Current and Future PVD systems and Coating Technologies

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Kobe Steel has been designing, manufacturing and selling AIP systems, a type of PVD equipment, since 1986. It has developed standard batch systems, in-line systems and special coating systems for piston rings, etc. Kobe Steel also developed coating technologies for a number of different applications. In 1998 the company started to sell UBMS systems and expanded PVD system applications. This article describes Kobe Steel's past, present and future developments related to PVD equipment and coating technologies.

Introduction

The PVD (Physical Vapor Deposition) method is a coating method using a vacuum technology. It feeds the coating material by evaporating or sublimating it, in part or in whole, from a solid material and then deposits it on the object to be coated. In 1986, we brought in the basic technology for the AIP (Arc Ion Plating) method from the USA and started manufacturing and sales of the related equipment in Japan. The film deposited by the AIP method has fine structure and good adhesion strength, and is suitable for wear resistant coatings. We have been developing coating systems and films in order to meet the users' needs in the hard coating field, mainly for cutting tools and sliding parts. In 1998, we started selling UBMS (UnBalanced Magnetron Sputtering) systems using the sputtering method, a type of PVD method. Since then, we have been working for the sales of the above system and job coating service mainly for DLC (Diamond Like Carbon) by taking advantage of UBMS. This paper explains the development background and present situation of our PVD systems and films deposited by using them.

1. AIP (Arc Ion Plating)

1.1 Principle of AIP method

The AIP method is a film-coating technology by using vacuum arc discharge between a target (coating film material) as a cathode and an anode, evaporating the target materials and ionizing, and then depositing it on the surface of substrate (objects to be coated) to which negative bias voltage is applied. This method provides a high ionization ratio of the evaporated materials and enables the deposition of a film with high density and good adhesion strength. The film deposited by the AIP method is now synonymous with coating technology for cutting tools, as represented by (Ti, Al) N coating.

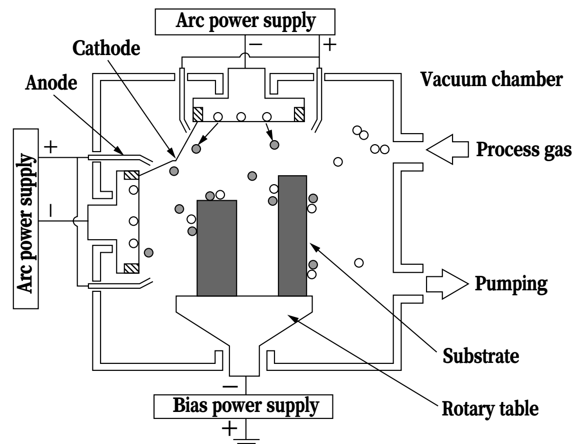

Fig. 1 Schematic drawing of AIP system

Figure 1 provides a schematic of an AIP system. In the AIP system, multiple evaporation sources with a plate target are equipped on the lateral side of a vacuum chamber and a substrate table is set in the chamber. The multiple evaporation sources are arrayed typically in the vertical direction so as to ensure the film thickness uniformity in the vertical direction and to provide wide coating area. The table is provided with a rotating mechanism so that a large quantity of substrates can be coated uniformly along the circumference.

We developed a batch type AIP system in 1986 for the first time domestically and have supplied more than 200 AIP systems including some styles of batch-type and inline-type systems that satisfy users' needs at high levels in not only domestic but also overseas markets. Their applications extend from research purposes to industrial uses including cutting tools, molds, automotive and machinery parts and decorations.

1.2 Batch type AIP system

1.2.1 General-purpose batch type AIP system

This type of AIP system is applicable for all purposes and has expanded into a broad range of industrial fields. As general-purpose batch type

Fig. 2 AIP/UBMS combined system / AIP-S70 Hybrid

AIP systems (AIP-S series), we have a full lineup ranging from small ones for research & development uses and large ones for industrial mass-production uses.

