Laser Metal Deposition Additive Manufacturing of TiC Reinforced Inconel 625 Composites: Influence of the Additive TiC Particle and Its Starting Size

In this study, laser metal deposition (LMD) additive manufacturing was used to deposit the pure Inconel 625 alloy and the TiC/Inconel 625 composites with different starting sizes of TiC particles, respectively. The influence of the additive TiC particle and its original size on the constitutional phases, microstructural features, and mechanical properties of the LMD-processed parts was studied. The incorporation of TiC particles significantly changed the prominent texture of Ni–Cr matrix phase from (200) to (100). The bottom and side parts of each deposited track showed mostly the columnar dendrites, while the cellular dendrites were prevailing in the microstructure of the central zone of the deposited track. As the nano-TiC particles were added, more columnar dendrites were observed in the solidified molten pool. The incorporation of nano-TiC particles induced the formation of the significantly refined columnar dendrites with the secondary dendrite arms developed considerably well. With the micro-TiC particles added, the columnar dendrites were relatively coarsened and highly degenerated, with the secondary dendrite growth being entirely suppressed. The cellular dendrites were obviously refined by the additive TiC particles. When the nano-TiC particles were added to reinforce the Inconel 625, the significantly improved microhardness, tensile property, and wear property were obtained without sacrificing the ductility of the composites.

Keywords: laser metal deposition, additive manufacturing, Ni-based superalloy, reinforcement, dendrite growth, mechanical properties

1 Introduction

Inconel 625 is a solid solution or/and precipitation strengthened Ni-based superalloy [1], which is extensively used in aviation, aerospace, chemical, and petrochemical industries due to its extraordinary properties such as excellent toughness, ductility, oxidation resistance, and corrosion resistance at high temperatures and pressures [2, 3]. Since the development of modern industries has a higher requirement for the performance of engineering materials, the specific strength, hardness, tensile strength, and wear resistance of metals and alloys can be improved significantly by means of the reinforcement of the harder and stiffer ceramic particles [4, 5]. Among these particle reinforcements, such as SiC [6], TiC [7], WC [8], and VC [8], TiC is the commonly used reinforcement for the formation of Ni-based metal matrix composites (MMCs) due to the high melting point, high hardness, and excellent wear resistance of TiC. In this situation, the incorporation of TiC particles into Inconel 625 is able to yield the even comprehensive and improved mechanical properties of Ni-based MMCs.

Typically, the ceramic particle reinforced MMCs have been fabricated by conventional manufacturing methods such as casting, forging, and powder metallurgy. Nevertheless, the conventional manufacturing processes still have the following technical problems: (i) The low cooling rates associated with these processes result in the formation of the coarsened grain structures and attendant poor mechanical properties; (ii) the limited wetting characteristics are induced by the insufficient melting of materials in the case of the relatively lower operating temperature, which causes the interfacial bonding defects (e.g., interfacial microcracks); and (iii) ceramic particles have a large difference with the metal matrix in densities, which is prone to generate the severe agglomeration of reinforced particles and, accordingly, to decrease the microstructural homogeneity and resultant mechanical properties [9]. In order to solve these problems, laser metal deposition (LMD), as a newly developed additive manufacturing (AM) process, has become a promising manufacturing route for the preparation of TiC/Inconel 625 MMC components. LMD is an advanced computer-aided AM technology, which combines rapid prototyping and laser cladding [10]. LMD is based on a novel materials incremental manufacturing philosophy, which is different to the conventional material removal method. LMD can fabricate near net-shaped components in a layer-by-layer manner according to the computer-aided design (CAD) model of a desired component, using a computer-controlled multi-axis handling machine and a high power laser as the energy source [11, 12]. The powder delivery system is composed of an inert gas assisted powder feeder that delivers the powder into the molten pool via a specially designed coaxial nozzle [13]. The nozzle is adjusted accurately to ensure that the powder streams can converge at the same point on the focused laser beam. LMD provides a powerful capability in the formation of complex components, demonstrating a high degree of flexibility in the control of the compositions, microstructures, and performance of the deposited components [14]. During the LMD process, the molten materials undergo a rapid heating and cooling cycle, which produces a considerably refined microstructure that differs substantially from the materials processed by the traditional methods [15]. The LMD AM technology has demonstrated the important prospects in the fields of aviation and aerospace, attracting a wide range of concerns from research and application departments.

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1 Corresponding author.

