Image courtesy of Empire Screen Printing.

The Importance of "Dry" vs. "Cure" for UV-Curable Inks

With the long history of solvent and water-based printing, determining when the printed ink is dry comes almost naturally. In these classic printing inks, typically the polymer that is used as the ink binder is already formed and just requires the solvent or water to evaporate off. When the print is no longer wet and cannot be rubbed off, the ink is dried. Working with UV-curable inks moves the printer into a whole different world. It would be very useful to get an understanding as to how UV-curable inks work before we tackle the question as to how to determine when the UV-curable ink is dry.

About UV-Curable Inks

As can be expected from its name, a press using a UV-curable ink print requires the use of UV energy as opposed to evaporating or oxidative (air-dry) curing to form the printed ink. Why is that different than the typical printing inks? Instead of having the binder already formed and suspended in water or solvent as in traditional inks, the starting raw materials for the binder make up the UV-curable ink formulation. When exposed to UV light after transfer on the press to the substrate, a chemical reaction takes place and the binder is formed in a fraction of a second while on the web. I like to think of it as having a miniature chemical factory taking place on the sheet or web after the printed wet ink is exposed to UV light. The differences in the two processes can be seen in Figure 1.

The polymerization process to create the ink binder is extremely rapid with the polymer formed typically under a second. If everything is properly adjusted, this will result in a dry ink almost as soon as the ink can be tested.

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Dry Time and Cure Speed

Unfortunately, in the real world of a press room, the rapid drying does not always happen. There are several variables that can affect dry time or "cure" of a UV ink.

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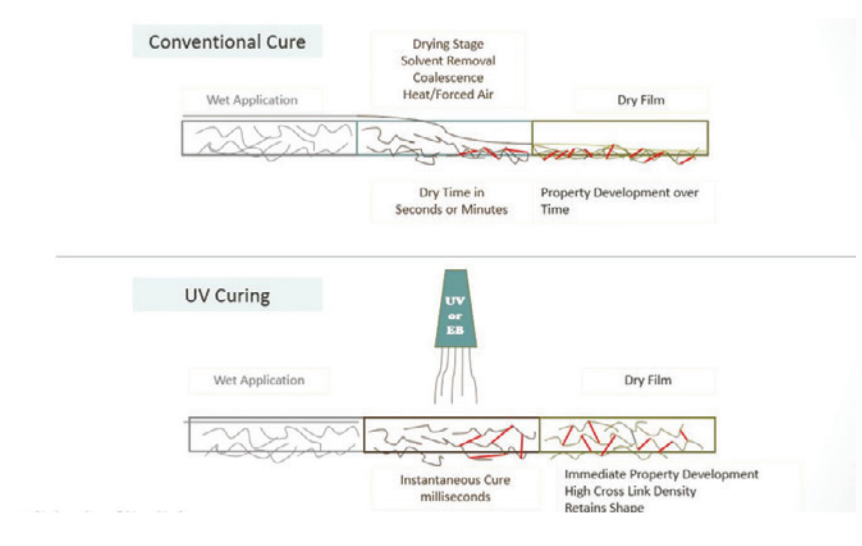
Figure 1: Traditional Thermal vs. UV-Cure Processes



The light source has a lot to do with the dry time, or cure speed, of a printed ink. The light manufacturer will have worked closely with the press manufacturer and formulator to specify the proper light along with its position on the web. The dry time/cure speed is dramatically affected when the intensity of UV light falls below a certain level for the ink. This usually occurs when a lamp starts to age and produces less light than its specifications. The loss of UV light cannot usually be seen visually and should be checked on a regular basis using a UV light meter or puck.

Another factor that can dramatically affect the dry time of a UV-curable ink is the mix of specific components in the ink formulation. With the polymer or binder being formed directly on the printed substrate, the type of components that are in the ink formulation have a dramatic effect on the time it takes for the binder to form. The ink formulator would have taken this into account and tuned the ink to get the desired dry time. Because the dry time/cure speed is dependent on the proper balance of the formulation, the addition of any components to dilute or extend the ink will affect the dry time.

So far, I have been using the terms "dry time" and "cure time" (or speed) interchangeably. However, unlike conventional printing inks, there is a significant technical difference between the two concepts. The term "dry" is easy to understand as we tend to think of something as "dry to the touch." In other words, there will be no liquid material transferred to your finger if you touch the printed ink. The idea of cure becomes important when thinking of UV-curing as reaction that has taken place with a polymer binder having formed. The polymer formed after UV-curing can be dry to the touch, but still not fully reacted or cured. This is because, when a polymer is being formed through UV-cure, the polymer will reach a solid state well before many of the reactive bonds in the components can participate in the chemical reaction.

Here's a more technical discussion on what happens after exposure to UV light. In the following, I will be referring to the use of UV-curable acrylates or methacrylates as the reactive chemical groups or components in the ink formulation. These materials are used in the majority of UV-curable printing inks and as such will be the materials the printer will most likely have on the press.

