# Fusing Parameters Effect on Gloss

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## Abstract

*Fusing is the last process in the laser printer and is known to have a significant impact on the image quality of the printed document. More must be done to understand the components of the fuser and the toner fusing process. This understanding would assist in the development of a basic model for describing the fusing process. Constructing such a basic model will help in the future design of fusers, toner, and media.*

*In this work, fuser effects on gloss have been studied and analyzed using two current HP Color LaserJet (CLJ) printers, the CLJ4700 and CLJ4650. These products differ in their fuser design, toner formulation, and gloss performance. To study the fusing parameters that affect gloss, the contribution of the fuser designs, fuser control conditions, and toner type were separated out by using an independent fusing system that allowed samples created in the two different printers to be fused using a common process. An experimental approach was used to build a foundation for developing a physical model of the fusing process.*

*The toner type was found to have the largest effect on gloss. The toner type effect on gloss can be credited to the rheological properties of the toner. Image density was the second largest effect on gloss and can be categorized by three regions: 1) low density (substrate dependent), 2) medium density (pattern dependent), and 3) high density (fusing process dependent). Nip duration, pressure, and temperature are secondary design variables that should be used to further optimize the fusing system, especially for high density images, once the fuser physical design and toner formulation are fixed.*

## Introduction

This research was done as a Master of Science in Mechanical Engineering Thesis project by Chaffin[1].

There is a need to develop and understand models of the color laser printer subsystems. The effect of the fusing process on gloss has not been well defined. This research is focused on the fusing parameters and their effect on the level gloss. The HP Color LaserJet 4700 and HP Color LaserJet 4650 printers are used to develop the image on the media and an independent fuser is used to fuse the print samples. The temperature, pressure, and speed are controlled by the fusing system. The Color LaserJet (CLJ) 4700 and CLJ4650 were known to have a significant difference in the gloss of the print samples printed by the printers. The printers were different in the fuser design and toner formulation and thus were superb printing systems to study.

Fusing is accomplished with heat and pressure applied to the unfused toner for a period of time. This process is designed to relax the toner and make the toner form new bonds with the media. The relaxation of the toner creates coalescence of toner particles and thus a new surface made up of the toner is formed. The ability of the toner to relax and form a new surface depends on the fusing parameters. The fusing parameters can be defined as the parameters that contact fusers have in common, media have in common, and toners have in common. 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 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.

Gloss is dependent on the fusing parameters through the physics of light reflection, transmission, and absorption which are dependent on the surface material, angle of incidence of the light to the surface, and wave length of the light. Gloss has been correlated to 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 micro-level, 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. Therefore, by increasing the gloss level, the color range and perceived depth of color can be increased.

## *Background*

There has been some initial investigation done by Hewlett-Packard (HP) toner specialist Holden[3] on two of HP's products. Holden has compared differential scanning calorimeter (DSC) data from the CLJ4650 toner and the CLJ4700 toner. A small difference in glass transition temperature of about 2 °C was found, while a significant difference in viscosity was found from temperature dependent rheology measurements. The scanning electron microscopy (SEM) images of the fused toner for the two printers show vast differences in the surface characteristics. Nakamura[3] has shown that gloss significantly depends on the rheological properties of the toner. By having two printers with differing toner types, the rheological properties may be different. This may explain the difference in gloss for the two toner types or printers in this research. The two printer models differ in many of the fusing parameters such as toner type, print speed, fuser temperature, fuser pressure, and fuser design.

Briggs and Tse[5] have studied the effect the fuser has on gloss by varying the print speed, fuser temperature, media type, and image density. Their results showed a dependency of gloss on media up to 50% visual density and a dependency on fusing parameters above 50% density. The relaxation rate of the toner depends on these and other fusing parameters.

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 unit-less groups. The fusing parameters used were toner density $\rho$, 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 $Ta$. In addition to toner properties $\rho$ and $D$, for a complete model parameters such as toner glass transition temperature and viscosity should be included.

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 so long as 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 relaxation and fusing of the toner.

