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AN INVESTIGATION OF HIGH TEMPERATURE TENSILE PROPERTIES OF SELECTIVE LASER MELTED TI-6AL-4V

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ABSTRACT: Ti-6Al-4V alloy is successfully used in selective laser melting (SLM) especially for production of metal dental and surgical prostheses. On the other hand Ti-6Al-4V alloy is widely used in aerospace industry including applications with temperatures up to 350°C (623 K). In this work, for investigation of high temperature tensile properties, Ti-6Al-4V alloy tensile specimens were fabricated by selective laser melting. Tensile tests were carried out at room and elevated temperatures (up to 350°C). For all considered temperatures, SLM fabricated Ti-6Al-4V shown more strength and less ductility in comparison with wrought material.

KEYWORDS: selective laser melting, SLM, titanium alloy, Ti-6Al-4V, high temperature tensile properties.

INTRODUCTION

In recent years, increasing attention has been given to additive manufacturing (AM) technologies both by researches and producers. To date, there are many types of AM technologies that different in working principle and material feedstock. Most metal AM technologies, including powder bed fusion based technologies, use spherical metal powder as a feedstock. Selective laser melting (SLM) is one of the most commonly used metal powder bed fusion based AM technologies (Gong et al. 2014).

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Titanium based alloys, particularly Ti-6Al-4V alloy, are one of the most successfully used materials in SLM especially for biomedical applications (Popovich et al. 2016). Ti-6Al-4V is the most widely used titanium alloy due to a combination of relatively low density, very high strength, good corrosion and fatigue resistance, high biocompatibility (Boyer et al. 1994). SLM of Ti-6Al-4V alloy has been extensively investigated (Zhao et al. 2016). A significant part of the investigations has been devoted to studying of the influence of SLM processing parameters on porosity and defect generation (Gong et al. 2014). Another significant part of the investigations of SLM processing of Ti-6Al-4V alloy have been focused on studying of microstructure and mechanical properties of SLM fabricated Ti-6Al-4V specimens. The microstructure of as-fabricated SLMed Ti-6Al-4V parts generally consists very fine predominantly α' martensite phase (Facchini et al. 2010, Murr et al. 2009) therefore tensile strength is higher and ductility is lower in comparison with wrought alloy that is most commonly used in the mill-annealed condition (Boyer et al., 1994). For improvement of ductility heat treatment is needed (Facchini et al. 2010, Vrancken et al. 2012). Also, SLM processing of Ti-6Al-4V alloy is generally accompanied by high tensile residual stress (Yadroitsava et al. 2015) that can lead to cracks formation, dimensions and shape distortion and even destruction of part during SLM processing and damage of powder spreading system of SLM machine. To reduce residual stress post-processing heat treatment is commonly used before removing of fabricated part from the substrate plate to avoid deformation. Another effective method of reduction of residual stress in SLM fabricated parts is powder bed preheating (Ali et al. 2017). SLM fabrication of Ti-6Al-4V alloy is of great interest for biomedical field. SLM technology allows to fabricate complex shape parts such as dental and surgical implants directly from CAD model (Lykov et al. 2017). In comparison with conventional manufacturing methods SLM technology is capable to produce bulk and porous parts from metals with bad machinability in very short times without expensive mold and tools (Song et al. 2012). Another perspective application of SLM fabricated Ti-6Al-4V parts is aerospace industry where Ti-6Al-4V is widely used since the 1950s including applications with working temperatures up to 350°C (623 K) (Boyer et al., 1994). However, to the author's knowledge, there is no study in the literature about of elevated temperature mechanical properties of selective laser melted Ti-6Al-4V excepting the work (Popovich et al. 2015) where elevated temperature tensile tests were carried out only at 350°C. Therefore, the aim of this work is to study the mechanical properties of SLM fabricated Ti-6Al-4V at ambient and elevated temperatures up to 350°C (623 K).

EXPERIMENTAL SETUP

SLM machine

A Sinterstation® Pro DM125 SLM System (3D Systems Corporation, USA) was used in this study. This SLM machine is equipped by a 200 W laser, an automatic powder spreading system, an inert gas protection system, and a powder bed preheating system. Laser has a focal diameter at the powder bed about 35 μm.

