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Recent advancements in 3D printing of lighting components and systems

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ABSTRACT

In the past 100 years, innovations in lighting have primarily involved new technologies for illumination. However, the manufacture of lighting fixtures over time has stayed relatively the same. Traditional manufacturing in many industries has started to be supplanted by a new innovation: 3D printing. While 3D printing is an opportunity to bring back lighting fixture manufacturing to the U.S., the few U.S. manufacturers remaining are not adopting it rapidly. To help the U.S. lighting industry, Rensselaer's Lighting Research Center has conducted research, education, and collaborative activities to disseminate information and encourage the 3D printing of lighting. This paper provides an overview of LRC research regarding the potential for using 3D printing for the manufacture of lighting components and systems, as well as an explanation of the lessons learned and improvements needed to make 3D printing the first choice method for lighting manufacturing.

Keywords: 3D printing, lighting, LED, optical, thermal, mechanical, electrical, education

1. INTRODUCTION

In the past 100 years, innovations in lighting have primarily involved new technologies for illumination, such as fluorescent lamps in the 1930s and LEDs in the 2000s. However, the manufacture of lighting fixtures over time has stayed relatively the same. In the past decade, traditional manufacturing and construction methods in many industries have started to be supplanted by a new innovation: 3D printing. The benefits of 3D printing include on-demand printing of products, custom designs not possible through traditional manufacturing methods, and local manufacturing services instead of overseas shipping. Understanding the potential benefits of 3D printing, many industries have already started exploring how to exploit this new promising technology to create value for their customers and have made the investment needed to transform their manufacturing processes. Some of these industries include, medical, automotive, and airplane.

Even though the U.S. led the way in the solid-state lighting (SSL) revolution during the past two decades, displacing most inefficient, traditional lighting with highly efficient LED light sources, lighting fixture manufacturing has now moved away from the U.S. This has increased the carbon footprint of LED lighting, negating the benefits created by the SSL innovation and transformation. While 3D printing is an opportunity to bring back lighting fixture manufacturing to the U.S., the few U.S. manufacturers remaining are not adopting it rapidly. A very small number of lighting manufacturers are presently producing lighting fixtures by 3D printing (e.g., Gantri and Signify). The others are more likely waiting to see how 3D printing can help them reduce production costs. Many of them have used older 3D printing technologies for prototyping products to analyze form and fit and have biased opinions against using 3D printing for production. Although new, advanced 3D printing technologies and materials can offer superior outcomes, organizations are taking a wait-and-see approach. To be fair, adopting a new technology means disruption to the status quo and can be risky for organizations.

To help the U.S. lighting industry, since 2015 the research staff at Rensselaer's Lighting Research Center (LRC) have conducted studies to understand if 3D printing of functional components such as heat sinks, secondary optics (reflective and refractive), electrical/electronic parts, and mechanical holders can fulfil the performance requirements of lighting fixtures.[1]-[11] Additionally, the LRC has conducted both undergraduate and graduate education as well as online educational seminars to disseminate information and encourage the 3D printing of lighting, and in 2023 organized SPIE's first conference on 3D printing for lighting to exchange technical information and facilitate a lighting industry transformation in the U.S.[12]-[14] This paper provides an overview of recent research findings at the LRC regarding the potential for using 3D printing for the manufacture of various lighting components and systems, as well as an explanation of the lessons learned and improvements needed to make 3D printing the first-choice method for lighting manufacturing.

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2. OPTICAL COMPONENTS

2.1 Key benefits of 3D printing lighting optical components

Secondary optics are a key component of an LED illumination system that transfers the luminous flux from the LED package to the target area. A well-designed optical system will maximize the total flux transferred and create the optimal beam shape and illuminance distribution for the lighting application. Traditional optics manufacturing uses either a subtractive method, where the material is cut away, or a forming method where the material is formed into shape (e.g., injection-molded lenses). Both of these methods have limitations when producing custom optics. The primary benefit of 3D printing for custom optics is its ability to produce novel or complex designs through its layer-by-layer deposition method. Optics with multiple lens structures, for example, can be built-up as a single piece through a digital model rather than assembled from various pieces. These custom optics have the potential to better match lighting application requirements with better efficiency.[4] An additional benefit is that no tooling is needed for low volume custom manufacturing, potentially allowing for shorter lead times and lower costs.

