Physical Vapor Deposition-Wear-resistant & Decorative Coatings

By Mark Podob

A plastic mold application for PVD processing is for the protection of compact disc mold surfaces.

Physical vapor deposition (PVD) includes vacuum evaporation, sputtering and ion plating. PVD processes are used to apply functional hard coatings and decorative thin films. The most widely used coating is titanium nitride (TiN). Other coatings successfully commercialized include titanium carbonitride (TiCN), chromium carbide (CrC), chromium nitride (CrN), zirconium nitride (ZrN), and titanium aluminum nitride (TiAlN). PVD coatings are very hard, have a low coefficient of friction, are chemically resistant and environmentally safe. When applied to different components, they act as chemical and thermal barriers.

Coating applications for TiN include cutting and forming tools, plastic molds, surgical instruments and prostheses. CrC and CrN can be a direct replacement for chromium plating for decorative applications, such as watch components, eyeglass frames, pen components, door and window hardware and plumbing fixtures. PVD coating processes, properties of coatings and commercialized applications are reviewed here.

Physical vapor deposition describes a family of coating processes that produce surface layers that are the result of the deposition of individual atoms or molecules. All PVD processes are carried out under a hard vacuum. Workpieces are heated to temperatures generally < 500 °C (930 °F) to enhance coating adhesion.

During PVD sputtering, argon is admitted into a vacuum chamber at relatively low pressure. A high DC voltage is applied to the target, which creates a gas discharge between the target and substrate holder. Argon ions, created during the discharge, strike the target with high energy and free atoms from the target, which are then transported to the substrate and deposited as a thin film.

PVD evaporative processes consist of heating a source material in a high vacuum, which produces a vapor that condenses on the substrate as a thin film. Ion plating—an evaporative PVD process—uses an electron beam gun to melt the source. The introduction of an inert gas at low pressure creates a plasma discharge between the source and the substrate. The ions impinge the substrate surface during deposition, resulting in changes in the interface region and improved film properties. A negative bias on the substrate enhances coating adherence. To produce compound coatings, the ions are reacted with a gas (*e.g.*, nitrogen or methane) to produce a nitride or carbide. This process is known as reactive ion plating.

Functional hard coatings are typically deposited by evaporative coating processes. Thin films for decorative applications are applied by sputtering processes, although either process may be adapted for either category of coatings. All PVD processes are line-of-sight, so to obtain coating uniformity, it is necessary to use specially shaped targets or multiple vaporization sources, and to rotate or manipulate the substrate uniformly to expose all areas to the coating source.

Cleaning Methods

To achieve good coating adherence, substrate surfaces must be free from the slightest amount of contamination (grease, dust, grinding burn or finger prints). Parts to be PVD-coated are normally bulk-cleaned in multi-station ultrasonic cleaning lines, which include a series of wet chemical rinses—usually detergents or solvents. Ultrasonics are used to activate the surface of the components being cleaned, and to assist in removing contaminants. The parts are dried to eliminate water spots. Hot-air dryers, equipped with micropore filters, prevent dust from depositing on the cleaned surfaces. While most precoating cleaning methods are satisfactory, some parts cannot be adequately cleaned. If components have been treated with a plastic rust preventive, for example, or salt-bath heat-treated where residual salt remains on the surfaces, special cleaning methods may be required.

Properties of Hard Coatings

PVD allows for the deposition of a wide variety of elements and compounds. Refractory materials may be deposited at temperatures below their melting points. For sputtering processes, virtually any material may be deposited (provided that it is available in the form of a target). Compounds deposited by evaporative reactive ion plating are limited by the ability of the source metal to be conveniently vaporized.

