

Research Progress on Hard-coated Tools

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ABSTRACT

With the development and widespread application of advanced machining technologies such as difficult-to-machine materials and green dry cutting, the cutting environment for tools has become increasingly harsh, leading to continuous updates and iterations of tool coating materials. Coatings have evolved from binary coatings to multi-component coatings; structurally, they have progressed from single-layer to multi-layer and high-entropy alloy coatings. This article summarizes the preparation methods of hard coatings, the current development status of tool coatings, and their applications. It introduces the characteristics and application limitations of the two major preparation techniques: chemical vapor deposition (CVD) and physical vapor deposition (PVD). It analyzes the performance advantages and development trends of binary and multi-component coatings, high-entropy alloy coatings, and self-lubricating coatings. The article points out that the future of hard coating technology will be directed towards sustainability, high performance, multifunctionality, and intelligence to meet complex processing demands and promote the sustainable development of the manufacturing industry.

KEYWORDS

Chemical Vapor Deposition; Physical Vapor Deposition; High-entropy Alloy Coatings.

1. INTRODUCTION

With the continuous development of cutting technology in the direction of high speed, high efficiency, high precision and green, cutting has put forward higher and higher requirements for the performance of tools, and the traditional tool coating is faced with problems such as high cutting temperature and large cutting force, resulting in serious wear of the workpiece, and can no longer meet the cutting requirements of dry cutting of difficult-to-machine materials such as titanium alloy under high-speed conditions [1-2]. Green dry cutting technology can not only reduce environmental pollution, but also achieve high-efficiency and high-quality processing and reduce production costs because it does not use cutting fluid, which will become the mainstream of the future development of the manufacturing industry [3].

Hard coating is a coating with high hardness, high temperature oxidation resistance, good wear resistance and other properties. Hard coating materials mainly include metal nitride (TiN/CrN), metal carbonitride, etc. At present, commonly used nitride coatings improve performance by adding different elements, and high-entropy alloys are composed of a combination of five or more alloying elements with mass ratios or near-equal molar ratios, and high-entropy alloys have excellent four major effects [4]. Batani et al. [5] used pulsed magnetron sputtering technology to prepare VNbMoTaWAl high-entropy alloy coatings, and found that VNbMoTaWAl high-entropy alloy coatings effectively improved the corrosion resistance of 304 stainless steel substrates in solution. Applying a self-lubricating hard coating to the surface of the tool is an effective way to reduce tool wear. The self-lubricating coating can reduce the coefficient of friction and cutting heat during the

cutting process, reduce the wear between the tool and the workpiece, and improve the service life of the tool and the machining quality of the workpiece [6]. Therefore, the development of high-entropy alloy coated tools with high hardness and low friction coefficient with self-lubricating function has become a research hotspot in the machinery industry. In the dry cutting process, with the increase of cutting temperature, the self-lubricating tool coating reacts with oxygen to form a lubricating phase, forming a lubricating film at the contact interface, so as to achieve friction reduction and wear resistance. Transition metals such as Mo, W, and V oxides have typical Magnéli phases, which have low shear strength, good stability at high temperatures, and easy sliding, making them ideal lubricating phases [7].

2. THE PREPARATION METHOD OF THE HARD COATING

Hard coatings are widely used in machining, automotive manufacturing, and aerospace. Commonly used preparation techniques include chemical vapor deposition (CVD) and physical vapor deposition (PVD). Among them, PVD is widely used in various fields due to its low deposition temperature and no pollution.

2.1. Chemical Vapor Deposition (CVD)

Chemical vapor deposition (CVD) is a technology that produces solid substances based on chemical reactions in a gaseous environment and deposits them on the surface of the matrix. First, the reactants (liquid) are transported into a vacuum chamber and activated by an energy source (e.g., high temperature, plasma, laser) to obtain enough energy to carry out a chemical reaction. Secondly, the atoms or molecules generated by the reaction are adsorbed by the surface of the matrix, diffuse and combine on the surface, and are deposited to form a coating.

