The water droplet erosion resistance of Ni-based composite coating through laser cladding

Yuling Gong¹,², Chen Cui¹,³, Meiping Wu¹,³*, and Xiaojin Miao¹,³*,

¹ College of Mechanical Engineering, Jiangnan University, Wuxi 214122, People’s Republic of China
² School of Shipping and Mechatronic Engineering, Taizhou University, Taizhou 225300, People’s Republic of China
³ Jiangsu Key Lab Adv Food Mfg Equipment & Technol, Wuxi 214122, People’s Republic of China
* Authors to whom any correspondence should be addressed.

E-mail: wumeiping163@163.com and miaoxiaojin126@126.com

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Abstract

Water droplet erosion (WDE) usually occurs in TC4 turbine blades under actual working conditions, which seriously endangers the safe and stable operation of the turbine. To solve the problem of WDE in TC4 turbine blades under high-speed solid-liquid impact, CeO₂/Ni₆₀A composite coatings with different laser powers were successfully developed on the surface of TC4 by using laser cladding technology. The working environment of the turbine blade under high-speed solid-liquid impact was simulated by water jet technique, and the effect of laser power on the coating resistance to water droplet erosion was analyzed. It can be seen from the results that the coating was composed of α-Ti, Ti₂Ni, TiB₂ and TiC, and laser power had a significant influence on the growth of grain structure. At 6000 W laser power, the average microhardness of the coating reached 1105 HV₀.₃, i.e., 3.25 times of TC4 substrate. However, too high laser power made the hard phases of TiC and TiB₂ brittle. In the water droplet erosion experiment, the high power resulted in the cracks in the coating. At the laser power of 5000 W, the grain refinement effect was the best. The width and depth of water erosion were 0.908 mm and 0.148 mm, respectively, which were lower than TC4 substrate by 27.5% and 41.5% times. The preparation of CeO₂/Ni₆₀A coatings on the surface of TC4 alloy was effective to solve the problem of WDE in TC4 turbine blades and prolong the service life of TC4 blades. Moreover, the finer the grain structure in the coating, the better the WDE resistance.

1. Introduction

The power of steam turbine increases gradually with the rapid development of electric power industry, which inevitably puts forward higher requirements for the manufacture of steam turbine blades [1, 2]. TC4 titanium alloy has gradually become the manufacturing material of steam turbine blades due to its advantages of high specific strength, low density, high temperature resistance, etc. However, steam turbine blades, especially the last-stage blades, are easily damaged by Water Droplet Erosion (WDE) when working in the wet steam environment for a long time, undoubtedly threatening the efficiency of steam turbine. Basically, WDE phenomenon is essentially an energy conversion process of moving water droplets impacting the blade surface [3, 4]. The high-speed water droplets impact the metal surface to form a large instantaneous force [5, 6]. When exceeding the yield strength of the metal material, the instantaneous force will cause residual deformation on the surface [7]. The repeated impact of water droplets on the metal surface will lead to the gradual development of microcracks and expansion, resulting in the falling-off of a large number of metal particles, and the WDE of turbine blades [8, 9].

In recent years, researchers have carried out extensive researches on WDE of turbine blades, and tests based on high-speed water-jet technology [10–12]. Oka et al [13] implemented the WDE tests with 0.4 mm diameter jet, and analyzed the damage of samples under different jet pressure and impact velocity. After the experiment, the WDE resistance of the sample was evaluated based on the water erosion depth. Seleznev [14] evaluated the
WDE corrosion resistance by the mass loss of the sample under high-speed solid-liquid impact. Mahdipoor [4] concluded that the microstructure of the sample was closely related to the WDE resistance. At the jet diameter of 460 μm and the impact velocity of 350 m s⁻¹, the mass loss of the sample with uniform microstructure was lower. Kirols et al [2] studied the effect of surface roughness of TC4 material on WDE resistance. During the experiment, when the surface roughness of TC4 changed from 37 to 12 μm, the erosion damage of TC4 was mitigated. However, with the surface roughness changing from 12 to 1 μm, the mass loss of the material remained almost unchanged.

For the improvement of the WDE resistance of TC4 turbine blade, it is effective to strengthen the TC4 alloys by using surface modification technology [15–17]. As an advanced surface strengthening technology, laser cladding technology is popular in industrial production [12, 18]. Nevertheless, the laser process parameters show a significant impact on the performance of the coating, and the reasonable selection of the appropriate laser power could have a positive effect on the WDE resistance of the coating [19–21].

