Microstructure evolution, mechanical response and underlying thermodynamic mechanism of multi-phase strengthening WC/Inconel 718 composites using selective laser melting

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For further understanding the underlying relations of microstructure evolution on mechanical properties of Inconel 718 composites reinforced by WC particles using selective laser melting (SLM), the influence of laser scanning speed on microstructure growth, evolution mechanism and mechanical properties was analyzed combining with experiments and mesoscopic simulations. The obtained results apparently reveal that the Ni2W4C primary dendrites exhibit with a reduced trunk length as well as the decreasing length and spacing of dendritic arms following an increasing scanning speed according to the combining analysis of X-ray diffraction spectrum and EDS, due to the significant reduction of operating temperature and the resultant weak atoms diffusion rate and thermodynamic driving force of dendrite growth. Meanwhile, the (Nb, M)C carbides (M representing Ni, Cr, W, Fe, Ti) generated in γ-Ni matrix are inversely refined as elevating the laser scanning speed. Both the experimental microhardness and ultimate tensile strength of SLM-processed WC/Inconel 718 composite is, therefore, evidently enhanced with a slight reduction of elongation as successively increasing the scanning speed, attributing to the combined strengthening effects of refined multi-phase of Ni2W4C primary dendrite and granular (Nb, M)C carbides. Furthermore, the underlying evolution mechanism of composite microstructure with variable processing conditions is discussed.

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1. Introduction

Nickel-based superalloys have experienced extensive development and attracted enormous attentions in the last decades and thus were widely applied in variable applications (e.g., industrial gas turbine, aircraft engine and hot end components, guide vanes, turbine disks, combustion chambers, etc), due to its excellent properties including corrosion resistance, oxidation resistance and appropriate strength at high temperatures [1]. In particular, under the combining activities of solid-solution strengthening, dispersion strengthening and fine grain strengthening, the gradually developed Inconel 718 alloy was considered as one of the commercially used nickel-based superalloys and hence was extensively used in various fields, attributing to its high ability of retaining mechanical stability at high-temperature applications up to 700°C [2–4]. Nevertheless, the limited mechanical performances of Inconel 718 alloy remained a serious concern for the application environments, where the severe abrasive and erosion phenomena commonly existed [5]. Normally, it was well known that the additions of ceramic particles incorporated into nickel-based matrix composites (CPNMCs) made a great effect on the strength, ductility and wear resistance, which also performed a considerable potential for commercial applications. Numerous research attempts, therefore, have concentrated on the application of various preparation techniques to produce CPNMCs parts for further improving its mechanical performances. Inconel 718 superalloy and its CPNMCs have been recently developed and the
bulk-form components were commercially realized through wrought, cast powder metallurgy techniques. Although the ultimately as-fabricated parts using these conventional methods have demonstrated the desirable microstructure and mechanical properties, the CPNMCs parts built through the conventional methods usually appeared with insufficient densification response and inhomogeneous microstructure. Meanwhile, since Inconel 718 and CPNMCs were prone to be considerably strengthened in a broad range of temperatures caused by solid-solution strengthening and precipitation strengthening, the resultant high hardness and low thermal conductivity make it impossible to use the conventional machining methods due to the excessive tool wear and poor workpiece surface integrity [6,7]. Moreover, the Inconel 718 superalloy and CPNMCs components highly demanded for geometry-complex shapes with many inner chambers or overhangs in the applications of aeronautics and astronautics, and thus were impossible to produce by a single processing method. As a result, the conventional processing techniques were not efficient and capable to produce the Inconel 718 parts with complex configurations and high performances.

Selective laser melting (SLM), which was well recognized as a promising additive manufacturing (AM) technology, enabled the quick fabrication of high-dimensional parts with any complex shapes directly from metallic powders using high-energy laser beam [8,9]. It can build the parts directly from the digital data of geometry models, using a computer controlled scanning laser beam as the energy source to melt the pre-spread powders selectively in a layer-by-layer fashion, which also presented a high flexibility in feedstock and shapes [10]. On the other hand, the geometry-complex components with a high dimensional precision and excellent surface integrity can be fabricated precisely using SLM technique nearly without any subsequent process requirements in comparison to the conventional techniques [11]. Furthermore, under the activities of high-energy laser beam, the ceramic particles were partially or completely melted within pool and hence it had a more strengthen bonding to matrix. Therefore, SLM technique provided a prospective potential to fabricate the high-performance composite parts with efficient and cost-saving characters.

