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# Nanocrystalline TiC reinforced Ti matrix bulk-form nanocomposites by Selective Laser Melting (SLM): Densification, growth mechanism and wear behavior

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ABSTRACT

Selective Laser Melting (SLM) Additive Manufacturing (AM) process was used to produce nanocrystalline TiC reinforced Ti matrix bulk-form nanocomposites. The influence of "volumetric energy density" ($\varepsilon$) on densification activity, microstructural feature, nanohardness, and wear behavior of SLM-processed parts was studied. The densification levels of TiC/Ti parts remained above 97% as $\varepsilon \geqslant 120\ J/mm^3$. A further decrease in $\varepsilon$ lowered the densification rate, due to the occurrence of balling effect. The TiC reinforcement experienced an interesting morphological change from the coarsened dendritic TiC (360 $J/mm^3$) to the accumulated whisker-structured TiC (180 $J/mm^3$) and to the uniformly dispersed nanoscale lamellar TiC ($\leqslant$120 $J/mm^3$). As $\varepsilon$ of 120 $J/mm^3$ was properly settled, the dynamic nanohardness (90.9 GPa) and elastic modulus (256 GPa) of SLM-processed TiC/Ti nanocomposites showed respectively ~22.7-fold and ~2.4-fold increase upon that of the unreinforced Ti. A uniform distribution of friction coefficient with a low average value <0.2 was obtained, leading to a considerably reduced wear rate of $1.8 \times 10^{-7}\ mm^3/(Nm)$. A disappearance of nanostructured TiC reinforcement at an elevated $\varepsilon$ of 360 $J/mm^3$ lowered the mechanical properties of TiC/Ti part consisting of the coarsened dendritic TiC.



## 1. Introduction

Titanium and its alloys, due to high specific strength, sufficient stiffness, and excellent corrosion resistance, have been widely used in the aeronautical, chemical, and defense industries [1–3]. However, the limited wear resistance of titanium is a serious concern for the application environments where abrasive and erosion phenomena exist. Considerable research attempts, accordingly, have focused on the application of various surface modification techniques to prepare ceramic particle reinforced titanium matrix composites (TMCs) coatings to improve surface properties of titanium [4]. In particular, laser processing methods such as laser melt injection [5], laser cladding [6], and laser surface alloying [7] have demonstrated a considerable efficiency in preparing high-performance TMCs coatings. Laser processing normally offers high heating/cooling rates ($10^3$–$10^8$ K/s) for the development of non-equilibrium phases with fine-grained microstructures and novel properties [8]. Furthermore, TMCs have been realized as bulk-form components, typically through powder metallurgy (PM) [9] and casting [10] methods, and afford more significant advantages in industrial applications.

For conventional particle reinforced TMCs, either as coatings or in bulk form, the micrometer scale ceramic particles such as SiC [11], TiB [6], and WC [12] are commonly used, varying from a few micrometers to several tens of micrometers. These relatively large-sized ceramic reinforcing particles are normally unmelted or partially melted during conventional processing. However, due to a considerably poor wettability between ceramics and metals, the interfacial bonding ability between the remaining ceramic particles and metal matrix is generally limited, especially as the larger-sized ceramic particles are used. The weak ceramic/metal interfaces are prone to crack during mechanical loading, resulting in a premature failure of TMCs [13].

It is widely recognized that the ceramic particle size has a strong effect on strength, ductility, and failure mode of TMCs. Generally, decreasing the ceramic particle size can lead to a substantial improvement in mechanical properties of TMCs, e.g., enhanced strengthening and reduced particle cracking [14,15]. Recent research attempts have ascertained that the mechanical performance of TMCs can be further enhanced by decreasing the size of

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ceramic particles from micrometer to nanometer level [16]. Such materials are termed as nanocomposites [17]. Nanocomposites differ from conventional composites due to the particularly high surface-to-volume ratio of ceramic reinforcement. A nanoscale dispersion of ceramic phase with controlled nanostructures in TMCs tends to introduce novel behaviors that are absent in the unreinforced titanium. To obtain desired properties of nanocomposite TMCs, especially in bulk form, the sufficiently high densification response of TMCs is of primary importance. On the other hand, in bulk parts condensed from ultrafine nanopowders, the uncontrolled agglomeration of nanoparticles due to a considerably large van der Waals attractive force may result in microstructural inhomogeneity and even disappearance of original nanostructures. Therefore, following a more microscopic criterion, the nanoscale ceramic reinforcement must avoid grain coarsening during processing and, meanwhile, distribute uniformly throughout the matrix.

