FEATURE

Opportunities for Functional Design

Using Physical Vapor Deposition and UV-Curable Coatings

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Interest in alternatives to electroplated chrome is expanding dramatically. Color and appearance effects are limited with traditional chrome electroplating and successful "paint-on-chrome" applications are expensive and highly proprietary. Collectively, the automotive, home appliance and cosmetic markets are actively searching for alternatives with the appearance and durability of electroplating, but without the environmental side effects; appearance and functional design limitations; and costs associated with this decades-old process.

As development of UV-curable coatings for PVD has progressed, so has the understanding of the process and its unique capabilities and applications.

"Chrome-look" processes and coatings for decorative and automotive lighting physical vapor deposition (PVD) applications have been used in the ultraviolet (UV)-curable coating industry for more than 20 years. As development of UV-curable coatings for PVD has progressed, so has the understanding of the process and its unique capabilities and applications.

This article will address the advantages of PVD as a chrome alternative to include functional/design capabilities that are either cost-prohibitive or impossible to achieve with electroplated applications, as well as describe some of the trade-offs associated with using coatings systems as an alternative for chrome electroplating.

General Background

- PVD has been used in automotive lighting applications (behind the lens) with thermal and UV-cured systems since the mid-1980s. Since that time, PVD has been used successfully for decorative applications—first and second surface in multiple industries to include cosmetic packaging, home appliance handles and knobs, and interior/exterior automotive applications such as air bag emblems, door spears and decorative instrument panel trim.
- The greatest uses of PVD technology for interior and exterior automotive applications seem to be occurring in Asia and Europe—primarily with thermal cure base coat and topcoat technology.
- A base coat is often required to provide an optimum surface on which to metallize.
- Thermal-cure coatings technology for PVD has some limitations in application, mostly due to the long cycle times (often

- measured in hours) associated with sufficient cure.
- A common observation with any base coat + PVD + topcoat system is that it performs more “like paint” when subjected to established electroplated part-testing protocol. UV coatings may offer a solution to this due to UV chemistry’s inherent potential for better scratch, abrasion and chemical resistance, and it has the advantage of near instantaneous cure.
- Due in part to its near instantaneous cure, UV coating systems for PVD allow for in-line production systems and smaller footprints that can then help improve the overall cost model of PVD technology.

Overview of PVD

PVD is the deposition of a metal onto a substrate through changes in the physical state of the metal (solid to gas to solid). For most automotive applications, a very thin layer of metal (approximately 600-1,000 angstroms) is deposited onto the base coat layer. A wide variety of metals can be deposited, including aluminum, chrome, titanium, stainless steel, nickel chrome, tin, etc. The PVD layer can be deposited by a variety of methods, including (but not limited to) thermal evaporation, cathodic arc, sputtering, pulsed laser deposition and electron beam deposition. The two more common methods we will focus on in this article are thermal evaporation and sputtering. Both are done in a vacuum, but the metals are deposited differently.

Thermal evaporation is the deposition of a metal via thermal vaporization in a vacuum environment. The metal is in the form of a cane. It is placed inside a tungsten coil. The number of coils can vary depending on the size of the chamber. Once the chamber is pumped down to a vacuum, the tungsten filaments are heated to 1,200°F (for aluminum), enough to melt the metal. The power to the filaments is then increased to roughly double the temperature and the metal is evaporated. The metal then recondenses on the parts in the chamber. This method is mainly used for pure elements such as aluminum.

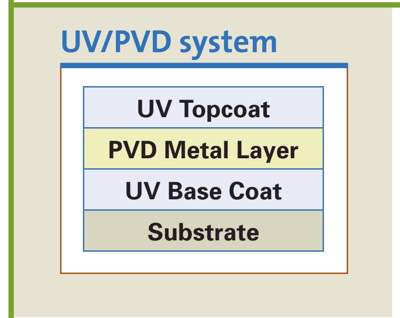
Sputtering is the deposition process in which atoms on a solid metal target are ejected into a gas phase due to bombardment of the material by high-energy ions. The bombardment releases atoms from the metal target, which are deposited directly onto the part within the vacuum chamber. Metal thickness will vary depending on the cycle time and power applied to the target.

