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White Paper

Reduction of Substrate Thermal Damage Using UV LED Pulsing

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Executive Summary

UV LED curing systems are becoming widely used tools in the manufacture of subassemblies for electronic, medical and consumer devices. These systems deliver continuous doses of narrow bandwidth, high intensity UV light for rapid spot or area curing of optically-activated materials.

Unlike traditional mercury arc lamp systems, LED curing systems do not deliver unwanted IR or visible light which can result in heat damage at the cure site. Yet some medical, storage media and electronics subassemblies use UV-absorbing substrates that may experience heating damage even with narrowband UV LED curing systems. This white paper demonstrates a method to reduce heat damage in UV-absorbing substrates by driving UV LED systems to deliver short, high-intensity pulses of light. Heat at the cure site dissipates between pulses, reducing heat damage and enabling higher manufacturing yields. Since more UV energy can be delivered with each pulse, this technique also results in curing times 60% faster than continuous operation, which allows production throughput to be increased accordingly.

Overview

High-power UV LED curing systems are enjoying more widespread use in the assembly of electronic, medical and consumer devices. These systems deliver continuous doses of narrow bandwidth, high intensity UV light for rapid spot or area curing of optically-activated materials. Unlike mercury arc lamp systems, UV LED curing systems deliver no IR light, reducing heat damage at the cure site especially when cure substrates are transparent to UV light. With less intrinsic heating effects compared to arc lamps, UV LED systems can operate at higher UV intensities to enable faster curing times and increased process throughput.

EXAMPLE: Hydrogel application produced with high UV dose levels and utilizing PWM methods to maintain low temperature levels.

Some subassemblies for storage media, electronic and medical applications use substrates that absorb UV light and transform it into heat. A number of medical devices incorporate thin-walled tubing and plastics made of polyamide, polycarbonate, PVC, PET, or polyethylene. Hydrogels for ECG and defibrillator electrodes, tissue scaffold implants, and contact lenses are also sensitive to UV-induced heating and can experience shrinkage, stress, discoloration and microcracks which can lead to lower yields or early device failure. Substrate heating may also increase curing times because certain UV adhesives grow discolored or less transmissive at higher temperatures. Lower yields, higher scrap and longer cure times all result in higher manufacturing costs. To reduce damage, the UV intensity can be decreased during curing, but this results in longer curing times and decreased production throughput.

Pulsed Operation of LEDs in UV Curing Systems

A promising approach to minimizing substrate damage involves on-off pulsing of the UV LED source. Pulsing allows delivery of UV light to the cure site during each "on" phase of a pulse, while the "off" phase allows sufficient time for the substrate to dissipate heat.

While UV LED curing systems usually provide continuous wave (CW) radiation, many UV LED curing systems such as the OmniCure® AC Series allow for both continuous wave (CW) and precisely-controlled pulsed operation because they have a PLC input that enables control of the LED power with an external modulation source such as a function generator. The modulation bandwidth of the LED controller electronics is usually tens of kilohertz, which is sufficient to enable pulse widths of a few milliseconds. This is short enough to reduce substrate heating in many applications.

The duty cycle (the ratio of the pulse width to period between pulses) is a key parameter when tailoring pulses for UV curing. If the pulse width is 10 ms and the period of the pulses is 20 ms, for example, the duty cycle is 50%. A stream of UV pulses with a 50% duty cycle delivers half of the UV photons over a fixed period of time assuming the peak intensity of each pulse is the same as in continuous operation. This directly results in increased curing times compared to continuous UV exposure.

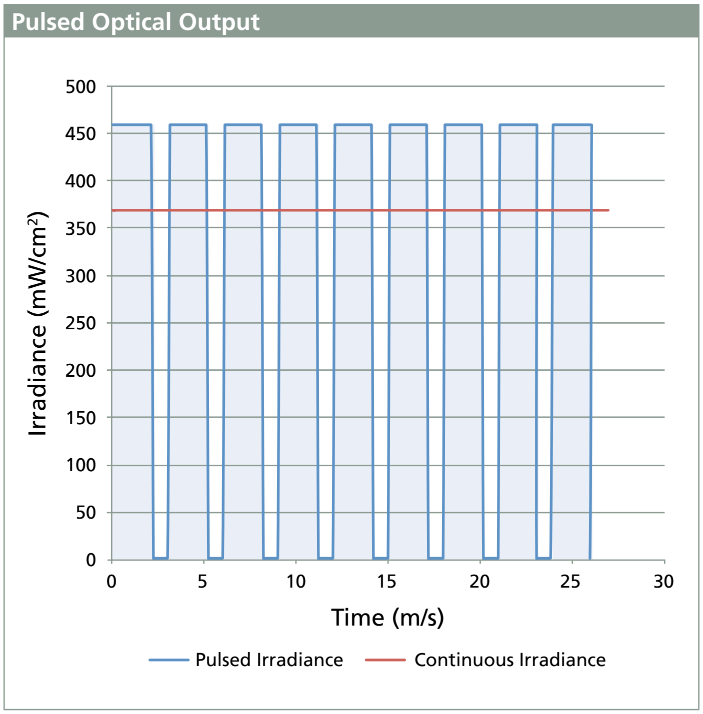

FIGURE 1: Pulsed vs. continuous wave (CW) operation of UV light sources allow a period between pulses during which heat at the curing site can dissipate, resulting in lower temperature curing.

