In situ synthesis and characterization of ceramic reinforced Inconel 718 coatings using B₄C-Inconel 718 powders by laser-directed energy deposition

Yunze Li¹ · Dongzhe Zhang¹ · Bo Zhao² · Weilong Cong¹

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Abstract

Inconel 718 has been widely used in aerospace, nuclear, and marine industries due to excellent high-temperature mechanical properties and corrosion resistance. In recent years, laser-directed energy deposition (DED) becomes a competitive method in the fabrication of Inconel 718 coatings. Compared with other surface coating processes, laser DED has the advantage of extremely fine-grained structures, strong metallurgical bonding, and high density. However, the hardness and wear resistance of Inconel 718 coatings still need to be improved. To further improve these properties, ceramic reinforced Inconel 718 coatings have been investigated. Compared with ex situ ceramic reinforcements, the in situ synthesized reinforcements have the advantage of refined ceramic particle size, uniform distribution, and low thermal stress. B₄C was a preferable additive material to fabricate in situ synthesized multi-component ceramic reinforced Inconel 718 coatings. The addition of B₄C could form a large number of borides and carbides as ceramic reinforcements. In addition, the in situ reactions between Inconel 718 and B₄C could release heat during the fabrication, thereby promoting the melting of material powders. However, there are currently no investigations on the in situ synthesis mechanisms, microstructure, and mechanical properties of laser DED fabricated B₄C-Inconel 718 coatings. In this study, the effects of B₄C on the properties of Inconel 718 coatings were investigated. Results show that Ni₃B, NbB, and Cr₃C₂ phases were formed. With the addition of B₄C, the size of Laves phase was refined and the porosity was decreased. The hardness and wear resistance of B₄C reinforced coatings were improved by about 34% and 28%, respectively.

Keywords Coating · Laser-directed energy deposition (DED) · Inconel 718 alloy · B₄C · In situ synthesis · Mechanical properties

1 Introduction

Stainless steel 304 are widely used as the primary main material of fasteners and flange manufacturing, automotive and aerospace components, and heat exchangers due to their excellent hot and cold forming process, great low-temperature performance, and good weldability. However, the corrosion resistance, wear resistance, and hardness of stainless steel 304 are relatively low, which limits its further applications. Inconel 718 is a good choice for strengthening the stainless steel 304 structural parts that are prone to be damaged under conditions with complicated stress and elevated temperature due to its remarkably high-temperature mechanical properties, excellent corrosion resistance, and good weldability with stainless steel [1, 2]. In recent years, laser-directed energy deposition (DED) becomes a competitive technology for repairing and coating structural parts, due to its advantages of excellent bonding quality, easy controllability, excellent stability, and the capability of functionally gradient materials fabrication [3, 4]. Due to these advantages, the fabrication of Inconel 718 coatings on stainless steel and nickel-based alloys by laser DED process have been received extensive research attention [5, 6]. Results show that the laser DED fabricated coatings are free of micropores and microcracks and have good adherence to the substrates. However,
the microhardness and wear resistance of laser DED fabricated Inconel 718 coatings is relatively low, which limited their further applications in many areas.

In order to further improve the service life and mechanical properties of laser DED fabricated Inconel 718 coatings, ceramc materials are added to Inconel 718 coatings as reinforcement phases. There are two different kinds of processing methods of ceramic reinforced Inconel 718 coatings, including the ex situ process and the in situ process. In the ex situ process, the ceramic reinforcements such as BN, SiC, and Al2O3 are directly added to Inconel 718 powder and remained in the deposited coatings as reinforcement phases [7–10]. The ex situ process has the advantages of low cost and easy manufacturing. However, there are also some drawbacks. Firstly, the improper dispersion of pre-mixed powders may result in particle agglomeration and clustering, leading to inhomogeneous microstructures and the decrease of mechanical properties. Secondly, the thermal expansion coefficients of ceramic reinforcements and Inconel 718 matrix are different. During the solidification process, the matrix cracking in composites can be generated. Finally, due to the high melting point of ex situ ceramic reinforcements, the feedstock powders are hard to be fully melted. The un-melted particles could decrease the fluidity of the molten pool, leading to the generation of fabrication defects [11].

