



Achieving fully-equiaxed fine β -grains in titanium alloy produced by additive manufacturing

Aitang Xue, Xin Lin, Lilin Wang, Xufei Lu, Lukai Yuan, Hanlin Ding & Weidong Huang

To cite this article: Aitang Xue, Xin Lin, Lilin Wang, Xufei Lu, Lukai Yuan, Hanlin Ding & Weidong Huang (2023) Achieving fully-equiaxed fine β -grains in titanium alloy produced by additive manufacturing, Materials Research Letters, 11:1, 60-68, DOI: [10.1080/21663831.2022.2115323](https://doi.org/10.1080/21663831.2022.2115323)

To link to this article: <https://doi.org/10.1080/21663831.2022.2115323>



© 2023 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group.



View supplementary material [↗](#)



Published online: 20 Sep 2022.



Submit your article to this journal [↗](#)



Article views: 7021



View related articles [↗](#)



View Crossmark data [↗](#)



Citing articles: 56 View citing articles [↗](#)



ORIGINAL REPORTS



Achieving fully-equiaxed fine β -grains in titanium alloy produced by additive manufacturing

Aitang Xue ^{a,b}, Xin Lin ^{a,b}, Lilin Wang ^{a,b}, Xufei Lu ^c, Lukai Yuan ^{a,b}, Hanlin Ding ^{a,b} and Weidong Huang ^{a,b}

^aState Key Laboratory of Solidification Processing, Northwestern Polytechnical University, Xi'an, Shaanxi, People's Republic of China; ^bKey Laboratory of Metal High Performance Additive Manufacturing and Innovative Design, MIIT China, Northwestern Polytechnical University, Xi'an, People's Republic of China; ^cInternational Centre for Numerical Methods in Engineering, Universidad Polit cnica de Catalu a, Barcelona, Spain

ABSTRACT

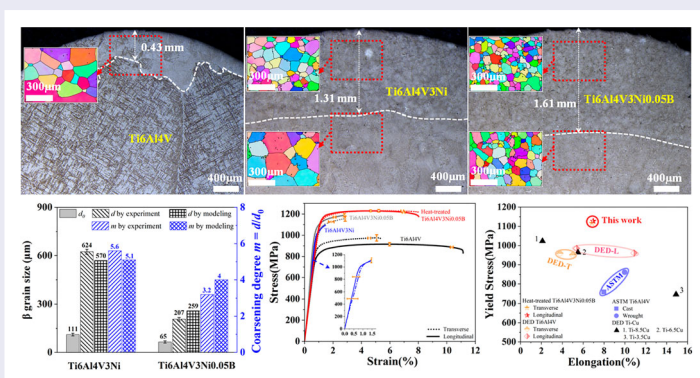
The achievement of fine equiaxed β grain with conventional intragranular (α -Ti+ β -Ti) microstructure in additive manufacturing titanium alloy remains a big challenge. We conquer this challenge by synergistically controlling β -grains during both solidification and subsequent thermal-cycles of laser directed energy deposition (DED), and a solution + quenching heat-treatment. Both the strength and plasticity of heat-treated Ti6Al4V3Ni0.05B are superior to those reported new DED titanium alloy and comparable to that of DED Ti6Al4V, because of the fine-equiaxed β -grains with intragranular (α -Ti+ β -Ti) microstructure. These findings provide new insight into the grain structure control and the composition design of AM titanium alloy.

ARTICLE HISTORY

Received 25 May 2022

KEYWORDS

Additive manufacturing; titanium alloy; grain refinement; fully-equiaxed β -grains; microstructure



IMPACT STATEMENT

The synergetic control of β -grain during both solidification and subsequent thermal-cycling is essential for achieving fully-equiaxed fine β -grains in additively manufactured titanium alloys.

1. Introduction

Additive manufacturing (AM) is a revolutionary technology that offers a promising approach for the near-net shape and flexible design of components [1–4]. Titanium-based alloys are one of the most mature alloys for the application in AM processing [5–8]. However, the intrinsic high cooling rates and high thermal gradients in AM often produce coarse columnar β -grains and continuous grain-boundary α -phases up to several centimeters long, along the deposition direction in titanium

alloy, resulting in a pronounced anisotropy in mechanical properties [9,10] and poor low-cycle fatigue properties [11–15]. Therefore, the achievement of equiaxed fine β -grains is imperative for fabricating high-quality AM titanium alloy parts.

Generally, it is believed that the equiaxed fine β -grains in AM titanium alloy are more easily obtained under large constitutional-supercooling (CS) because it can not only facilitate the columnar to equiaxed transition (CET), but restrict the grain-growth during solidification

CONTACT Xin Lin ✉ xlin@nwpu.edu.cn; Lilin Wang ✉ wlilin@nwpu.edu.cn State Key Laboratory of Solidification Processing, Northwestern Polytechnical University, Xi'an, Shaanxi 710072, People's Republic of China; Key Laboratory of Metal High Performance Additive Manufacturing and Innovative Design, MIIT China, Northwestern Polytechnical University, Xi'an, Shaanxi 710072, People's Republic of China

Supplemental data for this article can be accessed here. <https://doi.org/10.1080/21663831.2022.2115323>

  2023 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group.

This is an Open Access article distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

[16–18]. In addition, the development rate of a CS zone is proportional to the value of growth restriction factor $Q (= Q_n \cdot c_0)$ [19,20]. Thus, the elements with a large normalized growth restriction factor (Q_n) in Ti, such as B [21–23] and Si [24], were preferentially selected as the alloying elements in AM Ti or titanium alloy. Researches have showed that these elements are highly-effective in refining the β -grains by restricting the grain-growth during solidification, but they fail to produce fully-equiaxed β -grains due to the limited maximum-solubility $c_{0-\max}$ in Ti does not provide sufficient CS to promote nucleation. To solve this problem, the fast-eutectoid element Cu and Ni, with a large $c_{0-\max}$ and medium Q_n were added to Ti and Ti6Al4V, and the fully-equiaxed fine β -grains were achieved under relative low deposition efficiency (< 2 g/min) fabricated by laser directed energy deposition (DED) [6,25]. Nevertheless, the eutectoid phase is harmful to the ductility of Ti alloys, thus, the addition amount of the fast-eutectoid element must be deliberated. Apparently, achieving the equiaxed fine grains with $(\alpha + \beta)$ two-phase microstructure under traditional deposition efficiency (6–12 g/min) in AM titanium alloys is still challenging.

