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EVALUATION OF MECHANICAL PROPERTIES OF TI-6AL-4V FABRICATED BY SELECTIVE LASER MELTING (SLM)

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Abstract

Additive manufacturing of titanium components owns promise to deliver benefits for aerospace applications such as reduced cost, weight and carbon emissions during both manufacture and use. To capitalize on these benefits, it will be shown that the mechanical performances of parts produced by additive manufacturing can meet design requirements that are typically based on wrought material performance properties. This research evaluates the mechanical properties of Ti-6Al-4V specimens produced by the selective laser melting (SLM). For optimization the thermo mechanical treatment to minimize internal stresses and adjust the microstructure of the specimens were also used for further improving the mechanical properties. Some of the specimens were then thermo mechanically treated: annealed or hot-isostatically pressed. The tensile property, fracture toughness and fatigue resistance of the samples are accessed to understand the SLM technology.

1 Introduction

Additive Manufacturing (AM) is an innovative technological trend that will influence the future of the manufacturing industry. SLM's working principle consists of consecutive cycles where complex parts are fabricated layer by layer [1-3]. Each solid material level is formed after a metallic powder layer is dispensed and selectively melted. The energy source for the melting process is a laser beam. The lance then controls the beam, which focus and control the position and diameter of the beam. The manufacturing parameters are generated and controlled by software in order to fabricate sound parts with improved mechanical properties, low porosity and surface roughness, and optimized geometrical reproducibility. This software creates scanning algorithms based on the geometry of the part to be manufactured. The main parameters controlled by the software are: laser beam spot size, the scanning power of the beam, scanning speed of the beam, distance between individual scan lines, line order for the hatch pattern etc. With this additive approach, parts of greater complexity can be economically produced. Manufacturing near-net-shape components in a layer-by-layer fashion offers a great potential for time and cost savings in comparison to conventional manufacturing technologies. Especially aerospace components that are machined from costly wrought material at a low fly-to-buy ratio represent interesting applications [1-5]. To capitalize on these benefits, it should be shown that the mechanical performances of parts produced by additive manufacturing can meet design requirements that are typically based on wrought material performance properties.

There are some reports dealing with microstructures and property of Ti-6Al-4V alloy fabricated by AM processes related to different building locations in order to satisfy the industrial requirements [6]. In this research, microstructure evolution and mechanical properties have been studied for Ti-6Al-4V specimens produced with optimized processing parameters with SLM due to its versatility resulting from the good balance between mechanical properties, castability, plastic workability, heat treatability, and weldability [7]. For the SLM technology, the relation between microstructure and mechanical properties has not been only limited to the as-fabricated condition. Heat treatment of AM Ti-6Al-4V for different technologies has been extensively studied with the purpose of relieving stress and achieving an equilibrium microstructure, eliminating the metastable α' martensite phase and obtaining a microstructure with exclusively α and β phases [7,8]. The SLM process, similarly to other AM processes, does not completely prevent the presence of porosity in the build. Therefore, in order to mitigate the disadvantages caused by these defects, the effect of HIP treatment has been studied. The interest for the study of the mechanical properties in the as-hipped condition is that the SLM process requires heat treatment to obtain reasonable ductility and low residual stresses due to the fast cooling rate of the fabrication with the SLM process provide the presence of brittle α' martensitic phase from forming in the final microstructure, while the proper temperature for relieving the residual stress generated during the additive manufacturing process and the hipping for obtaining a balanced mechanical property, moreover, the stability of fatigue life is also improved after the hipping which are very important for the aerospace components.

2 Materials and Process

Ti-6Al-4V alloy powder was produced by the gas atomization process and was spherical with a maximum particle size 53µm. Ti-6Al-4V alloy samples were fabricated on an EOS M280 machine including a laser unit delivering a continuous single mode laser power of 400W, which produces a laser beam with a wavelength of 1070nm and an intensity distribution of Gaussian. The laser spot diameter was 100-500µm and the maximum scanning speed was 7m/s. In addition, the layer thickness can be selected between 20-100µm and the deposition was carried out on a 30mm thick Ti-6Al-4V alloy plate. The schematic principle of SLM process is shown in Fig.1. During the SLM process, the processing chamber will be filled with argon in order to maintain the oxygen level during the process. The SLM technology manufacturing parameters have been investigated through a series of planned design of experiments. Optimal manufacturing parameters were also established in terms of densification, surface quality, and mechanical behaviour of the alloy systems. Mechanical and surface characterization was executed on different building directions, and the initial information about technology performance was determined.

