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Chapter

Solid Particle Erosion

Wang Di and Yang Zhen

Abstract

When military helicopters and transport aircraft take off and land forcibly on desert or simple runway, sand and dust will cause solid particle erosion damage to aircraft blades, leading to compressor performance degradation and structural integrity damage, which seriously affects the reliability of the engine. For the field of erosion protection, this book introduces the following six aspects, including erosion mechanism, influencing factors, protection methods, preparation methods, coating systems and structures, and the application status of erosion resistant coatings. The research and development direction of erosion resistant coating technology in the future was clarified, which laid a foundation for further research and application of erosion resistant coating technology.

Keywords: solid particle erosion, erosion mechanism, erosion resistant coating, erosion protection, coating systems and structures

1. Introduction

Solid particle erosion (SPE) is one of the common wear modes in engineering field. When solid particulate matter (sand, fly ash, salt, ice crystal, volcanic ash, etc., as shown in Figure 1) is entrained by air flow and impacts the surface of components, solid particle erosion will occur. In various applications, including helicopter rotor blades, wind turbines, power generation gas turbines, aircraft windshields, fuselage and engines, etc., they may be subject to severe erosion wear, resulting in the removal of component materials. As early as the Vietnam War in the 1960s, the US military had realized the seriousness of sand erosion. Because Vietnam is in a sand and dust environment, the compressor blades of T53 turboshaft engine of the “Huey” helicopter and the “Cobra” helicopter of the US military mission suffered sand and dust erosion, and serious geometric deformation and structural damage occurred, resulting in engine power reduction, blade crack failure, etc., which necessitated the engine to be replaced in advance, and the average maintenance interval was significantly shortened. By the 1970s, solid particle erosion had become an urgent problem in the field of aerospace. During the Gulf War, the T-64 engine of the US CH53E helicopter had serious erosion and wear problems of compressor blades in this desert environment, which reduced the operating time of the engine from 2000 hours in the ordinary environment to 100 hours in the desert environment. During the war in Afghanistan, the mission of the Russian Mi-17 helicopter in the sand and dust environment, a number of blade fracture failures occurred, resulting in a significant reduction in the service life of the engine and a serious threat to flight safety. In 2010, the Eyjafjallajokull volcano eruption in southern
Iceland led to the closure of the largest civil aviation line since the Second World War, which is precisely due to the reduced visibility of the region and the volcanic ash caused by the volcanic eruption easily entering the engine and endangering flight safety. It is generally believed that when the speed reaches 300 m/s, sand will inevitably enter the turbine engine [1]. Once the engine inhales sand dust, the sand will start to impact and slowly erode the blades. At the same time, corrosive liquids such as rain will accelerate its corrosion. On the contrary, erosion will accelerate the destruction of the integrity of the blades, and the corrosion will intensify. Thus, erosion and corrosion will act together to erode and destroy the blades in a domino manner, leading to catastrophic consequences of the engine.

In other fields, gas turbines are eroded by 5 μm coal fly ash particles. When particles are driven into the gas turbine by the gas flow, they will cause erosion damage to the static and moving blades, which will change the shape and size of the blades, leading to lower working efficiency and worse performance. In 1990, BP conducted an investigation on throttle valve failures in Alaska oil field, which showed that 34% of failures were caused by wear of valve internals and valve bodies [2]. However, in the pipeline system of pumps and heat exchangers, there are huge hidden dangers of safety accidents [3–6]. In a word, erosion wear is very harmful in the industrial production field [7]. In order to effectively reduce the loss caused by erosion wear and improve the service life and reliability of equipment and materials, scholars at home and abroad have carried out a variety of researches. Among them, hard coatings are increasingly used to improve the service life of components, which can significantly improve the anti-erosion performance by endowing the components with surface mechanical properties other than their own.

2. Brief introduction of SPE

2.1 Erosion mechanism

There have been a lot of studies on the solid particle erosion mechanism. Researchers found that under the action of sand and dust in complex environment, multiple erosion failure mechanisms are coupled, and a single erosion theory cannot meet the requirements of revealing the erosion phenomenon. At present, there are mainly the following erosion wear theories.

