The Influence of Residual Toner Charge on 3D Laser Printed Objects

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Abstract

The recent advances in digital fabrication have nearly become synonymous with the formulation of functional inks and inkjet printing. Conversely, dry toner systems, despite their high productivity and maturity in 2D digital printing, have scarcely been utilized for 3D printing and digital fabrication, despite significant endeavor.

This paper reviews the advantages that laser printing offers digital fabrication (over inkjet) and provides insights to overcome the technical barriers which to date have prevented it from gaining traction as a 3D printing technique.

Introduction

Electrophotography (EP), the basis for laser printing, was the first digital printing technology and was predicted in the early 90's to be, "the most prevalent printer technology of the 2000s" [1]. Now twenty years on, electrophotography still plays a dominant role in the office printing sector, however it has not kept pace in digital fabrication (DF) and 3D printing contexts. Despite its inherent micro fabrication capability and investigations into its application for electronics (since the mid-50's), 3D printing (since the mid-80's) and bio-fabrication (more recently), EP has yet to be established as a definitive digital fabrication means [2-5].

Central to the technical reasons for laser printing being underutilized for 3D printing is a lack of understanding of how residual toner charge influences multilayer 3D laser printed objects. This issue is analogous to the need to manage, and ultimately dispose of, the carrier liquid in the inkjet process. In the same way that a carrier liquid is an essential element enabling inkjet printing, yet after printing is often regarded as a nuisance which needs to be eliminated (through evaporation, absorption into the substrate/pumping layer, or cross-linking/freezing into a solid matrix, etc.); electrostatic charge on toner enables laser printing, yet after printing, the residual charge on the toner (if left unmanaged) becomes a nuisance which needs to be eliminated in order to unlock its potential for multilayer applications.

This paper first elucidates the rationale for re-investigating laser printing as a fabrication means appropriate for applications that leverage its natural strengths over incumbent digital fabrication technologies. Then, the correlation and causation of defects arising during layer on layer laser printing are considered with regard to the retention of residual toner charge. Lastly, the findings offer some insights into overcoming defects by effective charge management throughout the fabrication process.

Strengths of Laser Printing

Although substantial achievements in digital fabrication and 3D printing have been predicated upon the merits of inkjet technology (thermal, piezo, aerosol, etc.), gaps in current capability provide incentives to investigate the suitability of alternative digital printing techniques to complement existing offerings.

Laser printing is a proven means of digitally depositing material with speed and resolution that rivals inkjet. Laser printing inherently deposits water-fast layers of dry powder materials typically from a few microns up to 100 µm in diameter. This makes its volume scalability superior to inkjet where depositing solid materials is the priority. In fact, recently at least two research groups have switched from inkjet technology to laser printing in order to print larger diameter solids (>5 µm dia.) [6, 7]. Büttner et al. emphasized this and other strengths compared to inkjet by saying, "Its main advantages are the possibility of printing larger particles, its much higher printing speed and the absence of solvents" [7]. Minimal use of solvents and additives (compared to inkjet) reduces contamination considerations and provides a more favorable outlook for recyclability. The fact that toner is normally a thermoplastic material reinforces its environmental friendliness and potentially provides better strength to consolidation speed ratio than thermosets [8, 9]. Furthermore the fact that it is a dry process avoids surface wetting issues, makes it more amenable to thermal processing, and enables water soluble materials to be deposited for use as support structures when fabricating complex geometries [10]. Also, the contact at transfer and fusing can improve the integrity of consolidation [8]. In short, for some materials, laser printing has a lower specific deposition cost with the potential to deposit nearly 100 wt./vol. % of the target material without unwanted additives. The long-standing coexistence of laser printing and inkjet technologies in 2D printing is evidence of their complementary natures which can also coexist in DF.

Multilayer Transfer Challenges

The fundamental ethos of 3D printing is to build objects by stacking and laminating multiple printed layers one on top of another. This requires that each printed layer form a suitable foundation upon which subsequent layers are deposited. Maintaining consistent *layer quality* throughout the build stack, which typically consists of hundreds of layers (depending on part size and resolution), is essential to ensure the correct shape is achieved and adequate *lamination strength* is imparted to the finished object. Past attempts to use laser printing for 3D objects have revealed layer quality shortcomings inherent in conventional transfer, and perhaps to a lesser degree, fusing steps.

