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Short Communication

Embedding Components During Laser Sintering

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A B S T R A C T

We propose an approach for embedding electronic components during a Selective Laser Sintering (SLS) process. Common SLS processes are incompatible with component embedding because generating voids in the parts developed using this production method is logistically challenging. Here, we use an inverted laser sintering (ILS) process that sidesteps the need for a powder bed, and can therefore trivially generate voids in printed components. We demonstrate this method by embedding an LED inside an SLS part cavity, and then resuming the printing process. The LED is then externally activated, confirming its functionality after several layers are added. This ability could help transform SLS from fabricating passive parts to active systems.

Introduction

A beneficial feature of many existing additive manufacturing technologies is the ability to pause the process mid-print in order to embed components into pre-designed cavities. Once embedded, the printing process resumes, with the printer covering over the inserted component and the surrounding void [1,2].

Component embedding allows for increased functionality of the manufactured pieces, transforming them from passive parts into active systems. A wide range of components are embeddable, including electronic and mechanical parts. Possible objects range from batteries and chips to sensors and actuators. Furthermore, other elements such as wires, mechanical linkages, stiffeners, and fasteners can be added to create stronger parts or shorten their time to use once removed from the printer [3,4].

Despite the usefulness of component embedding, not all additive manufacturing processes can easily support it. In multiple 3D printing subfields, embedding components is trivial. For example, embedding has been shown to be possible in fused deposition modelling (FDM) printers [5]. This is because these printers deposit and fuse material only where programmed. At present, the standard SLS processes that dominate the industrial landscape [6] are largely incompatible with component embedding, limiting their potential to printing passive, single material parts. This limitation can be overcome by incorporating secondary mechanisms into the printing process, but this generally adds complexity to the fabrication of the part [7]. However, SLS processes have a greater potential to fabricate end-use parts due to the greater strength of SLS fabricated parts and the wider range of available materials [8,9]. Therefore, the ability to embed components into sintered prints would result in higher strength parts with embedded components.

Standard SLS processes function by placing down homogenous layers of unfused, micron-scale powder into a single build volume, and then selectively fusing regions of this powder with a laser. These layers of passive powder are placed sequentially on top of each other, with the laser selectively fusing material in new layers to previous layers. This is repeated until a solid object has formed [10,11]. The unfused powder surrounding the part remains in the print bed and builds up with each layer, functioning as support. The use of homogeneous powder layers, therefore, makes embedding challenging.

One approach to embedding components in powder bed processes involves printing a placeholder object and later replacing it. However, placeholder replacement necessitates that an additional mechanism be added to the printer, increasing print complexity [12,13]. Additionally, without tight tolerances on the embedded component, attempts to cover this cavity with a powder layer becomes challenging as this powder might simply fall into the any remaining gaps surrounding the embedded component. This makes the covering layer uneven and challenging to fuse to the rest of the printed part. Furthermore, having the covering layer in contact with the embedded component could result in damage from laser penetration, powder contamination, or contact with heated material.

Inverted Laser Sintering

In prior work, we introduced the idea of an inverted laser sintering (ILS) 3D printer. This is a novel powder fusion process that produces solid parts out of micron scale powder by fusing particles with a laser, much like a standard SLS printer [14]. The ILS system involves coating a thin layer of powder material onto a glass sheet, then pressing a substrate onto the upper surface of this material layer. A laser is directed upwards through the bottom surface of the glass, selectively fusing a region of this powder layer to the substrate. The substrate can then be raised, the material can be replenished, and the process can be repeated, with new sintered regions being fused to previously sintered ones. This results in an SLS printed component that does not have the surrounding passive support powder. This printing process, therefore,

