Journal of Imaging Science and Technology® 54(6): 060406–060406-8, 2010.

Effect of Fusing Parameters on Print Gloss

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Abstract. *The effect of laser printer fusing parameters on print gloss was studied. Gloss level directly impacts color range and perceived depth of color and the perceived image quality by the customer. Analysis of gloss dependence upon fusing parameters would guide printer development. Two color printers that differed in fuser design, toner formulation, and gloss performance were tested. The fuser design and control condition and toner type effects on gloss were isolated by using an independent fusing system that allowed samples created in the two printers to be fused using a common process. It was found that image density had the primary effect on gloss and can be classified as low density (substrate dependent gloss), medium density (pattern dependent gloss), and high density (fusing process dependent gloss). Nip duration, pressure, and temperature had only a secondary effect on gloss and may be used to optimize the fusing system process once the fuser design and toner formulation are complete.* © *2010 Society for Imaging Science and Technology.*
[DOI: 10.2352/J.ImagingSci.Technol.2010.54.6.060406]

INTRODUCTION

The effect of laser printer fusing parameters on print gloss was studied. This research focused on the effect of fusing parameters on the gloss level of the resulting electrophotographic print.[1] Gloss level directly impacts the color range and perceived depth of color of the printed image. Color range and perceived depth of color have been directly correlated with the perceived quality of the printed image by the customer. A model for gloss dependence upon the fusing parameters would help guide printer development. As a first step toward eventual creation of such a model, the fusing parameters' effect on gloss level was studied, and the foundation for the model was begun.

The HP Color LaserJet 4700 and HP Color LaserJet 4650 printers were used to develop the image on the media and an independent fuser was used to fuse the print samples. The temperature, pressure, and speed were controlled by the fusing system. The Color LaserJet (CLJ) 4700 and CLJ4650 were known to have a significant difference in printed image gloss. The printers were different in the fuser design and toner formulation and thus were ideal printing systems to study.

Fusing is accomplished with heat and stress applied to the unfused toner for a period of time. This process is designed to result in melt flow of the toner and the formation of new toner-media bonds. The toner particle coalescence and melt flow forms a new surface. The ability of the toner to melt flow, coalesce, form a new surface, and relax depends on the fusing parameters. The fusing parameters are defined as the variables that affect gloss that contact fusers, media, and toners have in common across all laser printers. This definition of fusing parameters allows development of models for design across products that use contact fusing. Some examples of fusing parameters under this definition are toner temperature, toner type, or toner rheological properties, toner stress, toner strain, media surface roughness, and fuser sleeve roughness. These and other fusing parameters determine the form of the new surface and thus determine part of the print quality called gloss. Toner formulation is beyond the scope of this study.

Image gloss depends on the physics of the interaction of light with the image surface. Light interaction with the surface can be classified as reflection, transmission, and absorption. Light reflection, transmission, and adsorption depend upon not only the surface material and roughness but also on the angle of incidence of the light to the surface and wavelength of the light. Gloss has been correlated with the surface roughness as stated by Arney and Heo.[2] With reflection, the light contacts the first surface and immediately is reflected off the surface. On the microlevel, since the normal of the surface will change based on the surface roughness, the angle of incidence changes based on the surface roughness. The reduction of surface roughness causes white light scatter to decrease, thus increasing the color intensity by increasing the signal (color) to noise (white light) ratio at particular light source angles. Therefore, by increasing the gloss level, the color range and perceived depth of color can be increased.

Background

An initial investigation done by Hewlett-Packard (HP) toner specialist Holden[3] on two of HP's products found that the CLJ4650 and CLJ4700 had significant gloss difference. In Figure 1, the scanning electron microscopy (SEM) images of the fused toner for the two printers show vast differences in the surface characteristics and roughness.

The glass transition temperature for the CLJ4650 toner

Received Oct. 5, 2009; accepted for publication Aug. 4, 2010; published online Nov. 18, 2010.

1062-3701/2010/54(6)/060406/8/$20.00.

