Print Quality with Hot Roller and IR-Radiation Fixing Methods

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In electrophotographic office printing hot roller fusing is favored, whereas non-contact fixing methods are used especially in web printing. The aim of this study was to find out whether there are differences in quality and in the quality-forming characteristics between contact and non-contact fixing, and if so, what the reasons might be. The research was prompted by proliferation of web fed color printers for publishing applications. For the study an IR fixing installation with ceramic plates was built. Unfused print areas were obtained from a desktop color laser printer and fixed with a detached hot roller fuser, the IR radiation device and with a combination of these two. The fixing energy was varied by alteration of the temperature. In addition to basic quality measurements, the micro scale quality was measured with a multigeometrical optical testing device that was developed in our laboratory. The data on adhesion, toner coverage, density, gloss, small scale density and gloss variation, tangential edge profile and point spreading clearly proved that the surfaces are formed differently in the two fusing methods. Variation of energy in fusing also turned out to have a different impact. In hybrid fixing, the first phase determines the final outcome. This article presents a summary of the data and discusses the results from the viewpoint of fixing mechanisms.

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Introduction

The final step in electrophotographic printing is to fix the image areas to the paper surface. The most common fixing method is hot roller fusing, in which the toner is fused to paper with a combination of thermal and mechanical energy. IR radiation is mainly used in applications where contactless fixing is important, such as in digital web printing. In assemblies consisting of ceramic plates, radiative heat is the source of energy.[1–4] Some digital presses employ a combination of IR radiation and hot roller fixing. Quoted advantages include good image sharpness, no spreading of the toner and a good fixing level on all kinds of paper grades.[5]

Previous studies have suggested that the quality of fusing is primarily controlled by rheological characteristics of the toner but also by paper properties. At the same level of grammage, paper roughness has a significant effect, particularly in the range typical of uncoated papers.[6] In the case of coated papers, the composition of the paper surface is known to be a significant factor.[7] Paper permeability also plays a part in governing toner penetration into the paper structure.[3] On uncoated papers the surface size chemical is known to have an effect on the toner adhesion.[8–10]

The series of work reported here was prompted by observations in practical printing, implying that mechanisms in contact and non-contact fixing differ. Commonly, white specks or micro blistering type phenomena have been observed in IR fixed prints. The objective of the study is to identify the mechanisms by analyzing prints fixed in different conditions. Differences between coated and uncoated papers are also of interest. This analysis draws its material mainly from thesis studies.[11–14]

This article is structured as follows. The experimental methods and a hypothetical model of fixing phenomena are introduced in respective sections, followed by a combined Results and discussion section. This article is an extended version of a conference paper presented at IS&T´s NIP15.[15]

Methods

The experiments consisted of fixing of unfused prints with a hot roller fuser,[11,12] an IR radiation device,[13] and a combination of the two methods and characterization of the result. The hot roller fuser consisting of two elastomer coated soft rollers was detached from a Lexmark Optra C printer. Control electronics was added to the device to facilitate adjustment of the temperature of the rollers and the speed of the system and thereby also the dwell time. The temperatures of both of the rollers can be varied from room temperature to 250°C. Roller speed is adjustable from 0 to 0.745 ms^{-1}. In the experiments the speed was kept at 0.1 ms^{-1}, once it had been found that dwell time and temperature are interchangeable variables. In all experiments, nip pressure was kept at normal Optra C settings. The IR-radiation fixing device, which was constructed for the research, consists of two 250 × 250 mm sized radiant fields, a conveyor belt, a sledge for the paper and a frame. The radiation fields are located on both sides of the conveyor belt to enable duplex fixing. The device is illustrated in Fig. 1.

The surface temperature of the radiators can be controlled up to 700°C and the speed of the conveyor belt adjusted from 0.01 ms^{-1} to 1 ms^{-1}. Radiation power can be calculated from Stefan-Bolzmann law.[13]

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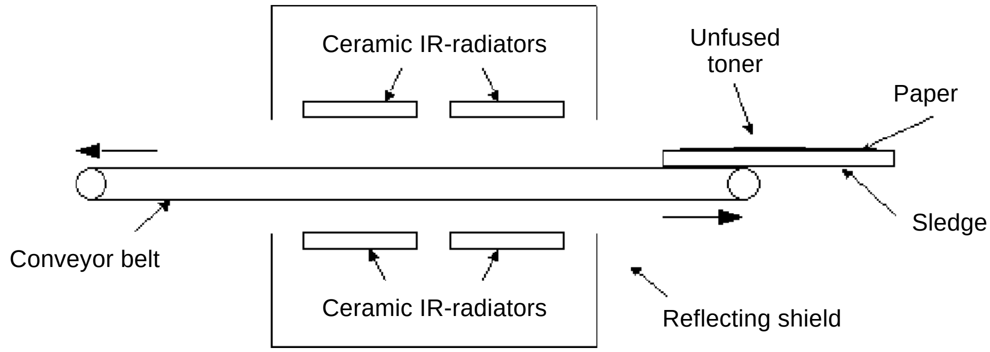

Figure 1. IR-radiation fixing device.[13]

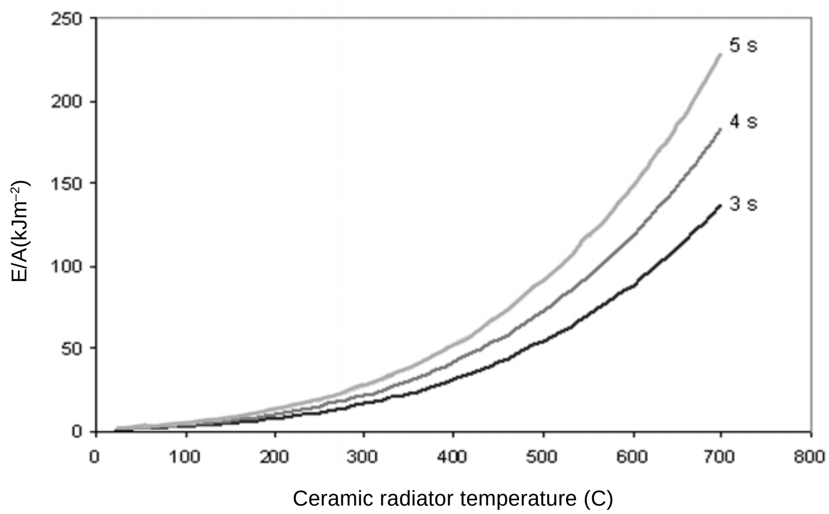

Figure 2. Energy density as a function of radiator temperature at different fixing times.

$$P = \varepsilon \cdot \delta \cdot A \cdot T^4 \tag{1}$$

where P is power [W], ε is emissivity of a ceramic radiator = 0.9, δ is Stefan-Bolzmann constant = $5.67 \cdot 10^{-8}$ [$Wm^{-2}K^{-4}$], A is area of the radiator = 0.0625 [m^2] and T is temperature of the radiator [K]. Fixing energy is $E{=}P{\cdot}t$, where t is fixing time. The energy density on the paper as a function of ceramic radiator temperature is shown in Fig. 2 at three different fixing times.