In the in situ process, the reinforcements are synthesized in the matrix itself by chemical reactions. Compared with the ex situ process, the in situ process could provide better ceramic reinforcement distribution and finer ceramic reinforcement particle size, which can improve the consistency and the mechanical properties of the fabricated coatings. In addition, the chemical reactions provide thermodynamic stability at high temperatures and a clean interface between reinforcements and the matrix. The large thermal expansion coefficient differences between ceramic particles and matrix were reduced, which suppresses the crack generation [12, 13]. The heat generated during the in situ process can also be utilized to melt the material powders, which can save the input laser energy.

Over the past decade, researchers have demonstrated interest in the fabrication of in situ synthesized ceramic reinforced Inconel 718 coatings. TiC has been the most commonly used as the reactant of in situ synthesized ceramic reinforced Inconel 718 coatings [14]. Results show that a large number of sub-grain boundaries appear in the TiC/Inconel 718 nanocomposite coatings, which significantly increases the hardness and wear resistance. Compared with TiC, B4C has more advantages to serve as the reactant of in situ synthesized ceramic reinforced Inconel 718 coatings. Firstly, due to the low molar mass of B4C, a small amount of B4C could form a large number of borides and carbides as hard phases that can significantly improve the hardness and the erosion resistance of the coating. Secondly, the borides generate from the reactions between B4C and Inconel 718 could provide heterogeneous nucleation sites for the Laves phase during the solidification, which could refine the size of Laves phase and improve the microhardness of the fabricated coatings. Finally, the in situ reactions between B4C and metallic materials always generate a large amount of heat [15]. The generated heat has the potential to be utilized to promote the melting of feedstock powders and reduce the laser energy input. As far as the authors know, there are no investigations on the fabrication of in situ synthesized ceramic reinforced Inconel 718 coatings using B4C-Inconel 718 powders. The in situ synthesis and characterization of the fabricated coatings are still unknown. In this study, the multi-component ceramic reinforced Inconel 718 coatings were successfully fabricated by laser DED process. The effects of B4C on molten pool size and temperature, element and phase compositions, microstructure, porosity, and mechanical properties of the fabricated coatings (including microhardness and wear resistance) were investigated.

2 Experimental procedures

2.1 Powder treatment

The powder materials used in this study were B4C powder (99.7% purity) (Atlantic Equipment Engineers Inc., Upper Saddle River, NJ, USA) and Inconel 718 powders (99.7% purity) (Carpenter Powder Products Inc., Bridgeville, PA, USA). A stainless steel 304 of 6.65 mm thickness was used as the substrate. The feedstock material powders (Inconel 718 and Inconel 718+2 wt% B4C) were adopted to fabricate coatings. As shown in Fig. 1, before the LDED process, B4C powder and Inconel 718 powder were mixed by a planetary ball milling machine (ND2L, Torrey Hills Technologies LLC., San Diego, CA, USA) for 4 h with the rotation speed of 200 rpm. The weight ratio of milling balls to powders was 1:1. B4C powders were mixed with Inconel 718 powders after the ball milling process.

2.2 Experiment setup

As shown in Fig. 2, experiments were conducted on an LDED machine (LENS 450, Optomec Inc., Albuquerque, NM, USA) equipped with a 400 W fiber laser source (YLM-1070, IPG Photonics, USA). Before the fabrication, to avoid the oxidization of B4C and Ti at a high temperature, argon gas was utilized to purge the chamber system. During the fabrication, the laser beam was generated and transformed to the substrate to generate a molten pool, which caught and melted the material
When the laser beam moved away, the molten pool was solidified to fabricate the first layer. After the fabrication of the first layer, the cladding head moved up the distance of a layer thickness to fabricate the second layer on the top surface of the first layer. By repeating this procedure, the coatings were fabricated layer by layer. The values or ranges of input fabrication variables are listed in Table 1.