In 1985, the micro cutting theory came out. Subsequently, the erosion theory, secondary erosion theory, adiabatic shear and local deformation wear theory of plastic/brittle materials have developed successively. From the current erosion theory, micro cutting theory [8, 9] (as shown in Figure 2a) has analyzed the cutting action in
the erosion process under the condition of small angle of attack (small angle), but there is a large error in explaining the erosion behavior at large angle of attack (large angle). The deformation and wear theory [10] revealed the deformation process and energy change analysis of samples after multiple impact angle erosion. The theoretical model believed that the micro cutting effect of particles was not obvious during large angle erosion, and the wear of materials was mainly related to the deformation caused by impact, which made the materials crack and fall off. The elastoplastic indentation fracture theory [11] analyzed the erosion of brittle materials by sand dust under the condition of high angle of attack (Figure 2b). The secondary erosion theory [12] provides a good explanation for the complex process of erosion process, namely, brittle particle fragmentation and re erosion of materials.

2.2 Factors affecting of SPE

The factors affecting the erosion behavior of materials are very complex, including external factors such as size and shape of erosion particles, as well as internal factors such as physical properties and microstructure of materials themselves. In addition, the parameters of erosion test such as erosion speed, angle, time, ambient temperature and other test factors will also affect the erosion results.

2.2.1 Erosion particle size and shape

The influence of erosion particle size on materials with different properties is different. For ductile materials, the “size effect” of erosion particles [13], determines the erosion rate of the material, that is, the particle size increases, the erosion rate increases, but the critical size no longer meets the “size effect”. The secondary erosion theory also believes that when the brittle particles reach a certain scale, they are easy to be broken in the erosion process. After the particles are broken, the erosion energy decreases, which is not enough to cause secondary erosion of materials, and the erosion rate will tend to be stable. For brittle materials, the erosion rate of small angle gradually increases with the decrease of particle size; Under the condition of large angle erosion, the erosion wear caused by large particles is more serious, which is usually a typical brittle fracture erosion mechanism. In addition, under the condition of the same particle size, the impact of particle shape on the material erosion rate is also not the same. Levy et al. [14], studied the influence of Al$_2$O$_3$ particles with different shapes on the erosion wear behavior of carbon steel. The results showed that the weight loss of irregular angular Al$_2$O$_3$ particles was much larger than that of spherical Al$_2$O$_3$ particles. Levy et al. believed that when angular Al$_2$O$_3$ particles impact the material surface, the contact area between the spherical particles and the matrix is much smaller, so the contact stress on the material surface is much larger under the same erosion conditions. The high stress
concentration on the surface of the material makes it easier to initiate cracks, and then crack, resulting in a large amount of wear [11].

2.2.2 Impact of erosion parameters

When evaluating the erosion resistance of materials, erosion parameters (erosion angle, velocity, time, etc.) are the key factors affecting the erosion process of materials. For example, Finnie et al. [15], studied the erosion behavior of two representative materials, Al (ductile material) and Al₂O₃ (brittle material). It can be seen from Figure 3 that the erosion rate of ductile material (Al) first increases with the increase of erosion angle and reaches the maximum value at about 15°, and then decreases with the increase of erosion angle. For brittle materials (Al₂O₃), the erosion rate increases with the increase of erosion angle. The results show that the erosion rate of brittle materials is lower at small angle of attack, while that of ductile materials is lower at large angle of attack. The analysis shows that the plowing effect of ductile materials with low surface hardness is significant in small angle erosion. Under the condition of large angle, the ductile material has a better inhibition effect on the generation of internal fatigue cracks, and the erosion rate is significantly reduced. On the contrary, the high hardness of brittle materials can resist the plowing effect of erosion at small angles of attack, but the high brittleness makes them vulnerable to impact fracture at large angles of attack, resulting in a large number of fatigue cracks and failure. Therefore, ductile materials and brittle materials are two distinct erosion behaviors under the same conditions.

In addition, particle velocity and erosion time are also the key factors affecting the erosion rate of materials. The general rule shows that the erosion rate increases gradually with the extension of erosion time. However, in the early stage of erosion, namely the so-called incubation period, the material will not suffer mass loss, and even a small amount of weight gain may occur. After initial erosion inoculation, the material enters a stable mass loss state. The length of incubation period is affected by erosion angle, erosion rate and material properties. The incubation period will be prolonged with the increase of erosion attack angle and the decrease of particle velocity. In addition, plastic materials usually have a longer incubation period than brittle materials [17]. For erosion particle velocity, lower velocity means lower impact energy, which makes it difficult to introduce high impact stress and reach the stress threshold of plastic deformation or crack initiation. Higher speed can cause surface
damage of materials. Therefore, there is a critical velocity for erosion particles. Below this speed, the particles will be bounced away without damage. Only after exceeding this speed, the material will start to suffer from erosion wear [16].

