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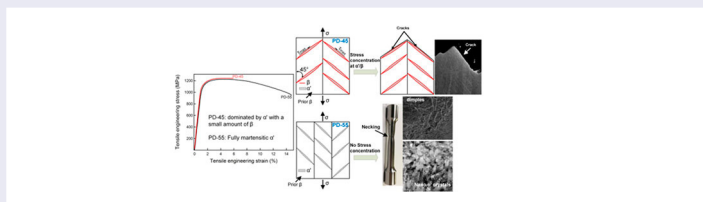
High Ductility in a fully martensitic microstructure: a paradox in a Ti alloy produced by selective laser melting

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ABSTRACT

A fully martensitic Ti alloy consisting entirely of hexagonal-close-packed α' was produced by selective laser melting (SLM), exhibiting an impressive combination of high strength and excellent ductility. A small quantity of body-centred-cubic β formed at some large primary α' plates oriented at $\sim 45^\circ$ to the tensile direction was found responsible for early fracture owing to α'/β strain incompatibility. Properly selected SLM parameters resulted in a β -free microstructure containing α'/α' interfaces only, preventing premature fracture. Consequently, large plastic deformation was enabled, creating randomly oriented nano- α' crystals. The investigation dispels the myth that α' is inherently brittle.



IMPACT STATEMENT

A fully martensitic α' Ti-6Al-4V with an impressive combination of high ductility and strength was produced using selective laser melting, dispelling the myth that α' is inherently brittle.

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KEYWORDS

Titanium alloys; martensitic phase transformation; ductility; deformation structure; selective laser melting

1. Introduction

Microstructures of the α/β alloy Ti-6Al-4V, one of the most widely used, can be easily manipulated through thermomechanical treatment thanks to a versatile combination of four phases: the equilibrium phases of Al-rich hcp α and V-rich bcc β , and the metastable martensitic phases of orthorhombic α'' and acicular α' which has the same hcp structure as α but is supersaturated with V [1–3]. Recently, particular attention has been paid to Ti-6Al-4V processed by additive manufacturing (AM) [4–11]. The high cooling rates ($\sim 10^6$ K/s) involved in AM processes such as selective laser melting (SLM) and electron beam melting (EBM) result in a microstructure dominated by α' with tensile elongations of $< 8\%$ [4–11]. The low ductility is generally attributed to the inherent brittleness of α' , and consequently, it is common practice to decompose it into α and β by post-AM heat treatments

[8], raising the substrate temperature during EBM [12], or in-situ aging during SLM [9–11].

However, the assumption that α' is inherently brittle has not been demonstrated and proven. Based on first-principles calculations, both Al and V would hinder the generation of prismatic dislocations [13]. While this would strengthen, reduced dislocation activity might contribute to poor ductility, considering the high contents of Al and V entrapped in α' . From experiments, on the contrary, α' has been shown to significantly improve formability and ductility in several α' dominated α/β Ti alloys, including Ti-6Al-4V [14–17]. The absence of β which would cause strain incompatibility at the strong α/β interface, leaves only interfaces between the hcp structured phases (i.e. α/α , α'/α' and α/α') that are capable of distributing strains more homogeneously, leading to much better ductility [17].

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More importantly perhaps, the martensitic transformation would generate acicular α' in intersecting directions with a broad size distribution [2]. This unique structure is different from the typical structure for α which forms parallel plates upon slower cooling. Although it is possible to produce a fully α' Ti-6Al-4V by quenching, the volume is necessarily limited in order to achieve sufficiently high cooling rates. Moreover, the β grains prior to quenching are usually coarse at several hundreds of microns. By contrast, SLM can generate smaller prior β grains and ultrahigh cooling rates throughout the built volume, ensuring an ultrafine, full α' microstructure.

Here, we report, for the first time, the fabrication of a fully martensitic α' Ti-6Al-4V using SLM, achieving a combination of excellent tensile elongation of 14–15% and yield strength of 1150 MPa, comparable to those obtained in dual-phase α/β Ti-6Al-4V in wrought form or following ageing at low temperatures [3,18–20].

2. Experimental material and procedures

A gas atomised Ti-6Al-4V powder (15–45 μm) was used. The Renishaw AM250 SLM system was employed for printing rods of 12 mm in diameter and 80 mm in height using stripe scanning strategy with layer thickness of 30 μm on 4 mm tall supports and a titanium substrate preheated to 170°C in an atmosphere containing < 100 ppm oxygen. AM250 uses a pulsed laser, and the scanning speed (v) is determined by the point distance (PD) between two consecutive laser spots and the laser exposure time (t) in $v = PD/t$ [21]. Table 1 lists the printing parameters for the two samples used, coded PD-45 ($PD = 45 \mu\text{m}$) and PD-55 (55 μm), respectively. Nearly full densities were achieved in both, as indicated by the high relative density of $\geq 99.5\%$ (to the density of 4.43 g cm⁻³ for bulk Ti-6Al-4V [1]) in Table 1.

