Technical Characteristics and Wear-Resistant Mechanism of Nano Coatings: A Review

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Received: 15 February 2020; Accepted: 29 February 2020; Published: 3 March 2020

Abstract: Nano-coating has been a hot issue in recent years. It has good volume effect and surface effect, and can effectively improve the mechanical properties, corrosion resistance and wear resistance of the coatings. It is important to improve the wear resistance of the material surface. The successful preparation of nano-coatings directly affects the application of nano-coatings. Firstly, the preparation methods of conventional surface coatings such as chemical vapor deposition and physical vapor deposition, as well as the newly developed surface coating preparation methods such as sol-gel method, laser cladding and thermal spraying are reviewed in detail. The preparation principle, advantages and disadvantages and the application of each preparation method in nano-coating are analyzed and summarized. Secondly, the types of nano-coating materials are summarized and analyzed by inorganic/inorganic nanomaterial coatings and organic/inorganic nanomaterial coatings, and their research progress is summarized. Finally, the wear-resistant mechanism of nano-coatings is revealed from three aspects: grain refinement, phase transformation toughening mechanism and nano-effects. The application prospects of nano-coatings and the development potential combined with 3D technology are prospected.

Keywords: nano-coating; wear-resistant; coating technology; nano-coating material

1. Introduction

Since the first acquisition of nanocrystals by German scientist Gleiter [1] in the 1980s, the application potential of nanomaterials has been closely watched by researchers around the world. Nanomaterial refers to a material with a size of at least one dimension in the three-dimensional space of nanometer size [2]. The nanometer size makes the nanomaterial have the volume effect and surface effect that ordinary materials do not have. The specific spatial structure of nanomaterials makes it different from ordinary materials in optical, thermal, mechanical and magnetic properties. Some nano-materials can form a good cross-linking network with other materials, and the mechanical properties, anti-corrosion properties, thermal stability and wear resistance of the matrix are improved. It exhibits remarkable effects even when the amount of addition is low, and has good wear resistance.

Nanomaterial is a further step in the world of human understanding of the world. It is the frontier technology of the new century that materials science and many subjects intersect. Nowadays, social economy, science and technology continue to develop vigorously, and machinery and equipment have been playing a dominant role in the manufacturing industry. However, it is not negligible that metal materials in mechanical equipment fail, including wear, corrosion and fracture, and wear is the most common phenomenon. It will not only have a certain impact on the production process of products, but also the consumption of resources. Research shows that friction and wear consume one third of the...
world’s disposable energy, resulting in 80% of the mechanical parts scrapped. China’s annual economic
losses caused by wear and tear are about 150 billion RMB [3]. For traditional materials, there is almost
no potential to continue to improve their properties in micron grain size. Therefore, it is essential to
study high performance nanomaterials in the field of wear resistance. At present, nanotechnology has
been widely used in wear and corrosive environment of machinery, mainly nano-composite materials
and nano-structure coatings for wear resistance, often used in turbine blades, combustion boilers,
cutting tools and other equipment.

Coating is a unique method to modify the surface properties of the matrix, which makes the
matrix adapt to the special working environment and prolongs its working life [4]. Coating can be
defined as a thin film formed or deposited on the surface of a component made of another material,
which is similar to the mechanical properties of the matrix and has good corrosion resistance and
wear resistance. At the same time, due to the influence of surface effect, small size effect and quantum
effect, nano-materials have many characteristics different from macro-materials in physical properties
and mechanical properties, such as high strength, high toughness, high specific heat, high thermal
expansion rate, high conductivity, magnetic conductivity, high characteristic spectrum absorption and
so on. It has become an important research field in the frontier of science and technology development
in the new century.

In this paper, through the introduction of the technical characteristics of the nano-coating and
the study of the wear resistance mechanism of the nano coating, the nano material and the surface
coating technology are combined to prepare a surface composite coating containing nano powders.
The coating on the surface of the part can improve the modification effect of the surface technology
and improve the anti-wear and anti-corrosion ability of the material surface.

2. Preparation Technology of Nano-Coatings

Successful preparation of nano-coatings is the basis for the application of nano-coatings. On the
one hand, chemical vapor deposition (CVD), physical vapor deposition (PVD) and other conventional
surface coating technologies are applied. They regulate the thickness and grain size of the coating by
process parameters. On the other hand, through the development of new preparation methods, such
as sol-gel method, laser cladding, thermal spraying and so on.

2.1. Chemical Vapor Deposition

2.1.1. Principles and Characteristics of Chemical Vapor Deposition

Chemical vapor deposition (CVD) is a technology that uses gaseous or vaporous substances to
react on the gas phase or gas–solid interface to produce solid sediments [5]. CVD can generally be
classified according to the parent material and energy source of the product in the deposition reaction.
Conventional CVD uses electrical resistance or electromagnetic induction heating, which is also known
as thermal CVD.

CVD involves the dissociation and chemical reaction of gaseous reactants in an activating (thermal,
optical, plasma) environment, and finally forms a stable solid product. Deposition involves homogeneous
gas-phase reactions occurring in the gas phase, and heterogeneous chemical reactions occurring near
and near the heated surface, resulting in the formation of thin films or coatings, respectively.

Figure 1 shows a schematic diagram of the CVD coating [6]. AB₂ in solid or liquid state reacts
at high temperature to form a gaseous AX₂, which is then transported to the precipitation chamber.
A chemical reaction occurs on the surface of the substrate to form a coating, and the remaining X₂ is
discharged as a gaseous form.
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Figure 1. A schematic diagram of the chemical vapor deposition (CVD) coating [6]. Reprinted with permission from [6]; 2003 Elsevier.

Although chemical vapor deposition is a complex chemical system, it has the following advantages [6]:

- Ability to produce high density and pure materials;
- Uniform films with good reproducibility and adhesion are produced at a rather high deposition rate;
- CVD is a non-line-of-sight process with fine ejection capability. It can be used to uniformly coat components with complex shapes and deposit thin films with good conformal coverage. This unique feature surpasses the PVD process;
- It takes on the capability to control the crystallographic texture, surface morphology and tropism of CVD products pass through controlling the technological parameter of CVD;
- The deposition rate can be easily adjusted, and the low deposition rate facilitates the growth of epitaxial films for microelectronic applications;
- Traditional CVD technology has low processing costs.