In fact, the final β -grain structure in the as-built AM titanium alloy depends not only on the grain nucleation and growth during solidification but also on the grain-coarsening during subsequent thermal-cycles. Regrettably, most studies have focused on the former to control β -grains, while very little attention has been paid to the latter. Recently, our research [26] has proved that the β -grains can be coarsened by 3–9 times under single instantaneous high-temperature thermal-cycles (< 1 s) during DED titanium alloy. Undisputedly, such coarsening also must be inhibited for refining β -grains. Therefore, a synergetic control of grain structure during both solidification and subsequent thermal-cycling is essential for achieving equiaxed fine β -grains in AM titanium alloy.

To this end, alloy-composition modification probably is an effective solution. The fast-eutectoid element Ni and B were selected as the alloying elements, based on the following facts: (i) Ni has a large $c_{0-\max}$ in Ti and a larger Q_n than Cu [27]; (ii) B has the second-largest Q_n in Ti; and (iii) B can inhibit the grain-boundary migration in titanium alloys during conventional heat-treatment. On the one hand, the co-addition of Ni and B in titanium alloy can reduce the amount of Ni addition alone for controlling β -grains during solidification; on the other hand, B could also probably limit the grain-coarsening during subsequent thermal-cycles of DED.

Thereby, the low-content Ni and trace B were chosen as the alloying elements in DED Ti6Al4V to synergistically control the β -grain structure during both

Table 1. Processing parameters for DED.

Laser power (kW)	Scanning velocity (mm/min)	Powder feed rate (kg/h)	Nominal increment (mm)	Spot diameter (mm)
2	900	0.5	0.15	5

solidification and subsequent thermal-cycles. The morphology and size of the β -grains in DED Ti6Al4VxNi_yB after solidification and subsequent thermal-cycling were respectively investigated by combining experimental observations with finite element thermal simulation. Also, the tensile properties and their anisotropy were analyzed.

2. Experimental details

The pre-alloyed Ti6Al4V, Ni spherical-powder (diameter: 80 ~ 150 μm) and B powder (diameter: 1 μm) were mixed with the nominal compositions of Ti6Al4V3Ni and Ti6Al4V3Ni0.05B (wt%) by a planetary ball milling. A series of single-walls ($110 \times 6 \times 110 \text{ mm}^3$) were deposited on the forged Ti6Al4V substrates using a reciprocating scanning strategy.

Details of the DED equipment was described in [21]. The processing parameters are shown in Table 1.

The β -reconstructed electron-backscattered-diffraction maps (area: $800 \times 600 \mu\text{m}^2$, step size: 1.4 μm , acceleration voltage: 20KV, working distances: 21 mm) and optical microscope maps were used to measure the β -grain size at the top and middle of the deposits, respectively.

Details about obtaining the β -grain coarsening parameters in Ti6Al4V3Ni-xB and the thermal simulation were described in Supplementary Materials.

The heat treatment for Ti6Al4V3Ni0.05B deposit is 990°C for 15 min followed by water quenching.

Two types of room-temperature tensile samples parallel (longitudinal) and perpendicular (transverse) to the deposition direction with a gage dimension of $24 \times 6 \times 2 \text{ mm}^3$ were machined from the middle of each single-wall deposit and were tested with a constant crosshead displacement rate of 1 mm/min using an Instron-3382 machine.

3. Results and discussion

The last-layer at the top of the deposit exhibits the solidification microstructure without experiencing any thermal-cycling. The β -grains at the top of the Ti6Al4VxNi_yB deposits and the schematic diagrams of their formation mechanism are shown in Figure 1. In the last layer, the as-built microstructure in Ti6Al4V consists of the columnar and equiaxed β -grains, while

Table 2. The Q , ΔT_0 , m_l , k and Q_i .

Alloy	Q	ΔT_0 (K)	Element	m_l (K/wt%)	k	Q_i
Ti6Al4V	5.1	5.4	Al	5.64	1.15	5.08
			V	0.42	1.01	0.02
Ti6Al4V3Ni	34.02	111.8	Al	6.26	1.09	3.38
			V	0.66	1.0	0
			Ni	-13.80	0.26	30.64
Ti6Al4V3Ni0.05B	39.05	188.7	Al	6.28	1.10	3.77
			V	0.68	0.99	-0.03
			Ni	-13.94	0.26	30.95
			B	-88.70	0.016	4.36

the microstructures are fully-equiaxed β -grains in both Ti6Al4V3Ni and Ti6Al4V3Ni0.05B. The thickness of the top equiaxed fine-grain zone in three samples is 0.43, 1.31 and 1.61 mm, respectively. Compared with Ti6Al4V, the average size d_0 of the equiaxed fine-grains in the last-layer in Ti6Al4V3Ni and Ti6Al4V3Ni0.05B is decreased by 48% and 69% down to 111 and 65 μm , respectively. Compared with Ti6Al4V3Ni, Ti6Al4V3Ni0.05B obtains a larger zone containing finer equiaxed-grains.

The formation criterion of CS ahead of the solid-liquid interface is given by Equation (1) [21]. A large degree of CS (ΔT_{cs}) can be obtained from a large value of the right side of Equation (1).

$$G/V < (m_l c_0/D) \times [(1-k)/k] = -Q/(Dk) = \Delta T_0/D \quad (1)$$

where G is the temperature gradient, V is the solidification rate, $Q = m_l c_0(k-1)$, m_l is the liquidus slop, c_0 is the normal solute concentration in wt%, k is the solute partition coefficient, ΔT_0 is the equilibrium solidification temperature range and D is the liquid solute diffusivity. The Q and ΔT_0 represent the developing rate and degree of CS, respectively. For multi-component alloys, $Q = \sum_{i=1}^{i=n} m_i c_i (k_i - 1)$. Table 2 shows Q and ΔT_0 for three alloys, and the values of m_l , k and Q_i of Al, V, Ni, B elements in each alloy, calculated using the Thermo-Calc software with TTTI titanium alloy database.