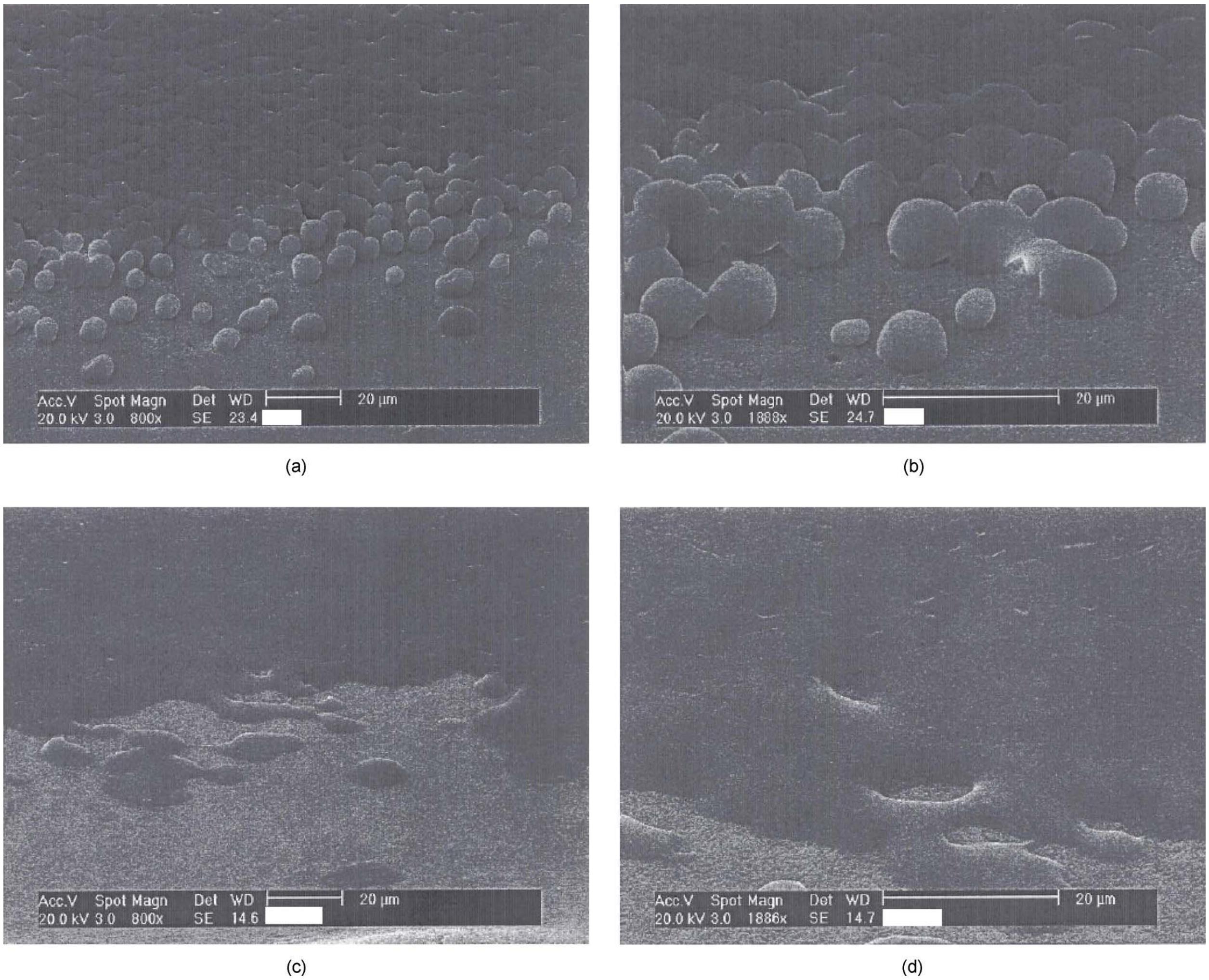

Figure 1. SEM images of the fused toner for the (a) CLJ4650 at 800X and (b) CLJ4650 at 1883X, (c) CLJ4700 at 800X and (d) CLJ4700 at 1888X.

is approximately 2 °C higher than that of the CLJ4700. This small difference in the glass transition temperature results in a significant difference in viscosity for the two toners for temperatures that produce well-fused print samples. Nakamura[4] has shown that gloss significantly depends on the rheological properties of the toner. The two printer models differ in many of the fusing parameters such as toner type, print speed, fuser temperature, fuser pressure, and fuser design. Fuser design or toner rheological properties may explain the difference in gloss for the two printers studied in this research.

Briggs and Tse[5] have studied the effect of fuser speed, temperature, and pressure, media type, and toner density on gloss. Their results showed a primary dependency of gloss on media type below 50% image toner density and a primary dependency of gloss on print speed, pressure, and temperature above 50% image toner density. These results suggest that below 50% image toner density the gloss is dependent upon the underlying media surface and above 50% image toner density the gloss is dependent upon the newly formed toner surface. The gloss of the newly formed toner surface depends upon the rheological properties of the toner and the fuser speed, pressure, and temperature.

