LED curing – reaction/behaviors of various inks to LED based UV sources

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Abstract

Recent advances in LED technology make high power LED based UV sources a viable solution for curing inks in digital print applications. UV LED systems with adequate power and peak irradiance for curing inks are now available. As part of our ongoing research into the optimization of UV curing processes, we have undertaken a study of the curing efficiency of various UV curable inks for digital print with UV LED sources. Due to the numerous advantages of LED based UV sources, such as less energy consumption, reduced heat load on substrate, longer system lifetime, etc., more attention has been given to LED based UV sources for digital print applications. However, the direct replacement of gas discharge lamps with LED systems is complicated by the fact that there are many differences between the two sources, most importantly the spectral content. Ink formulations optimized for conventional gas discharge lamps, which typically have multiple emission peaks from deep UV to IR range (broadband source), take advantage of the multi-wavelength source as well as other parameters to guarantee a high quality print, as characterized by properties such as adhesion, flexibility, and chemical resistance. Ink formulations may need to be correspondingly modified to maintain these desired performances with the use of LED curing. For this reason, it is necessary to study how existing and reformulated inks react to LED based UV sources. This provides input for the optimization of LED systems during development and for printer design by integrators who are planning to use LED based UV sources in their printing systems. EXFO Life Sciences and Industrial Division has performed a series of experiments with various types of arc lamp and LED formulated UV curable inks, investigating their curability with LED based UV sources. Our results show that surface cure issues are more pronounced when using an LED source due to the lack of shorter wavelength UV emission. Although LED sources are successful in achieving cure, a high UV dose is needed to cure conventional UV inks. Modification of the ink formulation to enhance the cure efficiency of LED based UV sources can reduce the need for UV power dramatically. Our research also indicates that having a controllable pre-cure system in front of the final cure, such as a pinning system, may ease the tight formulation requirement as well as lower the power requirement for final cure.
**Introduction**

There are many advantages of LED (light-emitting-diode) light sources such as lower energy consumption, reduced heat load on the substrate, longer lamp life and instant on/off. For these reasons there has been increased interest in adopting LED light sources for UV (ultraviolet radiation) curing in digital print applications.\(^1\)

Not very long ago, LED based sources were not considered a practical tool for full cure compared to traditional broadband gas discharge lamps for printing applications.\(^2\) Recent advances in LED technology and the parallel efforts being made by formulators of UV curable inks have made high power LED based UV sources a viable solution for fully curing inks in digital print applications.

From the UV LED system perspective, the peak irradiance as well as the total optical output power of newer LED based UV systems have reached or exceeded the minimum full cure requirement for digital print applications. From the ink supply perspective, more ink formulators have started to consider and work with LED based UV systems to offer ink formulations more reactive to LED based UV sources.

However, the direct replacement of gas discharge lamps with LED systems is complicated by the fact that there are many differences between the two sources, most importantly the spectral content. Those ink formulations optimized for conventional gas discharge lamps, which typically have multiple emission peaks from deep UV to IR (infrared radiation) range (broadband sources), take advantage of the multi-wavelength spectral content of the source as well as other parameters to guarantee a high quality print. This is characterized by full cure of the ink, and achieving properties such as adhesion, flexibility, chemical resistance of the cured ink film. If ink formulations remain the same while the curing source shifts from gas discharge lamp to LED, the curing of the inks would be different.

Even for those inks formulated specifically for the LED based UV sources, due to very narrow spectral distribution of the LED based sources, a slight shift of its peak wavelength may result in a significant change in ink curing performance. This problem is very common from supplier to supplier.

For this reason, it is necessary to study how the inks react to LED based UV sources. This provides input for the optimization of LED systems during development and for printer design by integrators who are planning to use LED based UV sources in their printing systems. We have performed a series of experiments with various types of UV curable inks, investigating their curability with LED based UV sources.

**Experimental**

The ink samples investigated are from various ink suppliers active in the UV curable digital printing market. They can be divided into two categories:

- **Group A:** formulated specifically for LED based UV sources
- **Group B:** formulated for traditional broadband gas discharge lamps
Wet ink films were prepared on selected substrates using draw down method with a #5 Wire-Wound Wet Film Applicator Rod for most of the experiments. According to the information provided by the wet film applicator rod supplier, the thickness of the wet ink film prepared in this way is approximately 12.8 micrometer.

The LED light sources used in the experiments are

- 365nm LED (max. peak irradiance: ~2W/cm²)
- 400nm LED I (max. peak irradiance: ~4W/cm²)
- 400nm LED II (max. peak irradiance: ~8W/cm²)

Figure 1 shows the spectral distribution of the UV emission from these modules. As we will discuss later, although these LED modules are labeled as 365nm and 400nm LEDs, the peak of their output spectrum is quite often not centered exactly on 365nm and 400nm. For example, higher LED junction temperature, which is typical for the high power LED based UV source for UV curing application, will make the peak of its UV emission shifting towards a longer wavelength.