Powder material

Inert gas atomized Ti-6Al-4V powder was used in this study for the SLM experiments. Powder was supplied by MTT Technologies GmbH (Lübeck, Germany) and produced especially for SLM technology. Powder was characterized in terms of particle size distribution and morphology. The morphology of powder particles was examined using a JEOL JSM-7001F scanning electron microscope (SEM) (JEOL Ltd., Japan). The particle size distributions were measured using an Occio 500nano particle analyzer (Occhio SA, Belgium). Powder particles have a good spherical morphology with a certain amount of satellites on surface of some particles and with a small amount of large particles with diameter about 100 μm (Fig. 1). d_{10}, d_{50} and d_{90} values are 19, 42 and 60 μm respectively.

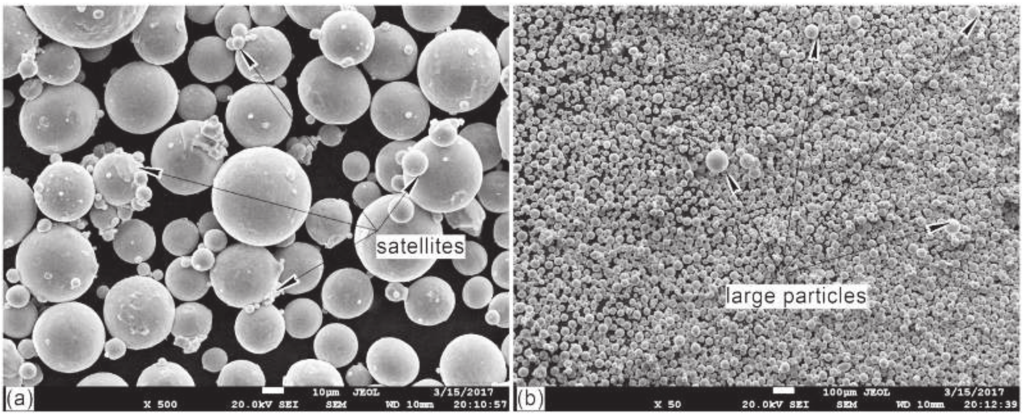

Figure 1. Morphology of TiAl6V4 powder. (a) x 500; (b) x 50.

Tensile tests and microstructure

Specimens for tensile tests were manufactured using follow SLM processing parameters: laser power - 200 W, layer thickness - 50 μm, point distance - 50 μm, exposure time - 200 μs, hatch space - 50 μm. These parameters allow to fabricate of Ti-6Al-4V with porosity less than 0.5% (Baitimerov et al. 2017). After manufacturing, specimens with substrate plate was heat treated to relieve of residual stress at 650 °C during 3 hours to avoid deformations of specimens during removing it from substrate plate and to facilitate of machining (Longhitano et al. 2018). Heat treatment was carried out under argon atmosphere with a heating rate of 10 K/min and further cooling at furnace. This heat treatment was selected in order to minimize of changes in morphology and microstructure of the material. Then, specimens were removed from the substrate plate and machined. The diameter and length of the gauge length was 5 mm and 25 mm respectively. Tensile tests at room and elevated temperatures (400 K, 500 K and 623 K (350 °C)) were conducted according to ISO 6892-1: 2009 and ISO 6892-2: 2011 using a Gleeble 3800 thermal-mechanical physical simulation system (Dynamic Systems Inc., Poestenkill, New York State, USA). For each test temperature, at least three specimens were tested to check repeatability. Young's modulus, tensile yield strength, ultimate tensile strength and elongation at fracture were determined using a 95% confidence interval. Specimens for microstructure characterization were prepared by cutting of tensile specimens after ambient temperature tensile tests. After cutting specimens were mounted, grinded, polished and etched using Kroll's reagent. Microstructural examination was carried out using OM by 4XB microscope (TIME Group Inc., Beijing, China).

RESULTS AND DISCUSSION

Microstructure

OM and SEM micrographs with microstructure of SLM fabricated Ti-6Al-4V after stress relieving are presented in Fig. 2. On Fig. 2, a, elongated primary β grains, which oriented toward building direction or heat source, can be seen. The width of this elongated grains is close to hatch space parameter value (50 μm) or, in other words, close to melt pool width (Longhitano et al. 2018). Microstructure within large grains have a matrensite character (Fig. 2, b), martensite needles are clearly seen even at relatively low magnification. α' type martensite is typical for the SLM fabricated Ti-6Al-4V (Facchini et al. 2010, Murr et al. 2009). Also, spherical 5-10 μm sized gas pores are observed. These pores were formed during SLM process by dissolving of the gas in melting pool and remaining of this gas in metal due to the high cooling rate (Vilaro et al. 2011).

