Transfer Methods toward Additive Manufacturing by Electrophotography

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Abstract

3D printing of complex structures by selective deposition is currently dominated by inkjet technologies. Dry toner systems, despite their high productivity and maturity in 2D digital printing, have only been used indirectly for Additive Manufacture of objects above the micro scale. Although electrophotography (EP) promises increased deposition efficiency and a means of utilizing materials not amenable to liquid ink formulations; this potential cannot be achieved using conventional electrostatic transfer methods.

This paper reviews the problems associated with conventional transfer in multilayer printing (including height limitation and defect exaggeration) and demonstrates alternative transfer principles which promise to unlock the potential of Additive Manufacturing by EP.

Introduction

Upscaling electrophotography (EP) to be a viable means of printing three-dimensional parts has been the elusive goal of many researchers throughout the twenty-five year history of additive manufacturing (AM).[1-6] Despite some success at the micro scale, AM systems benefiting from the speed, resolution and reliability of electrophotography for directly printing larger parts remains only a proposition to date.[7, 8]

Reinventing electrophotography in the context of additive manufacturing raises a host of challenges. Perhaps the most demanding requirements for implementing electrophotography as a fabrication means above the micro scale include: a range of functional toner materials, effective transfer methods which are not height limited, and test methodologies for evaluation of multilayer printing. Owing to the attention which has already been given to development of functional toners this paper focuses on the latter two needs.[9-13]

Previous attempts to overcome the limitations of conventional electrostatic transfer in multilayer printing are reviewed. A series of conventional and alternative transfer methods are considered. For consistency all transfer illustrations show negatively charged toner (even if positively charged toner was used). A test methodology for comparing transfer effectiveness based on build stack height and surface roughness is proposed. The findings highlight major factors contributing to surface defect exaggeration and stack height limitations.

Conventional Transfer Method Development

The transfer step initially used by Chester Carlson and Otto Kornei to develop EP, did not employ electrostatics at all, but relied on the toner in the developed image sticking to wax paper.[14] A wide variety of adhesives on paper were trialed for an entire year before it occurred to Schaffert to use electrostatics to transfer the toner from the photoconductor plate to the paper.[15] Drawing the toner off using a field generated through the paper (Figure 1) proved to be a far more effective transfer method, eliminated the need for sticky paper and has proven so reliable that it has become a universal convention.[14]

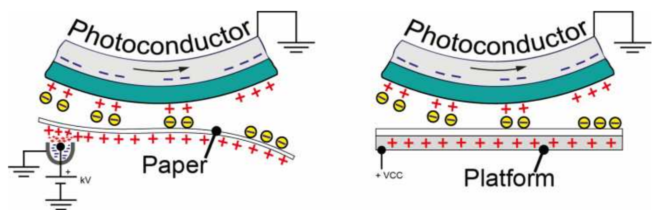

***Figure 1** – Conventional transfer method implementations*

Historical Attempts to Upscale EP

The progression from single layer prints to multilayer prints was made with the move from monochrome to color printers. This section will now consider attempts to print from tens to hundreds of layers with the intention of achieving specific functionality or form.

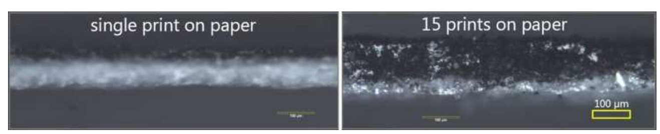

***Figure 2** – Comparison of the stack height from single to 15 layer prints*

Demonstrations such as the one pictured in Figure 2 have doubtless been repeated dozens of times as an early feasibility check when considering the potential of electrophotography for functional multilayer printing. The cross-sectional optical microscopy samples shown were printed using a Ricoh Aficio CL7000 (Ricoh Company Limited, Tokyo, Japan) on 80 gram paper. The print on the right was made by feeding the same sheet of paper through the printer 15 times, which accumulated a fused toner thickness of approximately 100 µm. Attempts to re-circulate the paper more than 15 times repeatedly resulted in paper jams. The engineering constraints of typical paper feed mechanisms in modern laser printers oblige researchers intending to print hundreds of layers to use an alternative substrate. This often takes the form of a rigid conductive platform as shown in Figure 1.