Modern conventional toner transfer techniques are derivatives of the method invented at Battelle Memorial Institute which used an electric field propagated through the paper substrate to pull the toner off of the photoreceptor [11]. Although conventional transfer methods have been successfully employed for digital fabrication of objects made from relatively small non-conductive toner build stack heights (<1mm) [6, 12], build stacks exceeding 1 mm begin to suffer from layer defects due to breakdown or insufficient transfer field strength (due to the difficulty of propagating a field through the printed layers which act as insulators) [13, 14].

Researchers have attempted a variety of single and double transfer hardware configurations to overcome the self-limiting nature of conventional and alternative field-based transfer methods which have had limited success and are comprehensively reviewed elsewhere [13].

Progress Overcoming Height Limitations

Recently, progress has been reported by departing from field-based traditions altogether in favor of transfer by heat and pressure – similar to the transfer step first employed by Carlson and Kornei [3, 13]. The first demonstration of image stack height growth independent of field strength was published last year, where a sample with a 10mm high stack height had been made using an electromagnetic brush (EMB) coating technique (based on developer subsystems from laser printers without photoreceptors [15]) which transferred and fused each layer exclusively by heat and pressure followed by offline oven fusing [13]. Building on the success of the EMB produced sample, the same team multilayer (over 50 layers) laser printed the ziggurat shaped object shown in Figure 1 which exceeded 5mm build height without significant layer defects [16]. To the author's knowledge this is the first sample in the public domain which exceeds the theoretical build stack height limit as calculated by Kumar and Dutta [14]. The sample was produced from the same developmental epoxy based toner used for the EMB sample, which when paired with a suitable carrier had a charge distribution with a mean q/d value of -2.83 fC/10 µm and between 3.1 and 2.2 % of positively charged particles (measured using a q/d meter, EPPING GmbH, Germany). The sample was made by a semi-automated method where five layers were printed using a dual component non-conductive laser printer (CTG 900, CTG PrintTEC GmbH, Germany) and then fused offline for 5 minutes in an oven at 155-160° C; the sample (and ceramic tile substrate) was remounted on the printer to repeat the cycle for each subsequent set of five layers [16].

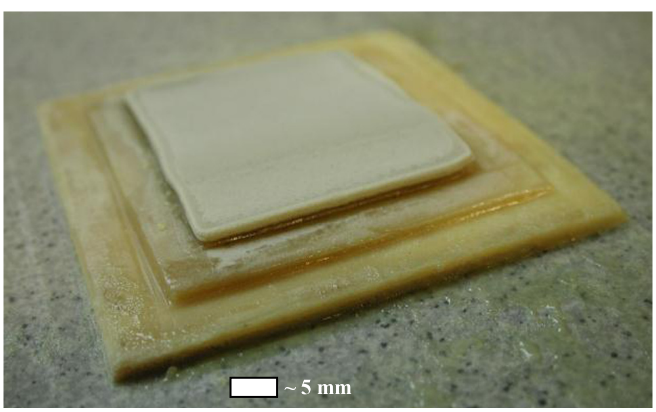

***Figure 1** – Laser printed ziggurat shaped object exceeding the theoretical height limit for conventionally transferred laser printing*

While this sample shows great promise, fully automating the procedure (and thereby accelerating cycle time by 10x) has produced parts with inconsistent quality that exhibit a spectrum of layer defects including pitting, corrugating, etc. (see images below) which are similar to defects reported by other researchers [13].

Characterizing Residual Toner Charge

In order to consistently achieve acceptable laser printed part quality at competitive speeds, it was deemed necessary to investigate the cause of the layer defects. Although the transfer method employed for the ziggurat shaped sample (Figure 1) did not use any induced transfer field, the nature of the defects manifest during fully automated trials to reproduce it showed parallels to problems experienced by Kumar Das which he attributed to "trapped volume charge" in the printed layers [17]. Since experimental evidence to demonstrate the role of electrostatics in a heat and pressure transfer was lacking, it became the initial point for characterization. The trials described subsequently were undertaken on the Selective Laser Printing (SLP) rig which has been described elsewhere [8, 13, 18]. In order to eliminate variables, initial trials were undertaken using industry standard toner which provides a baseline for subsequent testing with developmental toners.

