Modeling and Design of Materials Inkjet Printer LED Ultraviolet Curing Cartridges Using COMSOL Multiphysics® for Printed Electronics Applications

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Abstract: COMSOL Multiphysics coupled with Solidworks is used to design, simulate and fabricate cartridges for a materials printer to accomplish in-situ curing of UV curable ink patterns as they are printed on flexible media for printed electronic circuit manufacturing. The cartridges designed house a ultra-violet high-power light-emitting diode (LED) to expose and cure the ink as it is being printed. COMSOL Multiphysics was used to model the temperature profile of the cartridge under different cooling mechanisms, passive convection or forced air, to create a design which would allow excess heat to be dissipated from the LED with minimal rise in its temperature, the most critical design parameter determining the ultimate longevity of the LED as well as its efficient operation as a UV emitter. Quick coupling of the 3D CAD output with the heat transfer simulations of COMSOL facilitated choices to be made in geometry as well as the cooling method, whether a finned heat sink passive convection cooling or a forced air system with a fan, depending on the operating power level of the LED required. From the finalized 3D CAD model, a precise replica could be produced in plastic using a 3D printer, or in metal using a digitally-controlled precision CNC machine. Because inks cure with a band of wavelengths, several cartridges were machined to house LEDs of different wavelengths (365nm, 395nm, etc.) to aid in the determination of the optimal wavelength for the given material. In-situ tests were conducted resulting in the successful UV curing of the ink on paper.

Keywords: Inkjet cartridge design, UV curing, COMSOL multiphysics, heat transfer module, 3D printing.

1. Introduction

Materials ink jet printers are used to print various functional materials to make 3-dimensional mechanical objects and to print 2-dimensional circuits and electronic devices for printed electronics. Materials are ink jetted as liquid drops either (a) in the form of dispersions which must be heat treated to evaporate the carrier liquid or (b) in the form of a curable polymer ink which must be exposed to ultraviolet radiation at specific wavelengths and intensities after being printed. For the latter, ultraviolet light with wavelengths between 365nm and 405nm are needed, and an exposure dose of greater than 200mJ/cm^2 may be required.

In printing electronic circuits, many different layers, each with different electrical properties, must be printed. Critical to the process is ensuring not only that each layer is formed as a continuous pattern in high resolution from the jetted liquid ink droplets, but also that the next layer printed is in precise alignment with respect to the previously ink jetted layer and that it forms a film dried, cured, stabilized, and ready to receive the incoming droplets of the next material layer without being affected by it. Obviously, taking the substrate out of the printer for the curing or drying of previously printed layers would affect alignment when the substrate was placed back in the printer. This realignment problem would increase dramatically as the number of layers being printed increased. Therefore, a mechanism must be created to facilitate in-situ, and preferably instant, curing of the printed droplets during the printing process.

Such an in-situ, instant curing of the printed droplets can be achieved by using an inkjet replacement cartridge which fits into the printer head assembly, aligns with the other ink cartridges of the printer, and houses a UV LED powerful enough to provide the necessary exposure in one pass over the ink jetted drops. The work being reported here is an effort to design such a cartridge.

The primary challenge in this design has been the removal of the heat generated by the high-powered UV LED so that the LED's maximum safe operating temperature limit is not exceeded. Associated with heat removal is the constraint that the shape and size of the cartridge housing the power LED cannot be changed since it must fit into the printer head assembly tightly for consistent alignment with the other print cartridges. Figure 1 shows the inkjet cartridge (a Samsung "SEMJET Mini") used in our materials printer (UniJet, Co.'s [1] OmniJet 100 Deluxe model). Seen at the bottom center of the cartridge as a bright green square is a 16-nozzle Silicon MEMS chip used for ink jetting. A 3D CAD model of this cartridge was created in SolidWorks. [2] From this model, a precise replica could be produced in plastic using a 3D printer, or in metal using a digitally-controlled precision CNC machine. Figure 2 shows the 3D model, which includes a 5W-rated UV LED diode in a Mini Round MCPCB package [3] embedded in a circular cavity, replacing the MEMS chip. This model could easily be imported into COMSOL [4] for multiphysics analysis and digital prototyping.