Disadvantages of chemical vapor deposition include:

- Toxic, corrosive, flammable and/or explosive precursor gases are used in CVD processes, which can cause chemical and safety hazards;
- Because different precursors have different evaporation rates, it is difficult to use stoichiometric multi-component materials with well-controlled multi-source precursor deposition;
- CVD variants use more complex reactors and vacuum systems, which are manufactured by low pressure or ultra-high vacuum CVD, plasma-assisted CVD and photo-assisted CVD, etc., resulting in increased manufacturing costs.

2.1.2. Application of Chemical Vapor Deposition in Nano-Coating

In 1880, chemical vapor deposition was first applied to the patent “a pyrolytic carbon” by Sawyer and Man, who deposited carbon and metals on filaments to extend their life. In order to improve the wear resistance of tools, various metal carbides and nitrides were studied. In the research process, it was found that the grain size of the composite material has an important relationship with the wear resistance and hardness, and on this basis, nanocomposite was produced [7].

Diamond is currently the hardest crystal in nature. Since 1955, Bundy et al. [8] first synthesized granular diamond crystals at high temperatures and used them as abrasive particles and tools. After decades of development, nanoscale diamond coatings (NCD) have been produced.

CVD coatings can be used on parts that require wear resistance, oxidation resistance, corrosion resistance, and certain electrical, optical and tribological properties. For wear-resistant hard coatings, refractory borides, carbides, nitrides and oxides are generally used. Plating layers that meet these requirements include TiC, TiN, Al2O3, TaC, HfN and TiB2 and combinations thereof. However, due to the higher temperature of the CVD process, the hardness of the substrate will also decrease. At the same time, the quenching process will be required after the heat treatment, which will cause large distortion, so it is not suitable for the processing of high-precision parts [9–11].
At present, most of the diamond film coating tools that have appeared on the Chinese market are synthesized by direct current arc plasma spray chemical vapor deposition (DCCVD) [12]. NCD has the advantages of both diamond and nano materials. As a result of its low roughness, small friction factor and easy surface grinding and polishing, it is applied to the surface of cutting head and wire drawing core, and has good application prospects in the field of friction and wear.

2.2. Physical Vapor Deposition

2.2.1. Principles and Characteristics of Physical Vapor Deposition

The term “physical vapor deposition (PVD)” first appeared in the 1960s. It uses physical forms such as evaporation or sputtering to remove metals from the target source in the form of atoms or molecules, and then deposits these energy-carrying vapor particles onto the surface of a substrate or part through a vacuum or semi-vacuum space to form a film layer [13].

Distinguished from the principle of deposition, physical vapor deposition techniques can be divided into vacuum evaporation, sputtering, arc vapor deposition and ion plating. Although these methods differ greatly in specific technical measures, their deposition principles can be divided into three stages: (1) the emission of evaporation sources; (2) the transportation of vapor through vacuum space; (3) the deposition of vapor on the surface of substrates or parts [14].

Figure 2 is a schematic diagram of PVD (a) sputtering and (b) evaporating coating methods. As can be seen from Figure 2, the PVD reactor consists of a vacuum chamber and two electrodes connected to a high voltage power supply. During sputtering, the magnetron is located near the target. Ionic gas is introduced into the vacuum chamber in an accelerated manner, which explodes the target and releases the atomized particles to be deposited, which will be projected violently onto the substrate. In the process of electron beam evaporation, the target has an evaporation source containing the material to be evaporated and is used as a cathode. The released particles will collide with the gas molecules introduced into the reactor to accelerate the particles and form plasma through the deposition chamber, which will be more intense in the middle of the reactor. Particles will be deposited on the substrate to form a continuously compressed layer, which allows a good film to adhere to the substrate and form a coating.

**Figure 2.** Schematic diagram of physical vapor deposition (PVD) sputtering and evaporation coating methods: (a) the sputtering; (b) the evaporation [14].

The advantages of physical vapor deposition are as follows [15]:

- Very uniform coatings can be obtained, with thicknesses ranging from a few nanometers to thousands of nanometers;
- High repeatability.
- Good coiled parts, suitable for coating various complex shapes of workpieces;
- Possibility of selective deposition in choose sections;
- Material selection with almost no restrictions on the substrate;
- Sufficient flexibility in temperature requirements for substrates;
- A wide range of coating materials, including metals, alloys and compounds;
- Environmental protection and no pollution.

The disadvantages of physical vapor deposition are as follows:

- The complexity and high cost of technology and monitoring equipment;
- High requirements for the work of operators;
- The productivity is relatively low;
- High-precision chemical composition is required;
- Special preparation of the coating surface is required.

2.2.2. Application of Physical Vapor Deposition in Nano-Coating

Physical vapor deposition was first applied to tools and molds. By depositing TiC coating, the life of the mold can be effectively extended; depositing coatings on high-speed steel tools can improve the wear resistance, chip resistance and cutting speed of the tools. At the same time, the coated tools also have high hardness, high chemical stability, high toughness and low friction coefficient [16,17]. With the development of technology, it is also gradually used in the fields of building decoration, electricity and medicine [18].

With the development of technology, many researchers have applied physical vapor deposition to the surface of various parts to increase the wear resistance of parts. Wang et al. [19] studied the wear and corrosion of several metal and nano-structure coatings in different environments by vapor deposition. It was found that the wear rate of \( \text{Al}_2\text{O}_3-3\text{TiO}_2 \) nano-coatings was 30%–50% of that of conventional coatings. The better wear resistance of nano-coatings was due to the existence of equiaxed crystals.

Meanwhile, Kazmanli et al. [20] added Sb to the TiN coating by vapor deposition of the mixture. As a result, it was found that TiN nanocrystals were produced in the TiN coating. The maximum hardness of the coating can reach \( 38 \text{ GPa} \) by adding a small amount of Sb. When the crystal size decreases to about 5 nm, the nanocomposite coating suddenly softens to the hardness of 18 GPa.

In addition, some researchers have applied physical vapor deposition to aviation. Biksa et al. [21] prepared an adaptive nano-multilayer AlTiN/Me\(_x\)N coating by physical vapor deposition and added it to the aerospace alloy processing. These coatings had a significantly lower coefficient of friction at elevated temperatures, significantly increasing the wear resistance of the substrate. Figure 3 shows the type and morphology of the underlying surface of the various coatings during processing of the 718 alloy. Less friction and wear results in a smoother curled chip and lower surface morphology, and the surface morphology of the multilayer AlTiN/MoN coating (Figure 3d) appears smoother when compared to a single layer of AlTiN coating (Figure 3b).

