Experiments In Layered Electro-Photographic Printing

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Abstract

Electro-photographic printing processes employed by products such as laser printers and photocopiers are commonly used to deposit and fuse thin layers of thermoplastic powder onto paper. This report describes preliminary experiments aimed at adapting the electro-photographic printing process for use as a layered manufacturing technique. 3-D electro-photographic printing holds considerable potential as an inexpensive freeform fabrication technique that is suitable for office environments. The possibilities for selective coloring are also discussed.

Introduction

Electro-photographic printing processes employed by products such as laser printers and photocopiers are commonly used to print toner onto paper or plastic substrates. Although the printed images are routinely referred to as "two-dimensional", they obviously do have a finite and measurable thickness. The toner used to print these images is a blend of several materials, the largest constituent of which is typically polystyrene. Given the fact that laser printed images have thickness, and that conventional toner is primarily a thermoplastic (polystyrene), the natural question arises as to whether the electro-photographic printing process can be adapted for use in a layered manufacturing technique. If such a process could make use of existing mass produced laser printer engines, then the process would potentially offer an extremely inexpensive approach to prototyping. Furthermore, the process would have considerable potential in the area of selective coloring.

This paper reports on initial experiments designed to investigate the capabilities and potential of 3-D electro-photographic printing, and to identify the major technological hurdles that must be overcome in order for the process to become viable as a SFF technique. Issues pertaining to CAD model slicing for 3-D electro-photographic printing are also presented.

Layered Electro-Photographic Printing

One of the earliest references to the concept of layered manufacturing via electro-photographic printing can be found in Bynum's patent (Bynum, 1992). The patent describes four unrelated layered manufacturing techniques, one of which relates to electro-photographic printing. Bynum’s concept involves using an electro-photographic process to selectively deposit a thermoplastic toner onto a continuous teflon coated belt. The toner on the belt is heated to the point that it becomes “tacky”. The belt is then indexed such that the printed image is registered above the previously deposited layers. Finally, a platen presses the tacky printed image onto the top of the previously printed images. It does not appear that a functioning apparatus was ever built, or that experimental details have ever been published.

Johnson (1994) describes an interesting process that he terms Particle Deposition Fabrication. This process is similar to Bynum’s concept in the sense that thermoplastic toner powder is selectively printed and fused. However, the method of depositing the toner is slightly different. With this process, a magnetic core particle carrier drum has a thin uniform coating of magnetic toner particles applied to it. Beneath the carrier drum lies a matrix of control electrode apertures. Each aperture is individually addressable such that electromagnetic fields that induce toner to jump off of the carrier drum and onto the printed object can be selectively turned on and off. This technique is used to selectively deposit toner particles that are subsequently thermally fused to the substrate. As is the case with Bynum's approach, it does not appear that a functioning apparatus using this approach has yet been built.

Outside of the two conceptual techniques described by Bynum and Johnson, virtually no details on layered electrophotographic printing can be found in the literature. Despite the lack of published data, if a process could be developed that employed conventional electrophotographic print engines, then the process would hold considerable promise as an inexpensive SFF technique. Much of the promise would derive from the fact that the most expensive component (i.e. the print engine) is already mass produced and therefore is quite inexpensive. Furthermore, color laser printers are becoming quite inexpensive. For example, the Hewlett Packard LaserJet 4500 color laser printer currently has a street price of approximately $2,500 (U.S.). This indicates that a color layered electrophotographic printing process would also be relatively inexpensive.

Due to the fact that evidence of an actual functioning apparatus could not be located, a series of preliminary experiments designed to shed light on the challenges associated with developing a viable layered electrophotographic printing process were conducted.

Initial Printing Experiments

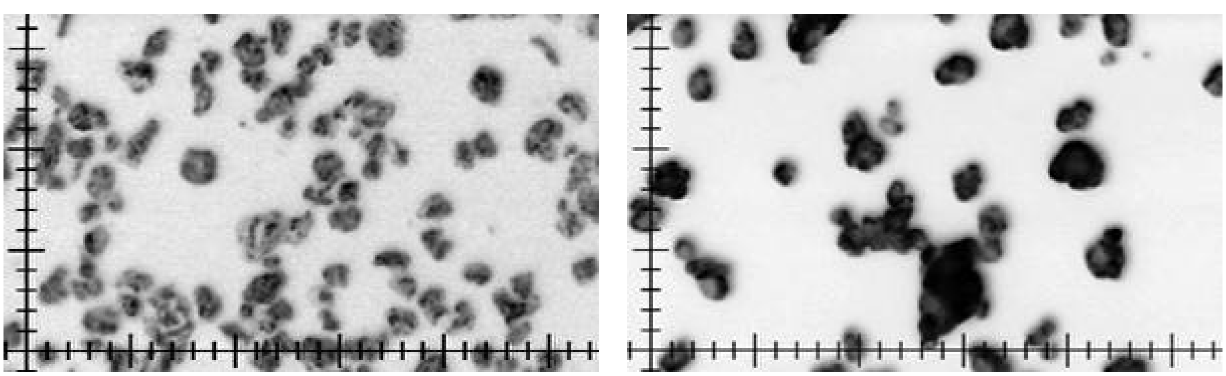
The initial experiment used a Hewlett Packard Laserjet 2100 laser printer. First, a layer of polyvinyl alcohol (PVOH) film was affixed to a paper substrate. The PVOH sheet was then fed through the laser printer 30 times while the same image of a simple rectangle was printed onto the same location of the sheet. Upon completion, the paper was placed in warm water. Since PVOH is soluble in water, the PVOH beneath the printed image dissolved, thus allowing the 30 layer thick printed rectangle to release from the paper. This basic process was repeated numerous times.

