Effect of excitation coil voltage on TiAlSiN coating on 42CrMo steel surface

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Abstract
TiAlSiN coating was painted on the surface of 42CrMo steel by arc ion plating technology, and the influence of excitation coil voltage on the structure and friction property of the coating were analyzed. Results showed that there were a lot of holes on TiAlSiN coatings under different voltages. With the increase of voltage, the structure and friction property changed a lot: the roughness and thickness of the coating increased obviously and all layers were in a state of tight bond and formed a columnar structure; many voids appeared led to the decrease of coating density; the coating with higher microhardness was obtained, which was higher than that of alloy steel substrate; the friction coefficient and wear rate of the coating first decreased then increased, and the minimum wear rate occurred when the voltage reached 30 V, under condition of which the coating mainly suffered from abrasive wear, so more flat surface and denser structure of the coating formed, which significantly improved the wear resistance.

TiAlSiN coating, a widely used hard film, has attracted the interest of many scholars whose research results contributed to the mature preparation technology of TiAlSiN coating. The coating has many advantages such as good mechanical properties, strong heat insulation performance and high temperature resistance, which make it an important surface modification material in the area of tool industry [1]. Some scholars have found that when the mass fraction of Al in TiAlSiN coating increases, the coating will have a stronger resistance to high-temperature oxidation [2–4]. Physical vapor deposition has become an important preparation process for TiAlSiN coatings. TiAlSiN coatings with specific Al content can be prepared by controlling the mass fraction of Al in TiAl. When the content of Al in the coating is increased, the surface of the workpiece will be significantly affected.

According to previous reports on TiAlSiN coating processed by arc ion plating, when TiAl target materials has a higher content of Al, more holes with larger particles clearly occurred on the surface of TiAlSiN coating. When using the same TiAl target material, larger holes will be formed in the TiAlSiN coating as the increase of target current. The change law of TiAlSiN coating properties first increased and then decreased as the increase of process parameters [5, 6]. PALDEY [7] also studied the process of preparing TiAlSiN coating by multi-arc ion plating technology, and found that the bonding force of coating was enhanced by adequately increasing the hardness of the coating or choosing a better growth technology. BEILIS [8] have carried out research on both the arc ion plating technology and other properties of TiAlSiN coating. He found that the microstructure of the coating was affected by combined action of gas pressure and electric current, and the surface quality of the coating could be significantly improved by setting cylindrical filter in the non-deposition process [9–11].

Generally, the magnetic field on the surface of the cathode target can be divided into two directions: the magnetic field that is parallel to the target surface and the normal magnetic field that is perpendicular to the target surface, in which the magnetic field in the parallel direction can form more stable arc spot that can avoid...
defocusing, and the magnetic field in the vertical direction can change the motion speed of the arc spot [12, 13]. However, few scholars have reported the influence of magnetic field on the coating of arc ion plating so far. In this paper, TiAlSiN coating was prepared by arc ion plating technology on the surface of 42CrMo steel, and the effect of excitation voltage on the structure and properties of TiAlSiN coating was emphatically analyzed.

1. Experiment

1.1. Preparation of TiAlSiN coating

42CrMo alloy steel (element mass fraction is shown in table 1) was treated by AS700DTXB Cathode arc ion coating machine under conditions as: the Ultimate Pressure was controlled at $5 \times 10^4$ Pa with temperature of 400 °C, and the workpiece rest used can complete revolution and rotation freely with revolution velocity at 3 r min$^{-1}$. Cr target and TiAl target were used as target materials, where the Ti and Al atomic ratio in the TiAl target was 30:70, under environment of high purity argon and nitrogen with the purity of both gases reaching 99.999% or above. By controlling the current passing through the excitation coil, the coil voltage measured was controlled in the range of 10 ~ 50 V, and the relationship between current and voltage is shown in table 2.

| Current/A | 129 | 143 | 165 | 182 | 201 |
|----------|-----|-----|-----|-----|-----|
| voltage/V | 10  | 20  | 30  | 40  | 50  |

The specific process is set as: the inner space of the furnace was firstly cleaned by using ions bombarding the substrate under a high negative bias environment, then a Cr/CrN coating with 1 μm thick was coated on the internal face, which was continually painted by a TiAlSiN coating, under the deposition conditions of TiAl target current being controlled at 100 A, negative bias voltage at 50 V, and N$_2$ pressure at 4.0 pa for 1.5 h.

Figure 1 shows the structure of cathode target seat used in experiment, in which the permanent magnet is installed in the rear of the cathode target and the excitation coil circles the edge of the target material. The magnetic field of the permanent magnet is parallel to the target surface, and that of the excitation coil is arranged perpendicularly to the target surface. When arc ion plating is applied to the sample, the discharge spot can be regarded as the parallel current containing countless electron beams which defocus and move outward under...
the action of repulsive force. In such case, the magnetic field parallel to the surface of the target can stabilize the arc, while the magnetic field perpendicular to the surface of the target can inhibit the circular motion of the arc spot. Therefore, the speed of arc spot, by regulating exciting coils, can be accelerated, and with the increase of voltage, the arc spot moves faster and forms a smaller arc spot radius.

