FEATURE

UV-LED Curing—It's Beginning to Look a Lot Like Christmas

By Paul Mills and Tom Molamphy

The 2007 holiday season reminded even the Grinchiest among us of the potential for LED technology to transform our everyday life.

From Rockefeller Center and Times Square to the nation's capital, the convergence of improved technology, record energy costs and environmental awareness is allowing consumers to turn green while saving some of their hard-earned green at the same time.

"When New York City Mayor Michael Bloomberg helped light the Rockefeller Center Christmas tree last month, the 84-foot-tall Norway spruce came alive with 30,000 twinkling lights. For the first time, the famous tree was illuminated with energy-efficient LEDs, or light emitting diodes, rather than traditional light bulbs. Major displays such as the Rockefeller Center tree, the National Christmas Tree in Washington and even the New Year's Eve Ball in New York's Times Square are making the move to LEDs this season.

But when it comes to environmentally friendly holiday lights, many homeowners have already moved ahead with the adoption of LED light sources. Manufacturers and retailers report that consumer sales of the efficient lights have been growing for years. Fans say the lights' versatility, safety and energy efficiency could soon make incandescent bulbs a ghost of Christmas past."

—USA Today, December 2007

GE Consumer & Industrial Lighting designer Kathy Presciano observed that traditional 26-light strings burned at 125 watts and lasted for about 1,000 hours. The same size string with LEDs lasts 20,000 hours and burns at 2.3 watts.

Despite the obvious benefits of LEDs, traditions in the UV-curing industry are harder to break than holiday customs.

One reason may be that the well-entrenched combination of a traditional mercury lamp and off-the-shelf coatings are often seen by users as simpler and lower risk approaches, since existing coatings have been tailored to the mercury spectra and often do not cure as well with UV-LED sources. While UV-LED sources for curing have been thought of as being "low power" and of having limited wavelength options, the most significant practical barrier to acceptance is not these factors.

The most formidable problem for UV-LED curing sources, especially in coatings applications, has been oxygen inhibition at the surface of the coating. The most popular UV chemistries employ free radical mechanisms to aid in the formation of long polymer chains. However, in the presence of oxygen, there is a race between the crosslinking of the polymer and the affinity of oxygen to bond with free radicals, which prematurely terminates the polymer formation. The result is a thin surface layer that can be "tacky" to the touch and compromises the final properties of the coating.

Underneath this top-most layer, coatings irradiated with UV-LEDs can be completely cured, often even better than with traditional mercury lamps. But coating beauty is frequently

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skin-deep and oxygen inhibition becomes a show-stopper.

Fortunately, there have been some significant developments for UV-LEDs that help overcome this problem, clearing the way for a full array of benefits that accompany UV-LED curing.

Carefree Inerting—A Case Study

One way to prevent oxygen inhibition is to remove the oxygen itself from the UV-LED curing environment.

This approach has been successfully used by Finnish-based Tikkurila Coatings, one of the largest coatings manufacturers in Europe and a leading formulator for wood products.

Tikkurila felt that the benefits of UV-LED based curing are so compelling that adding inerting to their process made great sense in the long run.

Tikkurila's UV-curing products have been optimized to work well with a new commercial UV-LED curing line at their facility. The Tikkurila pilot line successfully cures flooring products at normal production speeds with performance equal to or better than they experienced with medium-pressure mercury lamps in the past.

Several innovative techniques make adding inerting to the process inexpensive, easy and trouble free. Since the amount of gas required is relatively small, an innovative generation and delivery system has been developed that integrates it directly into Tikkurila's UV-curing systems. This process eliminates the need and cost of using bottled gas. This low-volume, low-flow technique minimizes the amount of gas required and provides uniform distribution of the inert gas in the small space between the UV-LED source and substrate.

The result is a beautiful, completely cured coating with the clarity, gloss and durability demanded for parquet flooring applications.

Increased Power Output

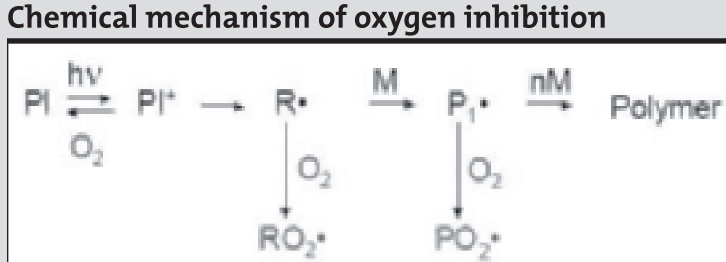
Oxygen inhibition is a race—a competition between free radicals promoting the polymerization of oligomers in the coating and oxygen scavenging the same free radicals. One way to solve the problem is to use a bigger hammer. It is well established that higher intensity light sources reduce the surface's susceptibility to inhibition.