2.2 LRC research findings for 3D-printed optical components

Successful 3D printing of optics requires knowledge of proper print materials and methods, design optimization methods, and performance evaluation. When creating a custom design, the lighting application requirements, the light source and optical material characteristics, and the initial geometry and surface properties of the lenses are all important considerations. LRC researchers have found that the design process to meet distribution requirements involves an iterative approach.[5] Ray-tracing studies are conducted iteratively to improve the optical efficiency of the design before it is translated into a CAD file for 3D print fabrication.[5] Additionally, selecting the right printing and post-processing methods is important to achieving optics that meet the lighting application requirements.

In a 2022 study, Udage and Narendran produced through 3D printing an internal cavity lens structure with a smooth planar outer surface.[6] In conventionally produced refractive optical systems, the lens consists of outer surface geometric structures that refract the light and shape the output beam distribution. These geometric structures are generally difficult to clean and maintain, which can decrease the light output over time due to dirt accumulation. Udage and Narendran investigated the feasibility of using 3D printing to create internal cavity structures with refractive spherical arrays to produce the required output beam. An optical system with two internal surfaces was printed, and the surfaces were polished during post-processing to allow the printed lens to produce high transmission with minimum light scattering. To validate the design method, the printed lens was positioned in an optical setup to measure the beam patterns and the total light output at the target surface to determine whether the printed lens matched with the ray-tracing results. Experimental data captured with a CCD camera were shown to match well with predicted optical losses. Overall, Udage and Narendran showed that it is possible to manufacture an optical system with internal cavity structures through 3D printing that can achieve specified illuminance distributions.

In another 2022 study, Perera et al. worked with a lighting manufacturer's research team to develop a fully 3D-printed, LED-based luminaire providing a Type V illuminance distribution for a parking lot lighting application.[5] In this study, the reflector optics system was designed, 3D-printed, and laboratory tested for total light output, intensity distribution, light output distribution, and optical efficiency. The test results were compared with ray-tracing simulation results. The results showed that the reflector system had an optical performance of 93% application efficacy at approximately 120 lumens per watt. Overall, Perera et al.'s study showed that 3D printing can be used today to print and integrate luminaires.

2.3 Areas for future development

3D printing of optics offers benefits to lighting applications, but one area requiring future study is how to tailor optical design software for 3D printing materials and technologies. In another study by Udage and Narendran,[8] the researchers found disparities between the ray-tracing and experimental results because of a mismatch between the index of refraction used in the ray-tracing simulations with that of the printing materials. Studies are needed to understand what types of changes are necessary in optical design software to accommodate differences between conventionally manufactured lenses and 3D-printed lenses with interlayer features. Additionally, in a recent study Perera et al. (2023) showed that short-wavelength radiation and heat are two factors that affect long-term lens performance.[9] Additional long-term performance studies of the materials used for 3D-printed optics are needed in order to understand how well they will endure the typical operating and environmental conditions found in various lighting applications.

3. THERMAL COMPONENTS

3.1 Key benefits of 3D printing lighting thermal components

The two key benefits of 3D printing thermal components for lighting are the ability to seamlessly consolidate parts and the opportunity for novel designs. Parts consolidation allows for a single integrated piece, such as a thermal heat sink and reflector, which can offer both price and performance benefits. For example, compared with producing a heat sink and reflector separately and assembling them, a single integrated component would eliminate the labor and material needed for integration, and it can provide better thermal contact and performance because no interface material is needed between the two components. The opportunity for novel designs could potentially provide better performance, aesthetic appeal, and reduced weight.

3.2 LRC research findings for 3D-printed thermal components

Thermal component research at the LRC has investigated the effects of print orientation on thermal conductivity, the use of different thermally conductive materials to 3D print heat sinks for LED-based MR16 lamps, and the design and performance of 3D-printed metal heat sinks for an LED-based luminaire.

In 2018, Perera et al. investigated how the layer-by-layer print orientation (in-plane vs. cross-plane) of different commercially available filament materials affected the thermal conductivity of the printed component.[2] The LRC researchers found that 3D-printed components with an in-plane orientation had >30% better effective thermal conductivity compared with components printed with a cross-plane orientation. Following on, Perera and Narendran (2023) printed and tested heat sinks made from materials of different thermal conductivity for use in LED-based MR16 lamps.[3] The authors found that the heat sink samples' heat transfer simulation results for three thermal power levels matched experiment results at three electrical power inputs (1.7W, 2.7W, 5W), indicating that thermally conductive composite and metal materials have the potential to maintain the LED case temperature below 105°C for 35-W halogen equivalent LED MR16 fixtures. Additionally, LRC researchers have continued this work in a study where a 3D-printed metal heat sink was designed for a LED light engine. The LRC worked with a lighting manufacturer's research team to design a novel 3D-printed heat sink with vented hollow fins and an internal structure and compared its performance with an identical 3D-printed heat sink with a solid structure.[10] The novel hollow design, not possible to manufacture with traditional methods, showed similar thermal performance to the solid heat sink at the LED case temperature (difference in Tcase<5°C between solid and hollow configurations), and a weight reduction of approximately one-third compared with the solid component. [10]