In addition, we developed a combined PVD system that was equipped with AIP evaporation sources and sputtering evaporation sources (UBMS[1)]) in a single coating chamber, by taking advantage of the expandability of this general-purpose batch type AIP system. It was put on the market in 2003. **Figure 2** shows the appearance of the system.

1.2.2 Thicker film AIP system[2), 3)]

The film deposited by the AIP method is usually as thick as several micrometers, but thicker coating of several tens of micrometers is required for some applications, like coating piston rings.[4), 5)] In order to enable stable arc-discharging for long hours and to reduce the target cost, that accounts for a large percentage of the processing cost, we put a thicker film coating AIP system into industrially practical use, designed to perform coating from the inside to the outside by arranging rod type evaporation sources at the center of the coating chamber. In 2004 we developed and started sales of a new thicker film coating AIP system (AIP-R600) for high-performance coating (**Figure 3**).

1.3 In-line type AIP system[6)]

In contrast with a batch type AIP system, an inline type AIP system performs a series of processes for pumping, preheating, bombardment, coating and cooling in the respective dedicated chamber. We have interlocked the preceding and subsequent transfer lines with this system, thereby putting the AIP-IV65 inline system (**Figure 4**) into practical use for continuous mass production of automobile

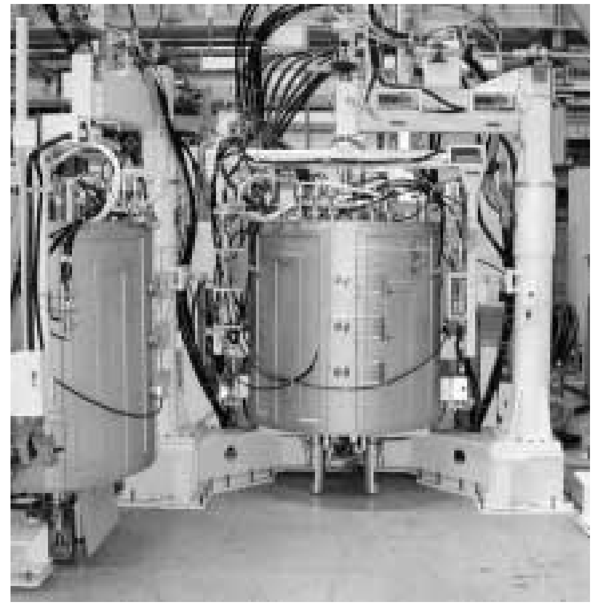

Fig. 3 New thicker film AIP system / AIP-R600

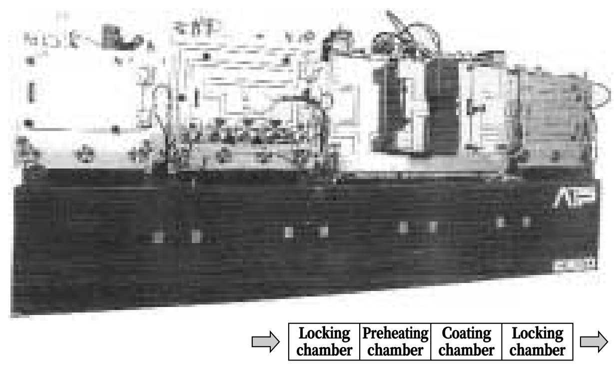

Fig. 4 AIP-IV65 inline series (mass production use)

parts and cutting tools. The coating chamber is always maintained at vacuum so high quality films can be deposited at high reproducibility as well as high productivity. The control system uses a full-automatic computer system that provides easy and comfortable operability through the same state-of-the-art man-machine interface as that of a batch type AIP system. With the interlocked preceding and subsequent equipment, this system allows for complying with full-automatic 24 hour operation.