Physical vapor deposition technology has been widely used in various industries, and many technologies have achieved industrial production. Its coating products involve many practical fields.
2.3. Sol-Gel Method

2.3.1. Principles and Characteristics of Sol-Gel Method

The principle of sol-gel coating technology is to use easily hydrolyzed precursors (metal alkoxides or inorganic salts) to react with water in a certain solvent. After hydrolysis and polycondensation, a sol is formed, and the sol is coated on the surface of the substrate. After drying and heat treatment, a coating is formed [22–24].

According to different preparation methods of sol, sol-gel method can be divided into colloidal gel route and polymeric gel route. The former is that the precursor is added to excess water, and the hydrolysis of salt is fast. The latter is to dissolve the precursor in an organic solvent. When a small amount of water is added, the hydrolysis rate of the salt is slow, and at the same time it is only partially hydrolyzed to form organic-inorganic polymer molecules [25,26].

The sol-gel method has many unique advantages over other methods [27]:

- The reaction can be carried out at a low temperature;
- Capable of preparing high-purity, homogeneous coatings;
- It is suitable for large-area film formation, and the composition of the film is relatively easy to control, and materials can be designed and prepared from the molecular level;
- The process is simple and the equipment requirements are low.

The disadvantages are:

- Raw materials are expensive and some organics are harmful to health;
• The preparation cycle is long, which usually takes days or weeks;
• There are a lot of micropores in the gel, and many gases and organics will escape during the drying process, and shrinkage will occur.

2.3.2. Application of Sol-Gel Method in Nano-Coating

The sol-gel method is an important method for synthesizing inorganic compounds or inorganic materials under low temperature or mild conditions, and plays an important role in soft chemical synthesis. It has obtained important applications in the preparation of glass, ceramics, films, fibers, composite materials, etc., and is more widely used in the preparation of nanoparticles [28–30].

Sol-gel method is commonly used to prepare nano-coatings to increase their wear resistance. Jiang et al. [31] improved the wettability and abrasion resistance of titanium dioxide (TiO$_2$) films by combining a polydopamine (PDA) adhesive layer between the TiO$_2$ layer and the glass substrate. They performed abrasion resistance and indentation tests by scratching the film surface with AFM probes and NHT nanoindentations, respectively, and showed that due to the formation of TiO$_2$/PDA hybrid films, they have higher wear resistance than pure TiO$_2$ films. The coating of the mixed layer with PDA increases the adhesion of the TiO$_2$ layer to the substrate.

Simultaneously, Claire et al. [32] developed a thin hybrid coating obtained by a sol-gel process for corrosion and wear protection of mild steel. This innovative system consists of an aluminosilicate epoxy-based sol-gel coating that acts as a barrier and improves mechanical properties when loaded with zirconia particles. For the first time, they combined an anti-wear test with EIS to assess the impact of abrasive wear on corrosion resistance. It was found that the lower zirconia-loaded coating lost the corrosion protection due to the formation of local defects after material removal. In contrast, the heavily loaded zirconia coating exhibits interesting corrosion and wear behavior, forming a dense layer on top of the outer layer, which provides a barrier to water and ion penetration.

The technology for preparing nanomaterials by sol-gel method is gradually mature and perfected. However, further research and development are needed to truly control the ultrastructure of materials and design at molecular level.

2.4. Laser Cladding Method

2.4.1. Principle and Characteristics of Laser Cladding Method

Laser cladding refers to the preparation of the selected powder system on the surface of the substrate, and then the high energy laser beam is used as the heating source to form the cladding layer after the heated part is melted and cooled. The cladding layer has a series of excellent properties, which can be an advanced technology to modify the surface of the matrix [33]. In the laser cladding process, there are a series of complex physical and chemical reactions. In this process, not only the composition of the coating material, the performance of the coating material and the performance of the matrix itself, but also the laser process parameters have a significant impact on the quality of the cladding layer [34–36].

Laser cladding process can be divided into one-step or two-step process [37]. Figure 4 shows the principle of laser cladding. In the one-step process, materials are continuously fed into the laser-generated molten pool, usually in the form of fine powder. In the two-step method, a thin layer of material (such as slurry) is deposited on the surface of the substrate, and then melted by using a laser beam.

Compared with other technologies, laser cladding technology has the following advantages: fast cooling speed (up to 106 °C/s); low dilution rate of coating; small heat input and distortion; almost unlimited powder selection; large thickness range of cladding layer; high cost performance; easy to realize automation.
Although laser cladding technology has developed rapidly in recent years and has been used in some industrial fields, the technology is still in the development stage and there are still some problems to be solved [38,39].

- The metallurgical quality of the laser cladding layer is poor;
- Porosity, cracks and other problems will occur, affecting the performance of the coating;
- Uneven composition and structure during laser cladding;
- Repeatability check.

2.4.2. Application of Laser Cladding in Nano-Coating

The coating obtained by laser cladding can significantly improve the optical and mechanical properties of mechanical parts. At the same time, it can also increase the service life of materials. As a rising surface modification technology, it has high value in the field of waste maintenance and support. It is mostly used in military, heavy industry, petroleum, air defense, medical equipment and other directions [40,41].

At present, metal-based composite materials such as iron-based, nickel-based, cobalt-based, aluminum-based, titanium-based and magnesium-based can be prepared using laser cladding technology. Functional classification: It is possible to prepare coatings that have multiple functions, such as wear resistance, corrosion resistance, high temperature resistance and special functional coatings. From the perspective of the material system constituting the coating, it has developed from a binary alloy system to a multi-element system. The design of multi-component alloy composition and multi-functionality are important development directions of new materials for laser cladding in the future.

The nano-coating prepared by laser cladding technology can reduce its friction coefficient and reduce the wear rate. Yan et al. [42] coated nano-Ni on nano-h-BN by high energy ball milling to improve the compatibility between h-BN and metal matrix in laser cladding process, and further studied the micro-structure and wear properties of self-lubricating composite coatings. The results showed that high energy ball milling of nano-Ni on nano-h-BN improved the interfacial compatibility between h-BN and Ni60 matrix remarkably. The friction coefficient of laser cladding Ni60/nano-Ni coated h-BN coatings decreases obviously. The cross-sectional morphology of laser cladding Ni-based alloy/nano-Ni encapsulated h-BN self-lubricating composite coatings is shown in Figure 5.
In the study of Zhao et al. [43], three different coatings were synthesized on Q235 steel by laser cladding from three powders: Ni-based composite powder (Ni60), Ni-based composite powder (h-BN/Ni60) added with h-BN solid lubricant, Ni-base composite powder with the addition of nano-Cu encapsulated h-BN solid lubricants (nano-Cu/h-BN/Ni60). The microstructures of these coatings were analyzed by means of scanning electron microscopy (SEM). The results showed that although the hardness of the coatings decreases with the addition of nano-Cu and h-BN, the nano-Cu/h-BN/Ni60 coatings had the lowest friction coefficient and wear rate in a wide temperature range of 25–500 °C.

