Direct-to-Metal Coatings: The Challenges and Solutions

By Kevin H. Joesel

Introduction

Ultraviolet energy cured coatings have been used for decades in industries as diverse as automotive, electronics, printing, packaging, medical converting, flooring, furniture, and metal pipe and tube. The commonality of all these applications is that UV curing technology delivers superior economic performance, and many times, is an enabling technology helping other technologies grow at very high rates. For example, optical fiber would not exist without the unique processing capabilities of UV technology.

UV technology is known for the following attributes:

- Lightning fast cure speed
- Low temperature/ambient curing
- Superior coating performance

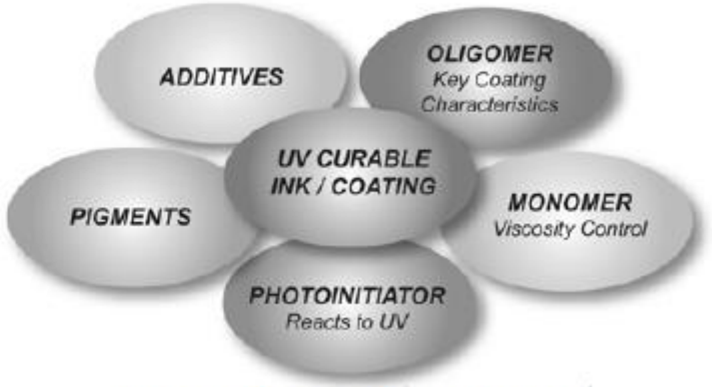
UV technology achieves these attributes primarily through free-radical polymerization. Thermal coatings employ various condensation reactions to achieve their cross-linking. When comparing these two types of reactions, the free-radical polymerization reaction rate can be 1 x 10^6 times faster!

In the free radical polymerization process the photoinitiator absorbs UV energy. The photoinitiator then cleaves to form a radical with a free electron. These free-radicals then react with acrylate functional groups on oligomers and monomers starting the crosslinking reaction to create a cured film with the desired properties within seconds.

The earliest and widest adoption for UV curing technology was in web based or flat-line applications. This was due to the ease of exposing the coating to the minimum UV energy to achieve cure. Also, many applications were limited to clearcoats or thin pigments coatings with a minimum performance requirement, such as printing, but requirements for high processing speeds. Over the decades, advances in raw materials, UV curing equipment, and processes have resulted in adoption into industrial coating applications for three-dimensional (3-D) parts.

Formulating and Process Challenges

The primary concern during the investigation phase of UV cured 3-D coatings is the requirement for line-of-sight curing by the UV source, i.e. no shadow areas. The other major limitation is that UV energy needs to penetrate the coating down to the substrate to achieve full cure and thus adhesion of the coating to the substrate. This is more easily achieved with clearcoats, but is a significant challenge with pigments systems. The pigments, and other constituents in an industrial coating, absorb some of the UV energy making through-cure a challenge to overcome. However, these issues are not insurmountable, they just need to be understood by the formulator.



Graphic 1; UV Formulating Components

Two key raw material developments helped significantly, photoinitiators that absorb in the longer UV wavelengths and new hyperbranched oligomers and monomers. These monomers and oligomers allow high cross-link density with a minimum shrinkage, maximizing adhesion to the substrate resulting in increased corrosion resistance. Also, monomers and oligomers with high polarity improve adhesion performance. Formulators are also incorporating nanoparticles as a new formulating tool for UV chemistries.

Market Drivers

No technology displaces another without strong economic incentives to do so. The primary reason end-users investigate and subsequently adopt UV curing technology is to lower costs through cellular manufacturing concepts, reduction in process footprint, reduction in energy consumption, and to decrease the environmental impact of their finishing operations.

In the case of the thermal systems, it is well known that the best economies are achieved through large finishing systems. Line density — specifically in the oven — is the primary driver. The most efficient oven arrangements are those that minimize the surface-area-to-volume ratio. Heat losses occur through oven openings, roof, walls and the floor. By increasing the volume, you decrease the relative heat losses. With UV curing technology, openings and enclosure surface area have no effect. The primary challenge is to provide adequate space between the parts and have the parts arranged/oriented in a way that maximizes the UV energy exposure to cure the coating with the minimum number of lamps.