The toner parameters that are desired are those that affect shear rate or toner relaxation. Time, temperature, and pressure are fuser parameters known to affect shear rate. The shear rate of a polymer[11] can be expressed by

$$\dot{\gamma} = \frac{\tau}{\eta} \quad (1)$$

where $\tau$ is the shear stress and $\eta$ 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 non-driven roller. The normal stress is due to the pressure. The friction of the non-driven 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 toner parameters identified 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 non-ideal case a function of position along the fuser roller axis. The temperature of the toner is a function of position in the process direction and a function of position 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 forms coalescence of toner particles and smoothing of the surface and may be the only significant driving stress for relaxation. The painting industry is one example of this. When paint is applied to a wall the surface tension drives shear of the polymer to reduce the surface tension, 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 keep in mind all the parameters that affect the relaxation of the toner.

## Methods

The 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. The page was loaded into an automatic scanner that found fiducial dots and then scanned each color patch or sample.

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 force and deformation, spring deformation, nip width and length, and print speed. None of the stated parameters directly affect toner relaxation, thus the parameters that affect relaxation must be calculated or modeled. Table 1 shows the parameters that will be varied and these are the control variables from the fuser, print sample, and printers.

**Table 1. 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 |

### *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 4 states: full speed, half speed, third speed, and quarter speed. The test bed fuser is shown in Figure 1.

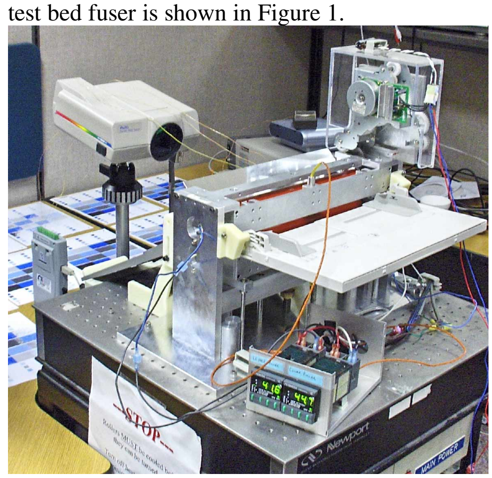


*Figure 1. Test Bed Fuser*

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 of fuser pressure in the industry. With advanced fuser designs the maximum nip pressure and its location in the nip are hypothesized to be a better characteristic of gloss than average nip pressure, but are not studied 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. The result is a highly fused area. The nip length is the length of the shortest roller which is 315 mm. The nip force setting of 255 N has an unusually large nip width indicating binding occurred in the guide system. This setting correlates to the pressure of 0.091 MPa setting and should be noted.

### 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. 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. The print sample was also designed to minimize the effects of the difference between first rotation and subsequent rotations the developer and fuser have on the 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. 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.

### 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.

### Rheology

The rheological data for the CLJ4700 and CLJ4650 was collected using a parallel non-circular rheometer. The toner viscosities differ by nearly a factor of 2 over the range of temperature for fusing. For the toners to be at the same viscosity at the fusing temperature, the CLJ4700 must be 10-15 °C less than the CLJ4650 as shown in Figure 2. The viscosity in the graph is normalized to the initial viscosity of the toner prior to the secondary phase transition or glass transition temperature.

