Toner Adhesion Measurement

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Abstract

Toner adhesion to printer components is an important factor in determining the force needed for good image quality. Controversy remains as to the dominance of electrical or mechanical (Van der Waals) forces as force measurements have yielded a large range of results. A new measurement tool has been developed to measure the cumulative distribution of toner adhesion from toner transferred onto an intermediate belt. The tool consists of a metered pulse of air directed perpendicularly onto a toner isopel pattern. Printed thin lines of toner were used to calibrate isopel removal to known air force. Air velocity at toner level was found through Navier-Stokes. Resulting removal distributions correlate to transfer field parameters. The last few percent of toner remain attached to the substrate due to toner damage which results in high mechanical adhesion.

Introduction

Toner transfers when the electric field pulling toner from the donating member, usually a photoconductor or an intermediate belt, toward the receiving member, usually a belt or media, is greater than the forces of electrostatics and mechanical adhesion pulling it back. Electrostatic forces are moderately easy to simulate, but mechanical adhesion forces are more elusive. In order to improve total system performance it is important to understand and measure all of the component forces. As toner diameter decreases, Van der Waals forces become more significant. It has been predicted that as toner diameters approach 5 μm that these forces will limit toner transfer [2].

If toner adhesion dominates in the small toner particle area, it will be important to minimize it in both toner and system design. The solution lies in finding ways to get mechanical adhesion uniformly down, and to do that it is important to be able to measure it. Many methods have been used to quantify the mechanical and electrical adhesion of toner [1]. A blow-off tool was used as it would be able to measure toner distributions as they actually exist in printer systems.

The concept of a blow-off tool to measure toner adhesion has been in process for over six years. The goal was to come up with a non-destructive and relatively quick method to quantifiably measure toner adhesion as it happened inside printers. Since we were looking to use the tool to improve system performance, the results had to predict actual transfer based results. A toner that had high measured adhesion needed to require more field to transfer for the tool to be considered valid. The tool had to quantify adhesion and be repeatable for the same set up tested months later.

Tool Design and Function

Any tool that will be practically useful for adhesion measurements will need to have the following five metrics:

Range – the tool needs to remove almost all of the toner down to almost no toner remaining.

Resolution – there needs to be enough of a gradual change in toner removal that useful comparisons between samples are possible.

Response – the tool needs to respond to changes in variables the same way that a transfer system responds to those variables.

Repeatability – when the same experiment is done two months later, it must give the same result.

Reasonable – the calibrated force values should be reasonable as compared to published values.

The method selected was blowing off toner with a pulse of air. The pulse was aimed directly downward, as that would allow for a closed form solution for the velocity profile. The toner removed at specific distances from the nozzle could be measured optically and the images converted to toner removal by the use of internally-written image analysis software.

Hardware design

Initial designs were improved to control positional and air pulse variables. The following photograph shows the blow off portion of the tool. The air pulse is held at one second and the pressure can be adjusted from 10psi to 20psi. The belt sample is placed in a frame that holds the material both during the blow-off phase of measurement and in a locating fixture on an X-Y table of a microscope.

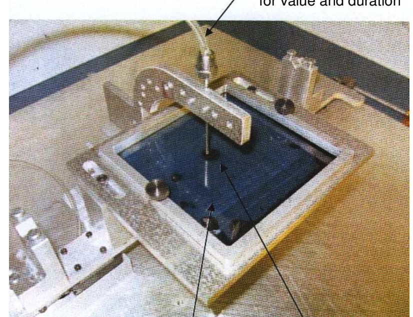

Figure 1: Blow-off tool

Calibration

Calibration of the adhesion tester falls into three parts, the first being determining the velocity of the air stream at the toner, the second being then determining the removal force from that air pressure, and lastly calibrating isopel removal forces from single toner removal forces.

Air velocity at the toner

The toner center line is sitting only a few microns above the surface of the belt, where the boundary layer makes the velocity laminar but non-uniform. The first step in determining that profile is to calculate the velocity at the edge of the boundary layer, U_r. Bernoulli is used to find the free stream velocity:

$$p + \tfrac{1}{2}\rho V^2 + \rho g h = \text{constant} \qquad (1)$$

Where p is the initial pressure, ρ is the density, V is the air velocity, g the gravitational constant and h the height.

Assumes:
Points 1&2 are on a streamline
The fluid has constant density
The flow is steady
No friction

The free stream velocity is then used as one of the boundary conditions for solving the Navier-Stokes equations. Navier-Stokes is described by the London Mathematical Society as being "widely accepted as an excellent model of the macroscopic motions of most real fluids, including air and water." Navier-Stokes are force balance equations, and due to symmetry of the system the chosen equation of interest is the summation of forces in the radial direction only. This equation can be stated in the form:

$$\rho(\delta U_r/\delta t + U_r\,\delta U_r/\delta r + U_z\,\delta U_r/\delta z) = -\delta p/\delta r$$

$$+ \mu[1/r\,\delta/\delta r(r\,\delta U_r/\delta r) + \delta^2 U_r/\delta z^2 - U_r/r^2] + \rho g r \qquad (2)$$

Where U_r is the velocity as a function of r only, p is pressure, t is time, g is the gravitational constant, ρ is density, μ is viscosity, r is the radius, and z is the perpendicular distance.