Although the initial experiments worked well, the resulting parts were quite brittle. According to Pickett (2000), toners come in both magnetic and non-magnetic formulations. The choice depends on which type of print engine is used. The HP 2100 laser printer uses the more common magnetic toner formulation which consists of a polystyrene-acrylic copolymer (approximately 60% by weight) and ferrous oxide (approximately 40% by weight) blend (Hewlett Packard, 2000). The polystyrene-acrylic copolymer has a glass transition temperature (T_g) that is approximately 55˚C. Since this T_g value is above room temperature (i.e. it is relatively brittle at room temperature), the powder can be inexpensively mass produced via conventional ball milling. Unfortunately, the polystyrene acrylic copolymer toner that is specially formulated to facilitate mass production also leads to brittle laser printed objects. Thus, the formulation of toners with more desirable mechanical characteristics is an open research issue for this process.

Any efforts to formulate new toners must obviously be compatible with the process that is used to print the toner. Pickett (2000) indicates that the rollers used to pick up toner within a toner cartridge have a texture that is specifically designed to pick up a single layer of toner particles. It is desirable, therefore, for newly formulated toners to have similar size and shape characteristics as conventional toner. In order to examine the basic size and shape of conventional toner, a sample was placed beneath a microscope (Figure 1-a). The scale in this figure is 10 _m per division, thus toner particles appear to be spherical with a diameter of 10 – 15 _m. For comparison, a sample of high density polyethylene (HDPE) was placed under the microscope (Figure 1-b). Although some of the particles tended to clump together, the individual particles are approximately 10 _m in diameter and also have a predominantly spherical shape. Based upon this fact, a toner cartridge was emptied and cleaned out with the assistance of a local toner cartridge remanufacturing firm. The conventional toner was replaced with the HDPE powder, and the printing experiment was repeated. Although the fusion temperature was not adjusted lower for the HDPE, the laser printer printed this powder without any difficulty.

Selective Coloring Experiments

Based upon the initial demonstration of feasibility, a second set of experiments involving selective coloring was attempted. This experiment used a Hewlett Packard LaserJet 4500 color laser printer. As was the case with the initial trials, PVOH film was attached to a sheet of paper that was subsequently passed through the color laser printer 30 times while the same image was printed. Initially, solid rectangles in a variety of colors were printed and released from the PVOH substrate. In subsequent experiments, multi-color images such as yellow and black bulls-eyes were printed (Figure 2).



(a) (b)

Figure 1 - (a) Toner Particles; and (b) HDPE Particles (10 microns per division)

Figure 2 - Yellow and Black Bulls-Eye

Initial trials with color printing revealed an interesting phenomenon. With each successive layer that was deposited, the parts grew darker and darker. It was hypothesized that the color toners are formulated such that the color and luminescence of the printed image account for the backlighting that occurs when light bounces off of the white paper after having passed through the toner. In order to test this hypothesis, two experiments were performed. In the first experiment, a series of red rectangles were printed, each of which had more layers than the previous rectangle. Images of these samples were captured using a flatbed scanner, and the color and luminescence were measured using Adobe PhotoShop. The experiment revealed that the color was independent of the number of layers, but that luminescence decreased as the number of layers increased.

For the second experiment, a sample of experimental white toner was acquired from a toner supplier. The printer's black toner was replaced with the white toner, and a set of rectangles with varying numbers of layers were again printed. With this set, however, all but the top layer were printed using white toner. Only the final (top) layer was printed in red. Again, the samples were scanned and analyzed using PhotoShop. It was found that both color and luminescence remained constant regardless of the number of layers when the samples consisted of a white "core" on top of which a color "skin" was printed. More complete details on these experiments can be found in Cormier et al. (2000).