Recently, a considerable number of research efforts primarily focused on the densification, wear resistance and thermodynamics of Inconel 718 composite reinforced by carbides through SLM technique. For instance, according to the favorable wetting ability of WC particles and Inconel 718 alloy, the WC/Inconel 718 composite was successfully fabricated with variable processing parameters using SLM technique by Rong et al. [5]. The result revealed that the graded interfacial layer with a composition of \((W, M)C_3 (M = Ni, Cr, Fe)\) was formed in SLM-ed WC/Inconel 718 composite, due to the sufficient diffusion of Ni, Nb, W and C elements surrounding the WC reinforcements. Simultaneously, the proper gradient interface and diffusion layer of SLM-processed WC/Inconel 718 composite generated using a reasonable laser scanning speed of 450 mm/s, and the worn composite part was dominate by adhesive wear with a significantly low friction coefficient of 0.35 and a reduced wear rate of \(2.5 \times 10^{-4} \text{mm}^3\ N^{-1}\ m^{-1}\) [12]. Shi et al. [13] adopted a three-dimensional finite element model of TiC/Inconel 718 composite using ANSYS multiphysics finite element package to investigate the thermodynamic behavior within pool and the evolution of the pore defects. Jia and his co-authors prepared Inconel 718 composite parts reinforced by TiC particles using SLM technique and declared that the laser energy density played a remarkable role on the densification, microstructure and wear resistance of composite parts [14]. Nevertheless, SLM technique involved series of non-equilibrium, rapid melting and solidification process caused by a high-energy laser beam, resulting in a considerable evolution of the temperature gradient, chemical concentration and microstructure growth within pool of the composite. In particular, the growth of microstructure was highly sensitive to the variations of temperature within molten pool under variable processing conditions during SLM. In case of this, there are still some exiting challenges concerning the microstructure evolution, types of formed carbides and its growth mechanism of SLM-processed composite reinforced by ceramic particles, leading to the resultant variations of mechanical performances. To date, few literature focused on the aforementioned problems and thus considerable efforts were greatly acquired to give a comprehensive understanding of the microstructure evolution and its underlying mechanisms of the SLM-processed composite parts.

In this study, the SLM-processed WC/Inconel 718 composite with novel microstructural characteristics with various scanning speed were performed. Meanwhile, the influence of processing conditions on the microstructure evolution and mechanical properties of SLM-processed WC/Inconel 718 composite parts was systematically analyzed. To further give a unique insight of the evolution mechanism of obtained microstructure of composite, the mesoscopic model with random distribution of WC reinforcements within the powder-bed was newly established to investigate the thermodynamic behavior within molten pool, and the corresponding mechanism of microstructure evolution was thus concluded.

2. Experimental procedures

2.1. Preparations of samples

The gas-atomized and spherical pre-alloy Inconel 718 powder was used with a purity of 99.7% and an average diameter of 30 \(\mu\)m. The irregular-shaped WC ceramic particles were applied as the reinforcements of composite with a purity of 99.7% and an approximately average size of 10 \(\mu\)m. The WC/Inconel 718 composite powder was homogeneously mixed using a Fritsch Pulverisette 6 planetary ball mill (Fritsch GmbH, Germany) with the reinforcement weight ratio of 20 wt% and a ball-milling duration of 4 h.

2.2. SLM processing

The SLM system (SLM-150, China), which mainly contained an IPG Photonics Ytterbium YLR-500-SM fiber laser ( Stuttgart, Germany) with a maximal power of 500 W and a focused spot diameter of 70 \(\mu\)m, an automatic powder layering apparatus, an inert argon gas protection system and an automatic processing controlling system, was employed to build the WC/Inconel 718 composite components. Based on the previous optimization of processing condition, the laser power was optimized as a constant of 121 W and the variable laser scanning speed was properly settled as 400 mm/s, 500 mm/s, 600 mm/s and 700 mm/s.

2.3. Microstructure characterization

The as-built WC/Inconel 718 composite parts, which were fabricated with various scanning speed, were cut with a three-dimensional dimension of 5 mm \(\times\) 5 mm \(\times\) 6 mm. Subsequently, the obtained specimens were ultrasonically rinsed with ethanol and then dried. According to the standard procedures for the preparation of metallographic specimen, the composite samples were ground and polished using diamond polishing media. Then, the polished parts were etched using a mixed etching solution of HCl (10 ml) and H₂O₂ (3 ml). The Quanta FEI 250 field emission scanning electron microscope (FE-SEM) was utilized to characterize
the microstructure morphologies of etched samples. Simultaneously, the chemical composition of generated dendrite and carbides were identified using the Energy dispersive X-ray spectroscopy (EDX; Oxford, UK).