Deposition of high-quality coatings by controlling process parameters. There are five types of chemical reactions that occur in the deposition process: thermal decomposition reaction, reduction reaction, oxidation reaction, hydrolysis reaction, and synthesis reaction. CVD is simple to operate, good winding plating, can be used to process parts with complex shapes and deep holes, CVD coating has a dense structure, strong adhesion, suitable for rough machining. However, CVD is easy to produce harmful gases to pollute the environment, which is not in line with green development. The deposition temperature of CVD technology is high (900 °C~2000 °C), which is easy to cause the degradation of mechanical properties.

2.2. Physical Vapor Deposition (PVD)

The basic principle of physical vapor deposition is the vaporization of molecules or ions by sputtering or evaporation under vacuum conditions, and the molecules or ions are transported to the surface of the matrix under the action of an electric or magnetic field, and condensed on the surface of the substrate in the form of thin films in a vacuum environment [8]. PVD technology enhances the wear resistance of the tool, resists the wear of the workpiece material on the tool during the cutting process, and prolongs the service life of the tool. At the same time, the corrosion resistance of the tool is improved, the cutting temperature and cutting force are reduced, and the service life of the tool is prolonged. The main methods of PVD technology include arc ion plating, magnetron sputtering coating, vacuum evaporation coating, etc.

2.2.1. Arc Ion Plating (AIP)

The working principle of arc ion plating is that the furnace cavity is used as the anode, and the target is used as the cathode to trigger the arc source discharge, and the surface of the target will form a ring-shaped arc spot, and a large number of atoms or ions will be sputtered on the surface of the target under the action of arc spot discharge, which will be deposited on the surface of the substrate under

the action of electric field. At the same time, after the reaction gas is introduced, a compound film is formed with metal ions on the surface of the matrix. High-energy particles impinge on the substrate, increasing the adhesion between the film and the substrate, which is conducive to the deposition of high-quality films [9]. Arc ion plating technology has the advantages of high ionization rate, high deposition rate, good film/substrate adhesion, and wide application range.

2.2.2. Magnetron Sputtering Technology

The working principle of magnetron sputtering technology is to ionize the gas to form plasma by filling the vacuum chamber with an inert gas and applying a high-voltage electric field between the target and the substrate. A special magnetic field design behind the target, such as a ring or runway shape, constrains the electron trajectory, lengthens its path and enhances the collision with the gas, thus maintaining a high-density plasma environment. Accelerated by an electric field, argon ions bombard the surface of the target, sputter out the atoms or molecules of the target through momentum transfer, and finally deposit them on the surface of the substrate to form a dense and uniform film. Magnetron sputtering technology has the advantages of high deposition rate, low temperature process, uniform film density and strong adhesion, and can sputter metals, ceramics and compound materials, which are widely used in semiconductors, optical coatings and other fields. However, the equipment cost is high, the target utilization rate is low, the process is complex, and the high-energy particles may cause film defects or substrate damage, which restricts the application of some scenarios.

3. THE CURRENT STATE OF DEVELOPMENT OF TOOL COATINGS

With the continuous emergence of difficult-to-machine materials and the rapid development of tool coating technology, the requirements for the quality and performance of tool coatings are increasing. Applying a self-lubricating coating to the surface of the tool can improve the tool's wear resistance, improve the tool's service life and surface quality. The development of high-temperature-resistant, long-life, wear-resistant tool coatings has become an urgent problem. It is often difficult for a single coating to meet the multiple requirements of difficult-to-process materials under different processing conditions at the same time, so the coating has developed from binary coating to multi-coating in terms of composition. In terms of structure, it has developed from a single layer to a multi-layer, high-entropy alloy coating [10].

