Fragmentation and refinement behavior and underlying thermodynamic mechanism of WC reinforcement during selective laser melting of Ni-based composites

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Abstract
The WC-reinforced Inconel 718 composites were successfully fabricated through selective laser melting (SLM) additive manufacturing technology. Influences of the applied laser energy densities on the thermodynamics within the molten pool, fragmentation behavior of WC particles, and underlying fragmentation mechanism were investigated through experiments and simulations. The results revealed that the fragmentation behavior of WC particles was greatly dependent on the applied laser energy input. As a relatively low laser energy density was applied, the alloyed reaction layer formed around WC particles, and then experienced a fragmentation into a certain number of carbides in the vicinity of WC particles, due to the temperature gradient and resultant thermal tensile stress exerted at the interface of WC particles and molten Inconel 718 alloy. This fragmentation of WC particle was defined as the dissolution-diffusion-fragmentation mechanism. For an elevated laser energy density of 330 J/m was used, an increased temperature gradient and attendant thermal stress formed, and the initially incorporated WC particles experienced a severe heat damage, thereby directly fragmenting the WC particles into the refined pieces. Meanwhile, the molten liquid with more intense thermal convections favored the homogeneous distribution of the broken WC particles and the formation of the alloyed reaction layer between WC particles and molten Inconel 718 alloy liquid, which was predominated by the fragmentation-dissolution-diffusion mechanism.

1. Introduction
Laser additive manufacturing (LAM) is acknowledged as one of the remarkable layer-upon-layer material additive manufacturing technologies that produce the 3D parts with complex geometries [1]. LAM is commonly characterized as a rapid melting and solidification process where a high-energy laser beam moves over the metallic powder, extensively applying in a wide range of alloys such as Al-based alloys, Ti-based alloys, Ni-based alloys, etc [2]. In particular, selective laser melting (SLM) is well known as one newly developed type of LAM, and exhibits an outstanding capability of producing the three-dimensional parts with arbitrary configurations based on a principle of selectively fusing and consolidation of thin layers of loose metallic powder directly using the 3D Computer Aided Design (CAD) data as a digital source [3]. It provides an almost unchallenged freedom of design without acquisitons of part-specific tooling, and also allows a full melting of metallic powder with a small thickness, hence producing a high-densification SLM part [4].
Ni-based alloys have been extensively developed, and have been proven to be attractive in various industrial applications such as the turbine blades and engine components where the combination of superior mechanical property and excellent workability are highly required, due to its excellent mechanical properties maintained at high temperature [5]. Inconel 718, typically considered as a nickel-based austenitic alloy, is featured by a high strength, as well as the oxidation, the creep performance and the fatigue strength at elevated temperatures up to 700 °C, making it as a potential candidate for the production of gas turbine, jet engine and nuclear reactor [6]. Normally, Inconel 718 alloy performs the excellent mechanical properties by means of the combined strengthening mechanisms, including solid-solution strengthening, dispersion strengthening and fine grain strengthening [2,7]. Nevertheless, with rapid advances in technology including the aircraft and nuclear industries, most of the Inconel 718 alloy parts, due to its limited mechanical properties, cannot satisfy the requirements of the parts acquiring complex configurations and high performance. Ceramic particles reinforced metal matrix composites (CPRMMCs) generally exhibit a promising potential for further improving the integrated properties of alloys by virtue of a high cost performance ratio, workability, and non-polluting properties [8]. As a consequence, the ceramic particles reinforced CPRMMCs have been regarded as an alternative approach to further enhance the service performances of Inconel 718 components.