A hybrid of the two methods was also used. A hot roller was attached either before or after the IR-unit. The temperatures for the experiments were chosen so that they covered the operational window of the equipment. In the case of hot roller fusing, the window is determined by cold and hot offset. In the case of IR-radiation fixing, quality defects at the lower end and deterioration of paper properties at the upper end were used as criteria. Unfused prints were obtained from a Lexmark Optra C color laser printer. The test print area composed of compact black areas (toner amount 9 gm^{-2}), vertical lines and text (TimesNewRoman 11pt).

For characterization of the fusing result, quality variables that had proved to be critical in the pre-study stage were measured. Optical density and gloss were measured from solid areas. The gloss values were converted into relative values (gloss contrast) to eliminate the influence of paper gloss. Toner adhesion was measured with the tape test. Adhesion percentage is obtained by dividing the density, measured after removing the tape, with the density measured before applying the tape to the surface. Surface roughness of prints was measured with a profilometer. Theta angle (θ_a, mean slope of the topological profile) was found to be the most sensitive single indicator of the roughness profile.

Solid areas were micro-imaged with a CCD camera and the surfaces analyzed with an image analysis program (Scion Image). Coverage in the solid areas, tangential edge profile and point spreading in the lines were determined. Text quality was measured with a high-resolution scanner. A quality index for text was calculated from contrast, point spreading and tangential sharpness.

In addition to macro scale quality measurements, micro scale quality was measured with a multigeometrical measurement device.[14] This set-up consists of a light source, a sample holder and a CCD camera. The angles of incident light and detection can be varied. Besides allowing determinations of several quality metrics, the sample holder is such that measurements can be made from both fused and unfused surfaces without damaging them. Spatial registration is also possible. The measurements in this work include rms (root mean square) variation of density and gloss. Sampling rate in the measurements corresponds to a pixel size of 18 µm.

TABLE I. Toner Properties

Property	Method	Value
Glass transition temperature	DSC; Mettler TC 11, 10°C/min	65°C
Particle size	Optical microscopy	8 μm
Viscosity at 150°C	Shear; Bohlin rheometer, 0.436 s^{-1}	150 Pas
Phase angle at 150°C	Oscillation; Bohlin rheometer, 10 Hz	76.5°
Resin content	TGA; Perkin Elmer TGA 7, 10°C/min	85 %

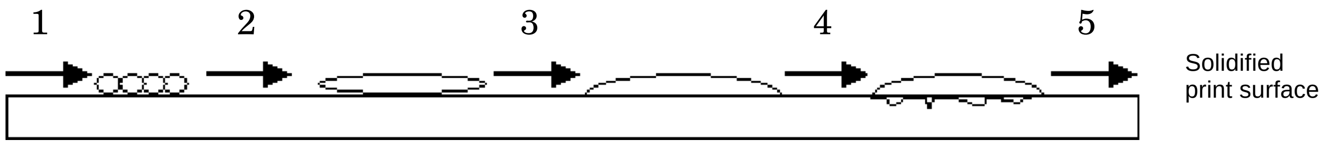

Figure 3. Toner transformation in fixing.

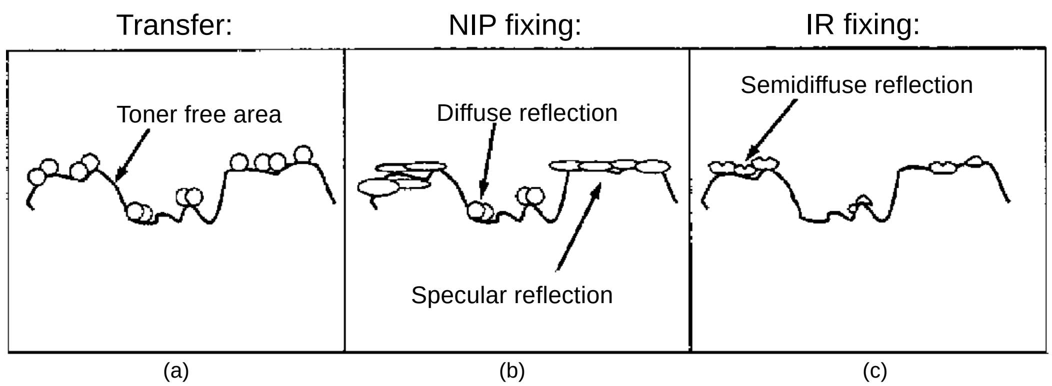

Figure 4. Reflections from the surface of the uncoated paper in unfused (a), hot roller fused (b) and IR-radiation fixed (c) surfaces.

The toner used in this printer is a conventional non-magnetic mono-component toner with a polyester resin. The toner was characterized by thermal and rheological measurements. A summary of toner properties is given in Table I.

Both uncoated wood-free copy papers and coated digital printing papers were used in the experiments. The grammage of the coated papers ranged from 80 gm^{-2} to 130 gm^{-2} and that of the uncoated from 80 gm^{-2} for plain copy papers to 100 gm^{-2} for pigmented papers. The papers were obtained from three European paper manufacturers.

Model

It is generally acknowledged that toner is fixed to the paper in five stages (Fig. 3).[1,4] First, heat is transferred from a hot roller to the toner layer and the toner is heated over the glass transition temperature (1). The toner particles are sintered together as a result (2). After this the toner melt wets the paper surface and the toner spreads (3). Some penetration into paper capillaries also occurs (4). When the heating element is removed, the toner cools off below the glass transition temperature and the surface is solidified (5). In hot roller fusing, both heat and pressure control the print result. In IR-radiation fixing only heat has an effect.

