Practical Considerations for Using UV Reactive Inks in Piezo DOD Printheads

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Abstract

UV curable jet inks are viable materials to meet some industrial printing requirements, especially on non-porous materials such as coated papers, plastics, and metals. The chemistry of these systems is well understood[1,2, 3, 4], but has not been widely discussed in the context of jet ink printing architectures.

This paper will discuss some of the challenges of using UV curable drop on demand inks, specifically free radical cured jet inks, and discuss some practical considerations for the printing system architecture.

Discussions will include various curing protocols and their affect on final ink properties, image quality and UV lamp power requirements.

Introduction

Ink jet printing technologies have facilitated the use of digital printing in a wide variety of traditional industrial printing fields. One of the general major disadvantages of ink jet technology however, which has limited its acceptance in industrial printing applications, has been the physical properties of the ink. An ink class that has the potential of allowing ink jet printing to carve a place amongst the traditional printing technologies, and compete with traditional inks for durability, water resistance and lightfastness, is UV curable ink.

UV curable inks for piezo drop-on-demand ink jet printheads, are typically 100% solids formulations, meaning that the inks do not contain solvents. Further, these inks are typically low-viscosity, reactive, liquid monomers that become solid on exposure to UV or EB energy.

As these materials do not contain solvents, the printing systems offer several advantages. First, the systems do not emit VOCs. Second, as the inks do not dry in the nozzles, cleaning, capping and maintenance stations can be less elaborate or eliminated. Further, as these materials, when cured, are cross-linked plastics; the solvent and chemical resistance properties of the final inks are high.

For industrial, high-throughput, jet ink systems that use aqueous or other solvent based inks, large thermal drier units are often required. Comparably, for UV curable jet inks, powerful UV lamps (often termed driers) are required to solidify the ink.

Unlike solvent, phase-change or water based inks, UV inks commonly remain low viscosity liquids until they are exposed to UV energy. This has led to some unique printing, handling, and curing protocols that system designers need to be aware of when determining system architectures. This paper will discuss various system architectures and the associated ink chemistry and physics considerations.

Background

Factors Affecting Cure Dosage

For free radical cured UV ink systems, there is a phenomenon known as oxygen inhibition that has a profound affect on the ability to cure thick layers of ink. During the cure reaction, UV light stimulates initiator molecules to produce free radical species. These free radical species are responsible for polymerizing the reactive ink monomer that comprises the bulk of the ink. The reaction then proceeds via a radical chain polymerization reaction. The free radical species, and subsequent growing chain radical species, can also react with oxygen molecules. When this occurs, the radical is quenched and the chain polymerization reaction is terminated. Such radical polymerization reactions are inhibited by oxygen.

There are several factors that affect the degree of oxygen inhibition and subsequently the required dosage to effect a full cure. High intensity UV light sources are more efficient at curing UV inks than lower intensity sources. Equivalent cumulative UV dosages from a focused and an unfocused UV source will produce a different degree of cure in an ink layer. The reason for this is a high intensity light source produces many more radical species per unit volume at any specific time than a lower intensity source. A portion of these species consume the available oxygen in that region of ink, leaving the remainder of the radicals to polymerize the ink inhibited only by the rate of diffusion of atmospheric oxygen into the ink. For a more diffuse UV light source, the number of radical species per volume is lower, resulting in fewer remaining to effect polymerization (Figure 1). Additionally, to apply an equivalent dosage per unit area, a diffuse light UV source needs to be applied for a longer time period. During this period, a greater time is available for oxygen diffusion from the atmosphere back into the ink. This further inhibits the rate of polymerization.

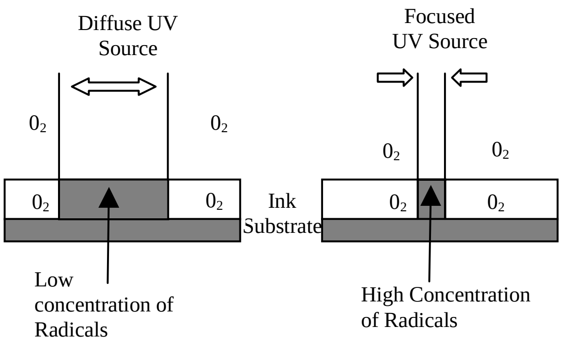

Figure 1. Effect of Intensity on Concentration of Radical Species

Increasing ink thickness increases the time it takes for oxygen to diffuse from the atmosphere to the ink-substrate interface and replace the oxygen consumed by the radicals. Assuming that the UV lamp provides sufficient intensity to the ink-substrate interface to consume oxygen and initiate polymerization, the dosage per ink volume for thick layers is lower than thinner ones.