A dimensional analysis[6] of the effect of the fusing process on fixing has been done by Chen and Yang.[7] Chen and Yang used seven parameters and found two dimensionless groups. The fusing parameters used were toner density ρ, toner diameter D, hot roll surface temperature T, average nip pressure P, nip residence time t, ambient temperature Ta, and toner pile height H. The resulting non-dimensional Pi terms were T/Ta and $Pt^2/\rho HD$. They concluded fixing was dependent on T/Ta and independent of $Pt^2/\rho HD$ for large values of $Pt^2/\rho HD$. For normal operating conditions, it is noted that the fusing process is only weakly dependent on Ta, thus T/Ta may not be a useful nondimensional Pi term for the fusing process. In addition to toner properties ρ and D, a complete model should include rheological properties.

The rheological properties of the toner change with temperature, frequency, and strain. To determine the temperature of the toner at some point in the nip area, thermal modeling must be done. Samei[8–10] et al. have investigated the effects of air existing in the fuser contact region and formed a finite element model (FEM) of the temperature profile. They have shown that the maximum toner surface temperature occurs just as the toner and print sample leave the nip region, provided there is no cooling. The maximum toner temperature is one of the characteristics of the temperature profile of the toner and may correlate to the melt flow, fusing, and relaxation of the toner.

Toner melt flow or shear rate when subjected to shear stress during the fusing process and relaxation largely determine the gloss of the newly formed toner surface. Thus, the toner parameters that are desired are those that affect melt flow and shear rate including time, temperature, and pressure. The shear rate of a polymer[11] can be expressed by

$$\dot{\gamma} = \frac{\tau}{\eta}, \tag{1}$$

where τ is the shear stress and η is the apparent viscosity. The shear modulus is a function of shear stress frequency, shear strain, and temperature of the toner. The applied shear stress is due to friction of the nondriven roller. The normal stress is due to the pressure. The friction of the nondriven roller is also affected by the pressure. The stress state of the toner must be determined to find the maximum shear stress and principle stresses.

The identified toner parameters that influence the shear rate are pressure, applied shear stress, temperature, time, toner pile height, and toner shear modulus. The pressure in the nip is a function of position in the process direction and in a nonideal case is a function of position along the fuser roller axis. The temperature of the toner is a function of position both in and normal to the process direction. For simplification, the differences in temperature and pressure along the normal to the process direction were assumed to be negligible. This is consistent with the assumption of small differences normal to the process direction. The shear rate is also affected by the surface tension.[12] Surface tension leads to coalescence of toner particles and smoothing of the surface, and may be the only significant driving stress for melt flow. The painting industry provides one example of this. When paint is applied to a wall, the surface tension drives shear of the polymer to minimize the surface energy, thus smoothing out the surface. Surface tension is a fuser design parameter that affects the toner shear rate but is not investigated in this research. It is important to be aware of all parameters that effect gloss while trying to isolate the pressure, temperature, fuser speed, and toner density effect on gloss.

METHODS

An experimental method was used to determine the effects of fusing parameters on gloss. The fusing parameters were varied and the gloss was measured. A 75° gloss meter, Ihara Gloss Mate 75, was used to measure gloss. This is the common gloss meter used by the HP Laser Jet group. The page was loaded into an automatic scanner that found fiducial dots and then scanned each color patch or sample.

Table I. Parameters to be varied.

Parameter	Number of variances
Color	2
Density	5
Fuser Roller Temperature	5
Print Speed	4
Spring Force	5
Toner Type	2

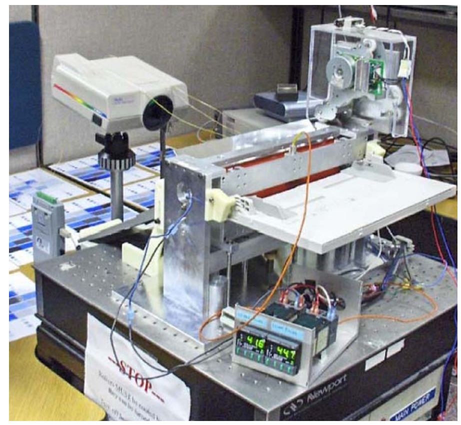

Figure 2. Test Bed Fuser.

The independent fusing parameters studied must be measured or calculated from a measurable parameter. There are a few parameters that are easily measured, such as voltage of the thermistors in the fuser, spring length, nip width and length, page length, and print time. None of the stated parameters are toner melt flow parameters, thus the parameters that affect melt flow must be calculated or modeled. Table I shows the parameters that will be varied and these are the control variables from the fuser, print sample, and printers.