Based on the general principles and preliminary experiments a hypothetical visual model, as shown in Fig. 4, was proposed to function as a reference with which experimental trends can be compared. It illustrates how the variations in density and gloss may arise in nip and IR fixing. In the transfer stage uneven toner transfer is manifested as white specks. These create small scale density variation, whereas gloss variation is minor (Fig. 4a).

In hot roller fixing (Fig. 4b), the toner-free areas cause variation both in density and gloss. The toner on the peaks of the paper profile becomes very glossy as a result of nip calendering. The reflection is specular compared to the diffuse reflection in unfused print areas. Calendering is physically manifested as a decrease in the slope of the topological profile in the print area. If the paper surface is very rough, the toner in the voids of the surface does not reach contact with the nip and the area remains matte. When the fixing temperature increases, specularly reflecting regions also increase in number. Because the surface of coated paper is smoother, the prints are glossier than on uncoated papers. The density level depends on the proportion of toner-free areas in the surface. Lower density levels are achieved with uncoated papers because of higher paper roughness, which is caused by higher amount of toner-free areas.

In IR-radiation fixing (Fig. 4c) the proportion of toner-free area is bigger than in hot roller fusing. Wilken and co-workers[16] have suggested that white specks are

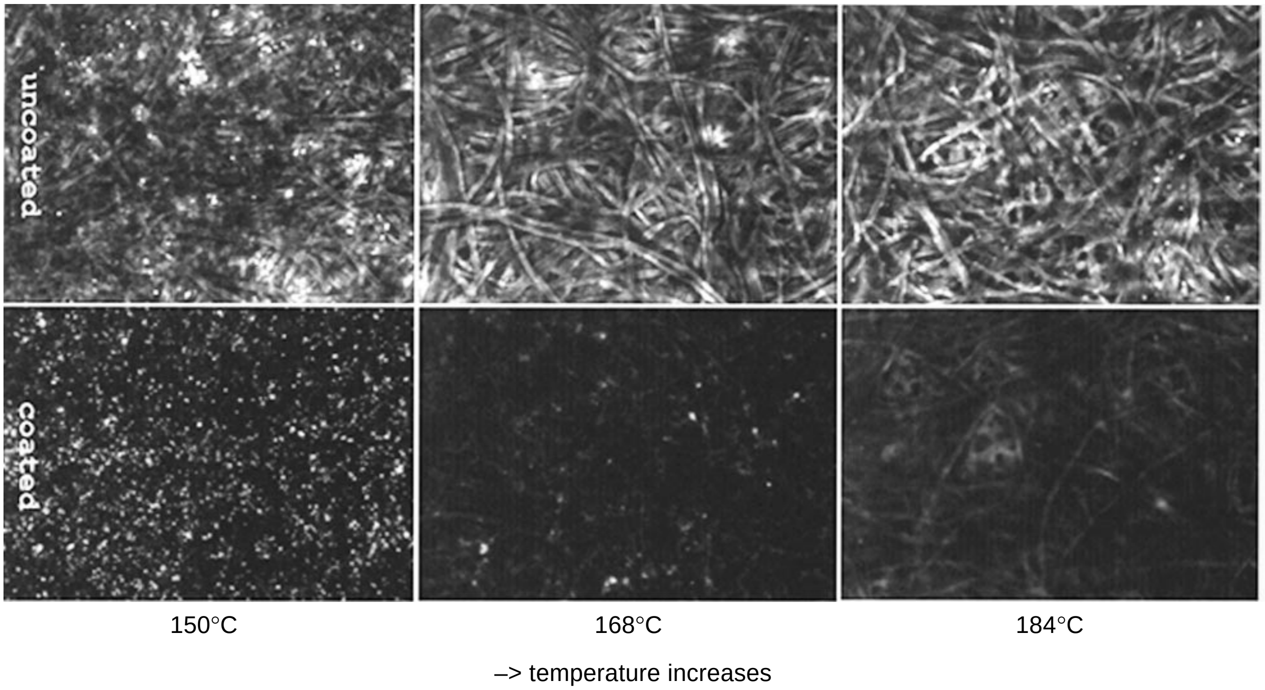

Figure 5. Print surfaces fixed with a hot roller.

formed as a result of local variations in paper surface energy. Low charge areas were found to occur particularly in spots that consisted of broad hydrophobic fiber bundles. The mechanism could explain the toner-free areas in hot roller fusing, whereas visual inspection suggests that the white specks in IR radiation fixing arise differently. The hypothesis is that as radiation reaches the paper, water molecules vaporize and penetrate through the toner layer, causing bubbling and through it sintering. Penetration of water through the toner layer also causes roughening. Reflection from the peaks of the surface becomes semidiffuse rather than specular.

As for details and lines, nip pressure forces the edges to spread. However at the same time the edges become smoother because, some of the closest satellite particles merge with the edge. This is proved by the fact that edge raggedness has been found to be lower in fused than in unfused prints. Because the fusing temperature has little effect on edge raggedness, it is evident that the phenomena are pressure-driven. Schleusener and Apel[17] found that IR radiation gives rise to higher edge raggedness than nip fusing. This was believed to be because toner can scatter from the print area also in the fixing step, unlike in hot roller fusing where the nip prevents scatter.

The toner adhesion is believed to be controlled by both physical and chemical properties of paper.[18] On uncoated papers the unmelted toner particles in the voids do not adhere as well as particles on the peaks of the profile, so paper roughness contributes to the adhesion level. On pigmented and coated papers the surface chemistry has a bigger role.

Results and Discussion

Fixing—Hot Roller

Figure 5 illustrates the appearance of hot roller fused prints. Some toner-free areas can be seen in surfaces fused at low temperatures. The white specks have been found to originate from the transfer stage. They reduce the coverage power and density and are most frequent in uncoated plain papers.

The toner penetrates in part into the paper structure. The penetration increases with an increase in the fusing temperature, which is clearly because of the lower viscosity levels. When fusing energy is increased even further on uncoated papers, the toner penetrates into the paper to the point that the fibers of the paper appear. This results in decrease in the coverage percentage. The surface of coated or pigmented papers is less porous, which prevents the toner from penetrating into the paper. As a result, the toner melt appears to move more in the xy-plane than in the z-direction.