2.3 Measurement procedures

During the fabrication, an infrared thermal camera (PYROVIEW 768 N, DIAS INC, Dresden, Germany) was used to obtain the thermal images of the molten pool. The infrared thermal camera was fixed in the chamber at a 20-cm distance to the molten pool. The professional software (PYROSOFT 3.22, DIAS INC, Dresden, Germany) was used to record the collected thermal data with a sample rate of 25 Hz. The phases of the fabricated coatings were analyzed by an X-ray diffraction (XRD) machine (Ultima III, Rigaku Corp., The Woodlands, TX, USA). The samples were scanned from 20 to 80° (2θ) with a scanning step of 0.02° (2θ), and the parameter in XRD tests are wavelength 0.154 nm, voltage 40 kV, and current 44 mA. Each peak was fitted by the MDI/JADE software (Version 2020, Materials Data, Livermore, CA, USA).

A scanning electron microscope (SEM) (Crossbeam 540, Carl Zeiss AG, Oberkochen, Germany) was used to observe the microstructure morphologies of the fabricated coatings. An energy-dispersive X-ray spectroscopy (EDS) system equipped was used to analyze the element compositions. Before the observation, a thin Iridium layer was coated on the samples to create excellent conductivity and the signal-to-noise ratio dramatically, resulting in crisp and clear SEM images. To further quantify the size and volume content of the reinforcements, the Image J software was utilized to process the SEM images for both Inconel 718 coatings and B₄C-Inconel 718 coatings under the mode of black and white. The volume fraction of Laves phase is quantified by the area ratio of Laves phase in the
cross-sectional surface. To obtain an accurate result, for both Inconel 718 coatings and B₄C-Inconel 718 coatings, five cross-sectional surfaces were analyzed to get the average volume fractions of Laves phases.

The microhardness of the deposited coating layers was tested by a Vickers microhardness tester (Phase II, Upper Saddle River, NJ, USA) with a 10-N normal load. Two samples fabricated by the LDED process were tested to measure the microhardness. For each sample, the microhardness test was performed ten times on random positions of the polished surface. The wear rate was tested and measured by dry sliding tests with a silicon carbide ball at room temperature using a mechanical testing system (PB1000, Nanovea, Manufacturer in Irvine, CA, USA). During the dry sliding test, the SiC ball was sliding on the surface of the coating for 15 min with a load of 0.2 N, a constant sliding speed of 3 mm/s, and a sliding distance of 3 mm. An OLYMPUS DSX-510 optical microscope (OM) (Tokyo, Japan) was used to observe the worn surface and obtain the scratching width after the dry sliding tests. The wear rate $W_r$ was calculated by Eq. (1).

$$W_r = \frac{V}{F(vT)}$$ (1)

where $V$ was the wear volume lost, mm$^3$; $F$ was the normal load, N; $v$ was the sliding speed, mm/s; and $T$ was the duration time, s.

### 3 Results and discussion

#### 3.1 Phase composition

Figure 3 shows the XRD results of the phase composition analysis on Inconel 718 coatings and B₄C-Inconel 718 coatings. In the XRD results of Inconel 718 coatings, the peaks matched up reasonably well for a γ Ni–Cr–Fe phase (PDF-# 65–0380) but were shifted to the left slightly. Most likely there were a small amount of other Nb-rich and Mo-rich precipitations doped into the structure. Similar results were also reported in the laser DED fabricated Inconel 718 parts [16, 17]. With the addition of B₄C, some new phases include Ni$_3$B (PDF-# 48–1223), NbB (PDF-# 32–0709), and Cr$_3$C$_2$ (PDF-# 65–0897) were identified by the XRD analysis. In addition, there was no peak representing B₄C in the XRD results. It could be confirmed that the feedstock B₄C powders were completely reacted with Inconel 718 to form multi-component ceramic reinforcements during the fabrication. Inconel 718 as a kind of nickel–chromium alloy also contained significant amounts of niobium, iron, and molybdenum along with lesser amounts of aluminum and titanium. Because of the instability of B₄C in liquid metallic materials, there were in situ reactions to form Ni$_3$B, NbB, and Cr$_3$C$_2$ phases:

$$12\text{Ni} + 4\text{Nb} + 3\text{Cr} + 2\text{B}_4\text{C} \rightarrow 4\text{Ni}_3\text{B} + 4\text{NbB} + \text{Cr}_3\text{C}_2$$ (2)
It could also be seen that compared with Inconel 718 coatings, the intensity of the Ni–Cr-Fe peaks in B₄C-Inconel 718 coatings was slightly decreased. The major reason was that Ni and Cr reacted with B₄C to form ceramics during the fabrication, reducing the content of Ni–Cr-Fe. The positions of Ni–Cr-Fe peaks in B₄C-Inconel 718 coatings were further shifted to the left, which was farther to the positions of the standard Ni–Cr-Fe phase. The peak shift indicated that the content of Nb-rich and Mo-rich precipitations (Laves phase) in B₄C-Inconel 718 coatings was higher than that in Inconel 718 coatings.

### 3.2 Molten pool size and temperature

The thermal image of the molten pool for the 3-layer single-track coatings (t = 25 s) and the maximum temperature during the fabrication are shown in Fig. 4. As shown in Fig. 4a, the shape of both Inconel 718 coatings and B₄C-Inconel 718 coatings was an irregular circle, when taking the melting point of the Inconel 718 (1450 °C) as the molten pool boundaries. With the same laser deposition input parameters of laser power, hatch distance, scanning speed, and powder feed rate, the molten pool size of B₄C-Inconel 718 coatings (~2.25 mm) was much larger than that of Inconel 718 coatings (~1.35 mm). As shown in Fig. 4b, the maximum temperature of Inconel 718 coatings was slightly increased from 1700 to 1800 °C during the fabrication due to the heat accumulation effects. As a comparison, the maximum temperature of B₄C-Inconel 718 coatings was much higher than Inconel 718 coatings, which were significantly increased from 1900 to 2200 °C during the fabrication. The higher temperature increasing rate and the higher maximum temperature of B₄C-Inconel 718 coatings indicated that the in situ reactions between B₄C and Inconel 718 released a large amount of heat [15]. A larger molten pool size and higher molten pool temperature had the potential to increase
the fluidity of the liquid materials in the molten pool, which could improve the bonding quality, coating density, and reinforcement distribution.

### 3.3 Element composition and microstructure

#### 3.3.1 Analysis of element composition

Figure 5 shows the element compositions of Inconel 718 coatings and B₄C-Inconel 718 coatings. In Inconel 718 coatings, there were white regions distributed in a grey matrix. Point 1 and point 2 were probed in the white regions and grey matrix regions, respectively. The element compositions of the white regions and grey matrix regions were shown in Table 2. Both white regions and grey matrix regions were rich in Ni, Cr, and Fe. Compared with grey matrix regions, white regions had a higher content of Nb and Mo and represented the Laves phase, which was generated during the solidification process through the segregation of Nb and Mo from the matrix [18, 19]. The grey matrix regions were Ni–Cr–Fe phase, in which the contents of Nb and Mo were lower than that in feedstock Inconel 718 powders. The reason was that the formation of Laves phase consumed the solid solution elements of Nb and Mo in the matrix.

Different from the Inconel 718 coatings, there were three kinds of regions in B₄C-Inconel 718 coatings. Besides the white precipitated regions and the grey matrix regions, there were also irregular black regions distributed near the white regions. The size and morphology of black regions were different from the feedstock B₄C powders, which could be considered as the in situ synthesized ceramic reinforcement. In the black regions, the major elements were Ni, B, Cr, and C. Compared with the grey matrix regions, the black regions had higher element content of B and C, indicating the black regions were mainly borides and carbides that were formed through the reactions between B₄C and Inconel 718. Combined with the

| Element | P1 atomic percent (%) | P2 atomic percent (%) |
|---------|----------------------|-----------------------|
| Ni      | 47.31                | 45.95                 |
| Cr      | 20.46                | 24.84                 |
| Fe      | 15.56                | 21.50                 |
| Nb      | 9.95                 | 3.47                  |
| Mo      | 5.16                 | 3.34                  |
| Ti      | 1.35                 | 0.67                  |
| Al      | 0.21                 | 0.23                  |

