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Laser Welding of Selective Laser Melted Ti6Al4V: Microstructure and Mechanical Properties

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Abstract

Ti6Al4V alloy exhibits an excellent potential for biomechanical applications as well as structural engineering applications, especially in the aerospace industry and marine applications. In this study, the effect of laser welding (LW) on grain structure and the mechanical properties in a selective laser melted (SLM) Ti6Al4V is reported. The studied material was SLMed at two different layer thicknesses t , 30 and 50 μm , and respective energy densities 69.4 and 60.3 J/mm³. Post-annealing treatment at 940 °C for 4 h was carried out to relieve stress, induce the β -phase and reduce the acicular α' martensite content, thereby helping to enhance its mechanical properties. Subsequently, LW was employed to join SLMed Ti6Al4V plates using a 2.4 kW laser travelling at 60 mm/s. The microstructures were studied as-built by SLM and after LW, followed by an evaluation of the mechanical properties. X-ray diffraction (XRD) and optical microscopy were applied for phase analysis and uniaxial tensile tests were conducted to study the joint strength. The most relevant results of the present work are that the layer thickness plays a key role on tensile properties of the SLMed Ti6Al4V. The SLMed material with $t = 50 \mu\text{m}$ showed higher strength with yield strength 940 MPa and ultimate strength 1130 MPa, while the corresponding properties of $t = 30 \mu\text{m}$ were 910 MPa and 1080 MPa, respectively. However, the fracture elongation of the as-built materials with $t = 30 \mu\text{m}$ was 15 % as compared to 9 % in the higher t . The tensile results of the laser welded materials did not reveal loss in the mechanical properties at both t .

[copyright information to be updated in production process]

Keywords: Selective laser melting, laser welding, Ti6Al4V, microstructure, mechanical properties

1. Introduction

Today, metal additive manufacturing (AM) is being employed for the fabrication of structural parts with a wide variety from medical implants to the aircraft industry and marine application solutions. AM processes have rapidly progressed to be a viable fabrication technology for a variety of metals and alloys in complex shapes, in particular, aluminum-silicon alloy, austenitic stainless steel, inconel alloys and titanium alloys. Qian et al. [1] categorized the different metal AM processes with respect to energy source, printing material and the addition technology. Considerable efforts have been directed towards the SLM of Ti6Al4V. In this context, Zhou et al. [2] studied the microstructures and mechanical properties of Ti6Al4V fabricated by SLM under vacuum at different chamber pressures and different input energy densities. Fousova et al. [3] processed three gradient porosity structure of SLMed Ti6Al4V to study the mechanical properties. Xu et al. [4] investigated different SLM processing routes for microstructural control of additively manufactured Ti6Al4V by SLM to reduce the unfavorable α' , via in-situ decomposition, into lamellar $\alpha+\beta$. Zhechao and Hongwei [5] studied how the Ti6Al4V properties and microstructure are affected by the laser power, speed and direction of scanning and heat treatment (HT).

It was established that the mechanical properties of the additively manufactured parts are affected by several parameters of the SLM technique, such as printing parameters, powder properties and HT. One of the largest

limitations of the SLM technique is the limited size of the parts that can be produced with the current equipment. Furthermore, the residual stresses associated with SLM process can induce distortion of components and cracks. Hence, laser welding is a promising candidate for producing large-scale products joined from additively manufactured smaller parts. From the open literature, the general weldability of AM components can be assured. Recently, several publications have worked on the weldability of AM products. For instance, Moeini et al. [6] studied the solid-state friction stir welding (FSW) process of AlSi10Mg parts fabricated via the SLM. Yang et al. [7] investigated the corrosion resistance, microstructural evolution and the mechanical properties of LW stainless steel fabricated by SLM. To the authors' knowledge, no laser welding experiments have been reported for SLMed Ti6Al4V alloy in the open literature. In the present study, two series of Ti6Al4V alloy have been AMed by SLM with two different layer thicknesses. Subsequently, the concerned material was laser welded after fixing the welding parameters to explore the feasibility of joining SLMed Ti6Al4V alloy.

2. Experimental and SLM fabrication

2.1. Test specimen manufacturing

The raw material used for this study was Ti powder of Grade 1 with extra-low interstitials and low oxygen content of 0.13 wt%. The powder particle size was 20-63 μm with the highest frequency of about 42 μm . Two sets of Ti6Al4V samples were fabricated directly by SLM technique (SLM 280 HL) with a laser power of 275 W and two different layer thickness 30 and 50 μm . The building platform was heated up to 200 $^{\circ}\text{C}$ during the fabrication process. The laser processing parameters used in the present work are shown in Table 1. The SLM process was conducted under an argon atmosphere at 12 mbar pressure and gas flow of 7,5 m/s. The specimen size was 120 x 20 x 2.5 mm. The bulk energy density formula can be calculated as follows [2]:

$$E = \frac{P}{v \cdot h \cdot t} \quad (1)$$

where P [W] is the laser power, v [mm/s] is the scanning speed, h [mm] is the hatch spacing and t [mm] is the layer thickness. This equation combines the joined effect of the used parameters as energy per unit volume absorbed by the powder.

