UV Processing of Digital Printing

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Abstract

UV (ultraviolet) curing is the process of photoinitiated conversion of polymeric materials from a liquid to a solid. It has become a popular alternative to conventional drying in a large number of printing and coating applications. The development of new UV-curable inks, and effective use of lamps systems, creates new opportunities to increase cure efficiency, speed, and the physical properties of the cured polymer film.

UV Curing is highly adaptable to printing, coating, decorating and assembling of a great variety of products and materials owing to some of its key attributes; it is:

- **a solventless process**—cure is by polymerization rather than by evaporation, so VOC emissions are eliminated;
- **a low temperature process**—heat is not required;
- **a high speed process**—cure is nearly instantaneous;
- **an energy-efficient process**—energy is invested only in the curing reaction, not in heating;
- **easily controlled**—inks and coatings do not "dry," so do not set up in printing/coating equipment.

UV-curable systems have recently succeeded in a large number of new applications, and replaced conventional solvent-based inks and drying in established processes. The effectiveness of a UV curing system is the practical result of a process design which combines the method of application of ink or coating, the photochemistry of UV-curable inks, and the UV lamp designs into an integrated system. Careful attention to the optical factors and the interaction of inks and lamps can provide a successful UV system with wide operating limits. New developments in digital printing make UV processing an attractive technology for drying.

Introduction

Solvent-based, thermally cured (or dried) inks or coatings are composed of a resinous binder, pigments and fillers, and diluent solvents. After application to the substrate, heat is applied, driving off the solvents and drying the coating film. The evaporated solvents are of special concern as airborne pollutants or hazards. In large printing operations, these solvent emissions can require the use of even more energy or capital investment to be incinerated or "scrubbed" and recovered by distillation.

Solvent-based inks may contain only 30-60 percent solids. When dried, the resulting film is substantially thinner than when it was applied, so will have a different density.

A UV curable system, by contrast, achieves the transition from liquid to solid by means of either chain addition polymerization or an epoxy reaction, triggered by a photochemical interaction. A *photoinitiator* is the active component of the material formulation. The photoinitiator absorbs energy when exposed to ultraviolet light, which starts the reaction. In UV curable material, the resin binder is replaced by a formulation of liquid monomers and oligomers, into which a pigment can be dispersed. The coating is completely reactive and because there is no mass transfer (evaporation) in the reaction, the ink film is essentially the same thickness after curing as it was when laid down wet. These systems are often referred to as "100% solids."

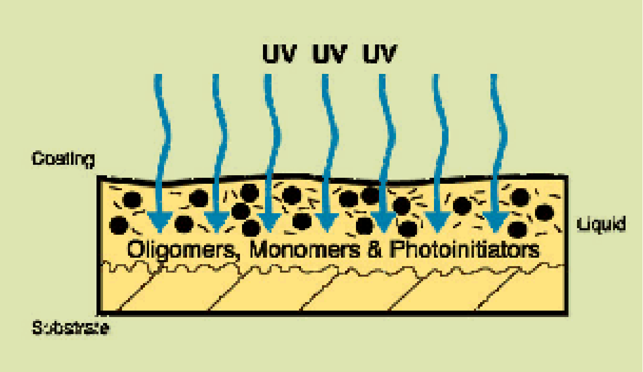

Figure 1. Illustration of the UV Curing Process

The principal ingredients of a UV-curable ink are:

Oligomers

Larger molecules; primarily determine ultimate physical properties.

Monomers

Smaller molecules; affect (wet) viscosity and rate of crosslinking reaction.

Photoinitiators

Respond to UV light and initiate reaction; low concentration (1% - 2%).

Additives

Pigments, surfactants, de-foamers, etc.—these do not enter into the cross-linking reaction.

In addition to the chemistry of the UV-curable ink or coating, an important part of the UV system is the lamp system used to expose the materials to UV light. UV curing begins with a photon-molecule collision. The effectiveness of the curing process is dependent on the ease or difficulty of projecting photons into a curable material to activate photoinitiator molecules.

The optical properties of the ink, such as optical density (opacity) and the optical characteristics of the curing lamp must be “matched” to produce an effective UV curing system.

A variety of photoinitiators is available to the formulators of inks and coatings. Each type of photoinitiator responds to a different but very specific wavelength range of UV light.