Table 2 Element composition of Inconel 718

| Element | P1 atomic percent (%) | P2 atomic percent (%) |
|---------|----------------------|-----------------------|
| Ni      | 29.63                | 51.40                 |
| B       | 29.28                | —                     |
| Cr      | 17.36                | 18.04                 |
| C       | 7.11                 | 7.30                  |
| Fe      | 6.55                 | 19.55                 |
| Nb      | 5.66                 | 1.45                  |
| Mo      | 2.91                 | 1.40                  |
| Ti      | 1.30                 | 0.32                  |
| Al      | 0.20                 | 0.54                  |

Table 3 Element composition of B₄C-Inconel 718
XRD results, the black regions could be confirmed as the in situ synthesized ceramic reinforcements of Ni$_3$B, NbB, and Cr$_2$C$_3$.

### 3.3.2 Analysis of microstructural morphology

Figure 6a shows the comparisons on microstructural morphologies of Inconel 718 coatings and B$_4$C-Inconel 718 coatings fabricated by laser DED process. In Inconel 718 coatings, it could be seen that the growth of long strip-shaped precipitated Laves phase was in the building direction (vertical direction). This phenomenon was caused by the unidirectional solidification direction. During the fabrication of Inconel 718 coatings and B$_4$C-Inconel 718 coatings by the laser DED process, the localized heat flux within the molten pool was the main factor influencing the grain growth, which was usually vertical downward due to the good thermal conductivity of Ti substrates [2]. The gradient of temperature in the vertical direction was higher than that in the horizontal direction, leading to the bottom-up generation of Laves phase.

With the addition of B$_4$C, the in situ formed ceramic reinforcements were generated along with the precipitated Laves phase. The ceramic reinforcements and Laves phase were uniformly distributed in laser DED fabricated B$_4$C-Inconel 718 coatings. The formation mechanism could be in three stages:

Firstly, the laser beam melted the substrates and generated a molten pool. As discussed in Sect. 3.1, the temperature of the molten pool reached the melting point of B$_4$C during the fabrication. Both B$_4$C and Inconel 718 powders were fully melted to form the liquid-state mixture. The added B element would react with part of liquid Nb and Ni constituent to form liquid NbB and Ni$_3$B.

Secondly, when the laser beam moved away, the liquid materials in the molten pool cooled down and started to be solidified. In the beginning, due to the high melting point, NbB and Ni$_3$B precipitated and grew into long strip particles, which provided nucleation sites for the Laves phase. Then, the Laves phase nucleated around the ceramics in the liquid Ni–Cr–Fe.

Finally, the liquid Ni–Cr–Fe solidified to generate the matrix. The in situ formed ceramics and precipitated Laves phase were uniformly distributed in the Ni–Cr–Fe matrix.

To further investigate the morphology, size, and volume fraction of precipitated Laves phase, the SEM images under the mode of black (matrix and ceramic reinforcement) and white (precipitated Laves phase) were shown in Fig. 6b. With the addition of B$_4$C, the size of

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**Fig. 6** Microstructure of laser DED fabricated Inconel 718 coatings and B$_4$C-Inconel 718 coatings. *The Laves phase was shown as the black regions in (b1) Inconel 718 and (b2) B$_4$C-Inconel 718.

|          | Inconel 718                                      | B$_4$C-Inconel 718 |
|----------|--------------------------------------------------|---------------------|
| Laves phase | 17.742%                                          | 6.396%              |

* The Laves phase was shown as the black regions in (b1) Inconel 718 and (b2) B$_4$C-Inconel 718.
precipitated Laves phase in B₄C-Inconel 718 coatings was decreased. The major reason was that the element B from the decomposition of B₄C reacted with Inconel 718 and then formed boride particles, which could act as the active nuclei in the molten pool. A large number of active nuclei increased the number of precipitated Laves phase grains in a certain melting volume, which suppressed the growth of Laves phase into a coarse strip-shaped structure during the solidification. It could be also seen that with the addition of B₄C, the volume fraction of Laves phase was significantly decreased from 17.742 to 6.396%. The major reason was that the Nb, an important constituent element of the laves phase, reacted with B₄C to form NbB during the fabrication, resulting in the lower Nb content in the molten pool. As a result, the formation of Laves phase in B₄C-Inconel 718 coatings was suppressed.