Ceramic particles, due to its high-melting temperature and excellent mechanical properties, typically possess a number of desirable properties and thus are considered as the potential reinforcements in metal-matrix composites [9]. For the direct addition of ceramic reinforcements in metallic matrix, tungsten carbide (WC) has attracted more extensive research interest in the last decades, and it has been employed as an appropriate potential in reinforcing the Ni-based matrix to enhance the mechanical properties due to its excellent high-temperature creep behavior, high hardness, etc [10]. Moreover, a number of effort attempts have recently disclosed that the LAM-processed WC reinforced Ni-based composites can acquire the tailored microstructures and attendant high performances, attributing to the production fashion and laser-induced non-equilibrium rapid melting/solidification mechanism. For instance, Wu et al. [11] have found that the WC particles exhibited an excellent bonding and wetting-ability to Ni matrix, thereby enhancing the wear resistance of Ni-based composites, due to the partial dissolution of WC particles during LAM at relatively high temperature. Farahmand et al. [12] have revealed that the Ni-based composite reinforced by an optimal addition of nano-WC particles possessed an enhanced wear resistance and excellent corrosion resistance, attributing to the greatly refined grain size, higher chemical stability and passivation capability. Ortiz et al. [13] and Xu et al. [14] have disclosed that the weight percentage of WC reinforcement had a significant effect on its distribution and the attendant mechanical properties of Ni-based composites. Moreover, in our previous researches [8,15], due to the excellent wetting-ability and in-situ reaction of WC and Inconel 718 alloy during SLM, a graded interfacial layer, which was consisted of (W, M)C3 and (W, M)C2, was in-situ formed around the WC reinforcement, hence acquiring a lower wear rate of the WC/Inconel 718 composite [15]. Nevertheless, the WC reinforcement have exhibited a high tendency to dissolve into molten pool of nickel alloy during hot processing, especially for the LAM process, resulting in a high susceptibility in the heat damage and attendant crack of WC reinforcement [16]. Wang et al. [17] have discovered that the cracks initiated and propagated rapidly in the interior WC reinforcement rather than the interface of WC reinforcement and metal matrix once the thermal stress occurred by the high temperature gradient during SLM, due to the large mismatch between WC and Fe-based alloy matrix. On the other hand, as the WC particles are irradiated by high-energy laser beam, the crack or fragmentation is possible to result in a loss in mechanical properties and an increasingly cracked susceptibility of its composite. It can be found that the fragmentation response of WC particles during SLM of WC/Inconel 718 composite still remains a major challenge in achieving a high-performance composite. Therefore, it is necessary to track the fragmentation behavior and its underlying mechanism of WC particles during SLM of WC/Inconel 718 composite for further producing the high-performance composite parts.

In the present study, in order to investigate the fragmentation behavior of WC reinforcement in the WC/Inconel 718 composite during SLM, the composites were successfully fabricated by SLM using the varied laser energy densities. Meanwhile, the temperature profiles and attendant velocity contours within molten pool of WC/Inconel 718 composite during SLM using variable laser energy densities were also provided to give an insight of the thermodynamic behavior of composite via simulation. Moreover, the underlying fragmentation mechanism of WC reinforcement of WC/Inconel 718 composite was thus concluded on the basis of experimental results.

2. Experimental procedures and numerical simulations

2.1. Preparations of composite powder system

The gas-atomized Inconel 718 alloy powder with a purity of 99.7% and a nearly spherical shape, and the irregular-shaped WC reinforcement with an average particle size of 12 μm were employed as the starting materials. Through our preliminary experiments, the WC reinforcement that was optimized with a weight ratio of 20 wt% was incorporated in the WC/Inconel 718 composite powder system to acquire an available process-ability and a sufficiently high densification response. The current WC/Inconel 718 composite powder system was homogeneously mixed using a Fritsch Pulverisette 6 planetary ball milling with a ball-to-powder weight ratio of 4:1, a rotation speed of 200 rpm, and a ball-milling duration of 4 h (Fig. 1).

2.2. SLM processing

The self-developed SLM system that was employed to produce the WC/Inconel 718 composite parts primarily consisted of an IPG Photonics Ytterbium laser system with a maximal laser power of 500 W and a focusing spot size of 70 μm, an automatic powder-
paving apparatus, an inert gas protection system and a computer system for process control. For a SLM process, the crucial processing parameters including the applied laser power, scanning speed, and hatch spacing played a significant role in controlling the microstructure and resultant mechanical properties of the ultimately solidified parts. Through a number of our preliminary experiments, the hatch spacing were optimized at 60 μm and, the laser power (P) were preset increasingly at 99, 110, 121 and 132 W combined with the scanning speed (v) variation at 1000, 800, 600, and 400 mm/s. In order to investigate the comprehensive influences of laser power and scanning speed on the fragmentation behavior of WC reinforcement during SLM of WC/Inconel 718 composite, the laser energy density, \( \eta \), was defined by the equation \( \eta = P/v \), and four different \( \eta \) of 99, 137.5, 201.6 and 330 J/m were also calculated. The WC/Inconel 718 composite parts were built onto the prepared Nickel-based alloy substrate under variable laser processing conditions, using the inert argon as the shielding gas to prevent the melt pool from oxidation.