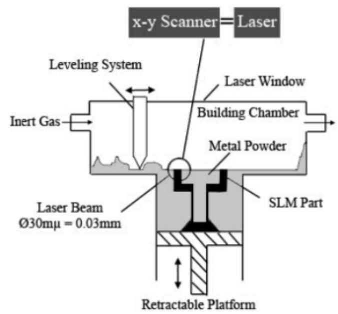
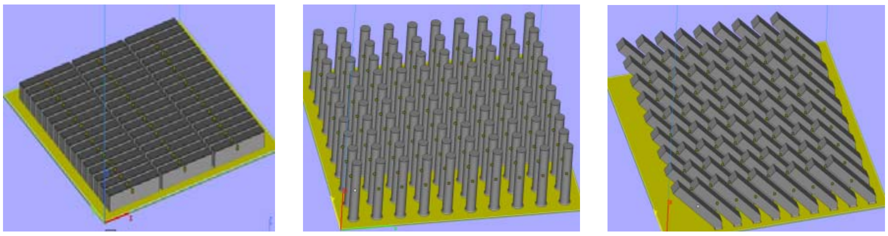


Fig. 1.The schematic principle of SLM process

3 Experimental

After the deposition with SLM, two post heat treatments were applied, firstly, stress relieving at 600°C, 700°C, 800°C, 900°C for 2 hours followed by furnace cooling (FC) to reduce residual stresses were carried out to observe the substantial change to microstructure. The heat treatments for this study were carried out using a Seco/Warwick vacuum furnace. Secondly, some of the samples were then hot isostatic pressed (HIP) with HIP-200, temperature up to 1450°C, pressure up to 200MPa to eliminate the porosities produced during the fabricating. The horizontal and vertical section microstructures of the samples were examined using a Leica optical microscope and scanning microscope (SEM). The chemical composition was carried out with the Oxford INCA energy dispersive X-ray (EDX) microanalysis software. The element concentration conforms to AMS 4998 regulation. The room temperature tensile property was tested according to ASTM E8/E8M. The build configuration and SLM reference axis system on the build platform of the EOS machine is shown in Fig.2. The cylindrical specimens (Ø10×70mm) are orientated with their longitudinal axis perpendicular to the build platform (parallel to the build direction/Z axis). The rectangular specimens have their longitudinal axis perpendicular to the build direction/Z axis, 10×10×70mm for horizontal samples. In this study, the terms vertical orientation and horizontal orientation are used to identify samples that are oriented parallel and perpendicular to the build direction/Z axis respectively. The diagonal samples to the build direction/Z axis also were tested as a comparison. The tensile test was employed for the evaluation of mechanical performance with SLM. An investigation using fatigue specimens fabricated using SLM were also carried out, Fatigue crack propagation testing with force controlled constant amplitude axial, the loading condition was cyclic tension with R= 0.1 for the specimen as HT and HIP. For budgetary reasons specimens were fabricated and tested in three orientations as stress relief and only X-Z directions for hipped condition for the fatigue life evaluation. The specimens underwent a stress relief heat treatment with exposure to 800°C for 2 hours in a vacuum furnace as specified in the optimization temperature of the stress relief heat treatment. Testing methodology was carried out according to ASTM E 466 standards. The number of failure cycles at different stress levels was also investigated for the fatigue life.



