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In-situ ultrafine three-dimensional quasi-continuous network microstructural TiB reinforced titanium matrix composites fabrication using laser engineered net shaping

Yingbin Hu [a], Bo Zhao [b], Fuda Ning [a], Hui Wang [a], Weilong Cong [a,*]

[a] Department of Industrial, Manufacturing, and Systems Engineering, Texas Tech University, Lubbock, TX 79409, USA
[b] College of Arts & Sciences Microscopy, Texas Tech University, Lubbock, TX 79409, USA

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ABSTRACT

In this study, we created an innovative ultrafine three-dimensional quasi-continuous network (3DQCN) microstructure by in-situ laser engineered net shaping (LENS) of TiB reinforced titanium matrix composites (TiB-TMCs). As a rapid solidification process, the LENS process enabled high degree of Ti grain refinement. The in-situ processed eutectic TiB aggregated at these Ti grain boundaries, forming the ultrafine 3DQCN microstructure. The microstructural characterizations of the ultrafine 3DQCN microstructure were investigated. Effects of the TiB reinforcement and the ultrafine 3DQCN microstructure on the mechanical performance of the fabricated parts were studied. The results demonstrated that the TiB-TMCs with the ultrafine 3DQCN microstructure exhibited superior mechanical properties.

1. Introduction

The low hardness and poor wear resistance of Ti and its alloys greatly restricted their wide applications under severe friction and wear conditions [1]. Fabrication of ceramic reinforced Ti matrix composites (TMCs) became a great solution to the problem above. Traditional ceramic reinforced TMCs manufacturing processes had high energy consumption and shape-restriction shortcomings [2–5]. In response to these problems, laser additive manufacturing technologies, mainly including selective laser melting (SLM) and laser engineered net shaping (LENS), were developed to produce ceramic reinforced TMCs [6–10]. Compared with SLM process, LENS process exhibited more advantages, such as capability of producing functionally graded materials, capability of surface modification, and small substrate deformation [8–10]. Therefore, LENS process was widely utilized to produce ceramic reinforced TMCs with superior mechanical properties over Ti.

Among different kinds of ceramic reinforcement materials (e.g. carbide [1,2], nitride [2,3], boride [2,4,6], etc.), TiB was considered as an ideal reinforcement that showed more specific advantages: (1) Reinforcement was chemically compatible with matrix [2]; (2) The similar densities and thermal expansion coefficients between TiB and Ti could reduce or even eliminate residual stresses at reinforcement-matrix interfaces [5]; and (3) A relatively small amount of reinforcement could largely increase the composites' modulus and strength [5]. Despite the improvements exhibited by LENS processed TiB reinforced TMCs (TiB-TMCs), problems resulted from lowered fracture toughness and ductility still existed [2].

In this investigation, innovative ultrafine three-dimensional quasi-continuous network (3DQCN) microstructural TiB-TMCs were successfully fabricated for the first time by in-situ LENS process. It was reported that the generation of 3DQCN microstructure could improve fracture toughness [4]. The specific 3D microstructure enabled isotropic reinforcement in all directions and was beneficial to uniformly load transferring and distributing [2]. Thus, in this work, formation mechanism of the ultrafine 3DQCN will be investigated. In addition, effects of ultrafine 3DQCN and TiB reinforcement on the mechanical performance of the fabricated parts will be evaluated.

2. Experiments and measurements procedures

The bulk parts were fabricated by an Optomec LENS system. Based on preliminary results, the powder feeding rate, deposition head scanning speed, layer thickness, and hatch distance were fixed at optimal values of 0.028 g/s, 11 mm/s, 0.42 mm, and

* Corresponding author.
E-mail address: weilong.cong@ttu.edu (W. Cong).

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0.38 mm, respectively. Two levels of laser power (125 W and 200 W) were selected for comparisons. The parts with dimensions of 8 mm × 8 mm × 20 layers were for microhardness test and those with dimensions of Φ6 mm × 15 layers were for compressive test.

The CP-Ti powders with the average particle size of 150 μm and B powders with the average particle size of 2 μm were used. For TiB-TMCs fabrication, the weight ratio of 98.4:1.6 between Ti and B powders was adopted for the purpose of generating eutectic TiB whiskers, being beneficial to fracture toughness and bending strength [5]. Prior to LENS process, the CP-Ti and B powders were mixed by planetary ball mill machine at rotation speed of 200 rpm, ball-to-powder weight ratio of 5:1, and milling time of four hours, in order to well distribute B powders into Ti powders without significant size reduction and Ti-B reaction.

Microstructure characterizations of the fabricated parts were observed using the scanning electron microscope (SEM), integrated with an electron backscatter diffraction (EBSD) detector. Before observation, the parts were etched with Kroll's Reagent (HF: 3%; HNO_3: 6%; and water: balance) for ten seconds.

Microhardness tests were performed on a Vickers hardness tester with 9.8 N load and ten seconds dwelling time. Ten measurements were conducted on each part. For each kind of fabrication condition, compressive tests were conducted four times at a constant cross-head speed of 0.005 mm/s by using a tensile tester.