The adhesion of the toner improves as the fixing energy is raised (Fig. 6). This can be seen clearly especially with uncoated and pigmented papers. In the case of the coated paper with higher grammage and therefore higher thickness, the lowest temperatures were not high enough to fix the toner to the paper and cold offset in the printer occurred. This is due to the fact that heating of the paper consumes a bigger proportion of the energy. When the fixing window was reached, the adhesion was immediately almost 100%.

In the case of the uncoated and pigmented papers no cold offset occurred, but the adhesion level was very low at the lower fixing temperatures. This could be due to the inadequate interaction between the toner and the sizing chemical, however further studies are needed on this subject.

Surfaces fused with a hot roller at high temperatures are very glossy. The calendering effect of the nip explains this, consistently with the previous model. Small scale variations in density and gloss increase as the temperature is raised. This is because of the fibers that emerge through the toner layer. There is little specular reflection from fibers, compared to the black toner surface. Fibers form quite large non-specularly reflecting areas.

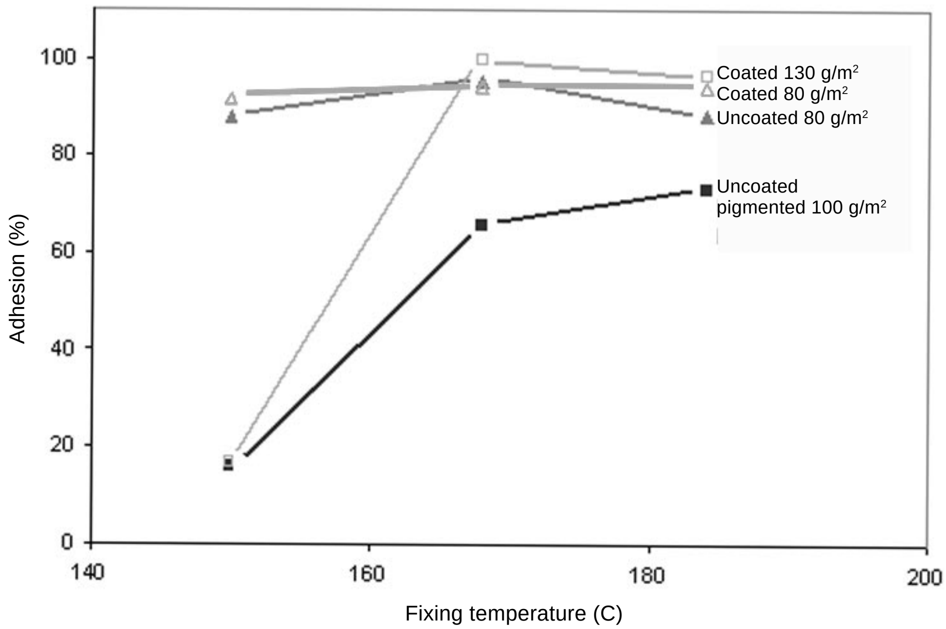

Figure 6. Adhesion of hot roller fused toner surfaces.

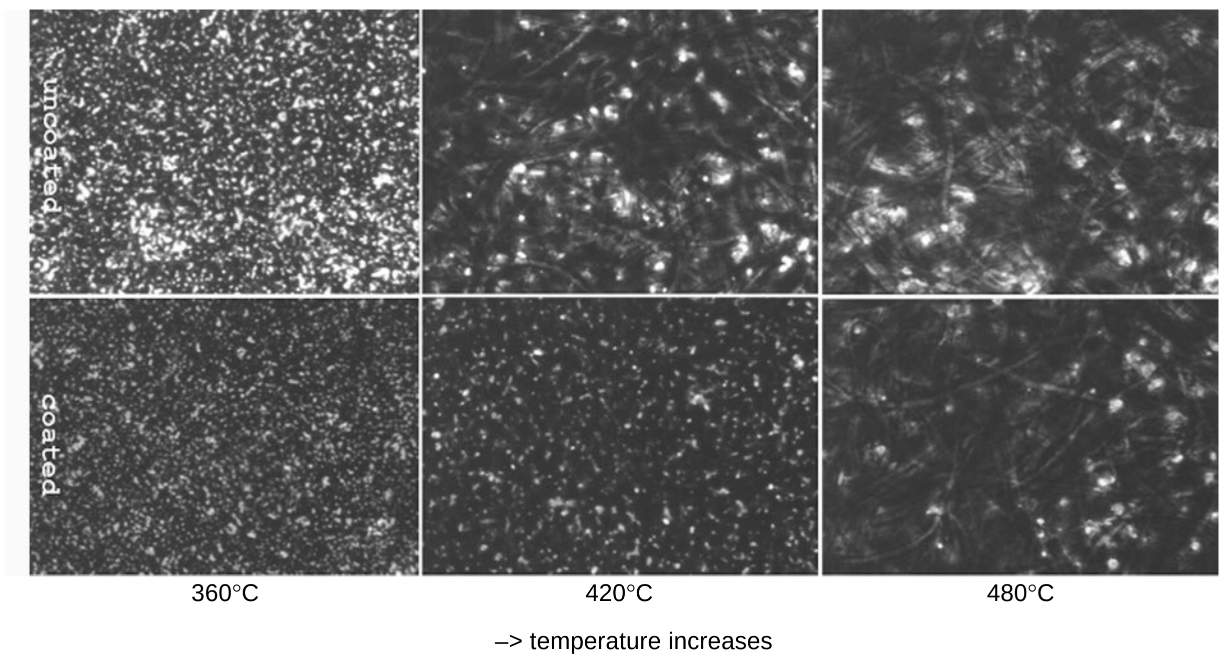

Figure 7. Print surfaces fixed with IR radiation.

Penetration effects were not expected to be significant and were not included in the model of Fig. 1. On coated papers specularly reflecting areas are smaller in size than on uncoated papers and their structure appears to result from variations in melting. Small scale gloss variation becomes pronounced.

It may be noted that point spreading was found to increase linearly with fusing energy. Because of the smoothing effect of spreading, text quality was improved. Text quality was found to be better on coated than on uncoated papers. The reason clearly lies in the more uniform surface. Over-fixing is seen as impairment of quality.