The solution to this problem is similar to that for Hiemenz flow and Homann flow. Hienmenz flow is 2-D flow of air vertically pushed against a flat plate and constrained to exit either in the +/- X direction. Because it is 2-D the bulk velocity goes down proportional to the distance traveled. In Homann flow a fluid stream approaches an axially symmetric blunt nosed body at zero angle of attack. This problem is solved in 3-D using cylindrical coordinates. Again since there is fluid coming in from all around and the object is a curved surface, a linear drop off in bulk velocity is expected. In this system the fluid velocity drops as the square of the distance traveled and is given by the Bernoulli constraint stated earlier. The other constraints are that the velocity of the air next to the boundary is zero, and then a Blasius boundary layer profile was used for layer thickness as a function of velocity and kinematic viscosity.

$$\delta(r) = (\nu r/U_r)^{1/2} \qquad (3)$$

Where:
δ(r) = boundary layer thickness
ν = kinematic viscosity

The solution is given in the equation below for the velocity profile as a function of the radius out and the height above the transfer belt surface.

$$U_r(z) = \frac{-U_0^2 r_0^2}{r^3}\left(\frac{z^2}{2\nu}\right) + \left[U_r - \frac{\left(\frac{-U_0^2 r_0^2}{r^3}\right)\left(\frac{\nu_r}{U_r}\right)}{2\nu}\right]\left[\frac{1}{\sqrt{\frac{\nu_r}{U_r}}}\right] z \qquad (4)$$

Toner removal force

The air pressure exerts a sideways force on toner, and the resulting removal force is found by summing moments. Recent work by Sweeney and Finlay [7] has resulted in a relationship for the Reynolds number for very small spheres in a Blasius boundary layer. From their work also it is possible to determine appropriate coefficients of lift and drag from the air velocity on the toner. The removal force will be the sum of the lift and drag forces. The force that the removal force needs to overcome is the adhesion force, which is the sum of the Coulomb forces and the Van der Waals forces.

Scanning Electron Microscope (SEM) images were used to find the contact area, used as the moment arm for the adhesion forces. Since the contact area is much smaller than the center of the drag force, the air has mechanical advantage in removing toner. The contact area found in the SEM image and that found from Johnson-Kendall-Roberts (JKR) theory [8] were fairly close, at about a tenth of a micron for the moment arm.

The following graph gives the calculated air velocity at a height of 6 microns above the belt surface for three different air pressures.

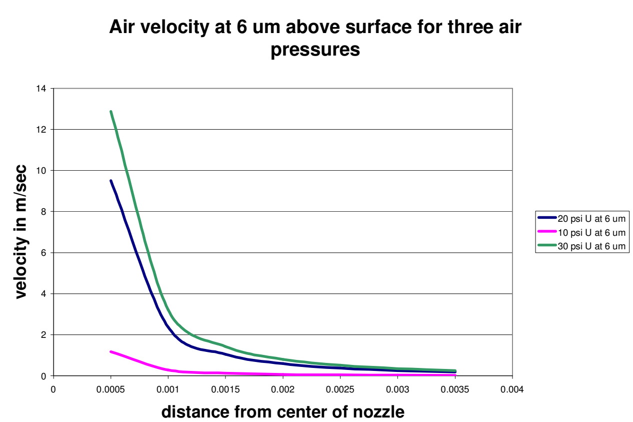

Figure 2: Air velocity at 6 microns above belt surface

The lift force and drag force calculations are very similar in structure once the coefficients of lift and drag are known.

$$F_L = \tfrac{1}{2} C_L \rho U^2 A \quad (5)$$

$$F_D = \tfrac{1}{2} C_D \rho U^2 A \quad (6)$$

Where F_L is the lift force, F_D is the drag force, C_L and C_D are the coefficients of lift and drag, U is the air velocity, and A is the area of the toner particle facing the wind. The coefficient of lift is roughly an order of magnitude lower than the coefficient of drag, and so the drag force is the dominant one in toner removal. Zoeteweij, van der Donck and Versluis [6] published the results of a series of experiments for removing small particles with air flow. They found that rolling was the removal mode for particles in the size range of toner, and this is borne out by the moment calculation.