Table 1. Laser processing parameters used for SLM of the fabricated Ti6Al4V alloy

Laser power, W	275
Scanning speed, mm/s	760, 1100
Hatch spacing, mm	0.12
Layer thickness, μm	30, 50
Energy density, J/mm ³	69.4, 60.3
Size of the SLM processes samples	120 x 20 x 2.5 mm

2.2. Post-processing of the SLMed samples

The as-built SLMed Ti6Al4V alloys were heated at 940 $^{\circ}\text{C}$ for 4 h followed by furnace cooling, all done in shielding gas (Argon). It was established that using sub-transus HT (decomposition of the martensite occurs above 780 $^{\circ}\text{C}$) for the Ti6Al4V in the α - β region can improve the ductility [1].

Ytterbium-doped:yttrium aluminum garnet (Yb:YAG) laser with a maximum output power of 4 kW and wavelength 1030 nm was utilized in this study. Pure argon was used for shielding the welding and blown into the process after the laser weld with a 30 l/min flow rate with a special 100 mm long shielding gas nozzle and to the root side at 18 l/min. Laser welding experiments were conducted with a 2.4 kW laser power and a constant welding speed of 60 mm/s. The laser head was held by a 6-axis industrial robot. The laser is continuous wave (CW) pumped

(wavelength of 1030 nm) and the used optical fibre diameter was 200 μm . Welding experiments were carried out by bead on plate type weld to prevent errors from a mismatch of the two separate parts and the detailed welding parameters are collected in Table 2. Number of trial welds were performed to find suitable parameters for the laser to achieve visually clean welds and good penetration. These were then used for all welds. Welding was performed perpendicular to the test piece with a continuous laser power and keyhole welds were used to keep the weld and the heat-affected zone narrow.

Table 2. Parameters for the laser welding of SLMed Ti6Al4V alloy

Speed (mm/s)	Power (W)	Focal point diameter (mm)	Focal length (mm)	Focal point level (mm)	Beam quality (mm*mrad)
60	2400	0.3	300	-1	8

2.3. Mechanical characterization

The tensile strength of the SLMed Ti6Al4V alloy with and without laser welding was evaluated by conducting tensile tests (according to SFS-EN ISO 6892-1:2016) in the direction perpendicular to the weld joint at a constant loading rate of 1 mm/min using Instron universal material testing machine. Specimens for these tests were cut parallel to the building direction from the SLMed material (30 mm parallel section, 8 mm width). Fig. 1 shows the specimen geometry used for uniaxial tensile tests.

Fig. 1. Specimen geometry and dimensions in mm for tensile tests.

Samples perpendicular to build direction and the weld were polished and etched using Kroll's reagent: HNO_3 (6 mL), HF (2 mL) and distilled water (100 mL) to study the microstructure of the SLMed Ti6Al4V.

3. Results and discussion

3.1. Microstructural evolution

SLMed titanium microstructures, i.e., as-built, and after post-annealing are shown in Fig. 2. The as-built Ti6Al4V alloy shows a fully acicular α' martensite. This is attributed to the rapid cooling, 103-105 K/s, of the melt pool in the SLM processing [8]. Subsequently, martensitic needles are formed, as shown in Fig. 2(a). However, with post-annealing at 940 $^{\circ}\text{C}$, the microstructure consists mainly of coarse α platelets with interlamellar β , i.e., lamellar structure from (α - β) is enhanced as a result of α' martensite decomposition. Since, the transformation of martensite to the lamellar structure of α - β is mainly thermally activated and diffusion-controlled process that depends on the transformation temperature [9]. At high magnification, a 'basket weave' pattern of α lamellar in different orientation with the presence of tiny β phase in blue color, between the α network can be seen, as shown in Fig. 2(c). The morphology of the formed phases from martensite transformation is shown in Fig. 2(d). Long and thick α - β lamellae with Widmanstatten morphology can be seen and in addition, the formation of thin α at phase boundaries, as indicated by the white arrows.

Fig. 2. SLMed Ti6Al4V alloy microstructure evolution: (a) as-built with layer thickness 50 μm , (b) post-annealed, (c) high magnification of (b), and (d) SEM-high magnification.

The XRD patterns of the as-built and post-treated structures of the studied material with different layer thicknesses are shown in Fig. 3. All Bragg reflections present in the X-ray profiles have been indexed. It is well known that α and α' -phase share the same hexagonal close-packed (hcp) crystal structure, with close lattice parameters which adds challenge to identify them by XRD peaks [10]. Hence, the differentiation of the twinned phases, α' -cph and α -cph phase structure, in the concerned alloy is based on intensive observations of the microstructure to detect the phase morphology. The peaks of the XRD patterns for the as-built material with different t , 30 and 50 μm , Fig. 3, were indexed for the α' -martensite, i.e., the structure of the as-built material is fully martensitic, as seen in the microstructure in Fig. 3(a). However, with post-treatment at 940 $^{\circ}\text{C}$, the same peaks were

Fig. 3. SLMed Ti6Al4V X-ray diffraction, as-built together with after post-annealing at 940 $^{\circ}\text{C}$ with t : (a) 30 μm , and (b) 50 μm .

indexed for α -phase, red lines. Small extra peaks pertaining to β -bcc phase were detected in the XRD patterns of the post-treated material, as indicated by the blue arrows.