Test Bed Fuser

The test bed fuser is designed to provide temperature, pressure, and speed control. The fuser rollers and heat lamps are from a CLJ8500. The quartz heat lamps are controlled by two Omega CN9000A temperature controllers. They control the fuser temperature through a proportional-integral-derivative (PID) control system. The pressure is controlled by a nut and bolt fixed to ground. The springs rest on the spring frame which is supported by the nut, and the springs support the lower roller frame. The lower roller is then guided up and down while the upper roller is fixed. The speed is controlled by the motor controller which has four states: full speed, half speed, third speed, and quarter speed. The test bed fuser is shown in Figure 2.

The nip width is a function of spring force, material properties of the fuser rollers, and fuser geometry. As the spring force increases the nip width increases. The average nip pressure is one of the pressure profile characteristics and is the most widely used parameter to describe fuser pressure in the industry. It was hypothesized that the nip pressure profile would be better characterized by three parameters defined as the average nip pressure, maximum nip pressure and the maximum nip pressure location. Also, it was hypothesized that the three parameter characterization of the nip pressure profile would yield more meaningful analysis and modeling of the nip pressure effect on gloss. However, a study of the three parameter characterization of the nip pressure profile was outside the scope of this project, and those hypotheses were not investigated in this research.

Nip width is measured by inserting an unfused page into the fuser then stopping the fuser. The page is then quickly pulled out so that the area in contact with the stopped fuser is easily distinguishable from areas outside that contact area. The result is a highly fused area. The nip length is the length of the shortest roller, which is 315 mm. The average nip pressure was calculated by dividing the spring force by the nip area. Nip area is found by multiplying nip length and nip width.

The nip force setting equal to the spring force of 255 N has an unusually large nip width, indicating fixture binding may have occurred in the guide system. This setting correlates to the pressure of 0.091 MPa setting.

Unfused Printing

The development of toner on a page is done prior to fusing. For this study, the sample was removed from the printer prior to fusing inside the printer and then fed through the test bed fuser. The media used was HP Gloss. Once the printer prints the page it must be guided out of the printer without touching any part of the developed image. The samples were carefully transferred from the printer to the test bed fuser immediately after development and placed face up on the feed tray with the left edge toward the fuser. The print samples were then fed through the fuser.

The print sample was developed to contain the nine image density and color samples on a single page. Also, the print sample was designed to minimize the effects of developer ghosting, fuser roller temperature change, and heat transfer normal to the fusing direction in the plane of the print sample. The print sample has 16 rectangles of varying color and density where density ranges from 0% to 100% visually. These 16 samples correspond to two sets of four image densities and two colors. The fifth density is zero, and is an undeveloped toner spot on the media. The 16 samples are centered on the page vertically and horizontally and positioned to minimize the above stated effects.

Developer ghosting occurs when the developer roller has developed all the toner on the first rotation. The next rotation of the developer has a fresh supply of toner that may be at a different charge, changing the amount of toner developed, and thus changing the density of the image. The variation in density should be controlled to get a consistent output of gloss. To avoid density variation, the colors were alternated at a distance less than the pitch of the developer, or the circumferential distance, as shown in Figure 3.

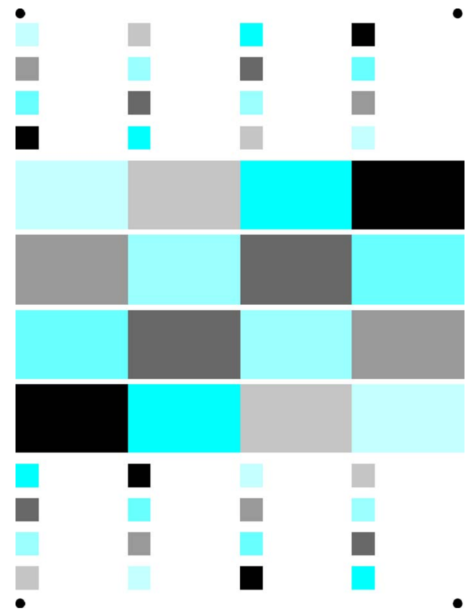

Figure 3. Print sample.