Surface Defects Problem in Multilayer Printing

To those unskilled in the art, directly transferring one image upon another seems primarily an engineering issue – all that is required is to replace the paper feed mechanisms with a moving platform. Following that logic, the sample in Figure 3 was produced by using a CTG-1C17-600 printer (CTG PrintTEC, Germany) with a conventional polyester toner (Samsung Poly-JZ) to print a rectangular pattern (120x80mm) twenty times onto a rigid substrate. After each print, the height of the platform was adjusted to maintain a consistent nip contact area and pressure between the drum and the upper layer of the image stack. Although the first few prints resulted in a uniform transfer, by the 20th image extensive surface defects were evident.[16]

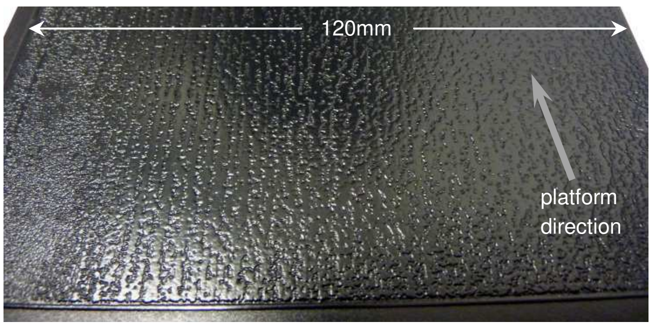

Figure 3 *– Surface defects arising during multilayer printing*

The surface quality degradation problem illustrated above is not an isolated occurrence. It has been described by researchers as "defects," "irregularities," "pitting," "valleying," and as having a surface which "corrugates" – the cause of the defects is often left unexplained, however it has been attributed to electrostatics and repeated surface re-melting.[4, 8, 17, 18] Due to the self-propagating nature of the defects they halt the uniform growth of stack height and thus limit the use of EP in mainstream additive manufacturing applications.[17] Every research group, to the author's knowledge, which has attempted to directly print image stacks using non-conductive toner to heights in excess of 1 mm has experienced some kind of surface defect.

Self-Limiting Nature of Conventional Transfer

Ashok V. Kumar et al. of the University of Florida have published prolifically about conventional transfer limitations and potential solutions.[18-24] Kumar and Dutta explain that when using nonconductive toner, conventional transfer is only useful for small parts because, "the electric field strength at the top layer decreases as the part height increases."[4]

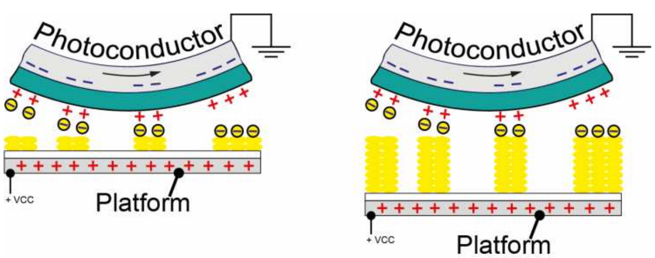

Figure 4 *– Self-insulating nature of multilayer printing*

Figure 4 illustrates the self-insulating nature of multilayer printing when using nonconductive toners. Since E=V/d maintaining a constant voltage (V) on the platform means that each layer printed increases the thickness (d) of insulation between the photoconductor and the transfer potential thereby diminishing the field strength (E) at the top layer. Therefore with each successive print, the thickness of the fresh toner layer deposited drops.[25] Eventually, there is no longer the critical field strength required at the top surface to attract any toner off of the photoconductor resulting in a "cessation of transfer."[25] Thus, the early innovation by Schaffert to draw toner off of the photoconductor using a field through the paper substrate is an inherent limitation for 3D printing.

