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Additive manufacturing of strong and ductile Ti–6Al–4V by selective laser melting via in situ martensite decomposition

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Abstract—Novel ultrafine lamellar ($\alpha + \beta$) microstructures comprising ultrafine (~200–300 nm) α-laths and retained β phases were created via promoting in situ decomposition of a near α′ martensitic structure in Ti–6Al–4V additively manufactured by selective laser melting (SLM). As a consequence, the total tensile elongation to failure reached 11.4% while maintaining high yield strength above 1100 MPa, superior to both conventional SLM-fabricated Ti–6Al–4V containing non-equilibrium acicular α′ martensite and conventional mill-annealed Ti–6Al–4V. The formation and decomposition of α′ martensite in additively manufactured Ti–6Al–4V was studied via specially designed experiments including single-track deposition, multi-layer deposition and post-SLM heat treatment. The essential SLM additive manufacturing conditions for Ti–6Al–4V including layer thickness, focal offset distance and energy density, under which a near α′ martensitic structure forms in each layer and then in situ transforms into ultrafine lamellar ($\alpha + \beta$) structures, were determined. This is the first fundamental effort that has realized complete in situ martensite decomposition in SLM-fabricated Ti–6Al–4V for outstanding mechanical properties.

Keywords: Titanium alloy; Selective laser melting; Phase transformation; Microstructure; Mechanical properties

1. Introduction

Selective laser melting (SLM) is a powder-bed-based additive manufacturing (AM) technology [1–3]. As with other AM processes [1–7], SLM offers distinct advantages over conventional manufacturing, such as design freedom, free of tooling, near-net or net shape production, efficient use of materials, short lead time, and substantial cost savings in many cases. A wide variety of metallic materials have been processed to date using SLM, and Ti–6Al–4V (wt.%) has received prime attention as the benchmark titanium alloy because of its broad applications in industry and the associated high cost of manufacturing and long lead time [2,8].

An important performance benchmark for additively manufactured metallic structural components is to achieve mechanical properties comparable or even superior to their wrought counterparts. For additively manufactured Ti–6Al–4V, this requires that its microstructure must be essentially pore free and comprise proper phases that can offer strong and ductile properties. This poses great challenges to the AM of Ti–6Al–4V by SLM.

Table 1 summarizes the literature data on the tensile properties of SLM-fabricated Ti–6Al–4V, Ti–6Al–4V additively manufactured by selective electron beam melting (SEBM), mill-annealed (MA) Ti–6Al–4V (the most commonly used state for wrought Ti–6Al–4V) and solution-treated and aged (STA) Ti–6Al–4V [1,4,9–12]. SLM-fabricated Ti–6Al–4V can achieve yield strength over 1300 MPa, but the tensile elongation is noticeably below the minimum threshold of 10% suggested for critical structural applications [13]. This disqualifies the SLM-fabricated Ti–6Al–4V and, accordingly, post-SLM heat treatment is often applied for ductility improvement [3,9].

The mechanical properties of the SLM-fabricated Ti–6Al–4V depend largely on its constituent phases and their morphology and characteristic length scales, as well as the size and orientation (texture) of the prior-β grains. In view of the current standard SLM practice, which is conducted at powder-bed temperatures less than 230 °C, the resulting microstructure often features columnar prior-β grains filled with acicular α′ martensite [1–3,11]. The elongated prior-β grain boundaries in conjunction with the presence of acicular α′ martensite favor intergranular failure

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Table 1. Tensile properties of Ti–6Al–4V fabricated by SLM, SEBM and traditional means.

Processing	Microstructure	$\sigma_{0.2}$ (MPa)	σ_{UTS} (MPa)	*EL* (%)	Ref.
SLM	Acicular α'	1125	1250	6	[1]
SLM	Acicular α'	1333	1407	4.54	[4]
SLM	Acicular α'	990	1095	8.1	[11]
SLM	Acicular α'	1110	1267	7.28	[9]
SLM	Acicular α'	1137	1206	7.6	[3]
SEBM	Lamellar $\alpha + \beta$	830	915	13.1	[11]
Ti–6Al–4V (MA)	Globular β in α matrix	945	1069	10	[10]
Ti–6Al–4V (STA)	Fine lamellar $\alpha + \beta$	1103	1151	13	[10]

$\sigma_{0.2}$, yielding strength; σ_{UTS}, ultimate tensile strength; *EL*, total elongation to failure.

[14]. In addition, such strongly textured structures lead to significant anisotropic mechanical behavior, causing large discrepancies in mechanical response when subject to external loading along different sample orientations [3]. Post-heat treatment is thus regarded as a must-do process to transform the acicular α' martensite into equilibrium ($\alpha + \beta$) microstructures, while reducing thermal stresses at the same time [3,9].

