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Economic Value of UV/EB

Photocuring Equipment Challenges: Medical Device Manufacturers' Point of View

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While photocuring has applications in various areas (adhesives, printing, coatings and polymerization of molded parts) and has evolved into many industries, the medical devices industry has its own unique set of challenges with these applications.

The design, development and manufacture of medical devices differs significantly from many other consumer and industrial products because of both compliance and regulatory requirements. That's why it's important to look at the high-level development flow of photocuring-based medical devices (from R&D through production), identify photocuring parameters and learn the equipment challenges throughout the workflow.

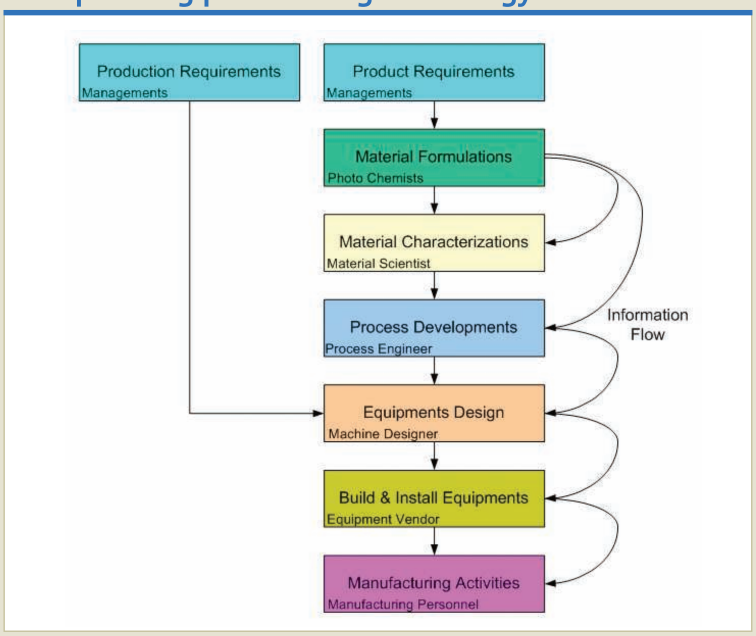
Photocuring equipment provides optical radiation at the appropriate UV or visible wavelengths. While systems vary, they usually contain the following components:

- **Light engine:** It may be in the form of fluorescent bulbs, mercury arc lamps or light emitting diodes (LED) operating in the UV or visible range.
- **Power supply:** Provides proper electrical power to the light engine.
- **Optics & reflectors:** Shapes and focuses the light for specific applications.
- **Radiometer:** Either built-in or external unit which measures and monitors the light output and may provide feedback control to maintain a constant light output.
- **Thermal management:** Cools the light engine for proper and safe operation.
- **User interface and software control:** Provides a means in which the user may interact with the photocuring system either directly and/or via software.

Medical device manufacturers are faced with ever challenging R&D and manufacturing activities while focusing on product performance, quality, cost and time to market. They also have to adhere to compliance and

Figure 1

A simplified workflow for medical device manufacturer incorporating photocuring technology



regulatory affairs. There are a number of medical device applications in which photocuring is incorporated as a part of their manufacturing process. For example, these applications may be as simple as applying a photo-cured adhesive to form a medical device or may be as complex as a photo-polymerization process to create a medical device.

Medical device manufacturers may be organized and operate differently from each other. However, they usually share similar high-level workflows to develop and manufacture their products. Figure 1 shows a simplified workflow that is impacted by photocuring activities spanning research through development and on to manufacturing. It is interesting to note that the technical personnel involved in this workflow have different job functions and come from different disciplines. For example, photochemists and material scientists are mainly interested in researching, exploring and characterizing new photocured formulations, whereas manufacturing personnel are responsible for maintaining the photocuring equipments in a production facility.

Therefore, it is important for R&D and manufacturing personnel to understand the photocuring parameters and to communicate those parameters from the early stages of development through to production. Failure to do so may result in suboptimal product quality and/or possibly prolonging the development cycle. For a high-volume medical device manufacturer, a few months of product launch delay could translate into millions of dollars in lost revenue and lost market share. These photocuring parameters include but are not limited to:

- Wavelength (measured in nm)
- Irradiance (measured in W/cm^2)
- Area (measured in cm^2 or diameter for spot cure)
- Uniformity (measured in %)
- Exposure cycle and time profile (measured in seconds)
- Dose which is Irradiance * exposure time (measured in J/cm^2)

Photocuring Equipment Concerns: During Research

Material research activities usually begin with material formulations. During this step, material scientists and photochemists are faced with ever increasing challenges of researching and formulating new materials. They usually depend on various techniques such as thermal analysis, rheology and spectroscopic techniques. There are a number of analytical instruments marketed toward these widely practiced techniques such as Differential Scanning Calorimeter (DSC), Rheometers, Dynamic Mechanical Analyzers (DMAs) and Fourier Transform Infrared Spectrometers (FTIR).