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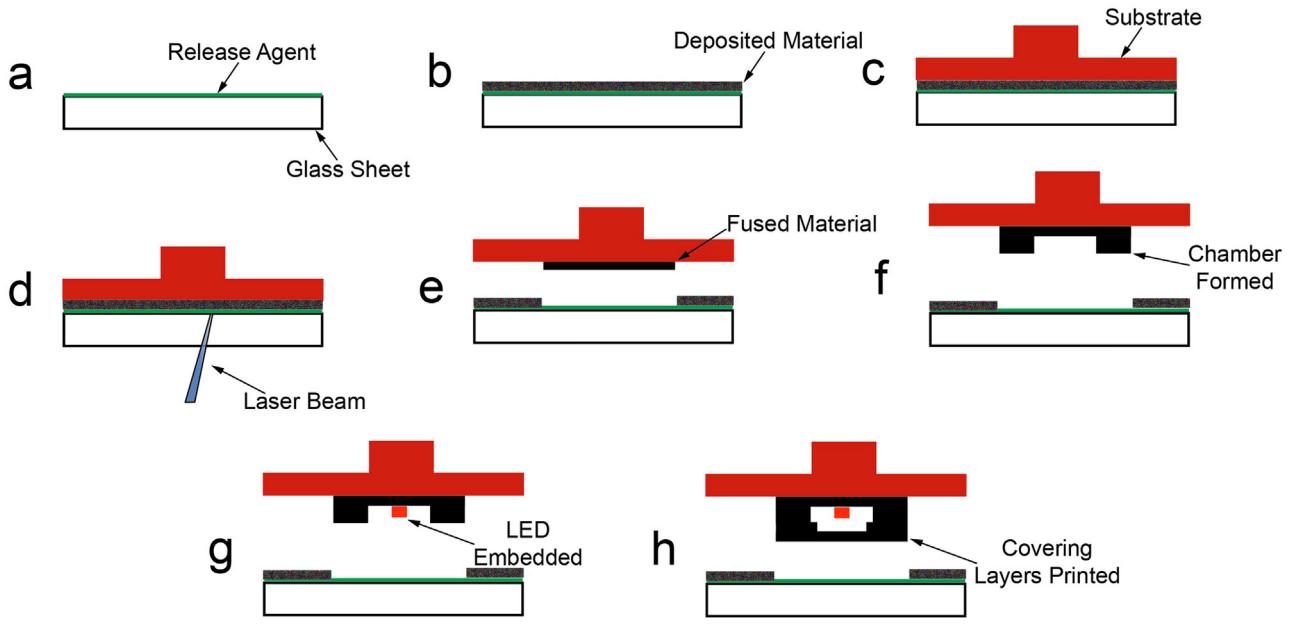


Fig. 1. a) The selected release agent is coated onto the glass b) The release agent fluidically captures a single powder material layer c) Substrate is pressed onto the upper surface of the powder d) The laser fuses a selected region of powder to the substrate e) The substrate is raised with the fused powder, the glass is then recoated with a new layer of powder f) The process continues, with several initial base layers and chamber layers being formed g) An LED with wires soldered to it is embedded in the powder chambers, the wires lead out of an open region in the walls of the chamber h) Several capping layers are added to finish embedding the print, there is still a small hole in the side of the chamber regions for the wires to protrude from.

has several advantages over existing SLS technologies. For one, the lack of surrounding, unsintered material allows the user to view the part during its entire printing process, enabling early print failure detection. This lack of passive support also makes multi-material powder printing simpler than a standard SLS printer [15]. However, the most relevant advantage of not having a print bed is the fact that embedding electronics again becomes trivial. Using this ILS process, a print can be paused after a pre-programmed cavity has been formed, some component can be embedded, and the printing process can then be allowed to continue, covering over the hollow space. In this paper, we demonstrate this ability by fabricating a printed component out of thermoplastic powder that has an embedded, functional LED using the ILS system.

Materials and methods

For this experiment, we utilized a 445nm diode laser (J Tech Photonics). This laser has a maximum operating wattage of 2.8W, but we reduced the power to 2W to extend the operating life of the laser. At focus, this laser has a beam diameter of 228.6μm. This is because lasers in this wavelength range can effectively transmit through clear, borosilicate glass surfaces, such as the one that the material layers in our ILS printer are distributed on. The laser was directed by set of mirror galvanometers that were controlled using an Arduino UNO microcontroller. The material used was a white thermoplastic polyurethane (TPU) powder (Sinterit). While this material might not optimally absorb the blue light, experimentally, this material has previously been shown to work in the ILS system. We fabricated substrates from an orange acrylic that is opaque to light at the 445nm wavelength. This acrylic was able to effectively absorb energy from the laser where it transmits through the first few powder layers. This efficient absorption both protects the test setup's surroundings and helps to increase the bond between the first few sintering layers and the substrate (Fig. 2b).