Similar results had been reported in the Inconel 625 with 0.4 wt% boron coatings fabricated by the gas tungsten arc deposition process [20].

### 3.4 Fabrication defects

The effects of B₄C on the fabrication defects of Inconel 718 coatings were shown in Fig. 7. It can be seen that the irregular-shaped defects were distributed in the Inconel 718 coatings. As a comparison, there was no irregular-shaped defect in the B₄C-Inconel 718 coatings. In the LDED process, the irregular-shaped fabrication defects on the cross sectional surface were usually caused by the lack of fusion, as demonstrated by Zhang et al. [21]. Since the molten pool size and temperature of B₄C-Inconel 718 coatings were much larger than that of Inconel 718
coatings (as discussed in Sect. 3.1), more feedstock powders could be caught and fully melted by the molten pool. The formation of sufficient overlaps was promoted, which could reduce the lack of fusion at the boundaries of the molten pool.

It can be also seen that there were also some micropores distributed in both Inconel 718 coatings and B₄C-Inconel 718 coatings. In the laser DED process, the cooling rate was extremely high. Entrapped gas bubbles were difficult to be efficiently expelled before the molten pool solidified [22]. Compared with Inconel 718 coatings, the number of micropores in B₄C-Inconel 718 coatings was much smaller than that in Inconel 718 coatings. There were two major reasons. Firstly, due to the heat generated from the in situ reactions between B₄C and Inconel 718, the molten pool of B₄C-Inconel 718 coatings had the thermodynamic conditions with higher fluidity. Gas bubbles could float upward faster and escape from the molten pool before the molten pool solidification. Secondly, the solidification process of B₄C-Inconel 718 coatings during the fabrication was extended by the exothermic reactions and the melting point depressant (B element), which could also promote the escape of gas bubbles [20].

3.5 Analysis of mechanical properties

3.5.1 Microhardness

Figure 8 shows the comparison of the microhardness of Inconel 718 coatings and B₄C-Inconel 718 coatings fabricated by laser DED process. The microhardness of B₄C-Inconel 718 coatings (348 HV) was significantly higher than that of Inconel 718 coatings (264 HV). As discussed in Sect. 3.3, ceramic reinforcement particles were uniformly distributed in the Ni–Cr–Fe matrix. These reinforcements had higher hardness than Inconel 718 alloy, which could bear the load during the microhardness tests. In addition, it was well known that a large amount of Laves phase in the form of long-strip morphology was detrimental to the strength and hardness of Inconel 718 since it depletes the elements needed for precipitation strengthening. With the addition of B₄C, the coarse and long strip-shaped Laves phase was changed to needle-shaped Laves phase with refined size, uniformed distribution, and lower volume fraction. The negative impacts of Laves phase on mechanical properties of Inconel 718 coatings were greatly reduced. In addition, the microhardness was positively correlated to the density. As discussed in Sect. 3.4, with the addition of B₄C, the fabrication defects and micropores were significantly decreased, which increased the ability to support the load and improve the microhardness.

3.5.2 Wear resistance

Figure 9 shows the differences in the morphology of worn surfaces between the Inconel 718 coatings and B₄C-Inconel 718 coatings. In the dry sliding tests of Inconel 718 coatings, scratches and a large area of coating delamination can be observed on the worn surface of the Inconel 718 laser cladding layer. These features indicated that local cold welds between the coating surfaces and silicon balls occurred under a load. Such phenomenon always occurred in adhesive wear, which had been reported by Hurricks [23]. In addition, some grooves could also be observed on the worn surface of Inconel
718 coatings, which occurred when a hard surface (SiC ball) pass over a soft surface (Inconel 718 coatings). The wear mechanism of Inconel 718 coatings in the dry sliding tests was the combination of adhesive wear and abrasive wear. Compared with Inconel 718 coatings, the worn surface of laser DED fabricated B$_4$C-Inconel 718 coatings showed less delamination and smoother grooves. The major reason was that the high hardness of the B$_4$C-Inconel 718 coatings made it difficult for the silicon ball to penetrate into the surface. The morphologies of the worn surfaces indicated that the abrasive wear played a dominant role in the B$_4$C-Inconel 718 coatings.