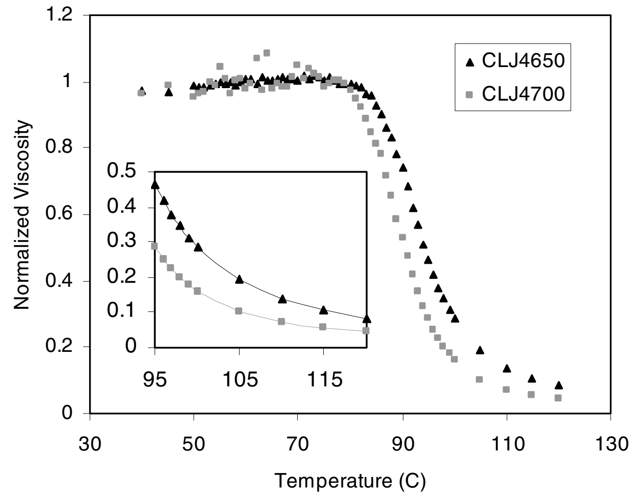


*Figure 2. Viscosity Vs. Temperature*

### Gloss Measurement

In total there were 294 pages printed and 11221 measurements of gloss. There were 4361 gloss measurements of cold offset (-1) samples, 3967 gloss measurements of the well fused (0) samples, 1490 measurements of gloss of hot offset (1) samples, and 600 gloss measurements of severe hot offset (2) samples. There were no gloss measurements of the severe cold offset samples since the toner was not fused to the page. The number of non-measured samples were as follows: 496 severe cold offset (-2), 192 cold offset, 0 fused, 0 hot offset, and 0 severe hot offset.

## 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 independent 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. The use of the well fused print samples describes the state over the fusing window, where the fusing window is the range from the minimum to the maximum of the control variables that develop well fused samples.

Figure 3 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. Figure 3 describes 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.

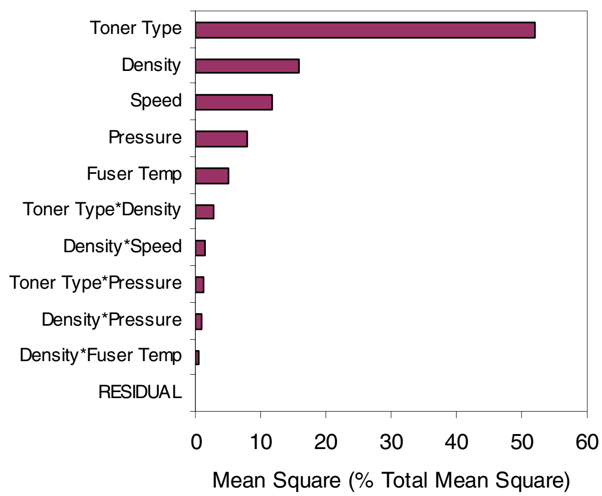


*Figure 3. ANOVA Mean Square Pareto*

Figure 3 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 spectrum of variance.

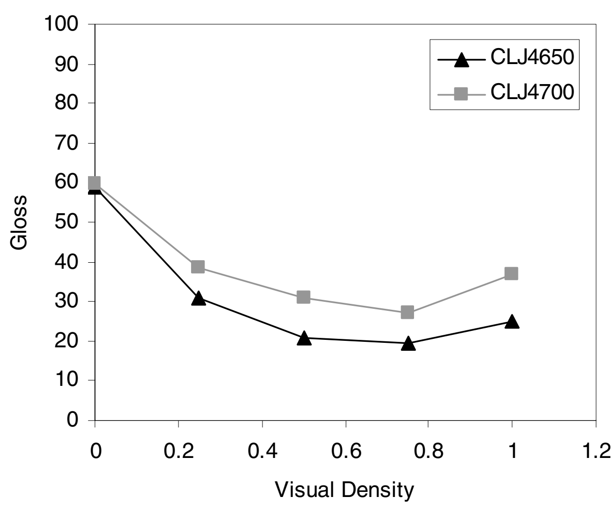


*Figure 4. Mean Gloss Vs. Density*

Figure 4 shows that each toner type starts at the same gloss at a density of 0 and that each curve has a concave-up shape. Figure 4 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 non-controllable design variable. The largest 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 5—7 the density is set to 1 and the average gloss is graphed for each control variable and toner type.

Figure 5 shows that as pressure increases, gloss increases. There is a difference in the response of each toner at 0.091 MPa, the questionable pressure setting. Notice that at 0.113 MPa the CLJ4700 gloss peaks and the CLJ4650 gloss is increasing. Imagine removing the 0.091 MPa values and fitting a line through the points for each toner type. The 0.091 MPa point for both toner types can be moved to the right where both points intercept their respective best fit lines. Thus, it is concluded that the pressure for the 0.091 MPa setting is likely larger than stated.