(a) Specimen building horizontal direction (b) Specimen building veridical direction (c) Specimen building diagonal direction

Fig. 2 A schematic drawing of the test pieces

4 Results and Discussion

4.1 Microstructure Characterization

Ti-6Al-4V is an α+β alloy because α and β microstructural phases coexist at room temperature. The α+β alloys are interesting because they combine the strength of α alloys with the ductility of β alloys, and their microstructures and properties can be varied widely by appropriate heat treatments and thermo mechanical processing [7,8]. The current study focuses on understanding the effect of different heat treatments on the unique microstructure of the SLM Ti-6Al-4V and its impact on mechanical properties. The heat treatments studied in this work were addressed using two approaches. The first investigated the effect of the annealing temperature on the formation of different microstructural phases and their morphology. The second approach assessed the effect of hipping on the microstructure and properties of the material, including fatigue life evaluation.

4.1.1 Microstructure as Fabricated

Fig.3 shows the microstructure features of Ti-6Al-4V alloy fabricated by SLM in the X-Z and X-Y sectional directions. The microstructure shows morphology as macrostructure of columnar prior-grains that are growing epitaxially across many layers vertically in Fig.3(a). They grow epitaxially during the processing and are much larger than the individual layer thickness (i.e. typically 30µm). Fig.3(a) shows columnar grains of a width of 200-300µm and very long (>1mm) i.e. involving many layers. Martensitic needles are visible and disposed according to a herring bone pattern within the grains. This type of microstructure is a typical of additive manufacturing process, which involves partial re-melting of the previous layers, resulting in the epitaxial growth of the strongly textured grains. Moreover, the time the melting pool remains liquid before a complete solidification in the β domain, depending essentially on the solidification rate and the thermal gradient, acts on the epitaxial growth and especially the number of nuclei formed. A different texture develops on the cut plane X-Y of Fig.3(b), where a layer of the X-Y directional microstructure seems equal-axis. The laser moves with a raster motion on this plane and melt locally a material volume by high-energy pulses. Rounded and fine grains (diameter of 100μm) form upon solidification of the melt pools. It seems to mean that this unidirectional grain growth may also influence the anisotropy of properties of the SLM as-built alloy.

4.1.2 Microstructure as post heat-treated

Fig.4 provides an overview of the microstructure for SLM Ti-6Al-4V, influenced by the post built-up heat treatments at 600°C, 700°C, 800°C, 900°C for 2 hours, respectly. It is assumed that the fine acicular morphology of the annealed SLM Ti-6Al-4V mainly consists of a' (martensite) or alpha due to the fast solidification and the overall lower heat input during the built-up and heat treatment at 600C and 700°C (Fig.4). An α+β lamellar microstructure is observed inside the prior β grains for planes both perpendicular and parallel to the build direction. The width of prior β grain is about 100-200μm. The structure of the lamellae is mainly Widmanstätten or 'basket weave', with an occasional colony microstructure. As increasing the heating temperature, the size of the columnar grains is not quantifiable due to the difficulty of grain boundary identification. However, the alpha lath is getting thicker as increasing the heating temperature. The average thickness of 1-1.5μm was measured at the 900°C heating temperature. The reference values of α lath thickness for the as-fabricated condition employed in this study are as 0.8μm.

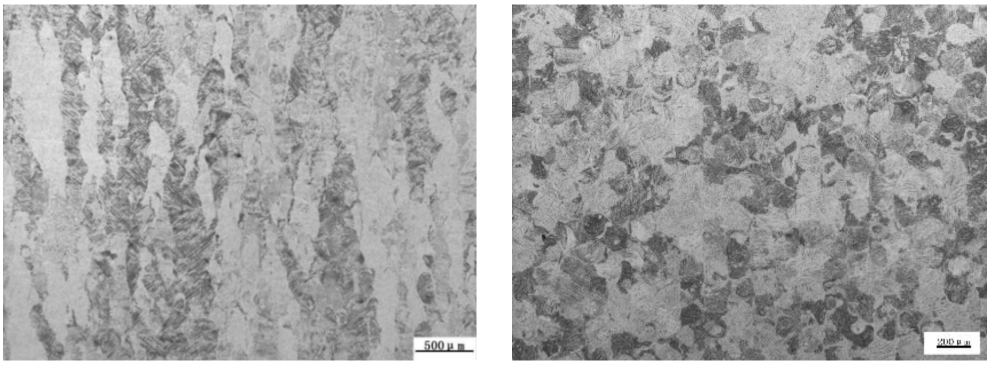
The time and temperature of the heat treatment are the critical factors affecting the final microstructure [8]. Fig.5 shows the microstructures as fabricated condition, 800°C /2 hours stress relief heat treatment and HIP heat treatment. Obviously, the microstructure has changed as increasing the temperature; first, the alpha morphology was changed from needle-like to a plate-like morphology after hipping, secondly, the alpha lath is about 1.5-2μm, which is much thicker than the one as fabricated and stress relief condition. The beta grain size becomes coarser than the other two conditions due to re-crystallization occurred during hipping.