"Another major benefit of extreme intensity UV application for free radical initiator chemistries (the most common) is in mitigating surface cure problems due to oxygen inhibition. In short, in addition to 'punch through' deep-cure mechanisms, extreme intensity effectively seals the surface instantly, preventing unwanted oxygen diffusion into the film afterward. The effects of this high-intensity mitigation were shown dramatically and documented by Jonsson. When very high intensities were used in a comparative study, initial rates of polymerization in air were the virtual equal of those cured in a nitrogen-purged environment. This was not the case, of course, with low-intensity irradiance." *The Case for Extreme Intensity in UV Curing,* Lesco White Paper Number 106.

In the semiconductor world, products get better, faster and cheaper over time. Like microprocessors or memory sticks, UV-LED capabilities have risen sharply over the last five years.

FIGURE 1

Chemical mechanism of oxygen inhibition



Coatings that could not be cured with the 200 mW/cm^2 sources only a few years ago now cure rapidly with sources producing over 4 W/cm^2 of output.* A parallel development in the last five years has been that these arrays have gotten larger and less expensive—an unusual but welcome occurrence in the industrial world.

** This discussion of output raises several points worth further discussion. Comparing the "output" of traditional UV sources and UV-LED emitters is not a straightforward exercise and must be approached with some caution and skepticism. See Sidebar "UV—How Do I Love Thee?" Be aware that some UV-LED sources specify output based on calculated output of the UV-LEDs themselves. When comparing UV to UV-LED, sources always consider where and how the output is being measured and over what area the peak irradiance is valid, as this will determine the exposure.*

Hybrid Design—A UV-LED Jump Start

Those wishing to begin taking advantage of UV-LED's benefits without inerting or reformulating can take a clue from the Toyota Prius. A UV-LED/mercury lamp hybrid solution offers off-the-shelf potential.

Like the hybrid car, adding an energy-saving UV-LED array to a traditional UV-curing lamp can noticeably increase the energy efficiency, performance and longevity of the overall system.

In recent trials, even adding a UV module prior to a single arc lamp showed significant benefits. The arc lamp, previously operating at 400 watts/inch, was reduced in power to 125 watts/inch. A UV-LED unit, which produces approximately 4 W/cm^2, was used to provide initial curing. The arc lamp was used to provide cure to the very top surface of the coating where oxygen inhibition would normally have occurred (Figure 2).

In this configuration, savings in excess of 50% of the energy consumption was realized. Derating the mercury arc lamp also results in increased lifetime of the arc lamp and better operational stability since arc lamps deteriorate faster as their output power is increased.

In addition, through-cure of the coating was actually improved without sacrificing surface properties.

It's worth noting that another recent advance in UV-LED technology has been the steady increase in footprint of the source (Figure 3). Early UV-LED curing units were only a couple of inches long, limiting their use for wide-Web applications such as wood curing, converting and other applications where arc lamps of a meter or more are popular.

Now UV-LED based curing systems of a meter or more are common. And, in fact, UV-LED technology offers advantages since they can be arranged in a staggered fashion with no ill effects on the curing process. It has been proven that these arrangements produce very good uniformity across the substrate and provide consistent properties anywhere the coating is tested. This is not true of arc lamps, which experience non-linear degradation as the lamp ages. Darkening at the electrodes results in a measurable drop-off of UV output and can result in changes of gloss, color or even loss of properties such as cure or adhesion.

FIGURE 2

Hybrid design: UV-LED with mercury lamp added

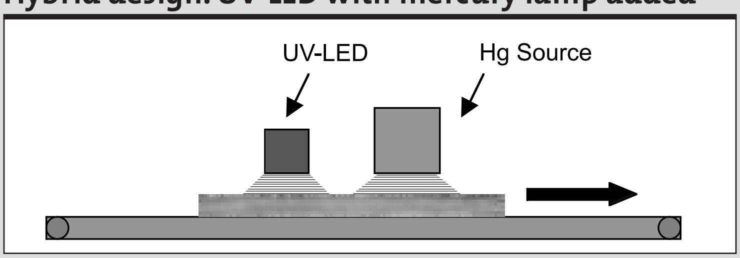
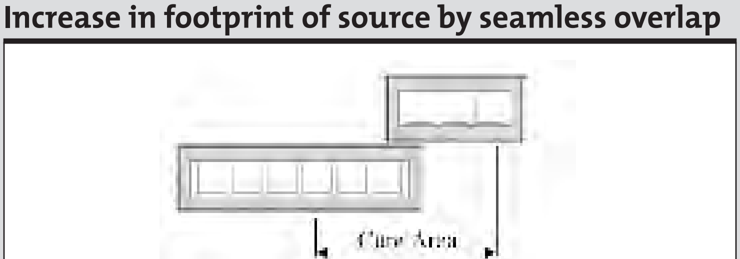