3.1. Binary and Multi-coating

CrN has high hardness, high wear resistance, and good corrosion resistance, while TiN has good chemical stability, low coefficient of friction, and good hardness, both of which are widely used in machining and other fields [11]. However, due to the fact that CrN and TiN are exposed to high-temperature environments, chemical reactions such as oxidation occur inside the coating, resulting in a transformation of the structure and properties of the coating, thereby reducing the protective effect of the coating on the tool and shortening the service life of the tool [12-13].

With the rapid development of high-speed cutting, although the binary coating has a high hardness, but in the extreme environment of high-speed cutting, its hardness can not meet the processing needs, by adding other elements to the coating, to improve the properties of the coating, so as to reduce the wear and impact of the coating in the cutting process. If Al is added to the TiN coating to form a TiAlN coating [14], the TiAlN coating has good hardness, oxidation resistance and wear resistance. The TiAlN coating replaces the position of Ti atoms in the fcc-TiN phase through the solid solution of Al atoms, resulting in lattice distortion and solid solution strengthening. The CrAlN coating improves the hardness and resistance to high-temperature oxidation by adding Al atoms to the CrN coating.

In order to further enhance the performance of the coating, a variety of elements are synergistically developed to develop quaternary or multi-component coatings. Cao [15] and Hus [16] studied the

microscopic morphology of TiAlSiN coatings and found that the addition of Si elements changed the microstructure of the coating from coarse columnar crystals to fine columnar crystals, and a colattice interface appeared between AlN and TiN phases, and the fine columnar crystals could not only improve the compactness of the coating, but also indirectly promote the improvement of coating hardness. Yang et al. [17] increased the hardness of the TiAlVN coating by adding V to the TiAlN coating and increasing the number of Ti-V bonds and V-V bonds, which increased the interatomic bonding strength in the TiN unit cell. As a result, multi-coatings enhance and improve properties such as hardness and wear resistance of the coating.

3.2. High-entropy Alloy Coating

High-entropy alloy coatings are widely used in tool protection, aerospace and machinery manufacturing due to their excellent mechanical properties, wear resistance and high-temperature thermal stability. In the construction of high-entropy alloys, various alloying elements increase the overall entropy value by introducing a variety of elements, and construct a crystal structure that is close to random disorder. The original design concept of high-entropy alloy is to adopt a mode in which one or two elements are the main elements, and the other elements are supplemented, and the various elements cooperate with each other to make the alloy have a higher configuration entropy, so as to form a stable chemically disordered solid solution phase. Generally, high-entropy alloys contain five or more elements, each with a content of between 5%~35%, which together form a disordered and complex crystal structure.

Due to the four major effects of high entropy effect, lattice distortion, hysteresis diffusion, and "cocktail" effect, multi-principal element high-entropy alloys have comprehensive properties such as high wear resistance, corrosion resistance, and good thermal stability [18]. Specifically, the high-entropy effect exhibits a high disorder in thermodynamics. Lattice distortion arises from differences in the atomic radii of each element; There are vacancy defects in the formation process of hysteresis diffusion, which increases the energy demand. The "cocktail" effect refers to the fact that high-entropy alloys are made up of a variety of elements, and the four effects combine with each other to give them unique properties.

3.3. Self-lubricating Coating

The self-lubricating coating can form a stable lubricating film on the surface of the parts, reduce friction and wear, adapt to various complex environments, improve processing efficiency, and extend the service life of the tool. Self-lubricating coatings are divided into the following types according to their types:

3.3.1. Self-lubricating Coating with Solid Lubricants

This type of coating mainly contains solid lubricants [19-20], such as graphite, molybdenum disulfide (MoS₂), hexagonal boron nitride (h-BN), etc. These solid lubricants typically have a layered crystalline structure. During tool cutting, when the tool is in contact with the surface of the workpiece and subjected to friction and shear forces, the particles or flakes of these solid lubricants are transferred from the coated surface to the tool-workpiece and tool-chip contact interface under friction, forming a thin lubricating film. This lubricating film effectively reduces the coefficient of friction and reduces tool wear. The coating is widely used in the cutting of various metallic and non-metallic materials, especially in high-speed cutting and dry cutting. For example, in the fields of auto parts processing and aerospace parts manufacturing, for the processing of aluminum alloys, titanium alloys and other materials, solid lubricant-coated tools can effectively reduce tool wear and improve the surface quality.