Figure 10 shows the wear rate of Inconel 718 coatings and B$_4$C-Inconel 718 coatings. The wear rate of B$_4$C-Inconel 718 coatings was much smaller than that of Inconel 718 coatings, indicating a higher wear resistance. As discussed in Sect. 3.5.1, the microhardness of B$_4$C-Inconel 718 coatings was much higher than that of Inconel 718 coatings. According to Archard’s wear equation, the volume of wear is inversely proportional to the hardness of the material. The higher hardness of B$_4$C-Inconel 718 coatings also had a great influence on the improvement of wear resistance. In addition, the metal matrix composite coatings with higher density always showed excellent wear resistance. Compared with Inconel 718 coatings, there were fewer fabrication defects in B$_4$C-Inconel 718 coatings, which were attributed to suppressing fracture and the spalling of hard particles and hard protuberances during the dry sliding test. Besides the effects of hardness and density on wear resistance, the wear mechanism also had great impacts on the wear resistance. The B$_4$C-Inconel 718 coatings with abrasive wear type had a smoother worn surface, which could reduce the coefficient of friction during the dry sliding test. Under the same test condition, the friction force was reduced, resulting in a smaller material removal volume and higher wear resistance.

**4 Conclusions**

In this study, the in situ synthesized semicontinuous network microstructural ceramic reinforced Inconel 718 coatings were fabricated by laser DED process. The in situ synthesis of the fabricated B$_4$C-Inconel 718 coatings and the effects of B$_4$C on the phase composition, microstructure, microhardness, and wear resistance were investigated. The major conclusions are drawn as follows:

1. During the laser DED process, there were reactions between B$_4$C and Inconel 718 to form Ni$_3$B, NbB, and Cr$_2$C$_3$. During the solidification, the needle-shaped NbB and Ni$_3$B whiskers were uniformly distributed in Inconel 718 matrix and provided nucleation sites for the Laves phase. With the addition of B$_4$C, the size and volume fraction of Laves phase were significantly reduced.

2. The in situ reactions generated a large amount of heat. The molten pool temperature was significantly increased, which could suppress the formation of the lack of fusion defects and micropores in B$_4$C-Inconel 718 coatings.

3. With the addition of B$_4$C, the microhardness of B$_4$C-Inconel 718 coatings was significantly increased due to the generation of ceramic reinforcements and the refinement of Laves phase. The wear mechanism of B$_4$C-Inconel 718 coatings was abrasive wear, which was different from the Inconel 718 coatings (adhesive and abrasive wear). The wear resistance of B$_4$C-Inconel 718 coatings was higher than Inconel 718 coatings because of higher hardness, lower porosity, and smoother worn surface.

**Availability of data and material** The data supporting the conclusions are included in the article.

**Declarations**

**Ethics approval** The authors confirm that they have abided by the publication ethics and state that this work is original and has not been used for publication anywhere before.