During this experiment, CeO₂/Ni60A coatings with different laser power were prepared on the surface of TC4 alloy. And the influence of laser power on the microstructure, microhardness and water erosion resistance of the coating was investigated. This paper aims to explore whether CeO₂/Ni60A coating is available for the improvement of the WDE resistance of TC4 alloy, and the factors correlated with the WDE resistance of CeO₂/Ni60A coating. The research of this paper could lay a theoretical foundation for the subsequent laser cladding to strengthen the WDE resistance of TC4 blade.

### Table 1. Chemical composition of TC4 substrate and Ni60A powder (wt.%).

| Elements (wt.%) | Materials | Ti | Al | V | C | Fe | N | B | Si | Cr | Ni |
|----------------|-----------|----|----|---|---|----|---|---|----|----|----|
| Ti6Al4V        | Bal       | 6.03 | 4.01 | 0.10 | 0.30 | 0.01 | — | — | — | — | — |
| Ni60A          | —         | — | — | — | 0.90 | 8.00 | — | 3.30 | 4.30 | 16.00 | — |

2. Experimental method and materials

2.1. Materials

Today, scholars have not reached an agreement on the standard for the study of the WDE performance. In most cases, the researchers utilize plates for water drop erosion test. However, the specific size is not unique, which is generally determined based on the size of high-pressure water-jet machine tool. In this paper, the size of water jet machine tool is large, therefore, the TC4 plate in the size of 120 mm × 120 mm × 10 mm is selected. The Ti-6Al-4V (TC4) titanium alloy cuboid plate (Nanjing Zhongke Yuchen Material Co., Ltd) was taken as the substrate. Prior to the preparation of the coating, the surface of TC4 was sandblasted to improve the uniformity of materials absorption. The particle sizes of Ni60A and CeO₂ (Hebei New Material Co., Ltd) are 25–50 μm and 10–150 nm, respectively with the morphology of Ni60A and CeO₂ powder shown in figure 1. The CeO₂/Ni60A composite powder at 2 wt.% was prepared and put into planetary mill for 3 h to obtain the homogeneity of mixed powder. At last, the composite powder was treated in the dryer at the drying temperature of 80 °C for 2 h. Table 1 lists the chemical composition of TC4 substrate and Ni60A powder.
2.2. Preparation of coating

The CeO$_2$/Ni60A composite coatings were prepared on TC4 substrate by using wide-spot laser cladding equipment (LDF 10000-60, Laser Line, Germany) which consists of powder feeding system, numerical control system, optical system, water cooling system and atmosphere protection system. The laser works in continuous mode at the wavelength of 960–1060 nm ± 10 nm. In the process of laser cladding, the forming process of coating involved the NC system and six axis linkage robots to ensure the uniformity of scanning speed. The laser cladding process follows the gravity powder feeding method, with Ar as the shielding gas and powder feeding gas. The preparation parameters of the CeO$_2$/Ni60A composite coatings are shown in table 2.

| Specimen | Laser power | Scan speed | Powder feed rate | Spot diameter | Gas flow rate |
|----------|-------------|------------|-----------------|---------------|---------------|
| C1       | 4000 W      | 10 mm s$^{-1}$ | 60 g min$^{-1}$ | 10 mm         | 11 l min$^{-1}$ |
| C2       | 4500 W      |             |                 |               |               |
| C3       | 5000 W      |             |                 |               |               |
| C4       | 5500 W      |             |                 |               |               |
| C5       | 6000 W      |             |                 |               |               |

2.3. Water drop erosion experiment

For the research of WDE, taking a reference to the previous experimental research methods [22, 23], the authors kept the relative position of the sample unchanged, and employed the high-speed jet for the simulation of the target impact conditions. In this experiment, high-speed solid-liquid impact test was carried out by using high-pressure numerical control water jet machine (DWJ3020-BB-X5, Nanjing Dadi water jet Co., Ltd), which consists of four parts, i.e., CNC machining platform, control system, high-pressure water generation system and cooling system. The schematic diagram of WDE experiment is shown in figure 2, and the specific test parameters are listed in table 3.