Once the image is fused, the sample is visually inspected to determine if the fusing caused any print quality defects. The samples may exhibit one common defect known as offsetting. Offsetting is where toner attaches to the fuser and then is transferred to the sample at the circumferential distance from the intended location on the page. The term *fusing condition* is then defined as cold offset, fused, or hot offset. Cold offsetting is caused by the toner not reaching melt flow and thus not fusing to the media. Fused indicates there was no offsetting. Hot offsetting is caused by the toner being at a higher melt flow temperature, which leads to splitting the toner film and leaving the toner on the page and fuser. Each page's fusing condition was determined by visually inspecting the trailing edge for hot offset and by smearing the finger across the sample area to determine if there is cold offset. The pages were then classified and quantified as: severe cold offset (−2), cold offset (−1), fused (0), hot offset (1), and severe hot offset (2). The severe conditions were easily detected at fuser exit. All other pages were individually inspected as stated above.

IR Thermal Imaging

For this project it was desired to characterize the effect of toner surface temperature on gloss. One characteristic of the toner temperature profile inside the nip is the temperature of the toner surface just as it leaves the nip. This gives the maximum toner surface temperature if there is no cooling in the nip. The temperature profile is desired, but the maximum toner temperature is the easiest to measure and is a universal thermal parameter across products. A thermal imaging camera was used to determine the toner temperature just as it leaves the nip. The surface emissivity, IR reflection, and IR transmission were corrected in the standard method of calibration for IR camera measurements. Measurement of the temperature with the IR camera was also validated with thermocouples for each page printed. IR camera tempera-

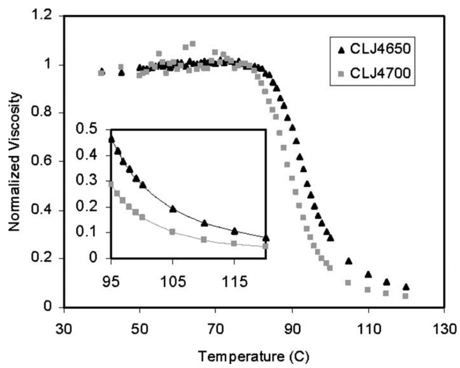

Figure 4. Viscosity vs temperature.

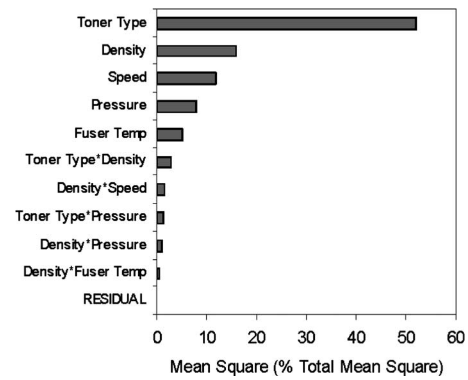

Figure 5. ANOVA Mean Square Pareto.

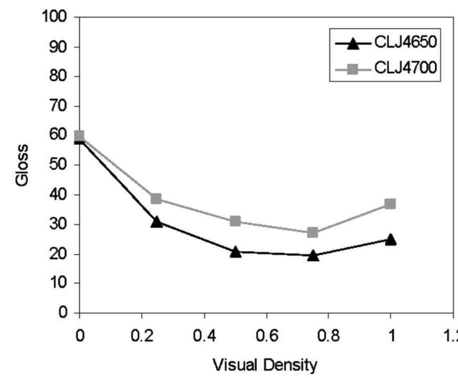

Figure 6. Mean gloss vs density.

ture measurements were used to create a temperature profile of the page just after the page leaves the nip. The IR camera was angled such that just as the sample leaves the nip it would be measured (see Fig. 2). That profile showed that there was not a significant temperature difference between the IR camera temperature measurement and the temperature just before the page leaves the nip.

Rheology

Figure 4 shows the normalized viscosity vs temperature for the CLJ4650 and the CLJ4700 toners. The rheological data for the CLJ4700 and CLJ4650 was collected using a parallel non-circular rheometer. Comparing the viscosity of the CLJ4650 toner with the viscosity of the CLJ4700 toner, the viscosities differ by nearly a factor of 2 in the range of temperature for fusing. For the two different types of toners to reach the same viscosity, the CLJ4650 toner must be as much as 10–15 °C hotter than the CLJ4700. The viscosity in the graph is normalized to the initial viscosity of the CLJ4700 toner prior to the secondary phase transition or glass transition temperature.

Gloss Measurement

In total there were 294 pages printed that yielded 11,221 measurements of gloss. There were 4361 gloss measurements of cold offset (−1) samples, 3967 gloss measurements of the well fused (0) samples, 1490 gloss measurements of hot offset (1) samples, and 600 gloss measurements of severe hot offset (2) samples. There were no gloss measurements of 496 severe cold offset (−2) and 192 cold offset (−1) print samples (5.78% of the print samples) since the toner was not fused to the page. Gloss was measured of the remaining 11,221 print samples (94.22% of the print samples).