Tensile specimens with a gauge section of $\phi 6 \times 30$ mm were machined from the rods printed along the build direction. Tensile tests were conducted at an initial strain rate of $2.5 \times 10^{-4} \text{ s}^{-1}$ according to ASTM E8/E8M-13. Nearly identical stress–strain curves were obtained from three repeated tests on each type of materials, showing excellent repeatability.

Microstructure characterisation was carried out by optical microscopy (OM, Olympus BH2-UMA), scanning electron microscopy (SEM, FEI Quanta FEG 200

ESEM), and transmission electron microscopy (TEM, FEI Tecnai F20). TEM samples were cut using focused ion beam (SEM/FIB, FEI Nova 200 Nanolab DualBeam). XRD (Rigaku MiniFlex 600) was performed using Cu-K α 1 at 15 mA and 40 kV with a scan rate of 2°/min and step size of 0.02° in the 2θ range of 20–80°.

3. Results

The optical microstructures of PD-55 and PD-45 are shown in Figure 1(a,b), respectively. The first-generation martensitic α' plates (arrowed) were oriented at $\sim 45^\circ$ to the build direction and extended across columns of prior β grains (dashed-line) formed through epitaxial growth during solidification [22], and such a texture was consistent throughout the entire build volume. The average length of the plates (over > 100 measurements) decreased by nearly 40% from $\sim 80 \mu\text{m}$ in PD-45 to $\sim 50 \mu\text{m}$ in PD-55. Much finer later-generation α' plates formed between them (Figure 1(c,d)). The microstructure appeared to consist entirely of these intersecting generations of α' , as confirmed by XRD in Figure 1(e). Indeed, TEM on all the sections of PD-55, including the grip and gauge as well as the necking area of the tensile specimen, detected no β . However, TEM on PD-45 (section AA in Figure 1(d)) revealed very thin layers of β between primary α' plates at isolated locations, as identified by SAEDP (Figure 1(f)) and DF (Figure 1(g)). Also, careful SEM over the entire build length found no AM defects such as lack of fusion or significant pores in both materials.

Figure 2(a) shows tensile stress–strain curves for PD-45 and PD-55, revealing yield stresses ($\sigma_{0.2}$) of 1150 MPa for both, and fracture strains (ϵ_f) of 5–6 and 14–15%, respectively. The good ductility of PD-55 is confirmed by observations of necking as well as cup and cone (Figure 2(b)) and dimples (Figure 2(c)), evidencing ductile fracture. The fracture surface of PD-45, on the other hand, is flat (Figure 2(d)) with both facets and dimples (Figure 2(e)), indicating a mixture of brittle and ductile fractures.

Figure 3(a,b) show SEM of PD-55 from the as-built and necking areas, respectively. The typical acicular α' (Figure 3(a)) was significantly deformed and refined so that its acicular morphology became barely recognisable (Figure 3(b)). This is confirmed by BF TEM in the necking area (Figure 3(c,d)), showing α' crystals of the order

Table 1. Main printing parameters used: PD denotes point distance, t exposure time, P power, h hatch spacing and v scanning speed.

Sample	PD (μm)	t (μs)	v (m/s)	P (W)	h (mm)	Stripe size (mm)	Rotation angle between layers (°)	Relative density (%)
PD-45	45	50	0.9	200	0.105	5	67	99.6
PD-55	55	50	1.1	200	0.105	5	67	99.5