| Parameters | Jet pressure | Jet diameter | Erosion distance | Moving speed | Erosion time | Impact speed |
|------------|--------------|--------------|------------------|--------------|--------------|--------------|
| Value      | 250 MPa      | 1 mm         | 10 mm            | 10 mm s$^{-1}$ | 100 min      | 500 m s$^{-1}$ |

2.4. Characterization

The phase composition of the coating was analyzed by an x-ray diffractometer (XRD-6100, Japan) under 40 kV and 150 mA, and the diffraction angle of 20°–90° was scanned at the rate of 8° min$^{-1}$. The cross-section of the CeO$_2$/Ni60A coating was polished by a polishing machine, and the corrosion solution of 10 HF + 10HNO$_3$ + 80H$_2$O (vol%) was used for the corrosion of the cross-section of the coating. The
scanning electron microscope (SEM, SIGMA HD, Germany) equipped with Energy Dispersive Spectrometer (EDS, 51-XMX1003, Germany) was utilized for the observation of the microstructure of the coating. Based on the thickness of the coatings, the microhardness of the coating was tested using a microhardness tester (HVS-1000ZCM-XYY, CHINA) with the applied load of 300 N and the holding time of 30 s. At the completion of the WDE experiment, the damage morphology of the coatings was observed by SEM with the width and depth of the damage analyzed by white light interferometer.

3. Results and discussions

3.1. XRD results

Figure 3 shows the x-ray diffraction patterns of CeO$_2$/Ni60A coating under the laser power of 5000 W. As indicated by the XRD results, the phase of the coating was composed of Ce$_2$O$_3$ (PDF#44-1086), $\alpha$-Ti (PDF#44-1294), TiB$_2$ (PDF#35-0741), TiC (PDF#32-1383) and Ti$_2$Ni (PDF#18-0898). Heated by the laser heat source, CeO$_2$/Ni60A powder and TC4 substrate melted simultaneously to form a melt pool. In this case, the elements in the melt pool contained both powder elements and the substrate ones. Consequently, complex physical and chemical changes occurred during the laser melting process, and the reactions in the melt pool were expressed as...
follows [24]

\[
2\text{Ce} + 3\text{O} \rightarrow \text{Ce}_2\text{O}_3
\]

\[
\text{Ti} + 2\text{B} \rightarrow \text{TiB}_2
\]

\[
2\text{Ti} + \text{Ni} \rightarrow \text{Ti}_2\text{Ni}
\]

\[
\text{Ti} + \text{C} \rightarrow \text{TiC}
\]

3.2. Cross-sectional morphology

Figure 4 displays the cross-sectional geometry of C1-5. As we can see, the top surface of CeO$_2$/Ni$_{60}$A coating was an approximate ellipse. The bonding area between the coating and TC4 substrate are presented in two forms, one is a flat straight line, as shown in figure 4(a), and the other is a wavy line shown in figures 4(b)–(e). The high-power laser beam followed the characteristics of Gaussian distribution, that is, the energy in the middle of the coating was relatively high, while the energy on both sides was low, which accounts for the elliptical feature on the top of the coating. At the laser power of 4000 W, the size of the molten pool was relatively small, and the bonding area between the TC4 substrate and the coating was even, thereby forming a flat straight line. There was no doubt that the size of the molten pool increased with the laser heat source absorbed by the molten pool, leading to the inhomogeneity of interface heat transfer. Therefore, the interface bonding area was a wavy line, and the larger the laser power, the larger the amplitude of wavy line.

Due to the Marangoni convection effect [25], the molten pool always flows from the center to both sides. The laser power has a significant effect on the extension of Marangoni convection in the molten pool. The Marangoni coefficient is an index to judge the extension of Marangoni convection, and the formula is as follows.

\[
\text{Ma} = \frac{\frac{\partial \gamma}{\partial T} \Delta TL}{\mu \alpha}
\]

where $\frac{\partial \gamma}{\partial T}$ denotes the temperature coefficient of surface tension, $\Delta T$ refers to the temperature difference between the center and the edge of molten pool, $L$ represents the radius of weld pool, $\mu$ is the viscosity of the molten pool, and $\alpha$ refers to the thermal diffusivity.