The photocuring methods also add additional challenges associated with light generation and measurements with respect to their cure research and material formulations. Historically, most of these analytical instruments were mainly intended for thermal curing and do not usually provide an adequate support for photocure research. Specifically, these instruments lack accurate and precise light generation (wavelength, irradiance and duration) and measurements. Therefore, the scientists are usually forced to create their own light source and/or at times deal with non-adequate supplied light by these instruments.

In general, these instruments should have the following photocuring attributes:

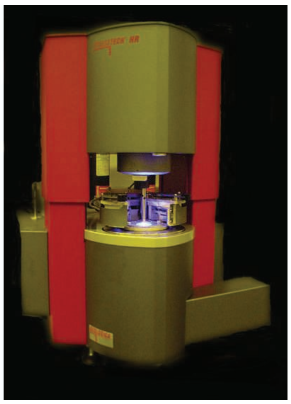
- **Spectrum:** The user should be able to easily control the light spectrum. This may be determined by the peak amplitude and spectral width of the optical energy source.
- **Alignment:** The light should be properly coupled to the sample area in the analytical instrument.
- **Irradiance:** The user should be able to control the irradiance at the sample area via a convenient way such as software.
- **Cycle time:** The user should be able to control the exposure cycle time via a convenient way such as software.
- **Synchronizations:** The photocuring operations should be synchronized with the analytical instrument operations.

Traditionally, mercury arc lamps have been used as a photocuring source for these analytical instruments. This type of lamp usually requires additional work to be performed by the scientists. For example, the scientists may have to filter out the light output to provide the correct light spectrum. This requires not only using optical components but also requires additional test equipment (such as a spectrometer) to verify the spectrum and to measure the peak wavelengths and full-width-at-half-max (FWHM).

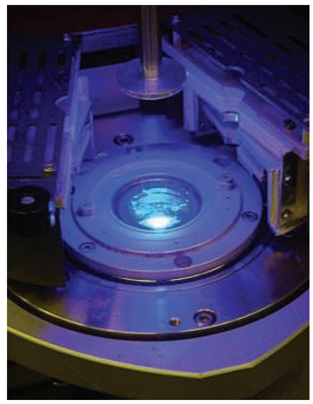
Another important parameter is the incident irradiance. It is crucial to control the light irradiance precisely and accurately at the sample area. Furthermore, it is important to measure the incident light irradiance at the sample area to ensure proper light alignment and irradiance. Test equipment (such as radiometers or spectroradiometer) are usually needed to measure the irradiance at the sample area. Additional care must be taken to make sure that the radiometers not only have proper spectral response, but are also calibrated at the correct wavelength. Furthermore, the placement of the radiometer detector

Figure 2

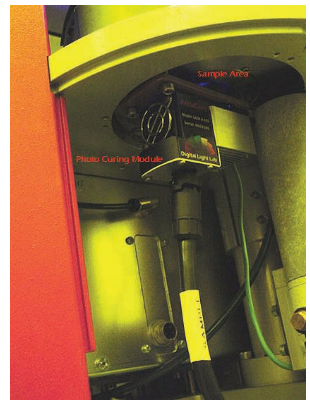
A. Photo rheometer system



B. Photocuring of sample area



C. LED-based photocuring accessory



in the sample area may be difficult due to accessibility and size limitations. These issues could hamper adequate and speedy material formulation and characterization as the material scientists or photochemists are challenged with light-related issues.