Referring to Ti6Al4V, Q in Ti6Al4V3Ni and Ti6Al4V3Ni0.05B increases by approximately 5.8 and 6.8 times, while ΔT_0 increases by about 19.7 and 33.9 times, respectively. Compared with Ti6Al4V3Ni, the synergy of Ni and B in Ti6Al4V3Ni0.05B prominently increases Q and ΔT_0 , resulting in a more rapid buildup of a larger ΔT_{cs} ahead of the solid-liquid interface.

During the initial solidification process of the last layer of the Ti6Al4VxNiyB deposits, the prior β -grains at the molten-pool bottom grow epitaxially from the previous layer ($\Delta T_n \approx 0^\circ\text{C}$) and, at the same time, the partitioned solute is discharged into the liquid, triggering a CS zone ahead of the solid-liquid interface (Figure 1(d-f)). Compared with Al and V, Ni has a larger partitioning in the liquid during the solidification of titanium alloy. The

larger Q and ΔT_0 in Ti6Al4V3Ni allow the rapid achievement of the larger ΔT_{cs} and, thus, plenty of new grains can nucleate only after a slight extent of epitaxial growth of prior β -grains due to $\Delta T_{cs} > \Delta T_n$, and the equiaxed-grains form at the molten-pool bottom. Consequently, the fully-equiaxed-grains are obtained in Ti6Al4V3Ni. Similar process also happens in Ti6Al4V3Ni0.05B, except that the synergy of Ni and B can more rapidly produce a larger ΔT_{cs} , leading to a larger zone containing finer equiaxed-grains.

It is conventionally believed that the size of the grains directly obtained from the solidification is inversely proportional to Q of titanium alloy. However, in this study the synergy of Ni and B pronouncedly reduces the d_0 value in Ti6Al4V3Ni0.05B to nearly 50% that in Ti6Al4V3Ni, leading to a much finer grain than the one predicted by the linear relationship of $1/Q$ previously reported (Figure 1(g)) [19,24,28]. Dramatically, an enhanced synergetic effect on grain refinement is achieved, similarly to previous report in aluminum systems [29]. Notably, the Q value calculated by the simple summation of Q_i for each single-element probably cannot account for this synergistic mechanism during solidification and, thus, it must be further studied.

Different from the last-layer in the deposit top, the previously deposited layers experience a series of thermal-cycling responsible for the final microstructures, as shown in Figure 2(a,b). Note that the microstructures in the middle of the Ti6Al4V3Ni and Ti6Al4V3Ni0.05B deposits are fully-equiaxed β -grains. Correspondingly, the average size d of β -grains is 624 and 207 μm , respectively; the β -grain coarsening degree m ($m = d/d_0$) is 5.6 and 3.2, respectively, referring to the β -grain size in the last-layer. Notably, only 0.05 wt% B indeed reduces m of Ti6Al4V3Ni0.05B to nearly half that of Ti6Al4V3Ni, resulting in a prominent reduction of d (by 67%) in Ti6Al4V3Ni0.05B.

According to the classic grain-coarsening model [30], a modified model suitable for the instantaneous temperature T during DED is given as:

$$d^n - d_0^n = k_0 M \quad (2)$$

$$M = \sum_{i=1}^{i=n} \int_{t_i^h(T_\beta)}^{t_i^c(T_\beta)} e^{-\frac{q}{RT(t_i)}} dt \quad (3)$$

where n is the grain-coarsening exponent, k_0 is a constant, M is an integral value related with temperature $T(t)$ and time t , $t_i^h(T_\beta)$ and $t_i^c(T_\beta)$ are the time when the heating and cooling temperature reaches the β -transus ($T_\beta = 887.3^\circ\text{C}$ for Ti6Al4V3NiyB), respectively; q is the grain-coarsening activation energy and R is the gas constant (8.314 J/(mol·K)). Only the thermal-cycles with a peak-temperature T_p satisfying $T_\beta < T_p < T_s$

