Technical Paper

UV-LED Curing for an Industrial Wood Coating Application

By Rob Karsten and Michael Beck

While the current economic downturn has affected all manufacturing markets, the UV curing segment continues to represent growth opportunities due to reduced operating costs, higher productivity and a more environmentally friendly solution which more and more end customers are demanding.

This article will describe several of the factors involved in the successful implementation and financial justification of a UV-Light Emitting Diode (LED) curing system designed to replace a traditional mercury-based, lamp-curing system in an industrial wood coating environment. This implementation, performed in Europe and designed for a variety of wood coatings (including a waterborne UV-curable coating), offered substantial advantages from a cost, energy consumption, environmental and carbon footprint perspective without compromising coating performance.

While the transition to a UV-curable manufacturing system represents a step forward from an efficiency, cost and environmental perspective, an additional quantum improvement can be realized if the rapidly evolving technology of LED-based lamps is used for the basis of the UV-curing system. UV-LED based curing lamps have already made substantial inroads into the digital printing market and are now beginning to be incorporated into a diverse variety of industrial manufacturing processes as well. The leading UV-LED lamp technology now offers a viable alternative to mercury-based curing technology since the UV power output and initial investment costs have approached and, in some cases, exceeded high-quality mercury lamp systems. However, in spite of the inherent advantages of a UV-LED curing system, there are several critical design components that must be considered; particularly related to the UV chemistry utilized.

Figure 1

Phoseon Technology UV-LED Lamp

This system outputs 8W/cm^2 or more and the lamp length can be extended to over 1.5M wide.

Cost-of-Ownership

A critical component in the financial justification of the UV-LED curing system was the system's cost-of-ownership (COO). A detailed COO model was developed in cooperation

Figure 2

Factory air extraction for an industrial mercury-based, UV-curing system

with two European firms, Tikkurila AB and Robert Bürkle. This model was developed to compare the costs of a UV-LED curing system and a traditional, mercury-based curing system. While many factors were used in this extremely detailed and comprehensive model, the primary variables included cost of acquisition; cost of energy and services; cost of installation; cost of maintenance and consumables; and operational availability of the manufacturing equipment, including yield and system uptime.

This initial cost-of-ownership model demonstrated that each UV-LED lamp system (1.4M wide) would result in an operational cost savings of approximately $14,000 per year, per lamp with approximately 60% resulting from direct energy savings. The primary remaining justification factors included the elimination of the ozone extraction requirement; a 50% reduction in HVAC/hot air extraction and treatment; an 80% reduction in preventative maintenance, repair and bulb replacement; and a >5% yield improvement due to the inherent process repeatability and reliability of the UV-LED system. After this system was implemented, additional significant financial advantages were discovered related to the far lower heat load of a UV-LED based curing system compared to mercury lamp technology.

Figure 3

Robert Bürkle KA line equipped with 1.4M wide UV-LED system

Environmental Impact

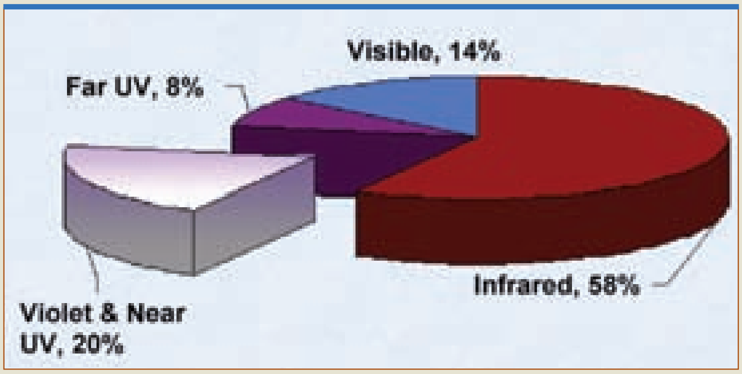
One driver for many companies today is the reduction of the environmental impact of a manufacturing process. In this specific implementation, each 1.4M wide UV-LED lamp cut the factory's carbon footprint by 25 tons of CO^2 annually. This equates to ten cars being taken off the road per year or the planting of approximately 200 trees.