Fixing—IR Radiation

Figure 7 illustrates the appearance of IR fixed prints. At low IR radiation energy levels the number of white specks is considerable. Toner-free areas occur on both coated and uncoated papers. At low fixing energies, the areas have very sharp edges, are rather small and evenly distributed. Compared to unfixed prints, it appears that at the very lowest energy levels toner spreading is insufficient. Toner particles do not melt and empty spaces are left between them. Printed surfaces are rough and hence the finish is very matte. As the fixing temperature is increased, toner particles melt and the white areas diminish in number. In addition to that, they also

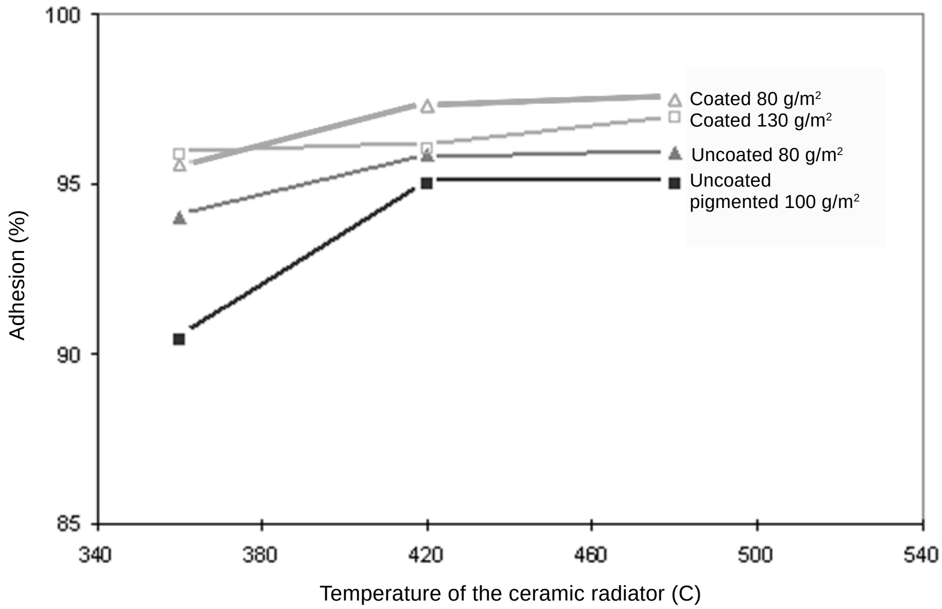

Figure 8. Adhesion of IR-radiation fixed surfaces on different paper grades.

change character and are now larger and have soft edges. These characteristics follow the theory of water vaporization introduced in the Model section.

Adhesion of IR fixed particles is very good also when the toner particles have not melted (see Fig. 8, IR-radiator temperature 360°C). This is true for all paper grades as can be seen from Fig. 8. A slight increase in adhesion is attained as the energy dose increases. Judging from the temperature versus adhesion curves (Figs. 6 and 8), the toner attaches to the paper surface differently in IR fixing compared to the nip.

It may also be noted that edge raggedness was found to increase at higher energy doses. On the other hand, line spreading is lower in IR radiation than in hot roller fusing. Text quality is poorer than in hot roller fusing, which is due to more intense edge raggedness. With uncoated papers, text quality is improved with an increase in the energy input. With coated papers, on the other hand, the best quality is achieved at the lowest energies.

Fixing—Hybrid

In the experiments on hybrid fixing, hot roller fusing was used before and after IR radiation fixing. When the hot roller is situated after the radiation unit, it serves as a finishing step. As the toner is already fixed by IR radiation, the main influence of the nip is on the optical quality variables. To support comparisons, the temperature levels were combinations of those used in the previous test series.

In hybrid fixing, the solid prints turned out to be fully covered by toner. Even at low fixing energies, toner-free areas are rare. A hot roller unit combined with IR radiation fixing improves the quality, despite the fact that line-spreading increases compared to using the IR unit alone. When the hot roller is placed after the radiation unit, white areas resemble the ones in IR radiation fixing at higher temperatures (see Fig. 9). Correspondingly, when a hot roller is used first, paper fibers appear as in hot roller fusing. So when the nip is placed after the radiation unit, the print quality resembles very much the quality of IR-fixed prints and vice versa. The relation of the temperatures in the two fixing methods contributes to the final outcome. The best quality is achieved with a moderate IR temperature and a relatively high hot roller temperature.

Comparison of the Fixing Methods

The phenomena in hot roller and IR fixing are compared by analyzing interrelations between measured print properties. If the relations are the same, it is concluded that the phenomena are also the same. Figure 10 illustrates the relations of small scale variation of density and gloss with respectively mean density and gloss. A rise in gloss level is accompanied by an increase in small scale gloss noise (Fig. 10 left). The plots for nip and IR fixing are, however, different. In nip fusing, gloss is higher at a given level of gloss noise than in IR fixing. This is interpreted to be an outcome of internal roughness consequent semidiffuse surface reflection from IR fixed toner particles.

As concerns density, the interrelations of rms variation and mean density level are similar, as shown on the right of Fig. 10. This is deduced to be due to the fact that the white specks cause most of the density variation and also control the density.

The plots of gloss versus density in Fig. 11 offer further proof for the dissimilarity in surface formation; the slopes are different. It is worth noting that the behavior is different in the groups of uncoated and coated papers. On uncoated papers, the marked role of coverage becomes evident as a steep slope. On coated papers, toner in both methods fairly evenly and fully covers the printed surfaces and the slope of the relationship is gentler.

The interrelations of point spreading and edge raggedness differ as illustrated in Fig. 12. In radiation fixing, increases in point spreading are accompanied by more ragged edges. In hot roller fusing point spreading has little or no effect on edge raggedness. There is altogether less noise in the lines fused with a hot roller. The pattern is also manifested as better text quality[15]. The observations are consistent with the model assumptions.