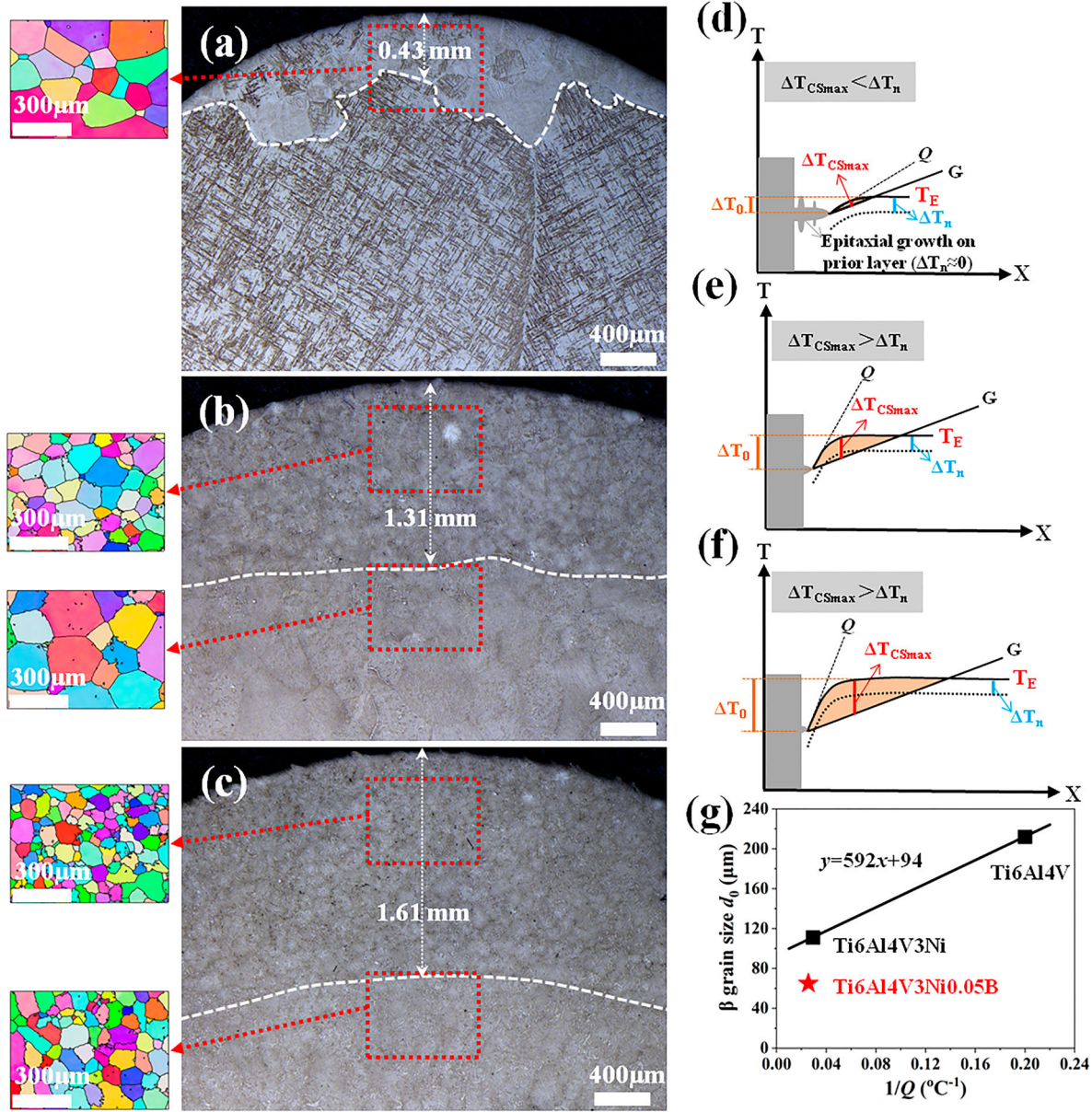


Figure 1. The β -grains at the top of Ti6Al4VxNiyB and the initial solidification mechanism of the last layer. (a), (d) Ti6Al4V; (b), (e) Ti6Al4V3Ni; (c), (f) Ti6Al4V3Ni0.05B; (g) grain size d_0 plotted against the inverse Q . (The dashed white lines in a-c separate the equiaxed grains obtained only by solidification from the ones subjected to subsequent thermal-cycling. T_E is the equilibrium liquidus temperature and ΔT_n is the critical undercooling for nucleation).

(alloy melting-temperature) can induce grain coarsening. The grain-coarsening parameters for Ti6Al4V3Ni and Ti6Al4V3Ni0.05B are: $n = 2.45$, $k_0 = 11.36 \text{ m}^{2.45}/\text{s}$, $q = 319.9 \text{ KJ/mol}$; and $n = 2.56$, $k_0 = 229.5 \text{ m}^{2.56}/\text{s}$, $q = 390 \text{ KJ/mol}$, respectively. Thereby, the grain coarsening at the middle of the Ti6Al4V3NiyB deposits can be predicted through Equations (2) and (3) once the corresponding temperature field is known.

According to the calculated temperature field (Figure 2(e,f)), the predicted values of m with respect to different d_0 for Ti6Al4V3Ni and Ti6Al4V3Ni0.05B are shown in Figure 2(d). The predicted and measured results show

a better agreement. In addition, the smaller the d_0 , the larger the m for the same alloy. Here, the measured d_0 in the Ti6Al4V3Ni0.05B (65 μm) is about half of that in the Ti6Al4V3Ni (111 μm). However, the m value of the coarsened-grain at the middle of Ti6Al4V3Ni0.05B deposit (3.2) is much smaller than that of Ti6Al4V3Ni (5.6). This is because that trace B can significantly curb the β -grain coarsening during multiple instantaneous high-temperature thermal-cycles (<1 s for each loading) by increasing q and n as shown above. Therefore, Ti6Al4V3Ni0.05B achieves the much finer equiaxed-grains than Ti6Al4V3Ni. This reveals for the first time