UV-LED Versus Mercury-Based UV Lamps

Mercury-based curing lamps have a broad output spectrum with peak UV outputs determined by the doping within the bulb. The output spectrum of such a lamp usually ranges from 200 to 800nm, ranging from the low UV B/C ranges through the visible range and into the infrared. In many cases (Figure 4), nearly 60% of the mercury

Figure 4

Typical mercury-based UV lamp wavelength distribution

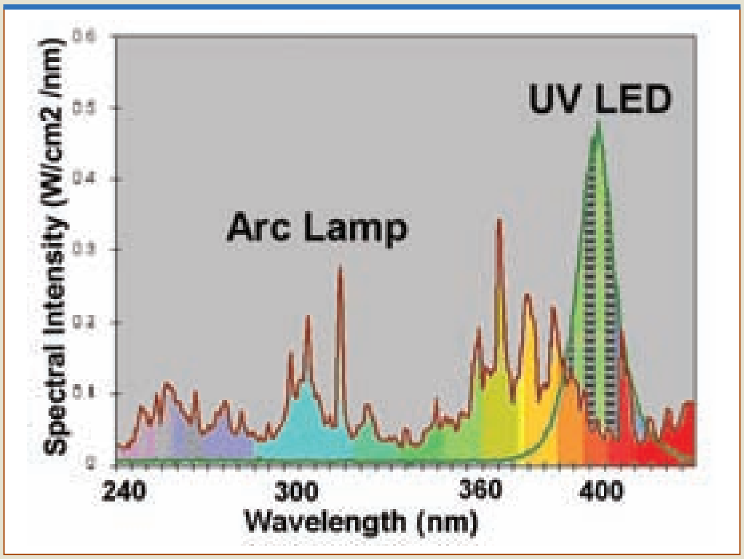


lamp's output is infrared energy which can result in high heat levels that must be managed from a hot air extraction and, more importantly, from a substrate cooling perspective.

In contrast, the UV-LED based curing system outputs a very intense, but narrow spectrum of light energy—typically approximately 40nm wide peak-to-peak (Figure 5). If the material is designed to accept this energy efficiently during curing, this system can be far more efficient since nearly 100% of the lamp's energy is used for curing. Also, the lack of infrared emissions will result in a far lower heat load delivery to the curing substrate. In the case of this wood-curing application, the far lower heat generated by the UV-LED system offered a critical process improvement and a major recurring cost advantage.

Figure 5

Mercury-based lamp versus UV-LED wavelength distribution



Materials Suitable for UV-LED Curing

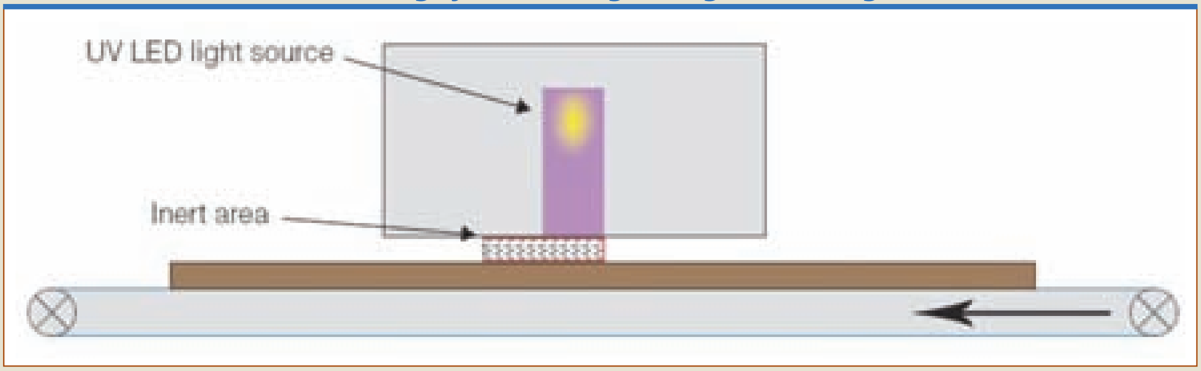
One major obstacle restricting the widespread adoption of UV-LED in spite of the inherent process and operational advantages of LED technology has been the availability of suitable materials that cure in the UV-A range and managing the traditional curing issue related to UV-A only curing, namely surface cure issues related to oxygen inhibition. In some cases, the surface cure/oxygen inhibition issue can be resolved with additives in the formulation. In other cases, the decision has been made to inert the area being cured, usually with nitrogen. Since the UV-LED system is designed to be as close as practical to the curing surface, the addition of nitrogen inerting did not present a substantial engineering challenge since the gap between the light sources and the substrate level were relatively low (~5mm). This gap was effectively filled with N_2 during curing using air knife technology and a cost-effective nitrogen generation system (Figure 6).