The electronic component we embedded was a 1608 SMD, red LED (SML-D15VWT86CT-ND, Digi-Key). This LED was powered using an Arduino UNO. To prevent damage to the diode, a 200 Ohm resistor was placed in series with it. To fabricate a SLS print layer, we manually coated the glass with a thin layer of an aerosolized mold release agent (Water Soluble Mold Release Agent, SLIDE). This release agent is dual purpose. For one, the fluidic state of this spray captures a single layer of TPU powder. Secondly, its placement between the powder and glass prevents adhesion of the heated material to the glass slide during sintering. Since the release agent is not cleaned off the part between layers, it might have some impact on layer to layer bonding strength. However, this is not examined here. After spraying the glass, the powder was deposited onto the release agent layer. This powder deposition was accomplished by non-selectively depositing material onto the glass/release agent using a wooden applicator. The deposited quantity was intentionally made larger that could be captured by the release agent to ensure a more even powder layer. Any excess deposited powder was then removed. The substrate was placed on the upper surface of this powder layer and pressed down. Loading was done by applying a 1kg weight to the upper surface of the plastic substrate, resulting in varying pressures on the powder layer depending on cross sectional area of the previous print layer in contact with the powder. This load was experimentally determined to produce solid contact between the unfused powder layer and the substrate/previous print layers for all stages of the printing process used to produce the print in this paper.

After the substrate is pressed to the powder, the laser was then shined through the glass, sintering a pre-defined region of the powder to the substrate. The substrate was then raised. Between each powder layer, the glass was cleaned and manually recoated (Fig.1a-e). The glass was then placed back above the laser and beneath the print, and the process was repeated, with the new print layers adhering to the previous ones.

To fabricate the ILS part in this paper, an initial 6 base layers were printed to act as a base onto which the LED could be adhered. Then, 30 chamber layers were added to create a region with an opening for the LED leads to channel through to connect the embedded part with the Arduino (Fig.1f). A 60 degree opening was left for wires. At this point, wires were pre-soldered onto both leads of the LED, and a small amount of quick-drying adhesive (Krazy glue) was placed in the chamber on the base layers. The LED was pressed to the adhesive, and the wires were directed out of the opening (Fig.1g). The LED was then held to the ad-