2.3 Methods of SPE protection

In order to enhance the erosion resistance of materials and prolong their service life, the erosion resistance can be improved by changing the overall structure of materials, but it is difficult to achieve for parts with more complex structures. As the erosion behavior first and mainly acts on the material surface, the surface quality of the material is the key to affect its erosion resistance. Adding protective coatings on the material surface to improve the erosion resistance is easier to achieve, and has been widely used. Surface coating technology is to obtain the required surface morphology, material composition, microstructure, etc. of parts and components through surface pretreatment, coating and other means. Therefore, it is of great significance to adopt modern surface modification technology for surface protection of related components.

3. Preparation method of SPE coating

The preparation method of the coating is physical vapor deposition (PVD) based on plasma technology. Physical vapor deposition is a common technology for preparing hard coatings. Its principles include: (1) gasification of coating materials, that is, providing energy to coating materials through collision, sputtering and other methods to ionize the coating materials and become a source of plasma gasification; (2) After sputtering and collision, the atoms or ions in the gasified coating materials are effectively separated from the plasma coating materials by the migration of atoms, molecules or ions in the coating materials, and the atoms or molecules in the coating materials are controlled to migrate to the substrate surface by magnetic field and other means; and (3) Coating atoms, molecules or ions are deposited on the body, that is, the separated atoms, molecules or ions are deposited or bombarded on the target surface by voltage or other methods. Physical vapor deposition (PVD) has become a promising coating preparation technology due to its high bonding strength, low deposition temperature, rich materials and multilayer coating.

The commonly used PVD technologies are mainly magnetron sputtering ion plating and arc ion plating. Magnetron sputtering ion plating is not suitable for preparing thick coatings because its ionization rate is much lower than that of arc ion plating due to its collision miss mechanism; At the same time, the toughness of the coating prepared by magnetron sputtering is far less than that of arc ion plating, and its erosion resistance is poor, so it is not suitable for the preparation of erosion resistant coatings. The other commonly used PVD technology, arc ion plating, is widely used for the preparation of hard coatings. Because the traditional cathodic arc ion plating is a thermal field emission miss target mechanism, the deposition particle energy is high, the flux is large, and the ionization rate is high (about 80%). At the same time, the technology can install different targets to achieve the deposition of multiple coatings, but the target will partially melt and eject micron sized molten metal particles due to arc discharge (as shown in Figure 4). These protrusions formed by micro-particles are easy to be eroded by sand and gravel, and will form pits after the micro-particles on the surface are washed away. These pits are easy to become stress concentration points of fatigue or erosion damage, thus leading to rapid failure of the coating.
Therefore, how to eliminate or reduce the metal droplets in the anti-erosion coatings prepared by arc ion plating is one of the current research focuses.

4. Material system and structure design of SPE coating

4.1 Material system of erosion resistant coating

In the past 25 years, there have been many studies on anti-erosion coating material systems, most of which are comparative studies aimed at evaluating the performance of specific materials. Most studies focus on two coating series: one is carbon based system [2, 18, 19] (diamond, diamond-like carbon (DLC), tetrahedral amorphous carbon (ta-C) and some carbides); The second is a system based on nitrides (mainly TiN) [20–26] (TiN, TiAlN, TiCN, TiSiN, TiSiCN, etc.). Other nitrides (CrN [27, 28], ZrN [21], etc.) have also been partially studied.

Diamond coating has many excellent properties, most notably high hardness and strength, which makes it an attractive choice for friction and wear resistant parts. Therefore, many researchers have carried out detailed experimental studies on the erosion resistance of diamond coatings, and have a more in-depth understanding and analysis of the impact of erosion grit material, shape, size, erosion speed and angle on the erosion resistance and erosion mechanism.