Fig. 4(a). shows an overview of the weld morphology of the laser welded SLMed Ti6Al4V after post-treatment. It can be seen that the weld zone is very narrow with bead width of 840 μm . The microstructures of the weld inside the areas highlighted in Fig. 4(a). are shown in Figures 4(b-c).

Fig. 4. Microstructural evolution of the laser welded SLMed-Ti6Al4V post-treated: (a) Overview of the weld morphology, (b) weld zone, and (c) heat affected zone HAZ

The microstructure of weld fusion zone consisted of needle α' -martensite, as shown in Fig. 4(b). In agreement, Zhang et al. [11] reported the microstructures of the weld fusion zone FZ with the laser welding and conventional welding. They found that acicular α' -martensite is the predominant phase structure in the weld. Fig. 4(c) shows the width of the heat affected zone (HAZ) that is about 100 μm in the current study, which is much smaller than reported 2 mm by Zhang et al. [11]. A small pore, as arrowed, is formed during welding. Fig. 5 shows a net-like structure of fine acicular α' -martensite in the weld metal microstructure of the as-built alloy. Similarly, a small pore

Fig. 5. Microstructural evolution of the as-built-Ti6Al4V after laser welding: (a) martensite formation along with small pore, and (b) fine features of martensite formation during laser welding.

with a dimension of $\sim 5 \mu\text{m}$ is formed in the welded built material, as arrowed in Fig. 5(a). However, the fine features of the martensite formed during laser welding of the as-built material is shown in Fig. 5(b), which clearly shows fine needle-shaped martensite with multi-directional distribution.

3.2. Mechanical properties

Uniaxial tensile tests were conducted in room temperature for the SLMed Ti6Al4V alloy with two separate layer thicknesses, which were welded by the laser. The measured stress-strain plots are presented in Fig. 6. It can be seen from the curves that the layer thickness has a clear impact on the properties. As the layer thickness is decreased from 50 to 30 μm , both the ultimate tensile strength (UTS) and the yield strength (YS) are reduced, but the opposite effect on the elongation can be observed: highest elongation at break (15%) is achieved with the 30 μm layer thickness. It is noteworthy that the laser welds do not exhibit a loss in the mechanical properties of the as-welded materials, as shown in Fig. 6. The mechanical properties extracted from the stress-strain data are listed in Table 3. For comparison, the tensile properties of the commercial Ti6Al4V and welded by two different techniques, gas tungsten arc welding (TIG) and laser welding, taken from Ref. [12], are also inserted in Table 3. It is well known that the mechanical properties of the weld material are roughly related to the weld quality that correlated to the material structure and the succeeded selective of the welding parameters. It can be seen in Table 3 that the strength properties of the commercial Ti6Al4V material is somewhat higher than those of the fabricated material by SLM. However, the mechanical properties of the welded material by the conventional TIG welding showed a significant loss in ductility and tensile strength. A small decrease in the mechanical properties of the laser welded material was reported by Gao et al. [12]. In contrast, the present work does not change in the mechanical properties of the welded materials by

Fig. 6. Engineering stress-strain curves of the fabricated Ti6Al4V by SLM, with different thickness layers, 30 and 50 μm , and the corresponding laser welded materials.

Table 3. Yields strengths and ultimate strengths from the tensile tests

	30 μm		50 μm		Ref. [12]		
	as-built	LW	as-built	LW	BM	TIG	LW
Yield strength [MPa]	912	887	937	939	1140	1050	1120
Ultimate strength [MPa]	1080	1075	1129	1129	1150	1105	1134
Elongation [%]	15.2	14.9	8.8	8.3	15.5	4	11.5

laser, as seen from the stress-strain curves in Fig. 6.

4. Conclusions

The results of the microstructural evolution and tensile properties of the additively manufactured Ti6Al4V at two different layer thicknesses 30 and 50 μm and their laser welded joints lead to the following conclusions:

1. The layer thickness t shows a notable influence on the formed microstructure of the fabricated Ti6Al4V by additive manufacturing. Acicular α' -martensite is the dominant phase structure of the as-built material, but after post-annealing at 940 °C the microstructure consists mainly of coarse α platelets with interlamellar β . Excellent strength–ductility combination was achieved with yield strength of 910 MPa and ultimate tensile strength of 1080 MPa and elongation to fracture 15% at $t = 30 \mu\text{m}$.
2. The weld zone microstructures in both as-built and post-annealing, show fine needle-shaped α' -martensite at multi-directional distribution.
3. The joint efficiency in terms of tensile strength of nearly 100% was obtained for the laser welded materials. Moreover, the laser welds did not show losses in ductility.

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