Trial 1 – Residual Toner Charge with Automated Processing

Typical surface quality degradation is illustrated in Figure 2, which shows 20 rectangular images (120x80mm) laser printed one on top of another with a 5mm shift (to the right to enabled the observation of individual layer quality and height measurement). Each print was made using a two-component printer (CTG-1C17-600, CTG PrintTEC GmbH, Germany) with a conventional polyester toner (Poly-JZ, Samsung, Japan); which when paired with an appropriate carrier had a charge distribution with a mean q/d value of -3.6 fC/10 µm and less than 1% of positively charged particles (measured using a q/d meter, EPPING GmbH, Germany). These images were printed onto a rigid ceramic substrate 120 x 120 x 1mm (ADS96R, CoorsTek, CO, USA) using a heat and pressure transfer (without any induced transfer field) in order to measure and examine the charge and behavior of the toner as it accumulated layer on layer.

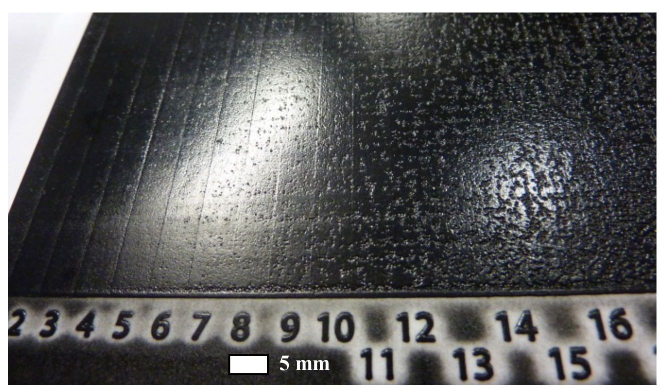

***Figure 2** – Surface quality degradation shown by successive prints of industry standard toner transferred one upon another using only heat and pressure*

The surface potential was measured in process immediately after each print using a field mill device (JCI 140 Static monitor, Static Direct Limited, England) calibrated for the area of the ceramic substrate. Each layer was fused using an infrared radiant heater to 150°C. After printing all layers, the cumulative thickness of the deposited toner was measured at 20 positions corresponding to the center of the exposed 5mm strip of each layer. The averaged surface potential and cumulative toner thickness are plotted in Figure 3 with ± error bars equal to $\sigma/n^{1/2}$ (n samples).

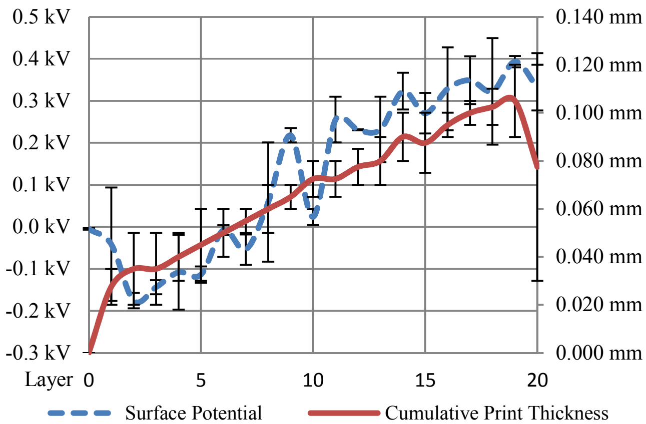

***Figure 3** – Graph of average post-print surface potential vs. average cumulative maximum print thickness*

The average surface potential of the samples initially decreased to a minimum of -0.18 kV at layer 2 and then followed an upward trend to a maximum of 0.39 kV at layer 19. The average cumulative print thickness correlated with the upward trend of surface potential with a maximum value of 0.105 mm at layer 19. The left hand portion of the sample in Figure 2, where only a few layers were printed, had a surface roughness of less than 1µm Ra (measured using white light interferometry, WYKO NT2000, PZ-06-CS-SF, Mikro Precision Instruments, USA), yet it was so degraded on the far right-hand side of the sample (where up to 20 layers were printed) that it was impractical to measure. The defects developed around layers 7-8, which correspond to when the average surface potential changed from negative to positive.

Trial 2 – Residual Charge after 10 min. Relaxation Delay

The same experimental conditions as above were replicated for Trial 2 except that after each layer was printed and fused, a 10 minute charge relaxation delay was introduced before the next cycle began. This delay was intended to replicate the timing used during the production of the ziggurat sample and allow observation of any influence from the passage of time on charge recombination. The surface potential was measured immediately following each layer printed and also after the 10 min. delay, and are plotted in Figure 4 along with the cumulative print thickness.