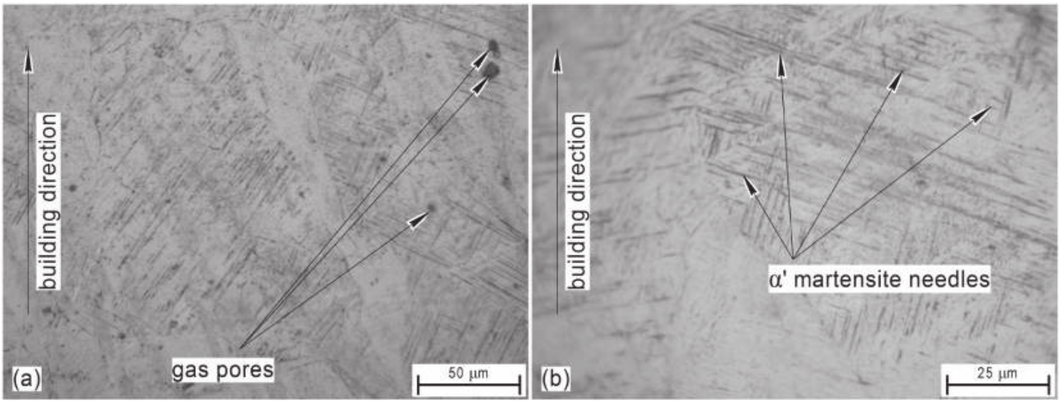

Figure 2. Microstructure of SLM fabricated TiAl6V4.

Tensile properties

The main aim of this research is the investigation of elevated temperature tensile behavior of SLM fabricated Ti-6Al-4V which have unique ultrafine acicular α' martensite microstructure that is very different from microstructures obtained by other manufacturing techniques. Thus, only residual stress relieving heat treatment, that almost did not change the original as-build SLM microstructure, was carried out to avoid deformations of tensile specimens during removing it from substrate plate and to facilitate of their machining. Data of tensile test results (mean values of yield tensile strength (YTS), ultimate tensile strength (UTS) and elongation at break (El.)) are summarized in Table 1.

Table 1. Tensile properties of TiAl6V4 at different temperatures. YTS is yield tensile strength, UTS is ultimate tensile strength, El. is elongation at break.

Temperature	YTS, MPa	UTS, MPa	El., %	Reference
RT	1120±40	1220±60	1.4±0.2	SLM this study
	1200	1280	2.4	SLM (Popovich et al. 2015) as-fabricated
	840	920	10	Wrought (Boyer et al., 1994)
400 K (127 °C)	1105±57	1140±75	4.3±1.2	SLM this study
	710	810	15	Wrought (Boyer et al., 1994)
500 K (227 °C)	1028±84	1085±57	8.8±1.6	SLM this study
	600	730	16.5	Wrought
623 K (350 °C)	837±67	910±50	12.3±1.9	SLM this study
	892	979	6.3	SLM (Popovich et al. 2015) as-fabricated
	515	650	18	Wrought (Boyer et al., 1994)

SLM fabricated Ti-6Al-4V shown a brittle behavior at room temperature. Obtained elongation at break value is very low (Table 1) in comparison with wrought Ti-6Al-4V at mill-annealed condition. SLM fabricated Ti-6Al-4V in the as-build or in the stress-relieved condition often show low ductility (Leuders et al. 2013, Zhao et al., 2016, Cao et al. 2017). In the same time, some works shown excellent ductility (elongation at break about 10%) for as-build Ti-6Al-4V (Simonelli et al. 2014). That differences in results can be explained by a large number of reasons, such as different geometry of specimens, different porosity, differences in microstructure (primary β grains sizes and orientation), differences in powder chemical composition and size distribution, differences in fabrication processing (oxygen content in building chamber) and other. The decreasing of ductility is explained by combined effect of predominate martensite microstructure, microcracks, porosity and residual stress (Facchini et al. 2010). On the other hand, strength of SLM fabricated material is significantly higher than in wrought alloy due to very fine martensite microstructure.

CONCLUSIONS

The specimens for room and elevated temperature tensile tests with more than 99.5% relative density were fabricated by SLM technology from Ti-6Al-4V spherical powder. Obtained specimens have very fine microstructure that contains predominantly α' martensite needles. In comparison with wrought material, SLM fabricated Ti-6Al-4V shown more strength and less ductile behavior for all considered temperatures (up to 350 °C). As expected, strength increased and ductility decreased with temperature increasing.

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