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Recently, there are some successful applications of LMD process in manufacturing TiC particle reinforced Inconel alloy parts with sound mechanical performance [16–20]. The effects of laser processing parameters and contents of additive TiC particles on the LMD behavior and microstructural development of TiC/Inconel 625, 690, and 718 composite parts have been studied. Nevertheless, the influence of TiC particle characteristics on the microstructural development of LMD-processed TiC/Inconel 625 composite parts, which plays a fundamental role in determining the composite properties, is still not clear and, therefore, is in an urgent demand to study. It is important to understand the specific contribution of the starting TiC particles with different physical properties to the microstructures and mechanical properties of the LMD-processed TiC/Inconel 625 composite parts. In the present work, LMD was applied to process the unreinforced pure Inconel 625 alloy and the TiC/Inconel 625 composites with the nano-TiC and micro-TiC reinforcing particles, respectively. The influence of the additive TiC particle and its starting size on the resulting phases of composites, microstructural features of molten pool, growth mechanisms of dendrites, and final properties was studied. The numerical simulation of the temperature evolution within the molten pool was also performed to provide a theoretical basis for the investigation of the influencing mechanism of the starting TiC particle size.

2 Experimental Procedures

2.1 Powder Materials. The raw materials used in this study included the gas atomized and spherical Inconel 625 powder with the particle size distribution of 15–45 μm (Fig. 1(a)), the polygonal TiC micropowder with an average particle size of 2–5 μm (Fig. 1(b)), and the near-spherical TiC nanopowder with an average particle size of 40 nm (Fig. 1(c)). The chemical compositions of Inconel 625 powder were 20–23 Cr, 8–10 Mo, 5 Fe, 3.15–4.15 Nb, 1 Co, 0.5 Mn, 0.5 Si, 0.4 Ti, 0.4 Al, 0.1 C, 0.015 S, 0.015 P, and balance Ni (in wt. %). According to the weight ratio of 97.5:2.5, the nano-TiC/Inconel 625 and micro-TiC/Inconel 625 were homogeneously mixed, respectively, using a Fritsch Pulverisette 6 planetary ball mill with a ball-to-powder weight ratio of 5:1, a rotation speed of the main disk of 200 rpm, and a milling time of 4 h.

2.2 LMD Process. The LMD process was carried out using a TRUMPF Nd:YAG laser system with a maximum output power of 3 kW and a focused spot size of 0.6 mm, integrated with a powder feeder system having a coaxial powder nozzle. When the specimens were to be built, a C45 carbon steel substrate was fixed on the building platform and leveled. Subsequently, the pure Inconel 625, nano-TiC/Inconel 625, and micro-TiC/Inconel 625 powders were injected into the molten pool through the coaxial nozzle with a powder feeding rate of 2.4 g/min, respectively. A set of LMD processing parameters (i.e., laser power $P$ of 800 W, scanning speed $v$ of 500 mm/s, and layer thickness $d$ of 1 mm) were used based on process optimization in order to obtain the sufficiently high densification level. The samples with dimensions of 45 mm × 25 mm × 10 mm were deposited. Three samples were deposited per batch for investigation using Inconel 625, nano-TiC/Inconel 625, and micro-TiC/Inconel 625 powders, respectively, and a total of three batches production was conducted.

2.3 Characterization of Microstructures and Mechanical Properties. The cross sections of the LMD-processed samples for metallographic examinations were cut, ground, and polished according to the standard procedures. To reveal the etched
microstructures, an etchant consisting of HCl (10 ml) and H₂O₂ (3 ml) was used with an etching time of 3 s. The procedures were based on the national standard GB/T 13298-1991 for metallographic specimen preparation and examination. Phase identification of the LMD-processed parts were performed by a D8 advance X-ray diffractometer (XRD; Bruker AXS GmbH, Karlsruhe, Germany) with Cu Kα radiation (wavelength λ = 0.15418 nm) at 40 kV and 40 mA, using a continuous scan mode. The microstructures were characterized with an optical microscopy (OM) and a Hitachi S-4800 field emission scanning electron microscopy (FE-SEM; Hitachi, Tokyo, Japan) at an accelerating voltage of 3 kV. The Vickers hardness was measured using a HXS-1000A microhardness tester (AMETEK, Shanghai, China) at a load of 0.2 kg and an indentation time of 20 s. The wear properties on the cross sections of the LMD-processed specimens were estimated by the dry sliding wear tests conducted in a HT-500 bearing steel ball of 3 mm diameter with a mean hardness of HRC 60 was taken as the counterface material, using a test load of 430 g. The friction unit was rotated at a speed of 560 rpm for 15 min and the rotation radius was 2 mm. The wear volumes (V) of specimens were determined gravimetrically using

\[ V = \frac{M_{\text{loss}}}{\rho} \]  

where \( M_{\text{loss}} \) was the weight loss of samples after tests and \( \rho \) was the density. The wear rate (\( \omega \)) was calculated by

\[ \omega = \frac{V}{WL} \]  

where \( W \) was the contact load and \( L \) was the sliding distance. The specimens for tensile tests were prepared based on the national standard GB/T228-2010 with the following dimensions: overall length of 30 mm, gauge length of 13.5 mm, width of 4.5 mm, and thickness of 3 mm (Fig. 2). The tensile tests were conducted at room temperature in a CMT5205 testing machine (MTS Industrial Systems, China) at a strain rate of 1 \times 10^{-4} \text{s}^{-1}.

