Microstructure and Properties of Laser Cladding Coating on the Surface of Superalloy Ti600

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Abstract. The laser cladding technology was used to prepare the Ti / TiB$_2$ composite coating on the surface of Ti600, and the microstructure and performance test results of the coating obtained under different laser specific energy conditions were analyzed. Studies have shown that the laser cladding coating and the substrate have achieved a good bond, and TiB$_2$ has formed into cellular TiB$_2$ after melting, and further solid solution becomes a whisker structure. The diffused TiC and TiN nuclei in the middle of the coating were fully grown and developed a dense dendrite structure with TiB$_2$ particles. A dual-phase structure of granular TiB$_2$ and many lamellar structures was formed under the coating. When the laser specific energy is 20 kJ / cm$^2$, the coating reaches the highest microhardness of 990HV, nearly 2.5 times the hardness of the substrate. The amount of wear shows a monotonic decrease with the increase of the specific energy of the laser, and the average friction coefficient shows a monotonous decrease as the specific energy of the laser increases.

1. Introduction

Ti600 has high strength and good thermal stability. The lamellar structure can obtain a good match of strength and plasticity, and excellent creep properties [1]. It has been widely used in aviation, chemical equipment, high-precision machinery, etc. On high temperature resistant structural parts. However, in practical applications, Ti600 cannot be used to manufacture friction components due to its low hardness and the inability to withstand high temperature corrosion. In order to effectively improve the performance of Ti600, many scholars have begun to study the surface coating processing method of this alloy in depth. The laser cladding process can significantly reduce the thermal impact of the substrate, so that the coating and the substrate are tightly fused in a metallurgical manner, thereby achieving higher bonding strength and reducing shedding. Xu Jiangning et al. [2] treated the surface of Ti600 by laser cladding technology and prepared a Ni80Cr20-40Al-20Si composite coating, and then comprehensively tested the coating's composition structure, composition, and high temperature resistance. According to the actual test results, it is known that Ti5Si3 / Al$_3$Ni$_2$ exists as a uniform reinforcing phase in the Al3Ti / NiTi matrix. After heating it to 800 °C and holding it for 32 hours, a composite oxide film coating composed of Al$_2$O$_3$ and NiO is obtained. Through observation, it was found that the coating formed a dense structure, and an oxidation test was performed to obtain a curve close to the shape of a parabola. It has excellent resistance to high temperature and oxidation. At the same time, no crack structure was formed in the coating. Part of the stomata. P. Wiecinski et al. [3] chose the vacuum arc method to prepare
a composite coating composed of Ti / TiN, Cr / CrN, and CrN / TiN with the same thickness and containing different components on the surface of Ti600. Tests on the above coatings revealed that there are also large differences in the microstructure of multilayer films with different interface types, and the growth mechanism of ceramic coatings is also significantly affected by the coherent interface, the semi-coherent interface, and the transition layer interface. The mechanical properties and grain size of the coating have been changed, but there is no systematic research on the corrosion resistance and wear resistance of the coating. Guo Weiming et al. [4] chose a hot pressing method to prepare a composite ceramic containing 20% TiB2 and 80% TiB2-B4C and made it into a tool. Testing the mechanical properties of the compound ceramic showed that the tool achieved excellent toughness and cutting performance. Tool life is also long. According to the above analysis, it can be found that the research content of most scholars mainly focuses on metal-based composite coatings and ceramic coatings. Xu Qingkun et al. [5] studied the content of cladding of quaternary TiB2 ceramic powder on the surface of Ti600.

TiB2 belongs to a class of TiCN quaternary ceramic materials obtained by boronizing treatment. Its lattice type is face-centered cubic structure, which can be used in the composite process of FCC-TiC, FCC-TiB, FCC-TiN. Among them, the Ti atom is located at the (000) lattice point, and the N, B, and C atoms are at the lattice (0, 1/2, 0) position, respectively. After the B element is introduced through the solid solution method, TiB2 ceramics can obtain some new characteristics, achieve better corrosion resistance, wear resistance, chemical stability, and higher hardness [6-8]. In this paper, laser cladding technology is used to prepare Ti / TiB2 composite coatings on Ti600 surface. The structure and performance test results of Ti / TiB2 composite coatings obtained under specific laser energy conditions are discussed. A certain experimental basis.