As the laser power increased from 4000 W to 6000 W, Ma increased with the increase of $\Delta T$ and $L$. In the meantime, $\mu$ decreased. As shown in figure 4, the width of C1-5 was 13.03 mm, 13.62 mm, 14.12 mm, 16.05 mm, 16.58 mm, respectively and the depth increased from 0.87 mm to 2.06 mm. Ma is in direct proportion to the depth and width of the coating. However, at the laser power of 5500 W and 6000 W, cracks appeared along the interface, as shown in figures 4(d)–(e). Besides, longitudinal cracks appeared in C2 and C5 coatings as well. Laser cladding technology is characterized by rapid heating and rapid cooling. In the process of coating preparation, large temperature gradient may result in residual stress in the coating, and eventually lead to the cracks in the coating [26]. When studying the temperature field of the coating, it is difficult to obtain the temperature field distribution of the coating directly by experimental means. Therefore, it is an effective method to study the temperature field characteristics of laser cladding by using the finite element analysis software.
3.3. Temperature field simulation
The temperature distribution of CeO2/Ni60A composite coating on TC4 substrate was simulated by using the APDL module of ANSYS 19.0 software. And the simulation parameters were consistent with the process parameters of the laser cladding experiments. The initial conditions were defined by the following formula.

\[ T(x, y, z, 0) = T_0(x, y, z, 0) \]

where \( T_0 \) denotes the room temperature set as 298 K.

The boundary condition was expressed by the following formula.

\[ -k \left( \frac{\partial T}{\partial Z} \right)_{Z=0} = Q - h(T_a - T_s) - \sigma \varepsilon (T_a^4 - T_s^4) \]

where \( k \) denotes the thermal conductivity of the materials, \( Q \) refers to the heat flow rate, and \( h \) represents the thermal convection coefficient. \( T_a \) is the room temperature, \( T_s \) refers to the temperature of the coating surface, \( \sigma \) represents the Stefan-Boltzmann constant, and \( \varepsilon \) is the thermal radiation coefficient. Gauss heat source was used for the simulation of the temperature field, defined as follows.

\[ I(r) = \frac{2AP}{\pi\omega^6} \exp \left( -\frac{2r^2}{\omega^2} \right) \]

where \( A \) denotes the laser energy absorption coefficient, \( P \) refers to the laser power, \( r \) represents the distance from the center of the spot, and \( r_0 \) is the diameter of the spot.

Figure 5 shows the temperature field distribution of C1-C5, from which it can be clearly seen that C1-5 have a similar temperature field, and the location of the heat affected zone is roughly the same. The temperatures at the top of the C1-5 molten pool include 3890 \(^\circ\)C, 4271 \(^\circ\)C, 4651 \(^\circ\)C, 5037 \(^\circ\)C, 5418 \(^\circ\)C, respectively, as shown in figure 6. With the increase of laser power, the heat absorbed by the coating and the temperature of the molten pool increased, moreover, the temperature difference between the top of the molten pool and the interface also increased. The generation of the cracks at the interface of C4 and C5 specimens could be explained in a way that there were differences between TC4 substrate and CeO2/Ni60A powder in terms of thermophysical parameters (such as thermal expansion coefficient, thermal conductivity, etc), which may result in uneven temperature field in the interface bonding area. In addition, the larger temperature gradient in the molten pool will produce the residual stress, leading to the cracking of the coating. In this manner, the cracks were formed, as shown in figures 4(d)–(e). As for the longitudinal crack shown in C2, we concluded that the reason lies in the lower energy absorbed by the molten pool. Compared with C1 and C2, C2 had a larger pool size, which reduced the heat input into the same area. Therefore, the CeO2/Ni60A molten pool in C2 could not melt completely at low laser power, which may cause the decrease of coating fluidity and the formation of cracks.
3.4. Microstructure

Considering the temperature field distribution in figure 5, the coating could be divided into top, middle and bottom regions, respectively, and figure 7 displays the microstructure of C1-5 in the three regions. Four kinds of microstructure exist in C1-5, that is, black massive phase, gray short rod phase, light gray flake phase and white bright granular phase. EDS analysis was made to further determine the element composition of the four phases with the results shown in table 4. It was found from the results of XRD that the light gray flake phase (Point A) mainly consists of the elements of Ti and Ni at the atomic ratio between them of about 2:1, therefore, the light gray flake phase was considered as Ti₂Ni. On the other hand, the gray short rod phase (Point B) is mainly composed of the elements of Ti and C with the atomic ratio of approximately 1:1, in this case, the gray short rod phase was considered as TiC. Similarly, the black massive phase (Point C) mainly includes the elements of Ti and B, and the atomic ratio between Ti and B is about 1:2, so the black massive phase was considered as TiB₂. There was no doubt that the white bright granular phase (point D) was considered to be Ce₂O₃.