As the diffusion rate of atmospheric oxygen has an effect on the degree of oxygen inhibition, it is possible to further decrease the required cure dosage by cooling the ink. Cooling the ink decreases the diffusion rate of oxygen.

A further, more obvious method to alleviate oxygen inhibition is to blanket the ink in an inert atmosphere such as nitrogen. Applying a nitrogen blanket to the cure zone of a UV printer can reduce the required cure dosage by up to six times.

Factors Affecting Adhesion

Adhesion for free radically cured UV inks is achieved primarily through mechanical interaction. For good adhesion, the monomer molecules of the ink need to make intimate contact with the substrate and remain in contact during the curing or polymerization step. To allow intimate contact of the ink with the substrate, the substrate needs to be clean and have the correct surface energy. Treatments such as solvent cleaning, wiping, blowing, corona, flame and UV pre-treatment, all offer adhesion advantages and should be considered as integral stations in printing system architectures.

Shrinkage during curing, and especially differential shrinkage of subsequent ink layers, also may affect adhesion.

Cure Dosage and Adhesion

The adhesion produced by single layers of ink cured either by one large dosage of high intensity UV light, or multiple low dosages of high intensity light, tend to be comparable. This assumes that the inks cured via the two protocols are polymerized to the same degree of conversion, which may require different dosages to achieve.

For multiple layer printing, other factors come into play. First, the considerations are no longer solely ink-substrate interactions, but also ink-ink interactions. UV ink, when cured to high conversions, is insoluble in uncured ink. The cured ink behaves like a plastic surface. As such, subsequent ink drops landing on cured ink are required to wet and adhere without the benefit of being able to partially solubilize the initial ink layer. Further, the surface energy of the cured ink is very similar to the surface tension of the uncured ink, resulting in a very difficult surface to wet.

One method to overcome this issue is to only partially cure the initial ink layer. The subsequent ink drop will be able to partially solubilize or at least swell the semi-cured ink. There are, however, two factors to this approach that need to be considered. The most obvious is that the dosage the initial ink layer receives must be sufficient to allow the ink enough green strength to resist roller offset, but not enough to prevent wetting of the subsequent ink drop. The second issue is potentially an adhesion issue and is very much dependent upon the ink chemistry. All UV curable inks shrink to some degree when cured. There is often a window of dosage that produces poor adhesion. This window occurs when two criteria are satisfied. First, the lower level of ink is cured to a degree such that the adhesive strength produced is not sufficient to overcome the stresses that occur when the upper ink layer differentially shrinks when it is cured. Second, when there are too few uncured monomer molecules remaining at the substrate interface capable of producing a new adhesive bond.

This window will vary based upon the ink chemistry, and is larger for inks that exhibit high shrinkage upon curing. Either side of the window, it is possible to achieve good adhesion.

Drop Spread and Dot Gain Control

Dot gain in solvent based inks is determined initially by surface tension / surface energy interaction. Further, longer term effects, feathering, reticulation, coalescence, and pooling, are rapidly arrested by evaporation or adsorption of the solvent into the media. Similarly, phase change inks solidify on contact with the substrate and the dot is fixed. For UV curable inks, however, the inks remain low viscosity liquids until cured. On porous materials, these behave like oil based inks and tend to feather with time until cured. On non-porous substrates, the inks essentially have no mechanism to arresting dot gain other than curing. For this reason, to minimize dot gain, the ink should be cured as soon as possible after printing. To prevent color mixing and pooling, it is necessary to cure the ink prior to a second ink drop landing next to or on the first. This is not always possible to arrange owing to constraints of some of the system architectures, but should be understood and considered prior to setting image quality expectations.