2. Preparation and test methods

2.1. Preparation
In this experiment, a Ti600 bulk material was used as the substrate. Table 1 shows the chemical composition of the material. The size of the sample was processed to 20 mm × 15 mm × 10 mm. Before performing the cladding treatment, firstly use 180 # sandpaper to fully erase the oxide layer on the surface of the sample, and then immerse it in acetone to clean and dry at room temperature. 30% titanium powder with a particle size of 120 ~ 220 μm (purity 99.5%) and 70% TiB2 powder with a particle size of 120 ~ 220 μm (purity 95.5%). The planetary ball mill completes the stirring and mixing process, and the ball milling process is performed at a ball milling speed of 500 r / min for a total of 4 h.

| Table 1. Chemical composition of Ti600 wt.% |
|--------------------------------------------|
| Al  | V   | Fe  | S   | C   | O   | N   | Ti  |
| 6.02 | 3.79 | 0.31 | 0.17 | 0.11 | 0.13 | 0.16 | 89.3 |

DMS-3D coaxial powder feeder is used to complete the cladding powder material transportation process. LDF4000-100 fiber-coupled laser is used to deliver energy to the cladding area. The parameters of the laser are as follows: the rated output power is 4000 W, and the wavelength 900 ~ 1050 nm, spot diameter 1.5 mm, focal length 200 mm. The specific process parameters of the experimental process: laser power 800W, scanning speed 5mm / s, spot diameter 1.5mm, air inlet rate 16L / min, powder feeding rate 200mg / min, laser specific energy 0-20kJ / cm².

2.2. Test methods
Observe the structure of the sample with a metallographic microscope, and test its phase with a D / max-rB type X-ray diffractometer. The hardness of the coating was tested using the HVS-1000 micro hardness tester and the hardness distribution was plotted according to the test results. The set load was equal to 1.98N, and the total load was 10 s.
The CHI660E electrochemical workstation was used to perform a potentiostatic polarization test on the sample. The sample and the graphite plate formed positive and negative electrodes with a scan rate of 1 mV / s. Nail polish was used to coat the surface of the substrate and the coating sample, and only an area of 1 cm² was leaked out. During the test, the sample was immersed in a 3.5% NaCl solution at 25 °C.

At room temperature, the MFT-R4000 reciprocating friction and wear tester was used to perform reciprocating dry friction testing. Considering the material of the cylinder liner, a GCr15 steel ball with an outer diameter of 5 mm was selected as the friction pair, and its hardness was equal to 65HRC. The test load was set to 10 N, the frequency is 2 Hz, the stroke is 5 mm, and the wear test is performed for a total of 20 minutes. The EX225DZH electronic balance was used to weigh the sample to obtain wear data.

3. Test analysis

3.1. Microstructure analysis
As shown in Fig. 1, it is the spectral data obtained by XRD characterization of the coating produced under the condition that the specific energy of the laser is equal to 20 kJ / cm². It can be found that the coating contains multiple microstructure phases such as TiB₂, Ti, TiN, TiC, TiAl, and the results are shown in Figure 2.

![Fig 1. XRD diffraction pattern of coating](image)

Figure 2 shows the microscopic morphology of the cross section of the coating prepared with 20 kJ / cm² laser specific energy as well. Analysis of Figure 2 shows that the coating and the substrate have reached a good metallurgical bonding state, and a dense structure is formed without defects such as cracks, pores, and slag inclusions. Because the upper part of the coating is strongly affected by high temperature, a large amount of bonding occurs between the Ti melt and the TiB₂ particles. Because of the obvious component undercooling tendency formed during the rapid solidification process, the crystal nuclei continue to grow towards the component undercooling zone. When Ti and TiB₂ particles are connected, they gradually transform into dendrites, and the position of TiB₂ is determined by the energy spectrum analysis of the measurement points. There are also some TiB₂ melts that form cellular TiB₂, and then further solid solution into a whisker structure. A-Ti and TiC together form the surface strengthening layer of the coating. The results are shown in Figure 2b. In the middle region of the coating, because there are fewer heat dissipation channels, a slow cooling process occurs, so that the dispersed TiC and TiN nuclei are fully grown and develop a developed dendrite structure together with TiB₂ particles. The results are shown in Figure 2c. In the lower area of the coating, because the solidification rate is very slow, it can be seen from Figure 2d that at this time, only a small component undercooling
tendency is formed, and at the same time, a granular TiB₂ and a dual-phase structure of many lamellar structures are formed.