There are other UV-curable materials, such as cationic or thiol components, which will exhibit a higher level of cure on the press after reaching the dry state, but they are a fraction of the overall UV-curable ink market. The higher the amount of the reactive groups in each component of the formulation, the expectations are that a higher rate of cure will be obtained along with a higher cross-link density.

With more reactive groups present, there is a higher probability that the groups will be close enough to another group to react. However, as bonds are created, the components with more than one group can no longer move through the ink and may not react again at all. This effect will tend to drive the amount of cure in the opposite direction. Thus, the total conversion of reactive bonds in the formulation decreases as the number of reactive groups on each molecule increases.

A Visual Experiment

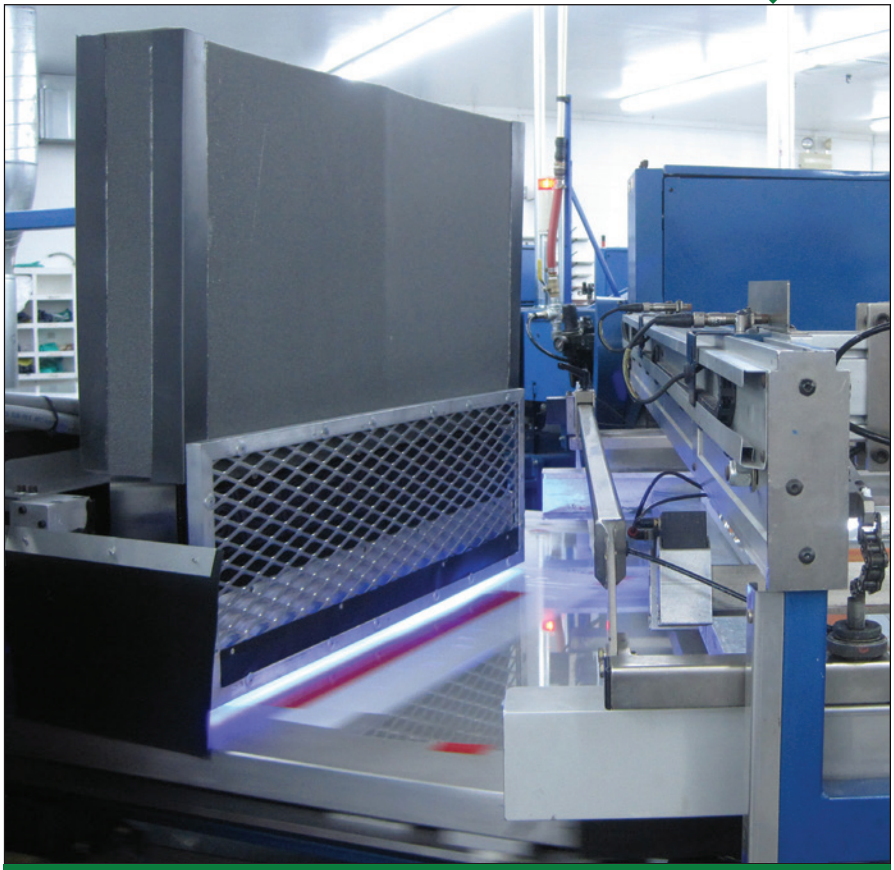
One way to visualize this is to imagine two containers: one holding a component containing only one group on each molecule, and the other holding a component that contains two reactive groups on opposite sides of the molecule. What starts the reaction in a UV-curable ink is the formation of reactive species called free radicals, which occur when an initiator in the formulation reacts when exposed to UV energy.

We begin our experiment by generating an equal number of free radicals to initiate the curing in each container when we apply the UV light. As the free radicals react with the reactive groups in each container, a polymer forms and starts to grow. This is what makes the ink feel dry. If we stop the reaction shortly after initiation, we would expect that a similar number of groups will have reacted in each sample.

Let's continue the experiment by allowing the UV-curing to proceed. In the case of the monofunctional component, the polymer continues to grow past the point that the overall system is highly viscous and on to the glassy or dry state. Each unreacted monofunctional component has enough mobility to move within the polymer cage that is formed and react with a free radical.

In the case of the difunctional component, the polymerization of the component will also proceed through the glassy state to a solid polymer. However, once one of the groups on the difunctional monomer reacts with a free radical on the growing polymer, it no longer has the mobility to move and locate another reactive free radical for the second group in the component. In other words, the difunctional component is now trapped by being anchored to the growing polymer and cannot get close enough to another unreacted component in the formulation to react. This will result in many unreacted groups after the curing process is complete. In the monofunctional component case, there will also be some unreacted starting material, but there is a greater probability that more monofunctional components will have reacted due to their movement within the growing polymer cage.

