papers in literature report results concerning cutting of pure Ti and its alloys using Nd:YAG lasers operating in pulsed mode (PM) [16–18,7] and CO_2 laser operating in continuous wave mode (CW) [19]. Recently, experimental results on CW fiber laser beam cutting of Ti6Al4V alloy thin sheets have been reported [20] for the first time. The advantageous characteristics as power efficiency, beam guidance and beam quality of high-power solid-state disk and fibre lasers, made them valid and reliable alternatives to the CO_2 and Nd:YAG laser sources, as demonstrated by many simulations and experimental results [21–27]. Comparing fiber and CO_2 lasers from a technical and commercial point of view, fiber lasers are better that CO_2 lasers when cutting highly reflective materials and thin section metals (below about 4 mm) [28]. The use of fiber lasers allows to implement the strategy to reduce the manufacturing costs because of the great reduction of processing time. In fact, using CW operation mode allows to obtain a much faster process with respect to the PM. These benefits are of special interest for applications like coil sheet cutting, laser blanking, trimming [29], the integrated cutting and welding with a multifunctional laser combi-head [30] and thus TWB. The possibility to apply laser welding to sheets cut by fiber laser, without the need for further edge machining due to the excellent cut edges quality, reduces the total processing time but makes critical the selection and control of the processing parameters. In fact, in applications with subsequent welding requirements the quality of laser cutting edges is essential for obtaining sound welds in the next manufacturing step [31–33]. Laser beam welding (LBW) is proved to be much more feasible for the production of Ti plate joints since laser welded joints have better combination of strength and ductility with respect to the TIG welding, which represents the most widely used welding methods for Ti alloy [34]. Furthermore LBW provide a significant benefit for obtaining reliable Ti alloy welds due to essential characteristics for TWBs applications like minimum distortion and higher fatigue strength [35–40]. For this kind of applications, an optimization of LBW joint quality based on response surface methodology (RSM) can be required since LBW is used in approximately 99% of all TWBs applications [41]. Anyway, the small values of beam diameter of laser welding process in contrast to hybrid laser-MIG welding make the workpieces and clamping tolerance a critical aspect in order to obtain a reliable joining process.

For this reason, experimental investigation on the effect of fiber laser cutting process parameters on mechanical behaviour of the subsequent Ti6Al4V LBW butt joints was carried out in this work. Once the best Nd:YAG welding parameters on 1 mm thick parts with edges obtained by machining were determined, this condition was used to weld sheets cut with a 2 kW fiber laser varying cutting speed and assist gas pressure. Mechanical characterization of butt joints welds on sheet metal part previously cut with fiber laser was carried out by tensile tests assisted by a digital image correlation (DIC) technique. DIC has been applied in literature to study the local deformative behavior in both formability and tensile tests [2]. In particular, investigations about local tensile properties of weld joints obtained by friction stir [42–48] and laser [49,50] of different metallic materials have been widely reported in literature. Recently DIC was also applied for laser welded Ti-6Al-4V [35,36].

In the present study, DIC technique was used to acquire strain maps in uniaxial tensile tests and to compare the strain behaviour of different types of welded specimens. To the author's knowledge, an experimental analysis concerning the influence of the cut edge quality by the variation of the cutting parameters on the subsequent laser welding of Ti6Al4V alloy sheets with fiber laser, has not been performed. The final aim is to detect the laser cutting process parameter window that allows to obtain edges well suited for subsequent direct laser welding process, i.e. that produces butt joints with mechanical properties comparable with the ones obtained by milling. The acquisition of a detailed level of knowledge about laser cutting and subsequent welding phase was obtained.

2. Experimental details

Cutting and welding experiments were performed on the as-received alpha–beta alloy Ti6Al4V (grade 5) sheets 1 mm thick. Sheets were characterised by a nominal composition of 5.50–6.75 wt% Al, 3.50–4.50 wt% V, <0.4 wt% Fe, balance Ti. The experiments were performed in three distinct phases illustrated in Fig. 1.

The objective of the first phase was the establishment of the best operating welding condition basing on tensile tests. In this case welding tests were performed on sheets with milling machined edges. In the second phase the effect of the cutting speed and the assist gas pressure on the quality of sheet edges cut by fiber laser was evaluated by means of roughness measurements. The final phase of experiments combines previous results: butt joints were thus realized with the best operating condition previously determined welding sheets whose edges were obtained varying the laser cutting parameters. In this case, mechanical characterization performed by tensile tests was realized in combination with a strain analysis performed using a DIC system. The present section describes the experimental procedures and the process settings used.

2.1. Butt joint welding tests

As regards the join operations, the experimental settings were kept unchanged during the two main experimental phases: the re-