When the TC4 substrate and CeO₂/Ni60A composite powder are irradiated by the laser source, the substrate and powder melt at the same time, thus forming a molten pool. The temperature field simulation in figure 5.
illustrated that the temperature could be as high as over 3500 °C during the coating preparation. The melting points of the hard phases of TiB$_2$ (3250 °C) and TiC (3067 °C) [27, 28] were extremely high, therefore, TiB$_2$ and TiC preferentially precipitated and nucleated from the molten pool. With the withdrawal of the heat source, the temperature of molten pool decreased gradually. In this process, TiB$_2$ and TiC continued to grow into black

![Figure 8](image)

**Figure 8.** Schematic diagram of the growth model of the TiC and TiB$_2$.

| Elements | Points |
|----------|--------|
| Ti       | Cr     | Fe     | Ni     | Mo     | Al     | C      | Si     | V      | B      | O      | Ce      |
|----------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|---------|
| A        | 49.08  | 8.30   | 1.22   | 25.17  | —      | 7.03   | —      | 6.87   | 2.32   | —      | —       |
| B        | 41.02  | 5.65   | 0.21   | 2.99   | 3.00   | —      | 46.19  | 0.94   | —      | —      | —       |
| C        | 31.15  | —      | —      | —      | —      | 1.21   | 2.83   | —      | 0.64   | 64.17  | —       |
| D        | —      | —      | —      | —      | —      | —      | —      | —      | —      | —      | 62.31   | 37.69   |

**Table 4.** EDS analysis of the phases (at%) in figure 7.
block and gray short rod, respectively. In most cases, TiB$_2$ shows hexagonal C32 structure, and TiC exhibits a NaCl type face centered cubic structure, as shown in figure 8. It is worth noting that the TiC phase was partly grown based on the ratio of nucleation alone, while the other one was in the state of TiC + TiB$_2$, which is due to the fact that, profiting from the high melting point of TiB$_2$, TiB$_2$ phase precipitates preferentially. However, the element of B as insufficient, while Ti and C were excessive when TiB$_2$ phase continues to grow. At this time, the saturation of Ti and C reached the nucleation condition of TiC, and the TiC phase precipitated in the coating. In addition, TiB$_2$ formed the core of TiC heterogeneous nucleation. Figure 8 depicts the forming diagram of TiC and TiB$_2$ in the molten pool.

Figure 6 illustrates the temperature curve of C1-5 from the top of coating to TC4 substrate. It can be clearly seen that the laser heat source made the coating temperature rise sharply, and then cool rapidly. The temperature of the molten pool reached the highest point after about 1 s, which tended to be stable after 20 s. The top of the molten pool was not conducive to the formation of microstructure due to the contact with the outside gas. As a result, the microstructure of the top of the coating showed insufficient growth with small grain size. The hard phase (TiC + TiB$_2$) in CeO$_2$/Ni$_{60}$A coating grew well in the middle of the coating, as shown in figure 7. In addition, with the increase of the laser power, the size of the hard phase in the middle region increased. It can be found from figure 6 that extremely high laser power made the molten pool stay longer in the high temperature region, providing energy for the growth of TiB$_2$ and TiC phase. At the interface between CeO$_2$/Ni$_{60}$A coating and TC4 substrate, the hard phase appeared for C4 and C5, which is because that the low laser power limited the heat absorbed by the molten pool. In the meantime, the temperature of the molten pool could not reach the melting point of TiB$_2$ and TiC, therefore, TiB$_2$ and TiC structures failed to appear at the bottom of C1-C3 coating. Nevertheless, the hard phase at the bottom of the coating was not beneficial to the performance of the coating. The formation of a large number of hard phases weakened the toughness and strength of the coating, and made the coating brittle [29], which was also one of the reasons for the generation of the cracks at the interface of C4 and C5 coatings [30]. Thus, laser power played an important role in the determination of the properties of coatings. Ce, as a kind of surfactant, was mainly distributed at the grain boundary of the coating, as shown in figure 8. According to the report of Liu et al [24], rare earth oxides are available for the reduction of the Gibbs free energy and critical nucleation work required for hard phase nucleation, and contribute to the formation of hard phase.