Some market segments have been quick to identify the potential benefits of UV-LED curing. Already in some industries (such as digital printing) there has been wide-scale adoption of this technology that has been enabled by a large and growing base of ink suppliers who have re-formulated their inks to work efficiently and effectively with UV-LED curing systems. With respect to industrial applications (such as wood coating), this effort is underway with substantial progress occurring in some sectors.

While current material compatibility still remains one of the biggest barriers, ongoing development by many of the world's leading material suppliers would suggest that it is only

Figure 6

Cross section of UV-LED curing system using nitrogen inerting



a matter of time before we can expect to see UV-LED suitable materials becoming widely available in many applications.

UV-LED Wood Coating Curing Results

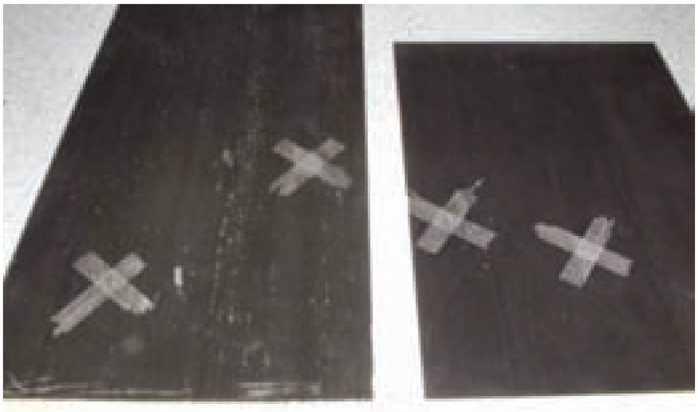
A summary of some specific tests conducted in conjunction with this application are presented along with the fourier transform infrared spectroscopy (FTIR) analysis of several topcoat formulations.

UV-LED Curing of Temperature-Sensitive Pine Wood

Temperature-sensitive pine wood was tested using a clear sealer as well as a waterborne pigmented system. The UV-LED curing of temperature-sensitive pine wood demonstrated significant improvement in adhesion on the knots. The class of adhesion after LED curing was 0-1 compared to very low adhesion levels equal to 4 after standard UV curing. No resin bleeding was observed (Figure 7b).

Figure 7

Clear 100% UV-curable sealer adhesion to temperature-sensitive massive pine wood



(a) Cured with conventional UV (b) Cured with UV-LED unit

Lower Heat Emissions, Lower Surface Temperature

Due to high operating efficiency and the inherent narrow output spectrum, UV-LED light sources generate very little heat. The surface temperature of a UV-LED light source was measured at 40-50°C, which resulted in very low product surface temperatures (25-30°C). Until now, excessive surface temperatures on coated products have caused problems on application lines. This can cause stains to boil; resins to exude from pine; delamination of glued veneer; and UV-cured products to turn yellow.

LED Curing of Waterborne Pigmented System

UV-LED curing results for a waterborne pigmented system in an inert atmosphere are shown in Table 1. Curing was carried out at oxygen concentration levels of 6% with a UV energy density of 356mJ/cm^2. Commercially available pigment paste concentrations were added, about 10 volume-% of each pigment paste.

The test results show that the pendulum hardness increases significantly with UV-LED curing in all shades when compared to conventional curing by Ga and Hg UV Arc lamps. The pigmented systems (which are

Table 1

Hardness of a clear waterborne paint cured by standard UV lamps and UV-LED technology

Pigment index	Paste added (w.-%)	Pendulum hardness UV LED curing	Pendulum hardness Ga + Hg curing
P.W.6 (white)	18.2	45	28
P.Y.42 (oxide orange)	16.7	26	11
P.R.122 (pink)	10.0	68	53
P.Bk.7 (black)	11.5	25	16

difficult to cure with conventional UV technology—even to tack dry) can be fully cured in a UV-LED oven.