3 Results and Discussion

3.1 Phase Identification. The typical XRD spectra of the LMD-processed TiC/Inconel 625 composites with the different particle sizes of TiC reinforcement are depicted in Fig. 3. The strong diffraction peaks corresponding to face-centered cubic Ni–Cr matrix phase and the relatively weak diffraction peaks for TiC reinforcing phase were detected. The weak intensities of TiC diffraction peaks were attributed to a small quantity of the additive TiC particles. Nevertheless, the incorporation of TiC significantly changed the XRD patterns of Ni–Cr matrix phase. With regard to the unreinforced Inconel 625, the (200) diffraction peak was strongest, while the (111) diffraction peak was relatively weak. For the TiC/Inconel 625 composites, the Ni–Cr phase exhibited the prominent (111) texture and the weak (200) texture, regardless of the initial sizes of the additive TiC particles. It indicated that when the TiC particles were added, the preferred orientation of Ni–Cr texture altered. It is known that when the laser beam with a high energy interacts with the powder, the energy is absorbed rapidly by the powder. The subsequent cooling of the molten pool is accomplished primarily by the conduction of heat through the substrate or the previously deposited layer which acts as a heat sink and leads to a unidirectional local heat flow [21]. The physical properties of TiC are distinctly different from Inconel 625. Due to the higher thermal conductivity of TiC (23 W/(m·°C) at 20°C [22]) compared with that of Inconel 625 (9.8 W/(m·°C) at 20°C [23]), the heat dissipation rate of the molten pool is elevated with the addition of TiC, inducing the change of the local heat and mass transfer condition of the pool. The altered solidification conditions of the molten pool including the solute, composition, temperature, and velocity distributions result in the preferred texture orientation of Ni–Cr γ phase changing from (200) into (111). A careful comparison revealed that the intensities of Ni–Cr γ phase showed a significant decrease with the addition of TiC particles into the pure Inconel 625, which demonstrated that the incorporation of TiC refined the crystals and microstructures of γ matrix phase in the LMD-processed composites. Furthermore, with the decrease in original size of TiC particles, the intensities of Ni–Cr γ phase exhibited a tendency of reduction, which verified the formation of the significantly refined microstructures in this instance.

3.2 Effect of TiC Particle on Dendrite Growth of Matrix.

The OM images showing the evolutions of cross-sectional microstructures of the LMD-processed Inconel 625 and TiC/Inconel
625 composites with TiC particles of different initial sizes are exhibited in Fig. 4. The cross sections of the LMD-processed samples are along deposition direction, i.e., parallel to the building direction. Generally, Fig. 4 revealed the layerwise morphology of the molten pools, which indicated that the LMD process produced components in a layer-by-layer manner. The layerwise shape matched the Gaussian distribution of laser energy. Most of energy was focused on the laser beam center, leading to the deep melting in the center of the molten pool and the shallow melting at the edge of the pool. During the LMD process, the adjacent two layers or scan tracks were overlapped, through which the previously melted track or layer could be remelted, thereby achieving a coherent metallurgical bonding between the adjacent layers or tracks. Generally, the microstructures of the solidified molten pool were considerably dense without any apparent large-sized pores, which demonstrated the capability of the LMD process to yield high densification level. The incorporation of TiC particles into Inconel 625, however, showed a great impact on the microstructural features of the molten pool. When the nano-TiC particles were added, the molten pool still maintained an apparent layerwise structure (Fig. 4(b)). As the original size of TiC particles increased to a microscale, the boundaries of molten pools became indistinct and the layerwise microstructure was difficult to identify (Fig. 4(c)). More important, the growth direction of dendrites affected simultaneously by the preferred orientation of crystal growth and the irregular direction of heat flux during laser scanning, resulting in the disordered microstructure of the molten pool, especially when the micro-TiC particles were added, as revealed in Fig. 4(c). In this study, the spatial intensity profile of the laser beam follows a Gaussian distribution. During the LMD process, the laser beam creates a mobile molten pool on the substrate or the previously deposited layer into which the powder is injected, thus developing a steep thermal gradient between the center and edge of the molten pool on the surface. Since the surface tension is a function of temperature, the existence of the temperature gradient and chemical concentration gradient leads to the variation in surface tension between the center and edge of the molten pool, producing the Marangoni convection and resultant turbulence in the pool [24]. The Marangoni convection was intensified due to the elevated temperature and chemical concentration gradient caused by the incorporation of TiC particles, resulting in a significantly intense turbulence in the pool. Due to the instability of the molten pool caused by the addition of micro-TiC particles, the microstructure of the solidified molten pool was severely disordered. It is worth noting that the micro-TiC particles do not have enough time to melt completely owing to its relatively large size along with the high melting point. Consequently, the remaining partially melted TiC particles during the solidification process hindered the smooth diffusion of liquid phase and the resultant movement of solid–liquid interface, which further caused the instability of the molten pool and the formation of disordered microstructure. Furthermore, the nucleation near the existing TiC particles zone was heterogeneous with the TiC particles acting as nuclei, which also produced the disorderly developed microstructures of the molten pool.