In examining the interaction of photons with photoinitiator molecules, we note an interesting and fundamental fact: *Photoinitiator molecules are dispersed uniformly throughout the material—but photons are not.*

Optically Thick Coatings and Inks

Inks and pigmented coatings pose special problems, owing to the fact that <u>opacity</u> or <u>color strength</u> are desirable properties. Distinct from the *physical* thickness of a film, its *optical* thickness is important.

The reduction of light energy as it passes into or through any material is described by the Beer-Lambert law. Energy which is not absorbed in an upper layer of the film and not reflected is transmitted and available to lower layers.

I_o is the incident energy at wavelength la, I is the energy absorbed, A_λ is absorbance at wavelength λ, and d is the depth from the surface or film thickness. This attenuation is illustrated in Figure 2.

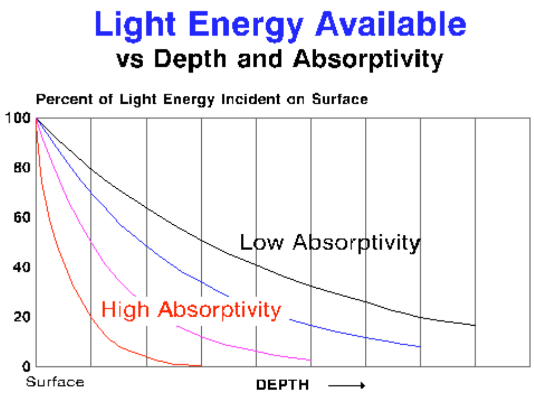

Figure 2. Effect of Absorptivity on Radiant Energy at Depth within Material

Significance of Absorbance

An examination of this equation reveals the relative energy absorbed in the top surface (1% layer) and the extreme bottom (1% layer) of a film, as a function of absorbance. This characteristic is illustrated in Figure 3. There is a great difference in the light energy in these two zones.

Calculations show that the "optimum" absorbance of a film of any thickness is 0.4 to 0.43. In other words, there is a "best" combination of film thickness and absorption. This also illustrates that <u>even at the best conditions</u>, energy absorbed at the top surface is **2 to 3 times** the energy absorbed at the bottom! For a film, such as an ink, with an absorbance of 3.0, this ratio is approximately **1 thousand**!

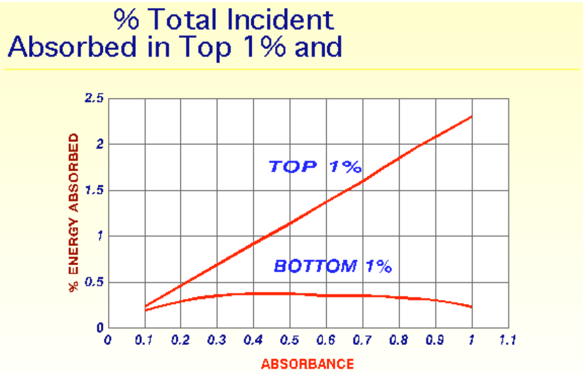

Figure 3. % of Total Energy Absorbed In Top 1% and Bottom 1% “Layers”

Significance of *Spectral* Absorbance

To further complicate the interaction, absorption for any material **varies with wavelength**. Figure 4 shows typical spectral absorption for a photoinitiator, a pigment, and prepolymer. It is readily apparent that short UV wavelengths (200-300 nm) will be absorbed at the surface and not be available at all to lower depths. Typically, film thickness is limited, and adhesion to a substrate is often the first property to suffer. Even the photoinitiator absorbs energy in the wavelengths it is sensitive to, and blocks that same wavelength from deeper photoinitiator molecules. The graph also illustrates that a photoinitiator which may be appropriate for a clear coating of for a thin film, may not be an appropriate selection for an ink. For ink, a photoinitiator with a longer wavelength response would be a better choice.

Significance of Wavelength

Most UV curing involves *two* UV wavelength ranges at work simultaneously (*three*, if we include infra-red). Short wavelengths work on the surface; longer waves work more deeply in the ink or coating. This is principally the result of the fact that short wavelength energy is absorbed at the surface (see Figure 4) and is not available to deeper layers.

Insufficient short-wave exposure may result in a tacky surface; insufficient long wavelength energy may result in adhesion failure. Each formulation and film thickness benefits from an appropriate ratio of short and long wavelength energy.