Top Charging Transfer Method

Attempting to circumvent this limitation, Kumar et al. installed a corona wire to charge the top surface of the printed image stack before each print as shown in Figure 5.[4, 18] By saturating the uppermost printed layer with ions it was intended that the electrostatic field induced between the fused toner and the photoconductor would be enough to transfer the toner onto the substrate. Theoretical calculations and empirical results by Fay and Dutta suggest that "…the part would continue to build indefinitely with adequate corona charging…" as long as the resulting build stack could be consistently discharged.[17, 25]

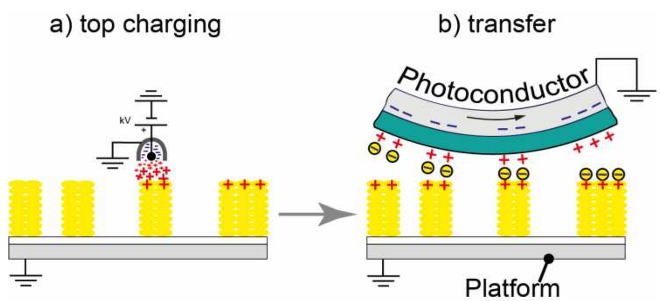

Figure 5 *– Top Charging transfer method steps as employed by Kumar et al.*

The top charging approach doubled the height of the printed image stack from 1 mm to 2 mm without noticeable surface degradation.[25] Although various trials showed image stack growth in excess of 2 mm, surface defects formed thereafter which were exaggerated with each successive print.

In the final analysis, Kumar Das surmised that the surface defects were caused by the accumulation of residual [negative] toner charge which was not being fully dissipated prior to fusing each layer.[26] He acknowledged that the positive charge from the corona wire counteracted the residual toner charge in the early layers (when it was close to the platform), but its effectiveness diminished as the platform moved further away from the wire.[26] In essence this is a parallel problem to that of conventional transfer. The grounded platform was being shielded from the wire in proportion to the increasing toner thickness, therefore the surface deposited coronal charge was limited by the breakdown strength of the air (Gaussian Charge Limit) and could no longer supply enough positive charge to fully neutralize each layer.[26] With the fusing of each new layer of negatively charged toner, an increasingly negative volumetric charge is accumulated in the printed image stack. When the repulsive force exerted by the volumetric charge on the incoming fresh toner exceeds the attraction created by the positive surface charge, defects form. Based on his attempts to fully discharge printed layers Kumar Das observes that, "Complete discharge of the volume charge of a printed insulator layer is very difficult to attain."[26]

Even though the top charging transfer method pushed the maximum image stack height to 2 mm, mainstream additive manufacturing applications require increasing the image stack height by two or three orders of magnitude. The limitation of conventional transfer had been replaced by a new limiting phenomena induced by charge retention in the fused nonconductive toner layers.

Transfer by Heat and Pressure

In 1992 David K. Bynum was granted two United States patents for using electrophotography to print individual lamina or layers to be stacked and fused together.[1] The method for his transfer step (Figure 6) was that each, "lamina is made tacky by the application of external heat, solvent vapor or induction heating."[1, 27] The fresh toner in the developed image would stick to the tacky layer beneath and after the transfer was complete a platen press applied enough pressure to fully densify the printed image stack.[1] In essence, Bynum's transfer approach operated in the absence of electrostatics and harked back to the earliest adhesion transfer method employed by Carlson and Kornei.

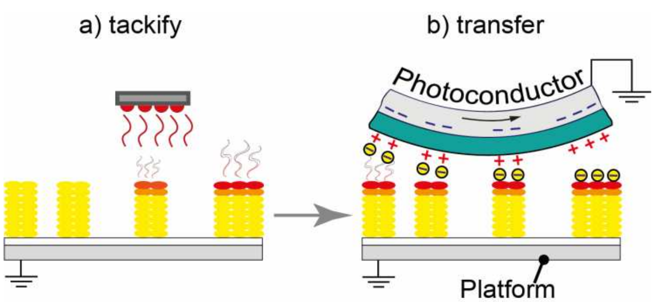

***Figure 6** – Transfer method by Bynum based on making layers tacky*

There is no evidence that Bynum ever built a functional system or published results from further trials, however others have implemented the principles that he asserts.[28] Ed Grenda, Dennis Cormier et al., Klas Boivie et al. and Banerjee and Wimpenny have developed hardware and published experimental results using some combination of heat and pressure for transfer and fusing.[3, 5, 6, 28-30]