1.2. Performance test
A wear test was carried out on TiAlSiN coating for two hours by Multi-function friction and wear tester (T100, United States), with load set as 1 kg at grinding speed of 0.2 m s\(^{-1}\). Then the wear mark size formed by the friction test was measured by using a profilometer (ST400, United States), and the wear rate (measurement errors Within \(\pm 0.001 \times 10^{-15} \text{m}^3(\text{N.m})^{-1}\)) of coating was calculated, and the friction coefficient (measurement errors within \(\pm 0.001\)) of coating was obtained. The microhardness (measurement errors within \(\pm 1 \text{HV}\)) was also measured by Vickers hardness tester (HXD-1000TMSC•Germany), with loading time of 20 s under load of 30 g; the phase of the coating was analyzed by x-ray diffractometer (XRD, Bruker D8 Advance•Germany), and the microstructure of coating and the wear marks were characterized by the scanning electron microscope (SEM, FEIQuanta 200, United States), the roughness (measurement errors Within \(\pm 0.001 \mu\text{m}\)) and thickness (measurement errors Within \(\pm 0.001 \mu\text{m}\)) of coating was obtained.

2. Results and discussion
2.1. Analysis of surface morphology
The microstructures of TiAlSiN coating prepared at different voltages were observed through scanning electron microscope (seen in figure 2). The changes of roughness and thickness in TiAlSiN coating obtained at different voltages were shown in table 3. When the voltage is set at 10 V, a large number of holes are formed on the coating surface, which leads to large roughness on coating surface. As the voltage rising to 20 V, the number of holes reduced and the coating surface is more smoother. With the continue increase of voltage, the roughness of the coating increases significantly, which makes it adsorb more holes. When other coating parameters are constant, the thickness of TiAlSiN coating increases from 2.16 \(\mu\text{m}\) to 4.85 \(\mu\text{m}\), as the voltage is raised from 10 V to 50 V. Under high voltage, the cathode arc concentrates on surface area of the target in a rotating state, which makes the target resist the ablation effect of higher temperature, accelerate the target ionization rate, and thus form a thicker deposited film. By Increasing the voltage, more fine cathode arc spots occur, making the coating...
roughness reduce and smaller holes appear. However, when the voltage is too high, a thick coating with large roughness will be deposited on the coating surface.

The microstructures of TiAlSiN coating prepared at various voltages are shown in figure 3. It is clear that the coating has formed a columnar structure in a tight bond state. Under low voltage, a more compact coating with partial columnar crystal structure was produced. When the voltage rise, the coating grows perpendicularly to the surface of substrate and forms obvious columnar crystal, resulting in more gaps and low density.

2.2. Hardness analysis

Table 4 shows the microhardness test results of TiAlSiN coating under different voltage. It is found that TiAlSiN coating with higher microhardness is obtained when the voltage of arc ion plating is gradually increased. As the voltage increases, the plasma near the target is accelerated faster and suffers restraint, resulting in a higher ionization rate and a greater microhardness of the coating. According to table 4, the coating becomes more thinker after deposition, whose hardness is higher than that of the alloy steel substrate. Thus the substrate has little influence on the coating.

2.3. Friction performance analysis

Table 5 shows the abrasion resistance test of TiAlSiN coating with voltage in the range of 10 V ~ 50 V. As the increase of voltage, friction coefficient of coating first decreases, then increases. The wear rate presents the same changing law, and the minimum wear rate occurs when the voltage reaches 30 V.

| voltage/V | 10   | 20   | 30   | 40   | 50   |
|-----------|------|------|------|------|------|
| microhardness/HV | 2485 | 2664 | 2928 | 3316 | 3433 |

Table 3. Roughness and thickness of TiAlSiN coatings at different voltages.

| voltage/V | 10  | 20  | 30  | 40  | 50  |
|-----------|-----|-----|-----|-----|-----|
| roughness/μm | 0.27| 0.23| 0.26| 0.31| 0.31|
| thickness/μm  | 2.18| 2.24| 2.60| 3.45| 4.76|

Figure 3. SEM images of TiAlSiN coatings at different voltages.
Figure 4 shows the micro-morphologies after wear tests were done on the surface of TiAlSiN coating under different voltage. In the process of the test, abrasive wear plays a major part. Under a low voltage, the coating has a dense structure, but a large roughness, which makes it easy to form debris during friction, resulting in obvious adhesion that leads to spalling of the coating. Under a higher voltage, the surface of the coating becomes more flatter and the coating structure becomes denser, which significantly improves the wear resistance. When the voltage was continually increased, the TiAlSiN coating is readily to collapse during the friction, and large particles formed will cause obvious impact on the coating and finally lead to the cracking and peeling off the coating.

3. Conclusion

(1) There are a lot of holes on TiAlSiN coatings prepared by different voltages. With the increase of voltage, the roughness and thickness of coating increase obviously. All layers formed a tight bond, no obvious gap structure, coating has formed a columnar structure. After increasing the voltage gradually, the coating with higher microhardness was obtained, and the hardness was higher than that of alloy steel substrate.

(2) As the voltage increases, The friction coefficient and wear of coating first decrease and then increase, reaching the minimum wear rate when the voltage reaches 30 V. The coating mainly suffered from abrasive wear. At 30 V voltage, a more flat coating surface was formed, and the structure of the coating became denser, significantly improving the wear resistance.

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