Both pure elements and alloys can be used with either method, but they will be deposited differently. For elements, the final deposit is the pure element by both thermal evaporative and sputtering, but, due to the method of deposition, the appearance can be slightly different. For alloys with thermal evaporation, the metal with the lowest melt temperature will evaporate first and deposit onto the part. Rather than having a deposition of an alloy, there will be distinct metal layers. For example, with nickel chrome, nickel melts around 2,500°F and chrome has a melting point around 3,400°F. When thermally evaporated, the nickel will melt, evaporate and condense on the parts followed by the melting, evaporation and deposition of the chromium—two distinct layers of metal. With sputtering, the metals will deposit at the same time to have a true nickel-chrome alloy.

UV/PVD as an Electroplating Alternative

The main target of the UV-curable coating development for PVD was to

FIGURE 1



provide an alternative to traditional inorganic chrome with a layer system of organic and inorganic materials. As illustrated in Figure 1, this involves applying a UV base coat on the substrate followed by a PVD metal layer and, lastly, the UV protective topcoat.

Design Functionality

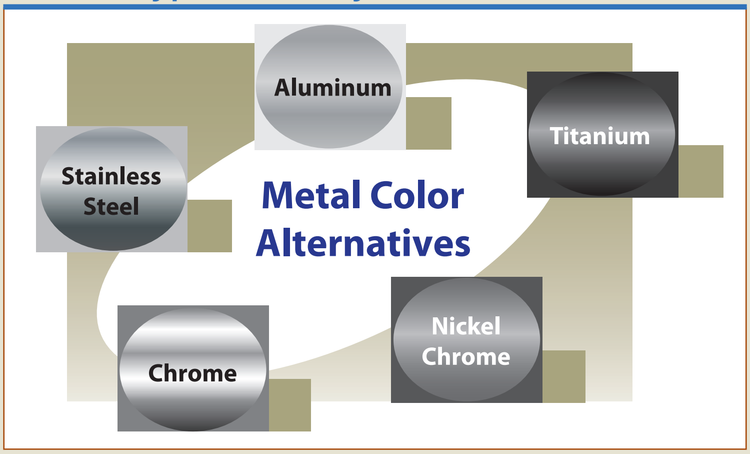
Day/night design in “chrome look” is attainable by laser etching the PVD layer, then backlighting the UV/PVD coatings stack. This technology also lends itself to a “chrome” daytime look, but with soft backlit colors for nighttime driving (e.g., a “hidden” display inside a metal-looking panel).

Wide Range of Appearances

PVD equipment suppliers are able to achieve numerous metal colors by using a mixture of various metals and gases within the vacuum chamber (see later section on limitations of color by PVD process). In addition, the topcoat can be modified to provide a satin or low-gloss finish, which has become popular especially for interior automotive applications. Although this same color affect can be achieved

FIGURE 2

Different types of metal yield different color effects



by using a chrome-plating process, the part must first go through a lengthy preparation process. Also, tinted clearcoats can be formulated to achieve different design effects.

Consumer Safety/Flexibility

Applications that require physical flexibility have not been chrome plated successfully. Limitations in plastic design for chrome plating are associated with how the plating is attracted to the part and where the plating may have more tendencies to build up. UV/PVD may provide an alternative. One of the key limitations in this development will be the flexibility of the PVD layer. Aluminum is quite flexible, but does not possess the integrity for exterior applications. Chrome and its alloys will work for exterior applications, but are rigid and susceptible to cracking on flexible substrates. To obtain the highest level of flexibility, coating and metal choices are critical. Consumer safety benefits include no change in substrate breaking strength when UV/PVD coatings are employed, no splinters or flying metal particles upon impact, etc. Potential applications include airbag emblems, overhead components, body security parts, etc.