Furthermore, it was revealed from Fig. 4(a) that for the LMD-processed pure Inconel 625, each molten track was composed of...
two different microstructural characteristics. The bottom and side parts of the molten track showed mostly the columnar dendrites, as indicated by arrow A, which were perpendicular to the interface of the molten pool. The cellular dendrites were prevailing in the central zone of the molten track, as indicated by arrow B. Owing to the layer-by-layer additive nature of LMD, the complex thermal histories, as experienced repeatedly, in different regions of the deposited layer. The thermal histories of LMD normally involve melting and numerous reheating cycles. A series of complex physical phenomena including heat transfer, phase change, mass addition, and fluid flow are involved in the molten pool during LMD [25]. Such complicated thermal histories and thermal behaviors during LMD result in the phenomenon that the different zones of the solidified molten pool have the diverse microstructural features. The solidification microstructure essentially depends on the local solidification conditions composed of solidification velocity \( V_s \) and temperature gradient at the solid/liquid interface \( G \). The ratio of \( G \) to \( V_s \), namely, \( GV_s \), is the key controlling parameter, which determines the characteristics of solidification microstructure. As \( GV_s \) is rather large, the solidification structure in the center part of the molten pool prefers to form the cellular dendrite. Nevertheless, the interface (i.e., bottom and side parts) of the molten pool is the overlapping region and experiences remelting process, in which the temperature gradient \( G \) is relatively low. Moreover, due to the reduced temperature in the interface of the molten pool caused by the Gaussian-distributed laser energy as well as the rapid heat dissipation through the substrate or the previously deposited layer and resultant high solidification velocity \( V_s \), the relatively lower \( GV_s \) is obtained in the interface of the molten pool. According to the theory of solidification, the microstructures tend to evolve from cellular dendrite to columnar dendrite as \( GV_s \) decreases [26]. At the boundary of molten pool, the heat is dissipated speedily from the molten pool to the substrate or the previously deposited layer along the heat conduction direction, which makes the growth direction of columnar dendrites perpendicular to the molten pool interface. A further comparison of microstructures in Fig. 4 showed that as the nano-TiC particles were added to fabricate TiC/Inconel 625 composites, more columnar dendrites were observed in the solidified molten pool (Fig. 4(b)). When the initial size of the additive TiC particles increased to microscale, the proportion of columnar dendrites was even higher (Fig. 4(c)). It was reasonable to consider that the microstructures had a tendency to change from cellular dendrites to columnar dendrites with the incorporation of TiC particles into Inconel 625 matrix. The content of columnar dendrites was elevated with increasing the initial size of TiC particles, because the addition of larger-sized TiC reinforcing particles might result in a smaller \( GV_s \) value.

Figure 5 illustrates the characteristic microstructures of the columnar dendrites in the LMD-processed Inconel 625 and TiC/Inconel 625 composites with TiC particles of different initial sizes. As shown in Figs. 5(a) and 5(b), the coarsened columnar dendrites with a cross-like shape and an average dendrite size of 4.0 \( \mu m \) were present in the LMD-processed unreinforced Inconel 625 parts, showing an insufficiently developed dendritic microstructure with an intermittent and fragmentized feature. As viewed in Figs. 5(c) and 5(d), the incorporation of nano-TiC particles into Inconel 625 induced the significantly refined columnar dendrites with an average dendrite size of 3.5 \( \mu m \). The secondary dendrite arms developed well in this instance and, meanwhile, the TiC reinforcing particles distributed uniformly, without the apparent large-scale agglomeration. When the micro-TiC particles were applied as reinforcement, the columnar dendrites were relatively coarsened with an average dendrite size of 3.7 \( \mu m \). Meanwhile, the secondary dendrite growth was entirely suppressed and, therefore, the dendritic arms could not be observed in most regions. The distribution of TiC particles still remained uniform and did not show any significant change, as exhibited in Figs. 5(e) and 5(f). It is known that the degree of undercooling influences the driving force for the growth of columnar dendrites, which is defined as the difference between the actual crystallization temperature and the theoretical crystallization temperature. Typically, the driving force improves with increasing the degree of undercooling [27]. Therefore, a larger degree of undercooling of the melt resulting from an increased cooling rate and a lower actual crystallization temperature facilitates the formation of the well-developed secondary dendrites of columnar dendrites. In addition, the refinement of columnar dendrite which is defined by the dendrite spacing can be explained by [28,29]