Nazari et al. [44] developed a new Ti-Fe composite coating by laser cladding. For the first time, a new Ti-Fe coating was coated on the titanium substrate with titanium powder recovered from mechanical processing. The post-deposited microstructures showed dendritic structure in the whole composite coating. Subsequently, the fine martensitic Ti phase, Fe in the form of Fe₂O₃ and Fe₃C, TiC and TiO₂ phase were formed in the heat affected zone, which significantly improved the hardness of the coating. This kind of hard composite coating could effectively improve the wear resistance of titanium alloy, which was applied in aerospace and national defense industry.

With the rapid development of technology and industry, the technical requirements for laser cladding will become higher and higher. The development of laser cladding in the future requires multi-disciplinary development, systematic development, large-scale cladding and quality control.

2.5. Thermal Spraying

2.5.1. Principle and Characteristics of Thermal Spraying

Thermal spraying is an important and rapidly growing surface modification technology that uses a wide variety of solid materials (including metals and alloys, hard alloys, ceramics and polymers). Particles, wires and suspensions are the main components. The heat source is used to heat the sprayed granular materials to the melting state, atomize them by air blowing, and then spray them to the surface of the parts at high speed to form a thermal spraying coating [45]. Figure 6 is a schematic diagram of the principle of thermal spraying. The material is in the state of complete melting or semi-complete melting under the heating of the spray gun. It is accelerated inside or outside the spray gun and impacts on the substrate to deform, while the substrate remains in the state of non-melting, thus forming a coating [46]. There are many types of thermal spraying technology based on heat source classification, mainly including cold spraying, flame spraying, arc spraying, plasma spraying and special spraying [45].
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*Figure 5.* Cross-sectional morphology of laser cladding Ni-based alloy/nano-Ni encapsulated h-BN self-lubricating composite coating: (a) the Neodymium-doped Yttrium Aluminium Garnet (Nd: YAG) laser cladding; (b) the CO2 laser cladding [42]. Reprinted with permission from [42]; 2017 Elsevier.

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*Figure 6.* Schematic diagram of thermal spraying [45]. Reprinted with permission from [45]; 2014 Elsevier.

Compared with other technologies, thermal spraying for preparing nanostructured coatings has many advantages, such as simple process, wide selection of coating and matrix, wide variation of coating thickness, high deposition efficiency and easy formation of composite coatings.

The main disadvantage of thermal spraying is that their inherent high temperature inevitably leads to changes in the microstructure of the coating, resulting in oxide inclusions, which can affect the hardness and wear resistance of the coating [47].

2.5.2. Application of Thermal Spraying in Nano-Coating

The preparation of nanostructured coatings by thermal spraying has broad application prospects in industry and has been one of the hot topics in recent years [48,49]. The preparation of nanostructured coatings by thermal spraying has broad application prospects in the industry and has been one of the hot issues in recent years. In the face of the new requirements of high-end equipment and parts for wear-resistant, corrosion-resistant and thermal barrier properties of coatings, thermal spraying technology provides a new way to solve the problem. Nano thermal spraying coating breaks through the size limitation of materials, and brings the unique properties of nano materials to the coating [50,51]. No matter the porosity, strength, hardness and toughness of the coating, it has a great progress compared with the conventional micron coating [52]. At the same time, nanostructures have a qualitative leap in wear resistance, corrosion resistance and thermal barrier performance compared with micron level coatings, and their service life can be extended by 3–5 times [53].

Compared with other methods, the thermal spray method is more widely used, and its development will be more comprehensive in the future, so its application is highlighted here. At present, the research on the preparation of nanostructured coatings by thermal spraying mainly focuses on oxides, carbides and their composites, as well as nickel-based alloys.

1. Nanostructured WC/Co Coatings

WC/Co is an excellent anti-friction and wear material that has been used in the preparation of hard coatings and is used industrially. In 1994, the University of Connecticut made high-temperature flame spraying to prepare nanostructured WC/10Co coatings, which had high hardness and good bonding strength [54]. Subsequently, the preparation of nanostructured WC/Co coatings has attracted widespread interest. Traditional WC/Co coatings are only melted in the surface area, which is a low-quality coating, while nano-WC/Co coatings are melted in full volume, which is a high-quality coating. After nano-WC cermet powder is used, the nano-materials are characterized by denser coating, finer grain strengthening, higher toughness and hardness, stronger adhesion, stronger strength and...
crushing resistance, and better wear resistance. The Schematic of wear mechanism of WC-(nano WC–Co) is shown in Figure 7.

Figure 7. Schematic of wear mechanism of WC–(nano WC–Co) [55]. Reprinted with permission from [55]; 2019 Elsevier.

Hangzhou Mechanical Design Research Institute adopts high Mach Oxygen-Kerosene supersonic intelligent thermal spraying process, spraying material adopts nano-modified tungsten carbide (S4020) powder, combined with advanced surface modification technology and 3D intelligent programming technology, to protect the turbine from abrasion and prolong the service life of the unit [56]. Wu et al. [57] used the above technology to spray WC/10Co4Cr coating on the surface of hydraulic turbine. Under the single high temperature, the WC phase in the coating distributed more evenly in Co and Cr phases. The microhardness distribution on the surface of the coating was more uniform, and the microhardness value was significantly improved. The wear resistance and sediment erosion resistance of the coating were greatly improved.

Myalska et al. [58] used a mechanical blending and ultrasonic assisted mixing method to mix WC/17Co raw material powder with different amounts of TiC nanoparticles and thermally spray it onto a carbon steel substrate using the high-velocity air-fuel (HVAF) method. TiC was gently oxidized but did not decompose or dissolve in the Co-based matrix. In addition, the addition of nanoscale TiC inhibited the dissolution and decarburization of WC. When the TiC nanoparticles were dried and sliding at 400 °C, the dense clusters of TiC nanoparticles protruded from the coating surface and carried most of the contact loads. Therefore, the wear rate was reduced. By reducing the direct contact between the WC/Co surface and the corresponding body, they also reduced the amount of friction oxidation debris clusters (based on CoWO4 and WO3·2H2O), which formed on the wear track and helped to reduce the friction coefficient.