2.3. Microstructure characterization

The as-built WC/Inconel 718 composite components that were built with a three-dimensional size of 5 × 5 × 6 mm³ using different laser energy densities were cut from the substrate. The specimens were ultrasonically rinsed with ethanol, and then dried using the argon gas. Subsequently, the as-built samples were ground and polished for the metallographic preparation. An AQuanta FE 250 field emission scanning electron microscopy (FE-SEM, FEI company, USA) was utilized to observe the microstructural morphologies of the SLM-processed samples that were etched using the etching solution containing of HCl (10 ml) and H₂O₂ (3 ml) for 10 s.

2.4. Numerical simulation

Since the WC reinforcement having an excellent wetting-ability to Inconel 718 alloy are employed in our material system, the physical and chemical metallurgical reactions of laser beam and powder particles are particularly complex. A novel physical model of SLM-processing WC/Inconel 718 composite was developed with a random distribution of WC reinforcement, considering the transition of solid/liquid phases, the interfacial heat and mass transfer, the thermo-capillary force of liquid, buoyancy force, and the recoil pressure, as shown in Fig. 2a. The proposed physical model was built with a three-dimension size of 300 × 200 × 60 mm³. The heat source employed in the simulation was defined as a heat flux, at which the laser energy was identified as a Gaussian distribution [19]. The motion of molten fluid generally followed the three basic physical conservation laws, i.e., the conservation of mass, momentum and energy [20]. Due to the existence of surface tension gradient induced by the temperature gradient within molten pool, the motion of molten liquid is primarily predominated by the Marangoni convection during SLM. The surface tension (\( \gamma \), N/m) is considered in this model and can be expressed by Ref. [21]:

\[
\frac{\partial \mu}{\partial z} - \frac{\partial \gamma}{\partial T} = \frac{\partial T}{\partial \alpha}
\]

(1)

\[
-\mu \frac{\partial v}{\partial z} - \frac{\partial \gamma}{\partial T} = \frac{\partial T}{\partial \gamma}
\]

(2)

To further ensure the complicated solution feasible, the incorporated WC reinforcement was assumed to be spherical-shaped with an average size of 12 μm and a weight ratio of 20 wt%. The random distribution of incorporated WC reinforcement within the powder-bed was achieved by developing the user defined files (UDF) based on the packed features of the composite powder system. The initial temperature of the as-built physical model was defined as 300 K in order to make a further accordance with the realistic processing condition of SLM. Considering the influence of physical properties and resultant interactions of laser beam and powder on the thermodynamics, the thermal physical properties of Inconel 718 alloy and WC reinforcement were provided according to Refs [19,22], and meanwhile, the heat conductivity of the interfaces between WC reinforcement and Inconel 718 matrix was reasonably taken into consideration in the physical model. To well evaluate the fragmentation behavior of WC reinforcement under various processing conditions during SLM, the temperature profiles and resultant temperature gradient of inner and outer monitoring points of WC reinforcement were recorded, as shown in Fig. 2b.

3. Results and discussion

3.1. Evolution of microstructural morphology

Fig. 3 depicts the characterized microstructural morphologies of SLM-processed WC/Inconel 718 composites fabricated with various processing conditions. It was apparent that a gradual decrease in WC size of the solidified composites using different laser processing conditions was observed in comparison to that of the initially incorporated one. According to our previous researches [8,15], it was mentioned that the obvious alloyed reaction layer formed around WC reinforcement was primarily composed of the carbides within the composite using a low laser energy density. Since a high-energy laser beam stroke the composite powder bed and tended to result in a rapid increase in the operated temperature and resultant heat damage of WC reinforcement, the W and C atoms that released from the dissolution of WC reinforcement could diffuse into the molten Inconel 718 alloy solvent, and meanwhile, a large amount of