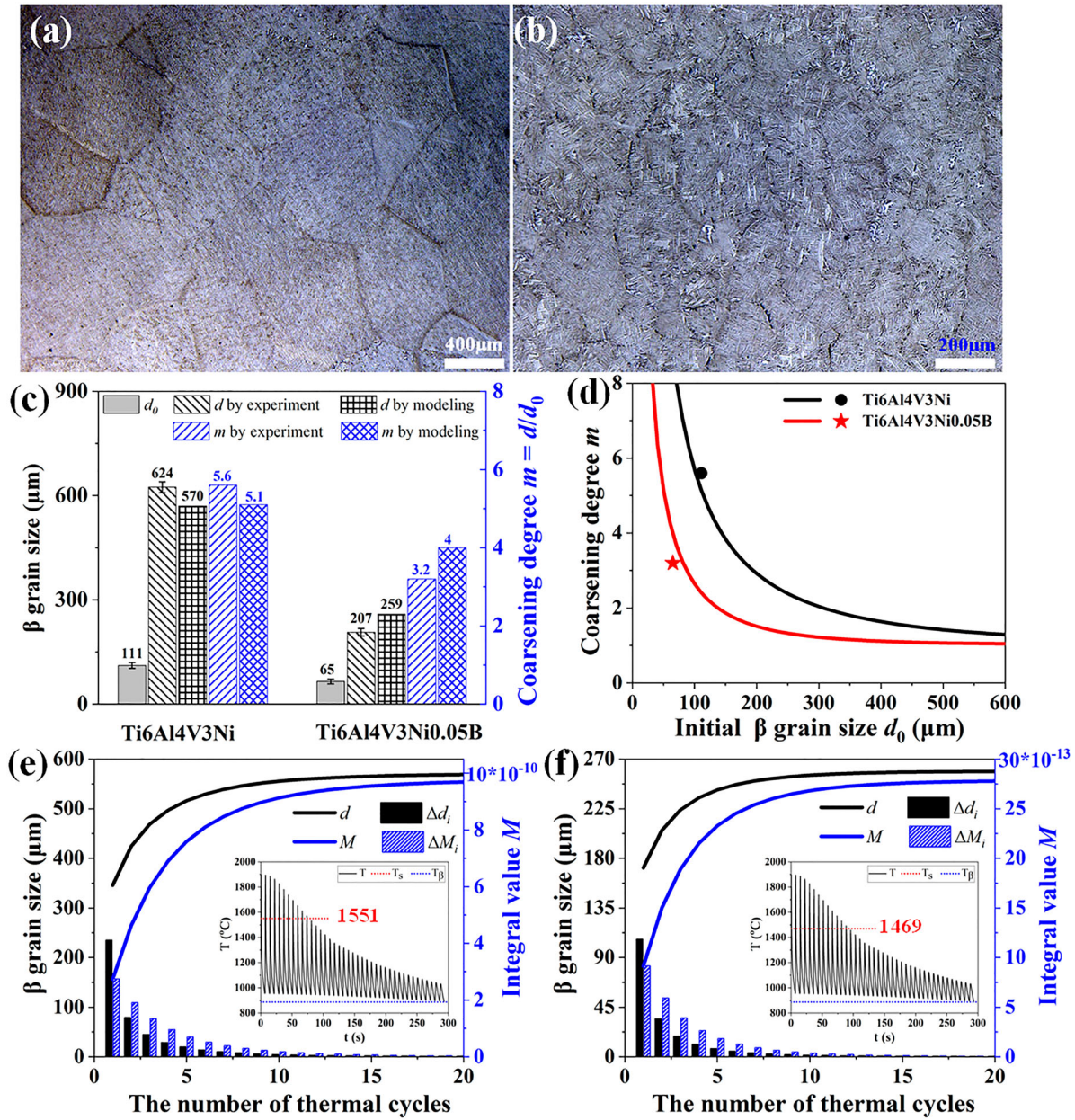


Figure 2. The β -grains at the middle of the Ti6Al4V3Ni0.05B deposits. (a) Ti6Al4V3Ni, (b) Ti6Al4V3Ni0.05B; (c) β -grain size and coarsening degree m ; (d) the function of the simulated m with regard to d_0 , and the symbols represent the experimental value; the simulated δd_i , $d = d_0 + \sum \delta d_i$, δM_i and $M = \sum \delta M_i$ with regard to the thermal-cycling number ($T_\beta < T_p < T_s$) in (e) Ti6Al4V3Ni and (f) Ti6Al4V3Ni0.05B. (T_s and T_β are calculated using Thermo-Calc.).

that trace B plays an equally important role in refining β -grains of DED titanium alloy during reheat-cycles and solidification process.

The final β -grains at the middle of the deposit result from the coarsening of the initial solidified β -grains during successive multiple thermal-cycles ($T_\beta < T_p < T_s$). Figure 2(e,f) shows the contribution of each thermal-cycling to the size of the coarsened β -grain δd_i and to the corresponding integral area δM_i for Ti6Al4V3Ni and Ti6Al4V3Ni0.05B. For both alloy deposits, the d value of the n th layer (black curve) firstly rises rapidly with the

thermal-cycling number, and then remains unchanged. This is because as the number of the deposited layers increases, the temperature that the n th layer suffers from each subsequent thermal-cycling gradually decreases, leading to the reduction of δM_i and δd_i . Strikingly, the d value is mainly affected by a few high-temperature thermal-cycles (< 10) when depositing the subsequent layers adjacent the n th layer. Consequently, only the adjacent several re-heating high-temperature thermal-cycles ($T_\beta < T_p < T_s$) are mainly responsible for the grain-coarsening of the n th layer in DED titanium alloy.

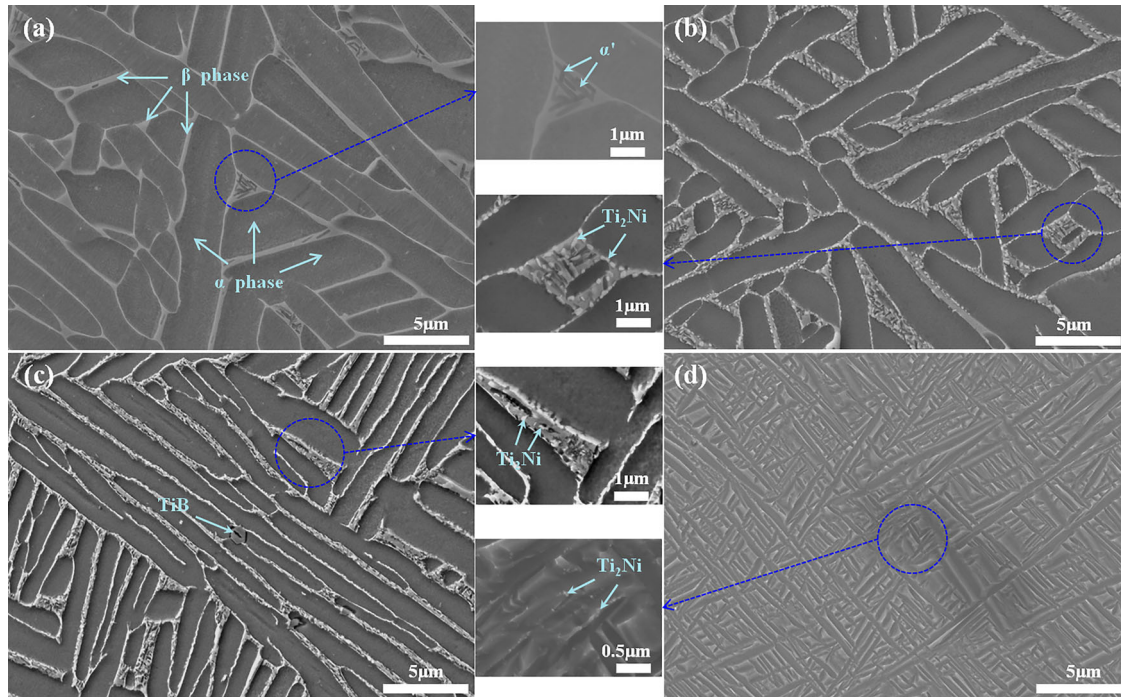


Figure 3. The microstructures at the middle of the Ti6Al4VxNi0.05B deposits. As-built: (a) Ti6Al4V, (b) Ti6Al4V3Ni, and (c) Ti6Al4V3Ni0.05B, (d) heat-treated Ti6Al4V3Ni0.05B.