3. Results and discussions

3.1. Phase constitution

Typically, the X-ray spectrum is employed to identify the consisting phases of WC reinforced Inconel 718 composite using SLM technique with a constant laser scanning speed of 400 mm/s, as depicted in Fig. 1. It was apparent that the as-built WC/Inconel 718 composite was mainly composed of γ-Ni, Ni₆W₄C, NbC and the residual WC particles. Despite of employing a high-energy laser beam, the incorporated WC particles were insufficient to be melted completely, due to its high melting temperature exceeding 3000 K. Owing to the limited diffraction intensity of Ni₆W₄C and NbC phases, the diffraction peaks plotted at a range of 34°—41° were performed (Fig. 1b). It was worth noting that the diffraction peaks, which were identities as the generating NbC phases, were slightly shifted with a small diffraction angle in comparison to those of the standard PDF card (marked by red dashed lines), indicating a visible lattice deformation of the generating NbC. According to the principle of Bragg’s law, the slightly shifting to a low angle of diffraction peaks (namely, decreasing the 2θ) primarily attributed to the solid solution of Ni matrix with large-scale W atoms, which directly derived from the incorporating WC particle.

3.2. Growth behavior of microstructure

The traditional FE-SEM images display the characteristic morphologies of WC reinforcing Inconel 718 composite using SLM with variations of scanning speed, as shown in Fig. 2. It was visibly apparent that the microstructure of SLM-processed WC/Inconel 718 composite exhibited with variable characteristics as varying the laser scanning speed. The EDS analysis apparently indicated that the primary dendrite was mainly composed of W, Ni and C with an approximate atomic ratio of 4:2:1. With the combing analysis of EDS and XRD spectrum, it was revealed that reactions of W, C and Ni atoms deriving from WC particles and Inconel 718 matrix occurred with a reasonable operating temperature during SLM, leading to the in-situ formation of Ni₆W₄C primary dendrites. The length of primary Ni₆W₄C dendrite arms of SLM-processed WC/Inconel 718 composite was evidently reduced ranging from 20.8 μm to 12.2 μm as successively increasing the laser scanning speed from 400 mm/s to 700 mm/s. When a low laser scanning speed of 400 mm/s was employed, a large-scale dendrite arms were obtained with an approximate length of 20.8 μm (Fig. 4a) and the primary dendrites grew with stagger features. On the contrary, the primary dendrite arms were formed with distinctly reduced length and distributed dispersely in the composite as further increasing the laser scanning speed (Fig. 4b, c, d). Normally, the operating temperature gradually decreased and the resultant abilities atoms diffusion reduced as elevating the laser scanning speed. It is, therefore, reasonable to deduce that the primary dendrite arms insufficiently grew with a relatively small length, due to the limited penetration of laser energy.

The high-magnification morphologies of microstructure reveal its specific length and spacing of primary dendrite arms prepared using various laser scanning speed, as illustrated in Fig. 3. It was apparently observed that the primary dendrites appeared with variable morphologies under various processing conditions. For the application of a relatively low laser scanning speed of 400 mm/s, the dominating primary dendrite arms presented a large length and spacing of 5.52 μm and 0.63 μm, respectively (Fig. 3a). As increasing the laser scanning speed to 500 mm/s, the primary dendrite arms were evidently observed with regular morphologies and its length was significantly reduced to a certain dimension of 4.51 μm with an average arm spacing of 0.54 μm (Fig. 3b). As even elevating the laser scanning speed to 600 mm/s, the reduced primary dendrite arms were evidently dominated with an approximate length and spacing of 3.32 μm and 0.47 μm, respectively (Fig. 3c), revealing a distinct refinement of primary dendrite arms. On further increasing the laser scanning speed to 700 mm/s, the primary dendrite arms with a small-size length of 2.28 μm and a low arm spacing of 0.31 μm were obviously obtained (Fig. 3d). As the laser beam scanned over the powder-bed under a giving laser power, the laser energy penetrated into powder-bed was notably decreased as increasing the scanning speed, which significantly reduced the resultant operating temperature within pool. In this situation, the limited energy was unfavorable for the coarsening of dendrite arms and thus the resultant dendrite were obviously refined with a small-size dimension. Hence, it was believable to conclude that the Ni₆W₄C primary dendrites of SLM-processed WC/Inconel 718 composite parts were gradually refined as successively elevating the laser scanning speed ranging from 400 mm/s to 700 mm/s. Fig. 4 elucidates the high-magnification features and its chemical concentrations of Nb-rich carbides generating in SLM-processed WC/Inconel 718 composite with various laser scanning speed. The carbides particles prominently dispersed in all the