Advancements in LED technologies have resulted in innovative photocuring equipment for these analytical instruments in which accurate lighting conditions (i.e., wavelengths, intensities and exposure cycle) can be created. For example, Figure 2 shows a photocuring accessory manufactured by Digital Light Lab for a REOLOGICA Instruments Rheometer. This innovative patent-pending photo-curing equipment can easily be added to commercially off-the-shelf DSCs, Rheometers, DMAs and FTIRs. They deliver UV and/or visible light with precisely tuned wavelengths and intensities to the material under investigation, empowering the scientists to repeatedly evaluate, fine-tune and troubleshoot their new materials research. These photocuring accessories allow the scientist to easily set the irradiance, duration and wavelength of interest, while exploring the solution space. Therefore, they can focus more on the material research and less on the light generation and measurements.

Photocuring Equipment Concerns: During Development

Once the material formulation has been completed, a photocuring process needs to be developed, characterized and validated. The importance of the process development lies within manufacturing and quality as required for a Good Manufacturing Practice. A Good Manufacturing Practice or GMP (also referred to as “cGMP” or “current Good Manufacturing Practice”) is a term that is recognized worldwide for the control and management of manufacturing and quality control testing of medical devices. Ideally, every manufactured medical device needs to be tested prior to shipping. This may be economically or technically impossible. Alternatively, products may be released as soon as it has been confirmed that the routine production cycle has fallen within the parameters established during validation. This is referred to as a “parametric release” which gives the assurance that the medical device is of the intended quality based on information collected during the manufacturing process and is in compliance with specific GMP requirements related to parametric release.

Process engineers usually collaborate with the material scientists and/or photochemists to develop and quantify the photocuring process and its associated parameters. The process parameters may be defined in terms of spectral characteristic of the photocuring source, required irradiance, uniformity and exposure cycles (please note material-related matters are not the focus of this article). The process development should establish the operating windows and sensitivity analysis for these parameters. For example, it should identify how sensitive the impact of irradiance variations is on the material performance.

For large medical device companies, it is not uncommon for these efforts to be spread among multiple departments in multiple locations and/or outsourced to outside companies. It is also not unusual for miscommunication between scientists and process engineers due to a lack of understanding of light generation and measurement techniques and equipment. For example, scientists may use a broadband light source with optical filters to photocure the material during the formulation phase. They usually have to characterize the light source in terms of peak wavelength, full width at half max spectrum (FWHM), uniformity, cycle time and irradiance. Such characterization usually requires an accurate understanding of the light source spectra, filter spectra, radiometer spectra and radiometer calibration method. While these are simple engineering measurements, scientists are usually not formally trained or may not have the right equipment to perform these measurements. Therefore, they may not characterize and communicate these photocuring parameters to the process engineers correctly. For example, scientists may use a general-purpose radiometer with broadband spectral response, which may be calibrated at wavelength λ_1 whereas the photo initiator may be sensitive to wavelength λ_2. Therefore, the radiometric measurements are not true photocure process parameters. This problem may even get more complicated as the process engineer uses a different radiometer with different spectral response and calibration to establish and validate the photocure process.

Digital Light Lab has developed a family of photocuring systems based on its AccuCure technology. These systems provide an accurate, precise light generation, delivery and measurement to the material being tested. The process engineers can easily configure these systems to prototype, characterize and validate their photocure process. For example, these systems can be configured for different spatial topology and can be programmed for specific irradiance and duration at user-defined wavelengths via software. These systems also incorporate internal radiometers that constantly measure and correct the light outputs to minimize any drift. These systems are inherently compatible with the photocure accessories that are used during the material formulation and research. This empowers the researchers to easily communicate their photocure process parameters to the process engineers and, thus, reduce any delays due to miscommunication and mismeasurements. For example, Figure 3 shows a system that contains eight channels of spot curing in which each channel may be configured for different wavelengths, intensities

Figure 3

An 8-Channel LED-based photocuring system with individual control for process development

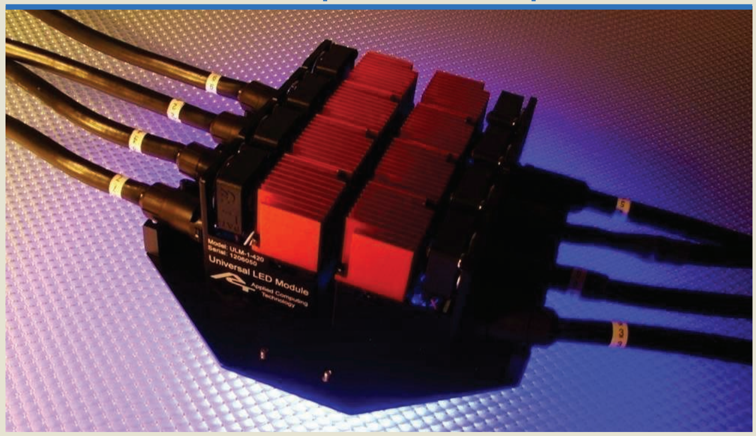


Figure 4

A 16-channel LED-based photocuring system for production environment

and exposure cycle times. This type of system enables speedy exploration and validation of the photocuring parameters.