Mi et al. [59] prepared nano-WC/Co coatings with low decomposition degree by high-velocity oxygen-fuel (HVOF) process, and studied the structure, mechanical properties and wear properties at high temperatures. The results showed that the nano-WC/Co coating had a compact structure and the friction coefficient decreased gradually with the increase of test temperature. The wear rate decreased first and then increased. The wear rate was the smallest at 450 °C. The continuous oxide film composed of WO3/WO3-CoWO4 on the wear surface could reduce the friction coefficient and wear rate. Figure 8 shows the morphology of WC-(nano-WC/Co) powder. The powder in Figure 8a is spherical, and the WC particle in Figure 8b shows bimodal size distribution.
but the elastic recovery rate of nanostructured 8YSZ coatings was higher than that of traditional 8YSZ coatings. In fact, the sealing layer of TiO₂ could fill some micro-holes in the substrates at various oxygen to acetylene ratios. The abrasive wear test was performed using SiC as a grinding medium, and the coating wear rate was calculated. It was found that changes in the indentation load and the microstructure of the coating affected the characteristic hardness and the Weibull modulus. According to the results obtained, the minimum number of notches needed to achieve the characteristic hardness value was calculated, and the Structure-Performance correlation was tested. The strategies based on Weibull parameters were proposed to obtain the best performance and performance.

(2) Nanostructured ZrO₂ Coatings

Nano zirconia coatings are often used as thermal barrier coatings because of their low temperature coefficient, high coefficient of thermal expansion, and good stability at high temperatures. The thermal barrier coating consists of a tie layer and a zirconia coating.

Wang et al. [61] prepared nanostructured conventional ZrO₂-8 wt% Y₂O₃ (8YSZ) thermal barrier coatings (TBCs) on 45 # steel substrates by atmospheric plasma spraying (APS). It was found that the elastic modulus of nanostructured 8YSZ coatings was lower than that of conventional 8YSZ coatings, but the elastic recovery rate of nanostructured 8YSZ coatings was higher than that of traditional 8YSZ coatings. From Figure 9, we can see that there are many defects (pore and fracture) in traditional TBC (Figure 9a), and the distribution of fracture is irregular and chaotic. The cracks in nanostructured TBC (Figure 9b) are relatively fine and few, and there is no obvious growth direction, which is mainly attributed to the increase of fine grain and toughness of nanostructured coatings.

Yin et al. [62] were used to spray FeAl powder and ZrO₂ nanoparticles and CeO₂ additives to form new multi component raw materials by spray drying. The raw material was used to deposit...
FeAl/CeO2/ZrO2 nanocomposite coatings by plasma spraying on 1Cr18Ni9Ti stainless steel. Vickers micro indentation tester and ball disc sliding wear friction mill were used. The mechanical properties and friction and wear properties of nano-composite coatings and pure FeAl coatings were compared and evaluated. The wear mechanism of the two coatings was discussed in terms of their microstructures and mechanical properties. The results showed that the nanocomposite coatings had higher hardness, fracture toughness and wear resistance than pure FeAl coatings, which may be attributed to the strengthening effect of ZrO2 nanoparticles.

In the study by Zhang et al. [63], ZrB2-containing composite coatings were prepared by plasma spraying ZrO2/B2O3/Al system, and the effects of ZrO2 particle size on the structure and properties of the coatings were studied. The results showed that ZrB2 was formed by the reaction of ZrO2, B2O3 and Al during plasma spraying. The reaction degree between ZrO2/B2O3/Al composite powder and nano-ZrO2 particles was greater than that of micro-ZrO2 particles, and more ZrB2 was formed in coating plasma sprayed with nano-ZrO2 particles. The coatings prepared by plasma spraying ZrO2/B2O3/Al composite powder and nano-ZrO2 exhibited layered structure. ZrB2 particles were uniformly distributed, the microstructure was dense and the quality was good. The hardness and toughness of the coatings prepared by nano-ZrO2 were much higher than those prepared by micro-ZrO2.

(3) Nanostructured Al2O3 and Al12O3/3/TiO2 Composite Coatings

Nanostructured Al2O3 and its composite coatings have excellent anti-friction and corrosion resistance and have been used in military and industrial applications. Navies of some countries have applied thermal sprayed Al2O3/TiO2 nano-coatings as a new anti-friction and wear material for ships.

Daroonparvar et al. [64] successfully applied plasma sprayed multilayer coatings to magnesium alloys. In the experiment, NiCrAlY coating, NiCrAlY/nano-Al2O3-13%TiO2 coating and NiCrAlY/nano-Al2O3-13%TiO2/nano-TiO2 coating were coated on the magnesium alloy matrix and formed three different plasma spraying coatings. The corrosion behavior of these three different plasma spraying coatings in 3.5 wt% NaCl solution was described. The results showed that the new coating (NiCrAlY/nano-Al2O3-13%TiO2/nano-TiO2) could reduce the corrosion rate and increase the impedance value of magnesium alloy. In fact, the sealing layer of TiO2 could fill some micro-holes in the Al2O3-13%TiO2 coating to slow down the corrosion rate of the coating. Figure 10 shows the fracture diagram of three layers of NiCrAlY/nano-Al2O3-13%TiO2/nano-TiO2 coating.

Figure 10. Fracture diagram of three-layer NiCrAlY/nano-Al2O3-13%TiO2/nano-TiO2 coating [64]. Reprinted with permission from [64]; 2015 Elsevier.
Yang et al. [65] successfully prepared plasma sprayed nano additives Al₂O₃/TiO₂ nanocomposite powders by spray drying, heat treatment and plasma treatment. The effects of processing technology and nano additives on the microstructure and properties of Al₂O₃/TiO₂ nanocomposite powders were studied. The Al₂O₃/TiO₂ composite powder prepared by spray drying and heat treatment was a nanostructured composite powder with high spherical shape and nano particle size. The nanocomposite powder of the three-dimensional network structure obtained after the plasma treatment was composed of an amorphous intercrystalline network film rich in Ti, Zr and Ce surrounding the α-Al₂O₃ colony. Due to the rapid melting and solidification of plasma treatment, spherical powders with smooth surface and dense microstructures were formed. Therefore, the fluidity and density of plasma treated powders were significantly improved.

(4) Nanostructured Ni-based Alloy Coatings

In order to improve the efficiency of gas turbines, thermal barrier coatings (TBCs) are typically applied to the surfaces of high temperature working parts to protect the parts from high temperature oxidation and hot corrosion. In order to increase the bonding force between the zirconia coating and the substrate, MCrAlY (M represents Ni and/or Co) is usually used as the bonding layer.