For functional applications, the coatings are deposited to a thickness

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Table 1 Common Compounds Reacted From Metallic Elements, Nitrogen & Carbon			Tab Hardn Functiona	le 2 ess of l Coatings	Table 3 Recommended Machining Applications	
			Material	Hardness (HVN)	PVD	Recommended
Element	Material	Film Color	Titanium carbide	3400	Coating	Application
Nitrogen	TiN	Gold (yellow)	Vanadium carbide	2800	TiN	Free machining steels, high-
	ZrN	Gold (green)	Titanium nitride	2600		strength steels, plastics,
	TiAlN	Violet/black	Niobium nitride	2400		hard rubber
	CrN	Silver	Chromium carbide	2200	TiCN	Tough machining steels,
Carbon	TiC	Gray-black	Chromium nitride	1600		cast iron, abrasive materials
	CrC	Silver	Cemented carbide	1600	CrC	Aluminum, titanium alloys
Carbon +	TiCN	Bronze/gray	Tool steel	900	TiAlN	Cast irons, abrasive
Nitrogen						materials, dry machining

of $2-5 \,\mu\text{m}$. (A greater thickness does not usually enhance coating performance.) Decorative coatings are generally 0.2–0.7 μ m thick.

The structure of deposited thin films determines their properties, including color (Table 1). Properly applied PVD coatings replicate the surface onto which they are deposited. A coating deposited onto a smooth, highly polished surface will have a mirror-like appearance, while the same coating deposited on a mattefinished surface (*e.g.*, one that has been vapor-honed) will have a matte finish. Table 2 lists the hardness of commonly deposited PVD coatings. (The harder a material, the better its resistance to abrasion.)

Most Common Hard Coatings

TiN is shiny gold in color and has a hardness of 2600 HVN. The coating acts as a chemical and thermal barrier between the surface onto which it is deposited and the environment. TiN has a low coefficient of friction that helps prevent galling and metal pickup.

Among the hardest of the PVD coatings, TiC is silver-gray in color, often resembling the metallic surface of the uncoated component onto which it is deposited.

TiCN ranges in color from bronze to silver-gray, according to the amount of carbon in the compound. The more carbon, the greater the tendency of the coating to appear gray in color. As a decorative coating, TiCN was developed for its close resemblance to bronze. For functional applications, it is used for machining stainless steel, high-hardness steels and high-alloy materials.

ZrN ranges from yellow-gold to brass in color, depending upon its stochiometry, and has mechanical properties similar to TiN. While not commercially popular as a functional hard coating, it is used as a decorative coating—particularly on brass hardware and plumbing fixtures.

Coatings are applied as either discrete single or multiple layers to provide different benefits, depending on the application. CrC is silver in color. When titanium or aluminum alloys are machined with tools coated with TiN, there is a tendency of the aluminum to chemically react with the nitrogen in the coating. This causes the tool to pick up metal. CrC is effective for machining aluminum because it is difficult to form aluminum carbide. Titanium alloys, such as Ti-6Al-4V, contain aluminum, so CrC is also effective for machining these materials. The chromium in the coating does not diffuse into the titanium surface as it does with TiN. CrN is also silver in color, and can be an excellent substitute for chromium plating, with no associated environmental concerns.

TiAlN is violet/black in color and, when used on cutting tools, it is believed that the aluminum in the coating oxidizes, providing hightemperature protection to the tool and extending tool life.

PVD Coating Applications Cutting Tools

Among commercial applications for PVD coatings, cutting tools are some of the most significant. Improvements in tool life for PVD-coated tools range from two to eight times when compared to uncoated tools. The additional improvement in productivity is substantial.

Tools routinely PVD-coated include:TapsMilling insertsDrills & sawsGear-cutting hobsReamersShaper-cuttersEnd millsBroaches

Dovetail formsCircular formsThreading toolsRoutersCounter-sinksCounter-bores

These coatings provide abrasion resistance, adhesion resistance, excellent lubricity and corrosion resistance. PVD coatings are also used to protect cemented carbide milling and turning inserts. Performance-enhancing features include:

- A smooth surface finish, coupled with thermal insulating properties, generates less heat during machining, preventing cutting edges from breaking down.
- The low temperature of deposition preserves the transverse rupture strength of the carbide, as well as the formation of *eta* phase (a carbon-lean, brittle phase). Both conditions can lead to premature tool failure.
- Sharp corners can be coated, resulting in lower cutting forces.

