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COMMENTARY

Demonstrations of Additive Manufacturing for the Hospitality Industry

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Abstract

This article demonstrates the potential application of additive manufacturing techniques and technologies in food safe applications for industrial, commercial, and consumer scales. We produced an entirely additively manufactured dinner to demonstrate use cases of the technology. Drawing on additive manufacturing's strengths of low production runs and low-cost geometric complexity, we directly produced tableware of complex form targeted for limited audiences. Current additive manufacturing techniques lack the required process control and certifications for widespread use in food contact applications. The use of coatings can mitigate the concern for prototypes and small-scale production. Directly printing food-related items is of use for tableware in increasing artistry, addressing niche markets, and prototyping. Other researchers in the commercial and private sectors can build upon this work to develop the processes and procedures needed to enable more widespread adoption of 3D printing in food-related industries. The article focuses on a potential new market for existing 3D printing technologies and lays out a series of barriers to be overcome.

Background

Additive manufacturing is undergoing a renaissance. The field has become flush with media attention and technical progress. New researchers are pushing the boundaries of the technology to develop applications in biomedicine, art, fashion, aerospace, and consumer goods. Companies are finding applications in new markets, and food-based applications provide a fertile ground for the development of this technology. When applied to the production of tableware and equipment, additive manufacturing opens up new design spaces to be exploited and presents a new take on old challenges. In this article, we present an overview of the current work and trends that relate to traditional 3D printing in food-related applications.

To demonstrate the viability of 3D printing in food-related markets, we produced an entirely 3D printed dinner service (Fig. 1). We produced two table settings that consisted of placemats, utensils, plates, bowls, glasses, and food. The wine glass was produced on a low-cost desktop 3D printer using the fused deposition modeling (FDM) process. The placemat was produced on a 250,000 dollar Polyjet printer and comprised two materials. The bowls and dishes were 3D printed by a service bureau in ceramic and glazed in a postprocessing step by the bureau. The utensils were fabricated using a metal printer, which we then sharpened and coated manually. We will focus on these items and others to demonstrate the applicability of 3D printing to prototyping and direct part production in the food market, as well as in the production of food directly.

In general, items are 3D printed because they need to be geometrically complex and/or produced in small numbers. Three-dimensional printing superiority in low-volume runs and complex geometry arises from its cost structure. The cost of producing an item using 3D printing is fixed with the quantity of the item; therefore, it costs roughly 100 times more to produce 100 identical items on a printer than to produce a single item on a printer. This is unlike mass production where the cost per item tends to decrease with the quantity of items produced. Injection molding and other traditional processes often require tooling to be produced. This cost tends to be amortized over the number of items produced. This drives up the cost of low production runs on traditional equipment since there are fewer items to spread the cost over. Three-dimensional printing does not require specialized tooling and therefore removes this initial cost barrier.

A part that is 3D printed costs less if it has less volume. The main drivers of part cost are material consumption and machine time consumption. A part with less overall volume requires fewer movements of the 3D printer and consumes less

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FIG. 1. Several items were produced using various 3D printing processes. The placemat **(a)** was produced on a Polyjet 3D printing system out of ultraviolet-cured resin. The system was then made food safe using a coating of silicone. The fork **(b)**, spoon, and knife **(c)** were produced from stainless steel and coated to be food safe. The intricate designs would be difficult to produce using traditional processes. The unique design was made for a germophobic audience, having food contacting surfaces not resting on the table. The bowl **(d)** was produced using a ceramic printing process and designed to adjust its angle with the plate based on the soup content **(e)**. This caused the bowls to tip away from the user and enforced proper etiquette. The wine glass **(f)** was produced using a fused deposition modeling system and coated with silicone to be watertight and food safe. Photographs credit of Tony Cenicola/The New York Times/Redux. Color images available online at www.liebertpub.com/3dp

material and therefore costs less to produce. A geometrically complex part costs less than a solid, uniform simple part because it has less material in the same bounding structure. Additionally, machining a simple part often costs less than 3D printing the same part, while a complex part often requires more machine time on a subtractive manufacturing system.