RESULTS AND DISCUSSION

The results were primarily based on the statistical analysis of the controlled variables and measured gloss. The analysis of variance (ANOVA) was done to understand the variance of gloss due to each controlled variable. The ANOVA was performed on the control variables because some of the fusing parameters were linearly dependent. For example nip duration is dependent on pressure. The hot and cold offset print samples were filtered out of the data used for the ANOVA. Toner type and density, along with fuser speed, pressure, and temperature, were varied. Gloss measurements were made on well fused print samples only. The range of parameter values for which well fused print samples occurred defines the fusing window.

Figure 5 shows the Pareto of the mean variance of gloss due to each variable and their interaction divided by the sum of all the mean variances. Fig. 5 shows the relative effect each control variable has on gloss in relation to the other control variables. This information is important in that it helps one determine the variables to investigate further and helps in determining the most influential design variables.

Fig. 5 shows that the toner type accounts for the largest variance in gloss. The toner type variable has 1 degree of freedom while the density has 4. Although, the degrees of freedom may be the reason for the large difference, the two toner types probably do not account for the variation of all the toners produced, while density was varied across its whole range of variance.

Figure 6 shows that each toner type at a density of zero has the same gloss as the media, and that each curve has a concave-up shape. Fig. 6 can be broken into three regions (1) media dependent, (2) halftone dependent, and (3) toner gloss dependent. The gloss value is the average for each printer at a given density across the toner fusing window. The fusing window will change based on the rheological properties of the toner, and thus the offset images were filtered out of the ANOVA data.

The density is determined by the image that the user prints and is a noncontrollable design variable. The largest

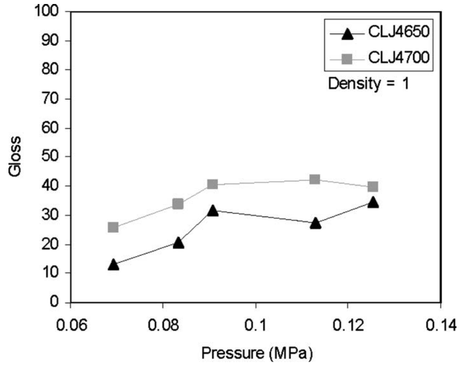

Figure 7. Mean gloss vs pressure.

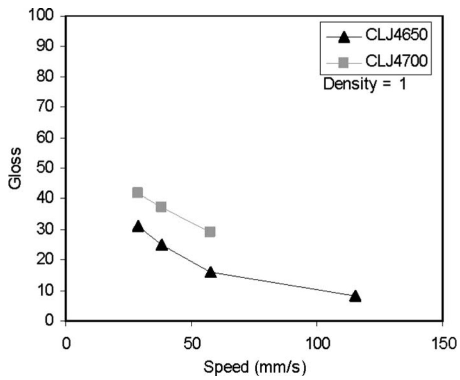

Figure 8. Mean gloss vs speed.

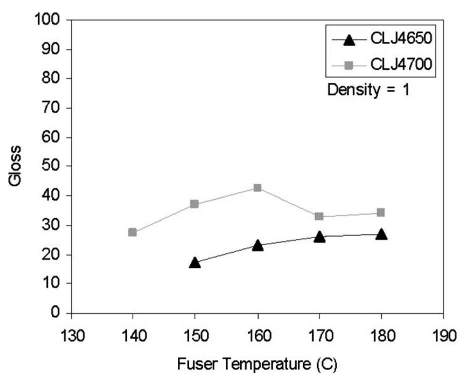

Figure 9. Mean gloss vs fuser temperature.

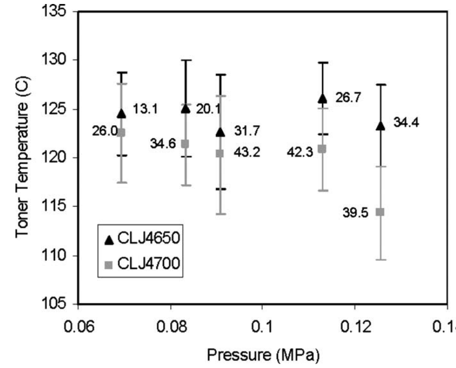

Figure 10. Toner temperature and mean gloss vs pressure.

range in gloss values occurs for a density setting of 1, and at this density the gloss is dependent on the fusing condition and toner type. For Figures 7–9, the density is set to 1 and the average gloss is graphed for each control variable and toner type.