Fig. 1. The X-ray spectrum characterizing the generating phases of WC reinforced Inconel 718 composites using SLM technique with a laser scanning speed of 500 mm/s in a wide range of 30°—100° (a); the characterized diffraction peaks of formed Ni₆W₄C and NbC phases with a narrow range of 34°—41° (b).
composites with consistently granular morphologies. The particle, which was marked with red point, were mainly consisted of a considerably high concentration of Nb elements and with less trace of Ni, Cr, W, Fe, Ti elements, according to the analysis of EDS spectrum. Hence, it was inferred that the granular-shaped particles dispersing in the composite were identified as NbC carbides with less solid solution of Ni, Cr, W, Fe, Ti elements, namely, (Nb, M)C carbides (where M = Ni, Cr, W, Fe, Ti), according to the combining analysis of aforementioned XRD spectrum and EDS. Xiao et al. [15] experimentally revealed that the Nb diffusion was strongly relied on the processing conditions during SLM Inconel 718 alloy. Specifically, a relatively high operating temperature and a lower cooling rate also provided the sufficient time for Nb atoms to diffuse from the solid phase to the liquid phase. Selective laser melting of WC/Inconel 718 composite at a relatively low scanning speed of 400 mm/s, the sufficient penetration of laser energy was beneficial for the adequate growth of (Nb, M)C carbides, indicating a remarkably coarsening morphology and a correspondingly average dimension of 1.11 μm (Fig. 4a). As an increasing laser scanning speed of 500 mm/s was employed, the generated (Nb, M)C carbides presented with a reduced dimension of 0.89 μm (Fig. 4b), ascribing to the limited energy penetration and resultant insufficient growth. As elevating the laser scanning speed to 600 mm/s, a certain number of (Nb, M)C carbides produced in the composite with a continuously reduced average dimension of 0.57 μm (Fig. 4c). As further increasing the laser scanning speed to 700 mm/s, a considerable number of (Nb, M)C carbides distributed discretely in matrix with a significantly refined dimension of 0.28 μm (Fig. 4d). Hence, it can infer that the granular-shape (Nb, M)C carbides are prone to be refined as increasing the laser scanning speed, attributing to the limiting diffusion of atoms and the resultantly insufficient growth during SLM.

3.3. Mesoscopic simulation and thermodynamic behavior within pools

To investigate the thermodynamic behavior within molten pool during SLM under various laser scanning speed, the newly mesoscopic powder-bed was proposed based on an improved volume of fluid (VOF) methodology, as shown in Fig. 5a. The WC
reinforcements of WC/Inconel 718 composite model were assumed to be sphere-like and were initialized randomly with a constant diameter of 10 μm and a weight ratio of 20 wt% within matrix to simplify the calculation (Fig. 5b). The generating WC particles were randomly distributed into the physical powder-bed, considering the essential physical aspects, including phase transitions, melting/solidification, interfacial interactions of liquid/gas and WC/Inconel 718, thermal conductivity, etc. Considering the requirements of numerical simulation and the calculated ability of central processing unit (CPU) equipped in the computer workstation, a novel mesoscopic powder-scale FVM model was established with a three-dimensional dimension of 400 × 300 × 60 μm³. According to previous literature, the molten liquid motioned within pool primarily followed the three basic physical conservation laws, i.e., the conservation of mass, momentum and energy [16,17]. A commercial computational fluid dynamics (CFD) calculation has been employed to give a quantitative analysis concerning the thermodynamics within molten pool of SLM-processed WC/Inconel 718 composite under variable laser scanning speed, which was in a full accordance to experimental processing conditions.