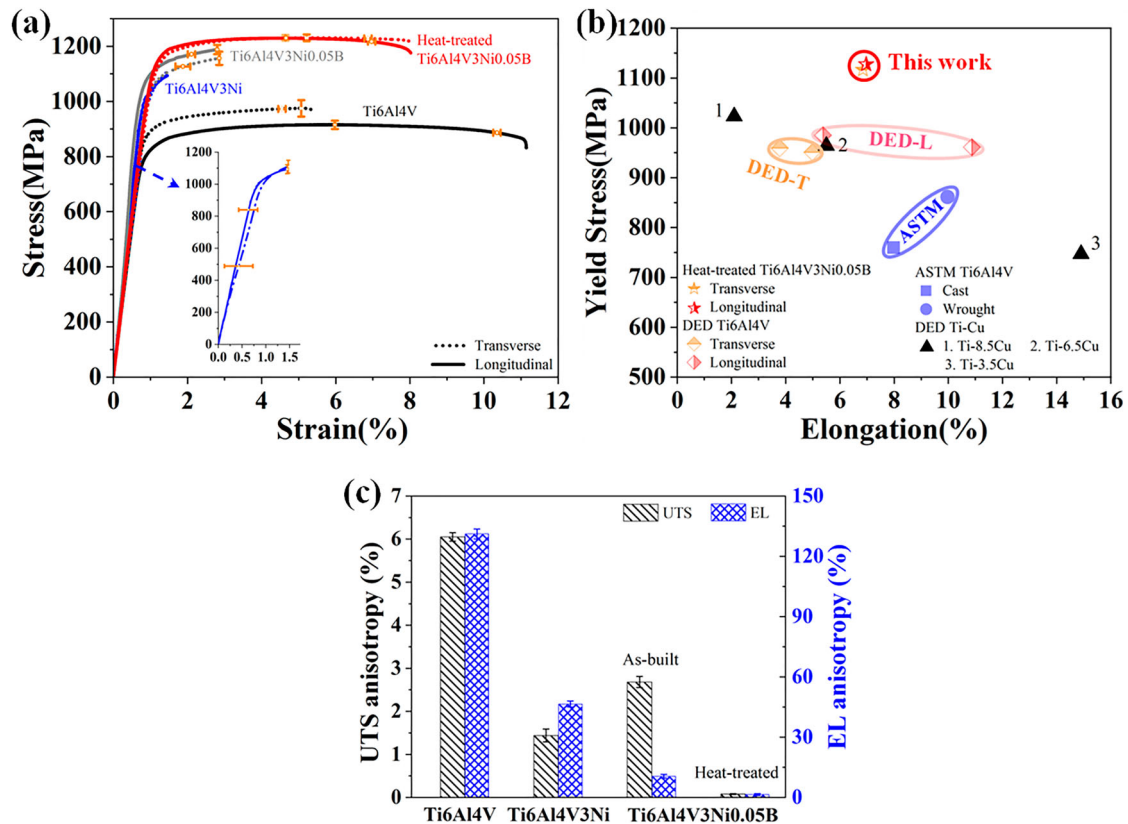


Figure 4. Mechanical properties of Ti6Al4VxNi0.05B alloys. (a) Representative engineering stress–strain curves; the error bars (UTS and EL) represent one standard deviation. (b) Tensile properties for heat-treated Ti6Al4V3Ni0.05B are comparable with Ti-Cu [6] and Ti6Al4V [10] by DED and the ASTM standard for Ti6Al4V [32]. (c) Anisotropy (the calculation method is shown in [21]).