3.5. Microhardness

Figure 9 depicts the trend of microhardness of C1-5 coating. It could be seen clearly that the microhardness of the TC4 substrate is about 340 HV$_{0.3}$. According to the distribution of coating microhardness, the coating could be divided into coating zone, heat-affected zone, and substrate zone [31, 32]. C1-C5 showed high hardness in the coating zone, and the microhardness decreased sharply in the heat-affected zone. At last, the microhardness remained the same as TC4 when reaching the substrate zone. Seen from the coating zone, all the microhardness values of the C1-C5 coatings exceeded 800 HV$_{0.3}$, indicating that preparing CeO$_2$/Ni$_{60}$A coating was a proven method for the improvement of the microhardness of TC4. In addition, another remarkable feature was that there was a small increase in microhardness with the increase of
the distance from the coating surface in the coating zone. The reason lies in the microstructure distribution of the coating. The top of the coating has less hard phases (TiC and TiB$_2$), which makes it hard to resist the force of 300 N. On the contrary, the middle part of the coating is rich in hard phases distributed, hindering the plastic deformation.

The higher the laser power used to prepare the coating, the higher the microhardness of the coating. The higher melt pool temperature will facilitate the growth of hard phase. Besides, the microhardness of the coating becomes higher when larger size of TiC and TiB$_2$ present on the coating surface. Within the coating area, the average microhardness of C1-C5 was 826 HV$_{0.3}$, 889 HV$_{0.3}$, 965 HV$_{0.3}$, 1033 HV$_{0.3}$ and 1105 HV$_{0.3}$, respectively, which indicates that the laser power had a significant effect on the microhardness of the coating. In the heat-affected zone, the elements in the CeO$_2$/Ni60A coating were heavily diluted into the TC4 substrate, thereby

![Figure 10. Macroscopic morphology of WDE area of TC4 and C1-5: (a) TC4 substrate; (b) P = 4000 W; (c) P = 4500 W; (d) P = 5000 W; (e) P = 5500 W; (f) P = 6000 W.](image)

| Table 5. WDE depth and width of TC4 and C1-5 coatings (µm). |
|-----------------|----------------|----------------|----------------|----------------|----------------|
| Samples         | TC4 substrate | C1             | C2             | C3             | C4             | C5             |
| Depth           | 0.253          | 0.235          | 0.218          | 0.148          | 0.167          | 0.209          |
| Width           | 1.252          | 1.107          | 1.044          | 0.908          | 0.958          | 1.013          |
significantly reducing the microhardness but contributing to the bond strength between the coating and the substrate [33].

3.6. WDE resistance

Figure 10 shows the three-dimensional morphology of TC4 substrate and C1-5 obtained by white light interferometry after the water droplet erosion experiments. The width and height of the water erosion morphology were measured by Gwyddion software with the results listed in Table 5. It can be clearly seen that the TC4 substrate suffered the largest width (1.252 mm) and depth (0.253 mm) of water droplet erosion. The widths of C1-C5 coatings under erosion were 1.107 mm, 1.044 mm, 0.908 mm, 0.958 mm, and 1.013 mm, respectively, and the depths were 0.235 mm, 0.218 mm, 0.148 mm, 0.167 mm, and 0.209 mm, respectively, showing that the CeO$_2$/Ni60A coating had a positive effect on the improvement of WDE resistance of TC4 substrate. It is noteworthy that the erosion degree of the coating by high-speed droplets was highly dependent on the laser power. Different from the pattern of hardness, the WDE resistance of the coating did not increase with the increasing laser power. At the laser power of 5000 W, the coating showed the highest WDE resistance. However, the WDE resistance of the coating decreased with the continuous increase of the laser power. In addition, it was found that the erosion width of TC4 substrate (1.252 mm) was larger, while that of C1-5 remained at about 1 mm, which was the diameter of water jet nozzle. During the WDE test, the expansion rate of water jet in terms of erosion width was low, while the depth of dormitory increased with the test time. In the initial stage of the WDE test, the high-speed jet could expand freely, therefore, the growth rate of the width was faster. However, when the width was expanded to the diameter of the water jet, the water jet was subject to greater lateral restraint, which made the impact direction of the water jet more concentrated. Therefore, the erosion morphology expanded in the depth direction, and slowly in the width direction.