The specific temperature counters of longitudinal section along scanning direction of SLM-processed WC/Inconel 718 composite fabricated with various scanning speed are depicted in Fig. 6. It was apparently observed that the operating temperature and profiles of molten pool were significantly reduced as increasing the laser scanning speed ranging from 400 mm/s to 700 mm/s. This phenomenon primarily attributed to that the increasing laser scanning speed also had a obvious tendency to reduce the laser interaction time of powder-bed and laser beam, and the less energy was thus penetrated into the pool. Normally, the regions, where the operating temperature exceeded the melting line, were defined as the molten pool. It was worth noting that the profiles leftward the centers of pools were visibly larger in comparison to those distributed along the right centers of pools, as well as the similarly asymmetric feature in SLM-processed Cu-based matrix alloys and Inconel 718 alloy [18,19]. It was mainly ascribed to the difference of thermo-physical properties of the latter raw powder and the previous solidified regions of the pool. Simultaneously, the thermal accumulations of the solidification rearwards the laser beam were also contributed to the asymmetric feature of pool.

Fig. 7 illustrates the calculated temperature profiles and corresponding temperature gradient distributing along the molten pool during SLM-processed WC/Inconel 718 composite with various scanning speed. According to the variable temperature distribution
profiles, it was distinctly apparent that the operating temperature approached its maximum at the center of pool, due to the application of laser beam with Gaussian energy density distribution. Similarly, the corresponding temperature gradient reduced from $4.36 \times 10^7$ K/m to $3.55 \times 10^7$ K/m as successively increasing the laser scanning speed from 400 mm/s to 700 mm/s.

Fig. 4. FE-SEM photos showing the high-magnitude morphologies of Nb-rich carbide with various laser scanning speed: (a) 400 mm/s; (b) 500 mm/s; (c) 600 mm/s; (d) 700 mm/s; (e) the chemical elements and its concentration of the Nb-rich carbide; and (f) the average size of Nb-rich carbide under various processing conditions.

Fig. 5. The mesoscopic SLM powder-bed model with random distribution of WC reinforcements established for the quantitative analysis of microstructure evolution during SLM-processed WC/Inconel 718 composite (a); and (b) representing the cross-sectional view of the established physical model.
The temperature gradients were in the same order of magnitude in comparison to those of SLM-processed Inconel 718 alloy [20]. Generally, acquiring a relatively high temperature and temperature gradient were prone to result in a sufficient melting of the laser-irradiated powder particles and the resultant thermo-capillary force within pool was significantly enhanced, favoring the adequate migration of particles within pool [21]. As a result, an intense thermodynamics was obtained by mean of using a relatively high laser energy density.

3.4. Evolution mechanism of microstructure

Generally, when the high-energy laser beam continuously stroke over the powder-bed, the powders absorbed the laser energy and then were melted with a liquid temperature exceeding the melting point through powder coupling mechanism [22]. During the laser beam moved over the powder-bed, the energy was initially absorbed by the surface of individual particle and the melting depth was primarily determined by the thermo-physical properties of the materials, leading to a high temperature gradient on the surfaces of powder. As the thermalization of the energy processed, the powders surface melted due to the accumulation of energy and the heat migrated mainly towards the center of particles until a local steady state of the temperature within the powder was obtained. As shown in Figs. 6 and 7, all the calculated temperature profiles within molten pool was lower than 2800 K and hence the Inconel 718 powders were completely melted with a relatively low melting point of 1633 K, while the WC particles cannot melt directly into the melt pool with a high melting point of 3143 K. Consequently, the Inconel 718 powders were preferentially melted to produce a molten pool and then the WC powders dissolved in pool with a certain thickness inwards, which provided a beneficial thermodynamic condition to synthesize various phases between the dissolved elements.

As shown in Fig. 8a, under the activities of high-energy laser beam, the dissolution of incorporating WC particles released free...
carbon and tungsten atoms into the molten Inconel 718 alloy liquid. The elements chemical potential gradient was primarily considered as the driving force of atom diffusion, which was strongly depended on the operating temperature under variable processing conditions. The chemical potential $\mu_i$ and the carbon activity in sub-stoichiometric carbide as $a_i$ can be described as:

\[ F_i = \frac{\partial \mu_i}{\partial x} \quad (1) \]

where $F_i$ denotes the driving force of atom diffusion, and the subscript $i$ stands for either one of W, Ni, and C atoms, $\mu_i$ is the chemical potential of elements. Simultaneously, the elements chemical potential can be expressed as:

\[ \mu_i = kT \ln a_i \quad (2) \]

where $k$ is a constant, $T$ represents the operating temperature, $a_i$ is the chemical activity of elements.

