Electrophotography as a Means of Nanofabrication: The Role of Electrodynamic and Electrostatic Forces

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Introduction

Recently, nanofabrication has become an extensive research topic and, as a consequence, an eminent goal of industry. While at this time nanofabrication technology is, generally speaking, a goal rather than a defined manufacturing process, nanofabrication has been in existence, at least in one area for a considerable time. For example, electrophotography could be considered a nano-fabrication process since it produces documents and images by precisely placing large numbers (often exceeding 10^{10} per 8 ½ × 11 inch page) of micrometer-size pigmented particles, usually referred to as toner particles, in specific sites, whereby each site has a diameter of the order of 20 μm or less, at process speeds that can exceed 75 cm/s. If the toner particles are not precisely placed, the image generated by these particles will lack resolution or sharpness, will exhibit shifts in color balance, will have an increase in grain or background, etc. In order to achieve an accurate placement of the particles onto the receiver, a precise balance of adhesion or electrodynamic forces and electrostatic forces has to be achieved between the toner particles and the chosen substrates–during the entire image-forming process. The forces controlling the motion and precise location of the micrometer-size toner particles in the electrophotographic process, as an example of nanofabrication, are described in this paper. We also demonstrate in this paper how nanofabrication can be correlated to an electrophotographic process in a general sense and illustrate this concept with several examples. Finally, the physics and engineering associated with extending this technology into the process of fabricating microscopic components and devices are explored in this paper.

Experimental

Usually, in an electrophotographic imaging process, a photo-receptive element is first uniformly charged. It is then image-wise exposed via flash exposure, laser scanner or LED array. This process generates an electrostatic latent image that is then developed into a visible image by bringing the photoreceptor into close proximity to a development station that contains charged toner particles. Subsequently toner is image-wise deposited onto the photoreceptor in either the charged or uncharged areas depending on the charge of the toner particles and the relative biases on the photoreceptor and the development station.

After development, it is necessary to transfer the toned image from the photoreceptor to a receiver such as paper, polymer, or some other material. This is accomplished by electrically biasing the receiver while the receiver is in physical contact with the toned photoreceptor. The image is then fused to the receiver. The photoreceptor is then cleaned to remove any residual toner and made ready for subsequent imaging. The electrophotographic process is described more fully elsewhere.[1]

In order to be used in other nanofabrication processes, the electrophotographic process often has to be modified. This is the case, for example, when electrophotographic technology is used to produce printed circuits. In this instance, electrophotographic technology was used to produce 2-dimensional motors used to drive the film advancement mechanism and operate the shutter, as well as the printed circuit board used to operate a Kodak Disc camera. In this example, the photoreceptor had first been coated with a thin layer of a fluorinated hydrocarbon (Fluo-HT) in order to reduce toner-to-photoreceptor adhesion prior to imaging.[2] Toner addenda such as silica could have been used to reduce the toner adhesion.[3] However this was not employed in this application because the accompanying decrease in cohesion would give rise to decreased resolution[4] as well as increased satellite toner particles around the image areas.[5]

Commercial flex-circuit material, which is a thin layer of copper on a Mylar™ polyester support, was the substrate. An electrostatic latent image was formed on a commercially available organic photoreceptor by applying a negative corona charge followed by an image-wise, contact exposure though a transparency corresponding to the design of the circuit. A commercially available electrophotographic developer, with positively charged toner, was used to develop the image. Transfer to the flex circuit receiver was accomplished by directly biasing the copper with a transfer voltage of 500 volts DC and pressing the receiver into physical contact with the photoreceptor using an elastomer-coated aluminum roller. The image was then placed in contact with a sheet of Kapton-H™, which served as a ferrotyping material to insure the absence of any pinholes. The Kapton-H – flex circuit sandwich was fixed by passing it through a pair of heated fusing rollers. The Kapton-H was separated from the flex-circuit after the package had cooled.

The printed circuit was produced by etching the toner-coated flex circuit material in a ferric chloride solution. The toner served to mask the copper from the etch solution. After rinsing and drying, the functionality of the circuits was evaluated without removing the fused toner.

The 2-dimensional motors were fabricated in a similar manner.