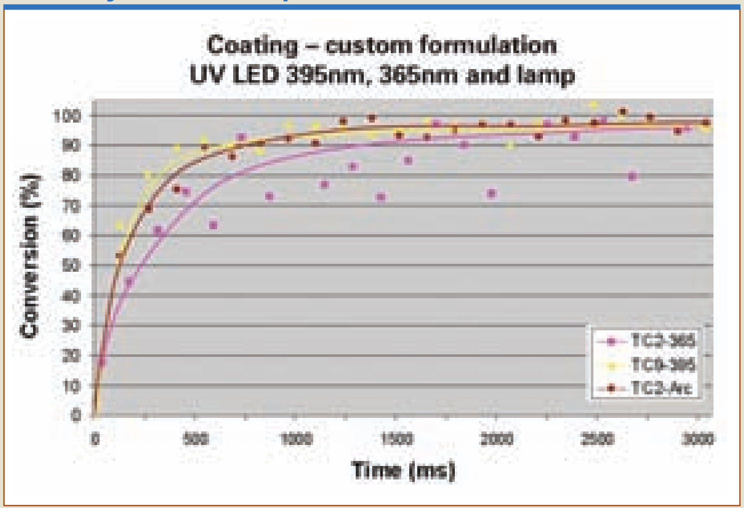
UV-LED Curing in Door and Stair Industry

In this test, waterborne clear and pigmented versions were tested at Tikkurila. Nitrogen inerting was not required which makes the curing of 3D surfaces more practical. Tests at Tikkurila on samples for a stair manufacturer and on door skins are ongoing. The aim is to develop pigmented products for lines currently using two Gallium and two Mercury lamps to be substituted with only one UV-LED lamp. The replacement of four traditional curing lamps with one UV-LED system would result in a cost justification far beyond what was demonstrated in the initial cost-of-ownership model.

For this application, the large reduction in heat delivered to the wood surface resulted in the use of lower grade "bottom wood" which resulted in a cost savings associated with each substrate cured over time—which improved the company's profit position while they enjoyed the operational reductions described earlier.

Figure 8

Conversion rate for UV-LED 395nm, 365nm and mercury-based lamp



UV-LED Curing in Parquet Industry

Tikkurila AB has developed top lacquer for use in the parquet industry formulated to be optimized for UV-LED curing. The test results found that the coating had less smell when cured. The lacquer was yellow when wet but it yellowed much less when cured using UV-LED compared to conventional UV-curing lacquer (ΔB 0,04/0,94). There was less difference chemically between surface and rest of lacquer and better chemical resistance (ethanol, ammonia). A higher friction coefficient (0,41/0,30) was measured and the curing performed as good or better in Stuttgart microscratch resistance.

Cure Rate Analysis

Real-Time FTIR is based on how infrared radiation is absorbed by chemical bonds. Each bond type has a distinctive response at a given wave number (1/wavelength) where the peak represents the number of bonds. The peak will decrease and finally disappear over time as the polymer chain is formed. This allows the measurement of the percent conversion as a function of time by measuring the change in area under the curve at different time intervals.

Tikkurila's UVIPAR TOP 2D single coating topcoat that was formulated to cure with a UV-LED light source was tested with three different light sources, including a mercury-based lamp; a UV-LED lamp using 395nm technology; and a UV-LED lamp with a peak at 365nm. Even though this material was formulated for the UV-A region, it shows that a UV-LED lamp not only cured the material, but cured the material at a faster rate than a mercury-based lamp. The 365nm UV-LED light source is not well matched to this material and does not cure as effectively with the light source.

It should be noted that the UV cure rate as measured using FTIR is only one of several decision factors in determining suitability of UV sources for curing. The physical, mechanical, chemical and process properties of the cured material are equal and, in many cases, even more critical.

Conlusions

UV-LED curing systems have advanced to the point that they can be an effective alternative to traditional mercury-based, UV-curing systems for a growing number of applications. These systems can offer substantial process, cost-of-ownership and environmental advantages. However, the success of such a transitional project in a market segment such as UV wood coating requires the close cooperation between the UV-LED lamp supplier, coating/chemistry/material supplier, and coating/machinery equipment supplier.

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