According to Kikuchi et al.’s results [23], the carbon activity $a_C$ in a ternary W-Ni-C system was generally controlled by the operating temperature $T$ and was followed by the equation:

\[
\ln a_C = \ln \left( \frac{V_C}{1 - V_C} \right) + \left( -1.07 + \frac{6806}{T} \right) + \left( 13.51 + \frac{9554}{T} \right) V_C \\
+ \left( 1.21 + \frac{9010}{T} \right) V_W 
\quad (3)
\]

where $V_i = X_i(1-X_C)$, $X_i$ represents the atom fraction and subscript $i$ denotes as either one of W, Ni and C atoms. According to the Eqs. (1)–(3), the driving force of diffusion with a constant composition was apparently proportional to the thermodynamic temperature $T$ within pool. The working temperature during SLM was associated to the penetrating energy of the powder-bed and was mainly evaluated by the scanning speed in this study.

On the other hand, according to the “Arrhenius equation”, the kinetic description of diffusion ability at constant composition was given as:

\[ D = D_0 \exp \left( -\frac{Q}{RT} \right) \quad (4) \]

where $D$ denotes the diffusion rate of element, $D_0$ is the diffusion coefficient at standard temperature of 293 K and $Q$ is the so-called activation energy of diffusion. It was evidently revealed that the diffusion rate can be significantly enhanced as increasing the operating temperature. In general, the lower energy penetration was obtained as elevating the applied laser scan speed $v$, which accordingly reduced the operating temperature $T$ [24,25]. In this case, the driving force of diffusion and diffusion rate of carbon within the molten liquid was thus increased, as revealed from Eq. (4). Simultaneously, the diffusion of carbon was considerably enhanced at a constant temperature in companion to other elements (e.g., Ni, W, Nb, etc), due to its variations of physical properties. Therefore, the atom diffusion zones surrounding the incorporating WC particles can be divided into two sequential regions (Fig. 8b): (i) the regions closely neighboring WC particles were abundant with W, C and Ni atoms, providing the thermodynamic formation condition of Ni$_2$W$_4$C phases; (ii) the diffusion regions outwards the above-motioned W-rich regions were primarily dominated with C, Nb and with less amount of Ni atoms.
favoring the formation of NbC carbides with solid solution of W and Ni elements. As revealed from Figs. 6 and 7, the operating temperature within pool was obviously reduced as increasing the laser scanning speed, which significantly decreased the solubility of elements and the dimensions of fore-mentioned diffusion regions with various atoms.

During the subsequent solidification of SLM-processed WC/Inconel 718 composite, the diffusion regions surrounding the incorporating WC particles presented with variable concentrations and dimensions under various processing conditions. Fig. 8c schematically depicted the growth morphologies of Ni$_2$W$_4$C primary dendrite and granular (Nb, Ni)C carbides with various laser scanning speed. Selective laser melting of WC/Inconel 718 composite with various laser scanning speed ranging from 400 mm/s to 700 mm/s, the calculated operating temperature varied with a reduction from 2800 K to 2200 K, which was favorable to generate a large dimension of diffusion regions and tended to acquire a considerable amount of elements. As expressed from Eq. (4), the diffusion ability of atoms was extremely sensitive to the variations of operating temperature and the diffusion rate distinctly reduced as decreasing the operating temperature. Meanwhile, the corresponding temperature gradient was reduced from 4.36 $^\circ$C/km to 3.55 $^\circ$C/km as elevating the laser scanning speed. The reduction of temperature gradient was normally related to the variations of chemical potential gradient and the resultantly thermodynamic driving force was visibly decreased, as revealed from Eqs. (1)-3). With the combing reductions of diffusion rate and thermodynamic driving force, the length of Ni$_2$W$_4$C primary dendrite trunks was accordingly decreased as elevating the laser scanning speed during solidification (Fig. 2). Moreover, based on the Bouchard et al.’s results, the spacing $l$ of dendrite arm was related to the tip growth rate $V_t$ and was determined by Refs. [26,27]:

$$
\lambda = 2\pi a \left( \frac{4f}{C_0 (1 - k_0) T_F} \left( \frac{D_I}{V_I} \right)^2 \right)^{1/3}
$$