4.2 Tensile Testing

In order to choose the best heat treatment parameters for SLM samples, a stress relieving heat treatment and hot isostatic pressing two categories, a total of 5 kinds of heat treatment system, from the room temperature tensile yield strength, tensile strength, elongation and microstructure evaluation under different heat treatment process were carried out as shown in Table1. By using optical metallographic analysis, scanning electron microscopy (SEM) analysis revealed the specimen under different heat treatment system, the microstructure change accordingly as shown on Fig 4&5, and further revealed that as heat treatment process, microstructure and mechanical properties show that a) in the stress relief temperature range, with the increase of heat treatment temperature, compared to the fabricated, yield strength and tensile strength gradually reduce, the elongation increase gradually, the mi^{c}rostructure analysis showed that 600-700°C range, alpha 'incomplete decomposition, martensite phase shows a higher strength, lower elongation; In the range of 800-900°C, stress annealing was performed, and the strength and elongation of the materials matched well. b) After hot isostatic pressing, the strength of specimen is decreased, however, plastic stability of the specimens is in a relatively good level, the reason for the good comprehensive performance with the hot isostatic pressing is that in the process of heat treatment, the test specimen under three directions to compressive stress, pore closure or disappear gradually, sample density increase. In addition, after the hot isostatic pressure, the microstructure is relatively coarse, resulting in a decrease in the strength level.

4.3 Fatigue and Fracture Property

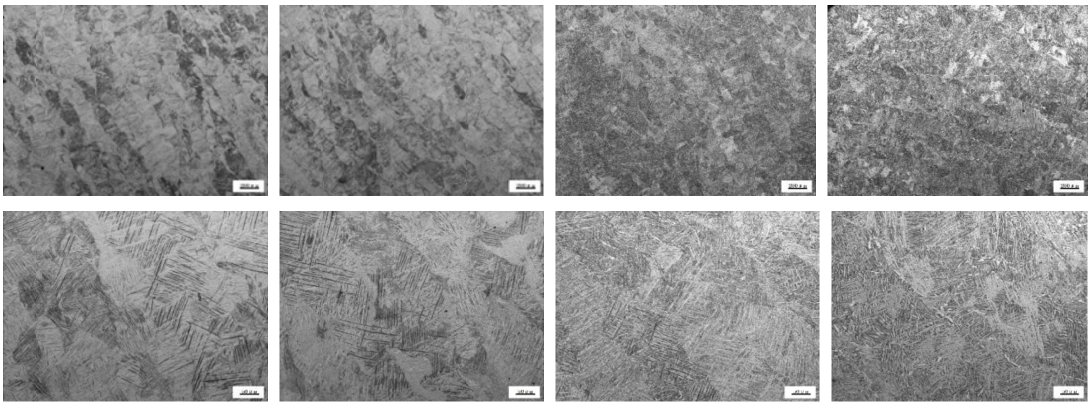
Fatigue crack propagations and fracture toughness results shown in Fig.6 and Table2. The stress direction in X-Z specimens is orthogonal to the laser deposition layers; the stress direction in X-Y specimens is parallel to the layers. The trend in a linear-log plot is well behaved with fatigue crack growth of the Z-X specimens that are considerably different and slower than the other two specimen orientations,



(a) Longitudinal section through columnar grains of the prior-β phase in the X-Z plane