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**Fig. 2.** The WC/Inconel 718 composite model with random distribution of WC reinforcement newly established through finite volume methodology (a), and the cross-sectional view of composite model of (a) showing the locations of the monitoring points A nearly closed to WC reinforcement and point B located in the interior of WC reinforcement, respectively (b).
Ni, Cr and Fe atoms derived from the solvent of Inconel 718 alloy also diffused towards WC particles [18]. In this condition, the alloyed reaction layer accordingly formed around WC reinforcement. Consequently, a high laser energy density, typically tailored by increasing the laser power or lowering the laser scanning speed, had an obvious tendency to elevate the operated temperature of the molten pool and resultant heat damage degree of WC particles. That is to say, an increase in the laser energy density could result in a high operated temperature of the molten liquid and a more powerful dissolution of WC reinforcement, leading to an increased thickness of alloyed reaction layer around WC particles. However, the alloyed reaction layer with an increased thickness formed around WC particles using a higher laser energy density, which inversely had a high tendency to break the incorporated WC into small blocky carbides due to its thermal shock caused by the irradiation of laser beam. Selective laser melting at the relatively low laser energy densities of 99 and 137.5 J/m, the alloyed reaction layer formed around WC reinforcement, and a limited thermal shock degree of WC reinforcement surrounded by the alloyed reaction layer generated, thereby yielding the fragmentation of the alloyed reaction layer into blocky carbides with an approximate size of several micrometers dispersing in neighboring areas of WC particles (Fig. 2a and b). It was worth noting that the WC reinforcement with a relatively less curvature radius was prone to perform a comparatively larger solubility in Ni-based alloy solvent, implying that the edge angles of WC reinforcement was preferentially dissolved and then exhibited a blunt angle. As the laser energy density increased to 201.6 J/m, the alloyed reaction layer with a comparatively large thickness generated due to an enhanced diffusion of the dissolved atoms. Meanwhile, the attendant thermal shock of WC that was surrounded by the alloyed reaction layer apparently occurred with an increased susceptibility, leading to the fragmentation of alloyed reaction layer into some blocky carbide with an increased size (Fig. 2c). As the laser energy density was further elevated to 330 J/m, the dominated thermal shock degree of WC particles was significantly enhanced, thereby giving rise to a rapid fragmentation of WC reinforcement into small-sized particles (Fig. 2d). Therefore, it was reasonable to conclude that the laser-induced fragmentation of WC particles played a crucial role in determining the microstructure morphologies of the SLM-processed WC/Inconel 718 composite parts using different laser energy densities.

The high-magnification FE-SEM images illustrate the characterized microstructural morphologies of the SLM-processed WC/Inconel 718 composite with various laser energy densities, as shown in Fig. 4. It was observed that the WC reinforcement irradiated by the various laser energy densities experienced considerable differences of the laser-induced fragmentation characteristics. Although a relatively low laser energy density of 99 J/m was applied, a number of cracks that propagated towards the radial direction of WC particles were generated within the alloyed reaction layer due to the thermal shock of WC particles. Meanwhile, the fragmentized carbide with irregular shapes dispersed in the neighboring areas of WC particles (Fig. 4a) under the action of the thermal convections with a limited intensity within the molten pool. When an increased laser energy density of 137.5 J/m was used, an extremely rough profile of the alloyed reaction layer with a reduced thickness around WC particle was observed, due to the separation of fragmentized carbide from the alloyed reaction layer caused by the enhanced thermal shock of WC particle (Fig. 4b). For a high laser energy density of 201.6 J/m, the incorporated WC

\[
\frac{C_{r1}}{C_{r2}} = \exp \left( \frac{3\sigma M}{RT \rho} \left( \frac{1}{r_1} - \frac{1}{r_2} \right) \right)
\]

where \( R \) represents the gas constant, \( M \) and \( \rho \) are the molecular weight and interfacial tension of WC reinforcement and Inconel 718 alloy solvent, respectively, \( T \) is defined as the operated temperature of molten liquid, \( \rho \) is the density of WC, \( C_{r1} \) and \( C_{r2} \) denote as the solubility of WC reinforcement with radius of \( r_1 \) and \( r_2 \) (\( r_1 > r_2 \)), respectively. According to Eqn (3), the initially polygonal-shaped WC reinforcement with a relatively less curvature radius was prone to perform a comparatively larger solubility in Ni-based alloy solvent, implying that the edge angles of WC reinforcement was preferentially dissolved and then exhibited a blunt angle. As the laser energy density increased to 201.6 J/m, the alloyed reaction layer with a comparatively large thickness generated due to an enhanced diffusion of the dissolved atoms. Meanwhile, the attendant thermal shock of WC that was surrounded by the alloyed reaction layer apparently occurred with an increased susceptibility, leading to the fragmentation of alloyed reaction layer into some blocky carbide with an increased size (Fig. 2c). As the laser energy density was further elevated to 330 J/m, the dominated thermal shock degree of WC particles was significantly enhanced, thereby giving rise to a rapid fragmentation of WC reinforcement into small-sized particles (Fig. 2d). Therefore, it was reasonable to conclude that the laser-induced fragmentation of WC particles played a crucial role in determining the microstructure morphologies of the SLM-processed WC/Inconel 718 composite parts using different laser energy densities.