System Architectures and Considerations

Continuous Web Printing Systems Considerations

For continuous web printing systems, where variable information or highlight spot color is being added to a pre-printed stock, the whole image needs to be printed in a single pass. In order to achieve this, large arrays of ink jet nozzles are required. Every pixel position in the cross web direction needs to have its own associated nozzle. Further, in order to minimize drop placement error, it is advisable to have the array of nozzles arranged as compactly as possible. This requirement leads to a printing system that images an entire color plane prior to being given an opportunity to cure the ink. The addressability of the printhead may be high, but the resolution is limited by the ink's flow properties on the substrate prior to being cured. To prevent further resolution loss, the ink should be cured in as short a distance from the printhead as possible.

Additionally, for continuous web printing systems, the ink must be cured to a degree such that it is handlable prior to reaching any contact points such as a roller. For most UV ink formulations, curing the ink sufficiently to resist roller offset also renders the ink surface non-wettable to the next ink color. For some UV ink formulations, however, it is possible to partially cure the first ink layer sufficiently so that it is able to resist roller offset yet still allow wetting of the second ink layer. This, however, is really only feasible for up to two colors. Once the first color laydown has passed under a second UV lamp, it is generally too cured to allow any subsequent ink drop to wet it.

For multi-color continuous web printing, it becomes necessary to utilize inter-station surface treatment, such as Corona Treatment, between each printing station. This will raise the surface energy of the cured ink and allow wetting of the subsequent ink. As such, multi-color continuous web UV ink jet printing systems require large printheads with large inter-station UV lamps and surface treatment stations between the heads. The costs associated with these inter-station devices mean that the continuous web architecture is only really suitable for high volume, industrial printing.

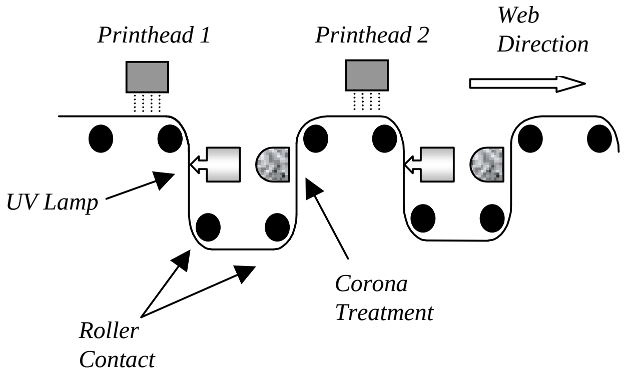

Figure 2. Schematic Representation of a Continuous Web Printing System

Drum Architecture Considerations

For drum style architectures, it is possible to have a UV lamp that irradiates the same location multiple times. It is also not necessary to cure the ink in one pass under the UV lamp. As such, lower power lamps or higher drum speeds are possible. Much smaller printheads with fewer jets can also be used and the image built up by multiple rotations of the drum. As such, these architectures may be much cheaper than multi-color, single-pass web systems.

The various architecture options allow for several curing protocols. With a drum architecture, partially curing the ink is a very viable option.

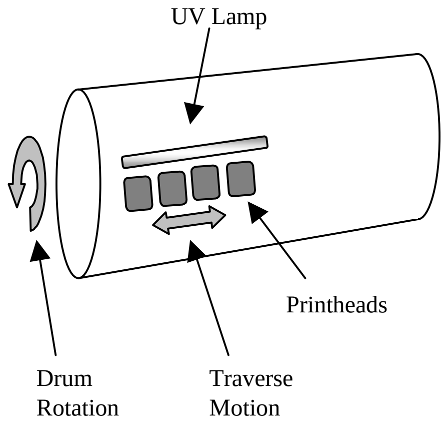

Figure 3a. Drum Architecture with Printheads Arranged Orthogonal to the Print Direction

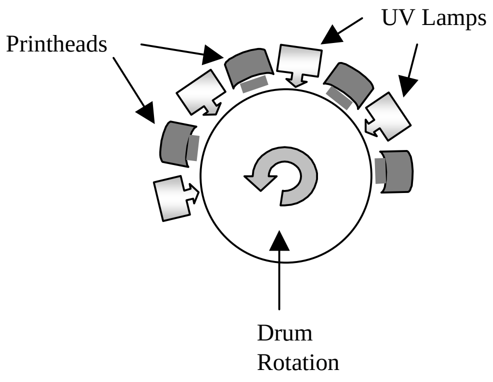

Figure 3b. Drum architectures with Printheads Parallel to the Print Direction

When determining the various factors associated with a particular architecture, the drum speed, lamp power, heads orientations, etc., several ink factors need to be considered.