Further to these is a heretofore unpublished sample, courtesy of David Wimpenny, built using Bynum's transfer approach. Figure 7 is the tallest (~10mm) directly deposited layer stack made from non-conductive tribocharged particles known to the author. Banerjee and Wimpenny commissioned CTG PrintTEC (Alsdorf, Germany) to produce the sample using an electromagnetic brush coating technique (EMB) which allowed great flexibility on the temperatures and pressures used. EMB coating develops a uniform layer of tribocharged particles onto a transfer roller that can be transferred off using only heat and pressure.[31, 32]

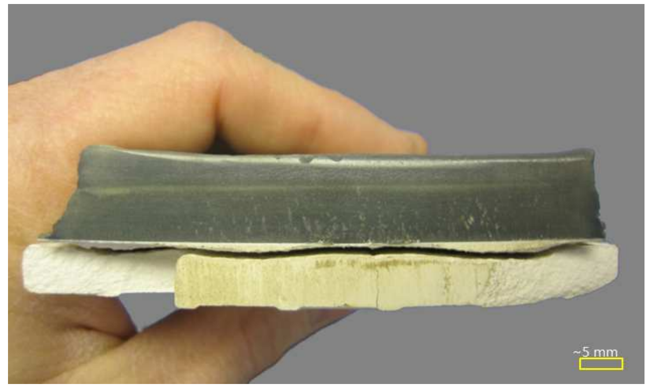

***Figure 7** – Multilayer sample produced using the Bynum transfer method*

Before depositing each layer of the sample in Figure 7 the previously deposited layers (and ceramic tile substrate) were preheated in an oven at 150°C for approximately five minutes. The tile was then mounted onto the platform of the EMB machine and another layer of epoxy-based powder was added with pressure that was substantially higher than would be used in an average office laser printer. A significant amount of manual manipulation of the sample was required to counteract the tendency for the edges of the sample to curl when heated in the oven. Despite the fact that producing a sample in this way does not allow for a like for like comparison with the samples produced on the systems mentioned in the second paragraph of this section (that use a photoconductor), this result provided preliminary proof of concept for Bynum's transfer approach.

Based on the sample produced above Wimpenny et al. in collaboration with MTT Technologies Group Limited (Stone, UK) built a demonstration rig (Figure 8) which uses two CTG-1C17-600 industrial laser printers (CTG PrintTEC, Germany) and infrared heaters (employing a Bynum transfer approach) as part of the European Union funded Custom-fit project.[9, 12, 33]

***Figure 8** – Selective Laser Printing (SLP) Development Rig*

Using this development rig a variety of samples were built including tensile test specimens which exhibited exceptional mechanical properties.[9] However, when attempting to replicate the stack height as demonstrated with the sample produced by EMB coating technology, surface quality issues began plaguing the polymeric parts when build stack heights exceeded 1 mm high.