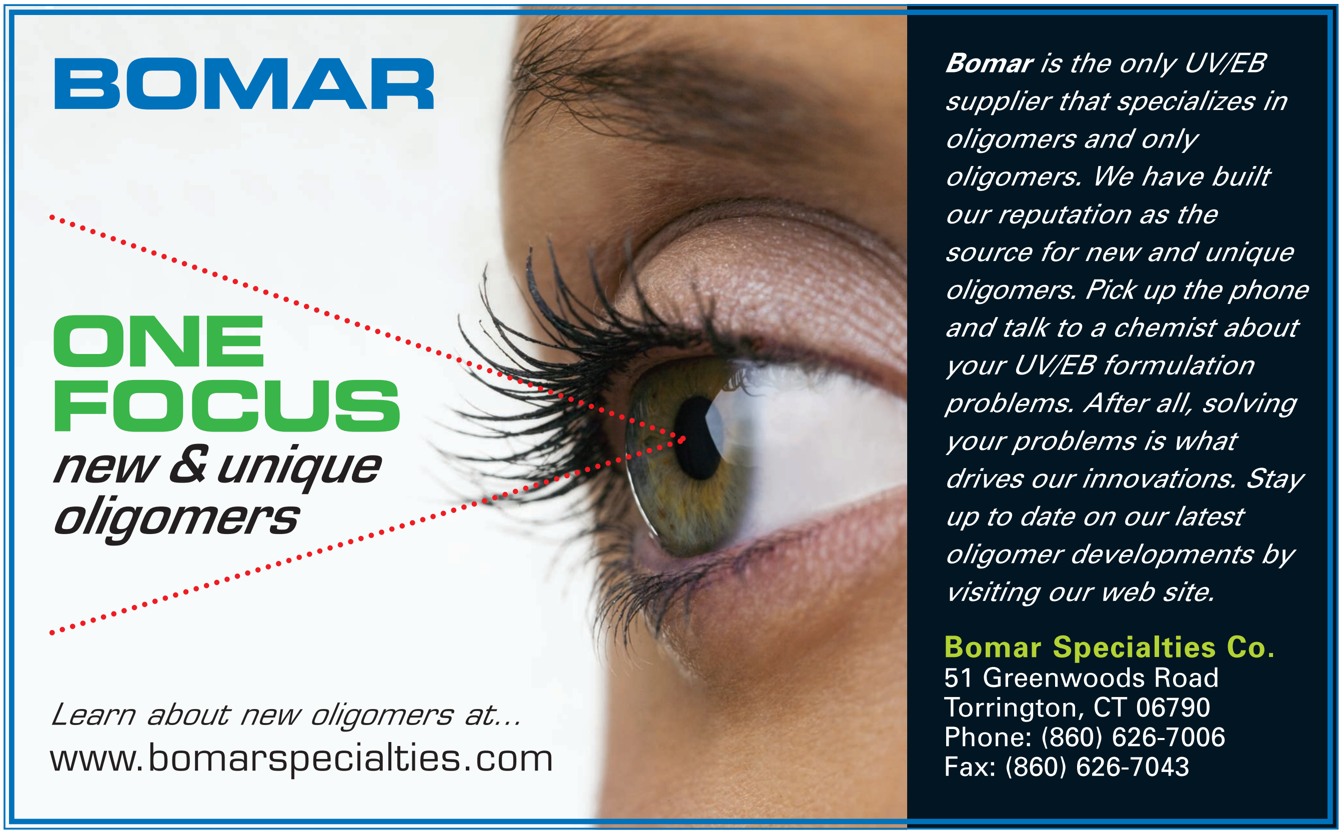
Photocuring Equipment Concerns: During Production

Once the photocuring process is developed, the production equipment needs to be designed. The photocuring production equipment is usually designed based on the developed process and other manufacturing requirements. Once again, the machine and equipment designers have to work with the process engineers (or possibly the material scientist) to make sure that production equipment is designed, built, installed and operates properly. Ideally, the machine designers would like to use the same photocuring equipment that is used by the scientists and the process engineers. However, other manufacturing requirements could impact the photocuring production equipment. Some of these requirements may include, but are not limited to, the following:

- **Control:** Automated manufacturing facilities usually incorporate Programmable Logic Controllers (PLCs) to control various processes in a production facility. The photocuring equipment should be capable of being controlled by an external device such as a PLC or PC.
- **Monitoring:** Due to parametric release (as mentioned earlier), it is important to monitor the photocuring parameters during the production cycle. For example, let's assume that a photocuring process calls for process parameters of 100 mW/cm_2 minimum irradiance at 365-nm to 375-nm for 60 to 80 seconds. If the light source has any long-term drift, then the light irradiance needs to be monitored for proper operations. If the light irradiance falls short of 100 mW/cm_2, then an error condition should be communicated to the operator and/or to the PLC. If the light source exhibits short-term drifts, then photocuring equipment needs to contain a feedback control to monitor and automatically adjust and compensate for the drift.
- **Production throughput:** There are usually other production processes before or after the photocuring process. It is important for these various processes to work seamlessly together to maintain throughput in a volume production facility. Let's review the previous example. If the cycle time of other processes is 30 seconds, then the photo-curing equipment should have two identical curing zones to maintain the minimum 60 seconds cure cycle and should provide proper queuing of incoming and outgoing products in and out of cure zones.
- **Reliability:** Up-time of the photocuring equipment is another important attribute of production equipments. The photocuring equipment should have low failure rates as it may impact the production throughput, especially in a high-volume production facility. In situations in which power cycle may often occur, the photocuring equipment should also have short warm-up and power-down cycle times.
- **Maintenance:** Medical device production facilities are usually subject to maintenance activities. These activities may be in the form of preventive maintenance that can be scheduled on a regular basis. Other maintenance activities usually involve equipment failure.

  Some of the more traditional photocuring equipment usually uses mercury arc lamps that typically have a rated lifetime of about 2,000 hours. In demanding photocuring applications, it is not unusual for these lamps to be replaced much sooner than 2,000 hours due to their aging and reduced output. Another maintenance item is the annual calibration of any radiometer units used in the production. This also includes some controller units that may contain internal radiometers to monitor and regulate the light output. These radiometers should usually be calibrated with NIST (National Institute of Standard and Technology) traceability.
- **Equipment cost:** Last but not least is the cost of ownership and operation of the photocuring equipment. While the upfront equipment cost is important, the operational and maintenance costs should also be considered. Additionally, the photocuring systems should scale up or down economically. For example, large volume manufacturers may have to cure a large number of products simultaneously to meet the production throughput. This requires systems with either large-area cure zones or large numbers of cure spots. This type of system should be economically scalable.

Figure 4 shows an example of a photocuring system for a high-volume production line which is inherently compatible with the systems used during R&D as described earlier. It is based on high-intensity UV or visible LED technologies providing extreme flexibility for on-demand custom intensities at different points within a production line. They are fully functional turnkey



photocuring systems, including the LED light engines, light shaping optics, controller, optional monitor, control software and power supply. These types of systems can be cascaded to provide longer or wider photocure areas. The light shaping optics allows circular, rectangular or elliptical light patterns. The intensities of the LEDs are easily controlled by the controller and/or via software. The intensities can be adjusted at each segment of the line resulting in extreme control of the irradiance pattern. Furthermore, the intensities may be either static or dynamic. In static mode, the pre-configured intensities remain the same throughout the operation. In dynamic mode, the intensities may vary based on a time profile. The controller contains optional active monitoring capabilities where the irradiance may be monitored at multiple locations during the cure process. This monitoring feedback ensures the cure dosage for the most demanding cure processes.

Conclusion

Photocuring technology has been and will continue to evolve in the field of medical devices. The main challenges associated with the incorporation of photocuring in the medical device field is the complexity of the lighting systems and light measurements devices as carried out among multiple groups of people with different disciplines. Lack of knowledge in lighting generation and quantification can slow down the effectiveness and wider adaptation of photocuring technology as a whole. Photocuring equipment vendors can play a major role by offering an integrated set of lighting systems addressing the needs from R&D to production floor. These systems should be accurate, controllable, scalable, easy-to-use and priced properly for higher adaptations by medical device manufacturers.

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