Wheeler et al. [2] have studied the erosion resistance of diamond coatings in detail. They used Chemical vapor deposition technology to prepare diamond coatings of 10–46 μm thickness, and carried out erosion tests at 90° angles of attack using grit with different average diameters and velocities, the erosion resistance was studied. The erosion rate is related to the kinetic energy of the erosion particles, and compared with tungsten carbide and stainless steel. It is concluded that the erosion mechanism of diamond coating is composed of three stages. First, the coating produces microcracks; Secondly, pinholes and interfacial debonding occur; The last is the complete failure of the coating. Wheeler and others also studied the impact of different impact angles on the erosion performance of diamond coatings. The results show that although the number of impacts required at the beginning of pinhole increases significantly at small angles, all angles will produce a “pinhole” damage feature. As shown in Figure 5, circular cracks and pinholes are observed on the eroded surface, and can be observed on the eroded coating at all angles. As a part of establishing their formation mechanism, the author measured the diameter of annular cracks, analyzed the Hertz fracture theory and proposed the stress wave reflection theory. According to these results, the author also proposed to use energy to describe the impact of solid particles on the erosion resistance.
of the coating: \( E_{\text{EP}} = E_{\text{c}} + E_{\text{E}} \), where \( E_{\text{EP}} \) is considered to be the total energy consumed by the elastoplastic damage caused by a single impact, while \( E_{\text{c}} \) and \( E_{\text{E}} \) are the energy dissipated by the coating and erosion damage, respectively.

Till now, TiN based coatings have been the most widely used SPE resistant coatings in aeroengines. Therefore, many researchers still focus on TiN and its multiple systems. In the past 20 years, more and more researchers have begun to study nanocomposite TiN based coatings with better mechanical properties. The research results of Reed et al. [29] show that the erosion resistance of (Ti, Cr) N nano coating is highly dependent on the coating thickness and Cr content, and the increase of CrN phase volume reduces the hardness of the coating. Under the attack angle of 30°, all the coated samples are better than the uncoated substrate; However, under the condition of 90° attack angle, the coating deposited at low bias voltage (−25 V, −50 V, and −100 V) and Ti: Cr ratio (N = 2.4) is superior to the uncoated substrate. Therefore, hardness does not play a decisive role in the erosion resistance of the coating.

In recent years, CrN coating has attracted extensive attention of researchers because of its excellent toughness, wear resistance, high temperature oxidation resistance and corrosion resistance, and low residual stress of the coating, which makes it easy to deposit thicker coatings [30, 31]. However, the hardness of CrN coating is low, only about 1800–2000 Hv. At present, multiple nitrides [32–34] can be formed by doping elements (such as Al, Ti, TiAl, Si, etc.) to improve the hardness of the coating. Among them, Al and N in CrAlN coating are bound by covalent bond, and the grains of the coating are uniform and fine, which not only improves the hardness to about 2500–3000 Hv, but also increases the thermal stability of the coating. In the high temperature environment, Al atoms and Cr atoms are easy to diffuse outward, and combine with oxygen to form a more compact \( \text{Cr}_2\text{O}_3 \) and \( \text{Al}_2\text{O}_3 \) oxide layer. After the formation of this oxide layer, the volume expands, forming a compressive stress on the coating, which can resist the crack initiation on the surface, effectively prevent the deep level of oxidation, and improve the high-temperature oxidation resistance of the coating [35, 36].

According to the experience in preparing coatings in the field of engineering machinery, the most common method to improve the mechanical properties of metal nitrides, including hardness, toughness and oxidation resistance, is to add Al. Many studies show that the nitride coating containing Al still shows good wear resistance at high temperature [37–39]. Ren et al. [40] deposited CrAlN and CrN coatings on the steel substrate respectively. They found that the addition of Al makes some Cr atoms replaced by Al atoms to form CrAlN phase, which is conducive to refining grains and improving the comprehensive performance of CrAlN coatings. Wu et al. [41] deposited four kinds of coatings: TiN, TiAlN, CrAlN and CrAlTiN on the steel substrate. It is found that the CrAlN coating has the best erosion resistance, which is 3.9 times of the substrate.

Figure 5.
Micrographs of the surrounding cracks and pinholes of diamond coating under multi-angle impact [2] (a) 30°, (b) 60°, and (c) 90°.
According to the erosion model proposed by Evans et al. [42] and improved by Hockey et al. [43], they believe that the volume loss of brittle materials during erosion is proportional to the velocity, radius, density and impact angle of erosion particles, and inversely proportional to the fracture toughness and hardness of coating materials. Under the condition of high angle of attack, micro brittle fracture caused by elastic-plastic deformation is one of the main modes of erosion damage of hard coatings. According to the micro brittle fracture theory [42], the erosion volume (W) of materials can be expressed as:

\[ W = C K ^ {3/4} / C \]

Where:
- \( W \) – Erosion volume;
- \( H \) – hardness;
- \( K \) – toughness;
- \( C \) – Constant (depending on particle size, velocity and particle density of erosive particles). It can be seen from Eq. (1) that the erosion resistance of the coating can be improved by improving the hardness and toughness of the coating material. Moreover, improving the toughness has a more significant effect on improving the erosion resistance of the coating. Therefore, when selecting coating materials, it is necessary to comprehensively consider the hardness and toughness. On the basis of ensuring a certain hardness, it is necessary to focus on improving the toughness. It should be emphasized that it is meaningless to simply discuss toughness instead of strength (or hardness). Only those hard and tough coating materials have engineering application value.