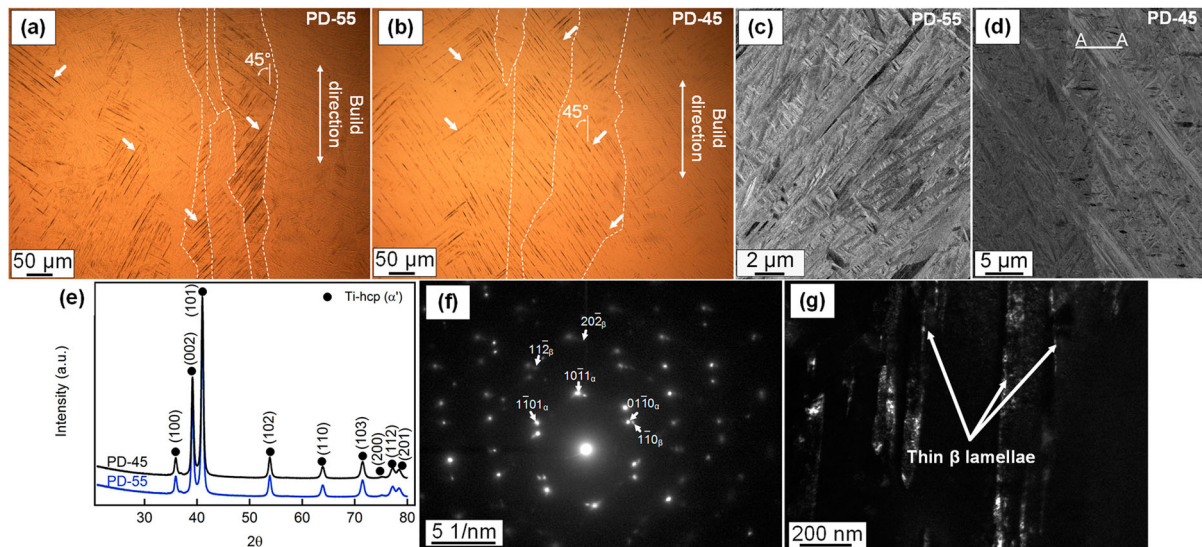


Figure 1. As-built microstructures of (a) PD-55 and (b) PD-45, showing first-generation α' plates, bounded by prior β grain boundaries (dashed-lines), at $\sim 45^\circ$ to the build direction. SEM of (c) PD-55 and (d) PD-45, showing much finer, later-generation α' plates. (e) XRD of PD-45 and PD-55, detecting α' only. TEM along section AA in (d), indicating β formation along first-generation α' plates in PD-45 using (f) SAEDP and (g) DF TEM.

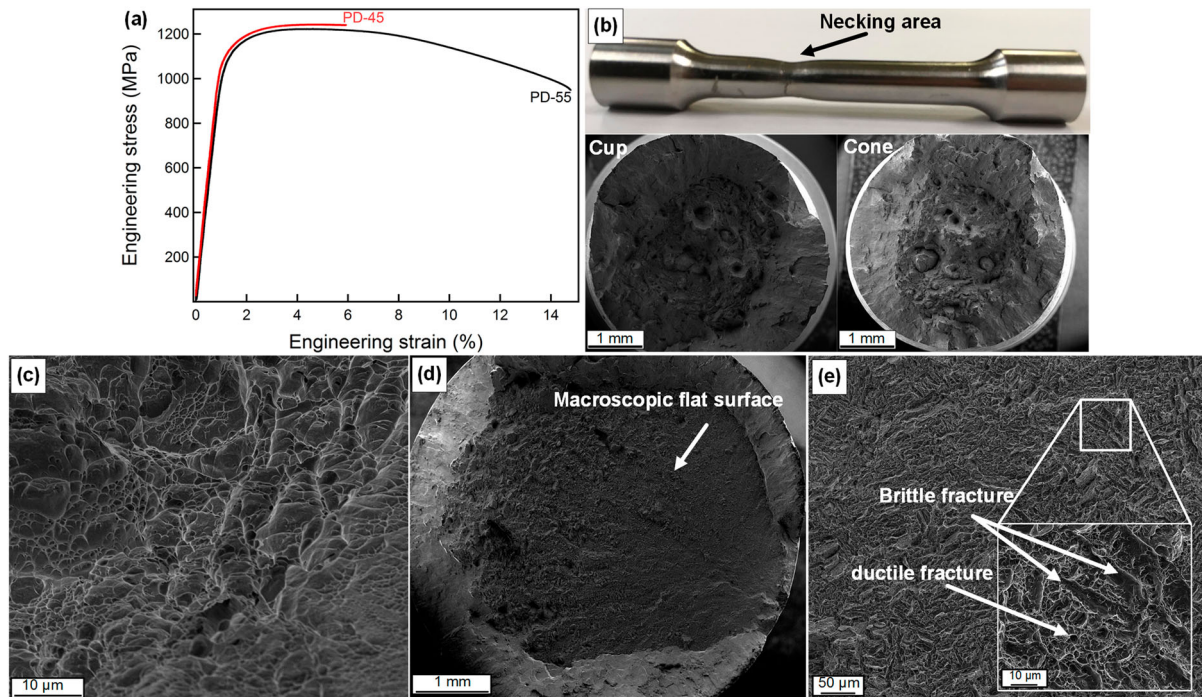


Figure 2. (a) Tensile stress-strain curves for PD-45 and PD-55. (b) PD-55 after tensile testing, showing necking (top), as well as cup and cone (bottom). (c) Dimples on the fracture surface of PD-55. (d) Flat fracture surface of PD-45 containing (e) both microscopic flat surfaces and dimples, indicating a mixture of brittle and ductile fractures.

of 100 nm. The corresponding SAEDP in Figure 3(e) shows rings for α' , implying random orientations.