Advanced Functionality

UV/PVD's advanced functionality such as RF transparent decorative PVD layers; highly nonconductive systems (<100 kΩ) for touchscreen displays; and "hidden" antenna or sensor technology UV/PVD coatings are also suitable for capacitive or infrared (IR) sensor technology.

Additional Features

UV/PVD systems can be suitable for pad or screen printing, gluing and realization of filigree surface structure (brushed effects) on plastics as well as metal substrates.

Wide Range of Plastic Substrates

Traditional chrome plating is limited to platable grade substrate (ABS and PC/ABS). Certain thermoplastics such as PA/PPE cannot be chrome plated due to their duration in high-temperature baths (up to 140°F for 11 minutes). With PVD, the possibility of substrate selection is greatly opened. ABS, PC/ABS, etc., does not need to be a platable grade material when used in conjunction with a good UV base coat, and the temperatures' duration generated during the process are much faster. Thus said, with PVD and UV processing, there still needs to be consideration of best fit of substrate to the process.

Environmentally Friendly

Environmentally, there is no question that UV/PVD coatings are the better choice. With no hexavalent chromium exposure or disposal; no hazardous waste to report; and full recyclability (due to the metal layer thickness in a nanometer scale), all work with UV-curable coatings to make for a much safer production environment.

Increased Throughput

From applying the base coat until packaging of the finished part, the cycle time for PVD can be as short as 15 minutes. In contrast, traditional chrome plating can take up to 2.7 hours (dependent upon the desired chrome thickness).

Trade-offs for Using UV/PVD

Challenges associated with the development of each of these layers and the processing of each are explained as follows.

UV Base Coat

The surface that the metal is deposited on must be smooth and continuous. If it isn't, the metal will not be reflective, leading to a dull appearance. This demands that molds must be maintained in optimum condition and polished regularly to ensure the surface of the parts are free from defects. Some parts are direct metalized; however, this requires a higher or more expensive grade of thermoplastic (substrate) to accomplish.

Furthermore, achieving direct adhesion of the metal to plastic can be more difficult than with a base coat layer. Direct adhesion is a skilled art and there is limited knowledge and expertise of finishers who can do this with consistent success. There are inherent performance limitations of a direct metalized system, such as less resistance to moisture (or a greater tendency to delaminate). Thus, the number of relevant applications for direct metallization to plastic substrates would be limited primarily to interior applications.

For the most robust system and adequate performance of an exterior durable-coating UV/PVD system, a UV-curable base coat is necessary. A successful coating must have excellent adhesion to a variety of substrates as well as be able to accept PVD metals. Chrome is more durable than aluminum and is preferred for exterior applications, thus a base coat must be formulated specifically to PVD chrome metal. Due to chrome being a very rigid metal, many commercial base coats that work well with aluminum may not work with chrome. Stress cracking is a very common failure mode if the base coat is not formulated specifically for PVD chrome. Many thermal cure coatings lack the proper crosslink density to be used with the more rigid metals.

Challenges for Base Coat Formulation:

- Formulation of the base coat must optimize its acceptance of PVD metal (adhesion), while avoiding stress cracking.
- Known paintability issues must be considered—adhesion for multiple substrate part design versus paint rheology versus application method and orange peel, or lack thereof for optimal smoothness and reflectivity (appearance) since the reflective surface exacerbates any flaws.
- UV cure still incorporates residual heat due to a heated convection, IR flash or combination prior to the UV cure. Matching the type of lamps used (arc versus microwave), (stationary mounted versus robotic cure) versus energy/intensity requirements versus heat sensitivity of the substrate must all be taken into account.

Consideration of these in formulation influences the process window for performance.