1.4 Activities for AIP coating technologies

We are actively developing not just coating systems, but films and coating technologies based on those systems. The following describes typical examples of such activities:

1.4.1 TiAl-based hard coating (TiCrAlN)[7)]

Titanium aluminum nitride (TiAlN), the current mainstream as a film for cutting tools, has higher hardness and oxidation temperature than titanium nitride (TiN) by adding aluminum (Al) to TiN. However, when the Al ratio to the total metal elements (Ti and Al) exceeds 60 atomic percent, the crystal structure starts changing from a hard cubic structure to a soft hexagonal one. Thus, the improvement of hardness is limited. We have developed a film that has the Al ratio to the total metal elements (Ti, Cr and Al) increased to about 70 atomic percent by adding Cr to TiAlN, while maintaining the crystal structure in a hard cubic structure by using our newly developed AIP cathode. This has resulted in improving Vickers hardness to 3,500 (about 2,800 for TiAlN), and the oxidation temperature to 1,000℃ or higher (about 800℃ for TiAlN) owing to the improved ratio of Al and the addition of Cr. In a high-speed dry milling test using a carbide end mill for alloy steel with high hardness (HRC50), tool life about 2 times as long as the one by the existing TiAlN film has been obtained. We have also verified that this film achieves about 2 times higher wear resistance in a high-speed dry milling test using a carbide ball end mill for low carbon steel, which is known to be difficult for TiAlN films.

1.4.2 Nano-scale multilayered coatings[8)]

In recent years, hard coatings for cutting tools and sliding parts, or tribo-coatings, are required to have high wear resistances performance under extremely severe environments. The improvements have been achieved typically by multiple additions of elements and multilayered structures. As a result the layer constituents and structures are diversifying.

We, on the other hand, have developed a technology of adding elements that are not evaporable by AIP method, by using an UBMS source installed in the same chamber while depositing the matrix material by AIP method at a high deposition rate. This led to the development of a hard coating with nano-scale multilayered structure exploiting both the features of AIP and UBMS methods. The films deposited by this method have unique structures in which hard layers are combined with functional layers, or the stacking period of layers is adjusted to express a variety of characteristics. **Figure 5** shows a TEM picture of an example in which CrN/BCN films are deposited by the combined PVD system.

1.4.3 PVD α-alumina coating[9)]

Alumina is deposited by PVD method or by CVD

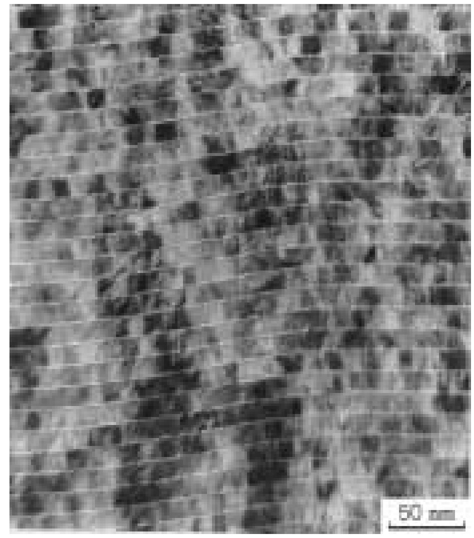

Fig. 5 CrN/BCN nano-multi layer film

Fig. 6 PVD α-Al_2O_3 film

method on cutting tools and sliding parts and provides an effective property for anti-oxidation and thermal resistance. Above all, the corundum structured alumina (α-alumina) has an excellent thermal stability at high temperature conditions and improves thermal resistances of the parts significantly. However, the CVD method, which requires heating above 1,000℃, tends to result in softening and deformation of the base substrates, limiting the choice of base materials. Reactive sputtering using our combined PVD system described previously allows deposition of α-alumina at 750℃, at a deposition rate between 0.5 and 0.7 μm/h. **Figure 6** shows a SEM picture of an example in which α-alumina films are deposited by the combined PVD system.