Application to Products Related to Food

Rapid prototyping

Three-dimensional printing has widely been used for the production of models in industry for the last two decades. According to the Wohler Report, over 73% of the 3D printing market is the production of models and visual aids.[1] It allows the designer a flexible development cycle. Traditionally, designers needed to create prototypes by hand through machining or mold production. These are time-consuming processes, which make iterating difficult. Three-dimensional printing streamlines the process. Once designers digitally design their piece, they can immediately print it. Printing can be done in the span of a few hours depending on the size of the object. After testing the initial print, the designers can make alterations to the original file and print additional prototypes if necessary. While each additional trial run of the design costs material and time, there is no material wasted on molds and no time consumed by handcrafting prototypes.

As a demonstration of rapid prototyping's usefulness in the food technology field, we produced the placemat and the wine cup. Each design was iterated over several times using a 3D printer, allowing us to prototype the design before committing to a final version. The wine glass was produced in 4 h using a low-cost FDM system. FDM printers are the most commonly used printers, which produce shapes from plastics such as acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA). In FDM machines, a robotic arm extrudes a strand of material and fills in a pattern for each layer. Like most FDM-produced objects, the wine glass was not naturally watertight. The printing process can produce defects in the structure in the form of seams and small holes in the walls of the structure. To make the surface watertight, we applied a thin coating of a food safe silicone by hand. The placemat was produced using an Objet Connex 500 3D printer, which relies on Polyjet technology. Ultraviolet (UV) curable material is jetted onto a surface and cured after each layer is deposited. The Polyjet printer allows for two materials to be printed at the same time. These materials can be of various shore hardness values and colors. This allows the printer to make objects with both rubber-like soft sections and parts as hard as ABS plastic.

Direct part production

Overview. Direct part production is the fastest growing segment of the 3D printing market.[2] Often ceramic, metal, or nylon parts are produced and then postprocessed to make a part, which is used in products that are sold to customers. The largest users of direct part production are the automotive, aerospace, and medical industries. These markets use 3D printing to produce parts that could not be made cost-effectively using any other method.

Low quantity production. Low quantity production provides three advantages to 3D printing over traditional processes. One is customization. Three-dimensional printing allows consumers to change the design to their particular liking, leading to unlimited design variations. This can be for purely esthetic or functional reasons. A user may desire a unique design of a bowl and plate to fit the décor for an event he/she is hosting. For instance, the bowl produced was designed to look like a mask from the Carnival of Venice to match an Italian-themed dinner. In the past, a consumer would have had to search through what was already available to find something mass produced or would have had to commission a custom work from an artist. Using a service bureau, we were able to have our exact design fabricated and delivered in 4 weeks for 120 dollars. Currently, one bureau allows users to produce a custom sake set through their online design tools.[3] As more designers begin to make design tools, users will be able to generate their own custom food safe designs for fabrication.

Artistic customization extends into the production of molds and cookie cutters. This has been a common application for 3D printers at home. Many users produce molds or cookie cutters out of nonfood safe materials on uncertified printers for use as personal cooking aids. They often overlook the need for food safe plastics and processes because of the limited usage of the parts.[4] Others produce custom-positive shapes out of ABS or PLA on a personal 3D printer, and then make molds using a food safe silicone. This allows the user to make a cookie cutter in the shape of a child's drawing or a lollipop in the shape of their head, as was done by FabCafe in Tokyo.[5] This process is safer, but can be more labor and time intensive.

Customization can also serve a functional purpose. In our designs, we incorporated a mechanism to enforce proper etiquette into the soup bowl. It is proper etiquette to tip the bowl away from oneself to scoop the last spoonful of soup out of the bottom.[6] However, it is common practice to tip the bowl toward oneself instead. We designed a bowl that rocked away from the user gradually as the bowl emptied, thus enforcing proper dining etiquette. This was accomplished by making the back of the bowl just heavy enough so that the center of mass, when empty, was behind a contact point, while the center of mass, when full of soup, was in front of the contact point. Changes in the volume of soup therefore adjusted the center of mass and therefore changed the angle the bowl made with the surface it was placed on.