PVD Application

There are many different PVD application philosophies and equipment technologies available. Some of the more common that have been used with coatings systems include ones from Vergason Technology Inc., Mustang Vacuum Systems, Leybold Optics, Oerlikon Balzers, Hauser, Innovative Systems Engineering and Kolzer. It should be noted that the properties of the metallization may differ from manufacturer to manufacturer or from machine to machine. Care must be taken to match UV base coat and topcoat technology to that particular metallization equipment, and only through comprehensive design of experiment might the particular window for that machine be found.

UV Topcoat

To protect the metal, a topcoat needs to be applied. This can vary from a thin layer of in-chamber siloxane or to a thicker thermal or UV-curable topcoat. The choice will vary depending on application and needed performance requirements. In some instances, there is investigation or proposal to not use a topcoat whereby a very thick layer of PVD will be used. For exterior purposes, there are currently original equipment manufacturer (OEM)-approved thermal, two-component coatings and thermal powder coatings on the market. However, these coatings are not a panacea. The 2K coatings lack both environmental and processing friendliness. Powder coatings are more environmentally friendly; however, not only do the long bake times hinder productivity, the high temperatures required to cure the powder will not work with most thermoplastic substrates. A UV-cured coating can satisfy both the environmental and process requests of the finishers and OEMs.

Although initial topcoat adhesion to chrome is relatively easy to achieve, maintaining that adhesion after humidity, water immersion, thermal cycling and weathering can be a bigger challenge. In order to balance proper adhesion to chrome and maximize abrasion, scratch, moisture and chemical resistance, it is imperative to find the balance formulation between too-rigid-to-get-adhesion and too-soft-to-pass-resistance testing.

The properly formulated UV-curable topcoat should pass gravel chip resistance; resistance to various solvents and cleaners; humidity water soak; Xenon-accelerated weathering; and at least two years of natural weathering.

In a direct comparison with chrome, PVD samples with a UV-curable topcoat show much performance equal to decorative chrome plating. PVD has superior performance to hydrofluoric acid tests. Chrome plating has shown to have superior scratch resistance to PVD. However, if the UV topcoat is compared to approved paint systems in the market today (2K clearcoat for automotive bumpers and fascias;

thermal-cure powder for automotive clear coats), differences in scratch resistance are harder to quantify. The reflective surface exacerbates scratches in the topcoat.

UV has inherently higher crosslink density and hardness than thermal-cure technology and can achieve better scratch and abrasion versus thermal cure, but it is still difficult to match chrome-plate scratch resistance.

Processing techniques such as cure in an inert environment (like nitrogen) can minimize oxygen inhibition and improve hardness. This too is an exercise in economics because the added cost of creating an inert environment may not justify the added performance. On three-dimensional parts, it is typically difficult to justify these economics versus added performance.

Challenges for Topcoat Formulation

- "Darkening" or "Yellowing" appearance in the topcoat due to reflectivity. (See Table 1)
- Achieving and maintaining adhesion after exposure/testing, especially with chrome.
- Cost-effective performance.
- Hardness and scratch/abrasion resistance due to organic coatings (PVD) versus inorganic chrome plate targets. Key targets for the next generation of UV topcoats will be to achieve greater hardness and scratch/abrasion resistance to narrow the gap between coating and chrome plate.

TABLE 1

Specular reflectance

Element	Bare	+ Topcoat
Traditional chrome plate	60.0	49.5
Chrome/aluminum	78.0	70.0
Chrome (machine 1)	53.5	37.8
Chrome (machine 2)	60.5	49.5
Chrome (machine 3)	57.3	45.5
PVD Cr (Hartec) + TC	78.0	70.0
Aluminum (machine 1)	89.0	84.0
Aluminum (machine 2)	85.8	78.3
Dark Chrome	28.6	17.3
* The higher the number, the brighter the appearance		

Part Design

Part design needs to consider part paintability. From an application standpoint, sharp edges, deep recesses and location of parting lines can affect the success and optimization of the application (not only for paint, but also for the PVD process). Furthermore, as UV coatings are line-of-sight cure, both part design and part racking in relation to lamp configuration need to be considered to ensure adequate cure of the coating and avoid any areas of tackiness or uncured coating. Uncured material can have a negative effect in the PVD chamber, especially on pumps and in pulling the vacuum.