<u>Build Speed and Resolution</u>

One of the initial concerns with layered electrophotographic printing was build speed. Intuition suggests that the printed layers are so thin that the process would be too slow to be of practical use. In order to estimate the build speed of the process, a laser profilometer was used to measure the thickness of 20 laser printed rectangles. The average layer thickness was 8.35 _m with a standard deviation of 1.67 _m. Mid-level laser printers that currently sell for approximately $700 (US) have a typical print speed of 14 pages per minute. Note that this rate is based upon printed pages that are 8_″ wide x 11″ long. If 8.35 _m per layer of material is deposited at a rate of 14 layers per minute, then a layered electrophotographic printer built using a mid-level print engine would build parts at a rate of approximately 7.014 mm/hr (0.276 in/hr).

$$0.00835\frac{\text{mm}}{\text{hr}} \times 14\frac{\text{layers}}{\text{min}} \times 60\frac{\text{min}}{\text{hr}} = 7.014\frac{\text{mm}}{\text{hr}}$$

Note that this build rate is based upon parts that require the full 11″ of travel per layer. As it turns out, this deposition rate is considerably faster than intuition would suggest, and it is well within the range of existing SFF processes for a part of this size. Smaller parts would not require the print carriage to travel as far, thus the build speed would be correspondingly faster for these parts.

With regards to resolution, low-end laser printer engines currently have resolutions of 600 dots per inch, while mid-level laser printer engines have resolutions of 1200 dots per inch. These two resolutions equate to 0.0017 inches per dot (0.042 mm/dot) and 0.0008 inches per dot (0.021 mm/dot) respectively. If perfect registration from one layer to the next is achieved, then these resolution figures represent the theoretical minimum feature size that can be achieved. As is the case with most commercial SFF processes, however, the actual achievable feature size is more a function of the material properties than the process capabilities.

Slicing for Layered Electro-photographic Printing

Due to the fact that layered electro-photographic printing uses a substantially different method to deposit the material, a slightly different approach to slicing is necessary. Most SFF techniques involve motion control of a laser, printhead, or some other device that produces solid layers in a raster fashion. In the case of layered electro-photographic printing, an image is printed, thus the slicing software must produce a graphic image of the slice to be printed. Furthermore, images of both the build and support material must be constructed.

In order to produce the required images, two different slicing algorithms have been developed and implemented. The first slices STL files via conventional slicing techniques. The second employs a direct slicing approach using the SolidWorks CAD system. Both implementations output a text file containing slice contour data for both build and support regions within each layer. An OpenGL program has been written in Visual C++ that reads in the slice contour data and graphically renders the build and support material images to the appropriate scale. At the present time, these images can be manually directed to a printer one at a time. The next step will be to select an archival file format for storing the slice image data.

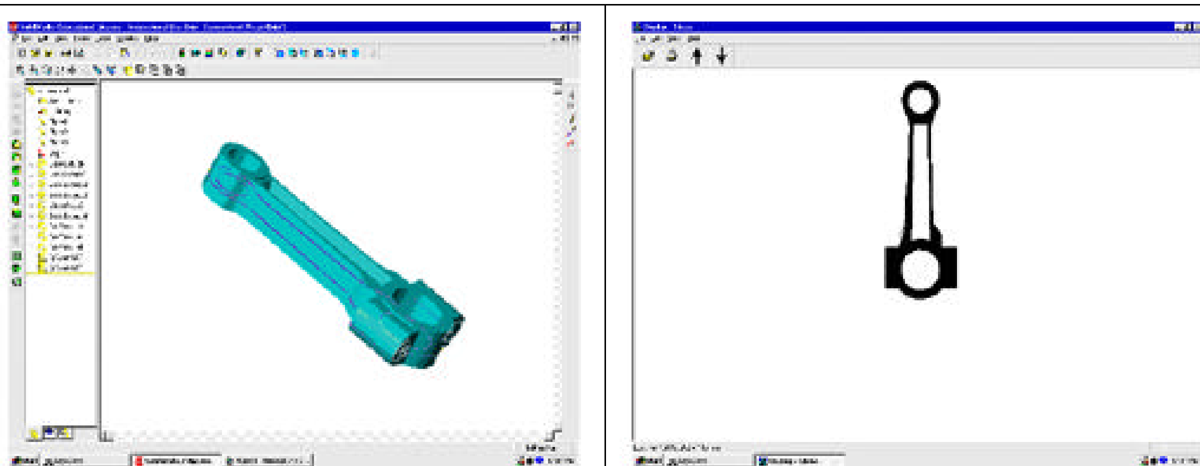
The direct CAD slicing algorithm employed within SolidWorks uses the following approach:

```
Procedure DirectSlice
For each slice
    Create a slice cube at the correct Z-height
    Intersect the slice cube with the part
    For each body in the intersection volume
        Get the number of loops in the current intersection volume
        For each loop in the current intersection volume
            Get the loop type (i.e. inner or outer loop)
            For each segment in the loop
                If the segment is a line
                Record the line end points
            Else
```

```
            Tesselate the loop
            Record the tessellation points in the correct order
        Next Segment
    Next Loop
  Next Body
Next Slice
```
End Procedure DirectSlice

This procedure has been implemented using the SolidWorks API. Note that a check must be made to ensure that outer loops are oriented counter-clockwise, whereas inner loops are oriented clockwise. This convention is necessary so that the images can be properly constructed. Figure 3(a) shows a screen dump from the SolidWorks window showing the slice outline for a connecting rod that is in the process of being sliced.