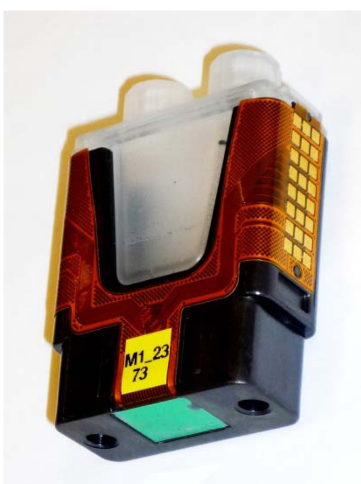

Figure 1. Materials Printer Inkjet Cartridge

The 3-D printed version of the prototype replacement cartridge, however, proved to be unsuitable because of the very poor thermal conductivity (about 0.2 W/ºKm) of the 3D printer materials available. Therefore, the design and simulation work presented here was done using an aluminum alloy with a thermal conductivity of 200 W/ºKm, approximately three orders of magnitude higher than that of the 3D printed material. The aluminum alloy material is also suitable for casting, enabling production of the UV LED cartridge in large quantities.

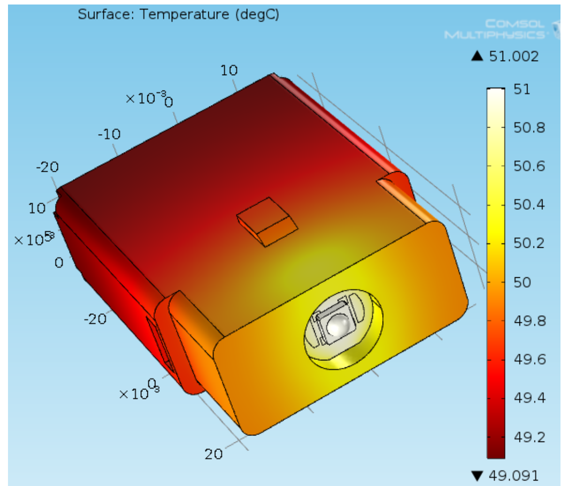

Figure 2. 3D CAD model of UV LED mounted cartridge

2. Heat Transfer Analysis

The most serious problem associated with the use of high powered LEDs is the heat dissipation. The LEDs' longevity and efficiency are reduced by an increase in temperature. [6] The three mechanisms of heat transfer are conduction, convection, and radiation; of which conduction and convection are the most critical.

2.1 Conduction Heat Transfer Theory

In a material with a simple geometry and with a thermal conductivity of k, the heat transferred via conduction in steady state is given by,

$$Q = -kA\frac{\Delta T}{\Delta L} \qquad \text{Eq (1)}$$

where A is the cross sectional area, $\frac{\Delta T}{\Delta L}$ is the temperature gradient. This is known as Fourier's law of heat conduction. This equation can be used to estimate the temperature difference between the heat source and the end of the cartridge, ultimately determining whether or not the thermal conductivity of aluminum is high enough for adequate heat dissipation. $\Delta T = \frac{Q*L}{k*A}$

By assuming the cartridge to be a block of aluminum, we estimated the temperature difference to be in the order of 2°C, showing that Aluminum would provide adequate heat dissipation.

2.2 Convection Heat Transfer Theory

Convection is the mechanism of heat transfer proved to be the most crucial to the cooling of our system. It transfers the heat conducted to the surface of the cartridge to the surrounding fluid or in our case air. The heat transfer by convection is given by,

$$Q_{conv} = h\, A_s\, (T_s - T_\infty) \qquad \text{Eq (2)}$$

where h is the convection heat transfer coefficient, A_s is the surface area exposed to the external fluid, T_s is the surface temperature, and T_∞ is the ambient temperature (temperature of the surrounding fluid). As can be determined from equation (2), the two feasible methods of increasing the heat transfer by convection are (a) to increase the surface area of the cartridge or (b) to increase the convection heat transfer coefficient (h).