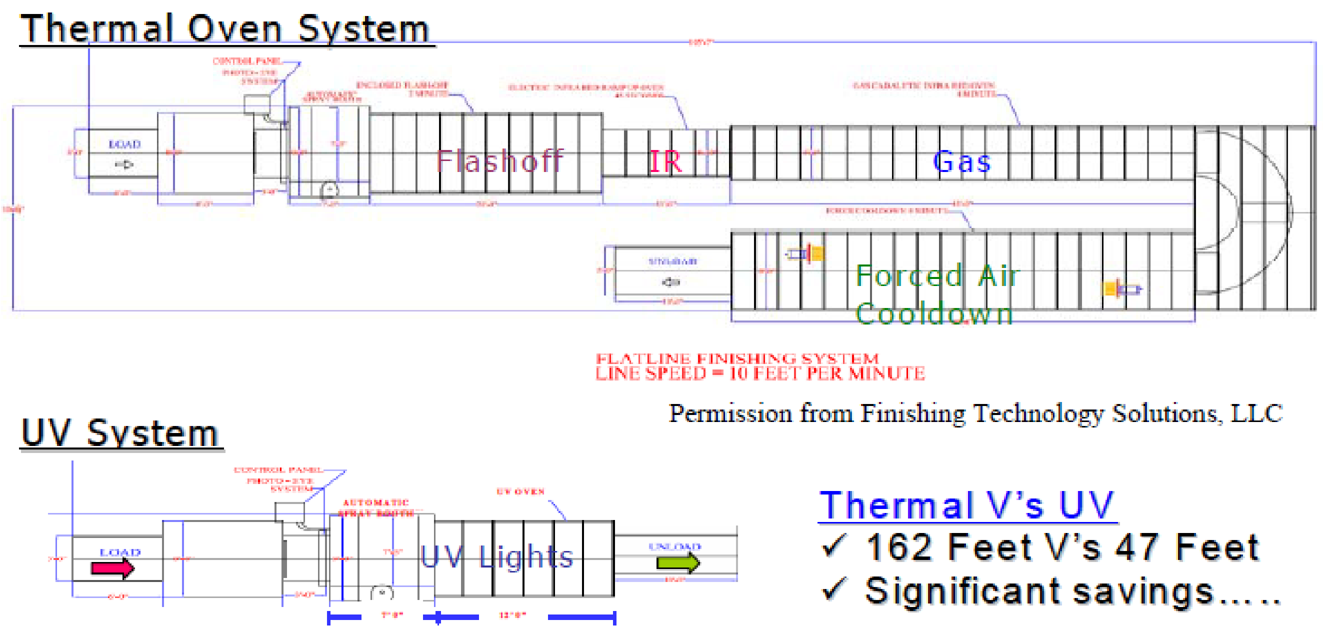
Applications

The applications of UV technology in metal finishing vary widely from shafts and cylinders to complex shapes, such as portable propane gas cylinders, hydraulic cylinders, motor assemblies, oil filters, and underhood automotive parts such as damper pulleys. Of course, not all applications are candidates for UV curing. Asking several key questions can help determine whether processes lend themselves to UV:

- Are the part surfaces easy to illuminate? The critical element here is the shadow areas on the part and its complexity. Parts that are convex in nature and with few or small appendages are ideal.
- Is there a large variation in the parts to be cured? The most cost-effective solutions are those with a minimum of variation. Typically, if two of the three dimensions have low variation, then there is a high probability of success.
- Are the color options limited? If a wide variety of colors are used, then providing the best UV spectrum might be difficult.
- How does the UV process fit with upstream and downstream processes? Matching productivity with cells before and after UV curing is a primary concern. If the finishing/curing of the coating is a bottleneck in your operations, then UV curing has to be a key technology candidate.