Figure 11. WDE morphology of TC4 and C1-5 coatings: (a) TC4 substrate; (b) $P = 4000$ W; (c) $P = 4500$ W; (d) $P = 5000$ W; (e) $P = 5500$ W; (f) $P = 6000$ W.
To further investigate the damage of coating and substrate due to WDE, SEM morphological analysis of the substrate and coating was performed. As shown in Figure 11(a), the high-speed water droplets exerted a huge instantaneous impact force on TC4 substrate, and discrete pits was observed at the beginning of the WDE experiments. With the increase of the test time, the impact of high-speed water particles made the pits on the surface of the substrate gradually increase in terms of number, and expand into deeper and wider pits, as shown in Figure 11(a). When the CeO2/Ni60A coating was prepared on the surface of TC4, the WDE erosion effect was mitigated. Figure 11(b) shows the WDE morphology of the coating at the laser power of 4000 W. Compared with TC4 substrate, only small pits appeared in the coating. The reinforced phases, such as TiC, TiB2 and Ti2Ni were formed in the coating, and these microstructure function as the ‘skeleton’. During the WDE process, these reinforcing phases is able to resist the impact of high-speed water droplets, and reduce the deformation caused by water droplets, resulting in the improvement of the WDE resistance. In the case that the laser power was increased from 4000 W to 5000 W, the WDE resistance of the coating was improved both in terms of three-dimensional morphology and WDE morphology. In particular, C3 specimens exhibited the smoothest surface morphology after the WDE test, and the depth and width of erosion were the lowest. Compared with TC4, the depth and width of WDE were reduced by 41.5% and 27.5%, respectively.

However, C4 appeared a plethora of microcracks after WDE, and showed a tendency to spalling. The length and width of the crack shown in Figure 11(f) were measured by using Auto-CAD software. And it was found that the crack with a length of 260 μm and a width of 8 μm appeared in C5 due to the changes in the C1-5 microstructure. The laser power at lower value was not favorable for the growth of the hard phase, therefore, the resistance to plastic deformation was limited. As can be seen from Figure 7, C3 had a finer TiB2 and TiC grain size, and according to the Hall-Petch relationship, the smaller the size of TiB2 and TiC in the coating, the more grain boundaries in the same area of the coating. The existence of grain boundaries could effectively impede the dislocation movement, therefore, when high-speed water particles hit the coating surface, the refined grains greatly impeded the dislocation movement, which ultimately enhanced the ability to resist the plastic deformation and crack expansion. At the laser power of 6000 W, these larger sizes of TiB2 and TiC showed high brittleness despite their high microhardness. Consequently, TiB2 and TiC were highly susceptible to fracture in the WDE test, leading to the increase of WDE. The coarse TiB2 and TiC were more sparsely distributed in the coating, which results in more α-Ti in the coating. In the WDE experiment, the soft α-Ti was eroded first, leaving the hard phase in contact with the high-speed water particles. Eventually, the hard phase fractured or flaked off directly, and cracks formed in the coating surface and gradually expanded.

4. Conclusions

In this study, the CeO2/Ni60A coatings were successfully prepared on TC4 Alloy by laser cladding. The main conclusions were drawn as follows.

(1) The width and depth of the coating increased with the increase of laser power. However, high laser power made the coating produce hard phases of TiB2 and TiC in the interface bonding area, which was not conducive to improving the metallurgical bonding ability.

(2) The increase of laser power was beneficial to the growth of the hard phase of TiB2 and TiC. With larger size of hard phase, the microhardness of the coating became larger as well. When the laser power was 6000 W, the average microhardness of the coating reached 1105HV0.3, which was 3.25 times of TC4 substrate. The formation of hard phase showed an excellent resistance to the applied load of 300 N.

(3) When the grain structure was refined, the coating exhibited higher resistance to the plastic deformation and cracks. Therefore, when the laser power was 5000 W, compared with TC4, the depth and width of WDE were reduced by 41.5% and 27.5%, respectively, showing the highest resistance to water drop erosion.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

ORCID iDs

Meiping Wu https://orcid.org/0000-0001-6213-4360
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