Figure 4(a) shows a low magnification SEM of the profile view of the fractured PD-45. The fracture facets (dashed-lines) are oriented at $\sim 40 \pm 5^\circ$ to the tensile direction. A close-up (Figure 4(b)) of the circled area in Figure 4(a) reveals that the facet is exactly parallel

to the first-generation α' plates (arrowed) in a prior β grain delineated by dotted-lines. At the same time, dimples can be seen in regions of fine, later-generation α' plates (Figure 4(b,c)). TEM in the dimpled area along section BB in Figure 4(c) shows severely deformed α' plates with entangled dislocations and dislocation cells (Figure 4(d,e)). The corresponding SAEDP in Figure 4(f)

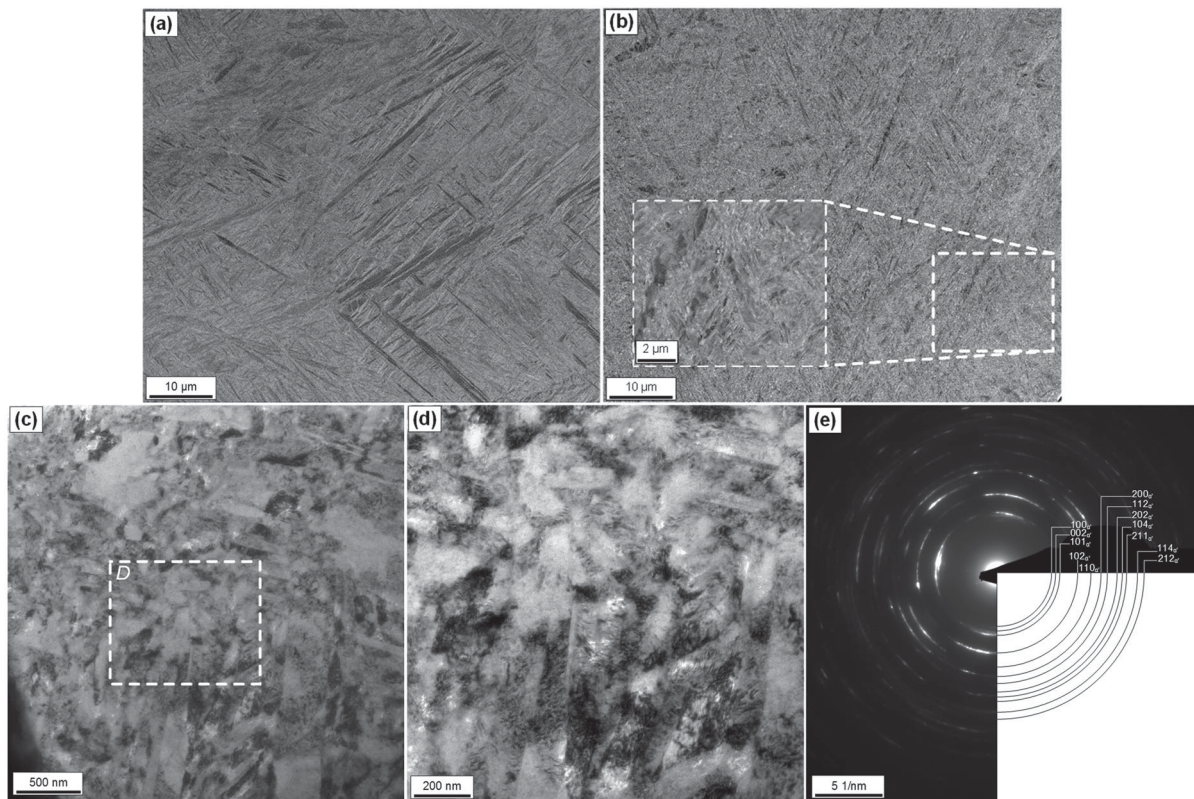


Figure 3. SEM of PD-55: (a) as-built and (b) in the necking area after tensile testing, showing substantial refinement of the α' structure in the latter. (c) BF TEM from the necking area and (d) a higher magnification of area D in (c), showing α' crystals of the order of 100 nm, and (e) corresponding SAEDP, identifying rings for α' only and indicating a fully martensitic structure with random orientations.

is similar to that for PD-55 (Figure 3(e)), indicating a randomly oriented α' structure.