In the study of Ajdelsztajn et al. [66], NiCrAlY powder was mechanically ground into micron particles with nanocrystalline structure, sprayed by high-speed flame, and then oxidized at 1000 °C. It was found that a continuous layer of α-Al₂O₃ was formed in NiCrAlY coating. However, discontinuous oxide layers were formed on the surface of the coatings sprayed with non-nanocrystalline NiCrAlY powder. These oxides were mainly NiO and Ni(Cr, Al)₂O₄. The formation and growth of these oxides caused cracks and the stripping of zirconia coatings, which seriously affected the service life of thermal barrier coatings.

Matthews et al. [67] sprayed Cr₃C₂-NiCr coatings using two HVOF technologies and plasma coating techniques to produce samples with broad-spectrum carbide dissolution and peritectic decomposition of Cr₃C₂. It was found that coated plasma spraying was very effective in reducing carbon loss and oxygen absorption. Differential scanning calorimetry (DSC) was used to characterize exothermic solid phase transformation in coatings. In plasma spraying, other higher temperature peaks were also observed, which was attributed to the transformation of (Cr, Ni)₇C₃ and Ni phase with high Cr content into equilibrium phase Cr₃C₂ and low Cr content Ni binder, which was beneficial to restraining crack formation.

In the future development, there are many factors that affect the quality and performance of coatings during the process of preparing nano-coatings by thermal spraying technology. A lot of research and development work will focus on process research and coating performance. At the same time, spraying equipment will also develop towards automation, so that extremely complex operations can be accurately repeated.

2.6. Summary of Each Preparation Technology

Table 1 is a comparative summary of each preparation technology.
| Preparation Technology | Principle | Advantages | Disadvantages | Materials |
|------------------------|-----------|------------|---------------|-----------|
| CVD                    | (1) Formation of volatile substances; (2) Transfer the above substances to the deposition area; (3) Produce chemical reactions on solids and produce solid substances [6]. | (1) Material purity; (2) High production efficiency; (3) Excellent performance; (4) Easy to control; (5) Processing costs [7]. | (1) Harmful gas will be generated; (2) Difficult to produce multi-component materials. | Refractory borides, carbides, nitrides and oxides (TiC, TiN, Al₂O₃, TaC, HfN and TiB₂) [9–11]. |
| PVD                    | (1) Generation of gas-phase substances; (2) Transportation; (3) Deposition [14]. | (1) The coating is uniform; (2) High repeatability; (3) Good coated parts; (4) Local deposition; (5) Almost unlimited material selection for the substrate; (6) Have sufficient flexibility for the temperature requirements of the substrate; (7) Wide selection of coating materials; (8) Environmental protection without pollution [15]. | (1) The complexity and high cost of technology and monitoring equipment; (2) High work requirements for operators; (3) Relatively low productivity; (4) Chemical components with high precision are required; (5) Special preparation is required for the coating surface. | Metal, alloy, compound [16,17]. |
| Sol-gel Method         | (1) Hydrolysis reaction; (2) Coating; (3) Heat treatment [22–24]. | (1) The reaction can be performed at low temperature; (2) Can prepare high purity and homogeneous coatings; (3) Suitable for large area film formation; (4) The process is simple [38,39]. | (1) Raw materials are expensive and some are harmful; (2) Long preparation period; (3) There are a lot of micropores in the gel. | Metal alkoxide or inorganic salt [22–24]. |
| Laser Cladding Method  | (1) Single-step method: material is continuously fed in a laser-generated molten bath; (2) Two-step method: deposition and melting [37]. | (1) Fast cooling speed; (2) Low coating dilution rate; (3) Less heat input and distortion; (4) Powder selection is almost unlimited; (5) The thickness of the cladding layer is large; (6) High cost performance; (7) Easy to implement automation [38,39]. | (1) The metallurgical quality of the laser cladding layer is poor; (2) Porosity, cracks and other problems will occur, affecting the performance of the coating; (3) Uneven composition and structure during laser cladding; (4) Poor repeatability. | Preparation of Fe-based, Ni-based, Co-based, Al-based, Ti-based, Mg-based metal-based composite materials [40]. |
| Thermal Spraying       | (1) Heat the material to the melting state; (2) Atomize materials with airflow; (3) Deposited on the substrate [45]. | (1) The process is simple; (2) Wide selection of coatings and substrates; (3) Large range of coating thickness variation; (4) High deposition efficiency; (5) Easy to form composite coating [47]. | Inherent high temperature will cause oxide inclusions, affecting the hardness and abrasion resistance of the coating. | Oxides, carbides and their composites and nickel-based alloys [53]. |
3. Type of Nano-Coating Materials

Nano-coatings are classified into functional coatings and structural coatings in terms of their action. Functional coatings impart properties that are not available to the substrate, thereby providing functionality not found in conventional coatings. For example, optical coatings for extinction, light reflection and light selective absorption, conductive, insulating and electrical coatings with semiconducting properties, as well as oxygen sensitive, moisture sensitive and gas sensitive coatings.

Structural coatings refer to super hard and wear resistant coatings, oxidation, heat and flame retardant coatings, corrosion and decorative coatings. Nanostructured coatings are also functional coatings from a whole concept. Therefore, it is difficult to accurately assign the nano-coating to which of the above two categories. Current research is based on the type of material that divides nano-coating materials into two broad categories: inorganic/inorganic nanomaterial coatings and organic/inorganic nanomaterial coatings. These two types are functional and structurally strong materials [68].

3.1. Inorganic/Inorganic Nanomaterial Coatings

Inorganic/inorganic nanomaterial coatings are coatings formed by the combination of inorganic nanomaterials and inorganic nanomaterials, and are a technique for adding inorganic nanoparticles and materials to inorganic nanomaterial substrates. These include ceramic/ceramic nano-coating materials, metal/ceramic nano-coating materials, and metal/non-ceramic nano-coating materials.

3.1.1. Ceramic/ceramic Nano-Coating Materials

The coatings are divided into nano compound coatings such as carbon, nitrogen and boron, nano oxide coatings (including nano rare earth oxide coatings) and composite substrates. Nowadays, carbide, boride and nitride composite coating materials are the most widely used ceramic/ceramic nano coating materials in the world. They are combined into a nanocomposite-based coating such as B$_4$C/SiC, B$_4$C/HfC, TiC/TiB$_2$, TiN/TiB$_2$, TiC/TiN and so on. Several nano-coatings of B$_4$C/SiC, HfC/SiC and HfC/B$_4$C are commonly used in knives to protect the surface from high temperature oxidation. In the patent “Methods of forming ceramic compositions”, some researchers added 100~300 nm SiC particles to Al$_2$O$_3$ and MgO nanopowders to make nano-coatings, which greatly improved their performance at room temperature and high temperature.