3. Experiment result and discussion

3.1. Formation mechanisms

The 3DQCN microstructure was reported in fabrication by reactive hot pressing (RHP, sintering) [2,4,5] and casting [3]. In RHP process, as illustrated in Fig. 1(a), Ti particles and relatively finer TiB_2 particles (for providing B element) were premixed to make the rigid TiB_2 particles embedded onto the outside surfaces of Ti particles [2]. With the sintering process of RHP, outer boundaries of Ti particles were melted, generating atomic bonding to join Ti particles together. In the meantime, the chemical reaction between Ti and TiB_2 ($Ti + TiB_2 \rightarrow 2TiB$) took place at the boundaries of Ti particles and generated TiB [11]. The TiB whiskers formed, grew, and connected at most boundaries of Ti particles, forming 3DQCN microstructure. The unit size, which was around 50–200 μm, and the shape of the network microstructure were determined by the original Ti particles [4].

The formation mechanism of 3DQCN microstructure in casting process, as shown in Fig. 1(b), was different from that in RHP (sintering) process. In casting process, the premixed Ti and B powders were fully melted and reacted for formation of TiB [12]. During solidification, βTi nuclei were firstly formed/separated from the liquid and then grown into crystal grains. On account of extremely low solid solubility of B in Ti matrix, the newly formed TiB was expelled from βTi nuclei to the surrounding liquid, aggregating at the boundaries of Ti crystal grains [12]. Due to long-time crystallization, the slow casting solidification process resulted in relatively large 3DQCN unit sizes of around 100–200 μm [3].

The aforementioned conventional processes (e.g. RHP and casting) fabricated parts exhibited worse reinforcement aggregation uniformity and coarser microstructure [5]. It was reported that grain refinement would significantly enhance strength and toughness [5]. In this investigation, a refined 3DQCN microstructure was successfully formed by in-situ LENS process. Fig. 1(c) shows the formation mechanism of 3DQCN microstructure in LENS process. With the small-size laser spot, the molten pool formed could be finely controlled, resulting in uniform distributions of energy input and B element. Similar to casting process, the premixed Ti and B powders were fully melted in the molten pool due to laser radiation in LENS process. McCartney et al. [13] reported that the rapid solidification processes would cause a significant reduction in grain size. As a rapid solidification process, the LENS process enabled high undercooling degree, leading to an increased nucleation rate and more nuclei [13]. Since each nucleus would grow into one grain, a great amount of Ti grains with ultrafine grain size could be expected.

3.2. Microstructural characterizations

Fig. 2 shows a stereo corner image taken from a fabricated part and corresponding microstructures on each side of the corner. Similar network-microstructure morphologies can be observed for all three sides. The QCN microstructure, forming along the Ti grain boundaries, was spatially distributed as a 3DQCN microstructure. The bright boundaries were identified by EBSD as orthorhombic

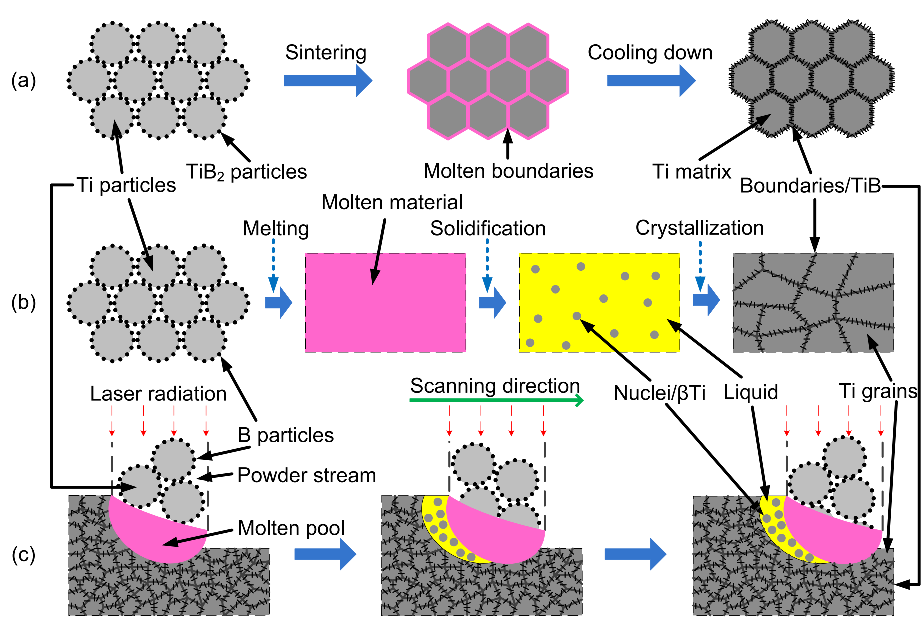

Fig. 1. Formation mechanisms of 3DQCN microstructure in (a) RHP (sintering), (b) casting, and (c) LENS processes.