Customization can lead to ergonomic improvements by tailoring the utensils to the user's hand. This may be unnecessary for able-bodied individuals, but could be extremely useful for patients with disabilities that impair the function of their hands or mouth. People with burns on their hands, amputations, or other conditions can benefit from utensils that are customized to their specific needs. Currently, there are specialized utensils for those with Parkinson's disease. These are generally in the form of utensils with weighted handles to minimize tremors, curved utensils to minimize wrist movement, and utensils with hand straps or finger holes, which prevent them from being dropped. Other adjustments include deeper bowls on spoons to avoid spills and softer handles for more comfortable grips. The utensils, which are fitted to the hand to avoid being dropped, can be made using 3D printing. While having finger holes on utensils is more convenient than hand straps because it allows the user to pick up and put down utensils without strapping their hand, it is difficult to make them in a generic size and shape that will still provide a snug enough fit. Three-dimensional printing of adaptive dining ware would allow patients to have utensils fitted specifically to their hand, allowing them the freedom to pick up and put down their silverware while still having it securely in their hand. Three-dimensional printing's customizability would also permit the utensils to be angled to their wrist and for the handle to be weighted according to their specific needs.

A second advantage of direct part production is the ability to service small markets. Designs can be produced on demand. The aircraft industry often uses 3D printing to produce ducts and other simple parts, which are used sparingly in production, on the order of 10–20 a month.[7] In the food space, this allows for the production of niche tools and designs, which have a high value and small sales volume. Our utensils are meant to be an example of this concept. The utensils had only the handle touch the surface they rested on. These are more sanitary than traditional utensils because the portion that went in the user's mouth never touched the table. This is ideal for highly germophobic individuals. Such specialized utensils may only sell a few a month, if on the market, but could be sold at a premium because of their unique functionality. In an industrial production setting, 3D printing is beginning to find applications in the development of molds for injection molding. These molds, designed for a limited run, allow injection molding services to provide parts out of the desired food safe plastics for simple shapes.[8]

The third advantage is the ability to test markets. Direct part production allows a user to make a small run of objects and test the market's response. Two hundred or 300 items could be produced, packaged, and sold in a store as a test. This allows a company to decide if committing the resources to produce thousands or more of the objects would be a worthwhile investment.

Geometric complexity. Geometric complexity is often used for ensuring a functional attribute of the part or an esthetic element of the part. Both are applicable to consumer food-related products. While the spoon and knife both could have been machined through traditional fabrication processes, the complex structure of the fork's handle would have been difficult or impossible to machine out of a single block. Three-dimensional printing allows for more complex artistic shapes to be realized since it can manipulate the object layer by layer. As seen in Table 1, if the items from the dinner were to be machined, the cost of production would be prohibitive. Three-dimensional printing has made the items affordable for high-end restaurants.

Functionality can be embedded in the geometry of a printed part. For instance, high efficiency heat sinks have been produced using 3D printing. The complex shape allows the flow of air to interact with a large surface area and increase heat conduction. Complexity can be useful in industrial equipment design since industrial equipment is often sold in small numbers, allowing 3D printing to be cost-effective.

Safety

In general, there are two concerns about the safety of 3D printed parts. One concern comes from a 3D printed part's layered construction. The layering process produces surfaces that are not uniform and not crevice free. Combined with complex 3D shapes, this surfacing problem makes producing a natively food safe part challenging since it can be difficult to clean. Pits and internal voids in the object can allow bacteria to grow and fester where chemical, mechanical, and optical cleaning cannot reach them. Designing the parts to be easily polished can limit the design space of a part.

The other concern is over the safety of the materials used. Plastic, UV, and metal printers each present a unique challenge. On FDM machines, the ABS or PLA shapes these printers produce cannot be trusted in food application. While PLA is naturally food safe, the safety of the dyes used in the plastic is also unknown and must be assumed to be unsafe. The extruders often are made with brass, potentially containing lead, which can contaminate the printed parts. While some extruders have been fabricated using stainless steel exclusively, as of yet, no 3D printer has been certified to natively produce food safe parts. Therefore, all parts produced on an FDM machine must be assumed to be unsafe.

The Polyjet and SLA processes use UV curable materials that are irritants to the skin and digestive track.[9] Uncured material is often left on the part that requires thorough cleaning to remove. Since the materials are cured using UV light, one cannot use UV light to clean and sterilize the material. Some postproduction UV light can induce additional curing, but overcuring the material can cause the parts to degrade and loose mechanical strength. In an environment where a device will be repeatedly used, UV light cannot be relied on for sterilization.