Fig. 3. The typical FE-SEM images showing the microstructural morphologies of WC reinforcement in WC/Inconel 718 composite by SLM with the various processing conditions: (a) \( \eta = 99 \text{ J/m, } P = 99 \text{ W, } v = 1000 \text{ mm/s; } \) (b) \( \eta = 137.5 \text{ J/m, } P = 110 \text{ W, } v = 800 \text{ mm/s; } \) (c) \( \eta = 201.6 \text{ J/m, } P = 121 \text{ W, } v = 600 \text{ mm/s}; \) and (d) \( \eta = 330 \text{ J/m, } P = 132 \text{ W, } v = 400 \text{ mm/s.} \)
particles experienced a fragmentation with a reduced size, and the alloyed reaction layer with a limited thickness formed surrounding the fragmented WC particles, attributing to the moderate thermal shock and elevated convection within the molten pool (Fig. 4c). As the laser energy density was further elevated to 330 J/m, the fragmented WC blocks exhibited a further reduced size and dispersed sparsely within Inconel 718 matrix, and meanwhile, the alloyed reaction layer with a moderate thickness formed around the broken WC particles (Fig. 4d). Normally, the laser energy is more readily absorbed by WC particles in comparison to Ni-based alloy powder during SLM, due to the obvious difference of the physical properties [23,24]. Using a high laser energy density, the incorporated WC particles could absorb more laser energy as compared with that of Inconel 718 alloy, leading to a high temperature gradient and resultant large thermal stress between WC particles and Inconel 718 alloy. As a result, the incorporated WC particles experienced a severe fragmentation during SLM, ascribing to the increased susceptibility of the thermal shock.

3.2. Thermodynamic behavior within molten pool

Normally, the previous research results [18,23,25] have demonstrated that the dissolution capability and the thermal shock of WC particles were strongly dependent on the complex thermodynamics within the molten pool during SLM. To be important, the aforementioned interaction between the laser and the composite powder system was also considered as a primary processing factor. In this study, the temperature profiles and the velocity contours were used to evaluate the thermodynamic behavior within the molten pool during SLM. Fig. 5 apparently depicts the dynamic temperature contours within the molten pool of Y-Z cross section perpendicular to X-axis of SLM-processed WC/Inconel 718 composite parts using different laser energy densities. The operated temperature within the molten pool was obviously elevated in the range from 2250 K to 2850 K as the laser energy density was successively increased ranging from 137.5 J/m to 330 J/m. Meanwhile, the molten pool that was commonly defined as the inner areas of melting line was evidently featured with an increased size. It was noteworthy that the isotherms within the molten pool were visibly observed with more or less metamorphosis, due to the apparent difference of naturally physical properties between WC particles and Inconel 718 alloy.

To well evaluate the interfacial thermodynamics of WC particles and molten Inconel 718 alloy during SLM, the temperature profiles and attendant temperature gradient along Y-axis through WC reinforcement within the molten pool using variable laser energy densities are revealed in Fig. 6. The calculated temperature profiles distributed through the WC reinforcement obviously elevated as the applied laser energy densities were increased. Nevertheless, the corresponding temperature gradient along Y-axis was observed with the presence of roughness profiles, indicating the formation of considerable fluctuations due to the difference of thermal-physical properties between the incorporated WC particle and Inconel 718 alloy. In particular, the temperature gradient at the interfaces of WC particle and Inconel 718 matrix experienced a sharp increase or decrease, and meanwhile, the maximum of the temperature gradient was significantly elevated for an increased in the laser energy input. Generally, due to the difference in thermal expansion coefficients, the temperature gradient was increased at the interfaces between WC particles and metallic matrix, which had a tendency to generate the thermal stress and the resultant initiation of cracks [25]. Moreover, Xu et al. [26] determined the thermal stress (σ) generating in the WC particle within the WC/Ni composite as:

$$\sigma = E_p (a_m - a_p) \Delta T$$

(4)

where $E_p$ represents the elastic modulus of WC particles, $a_m$ and $a_p$ are the coefficient of thermal expansion of Inconel 718 alloy matrix and WC particles, respectively. $\Delta T$ is defined as the variation of operated temperature during SLM. It could be concluded that the thermal stress generated in the WC particles was tensile during melting process, since the coefficient of thermal expansion of WC particles ($5.09 \times 10^{-6} \text{K}^{-1}$) was greatly lower than that of Ni ($13.3 \times 10^{-6} \text{K}^{-1}$). Moreover, the alloyed reaction layer or individual WC particle had an increased tendency to generate cracks due to

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**Fig. 4.** The high-magnification FE-SEM pictures depicting the characteristic morphologies of WC reinforcement of SLM-processed WC/Inconel 718 composite using various laser energy densities: (a) $\eta = 99 \text{J/m}, P = 99 \text{W}, v = 1000 \text{mm/s}$; (b) $\eta = 137.5 \text{J/m}, P = 110 \text{W}, v = 800 \text{mm/s}$; (c) $\eta = 201.6 \text{J/m}, P = 121 \text{W}, v = 600 \text{mm/s}$, and (d) $\eta = 330 \text{J/m}, P = 132 \text{W}, v = 400 \text{mm/s}$. **Fig. 5.** Apparent depiction of the dynamic temperature contours within the molten pool during SLM.
the existence of the large temperature gradient between WC particles and molten Inconel 718 alloy for the elevated laser energy input. It is, therefore, reasonable to deduce that a large temperature gradient formed at the interfaces between WC particles and Inconel 718 matrix plays a crucial role in controlling the fragmentation behavior of WC reinforcement during SLM.

Fig. 7 shows the three-dimension temperature contours of the individual WC particles during selective laser melting of WC/Inconel 718 composite parts using different processing conditions. It was found that the temperature distributed on WC reinforcement was significantly elevated as the laser energy input was increased. Meanwhile, the temperature contours distributed on the WC
reinforcements were prone to exhibit an increased number of colors as the laser energy density increased from 99 J/m to 201.6 J/m (Fig. 7a, b and 7c), indicating a large temperature gradient exerted on the WC particles. Moreover, it was noteworthy that the temperature contours apparently distributed on the WC particles with a high temperature and the limited area where a high susceptibility in stress concentration occurred as the laser energy density was further elevated to 330 J/m (Fig. 7d). Hence, a large laser energy input irradiated on the composite powder system has a high tendency to result in the concentration of thermal stress in a certain area on the WC particles, thereby elevating the crack initiation during SLM.

The typical velocity contours within the molten pool around WC reinforcement during SLM with the variation of laser energy input are depicted in Fig. 8. It was found that the dynamic velocity of molten liquid was considerably enhanced with an increased intensity for the successively elevated laser energy density. Normally, a large input of the applied laser energy resulted in a high temperature and resultant lower viscosity within the molten pool, revealing an enhanced migration of molten liquid under the action of thermal-capillary force [2]. As described above, since the laser energy was more readily absorbed by WC particles than that by Ni-based alloy powder [19], the WC particles have a great tendency to acquire a higher temperature on its surface as compared with Inconel 718 alloy, and thus the WC particles surrounded by Inconel 718 liquid are heated through the transient heat conduction where a temperature gradient is exerted, resulting in the formation of surface tension gradient within molten pool. In this condition, the molten liquid close to the WC particles, possessing a high temperature and the attendant low viscosity, tended to migrate to the outward areas where the one featured with a low temperature and high viscosity. As the initially polygonal WC reinforcement with a relatively less curvature radius was prone to perform a relatively larger solubility in Ni-based alloy solvent, the nearly sphere-like WC particles were obtained, thus completing the formation of the outward velocity patterns. Consequently, the velocity contours within the molten pool clearly exhibited the patterns of outer-circulation vortexes as the laser energy density was successively increased (Fig. 8). Yuan et al. [20] and Gu et al. [27] have demonstrated that the fluid dynamics had a significant influence on the migration of reinforcement during SLM. In our study, the alloyed reaction layer or WC particle experienced the fragmentation into the blocky ones which were prone to be migrated away from the WC reinforcement under the action of the intensive molten liquid surrounding the interface of the WC particles and molten Inconel 718 liquid. As a result, the molten liquid with an increased velocity was greatly favorable for the homogeneous distribution of reinforcement in the solidified composite parts.