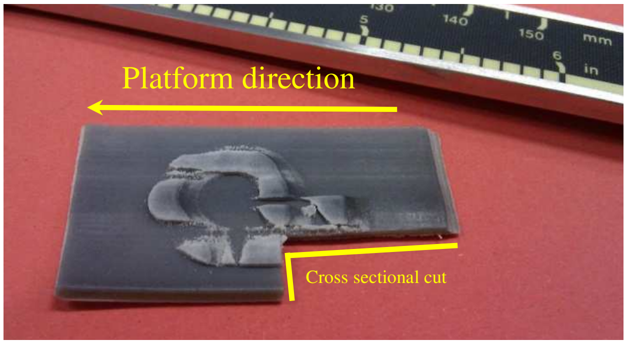

***Figure 9** – Tallest SLP sample from Custom-Fit project*

Figure 9 shows the tallest sample made on the SLP rig (courtesy of David Wimpenny), printed using surface coated Somos 201 material.[9, 30] The original intent was to create a benchmark of the maximum height the SLP rig was capable of at that time. The rectangular base was printed to a height of approximately 1.6 mm when the process was aborted due to waviness developing at the upper surface. After a one-hour recess the upper surface of the part was reheated to 130° C and printing of the text was attempted. Surface defect exaggeration was observed (which is why the text is not legible) as another ~0.7 mm of thickness was deposited non-uniformly onto the rectangular base and then the process was terminated.

Attempts to raise the tackifying surface temperature to match transfer conditions used for the EMB feasibility sample resulted in back transfer to the organic photoconductor (OPC) which required replacement.

Learning Outcomes from Heat and Pressure Transfer Methods

The disappointing initial results from the SLP development rig provided strong motivation to analyze any differences from the EMB process. Assuming that Kumar Das is correct – that toner charge retention is problematic provides a useful framework for discussion.[26] First, the EMB process had more time to discharge between each deposition cycle. The semi-automated nature of the EMB process meant that roughly ten minutes passed between each deposition cycle while the SLP rig printed more than once each minute. Secondly, the EMB sample had more exposure to elevated temperatures, which enhances conductivity in pure epoxy (and most nonconductive materials), therefore promoting charge recombination.[34] The oven heating regime for the EMB produced part meant that it had at least a five minute dwell time at 150°C, while the SLP sample was rapidly heated to 130° C by infrared heaters and then began cooling back toward room temperature. This meant that the SLP produced sample had a lower maximum temperature and that it was at elevated temperatures for far less time. Furthermore, epoxy has a higher dielectric constant (3.7-3.9) than Somos 201 (2.9) meaning that epoxy material may be less prone to retain charge.[35]

Similar to the way photoconductors can develop a residual image when the latent image is not properly discharged it follows that tribocharged toner can retain a residual charge even after final transfer and fusing. The results from early trials on the SLP rig indicate a strong possibility that electrostatic forces still play a crucial role even when the transfer method does not directly employ electrostatics.

Conclusions

Electrophotography still represents an untapped technology for direct deposition additive manufacturing systems.

As asserted by Cormier et al., “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.”[28] Although controlling the Bynum transfer method has proven impractical for producing high accuracy part features, the SLP development rig has been a versatile tool for understanding transfer principles, imitating past transfer configurations and exploring alternative transfer methods to enable additive manufacturing by EP.

A review of published and heretofore unpublished work on transfer methods reveals several common challenges. In many cases transfer methods are self-insulating because the image stack height and transfer efficiency are inversely proportional. Furthermore, residual toner charge, considered of negligible importance in conventional 2D printing, is proving problematic when trapped volumetrically in the consolidated layers. The results herein corroborate with and strengthen the previous assertion that the repulsive force exerted by the trapped volumetric charge is the cause for defects in the printed layers.

Future Work: Characterizing Multi-layer Transfer Phenomenon

The dominant theme moving forward will be characterizing residual toner charge after transfer and fusing including the rate of accumulation and its effects in multilayer printing.

The proposed methods of measuring its and its effects include: a) the surface potential of printed layers b) deposition thickness of each layer and c) the study of surface defect development using surface roughness and magnitude measures.

With proper understanding of the charge retention phenomena appropriate methods to combat and eliminate the residual charge will be forthcoming.

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Jason has undertaken research in the field of Additive Manufacturing since 2005. He was appointed as a Senior Research Fellow in 2007 to lead collaborative research projects. He explores applications for customised products and develops new layer based manufacturing techniques by electrophotography and direct writing. He is also actively developing international standards for Additive Manufacturing within ASTM. He currently shares research facilities with the University of Warwick and De Montfort University, both in the UK.

For five years prior to his research appointment, he worked in the CNC & 3D printing industry as Technical Manager for Unimatic Engineers Ltd, in London, England.