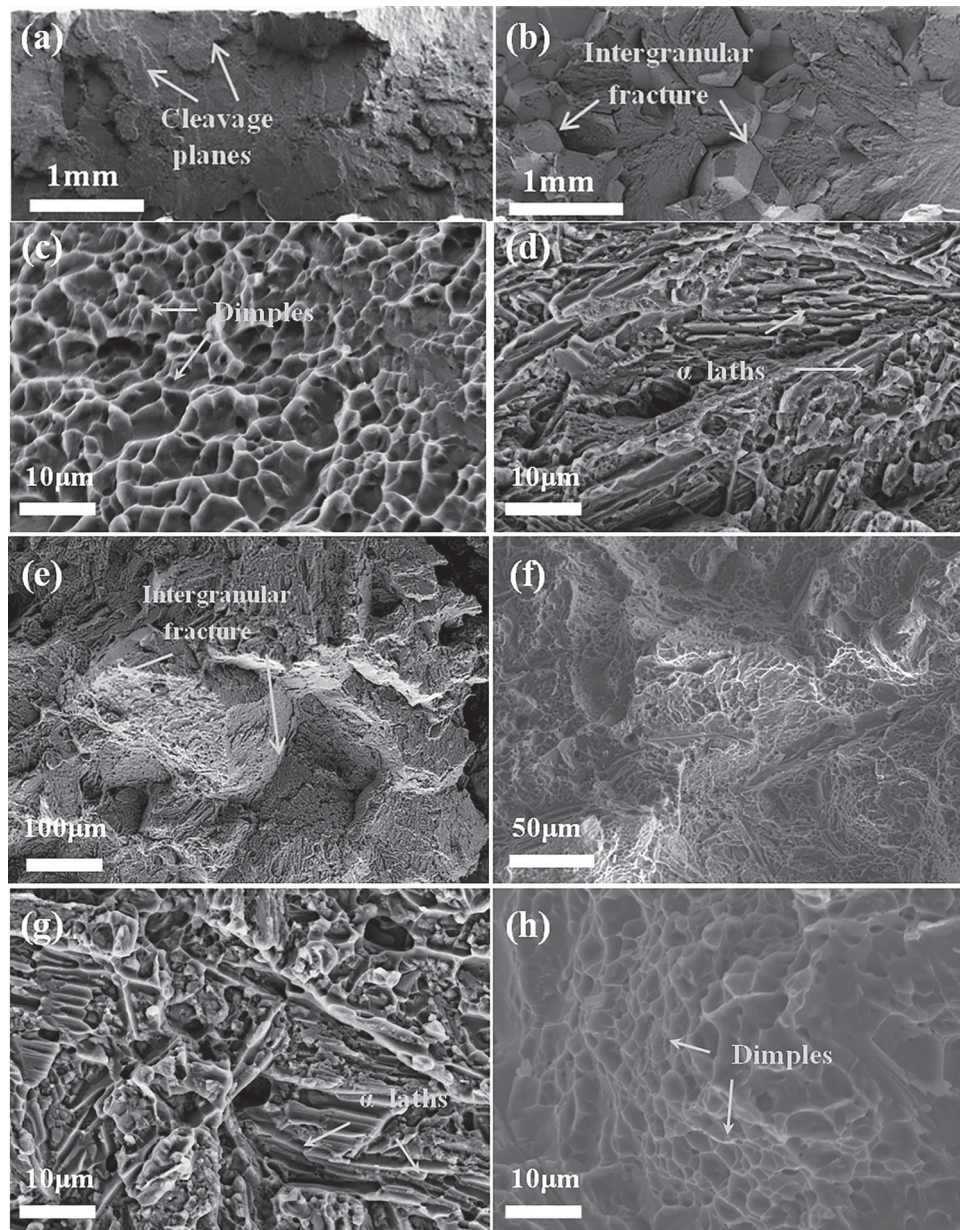


Figure 5. Fracture surfaces of longitudinal specimens: (a) (c) as-built Ti6Al4V, (b) (d) as-built Ti6Al4V3Ni, Ti6Al4V3Ni0.05B (e) (f) as-built and (g) (h) heat-treated.

As shown in Figure 3, compared with Ti6Al4V, the addition of Ni causes the formation of Ti_2Ni (139 nm) and reduces the aspect ratio of the α -laths (1.6 μm in width) in Ti6Al4V3Ni. Besides a lot of Ti_2Ni between the α -laths, some TiB phase is also formed, and the α -laths (1 μm in width) are refined in Ti6Al4V3Ni0.05B. For the heat-treated Ti6Al4V3Ni0.05B, Ni is almost completely dissolved into the β -matrix, forming (α -Ti+ β -Ti) intragranular-microstructure with a little amount of residual Ti_2Ni (<0.01 vol.%), and the width of α -laths is significantly reduced to 0.219 μm .

As shown in Figure 4(a), compared with Ti6Al4V, both the yield strength (YS) and the ultimate tensile strength (UTS) are increased, while the fracture elongation (EL) is decreased for as-built Ti6Al4V3Ni and Ti6Al4V3Ni0.05B. This should be attributed to the strengthening and embrittlement effect of Ti_2Ni . Compared with Ti6Al4V3Ni, all YS, UTS and EL in as-built Ti6Al4V3Ni0.05B are improved, especially the longitudinal EL is increased by ~ 3.4 times (2.1%). This may be attributed to the weakened detrimental-effect of the relatively dispersed Ti_2Ni caused by the finer

equiaxed-grains and α -laths. After the heat-treatment for Ti6Al4V3Ni0.05B, a significantly increased EL with slightly higher UTS (transverse: 6.87%, 1231Mpa; longitudinal: 6.97%, 1230Mpa) without mechanical anisotropy are both achieved (Figure 4 (a,c)). The significant enhancement of EL is attributed to the near-complete disappearance of Ti₂Ni, which favors the movement of dislocations and deformation compatibility of different phases. The improvement of UTS is due to the strengthen of refiner α -laths and solid-solution strengthening of Ni [31].

As shown in Figure 4(b), compared with Ti–Cu alloys manufactured by DED [6], the mechanical properties of the heat-treated Ti6Al4V3Ni0.05B exhibit a much higher strength with comparable plasticity. Compared with DED Ti6Al4V [10], the YS of the heat-treated Ti6Al4V3Ni0.05B is significantly higher, and the EL is between the transverse and longitudinal EL of Ti6Al4V. Also, the comprehensive tensile properties of the heat-treated Ti6Al4V3Ni0.05B are comparable to that of ASTM standard for cast and wrought Ti6Al4V [32].

As shown in Figure 5, the fracture surface of Ti6Al4V is a ductile-fracture with dimples. While an obvious intergranular brittle-fracture is presented in Ti6Al4V3Ni. The as-built Ti6Al4V3Ni0.05B shows a mixed ductile-brittle fracture because of its finer equiaxed-grains and the grain-boundary strengthening by B [23]. The heat-treated Ti6Al4V3Ni0.05B exhibits ductile fracture with small dimples, which is consistent with its improved ductility (Figure 4).

4. Conclusions

In summary, an alloy design method for achieving fully-equiaxed fine β -grains with good comprehensive tensile properties in AM titanium alloy is demonstrated, by synergistically controlling the β -grains during both solidification and subsequent thermal-cycle, and a solution + quenching heat-treatment. The fully-equiaxed β -grains are obtained in both Ti6Al4V3Ni and Ti6Al4V3Ni0.05B due to the significantly increased constitutional supercooling by Ni. Compared with Ti6Al4V3Ni, the grain size of Ti6Al4V3Ni0.05B is firstly reduced by $\sim 50\%$ during the initial solidification owing to the larger Q caused by the synergy of Ni and B, and then the grain-coarsening degree during thermal-cycles is further reduced by $\sim 50\%$ because of the increased grain-coarsening exponent and activation energy by trace B. This reveals for the first time that a $1 + 1 > 2$ grain-refinement effect can be achieved in solidified equiaxed-grains by co-addition of Ni and B, and trace B plays an equally important role in refining β -grains during reheat-cycles and solidification process. Both the

strength and plasticity of heat-treated Ti6Al4V3Ni0.05B are improved and comparable to that of DED Ti6Al4V, due to the fine fully-equiaxed β -grains with intragranular (α -Ti + β -Ti) microstructure. These findings provide new insight into the grain structure control and the composition design of AM titanium alloy.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

We acknowledge support from the National Key R&D Plan of China (No. 2018YFB1105901) and the Research Fund of the State Key Laboratory of Solidification Processing (NPU), China [grant number 2022 TS 02].