4. Discussion

It is an outstanding achievement that the high ε_f of 14–15% and $\sigma_{0.2}$ of 1150 MPa are obtained in a fully martensitic α' Ti-6Al-4V alloy (PD-55). To put this in perspective, Table 2 compares with other Ti-6Al-4V alloys produced by different processing methods. All the alloys dominated by acicular α' other than PD-55 exhibit much smaller ε_f of < 6% with comparable yield strength. Although, the coarse lamellar α/β alloys processed by EBM possess comparable ductility, their strengths are considerably lower by more than 200 MPa. Only those with ultrafine α/β lamellar structures are similar, although their ductility is still lower. It should be noted that the high strength and ductility achieved here are equivalent to those displayed by the best of commercial wrought Ti-6Al-4V with yield strength of 900–1100 MPa and tensile elongation of 10–18% [3].

The high strength in both PD-45 and PD-55 can be derived from the high solute contents in the supersaturated α' [13], fine crystallite sizes, as well as sub-structural dislocations and twins [2, 24–26]. The much

better ductility in PD-55, however, needs explanation. There are two major differences between the two materials. First, very thin β lamellae can be found, albeit at only isolated locations, in PD-45 (Figure 1(f,g)) while there is a total absence of β in PD-55. This is attributed to the reduction in ν by $\sim 18\%$ with decreasing PD from 55 to 45 μm (Table 1), resulting in $\sim 22\%$ increase in the average energy input (E) in PD-45 since $E \propto 1/\nu$ [21]. This extra E is apparently sufficient to raise temperatures at some small number of locations in the previously deposited layers to form thin β , but not enough to cause substantial α' decomposition as PD-45 is still dominated by α' (Figure 1(e)). Owing to different crystal structures and chemical compositions of α and β , strain incompatibility and stress concentration at the α/β interface are expected. Indeed, FEA demonstrates that both strain and stress are localised at the α/β interfaces [27], contributing to stress concentration at them. When the thin β plates formed in PD-45 (Figure 1(g)) are associated with the first-generation α' plates oriented at $\sim 45^\circ$ to the tensile direction (Figures 1(b) and 4(b)), the α'/β interfaces coincide with the plane of maximum shear stress. A high stress concentration is expected, causing crack initiation and propagation along the interface, as evidenced by the facets in Figure 4(a,b). Such a detrimental effect of β