3.3 Areas for future development

Further research exploring novel heat sink designs that improve the aesthetics of light fixtures and improve heat dissipation can help the technology gain wider acceptance. Creating a heat sink and reflector as a single piece can further improve the value of 3D printing. Also, another issue that requires attention is post-processing. Today, it is an additional step needed when making heat sinks; however, it adds cost. Future research must explore ways to avoid or minimize post-processing.

4. MECHANICAL COMPONENTS

4.1 Key benefits of 3D printing lighting mechanical components

In traditional building construction, each step of the interior finishing process is separated. The framing is completed, then HVAC, plumbing, and electrical wiring are run through the walls before sheetrock is put in place. In the case of lighting, a best guess is made as to where lighting fixtures will be placed, and wiring is pulled through for use with ceiling or wall-mounted fixtures that will be attached during the final stage. The off-the-shelf lighting fixtures procured may or may not fit well in terms of lighting application needs or aesthetics within the space because the lighting is added after the fact. Custom-designed lighting created specifically for the space is one solution, but it is generally very expensive to commission a low volume of custom fixtures from a fixture manufacturer.

In recent years, 3D printing has been tested as an alternative process for building construction. The layer-by-layer construction employed by massive 3D printers has been shown to speed construction time and reduce waste. In terms of interior construction and finishing, 3D printing of interior walls can offer a cost-effective and sustainable solution for custom features. With 3D-printed walls, custom lighting and other finishes such as wall textures can be integrated from the start as one element rather than added together as multiple, separate elements.

4.2 LRC research findings for 3D-printed mechanical components

In 2021, the LRC demonstrated a prototype 3D-printed interior architecture with integrated lighting.[11] A scale-model size wall resembling sheetrock was 3D-printed from polylactic (PLA) material. The wall included a decorative texture, crown molding, and baseboard (Fig. 1). The wall design included a non-functioning electrical outlet (to show how it could be integrated) and routing space behind the wall for the wiring to be run through the molding (although future advancements may allow for electrical conductors to be printed directly into the wall). Several wall sconces were printed and attached separately, with LED module packages added afterward (Fig. 2). Again, with future advancements, the possibility exists to print the wall sconce directly as part of the wall structure.

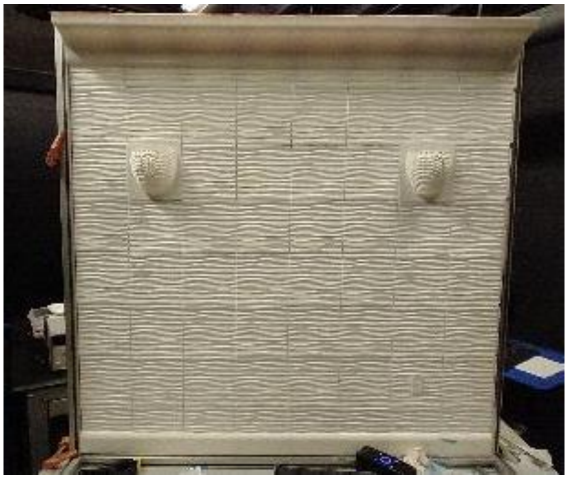

Fig. 1. (left) Prototype, scale-model sized 3D-printed interior wall with lighting (LRC photo)[11]

Fig. 2. (right) 3D-printed lighted wall sconce (LRC photo)[11]

As part of the same project, decorative wall tiles were 3D-printed to explore how to integrate lighting within or behind the wall rather than as a fixture. The wall tiles were printed with channels to accommodate LED backlighting and produce a wallpaper-like pattern (Fig. 3).