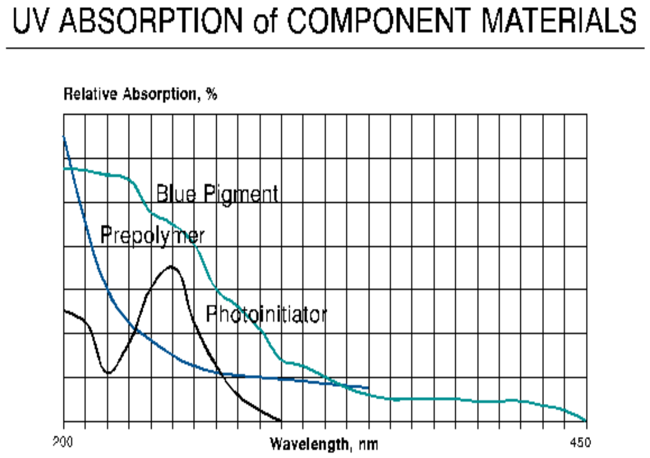

Figure 4. UV Absorption by Component Materials

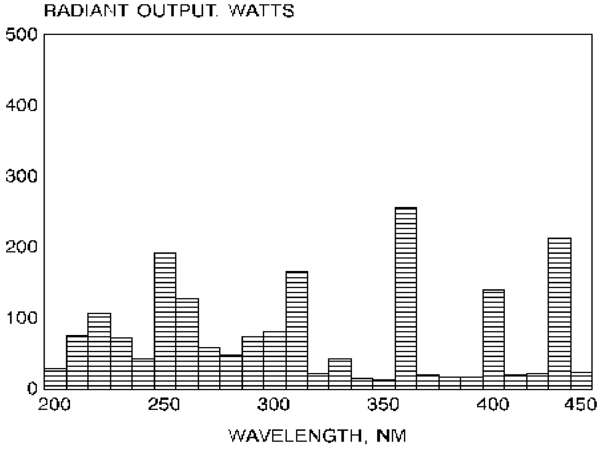

Figure 5. Spectral Distribution of Mercury (H) Bulb

The most basic mercury bulb emits energy in both ranges, but its strong emission in the short wavelengths make it particularly useful for coatings and thin ink layers (see Figure 5). Higher absorptivity materials, such as adhesives and screen inks are often formulated for longer wave cure, using long wave photoinitiators. These materials are cured with bulbs containing additives, along with mercury, that emit UV that is much richer in the long-wave UV (Figure 6). These longer-wave bulbs also emit some short-wavelength energy, which is often sufficient to assist with surface cure.

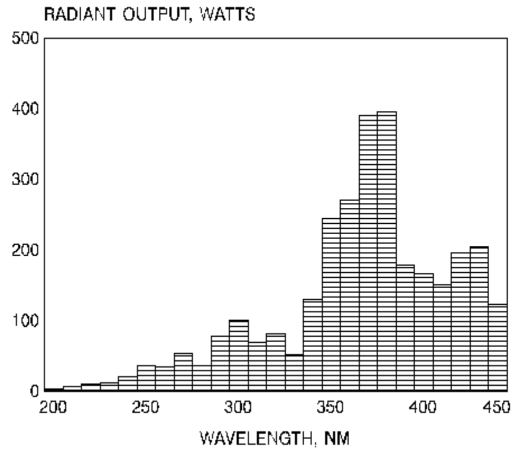

Figure 6. Spectral Distribution of Mercury Bulb with Metal Halide Additive (Type "D")

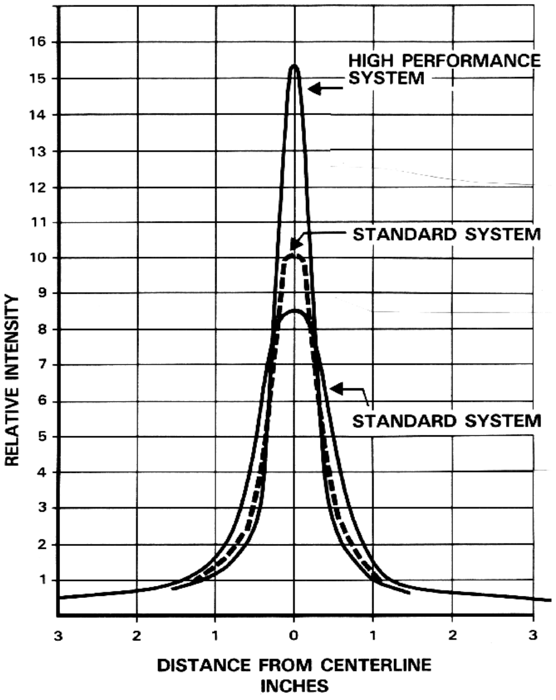

Figure 7. Irradiance at Focus of Typical UV Lamps

Optical Factors Which Characterize the Process

There are a number of factors (outside of the formulation itself) which affect the curing and the consequent performance of the UV curable material. These factors are the optical and physical characteristics of the curing *system*. Among them are the key elements of the UV source:

A. ***UV Irradiance*** is the radiant power, within a stated wavelength range, arriving at a surface per unit area. It is photon flux, and is expressed in Watts or milliWatts per square centimeter. Irradiance varies with lamp output power, efficiency and focus of its reflector system, and distance to the surface. (It is a characteristic of the lamp geometry and power, so does not vary with speed). The intense, peak of focused power directly under a lamp is referred to as *"peak irradiance."* Typical irradiance profiles are illustrated in Figure 7. Irradiance incorporates ***all*** of the individual effects of electrical power, efficiency, radiant output, reflectance, focus, bulb size, and lamp geometry.

When Irradiance is measured in any specific range of wavelengths, it is called *"Effective Irradiance."*

Higher irradiance at the surface will provide correspondingly higher light energy within the ink or coating. Depth of cure is more affected by irradiance than by length (time) of exposure (energy). The effects of irradiance are more important for higher absorbance (more opaque) films and inks.

B. ***Spectral Distribution*** describes the relative radiant energy as a function of wavelength emitted by a bulb or the wavelength distribution of radiant energy arriving at a surface. In order to display the distribution of UV energy, it is convenient to combine spectral energy into 10-nanometer bands to produce a distribution plot (or table). This permits comparison of various bulbs and is more easily applied to spectral power and energy calculations. Lamp manufacturers publish spectral distribution data for their bulbs (see Figures 5 and 6).

C. ***UV Effective Energy*** is the radiant energy, within a stated wavelength range, arriving at a surface per unit area. Sometimes loosely referred to as "dose," it is the total accumulated photon quantity arriving at a surface. "Dose" is inversely proportional to speed under any given light source, and proportional to the number of exposures (for example, rows of lamps). It is the time-integral of irradiance to which a surface is exposed as it travels past a lamp or a sequence of lamps, usually expressed in Joules or milliJoules per square centimeter.

D. ***Infrared Radiance*** is the amount of infrared energy primarily emitted by the quartz envelope of the UV source. This energy is collected and focused with the UV energy on the work surface, depending on the IR reflectivity and efficiency of the reflector. IR can be evaluated in energy or irradiance units, but usually the surface temperature it produces is of prime interest. The heat that it produces may be a benefit or a nuisance.

Benefits of Utilizing UV for Digital Printing

The benefits available to digital printing are many of the same benefits which have been proven in a number of other types of printing systems. The use of UV inks is common in offset, letterpress, flexographic, and ink-jet printing owing to the high effective speed of "drying." It is also effectively used in screen printing, where thick, rich, laydowns of ink provide the opacity and richness to process as well as solid color decoration.

Specific potential benefits to digital printing are:

- No solvents - No VOC's;
- High opacity and coverage because inks are 100% solids;
- Inks do not dry in the printing equipment;
- Inks maintain consistency - do not require adjustment;
- Ink strength remains constant;
- Dot gain is less than with solvent-based inks;
- Higher scratch and chemical resistance.

Conclusion

Most UV curable films are "optically thick," and much more radiant energy is absorbed near the surface of the material, and absorbance varies wildly with wavelength. Spectral absorbance a critical factor in achieving a sufficiently wide process window. UV absorbance affects the depth of cure, and IR absorbance affects the observed temperature.

The effectiveness of a UV curing system is the practical result of a process design which combines the method of application on ink or coating, the photochemistry of UV-curable inks, and the UV lamp designs into an integrated system. Careful attention to the optical factors and the interaction of inks and lamps can provide a successful UV system with wide operating limits.

Optical characteristics of lamp systems and their interaction with the optical properties of curable materials are an integral part of performance. Lamp characteristics, such as spectral distribution, peak irradiance, and controlled infrared energy can be effectively used, along with formulation strategies, to design UV systems with acceptably wide process windows.

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