![Figure 1: spectral distribution of the UV emission from 365nm and 400nm LED modules tested](image)

Samples were placed on a sample tray controlled by a precision high speed motion stage capable of running at a speed in the range from very slow to above 3m/s. This covers the speed range currently used by the digital print industry.

The properties of the cured ink films were evaluated to determine the curing performance of a UV LED source at a specific process setting. The evaluation for cured ink films is related to and measured as

- Color transfer
- Surface tack
- Surface hardness
- Resistance to alcohol rub
- Adhesion to the substrate

These are commonly used in print industry to gauge ink curing quality.
Results and discussion

Among inks in Group A, although all are formulated for LED based systems, there is a significant difference in their reaction to the LED sources tested. While many inks respond well to UV exposure, a few are not cured adequately despite the use of excessive UV dose at various irradiance levels and wavelengths (peaked at ~ 365nm or ~ 400nm).

Inks in Group B typically cannot be cured as easily as the LED formulated inks in Group A. Although some are cured to an acceptable level, they usually need more UV dose and require higher irradiance. In many cases, the difficulty is achieving satisfactory surface cure, while a through cure is much easier and can be adequately achieved with the LED sources.

Ink samples, particularly those not optimized for LED sources often have surface cure problems. Since the shortest wavelength high power LED source is peaked at ~ 365nm, results show that surface cure issues are more pronounced when using an LED source to cure an ink formulated for traditional broadband gas discharge lamps due to the lack of shorter wavelength UV emission.

At the ink thickness tested (~12.8 micrometer wet ink film), adequate through cure was usually achieved with 400nm LED sources. However, at shorter wavelengths such as 365nm the through cure often became problematic.

Unlike more transparent clear coatings or adhesives, for heavily pigmented ink films, UV irradiation peaked at ~ 365nm may not fully penetrate the ink layer at the thickness we tested. The situation is more favorable for a 400nm LED source. The individual absorption spectra of cyan, magenta, and yellow ink films from one of the ink set tested were measured and compared as shown in Figure 2. It clearly shows that, at least for cyan, the absorption at 400nm is much less than at 365nm. This partly explains why the deep-cure is more challenging with 365nm LED sources.

Figure 2: absorption spectra of cyan, magenta, and yellow ink films
The difference in depth dependence of the curing performance with 365nm and 400nm LED sources, both are popular for print applications, may be effectively utilized to control the surface appearance (from matte to glossy) of a printed image by a proper combination of these two sources.

The major difference between LED based UV light source and traditional gas discharge lamp is its much narrower spectral output. This makes the curing with a LED based system more sensitive to the ink formulation than before, not only because of the chemistry of the formulation, but also its colorants (pigments or dyes).

In addition to the response of the photo initiators used in the formulation, the wavelength dependence of optical filtering by the pigments needs also to be considered. For example, it is quite common that the peak wavelength of a 400nm LED device or module might vary from 390 nm to 410nm or even wider from supplier to supplier and, quite often, the peak of an LED element itself might be change due to the condition of the operation, such as the operating temperature and driven current (see Figure 3). If the wavelength is shifted from 390nm to 410nm the absorption will change significantly, for example, for cyan and yellow inks, as indicated in Figure 2.

Since the LED sources currently available deliver a lower total optical power compared to traditional gas discharge lamps, overexposure is not considered a big issue in the application. Also, typically, the inks can be quite tolerant of overexposure but may be totally intolerant of under exposure, particularly when the chemistry and optical properties are not well matched. Delivering sufficiently high UV dose at required irradiance level is desired for a successful curing.

In many cases, however, the need for a more powerful LED source is just because of the problem from a part of the ink set. It may not always be possible to balance the inks through formulation improvements thus pre-cure of individual color inks prior to the final cure may significantly improve the overall quality of cure without pushing the limits of ink formulation and final cure lamp power. Pre-
curing the individual inks to different level prior to the final cure may reduce the variation of their curing quality after passing the final curing stage. A pinning tool is not only useful for control the print qualities in term of control the graphic details\textsuperscript{2} but can also be used as a pre-cure tool which will be helpful for ease the tighter formulation control and the requirement for higher power final cure lamp.

**Summary**

Ink samples, particularly those not optimized for LED sources often have surface cure problems. Since the shortest wavelength high power LED source is centered \( \sim 365\text{nm} \), results show that surface cure issues are more pronounced when using an LED source to cure an ink formulated for traditional broadband gas discharge lamps due to the lack of shorter wavelength UV emission.

Although LED sources are successful in ‘getting the job done’ with many conventional UV inks commonly used on the UV printers with broadband UV lamps, a high UV dose is needed to cure those UV inks.

Modification of the ink formulation to enhance the cure efficiency of LED based UV sources can dramatically reduce the need for UV power.

If the LED source is well designed and the ink is properly formulated, full cure can be achieved.

To achieve a desired response or satisfactory rating for the critical property(s) of the intended application, a more careful selection of ink set to match the LED source are needed. Further print quality improvement and control is possible through the implementing of pre-cure units, such as UV LED based pinning heads, after some or all individual color print heads to balance the performance of different color inks at particular printing parameters.

**References**