As an example, consider a process color drum architecture where the four heads are arranged orthogonal to the printing direction as in Figure 3a. Further, assume that the nozzle spacing requires six revolutions of the drum to cover the image.

Several considerations need to be made: What is the minimum energy required to fix a drop? What lamp power does that equate to given the drum speed? Given the general architecture, what is the worst expected lay-down order?

In the example color lay down pattern shown in figure 4, the black color in the raster line 2 will receive twenty-four doses from the UV lamp prior to any final curing. The black drop in raster 7 will experience only six doses before it receives a drop of cyan. The black drop with then receive six more doses of whatever energy is able to pass through the cyan drop before the cyan drop receives a magenta drop. The black drop then receives a dosage filtered through both the magenta and cyan ink and so on until the yellow drop is printed. As such, the degree of cure of the two black ink drops can be significantly different. Further, any subsequent final curing will also be reduced by the filter effect of upper layers of ink, which for the black ink in raster 7 may be considerable.

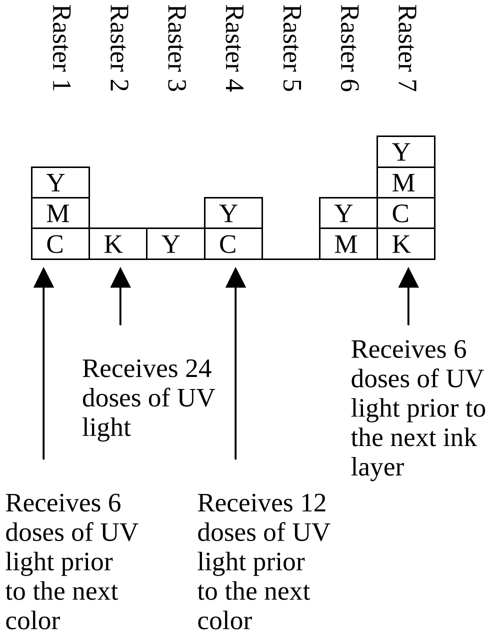

Figure 4. Example Image Lay-down from a Drum Printer Architecture with Printheads Arranged Orthogonal to the Print Direction

In the drum architecture example shown in Figure 3b, the printheads are arranged parallel to the printing directions. In this architecture, all of the colors in a raster line are laid down in one revolution. To prevent excessive color bleed and ink pooling, it is advisable to have inter-head UV lamps. With this arrangement, a different set of ink considerations need to be made. Is the inter-head UV dosage sufficient to fix the drops and prevent color bleed? Do all the possible curing scenarios produce good ink-substrate adhesion? Does the cured ink remain wettable after three revolutions passing under four UV lamps per revolution?

Using the same color image as before, but with a parallel head arrangement, the following curing considerations may serve as examples (Figure 5). The black color in raster line 2 is never masked by subsequent ink colors, whereas the color in raster line 7 receives only one dosage of UV light prior to being masked with C, M and Y. The black in raster 7 also receives single dosages filtered by cumulative layers of ink followed by multiple dosages filtered by all the ink layers. The black ink layer needs to be able to cure and adhere under both of these cure scenarios.