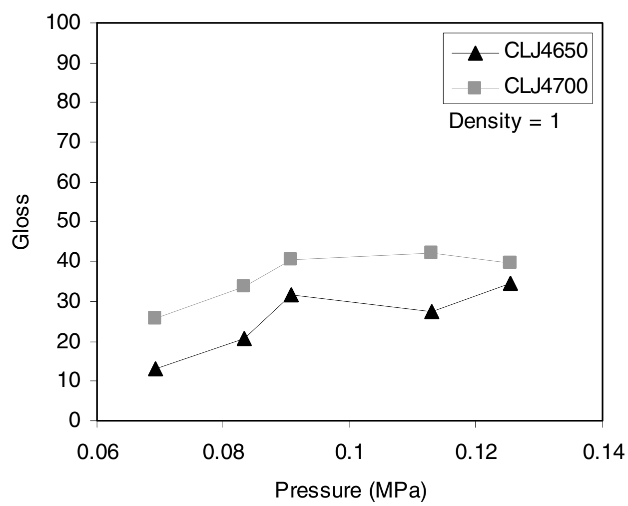


*Figure 5. Mean Gloss Vs. Pressure*

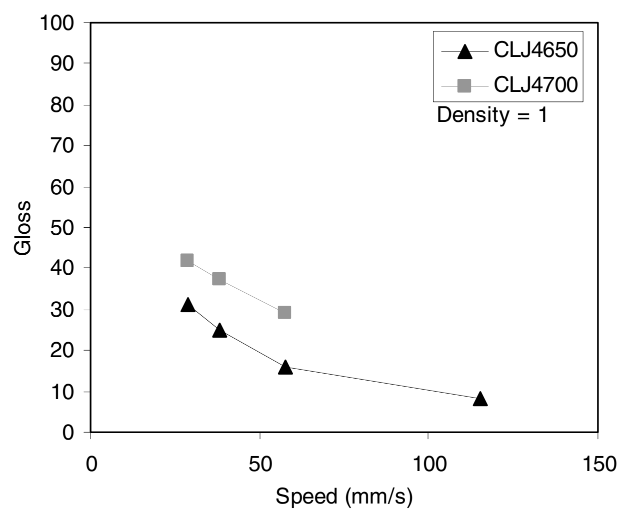


*Figure 6. Mean Gloss Vs. Speed*

Figure 6 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. This indicates the fusing window was not reached. 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.

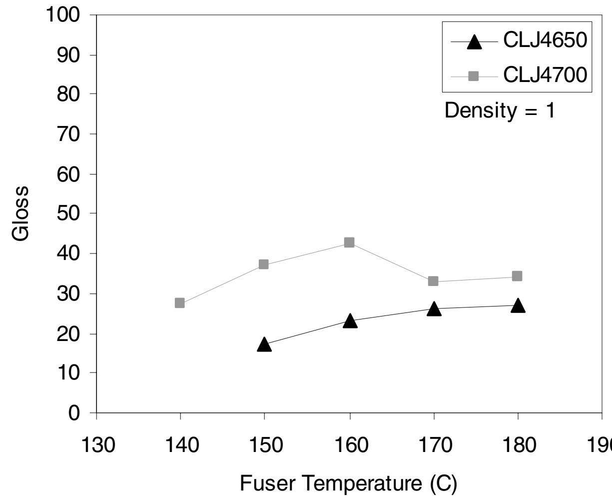


*Figure 7. Mean Gloss Vs. Fuser Temperature*

Figure 7 shows that as the temperature of the fuser increases so does the gloss. It also indicates that the CLJ4700 fuses at a lower temperature. 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. The steady increase of gloss for the CLJ4650 may indicate the optimal temperature was never reached.

