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Concentrated solar energy used for heat treatment of Ti6Al4V alloy manufactured by selective laser melting

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ABSTRACT

Ti6Al4V alloy manufactured by Selective Laser Melting (SLM) technology was heat treated for the first time in solar furnaces on Plataforma Solar de Almeria, Spain. This paper focuses on demonstrating feasibility of using Concentrated Solar Energy (CSE) to heat treatment of the Ti6Al4V alloy produced by SLM as a new approach of heat treatment and an alternative to conventional techniques. SLM process is characterized by a local high heating followed by fast solidification and rapid cooling, resulting in a microstructure consisting of a fine martensite called α′ phase. Long columnar original β grains, with the inside original α′ microstructure, were found in the as-fabricated SLM Ti6Al4V. Specimens were heat treated both in the horizontal (SF40) and vertical (SF5) furnace using CSE, below and above the β-transus, under argon atmosphere and a heating rate of 60 °C/min. Heat treatments below β-transus led to transformation the α′ initial microstructure into a mixture of α and β, but after some treatments the initial characteristics of the microstructure were maintained and the columnar prior β grains remained visible in the cross section of the specimens. Treatments above β-transus transformed the original α′ microstructure into a lamellar α + β one and they also led to formation of α colonies. Specimens have a slight weight gain after heat treatment due to contamination of SLM Ti6Al4V during heat treatment and alpha case formation. Specimens subjected to heat treatments at high temperatures close to β-transus (850 °C) and above β-transus (1015 °C and 1050 °C) have the highest variation in weight. After heat treatments, microhardness of the most specimens was slightly decreased comparing with the microhardness of as-fabricated specimens. Dispersion of microhardness values of the heat treated specimens is greater than the as-fabricated SLM Ti6Al4V.

1. Introduction

Additive Manufacturing (AM) is recognized as an alternative to conventional manufacturing processes, gaining a lot of attention throughout the world over the last few years. In 2012, *The Economist* described the AM as the third industrial revolution (Eco, 2012) used in aerospace, automotive, medical, solar industry and consumer products.

Among AM technologies, Selective Laser Melting (SLM) is one of the most flexible and promising technologies. Selective Laser Melting allows the creation of particularly complex geometries, components with a unique design and complex features which cannot be produced by conventional technologies. Selective Laser Melting (SLM) is an Additive Manufacturing (AM) process in which metallic powder is selectively melted by a focused laser beam to build high density components (Yadroitsev et al., 2014; Zhang et al., 2017; Thijs et al., 2010; Yadroitsev, 2009; Xu et al. 2015). Compared to conventional manufacturing methods, SLM offers a wide range of advantages, including direct production from CAD model, high material utilization, shorter time-to-market, near-net forming production without expensive dies, and a high level of flexibility (Yadroitsev, 2009; Wang et al. 2016).

Ti6Al4V is the most worldwide used titanium alloy within aerospace, automotive, chemical engineering, biomedical areas due to its high strength, toughness, biocompatibility, exceptional corrosion resistance, and low density (Wu et al., 2016; Vrancken et al., 2012; Burte, 1973; Leyens and Peters, 2003). Even if it has such intrinsic properties, Ti6Al4V cannot be used for manufacturing of complex shapes because of those shapes cannot be obtained through conventional manufacturing. SLM technology enables to overcome these constraints due to

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not only the efficient use of materials and cost-saving, and also offering a high geometrical flexibility and reducing lead time, which is hard achieved in the conventional manufacturing technologies (Zhang et al., 2017; Wu et al., 2016; Ali et al., 2017).

Ti6Al4V is an α + β alloy in which aluminium is α-stabilizer and vanadium is β-stabilizer. The majority of Ti6Al4V products are supplied in the annealed condition. Time, temperature, and cooling rate are selected so that the annealing treatment achieves a mixed α + β structure that is ductile and stable (Burte, 1973; Leyens and Peters, 2003; Ali et al., 2017).

Previous studies (Yadroitsev et al., 2014; Zhang et al., 2017; Thijs et al., 2010; Xu et al., 2015;Vrancken et al., 2012; Ali et al., 2017; Thöne et al., 2012; Facchini, 2010; Simonelli, 2014; Huang et al., 2015; Zhang et al., 2018) show that as-fabricated SLM microstructure contains mainly acicular martensite named α′ phase. The microstructure of SLM material is obtained by extremely high cooling rate, inherent in the SLM process, and it is not comparable to metal casting or forged Ti6Al4V. Many published studies show that a α′ microstructure exhibit high yield strength, high ultimate tensile strength but relatively low ductility (Vrancken et al., 2012; Facchini, 2010; Murr et al., 2009) due to the martensitic microstructure. The ductility of SLM parts can be increased by applying heat treatments to decompose α′ into microstructures consisting of α and β phases (lamellar microstructure). Due to the specific process conditions and hence specific microstructure, SLM Ti6Al4V parts need to be heat treated differently than wrought or cast alloy parts (Yadroitsev et al., 2014; Thijs et al., 2010; Yadroitsev, 2009; Vrancken et al., 2012; Facchini, 2010; Simonelli, 2014; Huang et al., 2015). For SLM Ti6Al4V parts post heating treatment may be the main and only way to control and make the microstructure evolved (Wu et al., 2016). Generally, post heat treatment for SLM Ti6Al4V parts is always carried out to modify the microstructure for relieving the stress, stabilizing the microstructure and improving the mechanical performance of the as-fabricated parts.