(5)

where $a$ denotes the dendrite arm-calibrating factor, which depends on the alloy composition and $T_F$ is the fusion temperature of the solvent, $f$ stands for the Gibbs-Thomson coefficient, $D_I$ is the solute chemical diffusivity in liquid, $k_0$ is the partition coefficient, $C_0$ is the alloy composition. The tip growth rate $V_t$ was controlled by laser beam scan speed $v$ and can be defined by Liu et al. [28]:

$$
V_t = \nu \cos \theta
$$

(6)

where $\theta$ is the angle between the vectors $V_I$ and $\nu$. A decrease in the applied laser scanning speed also resulted in a higher operating temperature at the tips of dendrite arms and thus a resultantly larger amount of heat was accordingly accumulated at the tips, where were generally regarded as the most instable areas, thereby providing significant internal energy and thermodynamic potentials for the growth of tips. As a result, the tip growth rates $V_t$ and the resultant length of dendrite arms appeared with an obviously reduced length as increasing the laser scanning speed. In addition, combining the analysis of Eqs. (5) and (6), it was apparently revealed that a successively increasing of the applied scanning speed was prone to decrease the dendrite armpacing $\lambda$, as depicted in Fig. 3.

Generally, the granular (Nb, M)C were formed through a dissolution precipitation mechanism by means of the heterogeneous nucleation rate and subsequent nucleus growth. During SLM, the nucleation rate was primarily referred to the thermodynamics nucleation rate and kinetics nucleation rate. The former was mainly influenced by the variation of free energy, while the latter was primarily dependent on the transfer capacity of solute atoms. As a result, the nucleation rate $N$ can be determined by Ref. [29]:

$$
N = K \exp \left( - \frac{\Delta G^*}{k_B T} \right) \times \exp \left( - \frac{Q}{k_B T} \right)
$$

(7)

where $K$ is a constant, $\Delta G^*$ represents the critical nucleation Gibbs free energy, $k_B$ and $k_B$ are the Boltzmann constant, $Q$ denotes the activation energy for transferring through the solid/liquid interface, and $T$ is the operating temperature. It was apparent that the nucleation rate $N$ was greatly enhanced as increasing the scanning speed.

Meanwhile, the nucleus growth rate of carbides precipitated in SLM-processed W-Ni-C ternary system was related to the operating temperature and was evaluated by Ref. [30]:

$$
T_t = T_M + MC_{li} \times \frac{RT^2}{M} \frac{V_t}{2H_f} \frac{1}{V_0}
$$

(8)

where $T_t$ represents the melting point of the pure component, $T_M$ is the operating temperature of tips, $m$ is the liquids slope, $C_{li}$ is the liquid solute concentration at the solid-liquid interface, $H_f$ is the latent heat of the material, $V_0$ is the kinetic constant, $V_t$ expresses the growth rate of tips and is tailored by the applied laser scanning speed. Combined with the analysis of Eqs. (7) and (8), the nucleation rate of (Nb, M)C carbides was significantly enhanced and the nucleus growth rate was inversely reduced as elevating the laser scanning speed, thereby generating a granular carbides with refined features, as shown in Fig. 4.

3.5. Mechanical properties of multi-phase reinforced composite

Fig. 9 illustrates the microhardness and its characteristic morphologies of indentations of SLM-processed WC/Inconel 718 composite with variable laser scanning speed. It was obviously apparent that the microhardness was increasingly reduced strengthened from 385.6 HV$_{0.2}$ to 475.2 HV$_{0.2}$ with gradually decreased size of indentations as successively increasing the laser scanning speed. A comparison of characteristic morphologies of indentations revealed that the SLM-processed WC/Inconel 718 composite parts experienced a larger deformation as increasing the laser scanning speed. Since the gradually refined Ni$_2$W$_4$C primary dendrite with small-size trunks and granular (Nb, M)C homogeneously dispersed within the composite with an increasing laser scanning speed, the resistance capacity to deformation was considerably strengthened during indentations, which was primarily responsible for the enhancement of measured microhardness. It was, therefore, reasonable to conclude that the combining strength of refined Ni$_2$W$_4$C primary dendrite and granular (Nb, M)C homogeneously dispersed in the composite was mainly attributed to the significantly enhanced microhardness of SLM-processed WC/Inconel 718 composite using a comparatively high laser scanning speed.