4.2 Structural design of erosion resistant coating

With the deepening of research, some defects of monolayer hard coating in the field of erosion resistance have been revealed: the high stress of the coating, the high brittleness, and the low toughness, which leads to cracks easily appear when the coating is eroded by solid particles [44]. According to the literature, the maximum thickness of metal nitride coating with monolayer structure is about 6–8 μm [45]. However, when the coating thickness is thin, its erosion resistance is difficult to meet the protection requirements of related parts. At present, gradient multilayer coatings with complex structure have become the research focus of erosion resistant coatings. This kind of coating has a large number of interfaces, through which the continuous growth of columnar crystals can be restrained, the energy of erosion particles can be dissipated, and the initiation of crack sources and the propagation of buffer cracks can be prevented; At the same time, the interlayer can release the residual stress to a certain extent, coordinate the deformation, and improve the film substrate bonding strength and coating toughness.

According to the principle of multilayer strengthening, the difference of crystal structure and elastic modulus is the main reason for the dislocation to be blocked at the interface, thus forming the strengthening. In the multi-layer structure with alternating soft and hard, even if the metal (Me) in the metal layer and ceramic layer is the same element, the crystal structures of Me and MeN are different, so they will not grow epitaxial structures. The difference of elastic modulus will form a certain strengthening effect. Zhang et al. [46] studied the evolution of the cyclic impact damage mechanism of TiN/Ti multilayers with the sharp shortening of the modulation period from micrometer (1000 nm) to nanometer (60 nm). The results show that with the decrease of modulation period, the ductile phase of the films decreases, and the microstructure changes from TiN/TixNy/Ti to TiN/TixNy (x > y). The results of cyclic impact show that the impact resistance and damage mechanism of TiN/Ti
multilayers are closely related to the modulation period. The smaller the modulation period of TiN/Ti multilayers, the lower the critical fracture load, the higher the fracture probability, and the worse the impact resistance.

Wieciński et al. [47] studied the erosion resistance and fracture mechanism of nanostructured Cr/CrN multilayer coatings. The researcher deposited seven multilayer coatings with different modulation ratios (Cr/CrN) by arc ion plating. These coatings have the same thickness (5–6 μm) and 16 layers of Cr/CrN, but the thickness ratio \( Q_{\text{Cr/CrN}} \) of Cr and CrN component layers is different. The small particles of silicon dioxide used in the erosion experiment impact the coating surface at an angle of attack of 90°. **Figure 6** shows the morphology of Cr/CrN multilayer coating before and after erosion. It can be seen that after erosion, the Cr layer grains uniformly elongate along the interface and rotate by 90° compared with that before erosion. This change may be due to dislocation sliding between grains. The microstructure change of Cr layer is caused by plastic strain produced by erosion particles, while the microstructure (grain size and shape) of CrN layer is basically unchanged. Compared with the columnar structure, the microstructure composed of Cr/CrN multilayer grains grown at different interfaces can effectively prevent the propagation and propagation of cracks along the grain boundaries.

Therefore, the essence of multilayer structure to improve coating toughness is deeply explored [48]. Its toughening mechanism usually comes from the following aspects: (1) the interlayer interface deflects cracks; (2) The soft phase layer has better plastic deformation ability and can relieve the interface stress at the same time; (3) The crack tip is wrapped by a soft phase layer, which can passivate the crack tip, inhibit crack growth, and improve the toughness of the coating material (**Figure 7**). In simple terms, in multilayer coating structures, the metal phase is used to absorb...
excessive plastic deformation, while the ceramic phase provides hardness and wear resistance. It can be seen that the multilayer structure improves the toughness of the coating by a variety of mechanisms. These toughening mechanisms have been verified in a number of studies.