Properly designed cutting tools can fail by adhesive or abrasive wear. Because PVD coatings act as a chemical and thermal barrier between the tool and workpiece, the hardness of the coating provides abrasive wear protection, and the chemical stability protects the piece from adhesive wear.

In addition to extended life, PVD coatings offer increased productivity and economic benefits. In the case of automotive gears, for example, PVD coatings on gear hobs, shapers and broaches have significantly reduced tooling costs. Several automotive companies have installed their own PVD equipment to take advantage of recoating tools, which can recapture some of the tool life that is lost when the coating is removed from the cutting edges during sharpening.

Table 4 TiAlN-coated Tools, Machining Case Study

Machining case beauty				
Operation:	Rough machining nickel base			
	jet engine turbine blades			
Machine:	5-axis CNC machining			
	center			
Cutting tool:	4 flute 3/8-in. diameter solid			
	carbide ball nose end mill			
Chip load:	0.015 in./tooth			
Speed:	4700 RPM			
Finish requirement:	80-120 RMS			
Uncoated:	11 pieces			
TiAlN-coated:	44 pieces			

Table 5 Cr-coated Tools,

An additional feature of the coatings is that they are generally applied in compression. Compressive stresses associated with the thin films serve to increase the fatigue strength of the components. It is common to apply PVD coatings as multilayered films to take advantage of the differences in compressive stresses of the individual layers. These differences allow cracks to blunt at interfaces, rather than propagate through the coating, delaying the onset of tool failure.

Benefits of PVD coatings on cutting tools is summarized as:

1. Extended tool life

- 2. *More regrinds*—The coating does not flake but maintains adhesion throughout the tool life, even under severe wear conditions, and remains secure on rake faces and wear lands. At least 30 percent less material is removed per sharpening.
- 3. Increased cutting speeds & feeds
- 4. *Improved surface finish*—The chemical resistance of the coatings prevents welding of the tool to the workpiece. Galling and tearing are effectively eliminated.

5. Increased up-time— Coated tools last longer and can stay in the machine longer than uncoated tools.
6. Part tolerances—Tools do not wear as quickly, so they hold tolerances longer.

Tables 4 and 5 define case study findings for TiAlNvs. Cr-coated tools.

Metal Forming (Punches & Dies) Coatings are commonly applied to the surfaces of punches and dies to extend the life of these products. The low coefficient of friction associated with the coatings allows for the reduction or elimination of the use of die lubrication and draw compounds, which reduces the cost associated with degreasing required for environmental reasons.

Table 6 is a listing of tool life improvement for

TiN-coated tools used in the metal stamping industry. As is the case with metal cutting, improvements in tool life and productivity are significant. The chemical resistance of the coatings provides protection from galling and metal pickup, which can lead to premature tool failure. PVD coatings are applied at low temperatures, normally below the tempering temperature of steels used to make punches and dies, so tool dimensions do not change as a result of the coating process. Fine blanking tools and other tightly toleranced stamping tools are excellent candidates for PVD coatings.

Plastic Molds

TiN and TiCN are used extensively in the plastic mold industry, protecting molds, gates, screws, tips, core rods and other associated mold components. Many plastics are abrasive, particularly those using glass-filled resins. The hardness of the coating provides abrasion resistance to mold surfaces, enhancing performance.

Polycarbonate plastics, such as those used for optical applications (see Fig. 1), are particularly corrosive. The use of TiN and TiCN for the production of clear plastic lenses has provided a tool life performance of up to eight times longer than other coatings. When TiN has worn away, it is evident to the operator, which is not the case with chromium plating. TiN and TiCN may be non-destructively removed, allowing the tool to be repolished, and then recoated for longer wear. The coating perfectly replicates the high polish required for the optical finish associated with the molded products, and the lubricity of the coating enhances mold release.