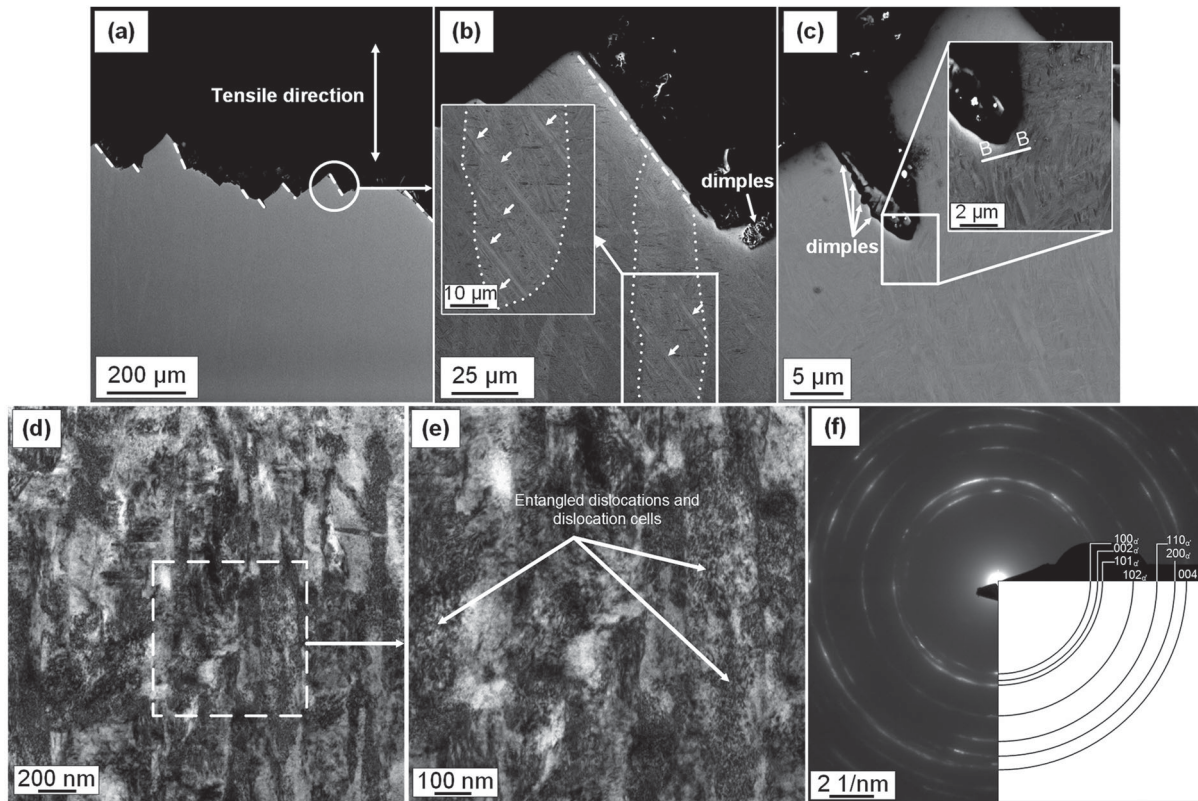


Figure 4. (a–c) SEM of the fracture profile of PD-45 after tensile testing: (a) macroscopic facets (dashed-lines) at $\sim 40 \pm 5^\circ$ to the tensile direction; (b) a close-up of the circled area in (a), showing the facet (dashed-line) parallel to the first-generation α' plates (arrowed) formed inside a prior β grain (dotted), as well as dimples next to it; (c) Close-up of dimples formed in the area of finer α' plates of later generations. TEM of section *BB* marked in the inset in (c): (d) BF and (e) the area framed in (d), showing severely deformed α' refined to crystals of 100–200 nm containing entangled dislocations and dislocation cells; (f) corresponding SAEDP showing rings for α' .

Table 2. Microstructure, yield strength ($\sigma_{0.2}$) and strain to fracture (ε_f) of Ti-6Al-4V produced by different processing methods.

Process	Microstructure	$\sigma_{0.2}$ (MPa)	ε_f (%)	Reference
Mill-annealed	Incompletely recrystallised α with a small amount of fine β particles	945	10	[3]
Duplex annealed	Primary α and lamellar α/β	917	18	[3]
ST ^a and aged	Fine lamellar α/β	1103	13	[3]
EBM at $> 600^\circ\text{C}$	Coarse lamellar α/β	820–850	13–16	[23]
SLM	Acicular α'	1100–1300	< 6	[5,6,9]
SLM	Ultrafine lamellar α/β	~ 1100 –1112	10.5–11.5	[9]
SLM + HT ^b	Coarse lamellar α/β	< 970	< 10	[8]
SLM (PD-45)	Acicular α' with small quantity of β	1150	6	Present study
SLM (PD-55)	Acicular α'	1150	14–15	Present study

^aSolution treatment.

^bHeat treatment.

on ductility is also observed in an α' dominated Ti-6Al-4V processed by conventional methods [17]. Even if β lamellae could form at later generation α' , they would be less damaging as their orientations are off the maximum shear plane and sizes much smaller. By contrast, the total absence of β in PD-55 means a microstructure containing α'/α' interfaces only, resulting in no strain incompatibility and significantly higher ductility. It should be noted that the same level of ductility (≥ 11 –12%) at the similar

strength level (~ 1100 –1200 MPa) can also be obtained in fully lamellar α/β , as shown in Table 2 (the ST + aged with fine lamellar structure, and the SLM with ultrafine lamellar structure). This is because the stress distribution in the alternating lamellar α/β structure is much more even, compared to that at the presence of an isolated β lamella as in the case of PD-45, thanks to the overlapping stress fields from neighbouring plates. As the stress variation decreases with decreasing lamellar thickness,

the stress concentration becomes insignificant in the fine and ultrafine lamellar structured materials, leading to improved ductility.

Although the large ($> 80\ \mu\text{m}$) first-generation α' plates oriented at the maximum shear stress appear to cause brittle fracture along the α'/β interface in PD-45, the areas between them are β free (Figure 4(f)) and contain much finer α' plates of later generations where the fracture is locally ductile with dimple formation (Figure 4(b,c)). Indeed, much refined, randomly oriented α' of 100–200 nm containing a large number of entangled dislocations and dislocation cells (Figure 4(d–f)) is observed there, suggesting substantial dislocation slip which cuts and reorients α' . Such refinement of α' is also observed after cold rolling by $\sim 90\%$ of several α' structured Ti alloys, producing nano-scaled dislocation cells [14–16]. Such local ductile fracture in a fully martensitic Ti-6Al-4V processed by SLM was also reported elsewhere [9].