Even though microstructure of the as-received Ti6Al4V alloy fabricated by different AM technologies has begun widely investigated, until now microstructure evolution and the optimum heat treated parameters for meeting best mechanical properties are not consistent in the literature due to the different as-received microstructures produced by the different processing and complex thermal history (Thijs et al., 2010;Vrancken et al., 2012; Simonelli, 2014; Brandl et al., 2011; Vandenbroucke and Kruth, 2007; Sames et al., 2016). They are strongly depended on the type of AM machine used, and also the selected processing parameters. All the heat treatments in all published researches were carried out using the conventional methods and furnaces.

In Herranz and Rodriguez (2010) was reported the use of Concentrated Solar Energy (CSE) has been researched as an alternative to other types of energy beams for treating and modifying the surfaces of metallic materials. CSE has the ability to provide large amounts of energy in small areas, enabling the achievement of high temperatures in very short times and rapid cooling rates that modify diffusion processes. In this line CSE has shown great efficiency in steels heat treatment to produce microstructural modifications, nitriding in very short times of Ti6Al4V alloy (mill-annealed) (Rodriguez et al., 2013), NiAl Self Propagating High Temperature Synthesis (SHS) coatings on carbon steels, and welding of steel or Ti6Al4V (Thöne et al., 2012; Romero et al., 2015; García et al., 2016). Other treatments using CSE have been carried out for sintering Ti6Al4V powder (Kovacik et al., 2017), steel and reinforced steel. They have been performed with a notable reduction in processing time (García et al., 2016). CSE was also used as heating source for the carbothermal oxygen production process through heating the lunar regolith (Mueller et al., 2016).

Regarding using CSE for heat treatment of Ti6Al4V processed by SLM, so far there are no published researches results on applying this renewable energy source in heat treatment of SLM Ti6Al4V. To date, information on microstructure and mechanical properties obtained after thermal treatment of SLM Ti6Al4V in solar furnaces using CSE has not been published.

Another question that might be asked is why to research the heat treatment of SLM Ti6Al4V using CSE?

As mentioned before, Ti6Al4V is widely used in the aerospace and aeronautic industries due to its combination of low weight, high strength, and corrosion resistance. In 2010, NASA elaborated a set of 14 Technology Roadmaps for guiding the development of space technologies (NASA, 2015a). In 2015, NASA expands the original roadmaps offering details about his future missions, the related technological development needs and the development ways for next 20 years (2015–2035). In Technology Area 12 (TA12) roadmap, *TA12 Materials, Structures, Mechanical Systems, and Manufacturing,* it is stated that additive manufacturing have enabled the introduction of new, lower cost space components and products for propulsion and spacecraft (NASA, 2015a, 2015b). In 2014, NASA launched the *3D Printing in Zero-G* technology demonstration mission, within In-Space Manufacturing (ISM) project, to explore the potential of additive manufacturing for in-space applications and demonstrate the capability to manufacture parts and tools on orbit using Fused Deposition Modelling (FDM). In 2016, NASA published the report on Phase I results of this project (Prater et al., 2016). The experiment conducted on board the International Space Station (ISS) demonstrated that parts of ABS plastic can be manufactured in microgravity using FDM technique. This project is considered by NASA the beginning of the development of a capability that is critical to future NASA missions. To reduce reliance on Earth-based platforms and enabling sustainable, safe exploration, NASA aims multimaterial 3D printing in space (NASA, 2015a). Therefore, NASA is evaluating various additive manufacturing metal processes for use in the space environment. NASA considers that additively manufacturing metallic parts in space is a desirable capability for large structures, components with high strength requirements, and repairs (NASA, 2015b; Prater et al., 2016). In this context, the use of CSE for the heat treatment in-space of components obtained from metallic powders by additive manufacturing in-space can be an alternative which deserves to be researched. The use of concentrated solar energy in the space has been also studied in Hoëz and Foëx (1972) where solar furnaces and high-temperature treatment under space vacuum conditions are considered.

The main aim of our research was to investigate for the first time the feasibility of using CSE to heat treatment the Ti6Al4V alloy produced by SLM as an alternative to conventional techniques of heat treatment. In this study, microstructure and hardness of selective laser melted Ti6Al4V alloy of as-fabricated and after heat treatment below and above β-transus (995 °C) (Leyens and Peters, 2003) by using optical microscope (OM) and Vickers hardness (HV) tester were investigated.

2. Materials and methods

Cylindrical shape specimens with height of 5 mm and diameter of 20 mm were fabricated on the SLM machine, Concept Laser M2 Cusing Multilaser (ADDITIVA Srl, Modena). Spherical Ti6Al4V powder supplied by the machine manufacturer has been checked and approved by Concept Laser after analyzing it by a certified external independent laboratory. The chemical composition, expressed as a percentage, of this powder is: Al: 6.34–6.45%, V: 4.02–4.10%, Fe: 0.16–0.18%, C: 0.013–0.010%, O: 0.091–0.092, N: 0.008–0.010%, H: 0.005–0.004%, Ti: rest.

All SLM specimens were fabricated in a single batch with layer thickness of 25 µm, laser power of 200 W in the skin surface and 370 W in the core surface, hatch space of 0.095 mm, and laser scanning speed range of 1200–1500 mm/s. The SLM process took place in Ar atmosphere and as scanning strategy was used a continuous on skin surfaces and alternate islands of 5 × 5 mm (so-called *island* strategy) (Fig. 1) on core surfaces. The building axes of specimens were parallel to the Z direction according to the ISO/ASTM52921-13 (ISO, 2013).

Heat treatments of SLM Ti6Al4V were carried out in the horizontal