3.3. Fragmentation mechanism

The schematics for illustrating the fragmentation mechanism of...
WC reinforcement in WC/Inconel 718 composites during SLM with the variation of the applied laser energy densities are shown in Fig. 9. The WC particles exhibited fragmented characters during SLM, due to the variation of thermodynamics between laser beam and composite powder system under the varied laser energy densities. For a relatively low laser energy density, the incorporated WC particles absorbed more energy and then obtained a high temperature as compared with Inconel 718 alloy, thereby yielding a sufficient dissolution of the WC particles. Meanwhile, a large number of chemical elements from molten Ni-based alloy solvent such like Ni, Cr, Fe and Nb atoms, diffused into the WC particles and then reacted with the W and C atoms, leading to the formation of alloyed reaction layer around the WC particles. The individual WC particle experienced a partial dissolution towards the inward radial direction, and meanwhile, the alloyed reaction layer with a gradually increased thickness formed for the successively elevated laser energy input. Nevertheless, due to the difference of the physical properties between the incorporated WC particles and the Inconel

Fig. 8. The typical velocity contours within molten pool surrounded the WC reinforcement during SLM using the various laser energy densities: (a) \( \eta = 99 \text{ J/m}, P = 99 \text{ W}, v = 1000 \text{ mm/s}; \) (b) \( \eta = 137.5 \text{ J/m}, P = 110 \text{ W}, v = 800 \text{ mm/s}; \) (c) \( \eta = 201.6 \text{ J/m}, P = 121 \text{ W}, v = 600 \text{ mm/s}, \) and (d) \( \eta = 330 \text{ J/m}, P = 132 \text{ W}, v = 400 \text{ mm/s}. \)

Fig. 9. Schematics for describing the fragmentation mechanism of dissolution-diffusion-fragmentation during SLM of WC/Inconel 718 composite using a relatively low laser energy density (a), and (b) the predominated fragmentation-dissolution-diffusion mechanism during SLM of WC/Inconel 718 composite with a large laser energy input.
4. Conclusions

In the present study, the WC-reinforced Inconel 718 composites achieved by SLM with the variation of applied laser energy inputs. The evolution of microstructural morphology of SLM-processed WC/Inconel 718 composite was experimentally analyzed, and the thermodynamics within molten pool were also acquired using numerical simulation based on a newly developed physical model. Moreover, the underlying mechanism of fragmentation WC particles during SLM was concluded and the main conclusions were drawn as follows:

(1) The microstructural morphology of WC/Inconel 718 composite using SLM was primarily controlled by the applied laser energy densities. For the relatively low densities of 99 J/m and 106 J/m were applied, the alloyed reaction layer in the high operated temperature (Fig. 9b). As a result, the incorporated WC particles experienced a combined tailoring mechanism of fragmentation-dissolution-diffusion during SLM WC/Inconel 718 composite using a large laser energy input.

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[21] L.A. Anesteiv, L. Froyen, Model of the primary rearrangement processes at 718 alloy, the alloyed reaction layer surrounded WC particles suffered from thermal tensile stress, and the corresponding fragmentation into the small-sized carbide occurred. Moreover, the WC particles were surrounded by a number of the fragmented carbides with several micrometers, which were homogeneously distributed in a certain area under the action of thermal convection within the molten pool. Consequently, the evolution of WC particles was dominated by a combined mechanism of dissolution-diffusion-fragmentation (Fig. 5a). By contrast, as an increased laser energy density of 330 J/m was employed, the transient thermal stress generated in WC particles was rapidly elevated to a considerably large tensile stress level, resulting in the initiation of cracks in the interior WC particles. In this condition, the incorporated WC particles were possible to be broken into small-size pieces which were distributed homogeneously within the molten pool under the action of more intense molten liquid. The directly fragmented WC particles could interact with Inconel 718 alloy solvent to complete the alloyed reaction layer in the high operated temperature (Fig. 9b). As a result, the incorporated WC particles experienced a combined tailoring mechanism of fragmentation-dissolution-diffusion during SLM WC/Inconel 718 composite using a large laser energy input.