Once the slice contour data file is generated, the images can be generated. A Visual C++ program that uses OpenGL graphics routines has been written that reads in the slice contour data and renders it to the computer screen. In order to do this, it is important to render outer and inner loops in the correct sequence so that inner loops are properly rendered. Figure 3(b) shows the slice contour image that has been generated for the connecting rod example from Figure 3(a).



(a) (b)

Figure 3 – (a) Direct Slicing Screen Dump; (b) Rendered Slice Image

Open Research Issues

Based upon the initial preliminary experimentation, a set of open research issues has been compiled. In order to address these issues, it is first necessary to understand the basic operating principles of a typical electro-photographic print engine, such as the one shown in Figure 4.

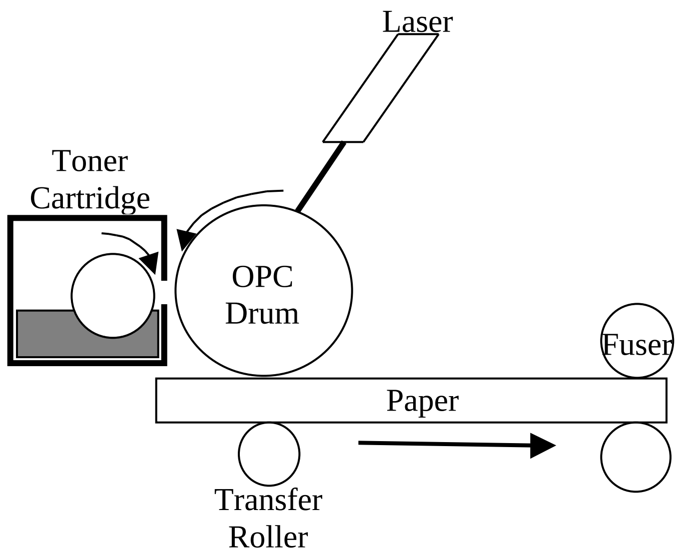


Figure 4 - Schematic of Typical Laser Printer Engine

The OPC (organic photo-conductive) drum is a cylinder with a special coating that is capable of locally holding a static charge. A laser or LED source is used to "write" a latent image onto the OPC drum as it rotates. This image is initially nothing more than selectively applied electrostatic charge. Within the toner cartridge, a thin coating of toner powder is applied to another rotating drum. As the toner cartridge drum and OPC drum rotate near one another, toner is induced to "jump" onto the OPC drum by the selectively applied static charge on the surface of the OPC drum. The OPC drum continues to rotate until the toner comes in contact with the paper. A transfer roller beneath the sheet of paper induces an even stronger force on the toner particles, thus inducing them to become deposited on the paper. As the paper exits the machine, the toner is thermally fused to the paper.

With regards to layered electro-photographic printing, perhaps the most significant technological challenge lies in inducing the printed image to leave the OPC drum and to be deposited onto the build platform. With a conventional laser printer, the paper sheet is thin enough that a transfer roller induces sufficient force through the paper. With layered manufacturing, the induced force will decrease as the part thickness increases. Therefore, an alternative method of transferring the toner powder must be employed. As stated previously, Bynum (1992) proposes heating the toner to the point that it becomes "tacky" and then mechanically pressing it onto the workpiece via a platen. Johnson (1992) identifies several other transfer techniques that have been used with printing processes, and which may have applicability for layered electro-photographic printing. These techniques include magnetization and triboelectrification.

Another issue that has not yet been mentioned is that of the support material. The approach that is being considered for the experimental apparatus is to use a second print engine that prints PVOH powder that is simply dissolved in water upon completion of printing. The challenge will be to formulate a PVOH material that has the same particle size as ordinary toner, and which has similar fusion properties as the toner. Furthermore, adhesion tests between polystyrene toner and PVOH will need to be run.

Summary

This paper has reported on preliminary tests designed to determine the basic feasibility of layered electro-photographic printing. Initial test results are encouraging, however, the investigation has also revealed several substantial technological challenges.

Efforts are currently underway to build a monochrome layered electro-photographic test apparatus. Every attempt is being made to design the initial prototype so that components and sub-systems can be interchanged while different configurations are evaluated. Collaborative efforts with Materials Science faculty are also underway to investigate issues pertaining to alternative toner formulation and their manufacture.

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