ORCID

Aitang Xue  <http://orcid.org/0000-0003-1301-8202>

Xin Lin  <http://orcid.org/0000-0002-7491-8928>

Lilin Wang  <http://orcid.org/0000-0001-7014-1923>

Xufei Lu  <http://orcid.org/0000-0002-5829-385X>

Lukai Yuan  <http://orcid.org/0000-0002-4708-3048>

Hanlin Ding  <http://orcid.org/0000-0003-4421-648X>

Weidong Huang  <http://orcid.org/0000-0002-1139-854X>

References

- [1] DebRoy T, Wei HL, Zuback JS, et al. Additive manufacturing of metallic components – process, structure and properties. *Prog Mater Sci.* 2018;92:112–224.
- [2] Herzog D, Seyda V, Wycisk E, et al. Additive manufacturing of metals. *Acta Mater.* 2016;117:371–392.
- [3] Martin JH, Yahata BD, Hundley JM, et al. 3D printing of high-strength aluminium alloys. *Nature.* 2017;549:365–369.
- [4] Panwisawas C, Tang YT, Reed RC. Metal 3D printing as a disruptive technology for superalloys. *Nat Commun.* 2020;11:2327.
- [5] Zhang T, Huang Z, Yang T, et al. In situ design of advanced titanium alloy with concentration modulations by additive manufacturing. *Science.* 2021;374:478–482.
- [6] Zhang D, Qiu D, Gibson MA, et al. Additive manufacturing of ultrafine-grained high-strength titanium alloys. *Nature.* 2019;576:91–95.
- [7] Todaro CJ, Easton MA, Qiu D, et al. Grain structure control during metal 3D printing by high-intensity ultrasound. *Nat Commun.* 2020;11:142.
- [8] Barriobero-Vila P, Gussone J, Stark A, et al. Peritectic titanium alloys for 3D printing. *Nat Commun.* 2018;9:3426.
- [9] Carroll BE, Palmer TA, Beese AM, et al. Anisotropic tensile behavior of Ti-6Al-4V components fabricated with directed energy deposition additive manufacturing. *Acta Mater.* 2015;87:309–320.
- [10] Kok Y, Tan XP, Wang P, et al. Anisotropy and heterogeneity of microstructure and mechanical properties in metal additive manufacturing: a critical review. *Mater Des.* 2018;139:565–586.

- [11] Ren YM, Lin X, Guo PF, et al. Low cycle fatigue properties of Ti-6Al-4V alloy fabricated by high-power laser directed energy deposition: experimental and prediction. *Int J Fatigue*. 2019;127:58–73.
- [12] Sterling A, Torries B, Shamsaei N, et al. Fatigue behavior and failure mechanisms of direct laser deposited Ti-6Al-4V. *Mater Sci Eng A*. 2016;655:100–112.
- [13] Sterling A, Shamsaei N, Torries B, et al. Fatigue behaviour of additively manufactured Ti-6Al-4V. *Procedia Eng*. 2015;133:576–589.
- [14] Zhang ZB, Hao YL, Li SJ, et al. Fatigue behavior of ultrafine-grained Ti-24Nb-4Zr-8Sn multifunctional biomedical titanium alloy. *Mater Sci Eng A*. 2013;577:225–233.
- [15] Saitova LR, Höppel HW, Göken M, et al. Cyclic deformation behavior and fatigue lives of ultrafine-grained Ti-6Al-4V ELI alloy for medical use. *Int J Fatigue*. 2009;31:322–331.
- [16] Chao Q, Mateti S, Hodgson PD, et al. Nanoparticle-mediated ultra grain refinement and reinforcement in additively manufactured titanium alloys. *Addit Manuf*. 2021;46:102173.
- [17] Tian X, Zhu Y, Zhang K, et al. Isotropic and improved tensile properties of Ti-6Al-4V achieved by in-situ rolling in direct energy deposition. *Addit Manuf*. 2021;46:102151.
- [18] Zhang G, Lu X, Lin X, et al. In-situ grain structure control in directed energy deposition of Ti6Al4V. *Addit Manuf*. 2022;55:102865.
- [19] StJohn DH, Qian M, Easton MA, et al. The interdependence theory: the relationship between grain formation and nucleant selection. *Acta Mater*. 2011;59:4907–4921.
- [20] Easton MA, StJohn DH. A model of grain refinement incorporating alloy constitution and potency of heterogeneous nucleant particles. *Acta Mater*. 2001;49:1867–1878.
- [21] Xue A, Lin X, Wang L, et al. Influence of trace boron addition on microstructure, tensile properties and their anisotropy of Ti6Al4V fabricated by laser directed energy deposition. *Mater Des*. 2019;181:107943.
- [22] Bermingham MJ, Kent D, Zhan H, et al. Controlling the microstructure and properties of wire arc additive manufactured Ti-6Al-4V with trace boron additions. *Acta Mater*. 2015;91:289–303.
- [23] Singh G, Ramamurty U. Reprint: boron modified titanium alloys. *Prog Mater Sci*. 2021;120:100815.
- [24] Mereddy S, Bermingham MJ, StJohn DH, et al. Grain refinement of wire arc additively manufactured titanium by the addition of silicon. *J Alloy Compd*. 2017;695:2097–2103.
- [25] Sui S, Chew Y, Weng F, et al. Study of the intrinsic mechanisms of nickel additive for grain refinement and strength enhancement of laser aided additively manufactured Ti-6Al-4V. *Int J Extrem Manuf*. 2022;4:035102.
- [26] Xue A, Lin X, Wang L, et al. Heat-affected coarsening of β grain in titanium alloy during laser directed energy deposition. *Scripta Mater*. 2021;205:114180.
- [27] Bermingham MJ, McDonald SD, StJohn DH, et al. Beryllium as a grain refiner in titanium alloys. *J Alloys Compd*. 2009;481:L20–L23.
- [28] Bermingham MJ, StJohn DH, Krynen J, et al. Promoting the columnar to equiaxed transition and grain refinement of titanium alloys during additive manufacturing. *Acta Mater*. 2019;168:261–274.
- [29] Gröbner J, Mirković D, Schmid-Fetzer R. Thermodynamic aspects of grain refinement of Al-Si alloys using Ti and B. *Mater Sci Eng A*. 2005;395:10–21.
- [30] Semiatin SL, Soper JC, Sukonnik IM. Short-time beta grain growth kinetics for a conventional titanium alloy. *Acta Mater*. 1996;44:1979–1986.
- [31] Xiong Z, Pang X, Liu S, et al. Hierarchical refinement of nickel-microalloyed titanium during additive manufacturing. *Scripta Mater*. 2021;195:113727.
- [32] Zhang D, Sun S, Qiu D, et al. Metal alloys for fusion-based additive manufacturing. *Adv Eng Mater*. 2018;20:1700952.