2. UBMS (UnBalanced Magnetron Sputtering)

2.1 Principle of UBMS method

The sputtering method is a typical process of the

PVD method, along with ion plating. This coating method is used in a broad range of industrial fields from semiconductor and electronic functional components to decorative coating. In a vacuum chamber, into which Ar or other similar inert gas is introduced, a solid target is used as a cathode and high voltage is applied to it to produce a glow discharge. Ar ions in the glow discharge plasma come into collision with the target at high energy, sputtering out atoms/molecules of the target materials. This sputtering evaporation phenomenon gasifies the target materials and deposits a film on the substrate placed in the facing position. The applicable target materials broadly range from conductive materials to insulating ones. The sputtering method is characterized by its ability to provide a very smooth film surface. It greatly differs from the ion plating method in that the sputtered particles are electrically almost neutral. The energy of sputtered particles is lower when compared with the AIP method where ions are used to deposit a film. For this reason, the applicability of the sputtering method has been limited in the hard coating fields requiring high adhesion strength and wear resistance.

The UBMS method is a new sputtering method in which means for actively irradiating ions to the substrate have been adopted in order to increase the energy of sputtered particles. In most of the sputtering methods, magnetron sputtering sources, which can generate high-density plasma using a magnetic field generated by magnets located behind the target, are provided just in front of the target. Unlike the conventional magnetron sputtering sources, the source used for the UBMS method is characterized by its unbalanced magnetic field that is intentionally made off its balance by intensifying the magnetic strength of the outer magnetic pole more than that of the inner one as shown in **Figure 7**. In an unbalanced magnetic field, some of the magnetic force lines from the outer magnetic pole extend to the substrate, and plasma that has been converged near the target partially tends to be diffused to the vicinity of the substrate along the magnetic force lines. As a result, the quantity of Ar ions that impinge on the substrate during coating can be increased.[2)] The assisting effect of Ar ions in the UBMS method can be considered as like ion plating effect and control the film properties with the suitable bias voltage applied to the substrate.

2.2 UBMS system

We put a UBMS system into the market in 1998 for the first time as a domestic manufacturer and have delivered more than 20 systems.

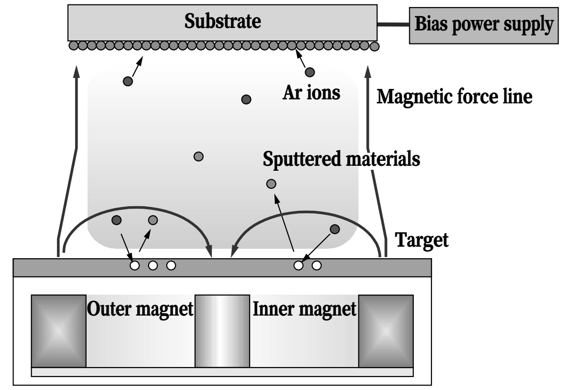

Fig. 7 Model of UBM sputtering source

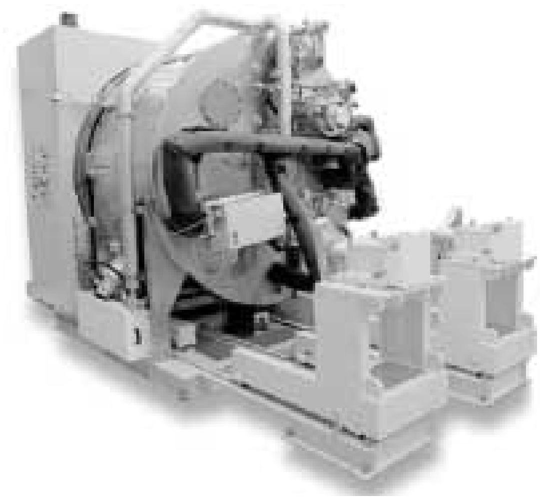

Fig. 8 UBMS roll coater

As in the case with AIP systems, we have a full lineup of general-purpose batch type UBMS systems ranging from a small model (UBMS202) for research and development uses to a large one (UBMS707) for industrial mass-production uses.