The second, although less significant, factor influencing ductility is the sizes of the α' plates. In the case of PD-55, not only there is no β anywhere, but also the first generation α' plates are considerably smaller (by $\sim 40\%$, comparing Figure 1(a,b)). For continuous laser, the prior β grain size (L_β —referring here to the width of the β columnar grain) can be related to the scanning speed (v) and solidification cooling rate ($\dot{T}$) by $\dot{T} = 2.07 \times 10^4 v^{1.2}$ [28] and $L_\beta = 3.1 \times 10^6 \cdot \dot{T}^{-0.93}$ for Ti-6Al-4V [29], i.e. L_β would increase with decreasing v . Although such a quantitative relationship has not been established for pulsed laser, the smaller v used for PD-45 (Table 1) indicates a larger prior β width and thus longer first generation α' . Since the sizes of the α' plates, in particular the first-generation ones bounded by β grain boundaries, increase with the sizes of the prior β grains [22,29], the various generations of α' in PD-55 are considerably smaller. Since twinning becomes more difficult with decreasing grain size in a variety of alloys including hcp structured Ti [30–33], twinning is likely to be more restricted in finer α' . Indeed, although quite a number of twins were spotted in the coarser, early generation α' in PD-45, there were hardly any twins in PD-55. The absence of twins is expected to enhance dislocation activity by reducing the number of barriers to dislocation movement, leading to enhanced ductility. In addition, a high amount of Al in α' promotes basal slip [13,34,35], and a finer α' structure can enable activation of a wider range of orientations for the basal slip systems, providing more compatible straining.

In summary, a combination of high yield strength of 1150 MPa and excellent tensile elongation of 14–15% is achieved in a fully martensitic α' Ti-6Al-4V alloy by SLM, which is comparable with the best of commercial

wrought α/β Ti-6Al-4V. It is critical to produce pure intersecting ultrafine α' plates free of β by optimising SLM parameters in order to avoid stress concentration at the α'/β interface and easy crack propagation along it. Plastic deformation would then proceed by dislocation slip which cuts and reorients α' into randomly oriented nano-scaled grains until final ductile fracture with necking and dimple formation. The usually observed poor ductility associated with α' is thus attributable to the difficulty in preventing the formation of β and in producing ultrafine α' by conventional processing, rather than to the myth that α' is inherently brittle. The present study demonstrates the potential for development of fully martensitic α/β Ti alloys, especially by AM.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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References

- [1] Welsch G, Boyer R, Collings E. Materials properties handbook: titanium alloys. Materials Park (OH): ASM International; 1993.
- [2] Banerjee S, Mukhopadhyay P. Phase transformations: examples from titanium and zirconium alloys. London: Elsevier; 2010; (Pergamon Materials Series; Vol.12).
- [3] Donachie MJ. Titanium: a technical guide. Materials Park (OH): ASM International; 2000.
- [4] Facchini L, Molinari A, Höges S, et al. Ductility of a Ti-6Al-4V alloy produced by selective laser melting of prealloyed powders. Rapid Prototyp J. 2010;16:450–459.
- [5] Vandenbroucke B, Kruth J. Selective laser melting of biocompatible metals for rapid manufacturing of medical parts. Rapid Prototyp J. 2007;13:196–203.
- [6] Murr LE, Quinones SA, Gaytan SM, et al. Microstructure and mechanical behavior of Ti-6Al-4V produced by rapid-layer manufacturing, for biomedical applications. J Mech Behav Biomed Mater. 2009;2:20–32.
- [7] Vrancken B, Thijs L, Kruth J-P, et al. Heat treatment of Ti6Al4V produced by selective laser melting: microstructure and mechanical properties. J Alloys Compd. 2012;541:177–185.
- [8] Vilari T, Colin C, Bartout JD. As-fabricated and heat-treated microstructures of the Ti-6Al-4V alloy processed by selective laser melting. Metall Mater Trans A. 2011;42:3190–3199.