The surface potentials from the Trial 2 sample measured immediately following the print and after the 10 min. delay decreased initially and then followed an upward trend peaking at 0.57 kV and 0.1 kV respectively. The surface potential after the 10 min. delay was much less variable and had a significant reduction in magnitude. The average cumulative print thickness correlated with the upward trend of the surface potentials with a maximum value of 0.11 mm at layer 19. Its appearance and surface roughness were nearly identical to the sample in Trial 1 (Figure 2) with surface degradation which first became evident around layers 5-6, when the surface potential changed from negative to positive, and then increased with the number of layers deposited.

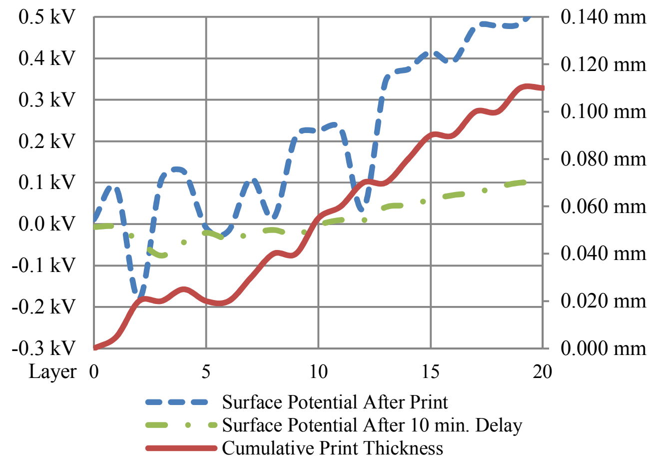

***Figure 4** – Graph of surface potential immediately after printing and after a 10 min. charge relaxation delay vs. cumulative maximum print thickness*

Trial 3 – Counteracting Residual Charge with a Field

Working from the premise that, if surface defects in previous samples were caused by electrostatics (via an accumulation of like sign residual charge in the printed object) then in theory they could be counteracted by using a transfer field to overcome any repulsion exerted by residual toner charge in the image stack. Therefore, Trial 3 was undertaken with the same conditions as Trial 1 except that a conventional electrostatic transfer was employed by means of a charged conductive aluminum plate placed directly under the ceramic substrate, which delivered an initial transfer field strength of 3MV/m. Since the sample was defect free after 20 layers the process was continued until the end of the day. The field enabled deposition of 176 defect free layers measuring a total of 0.865mm in height. After printing, the aluminum plate was isolated from the high voltage source. The sample was then allowed to cool to room temperature. When the sample was reviewed 18 days later, some cracks due to thermal contraction were evident, but more noteworthy was the fact that the aluminum plate was pinned to the ceramic substrate electrostatically as shown in Figure 5, with the plates partially twisted apart.

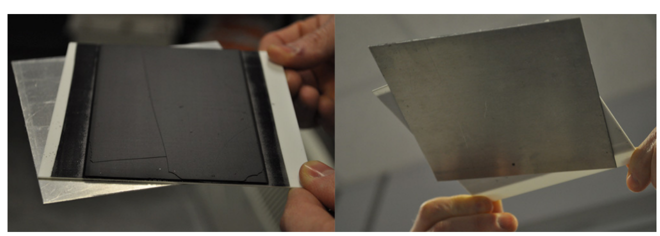

***Figure 5** – Aluminum plate (120 x 120 x 1 mm) electrostatically pinned to substrate 18 days after printing 176 layers using a conventional transfer field*

Trial 4 – Residual Toner Charge on Grounded Substrate

Trial 4 was undertaken with the same conditions as Trial 1 with two exceptions. As an alternative to waiting 10 minutes per layer for charge recombination (as in Trial 2), the ceramic substrate was replaced with a grounded aluminum substrate in order to promote charge dissipation through better connection to ground. This was also done to eliminate the possibility that the retained charge in Trial 3 was achieved by virtue of the ceramic substrate rather than the printed toner alone. Secondly, the shift between printed images was removed because it caused a reduction of newly deposited toner inside the calibrated measuring area for the field mill device with each print (which potentially biased earlier readings). As per Trial 1, the surface potential was measured immediately following each layer printed. Also, at layer 20 a sheet of paper was placed on top of the stack to test the efficiency of toner transfer onto the image stack in the nip. It is shown in Figure 6 with corner folded back.

It is noteworthy that the total deposition height of the image stack was the least so far at 0.075mm. Furthermore, the surface continued to be plagued with defects even though the defects had a finer resolution and more uniform distribution (Figure 6).