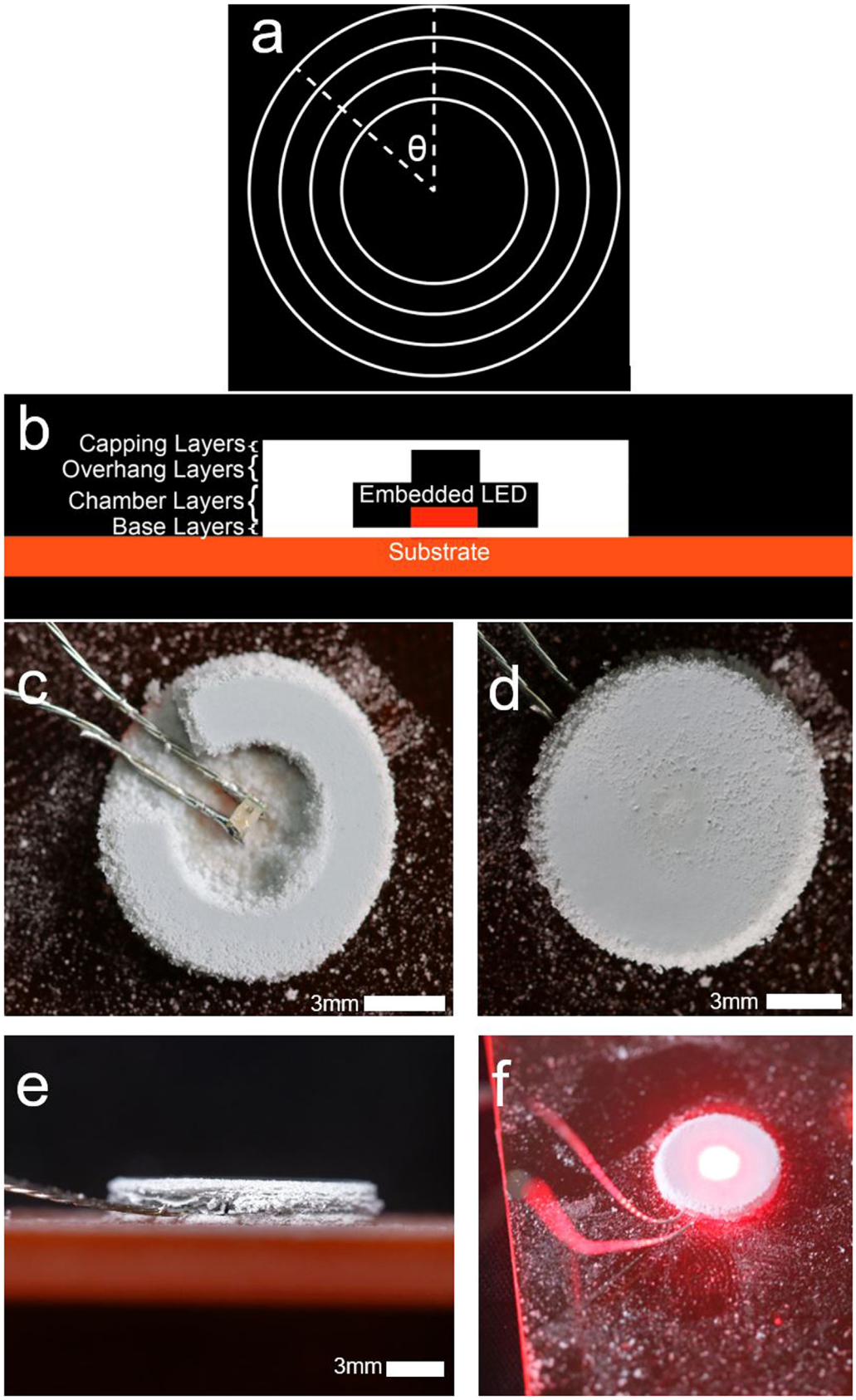


Fig. 2. a) Diagram of nested circle layer sintering pattern b) Layer diagram for the embedded LED sample c) Embedded LED adhered to the base layers, surrounded by material in the chamber layers d) Upper surface of the embedded LED sample e) Side view of the embedded LED sample showing the wires f) Activated LED shining through the upper surface of the sample.

Table 1
Processing and dimensional parameters used to produce different regions in the printed part.

Region	Outer Radius (mm)	Inner Radius (mm)	Laser Speed (deg/ms)	Distance Between Nested Circles (μm)
Base	6	0	0.2	200
Chamber	6	3	0.2	200
Overhang	6	1	0.2	200
Capping	6	0	0.1	200

hesive, which was allowed to set for 5 minutes. Finally, 19 layers were added to cover over the cavity. Of these 19 layers, 13 were initially used to cover over the channel and create a slight, covering overhang into the central chamber. These overhanging layers were included to create an intermediate area between the chamber and capping layers that had a larger surface area for the capping layers to bond to. These overhang layers may not be necessary depending on process parameters and material used. The final 6 layers created a solid capping surface (Fig.1h). Laser sintering was done with the beam being directed in a nested circle configuration (Fig. 2a). Parameters for each of these regions are listed in Table 1. To more easily define names for different print layer regions, we have included the diagram in Fig.2b. During sintering, the laser started with the outermost/largest circle and moved inwards. This circular geometry was selected as it was programmatically simple to produce with the current testing setup.

Results and Discussion

We were successfully able to fabricate a 55 layer, 2.06 mm tall, SLS printed, TPU component with a functional electronic component that was embedded during printing (Fig. 2c, d, e). This height was calculated by measuring the height of the sample from the substrate surface. This results in an average layer height of between 30 and 40 μm. Layer height was calculated by dividing the overall height by the number of layers. Initial base layers could be partially embedded in the substrate, affecting this average height calculation. To demonstrate the continued functionality of the LED, we wired it to an Arduino in series with a resistor to prevent shorting. The resulting red emitted light can be clearly seen through the print (Fig. 2f). This LED was also able to be repeatedly turned on and off after embedding (Supplementary Video 1). The visible presence of this light indicated that significant damage was not done to the embedded component (either the LED or the wires), though it is possible that minor surface damage occurred. Damage could also have been prevented to an extent by any adhesive that covered over the LED surface between the diode and the laser during embedding. While we did not determine the extent of any damage, future analysis that incorporates destructive testing of the print or x-ray imaging would be able to more thoroughly determine the effects of the embedding process on the internal components. Additionally, due to the presence of a hollow chamber, the first few layers of the overhang region likely did not perfectly retain their shape and could have sagged into the chamber. This sagging was corrected by the addition of multiple overhanging and capping layers, but still likely leads to some print “drooping” on the inside, which can be also be a problem with FDM overhang structures [16]. This amount of drooping will vary considerable with the number of overhang layers and the overhang distance.

Conclusion

The work in this paper demonstrates the ability of the ILS printing process to produce prints with embedded components. While in this example we embed a simple LED with wires protruding from the side of the part, more complex components could be possible using this process. In addition to chambers for electronic components, channels could be designed into the print into which wires could be placed to connect these embedded pieces. These wires and electronics would not have to be on the same plane or in the same layer region, as the 3D nature of the printing process allows these electronic regions to be stacked, producing functional multi-dimensional electronic circuits. Additionally, as the electronic embedding happens during the printing process, and excess material removal is unnecessary without passive support powder, these complex components would require less post-processing assembly. Future work will seek to demonstrate this further by fabricating parts that contain embedded electronic components connected by embedded wires.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary Materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.addlet.2022.100055.

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