In addition to the solidification rate, which greatly affects the growth morphology of TiB₂, the face-centered cubic structure of TiB₂ also has a significant effect. The Ti atoms in the unit cell and the light atoms such as B, N, and C present an alternately symmetrical arrangement. This allows the TiB₂ symmetrical crystal plane to grow at the same rate, thereby obtaining a symmetrical regular crystal structure. The crystallization process of adjacent TiB₂ particles is also self-organized. Under different molten pool locations and solidification principles, TiB₂ with different morphologies will be obtained.

![Fig 2. SEM morphology of coating at Es=20 kJ/cm², a) top zone; b) middle zone; c) bonding zone](image)

3.2. Coating performance analysis

Figure 3 shows the change in hardness of the laser cladding coating in the layer depth direction. It can be clearly seen that under different laser specific energy conditions, the coating can obtain higher microhardness than the Ti600 matrix (350HV). Among them, when the laser specific energy is equal to 20 kJ/cm², the coating reaches the highest microhardness, which is 990HV, which is nearly 2.5 times the hardness of the substrate. The coatings made with the laser specific energies of 10kJ/cm² and 5kJ/cm² decreased in order in terms of microhardness, but both reached more than twice the hardness of the substrate. According to Figure 3, it can also be found that there is a large difference in the thickness of the coating obtained at each laser specific energy. The overall performance is that when the laser specific energy is reduced, a thinner coating will be obtained. The laser specific energy is equal to 20 kJ/cm² and The coating thickness obtained at 5 kJ/cm² is 1.5 mm and 0.8 mm, respectively. It can be further inferred that the increase in the hardness of the coating is mainly because the ceramic particles in the coating can exert a dispersion enhancement effect and enhance the coating surface.

![Fig 3. Microhardness distribution of coating](image)
Since the Ti / TiB$_2$ coating has a lower friction coefficient than the substrate Ti600, the wear resistance of the sample can be significantly improved by preparing the coating, and the wear of the coating is significantly lower than that of the substrate. Figure 4 and Table 2 show the changes in the coefficient of friction and wear of the coating, respectively. It can be seen that the amount of wear shows a monotonic decrease with the increase of the specific energy of the laser, and the average friction coefficient shows a monotonous decrease as the specific energy of the laser increases. Improve the abrasion resistance of the coating.

![Graph showing changes of friction coefficient of the coating with time](image)

Figure 4. changes of friction coefficient of the coating with time

| Laser specific energy kJ/cm$^2$ | matrix | 5   | 10  | 15  | 20  |
|-------------------------------|--------|-----|-----|-----|-----|
| Average friction coefficient  | 0.475  | 0.306| 0.304| 0.315| 0.286|
| Abrasion loss /mg             | 6.57   | 1.212| 1.236| 1.292| 1.354|

Table 2. average friction coefficient and wear of coatings

Figure 5 shows SEM images obtained from abrasion tests on the substrate and coating. According to Fig. 5a, many furrow structures are formed during the wear process of the substrate. This is mainly due to the large plastic deformation of the surface of the substrate during the wear stage. As can be seen in Figure 5b, shallow short wear marks and some debris particles were formed on the wear surface of the coating. This is because micro-cracks are easily generated at the interface between the reinforcing phase and the substrate during the wear test, resulting in slight changes in stress. When the micro-cracks propagate, the coating surface will peel off.

![SEM images](image)

Fig 5. Microstructure of matrix(a) and coating(b) after wear
4. Conclusion
1) Laser cladding Ti / TiB₂ coating and good metallurgical bonding with the substrate, and formed a dense structure without cracks. After TiB₂ melts, cellular TiB₂ is formed, and further solid solution becomes a whisker structure. The dispersed TiC and Ti₃N nuclei in the middle of the coating were fully grown and developed a developed dendrite structure with TiB₂ particles. In the lower part of the coating, a granular TiB₂ and a bilayer structure with many lamellar structures were formed.

2) When the specific energy of the laser is 20 kJ / cm², the coating reaches the highest microhardness of 990HV, which is nearly 2.5 times that of the matrix. The amount of wear shows a monotonic decrease with the increase of the specific energy of the laser, and the average friction coefficient shows a monotonous decrease as the specific energy of the laser increases. The base body formed many furrow structures during the wear process. Short and short wear scars and some debris particles were formed on the wear surface of the coating.

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