In addition to general-purpose batch type systems, we have put a roll coater (**Figure 8**), which is intended to coat a sheet substrate like a resin film, into practical use. The roll coater allows for continuously coating a rolled film substrate while unwinding and rewinding it. The roll coater is designed to allow for continuously carrying out degassing by heating, plasma or ion irradiation, which is applied as necessary, and coating by the UBMS method during the transfer of the film. The UBMS cathode used for coating can be used with a power supply of DC, pulse DC or DMS (Dual Magnetron Sputtering). The most suitable power supply type is selected for each intended use.

2.3 Applicability of UBMS method

Table 1 summarizes the effects and applications

Table 1 Effect and application of UBMS

Effect	Application
High hardness	DLC
High density	DLC, SiO_x, SiON
High reactivity	TiN, TiAlN, Al_2O_3, etc. reactive sputtering
Low resistivity	ITO
High-activity catalyst	TiO_2

of UBMS. The UBMS method, which performs high-density plasma irradiation during coating, achieves superior coating characteristics in a broad range of coating applications including DLC films in the hard coating field, and alumina, MoS_2, TiO_2 and functional films (SiO_x, ITO).

DLC films collectively mean amorphous carbon (α-C) films that have a variety of properties. They feature high hardness like diamond and low friction coefficients like graphite. The UBMS method uses the assisting effect of Ar ions to allow for controlling the film hardness with bias voltage as shown in **Figure 9**.

In the UBMS method using a solid target as its material, DLC films can be deposited by controlling the content of hydrogen at various levels including the hydrogen-free level, and DLC films (Me-DLC), to which various kinds of metal elements are added, can also be deposited by sputtering those metal elements from the metal targets. Thus, the UBMS method is characterized by its ability to deposit DLC films that have a broad range of properties. In depositing a DLC film by the UBMS method, the adhesion strength between the film and the substrate, which has been practically the largest problem in the DLC coating, has been greatly improved by composing the film with a metallic layer that has been optimized to the substrate materials and an inclined metal/carbon mixed layer as an intermediate layer and by reinforcing the interface with the assisting ion effect.[10]

The attractive features of a DLC film lie in its optimal properties as a film on which something slides, such as high hardness and a low friction coefficient, as well as its high functionalities including high chemical stability and superior release and adhesion properties. With the improved adhesion strength, DLC films have been increasingly used in more diverse fields. The automobile parts field is particularly expected for uses of DLC films. The most important requirements of automobiles include reducing the weight of automobile bodies for improving fuel consumption and decreasing the friction loss between engine-related components. It has been verified that the use of metal-added Me-DLC films[11] or hydrogen-free DLC films deposited by the PVD method decreases a friction coefficient.[12] As one of the trends toward further sophisticated functionality of tribologic characteristics of automobile parts, activities for putting DLC films into practical use are becoming accelerated. We are now addressing the reduction of friction in oil by applying Me-DLC films and hydrogen-free DLC films that allow for taking advantage of the UBMS method.

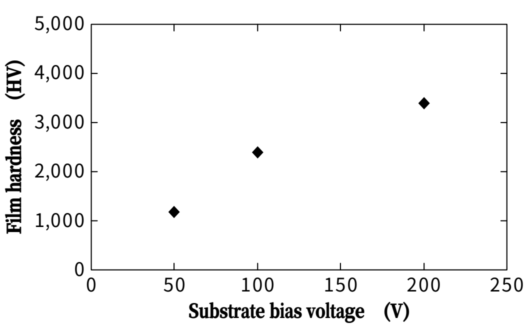

Fig. 9 Film hardness of DLC as a function of bias voltage

Conclusions

Our development activities on PVD system and films in the past twenty years have been described. Users' needs for the system and films have become more diverse and complex, encouraging stronger development work in a continuous manner. We will continue to develop systems and films, and expand the applications of our products.

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