The second ceramic coating is a common metal nano-oxide coating such as ZrO$_2$, Fe$_2$O$_3$, TiO$_2$, CdO and ZnO. Among them, nano ZrO$_2$/ceramic structural coating technology has attracted attention. It applies nano zirconia coating powder to various ceramics, which makes the performance of the coating better than traditional coatings. ZrO$_2$ nano-coatings are mainly used for heat shielding, high temperature resistance, corrosion resistance and abrasion resistance. They have lower thermal conductivity and high thermal expansion coefficient than traditional zirconia coatings, and the mechanical properties of nano-zirconia modified ceramics are also very good. In the study by Tang et al. [69], the short carbon fiber (CF) reinforced ceramic matrix composites were first acidified and oxidized, and ZrO$_2$ was deposited on the surface by sol-gel method. The microstructure analysis showed that ZrO$_2$-Cl/SiC composites were prepared by hot press forming and sintering compared with Cl/SiC and SiC prepared by the same method. The ZrO$_2$ coating was successfully deposited on the CF surface. A strong bond and an interface between the CFs and the substrate were formed. At the same time, CFs were found to be uniformly distributed in the SiC matrix with random orientation. The compressive strength of the three samples showed a gradual increase. ZrO$_2$-C/SiC exhibited the highest value, indicating that the introduction of CFs and ZrO$_2$ coatings had a large effect on mechanical properties. After heat treatment, ZrO$_2$-C/SiC exhibited better oxidation resistance than Cl/SiC. Figure 11 shows the morphology of (a) untreated CFs and (b) pre-oxidized CFs.
The third ceramic coating is a nano rare earth oxide coating. It is added to Y2O3 to ZrO2, sintered into zirconia ceramics at low temperature, and then zirconia ceramic was applied to metal cutters and wear parts to form a coating with high strength and toughness. Reghu et al. [70] applied an Y2O3/ZrO2 thermal barrier coating to automotive pistons using plasma spray for wear and tear caused by vibration and thermal fatigue. They performed thermal shock cycles and random vibration tests on the research pistons, and analyzed the cross-section metallographic materials through SEM. It was also found that the coating does not deteriorate under severe thermal shock.

3.1.2. Metal/ceramic Nano-Coating Materials

Metal/ceramic composites are widely used in aerospace, machinery and other fields due to their high hardness and high heat resistance and corrosive conditions. Atmospheric plasma spraying (APS) is also commonly used to prepare metal/ceramic composite coating materials, because of its high flame temperature and rapid deposition. The adhesion at the interface between ceramic and metal determines the service life and mechanical properties of the metal/ceramic composite [71]. Bigelow and Shen [72] used numerical analysis to investigate the initiation of shear bands during nanoindentation of Al/SiC multilayer coatings. According to the cutting performance requirements, hundreds of layers could be superposed, and the total thickness could reach 2~5 μm. The use of this coating significantly increased the hardness and toughness of the tool, making it excellent in friction and wear resistance and self-lubricating properties. Therefore, it was suitable for cutting.

3.1.3. Metal/non-Ceramic Nano-Coating Materials

The coating materials include metal/metal, metal/alloy, metal/metal containing salts and the like. The first thing worth mentioning is the metal/nano-diamond coating. It puts a small amount of nano-diamond into the paint and sprays it on the metal or alloy parts of the car’s surface. It can resist scratches and UV rays and improve the uniformity, firmness and wear resistance of automotive coatings. Apply it to the ship, it can resist seawater corrosion, spread on airplanes and tanks, and can be invisible. Secondly, nano-diamond nickel-plated, copper-plated, galvanized, chrome-plated composite plating solution. Composite plating of various cutting tools can increase their wear resistance by 2 to 4 times and microhardness by 1 to 4 times.

3.2. Organic/Inorganic Nanomaterial Coatings

Organic/inorganic nanomaterial coatings refer to the composite of organic nanomaterials and inorganic nanomaterials to form coatings, including dispersing inorganic nanoparticles on organic substrates and adding nanoorganisms to inorganic nanomaterials. In the entire system, one phase is called the matrix and is a continuous phase; the other phase is a reinforcing material and belongs to the...
dispersed phase. Organic/inorganic nanomaterial coatings can not only overcome the shortcomings of simple inorganic particles, poor stability of organic polymers, low strength, etc., but also can obtain better performance than inorganic particles and organic polymers under the combined action of the two, such as excellent performance in the mechanical, electrical, thermal and optical aspects of materials. Therefore, this type of new material, which combines many characteristics of inorganic, organic and nano, has better performance as a structural material [73–76].

Due to the excellent mechanical properties of organic/inorganic nanomaterial coatings, it is suitable for wear-resistant materials, and because of its good thermal stability, nanocomposites can be used in the manufacture of thermal insulation parts [77,78]. Scholars from various countries have done a lot of research on this. Wang et al. [79] prepared 2-(3,4-epoxycyclohexyl) ethyltriethoxysilane (ETEO) by hydrosilylation reaction. Surface grafting of nano-SiO$_2$ with ETEO gave a new type of silicon-based nano-SiO$_2$ (ETEO-SiO$_2$). An epoxy resin/ETEO-SiO$_2$ composite coating was prepared. When the amount of ETEO-SiO$_2$ nanoparticles added reaches 4%(mass fraction), the anti-corrosion and wear resistance properties were optimal.

Atta et al. [80] obtained a new exfoliated superhydrophobic nanocomposite based on hydrophobic montmorillonite (HMT) modification by using hydrophobic silver and iron oxide nanoparticles. The modified HMT nanocomposite is blended with epoxy resin, cured with a polyamine hardener and easily sprayed on rough steel surfaces by a simple and effective one-step spraying method. It has been found that the superhydrophobic epoxy nanocomposites have greatly improved the corrosion resistance and wear resistance in high salt seawater environment.

4. Mechanism of Nano-Coating Wear-Resistant

In general, component failures of equipment are mainly caused by abrasive wear, corrosion, fatigue wear and cracks. This obviously limits its application in engineering. Conventional coatings are difficult to avoid defects such as cracks, and the occurrence of cracks deteriorates the wear resistance of the coating. The addition of nanoparticles refines the grains, thereby suppressing cracks. Thereby improving the strength, toughness, corrosion resistance, heat resistance and the like of the nano-coating.