Selective Laser Melting (SLM), as a newly developed Additive Manufacturing (AM) process [18], enables quick fabrication of three-dimensional parts with any complex shapes directly from powders [19]. SLM builds parts in a layer-by-layer manner by selectively fusing and consolidation of thin layers of loose powder using a high-energy laser beam. The application of SLM in production of nanocomposite parts is expected to create new technological opportunities, because of the potential for developing novel nanocomposites with unique mechanical properties. SLM is processed based on a full melting/solidification mechanism, which means that even high-melting-point ceramics are melted completely during processing. Significant research efforts are required to study how the nanostructures of ceramic reinforcement are crystallized and developed during SLM. The underlying role of microstructural development in the variation of mechanical properties of SLM-processed nanocomposite parts should be determined. In this work, bulk-form TiC/Ti nanocomposites with unique nanostructures of reinforcement were successfully prepared by SLM. The microstructural evolutions under different SLM conditions were studied and the mechanical properties such as densification rate, microhardness, and wear resistance were assessed, with an aim to establish a relationship of process, microstructure, and mechanical performance of TMCs by SLM.

## 2. Experimental procedures

### 2.1. Powder preparation

The 99.7% purity Ti powder with a spherical shape and a mean particle diameter of 22.5 μm (Fig. 1a) and the 99.0% purity TiC nanopowder with a near spherical shape and an average particle size of 50 nm (Fig. 1b) were used. The TiC/Ti nanocomposite powder system containing 15 wt.% TiC was milled in a Pulverisette 4 vario-planetary mill (Fritsch GmbH, Germany), using a ball-to-powder weight ratio of 5:1, a rotation speed of main disk of 200 rpm, and a milling duration of 4 h. The TiC nanoparticles were homogeneously dispersed around the Ti particle surface after milling (Fig. 1c).

### 2.2. SLM processing

The SLM system consisted mainly of a YLR-200 ytterbium fiber laser with a power of ~200 W and a spot size of 70 μm, an automatic powder layering apparatus, an inert argon gas protection

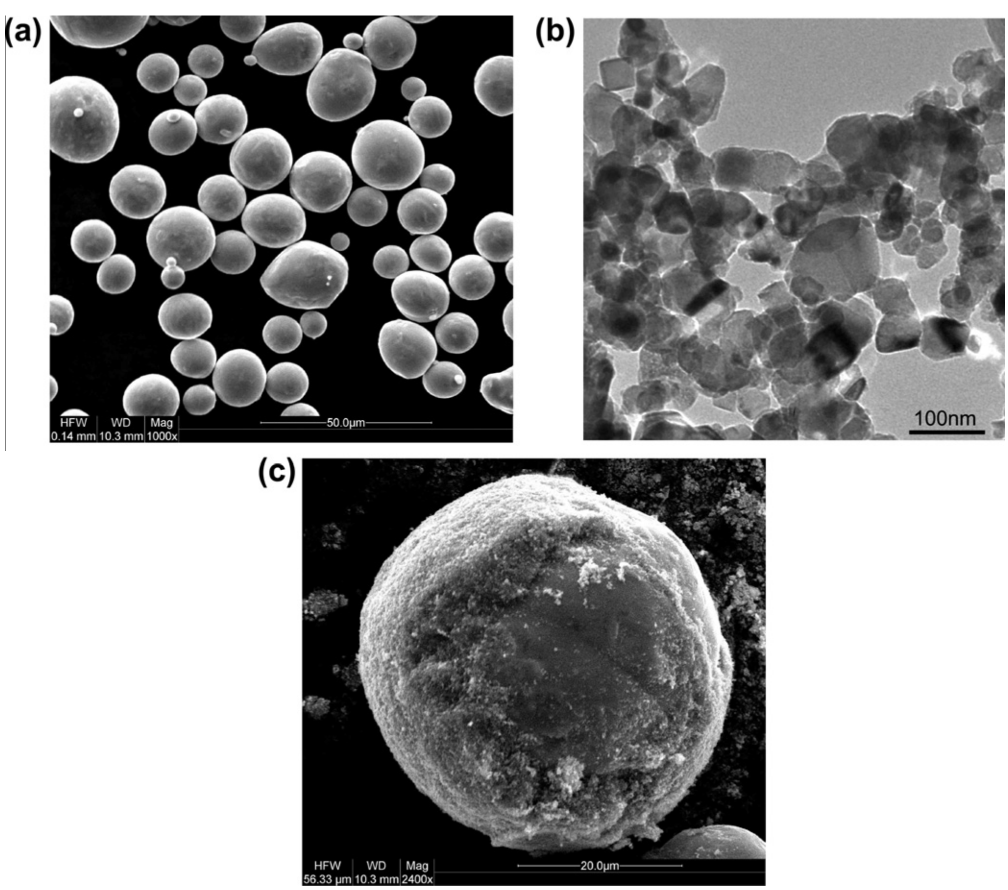


**Fig. 1.** Microstructures of the starting Ti powder (a), TiC nanopowder (b), and the homogeneously mixed TiC/Ti powder.