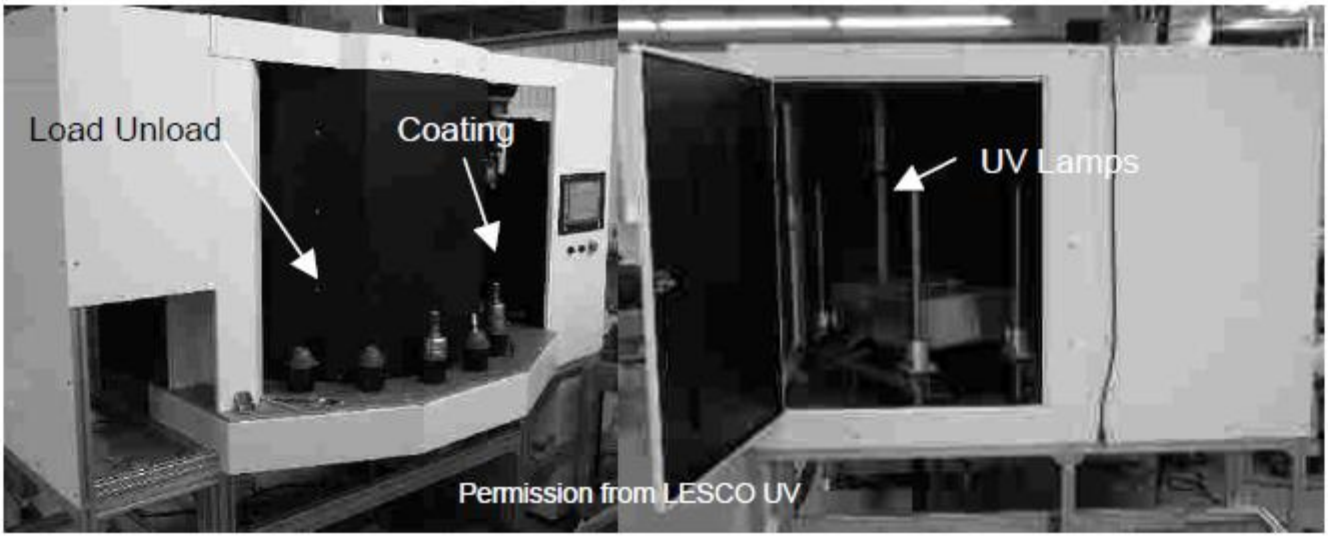
Cellular Manufacturing

Manufacturing operations increasingly have been adopting cellular manufacturing techniques to maximize productivity, minimize waste by linking manual and machine operations, and maximize value-added operations. Process balancing is a primary consideration. In the case of finishing, the idea is to have smaller finishing lines in the same scale as their other manufacturing operations, such as molding. UV technology allows much smaller finishing systems to be used. Below, Graphic 2 clearly demonstrates the significant space reduction between thermal curing and the UV curing of a 100% solids UV liquid coating.



Graphic 2; Thermal vs UV Curing Space

Several finishing systems have been developed with a very small footprint and sequential layout. The most popular design uses linear flow as shown in Graphic 2. Another popular design is a four-walled finishing cell with an internal turntable that indexes from station to station. The unit has self-contained spray application, air handling, liquid handling and UV curing. The size varies depending on the part envelope; in this case, the cell is approximately 8 x 8 x 8 ft. In one station, the parts are loaded and unloaded. The second station is where the coating is applied, and the part then indexes to the UV curing station. The parts typically rotate in this station. In some cases, the lamps may raise and lower scanning the part curing the curing process.



Photos 1&2; UV Finishing Cell

Photo 1 and Photo 2 show the front and side of the finishing cell. The parts are mounted on spindles mounted to a turntable. The turntable indexes as a specific cycle time. The coating applied is 100% solids achieving 90% transfer efficiency. Eventually the part reaches the UV curing lamps shown in Photo 2. In this case, the lamps have the ability to scan up and down as the part rotates to accommodate parts of varying height.

Another key advantage to UV curing in cellular manufacturing is that products can be finished with temperature-sensitive components such as seals, gaskets, and plastic components already on the part. In most cases, the finishing step can become the last step of the assembled product prior to packing.

Performance Specifications

One of the recent major achievements has been the success of formulators to meet the corrosion and appearance requirements for a variety of substrates, such as untreated and phosphate-treated steel, galvanized steel, and aluminum. All of these applications must meet aesthetic requirements, but the primary performance requirement is corrosion resistance. A typical requirement for corrosion resistance is salt fog resistance (ASTM MB117) of 250 to 1,000 hours. UV coatings are available that meet these requirements.

Another advantage to a UV-cured coating is that 100% of the properties are achieved upon cure. UV coatings are usually harder and cooler after curing, making the part ready for packing and shipping significantly faster. The typical film thickness ranges from 0.5 to 2.0

mils. Film thickness control is a critical process parameter for UV coatings, making it highly desirable to automate the application process. With UV coatings, the thicker the coating, the more UV energy it takes to maintain productivity.

UV Process Considerations

Many factors need to be taken into account when designing the UV curing process and how it will be integrated into the finishing line. The four primary considerations that should always start the analysis are:

- UV energy curing requirement of the coating
- Productivity
- Part size, geometry, and orientation
- Critical performance surfaces of the part

Some additional considerations that could impact the UV curing installation may also need to be defined including:

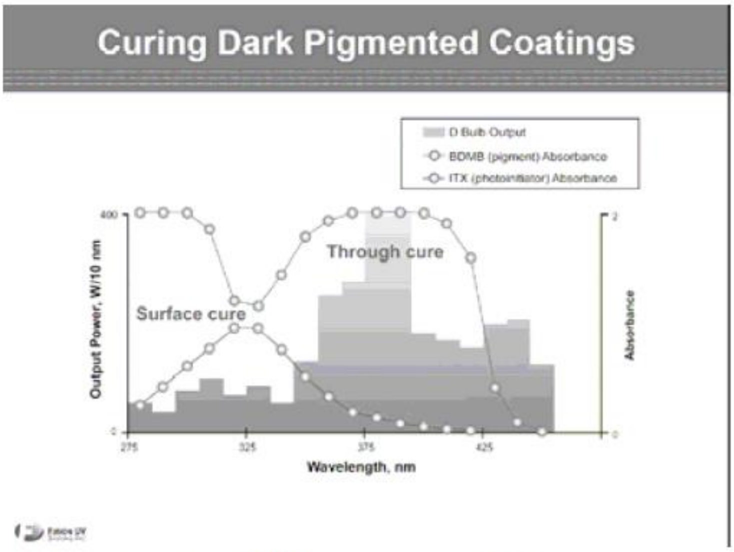
- New installation or retrofit on an existing line
- Physical constraints
- Conveyor type options
- Part arrangement
- Part movement

When designing the UV curing process, the primary concern is how the lamp optics relate to the part geometry to provide the UV energy required by the curing process window. Though this may be a complex problem, a number of standard solutions are used. They can be broken down into the following groups:

- Single lamp or one array of multiple lamps - This solution is used for simple shapes or for one- or two-dimensional substrates.
- Multiple arrays of UV lamps - This is the most common and most flexible solution. The lamp array usually is designed to provide UV energy to a defined part window.
- Automation of the lamp(s) - This can be as simple as a lamp or an array of lamps rotating on an axis or moving in a single plane, or as complex as a UV lamp mounted on a robot.
- Movement of the part. Lamps usually are fixed
- Hybrid systems - This uses a combination of fixed lamps with lamps that have some movement.

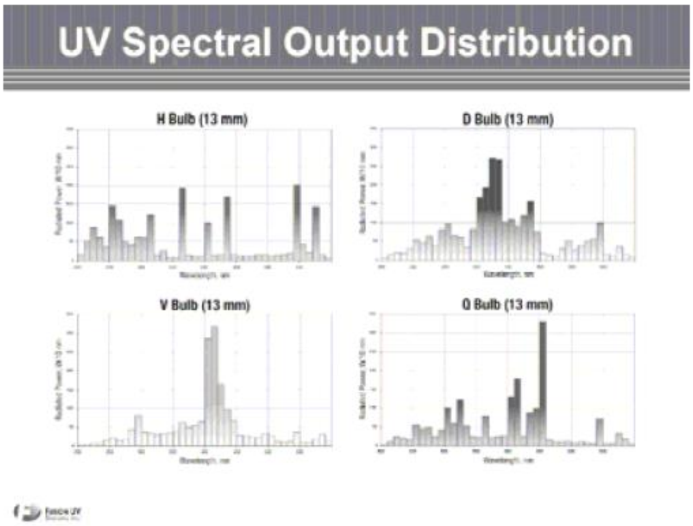
The curing of the pigmented systems usually comes down to two different strategies: using a single bulb cure or two different bulb types to crosslink the coating, or using a dual-spectrum cure achieved through two different UV exposures.

Single bulbs for pigmented systems most commonly use a D bulb. This type of cure is relatively common with dark or black coatings and is demonstrated in Graphic 3.



Graphic 3; UV Emission vs. Absorption

Often with direct-to-metal coatings, using a single bulb will not meet the performance requirement, and a dual-spectrum cure is needed. In some cases, typically with whites or pastels which have a significant amount of titanium dioxide, the best curing conditions are achieved using a long-wavelength bulb (most commonly a V bulb). In almost all cases, the V- or D-bulb cure is followed by an H-bulb cure. The long wavelengths more easily penetrate coatings and are used to achieve “through cure,” while the H-bulb exposure enhances surface cure. Again, the primary factors are color and film thickness.



Graphic 4; Various UV Bulbs Output

The range of UV energy requirements are 1,000 – 2,000 mJ/cm^2 UVA$_{EIT}$ with intensity ranges of 500 – 2,000 mW/cm^2 UVA$_{EIT}$.

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Conclusion

More than 25 years ago, UV coatings were starting to be adopted by the metal tube and pipe industry. Over the same time frame, UV-cured coatings on 3D plastic parts have become commonplace, demonstrating the development of proven UV process solutions. The success of UV technology in these market sectors, coupled with advances in raw materials, is accelerating the development of direct-to-metal coatings that meet market and customer performance requirements that were previously deemed too difficult. With continued developments and cooperation among the stakeholders, the growth of the direct-to-metal application is very promising.

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