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Effect of TiC particle size on the microstructure and tensile properties of TiC_p/Ti6Al4V composites fabricated by laser melting deposition

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ABSTRACT

TiC particle (TiC_p) reinforced Ti6Al4V (TiC_p/Ti6Al4V) titanium matrix composites with coated powders (TiC: <10 μm) and small-sized (TiC: 25–45 μm), medium-sized (TiC: 45–75 μm) and large-sized (TiC: 75–100 μm) mixed powders were produced by laser melting deposition (LMD). The influence of TiC particle size on the microstructure and tensile properties of composites was researched. The granular and chain shaped eutectic in-situ TiC phases distributed homogeneously in the composites with coated powders. Besides the eutectic TiC phases, the unmelted TiC particles existed in composites with mixed powders. The number of granular eutectic TiC phases reduced when the TiC particles size increased. The formation mechanism of the microstructure of composites was discussed in depth. The tensile properties of composites with small-sized and medium-sized mixed powders were similar, which were better than those of composites with large-sized mixed powders but were worse than those of composites with coated powders. Compared with that of composites with large-sized mixed powders, the tensile strength (1231.3 MPa) and elongation (2.12%) of composites with coated powders were improved by nearly 4.6% and 259.3%, respectively. This was attributed to the existence of more granular eutectic TiC phases that were difficult to crack, the homogeneous distribution of eutectic TiC phases and the strong bonding of the interfaces between eutectic TiC phases and matrix. The premature damage of the larger unmelted TiC particles during the LMD process or at the initial stage of plastic deformation and the decohesion of the interface between larger TiC particle and matrix deteriorated the tensile properties of the composites fabricated with large-sized mixed powders. The fracture mechanism of composites with coated powders was controlled by eutectic TiC phases cracking followed by ductile damage of matrix. However, the fracture mechanism of composites with mixed powders was controlled by unmelted TiC particles cracking followed by eutectic TiC phases cracking and then by ductile damage of matrix.

1. Introduction

Titanium matrix composites (TMCs) reinforced with discontinuous ceramic particles have been widely applied in aeronautical fields in recent years, because of their isotropic properties and low cost [1,2]. Ti6Al4V alloys possess the comprehensive performances such as good corrosion resistance and excellent mechanical properties, which are usually used as the metal matrix of TMCs [3,4]. Ti6Al4V alloys can be strengthened by hard ceramics such as WC [5], TiB [6] and TiC [7] particles to manufacture TMCs. Among the above reinforcements, TiC particles are regarded as preferred reinforcements for Ti6Al4V matrix composite due to their similar density to titanium, high hardness, outstanding thermal stability and excellent compatibility with titanium alloy [8,9].

Laser melting deposition (LMD) is a laser processing method that can produce the bulk materials through layer-by-layer additions including melting and solidification process of materials [10]. The metal matrix powders and reinforcement powders can be simultaneously fed into the molten pool generated by laser through LMD technology, so the composites can be fabricated [11]. Compared with those conventional methods that manufacture the composites such as in-situ casting and powder metallurgy [12,13], the merit of LMD is that it can realize the fabrication of near-net-shape composites that are difficult to process in a short time [14]. Therefore, TMCs are able to be fabricated by LMD technology efficiently.

Some researchers have manufactured TiC particle reinforced titanium matrix composites by LMD technology, and they have investigated the microstructure and properties of TMCs. Liu et al. [15] mentioned that TiC particles would be melted during LMD process. However, they found that the TiC particles with large size

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were difficult to be melted completely, and most of TiC particles with the size smaller than 45 μm could be melted greatly. Wang et al. [16] and Liu et al. [17] demonstrated that the primary and eutectic TiC phases that were different from the original TiC particles would form during LMD process. They found that the TiC would cluster in some local regions of composites when TiC volume fraction was high. The strength and ductility of composites decreased rapidly when the TiC volume fraction exceeded 10%. Because a large number of dendritic primary TiC and unmelted TiC particles would make the composites damage prematurely when the TiC volume fraction was high. Therefore, the reinforcement content of most TMCs rarely exceeded 10% [18]. Gu et al. [19] stated that the interfacial bonding ability between the larger-sized unmelted ceramic particles and metal matrix after laser melting deposition was generally limited. The weak interfaces between ceramic particles and metal matrix were easy to crack during the tensile tests, which led to the premature damage of titanium matrix composites [20]. Sun et al. [21] fabricated the in-situ TiC reinforced titanium matrix composites by hot-press sintering and hot rolling, and they studied that the interfaces between in-situ reinforcements and matrix were clean and owned a good bonding. It has been found that the size of ceramic particle affected the microstructure and mechanical properties of metal matrix composites. Choi et al. [22] produced the (TiB + TiC) reinforced TMCs by investment casting and researched the influence of B_4C size on the tensile properties of the composites. The results showed that the tensile properties of in-situ (TiB + TiC) reinforced TMCs by fine B_4C were higher than those of composites by coarser B_4C. That's because the size of in-situ synthesized reinforcements by fine B_4C was smaller and the distribution of these reinforcements in the matrix was more homogeneous. Sun et al. [23] investigated the influence of SiC particle size on the microstructure and mechanical properties of SiC/Al by powder metallurgy. The results showed that clustered and large-sized SiC particles were prone to obtain the voids, which resulted in the significant decrease of the mechanical properties of the SiC/Al. Chaubey et al. [24] found that when the Mg-7.4%Al particle size decreased, both the tensile strength and ductility of Mg-7.4%Al/Al composites increased due to the reduced particle fracturing.