\[
d = \left( \frac{\beta v_c}{GV_s} \right)^{-1/3}
\]

where \( \beta \) is a coefficient, \( v_c \) is the cooling rate, and \( d \) is the dendrite arm spacing. The equation can be applied to base alloy as well as composites, and the coefficient \( \beta \) is generally higher for composites than that for base alloy [30]. It is concluded that the greater the cooling rate, the smaller the dendritic spacing. Therefore, an increased cooling rate induced by the addition of nano-TiC particles favors the significantly developed dendritic arms of columnar dendrites having a refined microstructure during laser solidification process. The different cooling rates induced by the additive TiC particles with different origin sizes will be further depicted based on the numerical simulation of the thermal behavior of the molten pool.

Figure 6 shows the typical cellular dendrite morphologies of the LMD-processed Inconel 625 and TiC/Inconel 625 composites with TiC particles of different initial sizes. The dendrites were refined obviously by the additive TiC particles, and the refinement effect was further enhanced when the initial size of TiC reinforcement decreased. For the unreinforced Inconel 625 component, the average size of cellular dendrites reached 3.6 \( \mu m \) in diameter (Fig. 6(a)). When the nano-TiC particles were added as reinforcement, the mean diameter size of cellular dendrites decreased sharply to 2.3 \( \mu m \), showing a considerably refined microstructure (Fig. 6(b)). When the micro-TiC particles were used, the cellular dendrites exhibited a comparatively coarsened microstructure and the mean diameter of cellular dendrites increased to 2.8 \( \mu m \) (Fig. 6(c)). It is known that the additive TiC particles can serve as nucleation sites for heterogeneous nucleation of Ni–Cr phase, which is beneficial to increase the nucleation rate of crystals. The final grain size is determined based on the competition between heterogeneous nucleation and growth of crystals [18]. During the solidification process, the TiC reinforcing particles are captured in the solidification front, which improves the degree of undercooling of the solidification front. It accordingly favors the spontaneous nucleation of dendrites in solidification front when the degree of undercooling is sufficiently high [31]. Moreover, the TiC reinforcing particles tend to impede the grain growth of matrix metal, playing an efficient role in grain refinement. Therefore, when the nano-TiC particles were added as reinforcement, the dendrites of Ni–Cr matrix were quite refined. However, the specific surface area of the additive micro-TiC particles is smaller than that of nano-TiC particles in the case of the same weight percentage, which results in less nucleation sites for heterogeneous nucleation of matrix and a weakened effect on the inhibition for grain growth. In this situation, the comparatively coarsened dendrites of Ni–Cr matrix are obtained when using the micro-TiC reinforcing particles.

### 3.3 Microstructural Evolution of TiC Reinforcing particles

High-magnification FE-SEM images on specific positions are provided to reflect the microstructural features (e.g., characteristic morphology and distribution state) of TiC reinforcing particles in the LMD-processed composites with different original sizes of TiC reinforcement. When the original size of the additive TiC particles was in a nanoscale, a fraction of TiC particles distributed on the grain boundary and the rest of TiC particles distributed inside the grains, as shown in Fig. 7(a). Differently, when the additive TiC particles were micro-sized, all existing TiC particles distributed on the grain boundary, as shown in Fig. 7(b). The relatively smaller TiC nanoparticles with a
diameter of 120 nm were engulfed by the solidification front, leading to a uniform distribution inside the grains of the LMD-processed composites, as illustrated in Fig. 7(c). However, the relatively larger TiC particles distributed along the grain boundary of the LMD-processed composites (Fig. 7(a)), showing the significantly coarsened mean diameter of 510 nm (Fig. 7(d)). The coarsened polygonal TiC particles along grain boundary grow and develop by bridge connection of several nano-TiC particles into cluster. The cluster of TiC particles is caused by the nature of nanoparticles, the function of high temperature in molten pool as well as the complex and strong thermal convection. This fraction of the relatively large TiC particles resulting from the pushing of the advancing solid–liquid interface eventually distributes along the grain boundary [32]. During the LMD process, the Inconel 625 component experiences a complete melting within the molten pool owing to the relatively low melting temperature of 1300 °C, while the cores of TiC particles remain in solid state attributed to the high melting point of 3067 °C. With the sufficient wetting of the surrounding melt liquid, the edges of the polygonal particles become melted. In addition, the sharp corners of the TiC particles have higher specific surface areas, which is beneficial for the absorption of laser energy and heat transfer from the melt pool. As a result, the dissolution rate of the micro-TiC particles is higher at the corner than in the bulk area, thereby obtaining near-
spherical shape of TiC particles with a sharply decreased size (Fig. 7(b)). The interaction between the reinforcing particles and liquid solidification front is mainly determined by the solidification rate and the size of reinforcing particles, which leads to either the particle capture by the liquid front and resultant dispersion inside grains or the particle pushing and resultant distribution along grain boundaries [33]. If the moving velocity of the reinforcing particles is lower than the growth velocity of solidification front, the particles ahead of solidification front are pushed by Marangoni convection resulting from the presence of temperature gradient and chemical concentration gradient. According to the Stokes’ formula about particle floating (or setting) velocity which is defined by