FIGURE 3

Increase in footprint of source by seamless overlap



The Development of New Photoinitators and Better Formulations

The slowest but most promising avenue to the widespread adoption of UV-LED technology is the creation of new raw materials and better formulations that exploit the narrow, but highly efficient bandwidth of these devices.

Non-free-radical and hybrid-cure mechanisms are being tested, and new photoinitators that are less prone to the effects of oxygen inhibition are also being developed.

There is also promising work being done with the existing range of commercially available products. For example, in the digital inkjet world the potential of UV-LEDs to not only "pin" or set inks in advance of full cure by a mercury source is giving way to inks being formulated to fully cure with UV-LED sources.

Chemists have continually prompted UV-LED light source suppliers to produce devices with shorter wavelength output. The presumption being that this would make curing existing formulations easier. But experiments that have been carried out with commercially available UV-LEDs in the 365 nm region have shown this is not the case.

Today, these UV-LEDs are significantly more expensive and have much lower peak irradiance capability than 395 nm sources. Trials have demonstrated that any benefit of shifting to a slightly lower wavelength is lost to the lower output power of the emitter. The higher power of 395 nm more than compensates for its slightly longer wavelength. Future availability of UV-LEDs in the sub 320 nm range would add capability for curing of exiting materials, but the availability of such devices at practical costs and outputs for curing is not likely in the near term.

Conclusion

The widespread adoption of UV-LEDs for industrial curing are being prompted by their benefits—less energy and heat, longer lifetime, a cleaner environment and a safer, mercury-free cure. Successful conversions to UV-LEDs have been accomplished when the coatings have been appropriately matched to the UV-LED source.

Solutions to the nagging obstacle of oxygen inhibition have been overcome commercially through formulation, higher power sources, clever inerting techniques and even hybrid designs. Record energy costs and the specter of global warming may be prompting this change. As more solutions become available, the increased adoption of UV-LEDs will continue. ◗

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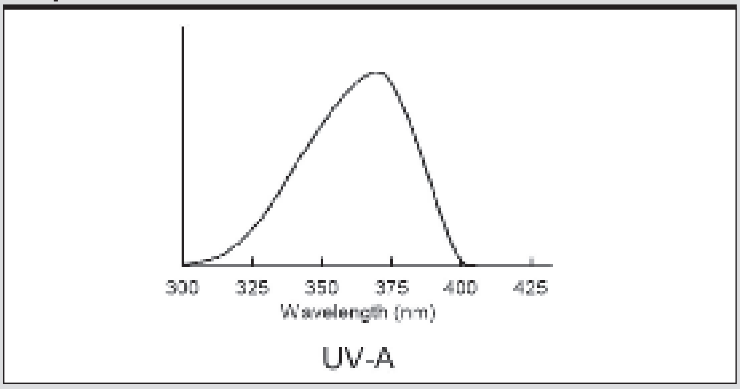
UV—How Do I Love Thee? Let Me Count the Ways

It's tempting to try and compare things, even when their inherent complexity makes direct comparison difficult and may even lead to silly conclusions. Trying to make judgments about the speed of two cars by comparing their horsepower is fruitless without information about their weight, gearing ratios, torque, etc. Similarly, comparing the UV output of a curing system without more data is fraught with problems. Yet the question is asked time and again—how much output does an UV-LED system produce compared to a conventional lamp?

FIGURE 1A

Response curves of handheld radiometers



To begin with, there is some confusion over the popular way of describing UV lamps. Conventionally, lamps are often described not by their UV output, but by the power applied to them—their input. Thus, a "400 watts-per-inch" arc lamp does not produce 400 watts-per-inch of UV output but rather consumes 400 watts of electricity-per-inch. It could consume more when considering the efficiency of the power supply/ballast system. The lamp's actual output can depend radically on a number of factors. The only way to determine the output of the lamp is by direct measurement.

Another concern. What UV output measuring method is commonly accepted? Industrial users commonly rely on standard UV measurement tools (e.g., handheld radiometers) for this purpose. For example, the ubiquitous Power Puck is one such