Calibration of isopels

In a real printer system single particles of toner are not the issue. Toner is transferred to intermediate member in small to large piles, generally one to two layers of toner deep. Electrostatic adhesion of toner is impacted by the existence of similarly charged toner in close proximity. In order to determine actual adhesion, it is important to remove particles as groups. The complexity of doing that is that as toner is removed by rolling away from its initial location, toner strikes other toner and the removal force is magnified by the momentum of colliding particles. Particle collision is a statistical event and is therefore calibrated as such.

The pattern used to measure adhesion had an isopel (25% coverage isolated dot) pattern on one half of the print area and very thin lines spaced 2mm apart on the other. The assumption made is that the toner adhesion characteristics of the line and isopel toner are equivalent. Toner is removed with the blow-off fixture from both sides of a sample and the percent toner removal is lined up. The line toner measurement is made in the first toner hit by the air, without other toner collisions. The isopel removal will contain toner collisions. By correlating the calculated force and removal percentage from the line samples, the equivalent spot can be found in the isopel pattern.

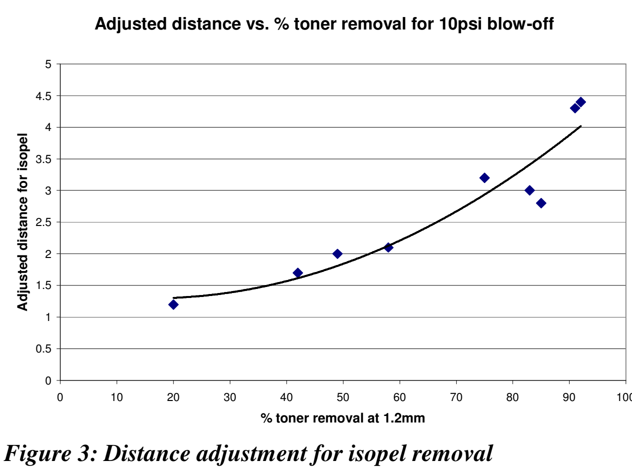

Figure 3: Distance adjustment for isopel removal

Figure 4 shows the relationship between the isopel removal rate and the removal of toner from a line sample. Doing this repeatably for samples with similar removal percentages gives a calibration curve for force at a distance in the isopel area. Since the number of collisions impacts the force multiplication, several calibration curves have been created for low, medium and high removal at a given air pressure.

Results

A review of the literature shows a wide range of force values for which toner has been removed, with "average" toner requiring anywhere from 40nN to 8000nN depending on EPA coverage, particle size and charge. EPA covered particles range from 40nN to 600nN, and uncoated toner from 100nN upwards. Using Coulomb's law a 6 micron diameter spherical toner at a relatively high charge of -40µC/g sitting alone should only require about 5-9nN to overcome the image force. The literature also suggests that a pile of toner has the impact of magnifying the image force by roughly seven times, so a range of 35nN to 63nN is a reasonable expectation for toner removal to over come image forces for toners in any kind of group. This would be electrostatic force only; any Van der Wals forces would be additional to that.

The other bracket on a range of adhesion force is the transfer force itself. The Paschen limit in a 10 µm air gap limits the electric field to 3.5E7 V/m. The Lorentz force for a toner of that charge would be 280nN. This represents the strongest field that can be induced on that particle in a transfer nip. Since most transfer nips are nearly 100% efficient, all but a few toner particles should be able to be removed with less than that field. That gives a bracket to the adhesion force found in current production printer systems.

An example removal curve

The following toner removal curve demonstrates the type of output typical from the toner adhesion tool. The toner being tested is from a production printer and the sample was taken at ambient temperature and humidity at full printer speed. The measured values of adhesion correspond well to the predicted values.

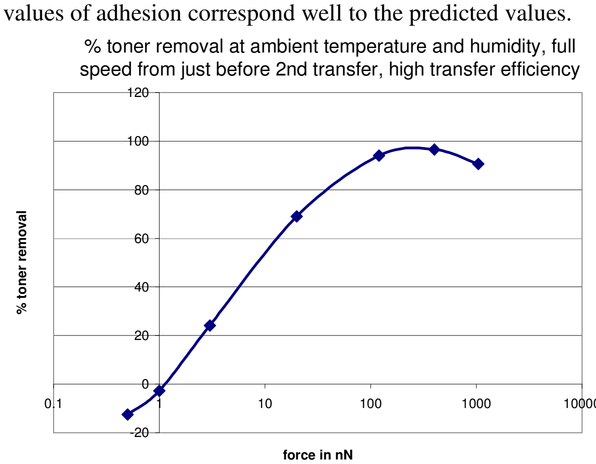

Figure 4: Toner removal as a function of force

This is an example of a toner that is working very well in this printer system. The second transfer efficiency is roughly 97% and the data reflects this in the fact that around that amount is removed by a force near 300nN. The force scale has been changed to a logarithmic scale so that the removal profile at lower forces can be easily seen. This particular sample had a mean charge of -27μC/g, which would give a "pile" image force of about 12.5 nN. The data above suggests that half of the toner had only a minimal mechanical adhesion. These are optimum conditions for toner transfer, and the system performance reflects that. Systems tested in less perfect conditions reflected less perfect results.