\[ v_p = \frac{2 \pi r_p^2 (\rho_l - \rho_p)}{9 \eta} \]

where \( v_p \) is the particle setting velocity, \( r_p \) is the radius of particle, \( \rho_l \) is the density of liquid metal, \( \rho_p \) is the density of reinforcing particles, \( a \) is the acceleration of gravity, and \( \eta \) is the viscosity of liquid metal, the moving velocity of the reinforcing particles is reduced at the smaller particle size. Consequently, the small-sized nano-TiC particles (Fig. 7(c)) tend to be captured by the solidification front and distribute inside the grains due to the lower moving velocity \( v_p \) compared with the solidification rate. For the relatively larger TiC reinforcing particles (Fig. 7(d)), they are pushed by the solidification front and eventually distribute along grain boundaries, which is attributed to the larger particle size and resultant considerably elevated \( v_p \) exceeding the solidification rate.

3.4 Thermal Behavior of Molten Pool by Numerical Simulation. Numerical simulation of temperature field and thermal behavior of the molten pool during LMD of Inconel 625 and TiC/Inconel 625 composites was performed, using a finite volume method. The detailed producers for numerical simulation including physical model, governing equations, and boundary conditions were referred to our previous work [34–36]. Figure 8(a) shows the established three-dimensional finite element model and multitrack scan strategy during the LMD process. The finite elements of TiC/Inconel 625 powder were activated synchronously as the coaxial nozzle moved through the tracks with the deposited height of 1 mm and deposited area of \( 9 \times 4.5 \text{ mm}^2 \). The C45 medium carbon steel block with the dimensions of \( 10.5 \times 6 \times 2 \text{ mm}^3 \) was taken as the substrate. Considering a beneficial compromise of computation time and accuracy, the solid 70 hexahedron elements with the fine mesh of \( 0.15 \times 0.15 \times 0.25 \text{ mm}^3 \) were used in the TiC/Inconel 625 powder layer; meanwhile, a relatively coarse tetrahedron mesh is adopted for the substrate. The processing parameters applied in the simulation were kept same as those used in the experiments. Figures 8(b)–8(d) depict the transient temperature distributions during the LMD process on the cross sections of the molten pool using pure Inconel 625 and TiC/Inconel 625 composites with different TiC particle sizes. The temperature profiles were composed of a series of isotherm curves, and the dashed lines presented the isotherm of the melting temperature of Inconel 625 powder. The area inside the dashed lines possessed higher temperature than that of the melting temperature of Inconel 625, which resulted in the formation of molten pool within this area. The length and depth of the molten pool in the LMD-processed...
The peak temperature increased from 2176.5 °C to 2422.4 °C due to the additive nano-TiC reinforcement, as compared with the LMD-processed unreinforced Inconel 625. However, the peak temperature decreased to 2268.2 °C due to the additive nano-TiC reinforcement, as compared with the LMD-processed unreinforced Inconel 625. The numerical simulation results and underlying variation rules are well consistent with the experimental results as shown in Fig. 4, which can be summarized as follows: The molten pool dimensions are enhanced with the addition of TiC particles, especially for the nano-TiC/Inconel 625 system having a higher working temperature.