Results and Discussion

The printed circuits and 2-dimensional motors produced electrophotographically were found to be totally functional. The etching process undercut any copper that had been under isolated satellite toner particles, eliminating any potential problem associated with copper in undesired locations. However, undercutting of fine lines also occurred, as it also does with conventional photolithographic means of producing printed circuits. Undercutting can be minimized by matching the thickness of the copper to the fineness of the lines that are to be produced. The presence of satellite toner particles is critical where lines or solid areas are in close proximity to one another, as illustrated by the narrow regions between sections of the armatures of the motors and the small open regions that allow for wires to be drawn between layers of the circuit board. While the tendency to fill in such areas arises from several factors, including the presence of fringe fields, the use of toner with low cohesion, such as those with particulate silica coatings, increase satellite formation and aggravate this problem. Accordingly, for this application it is desirable to decrease the adhesion of the toner to the photoreceptor, while maintaining relatively high cohesion.

Too much cohesion can also, on occasion, cause problems. Specifically, if toner cohesion and adhesion to the photoreceptor is too great, there may be a failure to transfer the centers of the lines. Defective circuits can result from insufficient masking of the copper as a result of an imbalance between toner cohesion and photoreceptor adhesion. The use of an electrophotographic process to produce printed circuits is not the only demonstrated novel application for this technology. Mutz, for example, used similar techniques to electrophotographically produce lithoplates for offset printing.[6] Mutz's method of producing these plates was very similar to the techniques discussed here except that the toned images were transferred to aluminum press plates instead of copper flex circuit material and, of course, there was no etching. The resulting plates were set in an ink press and, following normal offset techniques, the plates were sprayed with water. The water wet the bare hydrophilic aluminum, but was repelled by the polymeric toner. Oil based ink was then applied to the plate. The ink wet the dry letters formed by the toner, but not the wet aluminum. The plate was then pressed against paper and a printed page resulted. It was found that the plate lasted in excess of thousands of impressions.

It is apparent that electrophotographic technology can be used for nanofabrication. Moreover, the use of this technology for such applications depends on the proper balancing of electrostatic and van der Waals interactions. Specifically, there are cohesive forces between the particles and adhesive forces between the particles and the receiver and photoreceptor originating from van der Waals interactions. The cohesive forces minimize the number of satellite particles, but also can cause defects such as "hollow character", which is the failure to transfer the centers of fine lines and dots. There are also electrostatic forces present. These give rise to Coulombic repulsion between the particles that result in toner satellites. They also contribute to the adhesive forces via the formation of image charges in the electrically conducting substrate. Finally, an externally applied electric field produces an electrostatic toner transfer force that assists the transfer of toner to the substrate. In order to produce high quality electrophotographic images or to use electrophotographic technology for other applications, it is vital that these interactions be properly balanced and controlled.

The realization that with careful attention to electrostatic and van der Waals forces the precise placement of micrometer-size particles can be achieved and that the particles can be transferred to other substrates and fused, opens the door to the fabrication of other items. We illustrate this concept with a few examples.

First, consider the fabrication of a small plastic gear. This can be achieved by developing an electrostatic gear pattern using toner particles, transferring that image to a substrate, preferably one that would rapidly dissolve or deteriorate in water, and fusing the toned gear image. Upon dissolving the substrate, one is left with a plastic gear.

This concept can now be extended to produce a geared device such as a 2-dimensional transmission. An electrostatic latent image corresponding to the entire device can be formed on a photoreceptor, developed, and transferred to a receiver that comprises, for example, a water-soluble subbing layer on an insoluble support. Gears that are ganged together can be formed using multiple development cycles, in register, in a manner analogous to that presently used to form color images from the primary color separations.

Multiple layered structures can be produced by layering individual units over each other. Holes for axle shafts can be produced electrophotographically, and metallic axles inserted electrostatically.

Ceramic parts and devices can also be created. However, high sintering temperatures would be needed to fuse ceramic particles. The need for a high sintering temperature could also be used to eliminate any undesirable support that was necessary during the electrophotographic production process.

Conclusions

Electrophotographic printing is a form of nanotechnology involving the repetitive and controlled placement of micrometer-size particles to produce images. However, the use of this technology to produce devices such as printed circuits and lithoplates for printing presses shows that electrophotography can be used for nanofabrication applications. Moreover, electrophotographic technology appears to have the potential to be able to produce many other components such as gears and entire devices. To do so requires the careful control of electrostatic and van der Waals forces acting on the particles.

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