**Consent to participate** The authors are willing to participate in journal promotions and updates.

**Consent for publication** The authors give consent to the journal regarding the publication of this work.

**Conflict of interest** The authors declare no competing interests.
References

1. Ning F, Hu Y, Liu Z, Cong W, Li Y, Wang X (2017) Ultrasonic vibration-assisted laser engineered net shaping of Inconel 718 parts: a feasibility study. Procedia Manuf 10:771–778
2. Wang H, Hu Y, Ning F, Cong W (2020) Ultrasonic vibration-assisted laser engineered net shaping of Inconel 718 parts: effects of ultrasonic frequency on microstructural and mechanical properties. Ceram Int 276:116395
3. Hu Y, Cong W (2018) A review on laser deposition-additive manufacturing of ceramics and ceramic reinforced metal matrix composites. Ceram Int 44(17):20599–20612
4. Wang L, Felicelli S, Gooroochurn Y, Wang P, Horstemeyer M (2008) Optimization of the LENS® process for steady molten pool size. Mater Sci Eng A 474(1–2):148–156
5. Tabernero I, Lamikiz A, Martinez S, Ukar E, Figueras J (2011) Evaluation of the mechanical properties of Inconel 718 components built by laser cladding. Int J Mach Tools Manuf 51(6):465–470
6. Lambardi J, Leunda J, Navas VG, Soriano C, Sanz C (2013) Microstructural and tensile characterization of Inconel 718 laser coatings for aeronautical components. Opt Lasers Eng 51(7):813–821
7. Kim SH, Shin G-H, Kim B-K, Kim KT, Yang D-Y, Aranas C, Yu J-H (2017) Thermo-mechanical improvement of Inconel 718 using ex situ boron nitride-reinforced composites processed by laser powder bed fusion. Sci Rep 7(1):1–13
8. Zemzemi F, Rech J, Salem WB, Dogui A, Kapsa P (2014) Identification of friction and heat partition model at the tool-chip-workpiece interfaces in dry cutting of an Inconel 718 alloy with CBN and coated carbide tools. Adv Manuf Sci Technol 38(1)
9. Sahu SK, Jadam T, Datta S, Nandi G (2018) Effect of using SiC powder-added dielectric media during electro-discharge machining of Inconel 718 superalloys. J Braz Soc Mech Sci Eng 40(7):1–19
10. Yu Z, Tan H, Wang S, Cheng J, Sun Q, Yang J, Liu W (2020) High-temperature tribological behaviors of MoAlB ceramics sliding against Al2O3 and Inconel 718 alloy. Ceram Int 46(10):14713–14720
11. Zhang D, Li Y, Wang H, Cong W (2021) An investigation on Ni4Ti3 phase precipitation and its effects in laser directed energy deposition of TiC–NiTi composites. Mater Sci Eng A 809:140976
12. Zhang X, Song F, Wei Z, Yang W, Dai Z (2017) Microstructural and mechanical characterization of in-situ TiC/Ti titanium matrix composites fabricated by graphene/Ti sintering reaction. Mater Sci Eng A 705:153–159
13. Xia M, Liu A, Hou Z, Li N, Chen Z, Ding H (2017) Microstructure growth behavior and its evolution mechanism during laser additive manufacture of in-situ reinforced (TiB+ TiC)/Ti composite. J Alloys Compd 728:436–444
14. Muvvala G, Karmakar DP, Nath AK (2018) In-process detection of microstructural changes in laser cladding of in-situ Inconel 718/TiC metal matrix composite coating. J Alloys Compd 740:545–558
15. Zhao Y, Yu T, Sun J, Jiang S (2020) Microstructure and properties of laser cladded B4C/TiC/Ni-based composite coating. Int J Refract Met Hard Mater 86:105112
16. Liu Y, Li X, Li Y, Zhao Z, Bai F (2016) The lattice distortion of nickel particles generated by spark discharge in hydrocarbon dielectric mediums. Appl Phys A 122(3):174
17. Kaynak Y, Tascioglu E (2018) Finish machining-induced surface roughness, microhardness and XRD analysis of selective laser melted Inconel 718 alloy. Procedia Cirp 71:500–504
18. Radhakrishna C, Rao KP (1997) The formation and control of Laves phase in superalloy 718 welds. J Mater Sci 32(8):1977–1984
19. Janaki Ram G, Venugopal Reddy A, Prasad Rao K, Madhusudhan Reddy G (2004) Control of Laves phase in Inconel 718 GTA welds with current pulsing. Sci Technol Weld Join 9(5):390–398
20. Tian Y, Ouyang B, Gontcharov A, Gauvin R, Lowden P, Brochu M (2017) Microstructure evolution of Inconel 625 with 0.4 wt% boron modification during gas tungsten arc deposition. J Alloys Compd 694:429–438
21. Zhang B, Li Y, Bai Q (2017) Defect formation mechanisms in selective laser melting: a review. Chin J Mech Eng 30(3):515–527
22. Li Y, Zhang D, Wang H, Cong W (2021) Fabrication of a TiC-Ti matrix composite coating using ultrasonic vibration-assisted laser directed energy deposition: the effects of ultrasonic vibration and TiC content. Metals 11(5):693
23. Herricks P (1973) Some metallurgical factors controlling the adhesive and abrasive wear resistance of steels. A review Wear 26(3):285–304

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