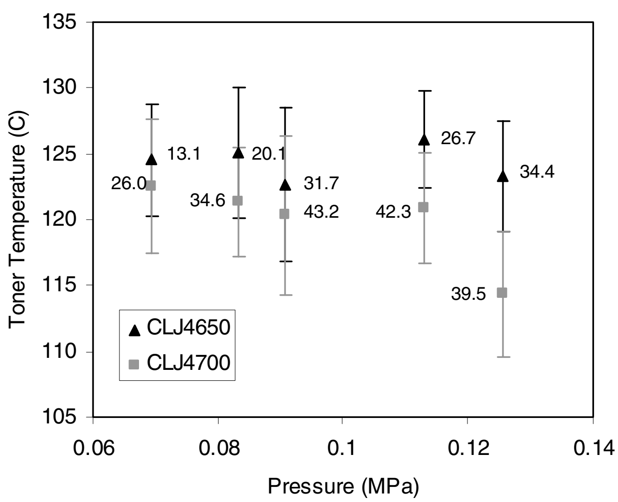


*Figure 8. Toner Temperature & Mean Gloss Vs. Pressure*

To further understand the fusing window, Figures 8—9 were created. Figure 8 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. The standard deviation of the toner temperature and average toner temperature experienced in the well fused cases is useful in determining the fusing window. The standard deviation describes the range and the average describes the value of the temperature at which fusing occurs.

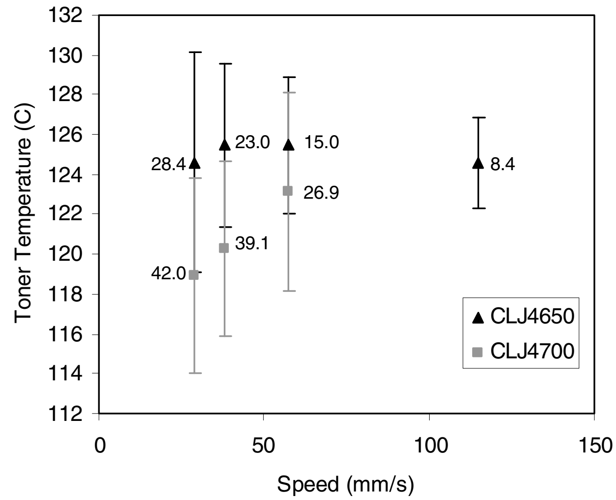


*Figure 9. Toner Temperature & Mean Gloss Vs. Speed*

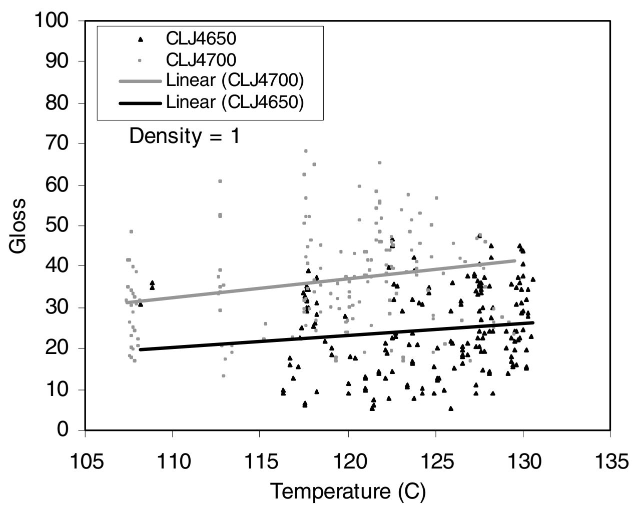


*Figure 10. Scatter Plot of Gloss Vs. Toner Temperature*

From Figure 9 one can see that speed or nip duration has a large effect on gloss. Also, there are no 115 mm/s data points for CLJ4700 because the fusing window 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 115mm/s yields an average temperature of 135 °C. This was not accomplished with the given fuser temps. It is suggested that the fusing window or range be considered when determining fuser temperature settings. 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 Figure 10. 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 separate the large difference between the CLJ4700 and CLJ4650. 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 (inkjet 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 to higher pressure during its relaxation period. With this in mind, the toner must reach its relaxation point 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 others as a foundation, further study will yield a well developed physical model of the fusing process. The effects of fusing parameters on gloss have been studied. The rheological properties of the toner appear to be the most significant contribution to the difference of gloss between the two toner types. 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.

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