4.1. Grain Refinement

One of the reasons for the enhancement of the wear-resistant ability of nano-coatings is the refinement of the grains by the nanoparticles. For example, in laser cladding, the addition of a certain amount of nano rare earth particles improves the microstructure of the coating [81]. The rare earth elements have a large atomic radius and play an important role in grain refinement. When the atomic arrangement is found to be irregular, the rare earth atoms on the grain boundaries are enriched to retain the lowest free energy of the system. The stability of the rare earth elements in the grain boundary is better than that in the interior of the grain. When the rare earth elements accumulate on the grain boundary, the rare earth elements will have a drag effect during grain growth, which hinders the growth of the grain. Grain refinement occurs when a large number of nucleation sites cause an increase in the number of grain boundaries, and increasing the area of the grain boundaries hinders the generation of cracks and improves the drag effect of crack propagation.

In addition, the rare earth elements are a surface active element and has a tendency to enrich at the grain boundary. They reduce the surface energy at the grain boundaries, thereby preventing dislocation motion and preventing microcrack nucleation and crack propagation.

4.2. Phase Transformation Toughening Mechanism

The improvement in wear resistance of the composite coating is attributed to the phase transformation toughening mechanism associated with tetragonal zirconia. It produces more ductile tribofilms during the wear test to participate in the pores of the filled coating [82]. ZrO$_2$ is a multi-phase system that is subjected to three phases in the influence of temperature: monoclinic, tetragonal and cubic, but it is a reversible phase transition process. Only monoclinic phase is stable at normal temperature.
The ZrO$_2$ phase transformation toughening mechanism is shown in Figure 12. By applying stress on zirconia, a four-direction monoclinic transition (T→M transformation) occurs, so that the stress field around the crack inhibits crack propagation.

![Schematic diagram of ZrO$_2$ phase transformation toughening mechanism](image)

**Figure 12.** Schematic diagram of ZrO$_2$ phase transformation toughening mechanism [82]. Reprinted with permission from [82]; 2019 Elsevier.

Previous researchers added various reinforcing materials to the Cr$_2$O$_3$ matrix, including nano-Al$_2$O$_3$ particles and nano-TiO$_2$ particles, to produce composites with denser microstructure, higher hardness and higher fracture toughness. Finally, the wear resistance is improved [83]. Meanwhile ZrO$_2$ is added to the ceramic composite to increase its toughness. ZrO$_2$ cannot exhibit T→M transformation in pure form. In order to produce tough ZrO$_2$, the presence of a metastable tetragonal phase is unavoidable. The addition of appropriate amounts of certain specific additives, such as CaO, MgO, Y$_2$O$_3$, CeO$_2$ and some rare earth oxides, can stabilize this metastable phase in ZrO$_2$ at room temperature. Others, such as 8YSZ consisting of 8 wt% Y$_2$O$_3$ and ZrO$_2$, have better wear resistance.

4.3. Nano-Effects

Nano-effects refer to nanomaterials with singular or abnormal physical and chemical properties not found in traditional materials [84]. The small-scale effect in the nano effect can improve the toughness and wear resistance of nano-ceramic coating materials. Ceramic materials are generally brittle, but nano-ceramic coating materials made from nano-nano-microparticles have good toughness. The nanomaterial has a large interface, therefore the atomic arrangement of the interface is quite chaotic, and the atoms are easy to migrate under the condition of external force deformation. Therefore, it exhibits excellent toughness and certain ductility, which makes the ceramic material have novel mechanical properties [85,86].

In the conventional coating, after adding appropriate nano-Al$_2$O$_3$ particles, the interfacial grains gradually grow from epitaxy to non-epitaxial growth. The crack near the interface of the matrix is eliminated, and the dispersed nano-Al$_2$O$_3$ particles are mainly distributed near the cell substructure and grain boundaries. It not only prevents the diffusion of alloying elements, but also inhibits the formation of new phases. The nano-effects of nano-Al$_2$O$_3$ particles plays an important role in improving the microstructure of the coating [87].

5. Future Scope and Conclusions

Currently, research and development of nanostructured coatings is still in the development stage, but surface nanostructures formed from nanopowder materials. Its potential applications cover important areas such as the high-tech industry, civil industry and national defense. Whether it is from the thermal barrier coating of turbine blades to the wear-resistant and corrosion-resistant coatings of
rotating parts, or the stealth coating of high-performance fighters, its potential application prospects are broad.

At the same time, compared with the traditional coating, the performance of the nanostructured coating in the true sense will be greatly improved in terms of strength, toughness, wear resistance and thermal barrier. Therefore, nanostructured coatings will promote the upgrading of traditional industries with their good performance and durability, and eventually replace traditional technologies and produce good social and economic benefits. With the continuous development and development of surface nanotechnology, nanostructured coatings will surely be used in larger scale applications in industrial production.

In the future, nanostructured coatings will be more closely integrated with 3D technology. In addition to the preparation techniques of nano-coating technology, materials are also an important aspect. Lu Bingheng, an academician of the Chinese Academy of Engineering, clearly pointed out that the prospect of additive manufacturing is “creating materials.” The development of new materials with ultra-high strength, ultra-high temperature resistance, ultra-high corrosion resistance and certain environmental adaptability will likely become China’s breakthrough in the 3D printing market. Moreover, the profitability of 3D printing materials is the strongest in the industry chain, and the gross profit margin of 3D printing materials is 60%–80%. The 3D technology promotes the cost reduction of nano-coating materials, promotes the technology update of nano-coating materials and shortens the production cycle of nano-materials. It has enormous application potential in the equipment manufacturing industry worldwide.

Author Contributions: All authors contributed to the preparation of the manuscript, as follows: Conceptualization and design of the work: Y.G., K.X. and J.M.; Writing—Manuscript Preparation: Y.G., K.X. and D.W.; Writing—Review and Editing: K.X., S.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Zhejiang Provincial Natural Science Foundation of China (No. LY19E050003), the National Natural Science Foundation of China (No. 51779226).

Acknowledgments: The authors gratefully acknowledge Key Laboratory of Surface Engineering of Equipment for Hydraulic Engineering of Zhejiang Province, Standard & Quality Control Research Institute, Ministry of Water Resources.

Conflicts of Interest: The authors declare no conflict of interest.

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