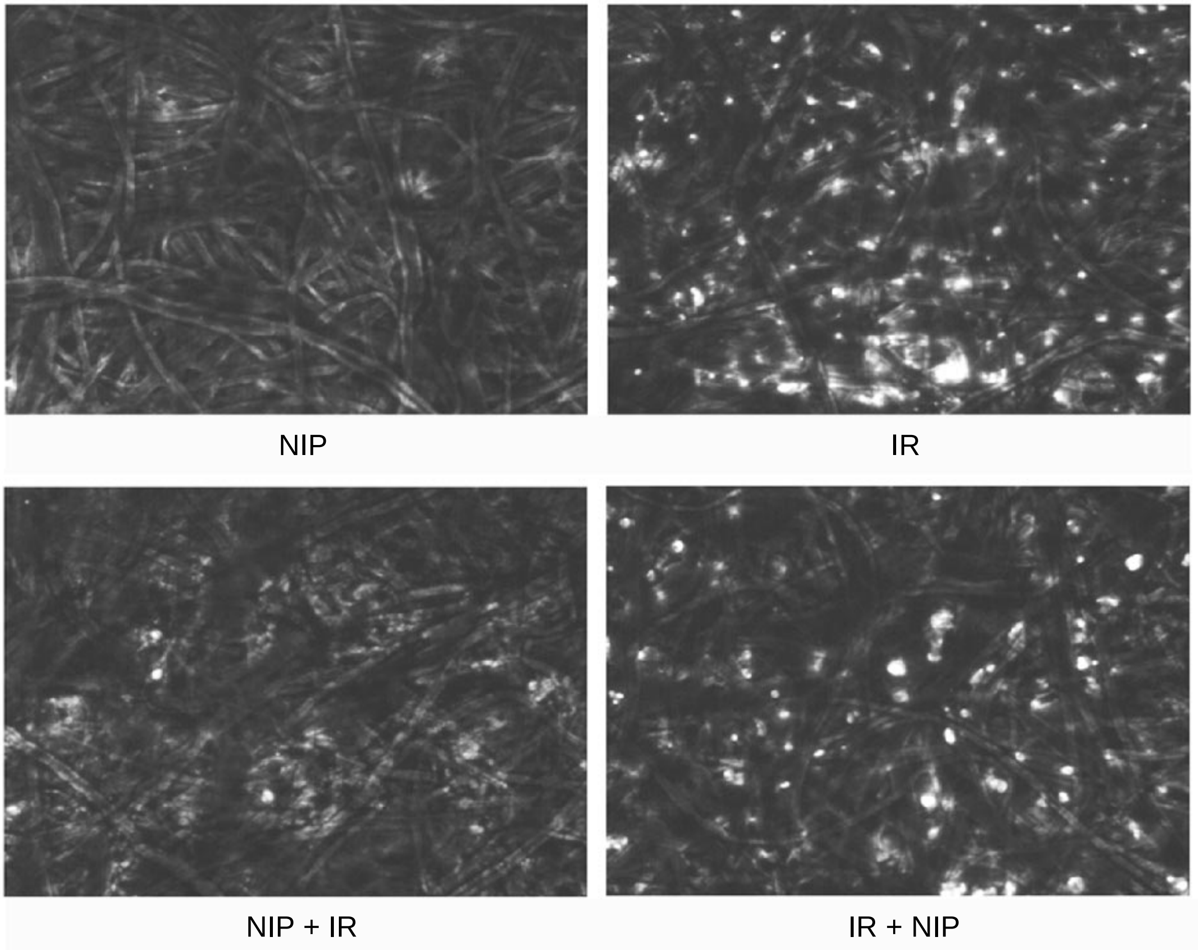

Figure 9. Print surfaces fixed with different conditions.

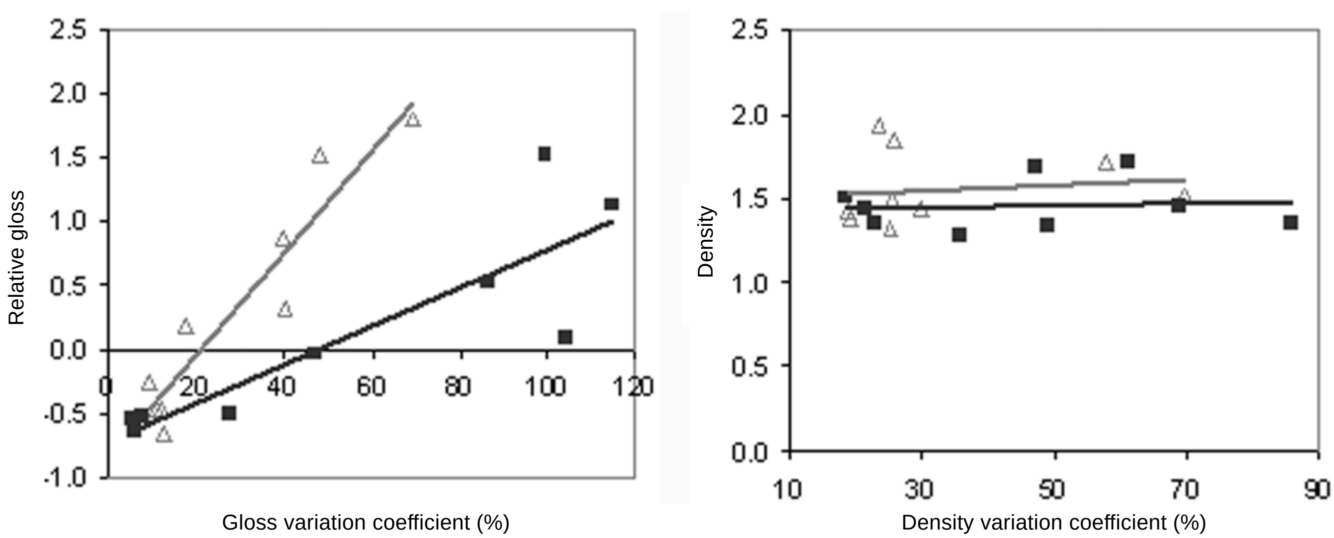

Figure 10. Relations of gloss and density with the respective rms variation. Δ, hot roller fusing (nip); ■, IR fixing. Uncoated and coated paper samples in different fixing conditions.