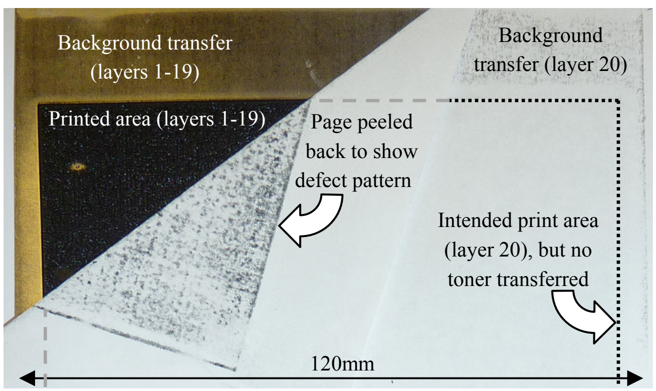

***Figure 6** – Sheet of paper as placed on top of the sample during the printing of layer 20. Note: the background toner transferred around the image stack (upper right hand corner), but not directly over it; this is evidence that residual toner charge in the image stack is repelling incoming toner. Also, the paper is folded back to show the defect pattern on the top surface of the sample.*

The dashed rectangular outline in Figure 6 shows the area where toner was expected to be deposited onto the paper, but was not. Despite the developed toner image not transferring, toner was transferred to other areas of the paper as background scatter.

Learning Outcomes: Residual Toner Charge

All of the trials reported indicate that residual toner charge is not eliminated or reduced to a negligible magnitude simply by proper fusing alone. This helps clarify the scope and context of statements such as, "When the powder is heated and reaches its fusing temperature its conductivity increases and this allows the charge on the powder to dissipate" [14]. While fusing can help dissipate charge, that does not mean that the residual charge will be reduced to a magnitude which will not cause defects in multilayer laser printing.

Next, surface defects are material composition dependent. Surface defects developed after only 5-10 prints with commercial toners which have an insulative volume resistivity (>1x10^{12}), while developmental toners with a dissipative volumetric resistivity (2.75x10^{11}) were difficult to tribocharge, yet they could be printed 30-50 layers or more before defects arose [8].

Regardless of the transfer method used (heat + pressure or electrostatic field), electrostatically favorable conditions are required for charged toner to transfer well. Trial 3 confirmed this for conventionally transferred toner. This was also demonstrated in Trial 4 by the toner transferred onto the background of the sheet of paper (Figure 6) which is evidence that a) sufficient toner was on the transfer roller and that it was electrostatically favorable to b) transfer onto the paper around the image stack, but c) not directly over it. Since the primary difference between the area where the toner did transfer and where it did not was the presence of the image stack, this supports the conclusion that the incoming toner was repelled due to retention and accumulation of like sign charge in the consolidated image stack. In spite of the fact that no field was being used in the transfer step, an electrostatic field was being exerted by the accumulated toner, which prevented additional toner transfer from the developed image. It is proposed that surface defects are another manifestation of this same phenomenon. Height limitations derive from this problem where surface defects are perpetuated (and exaggerated) because new layers cannot properly form on the poor foundations offered by defective layers.

Finally, the trends in Figures 3-4, toward an increasingly positive surface potential as toner accumulates, are counterintuitive since the toner was charged negatively in the printer. This may be evidence of the original toner charge being counteracted by contact charging from the positively charged final transfer roller. Although the results in these cases are not a net zero toner charge, the fact that the polarity can be swapped means it represents a possible method for neutralizing the toner charge if precisely controlled.

Conclusions and Future Work

Retention of residual toner charge is currently a fundamental impediment to 3D laser printing and DF. For the first time, it has been demonstrated that multilayer laser printing can realize objects above a few millimeters high by using heat and pressure transfer methods, which decouple the image stack height from transfer field strength dependence. Maintaining the quality of the print is reliant on managing the residual toner charge throughout the process, regardless of the transfer method used. Furthermore, compelling evidence has been presented to demonstrate that residual toner charge is not eliminated simply by virtue of melting it (fusing), but depends on the toner material, time and fusing conditions.

Future work will focus on the need to minimize overall toner charge for development (by less tribo/contact electrification) and neutralize toner charge either prior to transfer and consolidation or via fusing conditions/treatments which will simultaneously achieve charge recombination to eliminate any repulsive effect for new toner layers in order to maintain quality. Characterization of the influence of fusing conditions on the rate of charge recombination is needed to understand and achieve the conditions required to consistently produce laser printed objects with a net zero charge.

Understanding the influence of residual toner charge in 3D laser printed objects will enable the role of EP to be chiastic (definitive despite late entry into digital fabrication) rather than simply an enabling predecessor to DF.

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