- [9] Xu W, Brandt M, Sun S, et al. Additive manufacturing of strong and ductile Ti-6Al-4V by selective laser melting via in situ martensite decomposition. *Acta Mater.* **2015**;85:74–84.
- [10] Xu W, Lui EW, Pateras A, et al. In situ tailoring microstructure in additively manufactured Ti-6Al-4V for superior mechanical performance. *Acta Mater.* **2017**;125:390–400.
- [11] Lui EW, Xu W, Pateras A, et al. New development in selective laser melting of Ti-6Al-4V: a wider processing window for the achievement of fully lamellar $\alpha + \beta$ microstructures. *JOM.* **2017**;69(12):2679–2683.
- [12] Murr LE, Quinones SA, Gaytan SM, et al. Microstructures and mechanical properties of electron beam-rapid manufactured Ti-6Al-4V biomedical prototypes compared to wrought Ti-6Al-4V. *Mater Charact.* **2009**;60:96–105.
- [13] Kwasniak P, Garbacz H, Kurzydowski KJ. Solid solution strengthening of hexagonal titanium alloys: restoring forces and stacking faults calculated from first principles. *Acta Mater.* **2016**;102:304–314.
- [14] Matsumoto H, Watanabe S, Hanada S. A' martensite Ti-V-Sn alloys with low young's modulus and high strength. *Mater Sci Eng A.* **2007**;448:39–48.
- [15] Matsumoto H, Chiba A, Hanada S. Anisotropy of young's modulus and tensile properties in cold rolled α' martensite Ti-V-Sn alloys. *Mater Sci Eng A.* **2008**;486:503–510.
- [16] Matsumoto H, Kodaira K, Sato S, et al. Microstructure and mechanical properties of α' martensite type Ti alloys deformed under the α' processing. *Mater Trans.* **2009**;50:2744–2750.
- [17] Matsumoto H, Yoneda H, Sato K, et al. Room-temperature ductility of Ti-6Al-4V alloy with α' martensite microstructure. *Mater Sci Eng A.* **2011**;528:1512–1520.
- [18] Sherman R, Kessler H. Investigation of the heat treatability of the 6% aluminum-4% vanadium titanium based alloy. *Trans ASM.* **1956**;48:657–676.
- [19] Blackburn M, Williams J. A comparison of phase transformations in three commercial titanium alloys. *ASM Trans Q.* **1967**;60:373–383.
- [20] Fopiano P, Bever M, Averbach B. Phase transformations and strengthening mechanisms in the alloy Ti-6Al-4V. *ASM Trans Q.* **1969**;62:324–332.
- [21] Yakout M, Cadamuro A, Elbestawi MA, et al. The selection of process parameters in additive manufacturing for aerospace alloys. *Int J Adv Manuf Technol.* **2017**;92:2081–2098.
- [22] Yang J, Yu H, Yin J, et al. Formation and control of martensite in Ti-6Al-4V alloy produced by selective laser melting. *Mater Des.* **2016**;108:308–318.
- [23] Tan X, Kok Y, Tan Y, et al. Graded microstructure and mechanical properties of additive manufactured Ti-6Al-4V via electron beam melting. *Acta Mater.* **2015**;97:1–16.
- [24] Banerjee S, Vijayakar SJ, Krishnan R. Strength of zirconium-titanium martensites and deformation behaviour. *Acta Metall.* **1978**;26:1815–1831.
- [25] Moiseev VN, Polyak V, Sokolova AY. Martensite strengthening of titanium alloys. *Met Sci Heat Treat.* **1975**;17:687–691.
- [26] Manero JM, Gil FJ, Planell JA. Deformation mechanisms of Ti-6Al-4V alloy with a martensitic microstructure subjected to oligocyclic fatigue. *Acta Mater.* **2000**;48:3353–3359.
- [27] Ankem S, Margolin H. Finite element method (FEM) calculations of stress-strain behavior of alpha-beta Ti-Mn alloys: part II. Stress and strain distributions. *Metall Trans A.* **1982**;13:603–609.
- [28] Zhang B, Liao H, Coddet C. Microstructure evolution and density behavior of CP Ti parts elaborated by self-developed vacuum selective laser melting system. *Appl Surf Sci.* **2013**;279:310–316.
- [29] Broderick TF, Jackson AG, Jones H, et al. The effect of cooling conditions on the microstructure of rapidly solidified Ti-6Al-4V. *Metall Trans A.* **1985**;16:1951–1959.
- [30] Ghaderi A, Barnett M. Sensitivity of deformation twinning to grain size in titanium and magnesium. *Acta Mater.* **2011**;59:7824–7839.
- [31] Meyers MA, Vöhringer O, Lubarda VA. The onset of twinning in metals: a constitutive description. *Acta Mater.* **2001**;49:4025–4039.
- [32] Hull D. Effect of grain size and temperature on slip, twinning, and fracture in 3% silicon iron. *Acta Metall.* **1961**;9:191–204.
- [33] Lahaie D, Embury JD, Chadwick MM, et al. A note on the deformation of fine grained magnesium alloys. *Scr Metall Mater.* **1992**;27:139–142.
- [34] Zaefferer SM. A study of active deformation systems in titanium alloys: dependence on alloy composition and correlation with deformation texture. *Mater Sci Eng A.* **2003**;344:20–30.
- [35] Metzbowler EA. Stacking fault probability determinations in HCP Ti-Al alloys. *Metall Mater Trans B.* **1971**;2:3099–3103.