The reduction in UV dosage with pulsed UV light can be compensated by increasing the output power of the LEDs during each pulse. UV LED controllers such as the OmniCure PLC2000 used with the AC Series UV LED systems make it straightforward to increase the energy of UV pulses to reduce curing time. Figure 1, for example, shows the same UV dose delivered with continuous UV light and a pulsed configuration. A 25 second stream of 21 ms pulses with an 85% duty cycle at 460 mW/cm² peak irradiance delivers a total dose of 10 J/cm², as does 27 s of continuous UV exposure at 370 mW/cm². Increasing the energy in each pulse may also enable each to penetrate deeper into the curing site, which accelerates the cure and partially compensates for short pulse widths. The exact settings for a particular manufacturing process must be determined experimentally to understand the interplay of pulse width, duty cycle, UV power and cure time.

Table 1(A) and Table 1(B) show the results of testing a 365 nm UV LED curing system in CW and pulsed mode with a UV-absorbing substrate. In CW mode (see Table 1(A)), curing was attempted with an exposure time of 27 s with irradiance levels of 220 mW/cm² to 590 mW/cm². Substrate heating damage occurred at irradiance levels above 220 mW/cm², corresponding to a dose of 6 J/cm² and a curing site temperature of 41°C. But a sufficient cure was not achieved until irradiance reached 520 mW/cm², corresponding to a total UV dose of 14 J/cm² and a temperature at the cure site of 65°C. This is far above the observed damage threshold. These measurements suggest irradiance must remain at 220 mW/cm² or less to avoid heating damage, while the exposure time must increase by at least 133% to at least 63 s to achieve a total UV dose of 14 J/cm² to achieve a successful cure for production. This is a typical trade-off in designing curing processes: UV irradiance is decreased to a level that avoids heat damage, but curing time must be increased to ensure a full cure.

With pulsed UV LED curing, the results are strikingly different (see Table 1(B)). Using pulsed UV light with duty cycles of 80% and 85% and a repetition rate of 25 Hz, a cure is achieved in just 25 s at an irradiance of 440 mW/cm², which corresponds to a dose of 10.2 J/cm². This is a 60% reduction in cure time compared to the extrapolated cure time with CW operation. At this UV dose, the temperature of the cure site reached 40°C compared to a damaging 56°C at a similar UV dose with continuous operation. The lower temperature in pulsed operation is a result of the brief pause between pulses which allow heat to dissipate at the cure site. In direct contrast to CW operation, substrate damage was not observed at irradiance levels of 380 mW/cm² to 520 mW/cm² using duty cycles of 80% to 85%.

The results in the demonstration of pulsed UV LED curing systems show a dual benefit. Irradiance can be kept high to allow for faster curing times, while pulses allow for heat dissipation which reduces or eliminates damage during the cure.

Data for continuous wave (CW) operation

Irradiance mW/cm²	Time (s)	Dose J/cm²	Temp. °C	Sufficient Cure	Substrate Damage
590	27	16	70	YES	YES
520	27	14	65	YES	YES
450	27	12	60	YES*	YES
370	27	10	56	NO	YES
300	27	8	50	NO	YES
220	27	6	41	NO	NO

* Achieved minimum acceptable level. May not be suitable for production requirements.

TABLE 1(A): Results of curing with CW UV light shows heat damage occurs at irradiance levels that are insufficient for curing. The cure achieved at an irradiance of 450 mW/cm² was marginal.

Data for pulsed (PWM) operation

Duty Cycle %	Irradiance mW/cm²	Time (s)	Dose J/cm²	Temp. °C	Sufficient Cure	Substrate Damage
80	380	27	8.3	38	NO	NO
80	440	28	10	40	NO	NO
85	440	27	10.2	40	YES	NO
85	460	25	10.0	42	YES	NO
80	390	37	11.4	45	YES	NO
85	520	27	12.1	49	YES	NO

TABLE 1(B): Results of curing with pulsed UV light shows heating at the cure site is reduced, damage is avoided, and cure times are reduced compared to CW operation.

Benefits of Curing with Pulsed UV LED Systems

Driving UV LED curing systems in pulsed mode reduces heating and damage of UV-absorbing substrates while reducing overall exposure times compared to continuous operation. For LED pulse-widths of tens of milliseconds or less, light is delivered to the cure site without causing damaging heat build-up in the substrate, and each pulse can contain more energy than continuous operation. The example in this white paper shows reduced heating at the cure site, reduced damage to the cure, and reduced cure times of more than 60%. The benefits of this approach include:

- Improved yield and reduced scrap costs through reduction of substrate damage via heating.
- Increased production throughput because of faster cure times.
- Increased UV penetration of opaque material such as colored tubing in medical devices using high-intensity pulses.
- Increased depth of cure for adhesives and hydrogels because higher-energy UV pulses can penetrate deeper into cured surface material.
- Reduced heat-induced shrinkage of cured material and induced stress at the bond point, which may reduce early failure of devices.
- Longer LED lifetime because of overall reduced on-time for the UV LEDs.

Pulsed curing with UV LEDs can be implemented in manufacturing lines using commercially-available systems such as the OmniCure AC Series UV LED systems used with the PLC2000 controller, and a low-cost off-the shelf function generator.

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