This is the reason why UV ink formulators will differentiate between a fully dry UV ink and a fully cured UV ink. The term fully dry is exactly what it sounds like, with the ink being dry to the touch after UV exposure. The term fully cured, or percent cure, refers to the number of groups in the ink that have reacted and are now part of the polymer ink binder. Most UV inks will convert from the liquid state to a dry polymer state when somewhere around 50%–60% of the groups have reacted to become part of the ink binder. Depending on how many groups become trapped in the polymer cage, this will likely limit the percent cure to less than 100%. I have seen typical percent cure numbers of 80%–95% after the printed ink was analyzed off press. It is important to note the press operator can print a UV ink that is fully dried and has all the desired properties but is not fully cured based on the amount of unused reactive groups in the final ink.



Phoseon UV LED on a carousel screen press. (Image courtesy of Empire Screen Printing.)

Testing Methods

Now that we have cleared up the confusion between fully dried and fully cured ink, how is this determined on the press? In the lab, the most common method for testing the percent cure is the use of a spectrophotometer called a FTIR. This instrument measures the number of unreacted bonds in the liquid or dried ink. When compared to a reference sample of unreacted ink, the difference or percent cure can be calculated.

When you see a published paper or hear a presentation where the ink formulator gives the percent cure, this method is by far the most likely way this value was determined. However, this is not a practical method for testing for percent cure on a production press as it requires a printed sample to be removed and tested in the lab.

A more practical test that is used in the development of UV inks is the well-known rub test. A coin — or even a finger — is rubbed on the print after it has been exposed to UV on the press. If there is no smearing of the ink, the print sample is considered both dry and, in a practical sense, fully cured. It is always good to adjust the press conditions so the print has been exposed to enough UV energy and the ink is pushed to a higher level of cure than simply at the stage where it has gone from liquid to solid.

Does it matter that a UV-curable ink is not fully cured but is dry to the touch? In many cases this will not be a problem. It should be sufficient to have the ink dry but at a level that is less than 100% cured. Many, if not most, of the desired properties the ink binder brings to the performance of the printer ink will be obtained shortly after the ink is dry to the touch but with unreacted groups in the binder still present.

Where the issue of unreacted groups may be of concern is in printed applications where extractables are a problem, such as certain indirect food packaging and medical applications. The concern is usually not the multifunctional components in the ink but focused on any monofunctional components. As can be seen in the experiment described earlier, unreacted monofunctional components can migrate through the cured polymer and potentially bloom to the surface. This would result in an increase in extractables along with contamination of the item being packaged.

So far, I have been taking the position of a scientist speaking from the lab. This is fine from a theoretical point of view, but how does it translate into the real world? Keith Prichard, CEO, Timsco Graphics, a well-established digital and screen printing company, weighed in on the printer's side of the story.

The Printer Perspective

Timsco understands the importance of knowing when a UV ink is reacted enough to be considered dry. They keep track of the hours on their UV lights and change them when they reach a certain number of operational hours. This is important as there is never a clear indication on when a light no longer good. It can become subjective, therefore risky, to keep the light in use.

Some lights (even from the same manufacturer) last longer than others. As Timsco's belt is run at a predetermined speed using the same brand inks every day, the result is a consistent cure. UV inks requiring more energy to cure, such as black, can run a little slower. For routine testing, a rub-off test is mostly used. However, when there is an adhesion or stickiness issue and the line speed or light hours are not a concern, then a UV light measuring puck is run on the web to measure the usable UV light. If there is still an issue with the ink not fully drying, the ink is changed to see if a bad batch is the cause.

When asked the most typical sign indicating a UV ink is not completely drying, Prichard observed that the odor of unreacted UV ink is usually the first complaint. Second, there will be fingerprinting or smudging of the ink after printing. In rare cases, the printer will see blocking of ink onto another part of the printed web or sheet. However, Prichard added, printers generally see no practical difference between a UV ink being dry and completely cured, although many know there is a technical difference.

Finally, I asked if he had any advice for someone using UV inks other than what we discussed. Prichard suggested checking the light and the reflector occasionally since these can get dirty from routine use or the occasional mishap. Be careful of black and other non-transparent dark colors as they could have a slower cure. Use a fine mesh for minimum thickness of ink laydown with the preference of 305 or higher. Timsco prefers a 355 mesh.

In addition to Prichard's advice, be aware UV inks do not adhere well to conventional inks, but conventional inks do usually adhere to UV inks. This is important, as while it may seem to be a lack of cure of the UV ink in the first case, this is a simple adhesion problem.

Dr. Mike J. Idacavage's work in UV-curing started at Eastman Kodak with the establishment of a UV-curing lab in 1985, and he has continued in the energy curing industry since. Mike has served as President of RadTech North America for the 2009–2010 term. Currently, he is the Vice President of Business Development for Colorado Photopolymer Solutions. In his current role, Mike serves as a technical advisor on a wide range of UV projects with a focus on 3D printing. Mike is also an Adjunct Associate Professor at SUNY-ESF in Syracuse, New York, teaching courses in UV- and EB-curing technology and UV-curable 3D printing.