These previous research proved that refining the size of reinforcements improved the mechanical properties of composites, and the eutectic TiC phases could form during the laser melting deposition process. However, few studies have been conducted to research the effect of original TiC powder size on the microstructure and tensile properties of the TiC particle (TiC_p) reinforced Ti6Al4V (TiC_p/Ti6Al4V) titanium matrix composites manufactured by laser melting deposition technology in the previous literature. Although there have been several attempts to study the influence of ceramic reinforcement size on the tensile properties of titanium matrix composites via the conventional approach such as investment casting, the mechanism of the microstructural evolution of composites by LMD was different from that of the composites by the conventional method. Because the cooling rate of composites by LMD was much faster than that of composites by the conventional materials process. Furthermore, the previous research mainly focused on the effect of unmelted TiC particles on the tensile properties of titanium matrix composites. Nevertheless, insufficient work about the contribution of the in-situ eutectic TiC phases to the tensile properties of TiC_p/Ti6Al4V composites by LMD has been presented in the previous research. The purpose of this paper was to improve the weak tensile properties of TiC_p/Ti6Al4V composites fabricated by large-sized TiC particles through manufacturing the in-situ TiC reinforced Ti6Al4V composites by LMD. In addition, the mechanism of microstructure formation and fracture of composites with different original TiC particle size was elucidated in depth to obtain high-performance laser melting deposited TiC_p/Ti6Al4V composites.

In this present paper, TiC_p/Ti6Al4V composites with 5 vol.% TiC were fabricated by LMD technology using Ti6Al4V powders and TiC powders with different particle size. Firstly, the phases and microstructure of TiC_p/Ti6Al4V with different TiC particle size were investigated. Secondly, the correlation between the different microstructure and the tensile properties of TiC_p/Ti6Al4V was analyzed. At last, the fracture mechanism of TiC_p/Ti6Al4V with different TiC particle size was discussed.

2. Experimental procedure

The matrix alloy materials used in this research were Ti6Al4V powders with nearly spherical shape and size diameter distribution of 45–100 μm. The reinforcement materials were irregular shaped TiC powders with four different particle size. They were ultrafine TiC powders with the size less than 10 μm, and three kinds of coarse TiC powders with the size ranging from 25 μm to 45 μm, 45 μm to 75 μm and 75 μm to 100 μm, respectively. The micrographs of TiC powders and Ti6Al4V powders are exhibited in Fig. 1. In order to overcome the difficulty of ultrafine TiC powders delivery, the ultrafine TiC powders should be coated in the surface of Ti6Al4V powders, and then delivered together with Ti6Al4V powders. The volume fraction of ultrafine TiC powders was 5%. In order to overcome the bad flowability of irregular shaped TiC powders and ensure the Ti6Al4V and TiC powders mix uniformly, the powders mixtures containing Ti6Al4V powders and 5 vol% TiC powders with the size ranging from 25 μm to 45 μm, 45 μm to 75 μm and 75 μm to 100 μm were premixed. The schematic diagram of the process of mixing powders is described in Fig. 2. The powders mixtures containing Ti6Al4V powders and TiC powders with 5% volume fraction were mixed through low energy ball milling in a QM-3SP2 ball mill. The ultrafine TiC powders were coated homogeneously around the Ti6Al4V powder surface and the coarse TiC powders were distributed homogeneously in the gap between the Ti6Al4V powders after the ball milling process, as described in Fig. 3. In order to distinguish the powders mixtures conveniently, the Ti6Al4V powders coated with ultrafine TiC powder particles were named as coated powders, and the mixed TiC/Ti6Al4V powders with TiC size ranging from 25 μm to 100 μm were named as mixed powders in this paper. The mixed powders with TiC size ranging from 25 μm to 45 μm, 45 μm to 75 μm and 75 μm to 100 μm were referred to as small-sized mixed powders, medium-sized mixed powders and large-sized mixed powders, respectively. The substrate used in this experiment was an annealed Ti6Al4V plate (8 mm in thickness), which was polished and then ultrasonically degreased with alcohol for 30 min prior to the laser melting deposition process. The experiment was performed using an YLS-5000 fiber laser (wavelength 1064 nm) processing system, which was integrated with a KUKA robot and a coaxial nozzle. A GTV powder feeder system was used to deliver the pre-mixed powders via the carrier gas. During the laser melting deposition process, as shown in Fig. 4, the coated powders and mixed powders were delivered through the coaxial nozzle into the melt pool and then solidified quickly to form the deposited layer. After the deposition of each layer, the distance of the coaxial nozzle moving up in Z-direction was the same as the thickness of each layer (about 0.8 mm). The experiments were performed in a chamber using argon gas as the shielding gas to prevent the melt pool from oxidation. The optimized process parameters were adopted to deposit each layer. The laser power, the laser scanning speed, the gas flow rate and the laser beam diameter on the substrate were kept at 500 W, 0.3 m/min, 5 l/min and 2.3 mm, respectively. Wall-like samples with ten layers were manufactured after