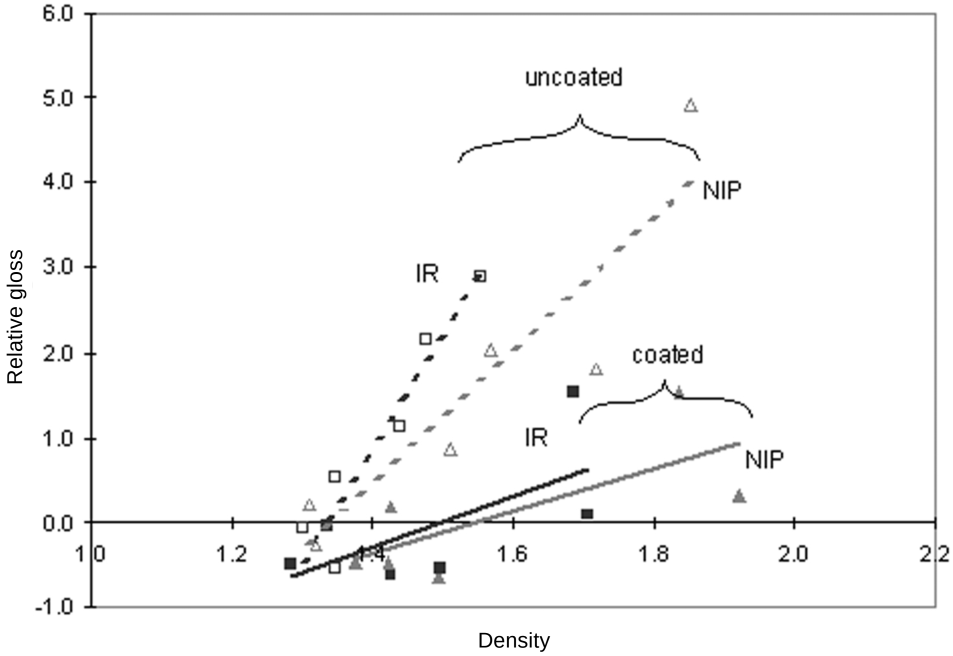

Figure 11. Relationship between gloss and density; Δ, hot roller fixing (nip); ■, IR fixing; solid symbols, coated papers.

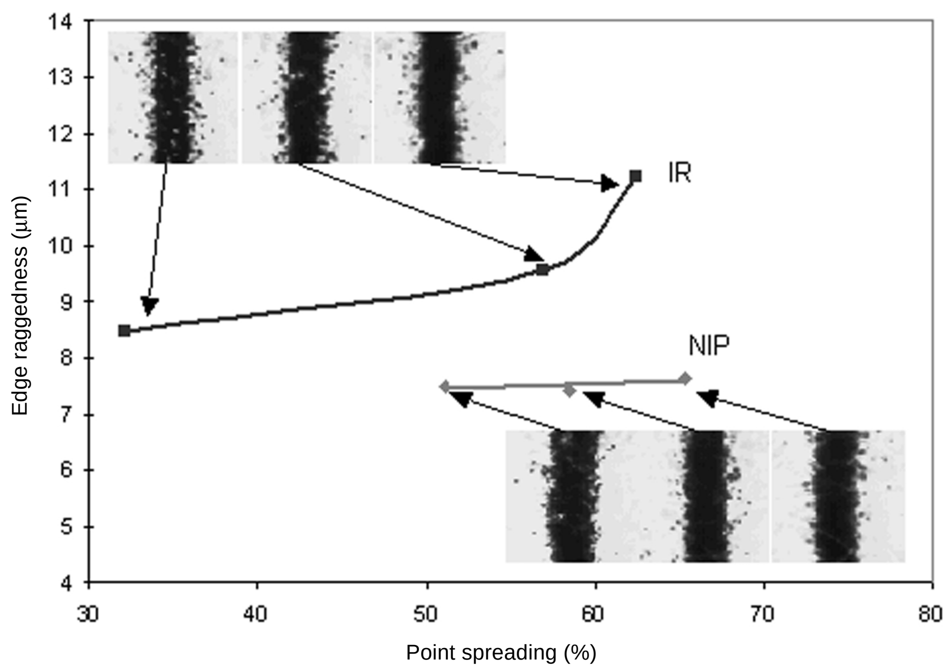

Figure 12. Relationship between edge raggedness and spreading.

Wire frame images were made with an image analysis program from the pictures of Figs. 5 and 7. The images shown in Fig. 13 visualize density values in the pictures as z-direction profiles. Visual comparisons suggest that they give a very realistic picture of the phenomena. The surfaces on the upper row were fixed with a hot roller and on the lower row with IR-radiation. The thickness of each image depicts the magnitude of whiteness in the toner-free area (depth of the deepest hole). Clearly IR-radiation fixed surfaces contain a large proportion of toner-free area. As the energy increases, the hot roller fixed surfaces become more solid and only minor density losses can be seen where paper fibers appear.

As for hybrid fixing, the question is to what extent the characteristics of hot nip and IR fixing become evident in the prints, depending on the order of applying the two methods. Figure 14 illustrates that toner adhesion is sufficient at all density levels when IR-radiation fixing is used alone or before the hot roller. When hot roller is used first or alone, the adhesion is poor at low density levels. When the fixing energy is increased, the adhesion improves.

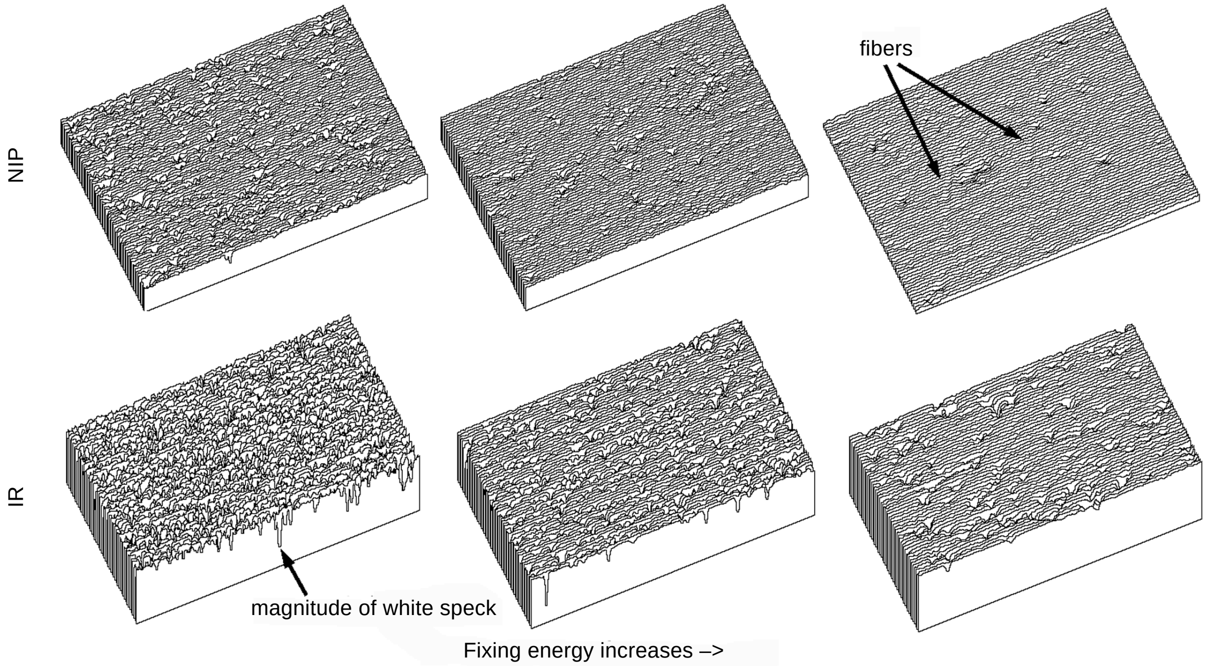

Figure 13. Wire frame images of fixed surfaces (upper row: hot roller fused, lower row: IR-radiation fixed).