The tool was tested for repeatability and found to very accurately reproduce the same adhesion curve when the same system was tested after a two month break.

Adhesion Factors – Van der Waals forces

Scanning electron microscope images of toners from these samples reveal the cause of much of the difference between the easily removed toner and that which is tightly held. As has been anticipated the average toner in the sample are strongly impacted by EPA coverage and how well that coverage, or the shape of the toner, minimizes contact area with the transfer belt. Loosely held toner can be seen sitting up on a few EPA's or resting on only a tiny portion of the toner radius. These toners exist in high percentages in toner that is removed with little force.

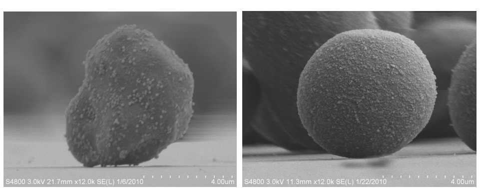

Figure 5: Lightly held toner particles

The toner that is tightly held can frequently, but not always be seen to have high mechanical adhesion. This can be caused by lesser quantities of EPA's or from damage to the toner that happens during the transfer process.

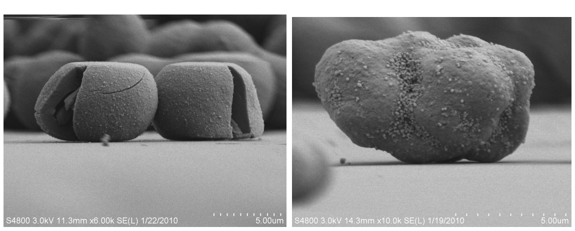

Figure 6: High mechanical adhesion toner particles

Adhesion Factors – Charge

Charge also turns out to be a significant factor in toner adhesion. Samples of the same toner system were charged differently and measured as they entered 2nd transfer. If the toner removal at the same distance is plotted against the mean charge of the samples, the result is a linear relationship until the mechanical adhesion limit is reached. At that point reducing charge does not increase toner removal. The mechanical offset varies from test to test as the data was run in multiple environments.

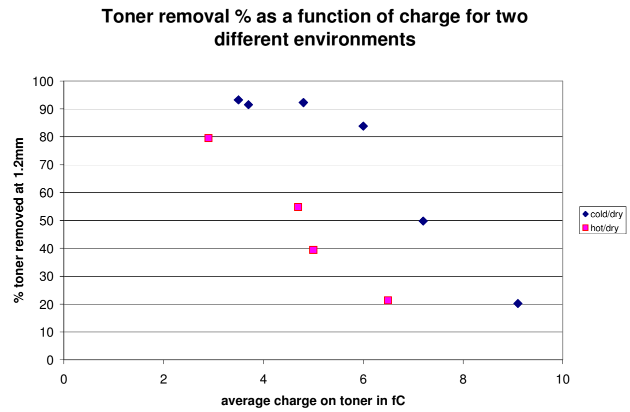

Figure 7: Toner removal as a function of average particle charge

The charge relationship is not a simple image force only relationship with adhesion. Theories have been advanced concerning non-uniform charge which could result in changes in toner adhesion characteristics [9-11]. The following SEM image shows such a charge-patch non-uniformity at work just before 2nd transfer.

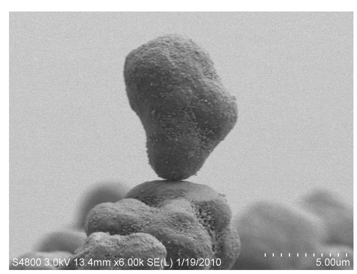

Figure 8: Non uniform charge causes unusual adhesion behavior.

Conclusions:

A toner adhesion measurement tool has been created that measures toner as it exists inside a printer system. The tool has been calibrated and gives results that correspond with predicted adhesion values. Both electrostatic and mechanical adhesions are seen in the toner samples, and increased charge or increased contact area causes measurable increases in toner adhesion.

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Author Biography

Julie Whitney received her BS in Mechanical Engineering from Purdue University (1982) and her PhD in Mechanical Engineering from the University of Cincinnati (1992). She has worked for Lexmark International since 1998 in both inkjet and laser development. Her current work is focused on transfer physics in color laser systems.

Brandon Kemp received his BS in engineering from Arkansas State University (1997), his MSEE from the University of Missouri-Rolla (1998), and his PhD from the Massachusetts Institute of Technology (2007). His work has focused on the application of advanced analytic methods to a variety of technical areas including laser printer technology and electromagnetic theory and applications.