The surface area can be increased passively by simply adding fins. To increase the heat transfer coefficient, the fluid flow around or through the cartridge must be increased. For the cartridge, in which the fluid is air, the simplest method is to add a fan to increase the air flow.

2.3 Radiation Heat Transfer Theory

Radiation heat transfer transmits heat from a surface to the surroundings through electromagnetic waves. The heat transfer by radiation is given by,

$$Q_{rad} = \varepsilon\, \sigma\, A_s\, (T_s^4 - T_{surr}^4) \qquad \text{Eq (3)}$$

where ε is the emissivity, a unit-less quantity in the range of $0 \le \varepsilon \le 1$ which takes into account the surface conditions, as compared to that of blackbody radiation where $\varepsilon = 1$. Blackbody radiation produces the maximum rate of heat transfer for the given temperature and exposed surface area. σ is known as the Stefan-Boltzmann constant; it has a value of 5.67×10^{-8} W/m^2K^4. T_s is the surface temperature, and T_{surr} is the temperature of the surrounding medium. As can be determined from equation (3), the effects of radiation heat transfer will be minuscule, as the heat transfer by radiation requires very large temperature values to be effective.

3. Use of COMSOL Multiphysics

Because high-powered LEDs were used, heat dissipation was critical to prevent excessive heat buildup, which would result in the LED's UV output dropping, or worse, the LED burning out. The optical output and longevity of LEDs greatly declines as the temperature rises, making heat dissipation a key factor in this design. The SolidWorks model of the cartridge was conveniently imported into COMSOL Multiphysics 4.3a. COMSOL Multiphysics Heat Transfer in Solids (ht) was used to solve for the ability of the aluminum to conduct the heat away from the LED and dissipate it to the surroundings. Figure 2 shows the thermal analysis of a UV cartridge powered by an embedded 395nm wavelength LED operating at 5W, which was deemed to be the most critical case.

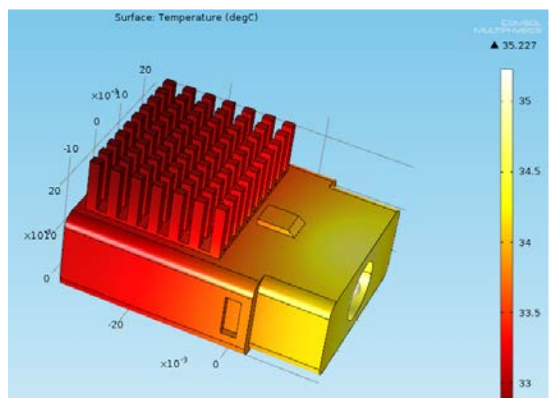

Figure 3. Improved UV LED Cartridge Design with additional heat dissipating fin structure

The convenience of the easy coupling of a SolidWorks 3D CAD model with COMSOL facilitated the quick turnout of design modifications and Multiphysics verifications to be made to check the improvements achieved. Two devices were modeled to improve the heat transfer from the surface. To improve the heat transfer from the surface of the cartridge, we added a fin structure to increase the surface area of the cartridge (Figure 3). This nearly doubled the surface area for convection heat transfer. The other modification was to add a fan to the side of the cartridge and drill holes in the side and the top of the cartridge to allow the air to flow through (Figure 4). This not only increased the heat transfer by forced convection but also increased the surface area.