Fig. 7 shows that as pressure increases, gloss increases. The gloss measurements for each toner type at 0.091 MPa appear to be outliers—it was noted in the Methods section that binding in the fuser fixture guide system may have occurred corresponding to the 0.091 MPa pressure setting.

Fig. 8 shows gloss vs speed and that gloss decreases as speed increases. There is no value for CLJ4700 at 115 mm/s speed since all the samples at this point cold offset. Cold offset was determined visually and tactilely and was consistent with the trends in fusing condition data across the fusing parameters test matrix. Cold offset indicates the fusing window was not reached. At 115 mm/s, the print sample conditions of cold offset for the CLJ4700 and well-fused for the CLJ4650 may seem paradoxical to the fact that the rheological data show the CLJ4700 toner has a 2 °C lower glass transition temperature and lower viscosity at any given temperature than the CLJ4650 toner. However, the difference between the CLJ4700 toner not being well fused and the CLJ4650 being well-fused may be attributable to a difference in toner formulation. Toner formulation is outside the scope of this work. Given that the fusing parameter matrix did not span the fusing window for each control variable, the data may be biased for those variables. Thus, the averaging data for the highest speed must be considered carefully when drawing conclusions.

Fig. 9 shows that as the temperature of the fuser increases, so does the gloss. It also indicates that the CLJ4700 fuses at a lower temperature and is capable of fusing over a larger range of temperatures. The drop in gloss for the CLJ4700 may indicate the optimal temperature was reached for the given control variables or may indicate a bias of the fusing window on the data. Another possibility is that the drop in gloss indicates the onset of hot offset, although data for print samples where hot offset was directly observed visually or tactilely were not included in the print sample data used to generate Fig. 9. The onset of hot offset would be consistent with observing hot offset in some CLJ4700 toner print samples with higher pressure and slower speeds at 170 and 180 °C. For the CLJ4650, the gloss increases to what appears to be the optimal or nearly the optimal temperature for maximum gloss.

To further examine the fusing window, Figures 10–12 were created. It is emphasized that the data used to create the plots are from well-fused print samples only. Previous plots showed the dependent mean gloss vs the independent fusing parameters temperature, pressure, speed, and density. Fig. 10 shows the average toner temperature from the IR camera, the standard deviation of toner temperature in the fusing range, and the average gloss for density setting of 1.0. What makes Fig. 10 different from previous plots is that it shows the interaction between temperature and pressure for the print sample to become well fused and gloss. As the

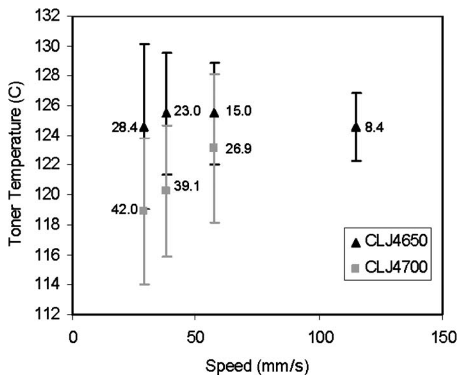

Figure 11. Toner temperature and mean gloss vs speed.

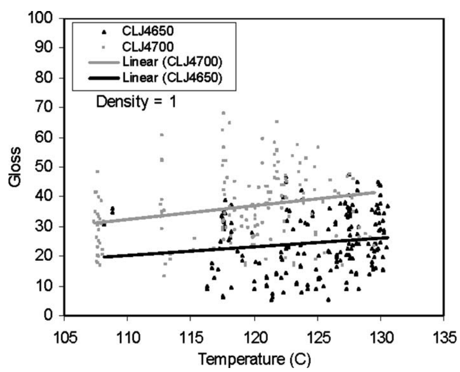

Figure 12. Scatter plot of gloss vs toner temperature.

pressure increases, the driving force for toner flow increases, the required temperature for fusing decreases, and the mean gloss increases. The standard deviation of the toner temperature and average toner temperature are useful in characterizing the fusing window. As a way to characterize the fusing window, one could take the view that the standard deviation describes the range and the average describes the value of the temperature at which fusing occurs. For the CLJ4700 toner type, the toner temperature required for fusing decreases only slightly with increasing pressure, although the gloss increases significantly with increasing pressure. For the CLJ4700 toner type, the toner temperature required for fusing decreases significantly with increasing pressure, while the mean gloss increases rapidly and levels off with increasing pressure.