3.3.2. Polymer-based, Self-lubricating Coating

Polymer materials are used as the main components, such as polytetrafluoroethylene (PTFE) and nylon, which are commonly used [21]. PTFE is a polymer material with a very low coefficient of friction, and its molecular chain is composed of carbon atoms and fluorine atoms, and the presence of fluorine atoms makes the intermolecular chain force very small, showing excellent self-lubricating properties. Nylon is a polyamide material with a certain degree of crystallinity, and the molecular chain contains amide bonds, which has good wear resistance and self-lubrication. Polymer-based coatings are lubricated primarily through their own low coefficient of friction and good flexibility. During tool cutting, when the coating comes into contact with the workpiece or chips, the polymer molecular chains are able to slide on the surface, reducing friction. At the same time, the polymer coating can also be adsorbed on the surface of the workpiece to form a protective film to further reduce friction. It is widely used in the processing of some materials with high requirements for surface quality, such as plastic products processing, non-ferrous metal processing, etc. For example, in the processing of precision injection molds, the use of polymer-based coated tools can reduce the friction between the tool and the mold material and improve the finish of the mold surface.

3.3.3. Ceramic-based, Self-lubricating Coating

It usually consists of ceramic materials and lubricating additives. Ceramic materials such as Al_2O_3 [22], TiN [23], TiAlN [24], etc., have high hardness, high wear resistance and good high temperature stability. During the cutting process, the high hardness of the ceramic-based coating resists the wear of the tool, while the lubricating additives form a lubricating film on the surface of the tool under high temperature and friction. It is widely used in high-speed cutting, hard cutting and other processing methods. In the processing of high-hardness materials, such as quenched steel, cemented carbide, etc., ceramic-based coated tools can give full play to their advantages of high hardness and self-lubrication, and improve cutting efficiency and tool life.

3.3.4. Composite Self-lubricating Coating

Composite coatings are a combination of two or more different types of materials, such as solid lubricants and ceramic materials, polymers and metals. Self-lubrication is achieved through the synergy of different materials. For example, ceramic materials provide hardness and wear resistance, and solid lubricants provide lubricating properties. During cutting, when the tool is rubbed, the solid lubricant acts as a lubricating agent, while the ceramic material acts as a support coating to prevent excessive wear. At the same time, the multi-layer structure or nanocomposite structure of the composite coating can increase the toughness and crack resistance of the coating, and further improve the service life of the tool. Composite coated tools are suitable for processing under complex working conditions, and at the same time have high hardness and toughness requirements. In the fields of aero engine blade processing and military parts manufacturing, composite coating tools can combine the advantages of a variety of materials to meet the demanding processing requirements.

4. SUMMARY

Hard-coated tools are widely used in industries such as machining, automotive manufacturing, and aerospace due to their excellent wear resistance, corrosion resistance, and high-temperature stability. The preparation of hard coatings mainly includes two technologies: chemical vapor deposition (CVD) and physical vapor deposition (PVD), each with its own advantages and disadvantages. The CVD deposition temperature is high and the coating is dense, but it is easy to pollute the environment. PVD has the advantages of low deposition temperature and no pollution. The tool coating has developed from a single coating to a multi-layer, multi-layer and high-entropy alloy coating, and the performance has been continuously improved. The self-lubricating coating reduces the coefficient of friction through the synergy of different materials, increasing tool life and machining efficiency. The development of these coating technologies provides more efficient and environmentally friendly solutions for fields such as machining, automotive manufacturing, and aerospace.

CONFLICTS OF INTEREST

The authors declare that they have no conflict of interest.

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