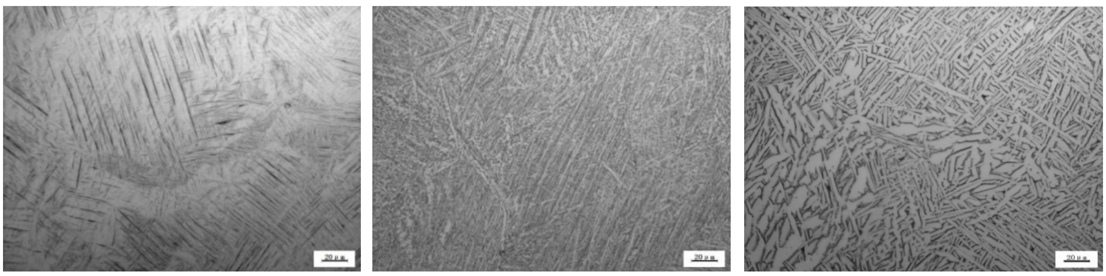
(b) Cross-section through columnar grains of the prior-β phase in the X-Y plane

Fig.3 Microstructure of Ti-6Al-4V alloy fabricated by SLM



600°C 700°C 800°C 900°C

Fig.4 Microstructure of Ti-6Al-4V alloy heat treated at different temperature after fabricated by SLM



SLM 800°C/2H 800°C/2H+SR+HIP

Fig.5 Microstructure of Ti-6Al-4V alloy as fabricated by SLM and post treated by HT and HIP

Table1 Ultimate strength and Yield strength and elongation values for the microstructures obtained after different heating temperature

Condition	Sample direction	YS MPa	UTS MPa	EL %	Sample Direction	YS MPa	UTS MPa	EL %	Sample Direction	YS MPa	UTS MPa	EL %
SLM	horizontal direction	1040	1201	9.5	veridical direction	1050	1195	10.2	diagonal direction	1070	1222	9.9
600°C/2H/FC		1085	1177	9.1		1081	1157	9.7		1097	1177	10.2
700°C/2H/FC		1006	1089	12.6		1011	1078	12.5		1025	1102	13.1
800°C/2H/FC		945	1036	14.9		965	1036	14.6		967	1053	16.3
800°C/2H/FC		922	1016	15.7		943	1038	15.7		941	1032	15.1
800°C/2H/FC		924	1019	15.4		935	1014	15.5		933	1027	15.1
800°C/2H/FC		856	967	16.3		876	975	16.2		878	992	15.9
SLM+SR+950°C/150MPa/4H		867	961	16.1		851	950	15.3		869	976	15.7
SLM+950°C/150MPa/4H		860	969	16.7		864	968	17.4		870	980	15.8

this trend is same for the fracture toughness due to the typical process conditions, (i.e. layer by layer generative principle, short energy pulses resulting in highly localized melting and solidification and strong temperature gradients of this manufacturing process), the microstructure exhibits strong directionality, consequently anisotropic structure, i.e. columnar grain structure. The strongly textured microstructures results in anisotropy of the mechanical properties. Experimental results also show that the impact of different heat treatment process on the fatigue performance as shown in Fig.7, samples as fabricated and annealing heat treatment states fatigue life is scattered, but the fatigue test performance of the samples after hot isostatic pressing treatment the data divergence seems small, and the repeatability of the sample in each direction is obvious, the analysis indicate that the hot isostatic pressing may eliminate the sample internal defects such as porosity, incomplete fusion, make samples of fatigue life and stability are greatly increased.

The SLM technology was accepted by aerospace industry are somehow hampered by the relative slow pace of material characterization, which is a fundamental ingredient of part design and qualification. Many work has done to discuss the link between process parameters and static mechanical properties of SLM Ti-6Al-4V, the fatigue strength characterization appears more recently in the literature [9-19] Fatigue testing is known to be expensive and time consuming as it is susceptible to a number of intrinsic and extrinsic factors that complicates the data generalization and exploitation [16, 17]. On the other hand, the fatigue behavior of SLM Ti-6Al-4V is critical for sectors, in which high structural integrity is a paramount requirement for aerospace. the fatigue behavior of SLM Ti-6Al-4V is influenced by: microstructure, because it introduces a directional effect; defects, that being typically located between adjacent layers, affect most the direction Z, Thus, a HIP treatment was considered to reduce that influence of defects but would lower the material strength as shown in Table1. Therefore, the post-fabrication heat treatment, is not only relieves residual stresses but should be selected to simultaneously optimize strength, ductility and fatigue behavior [18-21].