Figures 9(a) and 9(b) illustrate that the temperature distribution profiles on the top surface of the molten pool during LMD processing of Inconel 625 and TiC/Inconel 625 composites along Y-axis and Z-axis, respectively. The peak temperatures along Y-direction and Z-direction showed the same variation tendency. The peak temperature increased from 2176.5 °C to 2422.4 °C due to the additive nano-TiC reinforcement, as compared with the LMD-processed unreinforced Inconel 625. However, the peak temperature decreased to 2268.2 °C with increasing the initial size of TiC particles from nanoscale to microscale. The basis for a successful LMD process is the absorption of laser energy by powder material and the subsequent thermalization. Compared with Inconel 625 having an absorption rate of 60–70% at laser wavelength λ of 1.06 μm, the addition of TiC particles with a higher absorption rate (82% at λ of 1.06 μm [37]) significantly enhances the laser energy absorption of the mixed composite powder and resultant sufficiently high heat generation, inducing higher working temperature in the molten pool. Furthermore, the nano-TiC particles have the significantly larger specific surface area to absorb more laser energy and, accordingly, the absorptivity of nano-TiC particles is superior to the micro-TiC particles. The elevated working temperature of the molten pool is obtained with decreasing the original size of TiC particles, which accounts for the formation of larger-sized molten pool (Fig. 8(b)). In addition, the curve slope of the temperature distribution profile represents the temperature gradient, which varied with the different locations and original sizes of TiC particles. The temperature gradients of the side and bottom zones in the molten pool were apparently lower than other zones, as depicted in Figs. 9(a) and 9(b), which was consistent with the evolution and mechanism of dendrite growth studied above (Fig. 4). Figures 9(c) and 9(d) reveal the variations in the maximum temperature gradient within the molten pool along Y-axis and Z-axis during the LMD process using different TiC particle sizes. Either along Y-axis or along Z-axis, in the molten pool during LMD processing of unreinforced Inconel 625, was lowest. With a decrease in the original size of TiC reinforcing particles from microscale to nanoscale, the maximum temperature gradient in the molten pool of the composites showed a significant enhancement.

The temperature evolutions with time at the center of the currently deposited track (point 1, Fig. 8(a)) using different sizes of TiC particles are presented in Fig. 10(a). The slope of curves in Fig. 10(a) denotes the cooling rate of this point. The temperature distribution showed an apparent fluctuation. The temperature increased rapidly when the laser beam scanned the point and, subsequently, cooled down sharply when the laser beam moved away, which accordingly gave rise to a high cooling rate during the LMD process. Figure 10(b) depicts the different maximum cooling rates of the deposited point. The local cooling rate of the point increased from 3.58 × 10^4 °C/s to 4.03 × 10^4 °C/s as the nano-TiC particles were added into Inconel 625. Nevertheless,
the cooling rate decreased considerably to $3.75 \times 10^4 \text{C/s}$ when the original size of TiC particles changed into micrometer. Similarly, the investigation of Hanumanth and Irons also revealed an increase in the cooling rate for MMCs relative to the unreinforced alloys [38]. The effective thermal conductivity of the composite melt tends to increase in the presence of the ceramic reinforcing particles, which accelerates the heat extraction from the molten pool. With the incorporation of TiC particles into Inconel 625, there is a significant increase in the cooling rate and resultant reduced dendritic spacing [39], forming an extremely refined columnar dendrite (Fig. 5). Moreover, the critical nucleus radius and nucleation energy decrease due to the enhanced degree of undercooling, which is attributed to the elevated cooling rate. The nucleation rate increases with the addition of nano-TiC reinforcing particles, thus favoring the formation of the refined cellular dendrites (Fig. 6).

3.5 Effect of Reinforcement Scale on Mechanical Properties

3.5.1 Microhardness. The effect of primary size of TiC particles on the microhardness of the LMD-processed TiC/Inconel 625 composite parts is depicted in Fig. 11. The additive nano-TiC particles extremely increased the microhardness of the LMD-processed Inconel 625 from 292 HV0.2 to 345 HV0.2. Nevertheless, the microhardness slightly decreased to 314 HV0.2 with
incorporation of micro-TiC particles into Inconel 625. It is known that TiC is a hard ceramic exhibiting the characteristic of high microhardness and can cause a higher constraint to the localized deformation of metal matrix during indentation, leading to a higher microhardness of TiC/Inconel 625 composites in contrast to the unreinforced superalloy. Furthermore, the nano-TiC particles refine the microstructures of the matrix considerably and, meanwhile, distribute uniformly throughout the matrix. In this situation, the incorporation of nano-TiC particles into Inconel 625 can yield the highest microhardness.

3.5.2 Tensile Property. Figure 12 depicts the evolutions of tensile strength and elongation of the LMD-processed Inconel 625 and TiC/Inconel 625 composites with different sizes of additive TiC reinforcing particles. The tensile strength of as-built Inconel 625 part was significantly improved from 963.8 MPa to 1073.6 MPa with the addition of nanoscale TiC particles, while the elongation almost remained unchanged from 23.6% to 23.2%, demonstrating that the TiC nanoparticles showed no obvious harm on the ductility of composite part. However, when the micro-TiC particles were used as reinforcement, although the tensile strength of 1023.3 MPa showed an apparent enhancement as relative to the unreinforced Inconel 625 part, the elongation of micro-TiC/Inconel 625 composites decreased markedly to 14.7%. Normally, the tensile properties of the LMD-processed TiC/Inconel 625 are influenced by the particle size and distribution state of the reinforcement within matrix. The increase in tensile strength while maintaining the sufficiently sound ductility induced by the incorporation of nano-TiC particles can be attributed to the following coupling effects:

(a) Grain refinement strengthening: The existence of TiC nanoparticles in Inconel 625 matrix causes the considerably refined grain of matrix and resultant enhanced density of grain boundary. The grain boundary has a strong hindering effect on the dislocation movement. When the dislocations inside the grain move to grain boundary region, it is hard to move further. Consequently, the dislocations pile up in the grain boundary neighborhood, thereby increasing the dislocation density near the reinforcement/matrix interfaces and resultant tensile strength [40].

(b) Orowan strengthening: When the composite part bears the load, the nanoscale TiC particles distributing inside the grains (Fig. 7(c)) act as barriers to the movement of dislocations, leading to an enhancement of strength due to the large quantity of ultrafine TiC particles. During the deformation, the uniformly distributed TiC particles will delay
the propagation of cracks that initiate in the interfaces, thus improving the tensile strength.

When it refers to the elongation, the additive micro-TiC particles into Inconel 625 significantly reduce the elongation due to the brittleness of TiC reinforcement. Differently, the considerably refined grains induced by the incorporation of nano-TiC particles into the Inconel 625 give rise to a larger number of grains in a certain volume, making the deformation uniformly dispersed in more grains under the same degree of plastic deformation and, accordingly, weakening the stress concentration. Furthermore, the formation of cellular dendrite microstructure helps in keeping ductility intact [41,42]. The results of the present study prove that LMD can be an efficient technique for the fabrication of TiC/Inconel 625 composite components having an improved mechanical strength without sacrificing the ductility.

3.5.3 Wear Property. The changes of coefficient of friction (COF) and wear rates of the LMD-processed Inconel 625 and TiC/Inconel 625 composite parts are illustrated in Fig. 13. A comparative study revealed that the LMD-processed TiC/Inconel 625 composite parts generally demonstrated lower COF and wear rate than that of the unreinforced Inconel 625 part with an average COF value of 0.51 and 10.8 × 10^{-4} \text{mm}^3/(\text{N}\cdot\text{m}) respectively. The wear resistance was improved obviously with the incorporation of micro-TiC reinforcement into Inconel 625 matrix, which possessed considerably lower COF of 0.46 and wear rate of 6.5 × 10^{-4} \text{mm}^3/(\text{N}\cdot\text{m}) respectively. The even lower COF of 0.41 and wear rate of 5.2 × 10^{-4} \text{mm}^3/(\text{N}\cdot\text{m}) were obtained with the addition of nano-TiC particles. The COF curves generally exhibited a severe fluctuation at the initial running-in stage of the wear tests. With
4 Conclusions

The LMD process was applied to prepare the unreinforced Inconel 625 and TiC/Inconel 625 composites with the nano-TiC and micro-TiC particles, and the following conclusions were drawn:

(1) The incorporation of TiC reinforcing particles significantly changed the XRD patterns of Ni–Cr γ matrix phase. With regard to unreinforced Inconel 625, the diffraction peak of (200) was strongest while (111) was weak. For the TiC/Inconel 625 composites, the Ni–Cr phase exhibited a prominent (111) texture and a weak (200) texture. The intensities of Ni–Cr γ phase showed a significant decrease with the incorporation of TiC particles into the pure Inconel 625.

(2) The molten pool exhibited the layerwise morphology, due to the layer-by-layer building manner of LMD process. Nevertheless, the layered boundary was blurred and layerwise structure was difficult to identify with the addition TiC particles having microscale.

(3) The bottom and side zones of each molten track showed mostly columnar dendrites, which were perpendicular to the interface of molten pool. The cellular dendrites were prevailing in the microstructure of the molten track in the central zone. As the nano-TiC particles were used to fabricate the TiC/Inconel 625 composites, more columnar dendrites were observed in the solidified molten pool.

(4) The relatively coarsened columnar dendrites of unreinforced Inconel 625 parts manufactured by the LMD process were insufficiently developed and had an intermittent and fragmentized feature. The incorporation of the nano-TiC particles induced the significantly refined columnar dendrites with secondary dendrite arms developed considerably well. When the micro-TiC particles were applied as reinforcement, the columnar dendrites were relatively coarsened, with the secondary dendrite growth being entirely suppressed. The cellular dendrites were obviously refined by the additive TiC particles, especially with TiC reinforcement decreased to nanoscale.

(5) When the nano-TiC particles were added into Inconel 625, the significantly improved microhardness, tensile property, and wear property were obtained without sacrificing the ductility of the composites.

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