Three-dimensional printing can produce objects out of stainless steel and gold, traditionally considered food safe materials. Stainless steel tends to be infused with a bronze matrix and gold and silver tend to be produced from a lost wax casting process. While neither of these processes is inherently unsafe, no organization has the quality assurances in place to certify that they are food safe.

Currently, there is only one material that can be 3D printed and advertized as food safe. Several companies, including Shapeways and Kraftwurx, offer a fire-glazed ceramic. This material was used to produce the bowl and plates for the dinner. In general, the glazing results in a surface that is uniformly smooth, durable, and is crack and crevice free, making it easy to mechanically clean. Often the glaze is thick enough to smooth the effects of a layered construction. However, the firing process for the ceramic also limits the design space, ensuring that most surfaces are easily mechanically cleaned.

Currently, the only advisable method of making safe parts is to apply a coating on the surface, as with ceramics. For the FDM and UV-cured materials, we applied a silicone coating on the surface. This was done on the placemat and the wine glass. The uniform coating prevents the unsafe materials from coming in contact with food. This coating, however, can wear away over time through repeated usage. Thus, it should only be used in prototyping settings to allow users to test a design in a realistic setting for a short period of time. For the metal parts, applying the coating on printed parts is the best way to allow geometric complexity. The coatings can ensure that the surfaces are smooth, durable, and free of cracks and crevices. For a coating to be considered safe for contact with food, in the United States, it must conform to the FDA code of regulations. This requires that the coating be continuous, formulated from approved substances from Title 21 of the Code of Federal Regulations, and applied on metals or other suitable substrates.[10]

TABLE 1. COST OF VARIOUS CUSTOM FOOD-RELATED ITEMS, WHICH ARE PRINTED OR MACHINED

Process	*Qty*	*Cup (plastic)*	*Fork (steel)*	*Spoon (steel)*
3D printing	1	$31.99	$75.35	$63.83
Machining	1	$1881.24	$1561.04	$1023.09
Machining	10	$1354.66	$1522.42	$881.09
Machining	100	$1348.62	$1517.34	$759.75

The custom machining processes do not work for a small restaurant-scale production. Even at quantities of 100, the cost of machining an item can be over 1000 US dollars. The cost of 3D printed equivalents is affordable for high-end restaurants.

Future Trends

To further develop direct part production for food applications, printers and services will need to undergo a certification process. Several processes will require the selection of properly certified food safe materials, which will differ from the traditional materials in some processes. Software limitations will need to be placed on equipment to ensure that the machines are not used with nonfood safe materials. Service Bureaus will need to go through certification processes by their national and local governments to ensure that they are maintaining the standards needed to produce food safe items by using appropriate machines and by maintaining health standards in the production of parts.

Once bureaus are up to the requirements to produce food safe-certified metals, utensils will be an early consumer-focused market. This will be a logical extension of the ceramic food safe bowls and cups already sold. Industrial equipment manufacturers will benefit from the ability to produce complex functional parts for their equipment out of food safe 3D printed metals. Consumer device designers will benefit from the ability to add complex functional parts such as high efficiency heat exchangers to their design.

The ability to directly 3D print molds for consumers and artisans will also provide a new market for 3D printing food-related items, allowing consumers to produce custom shapes on demand. This will require the development of food safe flexible materials for 3D printing processes. Materials such as silicone have already been developed for use by the Fab@Home project, but currently require too long a time to cure and do not have sufficient resolution for artistic molds, which would require a 0.025 mm layer resolution or lower.

Conclusion

As 3D printing matures as an industry, it will likely find applications in the area of food science and technology. These applications will draw from the power of the platform as a tool for customization and geometric complexity. These will allow companies to refine their products through prototyping, market testing, and added complexity of design. It will allow for customized food items and new levels of artistry and control. Much work needs to be done to develop certified machines and bureaus to support these potential markets. It will draw on regulatory agencies, mechanical engineers, chemists, and more to ensure that the right materials, process, and standards are in place.

Author Disclosure Statement

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