Fig. 10 depicts the specific relations between strain and stress during tensile process of SLM-ed WC/Inconel 718 composite using various scanning speed. It was obviously revealed that the ultimate tensile strength of SLM-processed WC/Inconel 718 composite parts was highly enhanced ranging from 1299.6 MPa to 1464.6 MPa as successively increasing the laser scanning speed from 400 mm/s to 700 mm/s, indicating a remarkable enhancement of the ultimate tensile strength. The as-built WC/Inconel 718 composite parts performed a visibly high ultimate tensile strength in comparison to the experimental ultimate tensile strength of SLM-processed 718 alloy in Refs. [8,31], distinctly showing a significant strength of...
composite. It was worth noting that the resultantly measured elongation was inversely decreased from 22.12% to 19.74%, leading to a slight reduction of the plasticity of composite part. According to the literature, the ultimate tensile strength of SLM-processed 718 alloy part was normally enhanced with a considerable reduction of elongation [8,31]. However, the as-built WC/Inconel 718 composite

Fig. 9. FE-SEM images displaying the characteristic morphologies of microhardness indentations of SLM-processed WC/Inconel 718 composite using various scanning speed of (a) 400 mm/s; (b) 500 mm/s; (c) 600 mm/s; (d) 700 mm/s; and (e) presenting the specific hardness of composite.

Fig. 10. The tensile strain-stress curves of SLM-processed WC/Inconel 718 composite using various scanning speed (a); and (b) displaying the experimentally ultimate tensile strength and elongation of the composite fabricated with variable processing conditions.
performed an apparently increasing of ultimate tensile strength with a slight reduction of elongation as elevating the scanning speed, attributing to the incorporation of WC reinforcements. Since the reinforcing multi-phase of Ni$_2$W$_4$C primary dendrite and granular (Nb, MC) generated during SLM acted as barriers to the movement of dislocations, the resultant strength was enhanced under the combined activities of reinforcements according to the principle of Orowan strengthening [32]. Moreover, the multi-phase of Ni$_2$W$_4$C and (Nb, MC) were significantly refined as increasing the scanning speed, which dramatically strengthened the hindering effects on the slipping of dislocation during deformation and the resultant ultimate tensile strength [33]. In addition, when it referred to the slight reduction of elongation, the composite deformed uniformly and the stress was weakened during tensile processing under the synergistic effect of the relatively large-size Ni$_2$W$_4$C primary dendrite with several micrometers and small-size (Nb, MC) carbides with submicron characters. It was, therefore, believable that the ultimate tensile strength of SLM-processed WC/Inconel 718 composite components was enhanced with an increasing enhancement as elevating the laser scanning speed, due to the prominent effects of combined refining Ni$_2$W$_4$C primary dendrite and (Nb, MC) carbides.

4. Conclusions

In present study, the WC reinforced Inconel 718 composite parts were achievable to be fabricated using SLM with variable laser scanning speed. Combing with the experimental characterizations of microstructure and the mesoscopic numerical simulations, the microstructure growth behavior, mechanical properties and its evolution mechanism were discussed and the main conclusions were drawn as followings:

(1) Combined the analysis of X-ray diffraction spectrum and EDS, the Ni$_2$W$_4$C primary dendrites and (Nb, MC) carbides were formed with apparent variations of morphologies as increasing the applied laser scanning speed.

(2) Due to the combing enhancements of diffusion rate and thermodynamic driving force with a high operating temperature and large temperature gradient using a relatively low scanning speed, the primary Ni$_2$W$_4$C dendrite exhibited with an average trunk length of 20.8 µm, and appeared with a mean length and spacing of dendrite arms of 5.52 µm and 0.63 µm, respectively. On the contrary, when an elevated scanning speed of 700 mm/s was applied, the primary Ni$_2$W$_4$C dendrite presented an average trunk length of 12.2 µm and observed with a reduced length and spacing of dendrite arms of 2.28 µm and 0.31 µm, respectively.

(3) The granular (Nb, MC) carbides were evidently refined ranging from 1.11 µm to 0.28 µm as elevating the laser scanning speed from 400 mm/s to 700 mm/s, due to considerably increasing nucleation rate and reduced growth rate as decreasing the operating temperature from 2800 K to 2200 K.

(4) The measured microhardness and ultimate tensile strength of SLM-processed WC/Inconel 718 composite were apparently enhanced with a slight reduction of elongation as increasing laser scanning speed, primarily attributing to the combined strengthening of refined multi-phase of primary Ni$_2$W$_4$C dendrite and granular (Nb, MC) carbides.

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