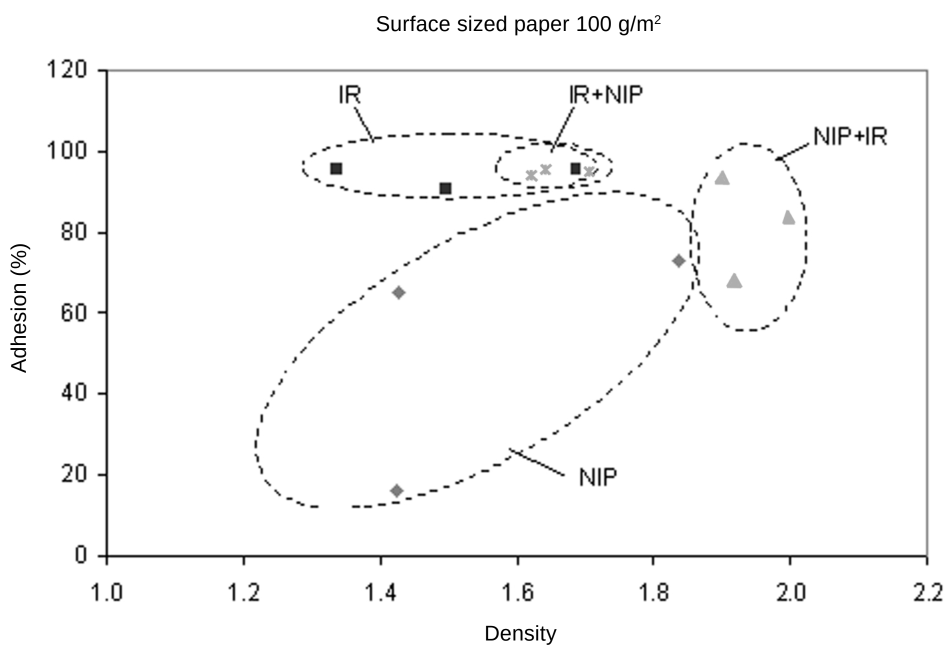

Figure 14. Formation of toner adhesion with different fixing methods.

In general, the subsequent step causes a change in most quality variables and their small scale variation. As an example of the effect of the second fixing method, the edge raggedness is reduced when the hot roller is situated after the IR radiation unit, but increases when the nip is ahead of the IR unit (Fig. 15).

Conclusions

The data on fusing quality were fairly consistent with the preliminary descriptive models. The origin of toner-free specks and roughening of the toner surface and their influences on density and gloss and their small scale variation could be understood. Differences in point spreading phenomena and edge raggedness in hot nip and IR fixing could also be explained. The preliminary models, however, failed to predict the influence of fibers penetrating through the toner layer. The phenomenon became more pronounced at high levels of fixing energy. It caused deterioration in gloss, density and coverage percentage and also resulted in increases in small scale variations.

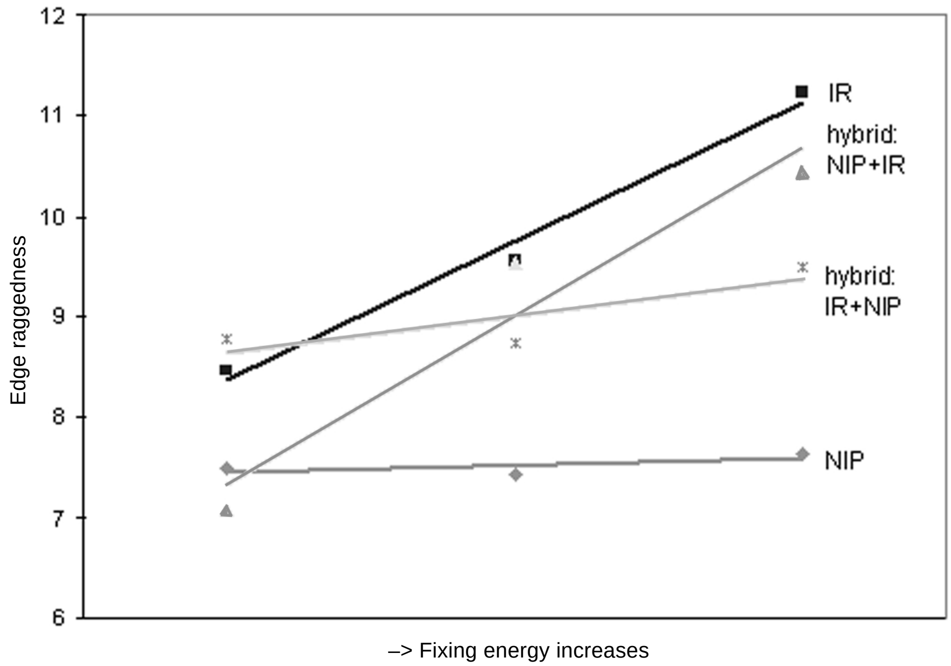

Figure 15. Influence of energy increase on edge raggedness.

Hot roller fusing and IR radiation fixing both have favorable characteristics. Overall, hot roller fusing is superior as far as optical print quality is concerned, whereas good toner adhesion and contactless operation are advantage offered by IR fixing. The behavior associated with white specks limits the potential of IR radiation fixing. The differences in adhesion levels between the two fixing methods needs further study. The IR method is more sensitive to fixing conditions and it tends to lead to noisier solid areas and lines. A combination of the two methods may offer an optimal solution.

The plain uncoated papers examined in the study were more homogeneous as a group, but were characterized by poorer print quality overall. Coated papers on the other hand appeared to be more sensitive to variations.

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