In general, the ductile interlayer improves the erosion resistance of the hard coating by improving the film substrate bonding strength and toughness. In the structural design of erosion resistant coatings, the multilayer structure of ductile interlayer/hard surface layer can be used for reference as the research direction of strengthening and toughening coatings.

5. Research and application status of SPE coating

In the past 30 years, the United States, Russia and other countries have cooperated with GE, Canada MDS, Liburdi and Russia PRAD, etc., and carried out research work in terms of material system, preparation technology and process, engineering test assessment and evaluation. Now, this technology has been successfully applied to dozens of models of engines.

As early as 1988, Liburdi Company in Canada began to develop erosion resistant coatings, and the coatings were gradually applied to various types of engines until the early twenty-first century. From 2000 to 2003, the anti-erosion coating prepared by the company was applied to T55, T58, T64 and AE1107 engines. In 2004, the company processed more than 2000 sets of T56 compressor blades with erosion resistant coatings for Rolls Royce. Since 2007, the Saudi and Jordanian Air Forces selected the T56 engine (compressor blades are provided with erosion resistant coatings prepared by Liburdi). In 2008, the third generation anti erosion coating (mainly TiAlN, as shown in Figure 8) was introduced, which can make the service life of the engine more than three times that of the uncoated engine, and improve the engine performance by 3% [44].

On the basis of the extensive application of binary anti-erosion coating, MDS-PRAD and GE further improved the material and structure of the anti-erosion coating, and applied ER-7 and Black Gold ceramic coatings, which are mainly composed of TiN and TiAlN, to helicopter and transport engine blades. The main component of ER-7 coating is TiN. It adopts a multilayer structure with alternating soft and hard. The substrate is a hard and dense nickel base metal. A transition layer between the substrate and the coating is used to improve the film substrate bonding strength. At the same time, the coating has strong resistance to fatigue crack growth and multi angle sand erosion.

Figure 8.
I & II generation coating (TiN series) III generation coating (TiAlN series) [44].
Praxair Surface Technologies has developed a sub stoichiometric TiN/TiN\textsubscript{1-x} (called “24k Type II™”) Compared with the traditional TiN coating, its erosion resistance has been greatly improved. This coating system has been tested to provide excellent gravel erosion protection in a variety of aircraft engines, including civil engines. Due to the increased demand for erosion resistant coatings in desert environments, the U.S. Navy has implemented a plan to extend the life of compressor blades of T64 helicopter engines by applying erosion resistant coatings [49, 50]. The company has established a production base, which can effectively prepare 24 k Type II™ Multilayer coating, and has become one of the major suppliers in aviation applications. Since then, the coating has been applied to hundreds of thousands of blades. The coating structure is shown in Figure 9 TiN\textsubscript{1-x} layer thickness is less than 0.2 μm, TiN layer thickness is 1 μm. The total coating thickness is usually 15–25 μm. Figure 10 shows the comparison diagram of erosion rate of multilayer coating and monolayer TiN coating, thermal spraying coating (chromium carbide and tungsten carbide) and Ti-6Al-4 V base material at 20° and 90° attack angles. The results show that the multilayer coating is obviously superior to other coatings [51].

Oerlikon Balzers has also provided BALINIT TURBINE PRO coating for erosion protection in recent years (the relevant performance is shown in Figure 11). This coating uses TiAIN series multilayer structure to achieve the best matching of high hardness and residual compressive stress, providing excellent erosion protection performance.

Figure 9. TiN/TiN\textsubscript{1-x} “24k Type II™” multilayer coating structure [51].

Figure 10. Erosion rates of Ti-6Al-4 V base material, thermal sprayed Cr-C and WC coating, TiN coating, and TiN/TiN\textsubscript{1-x} “24k Type II™” multilayer coating at attack angles of 20° and 90°, respectively [51].
German MTU Company has designed and developed erosion resistant coatings (ERCoatnt Generation I and II) for aircraft engine compressor blades, as shown in Figure 12. Figure 13a shows the metallographic micro-section of the coating, clearly showing the total thickness of 25 μm and the ceramic and metal interlayer of about 3 μm per cycle. Figure 13b shows the high-resolution scanning electron micrograph of the coating, showing that the ceramic interlayer is a nano multilayer structure. The chemical composition of the continuous nano layers varies slightly, and the thickness of each nano layer is only 20 nm to 50 nm. Compared with traditional coatings, this nano design again significantly reduces the size of potential cracks or defects. In general, it is essentially chemical composition, and nano design and multilayer structure jointly achieve the ideal erosion resistance of the coating (Figure 14). Figure 15 shows the effect of ERCoatnt coating on high cycle fatigue and low cycle fatigue.