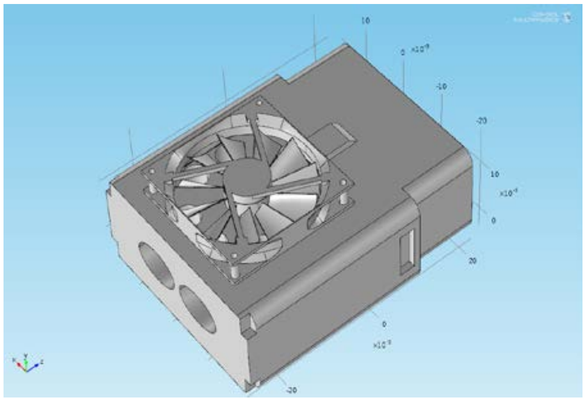

Figure 4. Improved UV LED Cartridge Design with cooling fan

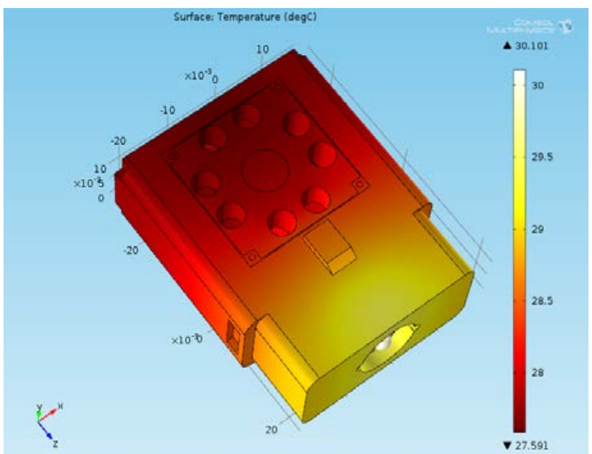

Figure 5. Improved UV LED Cartridge with fan Temperature Profile (fan eliminated in mesh)

4. Results

As depicted in the COMSOL Multiphysics Heat Transfer analysis in Figure 2, a cartridge machined out of aluminum is suitable for the required heat dissipation. This analysis was performed assuming a 20 °C ambient temperature. It was observed that the aluminum body of the cartridge conducted the heat flux with a temperature drop of 2 to 3 °C. The temperature rise of up to 50 °C in the cartridge is mostly due to insufficient removal of the heat from the surface to the surroundings via air convection. Inside a materials printer, the ambient temperature can potentially reach 50 °C, bringing the LED case temperature above 80 °C, a critically high value for LED degradation and failure. Figure 3 shows the improvements achieved with the addition of a heat-dissipating fin structure on one side of the cartridge. This modest change in the design resulted in about a 15 °C reduction in temperature and showed that a UV LED replacement cartridge with its UV LED operating at a power level as high as 5W was feasible for in-situ and instant curing of the printed droplets in a materials printer. Furthermore, the addition of a cooling fan resulted in greater heat dissipation, lowering the temperature by about 20°C (Figure 5). This reduced the effects of temperature on the UV output of the LED, making this the optimal design.

5. Exposure Testing

Testing of the operation of the UV curing LED cartridges were done on samples coated uniformly with the UV ink. These samples were prepared by simply spreading the UV ink onto paper substrates. Although the thickness of the ink film was significantly greater than the typical 60 microns value it would be if ink were jetted, it would prove whether or not our LEDs would cure our ink. Because of better sensitivity of our ink to 365 nm wavelength these tests were done using a cartridge with a 5W rated 365 nm LED embedded in it. At the nominal printing speed of our printer, i.e. 3 cm/s the samples responded well and got solidified at all exposure levels we tried, 6 passes, 2 passes and 1 pass resulting in an estimated minimum exposure value better than 25 mJ/cm^2 which is a typical exposure sensitivity for most UV sensitized inks and photoresists. Considering the fact that the LED was actually powered at about 50% of its rated maximum, there is room to accommodate less sensitive UV inks or doubled printing speed.

Conclusion and Future work

Coupled SolidWorks 3D CAD models and COMSOL Multiphysics analysis enabled rapid design and design verification, producing a working design and rapid prototyping of a UV LED cartridge, which allowed the instant curing of the printed droplets as they were printed in a materials inkjet printer.

Future work is planned to include drying/baking/annealing through in situ heating of non-UV ink patterns by exposing them to visible and/or infrared radiation. Such processes, compared to UV curing, demand much higher levels of intensities and LED power, therefore constitute a greater challenge for thermal design. However, with thermal simulation guidance obtained from COMSOL running directly from Solidworks 3D CAD designs as shown in this work, we are confident to overcome these hifger power challenges and design and produce in-situ heat-treating high power LED embedded cartridges for materials inkjet printers that will meet needs of printed electronics fabrication.

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