Materials and Design 144 (2018) 14–24

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Examination of the twinning activity in additively manufactured Ti-6Al-4V

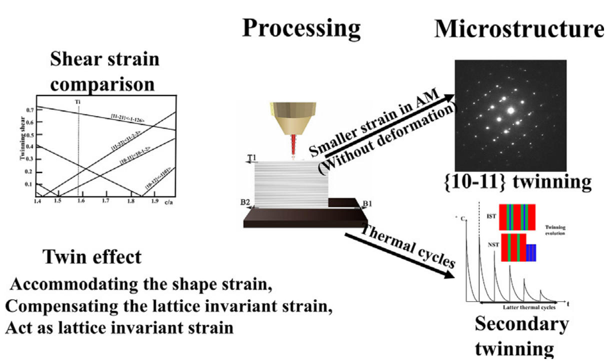
H.Z. Zhong [a], X.Y. Zhang [b], S.X. Wang [c], J.F. Gu [a,b,*]

[a] Institute of Materials Modification and Modelling, Shanghai Jiao Tong University, Shanghai 200240, China
[b] Shanghai Key Laboratory of Materials Laser Processing and Modification, Shanghai Jiao Tong University, Shanghai 200240, China
[c] Materials Genome Initiative Center, Shanghai Jiao Tong University, Shanghai 200240, China

HIGHLIGHTS

- {10-11} twins with small stress and strain are preferred in additively manufactured Ti-6Al-4V.
- {10-11} twins play threes effects of accommodating shape strain, assisting sheas strain and acting as LIS.
- The secondary twinning forms in the latter thermal cycles with small driving force to promote martensite transformation.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 3 November 2017
Received in revised form 4 February 2018
Accepted 5 February 2018
Available online 07 February 2018

Keywords:
Titanium alloys
Twinning modes
Secondary twin
Variant accommodation
Lattice invariant shear

ABSTRACT

This present paper investigates the dominant twinning mode and secondary twin via transmission electron microscopy at different positions of additively manufactured (AM) Ti-6Al-4V deposition wall fabricated by laser metal deposition (LMD). {10−11}⟨−1012⟩ twinning system is observed as the dominant twinning mode. Secondary twins, including the inserting secondary twin and neighboring secondary twin, are characterized at position with sufficient thermal cycle history. These twinning morphologies can be rationalized to some degree from the standpoint of the twinning effect and thermal condition in additive manufacturing. This work gets insight into the twinning evolution in additively manufactured Ti alloys.

1. Introduction

Additive manufacturing (AM), which includes laser metal deposition (LMD), selective laser melting (SLM) and selective electron beam melting (SEBM), is a new processing technique and often characterized for its material saving, precise formation and decreased defect properties. AM possesses the complex thermal condition with multiple thermal cycles, rapid cooling rate of 10^3–10^8 K/s and significant thermal gradient of 10^4–10^7 K/cm [1], which differentiate the as-deposited microstructure from the ingot or cast microstructure. Knowing that mechanical properties are relevant to microstructures, it is of interest to get insight into the microstructure of AM-ed components.

Generally speaking, the morphology can be classified into three groups from macro- to micro-scales. As shown in Table 1, the first group consists of the columnar, equiaxed or cellular grains. The second group consists of the martensite variants and self-morphology. The

* Corresponding author at: Institute of Materials Modification and Modelling, Shanghai Jiao Tong University, Shanghai 200240, China.
E-mail address: gujf@sjtu.edu.cn (J.F. Gu).

https://doi.org/10.1016/j.matdes.2018.02.015
0264-1275/

Table 1
There groups of morphologies in AM-ed components.

	Three groups of the morphologies in AM-ed metal		
Groups	The first group Macro-morphology	The second group Micro-morphology	The third group Substructures
Morphology	Equiaxed grains columnar grains	Martensite plates	Slip systems (dislocations)
	Cellular grains Dendrite	Martensite clusters	twinning
References	[2–4,6]	[7–9]	

third group consists of the substructures. It is admitted that the microstructure evolution in additively manufactured metallic alloys has been reported extensively. Most relevant reports involve in the first group of morphology. In particular, the columnar grains and equiaxed grains have been widely studied. Some researches relate to the second group of morphology. Our previous work has reported that these martensite plates cluster into the triangular morphology in order to accommodate the shape strain [8]. In contrast, very few literatures deal with the third group of morphology. The substructures in the third group mainly include slip systems (dislocations) and twins. To date, there is no systematic study on these substructures. Twins in Ti-6Al-4V processed by SLM and SEBM have been characterized in references [9,10]. However, these twins have not been analyzed in depth.