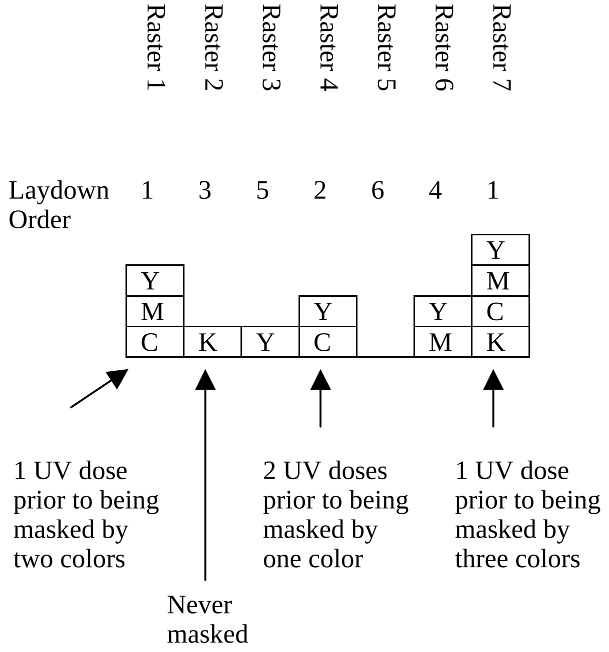

Figure 5. Example Image Lay-Down from a Drum Printer Architecture with Printheads Arranged Parallel to the Print Direction and With Inter-Station UV Lamps

For raster line 4, the cyan color receives two UV dosages prior to a second color, yellow, being applied. It is important that the cyan is not cured such that it becomes non-wettable, as that may result in poor drop spread control and poor ink-ink adhesion.

Traversing Roll-To-Roll Architecture Considerations

Many of the same considerations that were made for drum architectures are identical in traversing roll-to-roll architectures. It is possible to align the heads in an orthogonal or parallel orientation to the print direction (Figure 6) and produce example curing schemes similar to

Figures 4 and 5. For traversing roll-to roll systems, there are additional factors that may be considered.

A roll-to-roll system is most effective if the printing can be made bi-directionally. As such, for a system with the printhead mounted orthogonal to the print direction, it is necessary to mount at least two lamps to the carriage. This will alter the cure profile of the example color images, and will need to be considered.

For parallel oriented printheads, it may not be possible to mount five UV lamps on the carriage owing to the weight limitations of the carriage. This prevents the ability to have inter-head curing and may result in a compromise in resolution. In addition this will again alter the cure profile that the ink is subjected to.

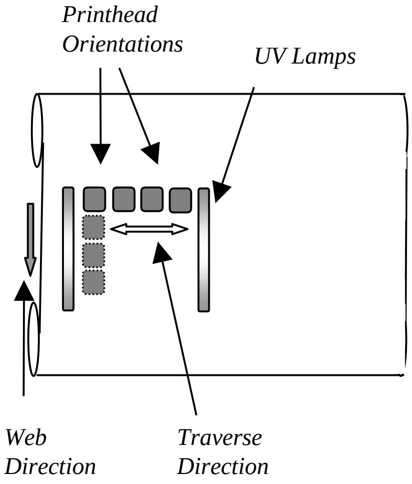

Figure 6 . A Roll-to-Roll System Showing Two Possible Head Orientations

Alternately, it is possible to adopt a scheme where every other pixel position is printed, resulting in all of the drops of a particular pixel being printed wet but allowing at least one pass under a UV lamp prior to any neighboring pixels being printed. Throughput loss caused by printing alternate pixel positions may be regained by increasing the speed of the media or the traverse rate of the heads, but again, the impact of this on ink curing and performance must be considered.

Conclusions

When testing and evaluating UV curable inks for various applications, it is extremely important to understand and consider the effects that various architectures and curing schemes may have on the final properties of the ink. It is necessary to predict the worst possible curing situations and test the limits of the ink. Inks ideally should be designed to function optimally in a specific architecture, and, as a result, may not necessarily be useful in others.

It is also important that system engineers are educated to the potential ramifications of various architectures on resolution, system costs and power requirements.

Acknowledgements

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Biography

Richard Baker received his B.S. degree in Chemistry in 1989 from the University of East Anglia, Norwich, England and his Ph.D. is Organic Chemistry from the University of Massachusetts, Amherst, MA in 1994.

Richard is presently working at Spectra, Inc. NH. as the Ink Development Manager.

Prior to Spectra, he worked at Markem Corporation, NH, for three years where he was responsible for formulating industrial jet inks.

Richard holds several US and European Patents in the field of jet ink.