Fig. 11 shows that speed or nip duration has a large effect on gloss. This plot shows the interaction between toner temperature and speed and mean gloss. Note that there are no 115 mm/s data points for CLJ4700 because the temperature required for the print sample to be well fused was not reached. The standard deviation for the CLJ4650 decreases with increasing speed, while the CLJ4700 is constant. The average temperature for fusing in the CLJ4700 linearly increases with speed. Extrapolating out to a speed of 115 mm/s yields an average temperature of 135 °C. This temperature was not achieved or planned for due to the physical limitations of the test bed fuser. It is suggested that the fusing window or range be considered when determining fuser temperature settings. As speed increases, the nip duration decreases and there is less time for toner flow. This leads the required temperature for fusing to increase and gloss to decrease. For the CLJ4650 toner, the average required fusing temperature increases and then decreases slightly, but the range of required fusing temperatures for well-fused print samples decreases with increasing speed. The average gloss decreases with increasing speed as well. For the CLJ4700 toner, the average required toner temperature increases significantly while the range of toner temperatures remains constant, and the average gloss decreases as speed increases.

The average toner temperature for well fused samples with a density setting of 1 for the CLJ4700 was 118.8 °C and for the CLJ4650 was 125.5 °C and the data is shown in Fig. 12. The 7 °C difference in fusing temperature may be due to the lower viscosity. The viscosities of the toners are shown in Rheology subsection. The glass transition temperature and viscosity are rheological properties of the toner. The toner types are assumed to differ only by the rheological properties based on the studies of the two toner types described in the Introduction and Methods sections.

CONCLUSIONS

The toner type has the largest effect on gloss. Further research on the effect of toner properties on gloss is needed to fully understand the large gloss difference between the CLJ4700 and CLJ4650 printers. It is intuitive that the surface roughness of fused toner depends on rheological properties of the toner and the fusing process, given that the rheological properties determine flow.

The density has the second largest effect on gloss and can be characterized by three regions: (1) substrate dependent, (2) halftone dependent, and (3) toner fusing dependent. The substrate or media surface dominates the gloss at low levels of density. Then in the halftone region gloss is a combination of the substrate gloss, toner gloss, and halftone pattern. The halftone pattern creates a roughness that disperses light. The roughness is caused by developing full density dots that are spaced apart, rather than a uniform density toner layer. The methods used to eliminate gloss dependency on density are clear coating on top of the fused toner and substrate absorption of toner (as with ink jet printers). With full development or full density, the gloss depends on the surface of the toner. In this case, the achievement of high gloss or a mirror like surface depends on the flow of the toner and thus the fusing condition and toner type.

For the design of fusers, the variables to be optimized are nip duration, pressure, and temperature. Nip duration is derived from nip width and speed. Increasing the nip width is one method of increasing nip duration. As laser jet printers continually increase print speed a longer nip and/or multiple passes are needed to maintain or increase gloss.

Increasing pressure can be used to achieve more gloss, although there are compromises between gloss, fuser design, reliability, and drive motor power consumption. The designers of current fusers are using variation of the pressure profile inside the nip. The general idea is to subject the toner tohigher pressure during its melt flow period. With this in mind, the toner must reach its melt temperature inside the nip, and the quicker this can be achieved and maintained within the fusing window the higher the gloss will be. In design of a fuser, one needs to recognize the limits of increasing gloss by increasing pressure. Also, pressure highly affects other printing processes and failure rate.

Increasing toner temperature increases gloss. Results indicate a limit to the benefit of increasing toner temperature. This parameter should be used to optimize fusing with consideration of heating element power consumption, reliability of the fuser, and heat transfer to other printer components.

With this work and that of others as a foundation, further study may yield a well developed physical model of the fusing process. The effects of fusing parameters on gloss have been studied. The toner rheological properties appear to be the most significant contributors. The effect of density on gloss has been characterized. This study suggests that fuser design variables should be addressed in the following order: (1) nip duration, (2) pressure, and (3) temperature. Suggested future work includes the study of the effect of the toner halftone pattern on gloss, stress state and temperature profile in the nip, and rheological behavior.

ACKNOWLEDGMENTS

The authors would like to thank Jennifer McFerran Brock, Jim Ferguson, Jim Chauvin, Jerry Young, Steve Johnson, Rich Beaufort, Michael Lloyd, Santiago Rodriguez, Brian Renstrom, Bob Lawton, and Eric Maggard for their help on this project.

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