For the other thing, twinning activities in deformed Ti alloys have been studied extensively and deeply from the fundamental and practical viewpoints [12–16]. Some concepts, such as secondary twinning, de-twinning and re-twinning, are applied into this study. Twinning is an important and complex mechanism of accommodation in phase transformation. De-twinning, re-twinning and secondary twinning are involved in this accommodation mechanism. According to the previous study [26], re-twinning represents the activation of a new twin within existing twin. The twin variant could be same as or different from the pre-existing twin variant. If the variant is same as the pre-existing twin, it corresponds to de-twinning by the nucleation of a twin. If the variant is different from the pre-existing twin, it corresponds to secondary twinning through the nucleation of a new twin variant in the twin. Also, the de-twinning is characterized by the thickness reduction or disappearance of existing twin lamellae, with the twin lamellae rotating back to the matrix orientation [25,27]. Additionally, quantitative analyses, which take the shear strain into account, are successfully applied into explain twinning phenomena. Plastic deformation of hcp titanium is usually accommodated by a combination of dislocations and deformation twinning, as shown in Fig. 1. Due to its limited number of slip systems, the twinning plays a significant role in deformation.

The aim of the current investigation is to understand more clearly which twin systems are activated during AM and what roles they play in the corresponding martensite transformation. We employed a commonly used Ti alloy, i.e., Ti-6Al-4V to carry out this investigation. Transmission electron microscopy (TEM) is used to characterize twins. The $\{10-11\}\langle -1012\rangle$ twinning system is frequently observed. The corresponding effects of twinning are proposed. Twins are conducive to accommodate the shape strain, assist the shear strain of slip systems or act as the lattice invariant shear. Secondary twins are characterized. Phase transformation which occurs in the latter thermal cycles is featured by smaller driving force compared with the primary thermal cycle. Secondary twins occur in the latter thermal cycles and promote phase transformation.

2. Material and experimental methods

2.1. Material

A single-track deposition wall was fabricated by LMD (Fig. 2). A fiber laser with a 1070 nm wavelength was used as the heat source. The LMD process was protected by an argon shielding gas (purity of 99.99%) fed through a coaxial nozzle with a flow rate of 6 L/min. The processing parameters were as follows: laser power was 500 W, beam diameter was 2 mm, scanning velocity was 5 mm/s, powder feeding rate was 9 g/min. Samples were machined in super computer numerical control (CNC) wire cutting machine. As shown in Fig. 2, samples of the last layer T1 (top position) and first layer B1 and B2 (bottom position) were used for microstructure characterization.

2.2. Material characterization

A TESCAN LYRA3 SEM was used to examine microstructures from position B1, B2 and T1, respectively. JEM 2100 TEM instrument operated at 200 kV was used to characterize dislocations and twins. TEM samples were carefully prepared for microstructural characterization. TEM samples were obtained by a standard twin-jet electro-polishing technique with a solution of 60% methyl alcohol, 35% n-butanol and 5% perchloric acid at an applied potential of 30 V and at −35 °C. Tilting experiments in TEM were used to determine the Burgers vector of dislocations (slip systems). No contrast was expected if the Burgers vector b was normal to the operating reflection g, i.e., $g \cdot b = 0$, as shown in Table 2. From two independent diffraction conditions g_1 and g_2, the Burgers vector b could be determined uniquely.

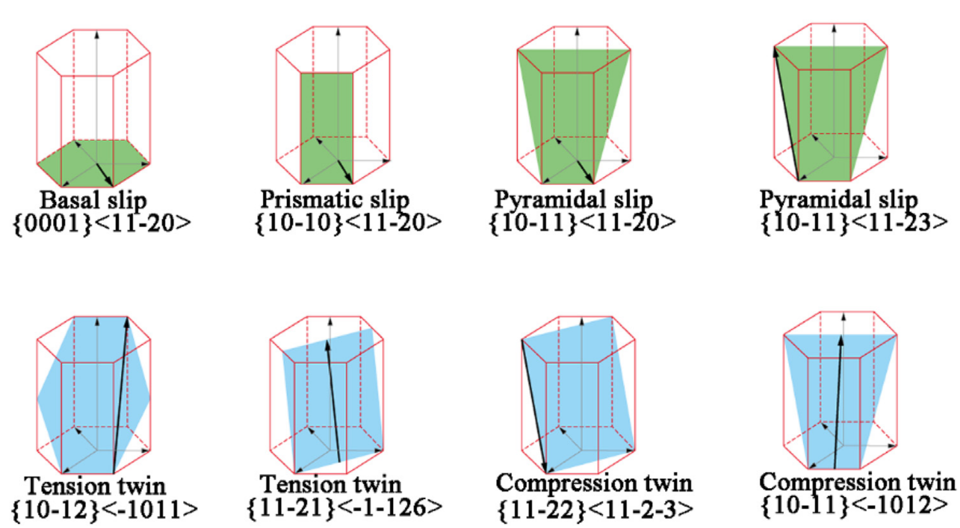


Fig. 1. Elements of the slip systems and twinning modes in Ti alloys.