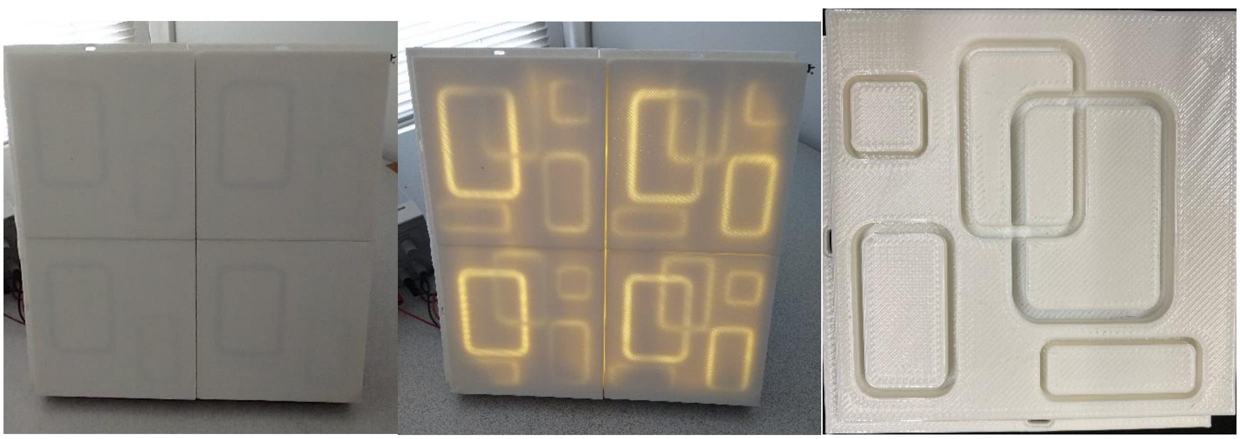

Fig. 3. Decorative wall tiles were 3D-printed with channels to accommodate LED backlighting (LRC photo)[11]

4.3 Areas for future development

These early prototypes show the possibilities for interiors with integrated mechanical components, but several obstacles remain, namely the lack of suitable wall printing materials meeting building codes and standards, the availability of different sizes of printer beds, and the speed of current printing technologies.

5. EDUCATION AND INDUSTRY COLLABORATION

While research is vital to understanding the possibilities of 3D printing for lighting, education and collaboration also play important, intersecting roles in furthering the adoption of any technology. Education and collaboration are both required in order to achieve the larger goal of promoting a technology for mainstream use. As a university research organization, the LRC has been able to deliver education and encourage collaboration at both the academic and professional levels.

At the academic level, the LRC has incorporated 3D printing lessons and projects within its lighting curriculum for both undergraduate architecture students and graduate lighting students. At the undergraduate level, these lessons and projects give students a foundation in 3D printing technology that will serve them when they move into their professional careers. At the graduate level, students have chosen 3D printing studies for master's projects and doctoral dissertations that have provided much-needed research and advanced knowledge that can lead to professional advancement.

At the professional level, the LRC has provided opportunities for both online workshops and industry collaboration. In 2020, the LRC began conducting a 6-week live, online course on how to use 3D printing for manufacturing lighting components and systems, which was intended for lighting professionals interested in implementing this technology at their places of business.[12] The LRC's ASSIST 3D Printing for Lighting Consortium draws members from both lighting and 3D printing industries to discuss each other's needs and opportunities, and to collaborate on mutually beneficial research with the goal of helping both industries to successfully apply 3D printing technology to the lighting field.[13] Additionally, in 2023 the LRC and the consortium established the first 3D printing for lighting conference within the SPIE Optics+Photonics meeting for both lighting and 3D printing researchers to share knowledge and make connections.[14]

6. LESSONS LEARNED

LRC research of 3D printing technology for lighting over the last several years has resulted in a number of lessons learned and concepts to take forward in future research:

- Primary takeaway: Suitable optical, thermal, and mechanical components for light fixtures can be built using presently available materials and machines.
  - Optical components
    - The availability of materials for printing lenses is limited.
    - The short-term performance of optical printing materials is good but the long-term performance needs improvement.
    - Lighting-specific materials need to be engineered with consideration given to:
      - Short-wavelength optical radiation, elevated temperature, and environmental conditions such as UV in outdoor applications, humidity, dust accumulation, etc.
    - Some promising materials and printing methods might require post-processing and finishing operations.
  - Thermo-mechanical components
    - Material combinations are available when considering metal, polymer, composites, electroplating, etc.
    - However, 3D printing materials (polymer and polymer composites) for thermally conductive components need to be engineered in the 10-40 W/(m*K) range.
    - Long-term material performance information and material certification are needed.
  - Electrical components
    - The 3D printing of electrical and electronic circuits is the most challenging task today.
      - Very low power circuits can be designed and printed to demonstrate concepts.
      - The current-carrying capacity of electrical traces is low.
      - Better materials for electrical and electronic components are needed.
- Benefits for 3D printing compared to traditional manufacturing methods:
  - Unique designs are possible that can be made only using 3D printing technology.

- Parts consolidation and integration with 3D printing may provide better price and performance.

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