**Figure 11.** Basic properties of BALINIT TURBINE PRO coating.

**Figure 12.** First generation coating (TiN series) second generation coating (TiAlN series) [40].

**Figure 13.** Multilayer structure of ERCoatnt coating [40]: (a) cross section (b) high resolution electron microscope cross section morphology.
The strength of titanium alloy. The test data showed that the high cycle fatigue strength decreased by as much as 15% depending on the coating system, the substrate material and the selected geometry. When the critical strain level is exceeded, ERCoatn coating may accelerate crack initiation under low cycle fatigue load [40].

The team of Guangdong Academy of Sciences Institute of New Materials successfully developed 5–30 μm thick TiN based and CrN based alternating soft and hard multilayers by using vacuum cathodic arc ion plating technology [52–57]. The results show that: (1) The multilayers have good comprehensive properties: the thickness can reach 20 μm or more (see Figure 16), the adhesion is greater than 70 N, and the

![Figure 16](image1)

**Figure 16.**
*SEM cross-sectional morphology of Ti-TiN-Zr-ZrN multilayer film [52].*
hardness is greater than 30 GPa. It has a good anti-erosion protection effect on
titanium alloy and steel base materials. (2) The coating prepared by arc has large metal
particles which are not ionized, and these particles lead to a significant reduction in
the overall performance of the coating, especially the erosion resistance. And (3) Due
to the high hardness, the existing hard coatings form an “eggshell effect” with the
titanium alloy substrate, which has a negative impact on the high stress low cycle
fatigue performance of the substrate.

6. Problems and consideration of SPE coating

To sum up, in the research field of erosion resistant coatings, arc ion plating
technology is widely used in the preparation of erosion resistant coatings for engine
compressor blades. The coating system has gradually developed from binary TiN
series coatings to multiple multilayer composite structure systems, and the compre-
hensive performance of the coatings has also been improved to varying degrees.
However, up to now, the following problems still exist in the anti-erosion coating.

6.1 The internal influence law between composition, structure and performance
of SPE coating

The composition selection and structure design of the coating are the key to
determine its erosion resistance. At present, the research on erosion resistant coatings
has been carried out to optimize the performance from the aspects of preparation
parameters, coating microstructure, etc. The research results are one-sided and lack of
systematicness and guidance. There is little research on the internal correlation
between the composition structure and the residual internal stress, the interlayer
interface and the erosion resistance of the coating. At the same time, there is a lack of
in-depth study on the mechanism of coating erosion failure. In addition, according to
the service condition requirements of the erosion resistant coating, it should also have
high temperature resistance, fatigue resistance and other related properties. There-
fore, based on the above performance requirements and actual service conditions, a
complete anti-erosion coating design theory, such as material selection and structure
design, should be established.

6.2 Matching of strength and toughness of SPE coating

A large number of research results have shown that the high hardness of the hard
coating itself can well solve the micro cutting problem of the substrate caused by small
attack angle erosion. However, due to the lack of toughness of the monolayer hard
coating, the coating is prone to rapid failure in the form of brittle fracture when
coping with the erosion of sand and gravel at high angles of attack. Therefore, the
matching of strength and toughness of the coating is the key to breakthrough of the
erosion resistant hard coating. How to obtain a hard and tough erosion resistant
coating is also a research difficulty that has not been overcome so far.

6.3 Micro-particles in anti-erosion coatings prepared by arc ion plating

Arc ion plating technology has been widely used in the preparation of hard coat-
ings. However, due to its physical characteristics of arc discharge, it is difficult to
avoid the deposition of micro-particles of micrometer scale in the coating, which has a negative impact on the performance of the erosion resistant protective coating on the surface of precision parts. Therefore, how to eliminate or reduce the micro-particles in the anti-erosion coating prepared by arc ion plating is also one of the focuses of current research.

Author details

Wang Di\textsuperscript{1,2} and Yang Zhen\textsuperscript{2}

1 Shaanxi Key Laboratory of Surface Engineering and Remanufacturing, Xi’an University, Xi’an, China

2 Xi’an Flat Heat Treatment Co., LTD., Xi’an, China

*Address all correspondence to: wangd@xawl.edu.cn
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