In contrast, the fabrication of Ti–6Al–4V by SEBM is often performed at powder-bed temperatures above the α' martensitic transformation temperature (M_s, 575 °C [15]), which favors the formation of α and β instead of α' martensitic transformation [16]. The occurrence of both α and β not only leads to a near-equilibrium lamellar ($\alpha + \beta$) structure, but also breaks up the textured columnar prior-β grains alleviating the texture [14]. As a result, the SEBM-fabricated Ti–6Al–4V often exhibits better ductility than the SLM-fabricated Ti–6Al–4V, as well as improved isotropic mechanical behavior. However, the better ductility of the SEBM-fabricated Ti–6Al–4V usually corresponds to lower strength (Table 1), falling into the so-called strength–ductility trade-off dilemma [17]. STA Ti–6Al–4V seems to be able to evade the strength–ductility dilemma, standing out with high yield strength ($\geqslant$1100 MPa) at no ductility trade-off. The STA approach involves solution treatment above β transus, followed by water quenching and low-temperature aging [18–20]. The resultant microstructure is composed of fine lamellar α and β with or without primary α, thanks to the decomposition of α' martensite during aging (4–8 h or longer) [20]. This raises an intriguing question: Can such strong and ductile Ti–6Al–4V be produced by SLM in the as-fabricated state?

This study focuses on addressing this challenge. It is shown that, through novel fabrication design based on both phase transformation and processing optimization, in situ α' martensite decomposition can be realized during SLM to produce an ultrafine ($\alpha + \beta$) lamellar structure, analogous to that obtained by STA. Consequently, better than forged tensile mechanical properties are achieved in the SLM-fabricated Ti–6Al–4V.

2. Experimental procedures

Gas atomized Ti–6Al–4V powder (ASTM Grade 23, ELI, 0.1 wt.% O, 0.009 wt.% N, 0.008 wt.% C, 0.17 wt.% Fe,<0.002 wt.% H; TLS Technik GmbH & Co.) in the size range 25–45 μm was used. Specimen cubes (10 mm each dimension) and cylindrical bars (10 mm in diameter) were fabricated vertically onto support structures using an SLM facility (SLM Solutions GmbH, SLM 250 HL) with a maximum power of 400 W. There, different layer thicknesses, 30, 60 and 90 μm, were applied. The powder bed was pre-heated to 200 °C and purged with argon until the oxygen level was reduced to 100 ppm. The as-fabricated Ti–6Al–4V samples contained 0.1 wt.% O, 0.02 wt.% N, 0.02 wt.% C and 0.17 wt.% Fe. Compared with the starting powder, the nitrogen and carbon contents increased by 0.011 wt.% and 0.012 wt.%, respectively. Potential reactions between molten Ti and traces of N_2 and CO_2 in the building chamber are likely to be responsible for the small pick-up [21].

Table 2 lists the processing variables used during SLM. Samples are divided into three major groups by layer thickness. Group I, coded as S1, refers to a layer thickness of 30 μm, which is a common practice for SLM of Ti–6Al–4V and serves as a point of reference. Group II and Group III refer to layer thicknesses of 60 and 90 μm, respectively. In these two groups, samples S2–S4 (Group II) and S6–S8 (Group III) were designed to evaluate the effect of the focal offset distance (FOD) on the resultant microstructure, while samples S3 and S5 (Group II) and S8 and S9 (Group III) were fabricated to clarify the influence of the energy density *E* (the energy applied to per unit volume of sample). *E* is defined as $E = P/vth$, where *P* is the laser power, *v* is the laser scanning velocity, *t* is the layer thickness, and *h* is

Table 2. Processing parameters for SLM-fabricated Ti–6Al–4V in this study.

Group	Sample	*P* (W)	*t* (μm)	*v* (mm s^{-1})	*h* (mm)	*E* (J mm^{-3})	*FOD* (mm)
I	S1	175	30	710	0.12	68.47	2
II	S2	375	60	1029	0.12	50.62	4
	S3	375	60	1029	0.12	50.62	2
	S4	375	60	1029	0.12	50.62	0
	S5	375	60	1029	0.18	33.74	2
III	S6	375	90	686	0.12	50.62	4
	S7	375	90	686	0.12	50.62	2
	S8	375	90	686	0.12	50.62	0
	S9	375	90	686	0.18	33.74	0

P, laser power; *t*, layer thickness; *v*, scanning velocity; *h*, hatch spacing; *E*, energy density; *FOD*, focal offset distance.