As regards the fatigue performance of SLM Ti-6Al-4V in relation to wrought Ti-6Al-4V, only the clarification and understanding of the different affecting factors (internal and external) on the material behavior may lead to process optimization and full exploitation of SLM technology in the design and fabrication of durable, safe and cost competitive parts.

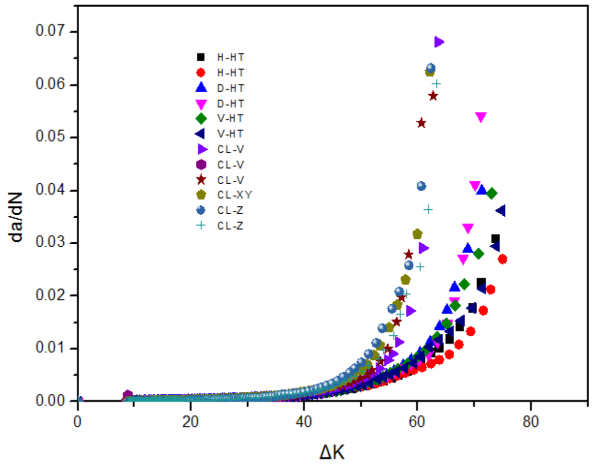


Fig.6 Typical fatigue crack growth curve showing the as-fabricated and HT specimen of X–Y specimens and Y–Z specimens

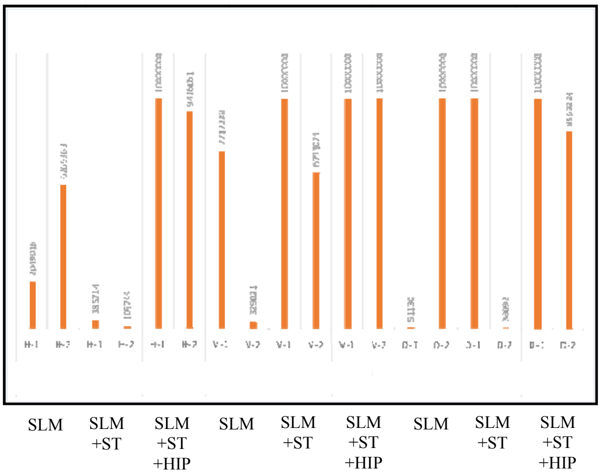


Fig.7 The effect of the different heat treatment on the fatigue life

Table2 Fracture Toughness Results

Sample ID	KIC(Kq)	Condition
X-Y-001	73.1	SLM+HIP
X-Y-002	70.9	
X-Z-001	76.9	
X-Z-002	72.7	
X-Y-003	68.1	800°C/2H/FC
X-Y-004	68.4	
X-Z-003	68.0	
X-Z-004	70.7	

5 Conclusions

A detailed study of AM applicability for different mechanical systems has been performed; the main goal of the study was to increase the understanding of AM technology in the aerospace field. For that, it was necessary to develop flight components to verify their real applicability and manufacturing feasibility, evaluating their potential benefits, limitations, and drawbacks. For the case of the flexible manufacturing mechanism with SLM, a topology and shape optimization for the functional components has a huge potential. Current maximum dimensions reachable with most of the available AM technologies recommend concentrating the short-term efforts in small parts, such as brackets can benefit from AM, especially if a topology optimization exercise is implemented. If it can be designed and manufactured using topology optimization procedures, it will leading into weight reductions and the manufacturing cost benefit in such high strength alloy. Process control, including inspection and qualification approaches is the key aspect for future AM adoption, where a serial production is expected.

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