An additional plastic mold application is for the protection of compact disc mold surfaces. The coatings replicate the surface onto which they are deposited. The molding of compact discs requires an extremely high surface finish. Careful polishing produces a flat, parallel surface, with a finish close to 0 RMS. Visual inspection with low-powered microscopes ensures that all surface imperfections have been removed.

Compact disc mirrors and other associated mold components are normally coated by reactive ion plating. This process ensures that the coating is free of porosity and defects. The use of TiCN in place of TiN for this application is growing. The higher hardness of TiCN provides better abrasion resistance for the polycarbonate plastics that flow onto the mold cavity surfaces. The reported improvement in life for CD mirror blocks is twice as long with TiCN, and better release allows for less downtime associated with required mold maintenance.

Aluminum Die Casting Molds

CrC is an effective coating for protecting aluminum die casting molds, because the corrosion resistance of this coating serves to delay the onset of soldering (a common failure mode for die casting molds). Reported improvements in tool life for CrC-coated molds, core pins and related hardware is on the order of three times that of uncoated components. The high oxidation temperature of the coating (1400 °F), coupled with its hardness, also aids in improving mold component life.

Wear Components

Applications for thin-film PVD coatings as wear coatings include



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gears and bearing surfaces. Additional applications exist in the automotive industry for antilock brake systems and fuel injector components. PVD coatings have improved properties over traditional steel surface treatments such as carburizing and nitriding. The large quantity of components available for coating has also served to reduce the price-perpiece for the coating. Additional uses are chemical ball valves and seats to provide corrosion and abrasion resistance, and jet engine compressor blades where the coatings provide enhanced erosion resistance.

Medical Applications

The combination of mechanical properties of TiN, particularly wear and corrosion protection, has led medical researchers to apply TiN and other coatings onto prosthetic implants. Because the coatings are applied in compression, the increased compressive strength of components results in a corresponding improvement in low cycle fatigue life. When coated, prosthetic implants (e.g., hips, knees and other joints) have shown up to three times improvement in life. This is significant when considering the age of patients who undergo joint replacement surgery.

Other applications in the medical industry include surgical tools where the combination of high hardness and corrosion protection play a key role in extending the life of these tools. Surgical tools must also be nonreflective (because of glare in the operating theater), and these coatings meet that requirement.

Decorative Applications

The use of PVD for decorative applications is increasing for a number of reasons, such as:

- 1. The ability to compete favorably on an economic basis with decorative electroplating processes, particularly in light of environmental considerations.
- 2. A broad range of available colors.
- 3. Corrosion resistance equivalent to, or better than that of the coating processes being replaced.
- 4. Use of less expensive substrates.

Decorative applications include: Watch components and bands, jewelry, eyeglass frames, cigarette lighter cases, pen parts (barrels, clips), knives and other accessories. Brackets used for orthodontic braces, where gold is a desired alternative to the silver-colored stainless steel typically used for these components, is another successful application.

One of the more interesting and widespread applications is for door and window hardware and faucet parts. While brass hardware is attractive, the corrosion resistance of brass is somewhat limited. Unlike copper, which develops an attractive and uniform green patina on weathering, brass turns a dull, dark brown, and requires continual polishing. The introduction of ZrN PVD coatings onto brass hardware has allowed suppliers of these components to offer "lifetime" guarantees on surface finishes. When deposited to the appropriate stochiometry, ZrN has a finish that perfectly matches that of brass, and it offers excellent corrosion resistance.

Another interesting decorative application for PVD coatings is for jewelry. TiN has an appearance that resembles gold, and has the further advantage of abrasion resistance. Substituting stainless steel for gold offers a significant cost savings. TiN- coating stainless steel jewelry provides the desired color and, because stainless steel has high hardness and excellent corrosion resistance, it is also durable.

The Future for PVD Coatings

PVD is being used to deposit functional and decorative thin films. A wide variety of coatings can be deposited. As environmental concerns regarding plating processes become greater, the use of PVD coatings will grow, finding new applications for the coatings and processes. **PASF**

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