PVD sputtering deposition is also line-of-sight, so part design or movement of the part in front of the target may be necessary for covering and consistency of PVD thickness/appearance.

Finally, the nature of the racking should be noted to consider that metal racking could interfere with the PVD process by arcing or attraction of the PVD metal to a particular area.

Substrate

A wide variety of thermoset and thermoplastic substrates can be coated with a UV base coat to achieve a bright finish. BMC, PC, ABS, PC/ABS, PA/PPE and PC/PBT are commonly used plastics for exterior rigid and semi-rigid automotive parts. The substrate surface is critical to the film formulation process and for obtaining good adhesion of the base coat to the substrate or for PVD to the substrate in direct substrate-to-metallization applications. The substrate surface should be characterized to the extent necessary to obtain a reproducible film. Care must be taken that the surface properties are not changed by cleaning processes or recontamination, either outside the deposition system or inside the deposition system during processing.[2]

Challenges for Substrate Selection

Typical challenges of substrate for PVD are similar to other painting applications. For injection molding, it is important to choose substrates with melt-and-flow characteristics that adequately match the part design and can mold in desired cycled times. Additionally, designing the part with sufficient gate height and width in relation to the overall part size is critical to avoid issues of low pack/hold or high stress where key properties or paintability could be compromised. Stress affects surface tension of the part—the more stress, the less paintable the part will be. It should also be noted that this may not manifest itself immediately, but may shorten the lifetime of the part and finish. Also, as it is economically desirable to recycle or to use regrind material, it should be managed appropriately as to not disrupt paintability or performance. In short:

- Substrate tooling and surface quality affect the appearance of the finished part as the base coat may not cover all surface defects.
- PVD system flexibility (such as TPEE versus PCABS) is a balance between a stable surface rigidity versus structural flexibility. It needs to be rigid enough for the deposited PVD to stay aligned to keep the highly reflective surface, but flexible enough to not crack when flexed.
- Heat must be considered to avoid deformation of the substrate. Coatings with weathering requirements will need more UV energy and irradiance to cure properly. This adds more heat to the substrate. If the surface deforms, the PVD film will become stressed, potentially causing failure.

Color Matching and Control

The presence of pigments and colorants in UV-cured coatings can greatly impact the cure and subsequent performance of UV-cured coatings compared to clear coatings. The formulator must understand the output characteristics of the curing system; absorption characteristics of available photoinitiators; and spectral characteristics of pigments. Improper spectral matching of any of these parameters will result in reduced cure and performance.[3]

When incorporated into UV, some matting agents can also change the cure properties. Thus, consideration for appropriate matting agents is required in formulation.

UV coatings tend to be inherently lower in viscosity, resulting typically in lower sag points. When incorporating tints into the system, careful consideration must be given to formulation and rheology to ensure there is consistency of film build and no collection points. This becomes more of a challenge with complex three-dimensional parts or when part designs incorporate sharp edges. Another challenge with tinting clearcoats for PVD is the fact that the highly reflective surface will easily show any incompatibilities (haze) or poor dispersion of the pigment. It is important to incorporate proper tint dispersions to obtain the clarity and appearance of tinted metal. Typically, dyes would be considered ideal for such clarity, but dyes do not provide adequate light fastness and color stability to withstand the rigorous performance targets.

Finally, as with any pigmented system, even pigment distribution and preventing flocculation or mottling is a challenge.

Conclusion

Demand for plastic products and alternatives to traditional electroplated systems continue to grow. Markets once driven by cost-per-piece and “green” or environmental concerns are now giving way to demand for functional capability. PVD—when combined with UV-curable coatings—offers design engineers an almost unlimited color and appearance pallet, while simultaneously offering consumer safety and innovative functionality.

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