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Paper Material Considerations for System Printers

Laser printing of continuous forms by means of electrophotographic imaging requires that the paper on which the printing is carried out show good handling characteristics at fast machine speeds and be compatible with toner transfer and fixing. Toner transfer requires suitable electrical paper characteristics, similar to those of xerographic cut sheets intended for use in electrophotographic cut-sheet copiers and printers. Hot-pressure fusing in the IBM 3800 printing subsystem has been shown to require adequate paper-fiber wettability by the hot molten toner. Therefore, characteristics of paper chemistry, and in particular paper sizing, are essential in creating good image fixing (fusing). In addition, the temperature and pressure in the fusing assembly affect the thermal and dimensional stability of the paper. For the 3800, this necessitated modifications in roll design within the fusing station in order to ensure satisfactory paper handling.

Introduction

During the last decade, a number of high-speed printers have been developed that print on plain, bond-type paper via electrophotographic, non-impact printing techniques. Using either cut sheets or continuous forms, typical process speeds of these printers produce print in excess of one million sheets per month; the requirements for paper handling are severe. Yet these high-volume printing systems do not require special paper, and maximum performance can be achieved by using commonly available types of paper. This paper reviews aspects of the printing process related to paper interactions for electrophotographic, cut-sheet and continuous-forms printers. Specific examples are presented which pertain to the IBM 3800, for which the paper path and the fuser assembly have been described previously [1, 2].

Electrophotographic printing requires the transfer of polymeric toner particles to the paper base and subsequent fixing on the paper surface, most commonly using heat and pressure. In contrast to other printing processes, the majority of toners do not penetrate into the fiber material. At high magnification (**Figure 1**), the sintered toner material is readily visible on the fiber surfaces [3]. Transfer and fusing of toner particles require suitable electrical and chemical paper characteristics in addition to the possible adjustment of some of the more conventional (classical) paper properties, as shown in **Table 1**. The effect of paper characteristics on continuous-forms and cut-sheet handling are shown in **Table 2**. Xerographic cut-sheet specifications result in improved processability by tightly controlled moisture content, resistivity, and curl levels.

Thus far, the electrophotographic requirements of the printing process have affected the making and converting of paper for cut-sheet printing far more than that for continuous forms. Possibly this is because several printer designs have been modifications of existing copiers for which the xerographic cut-sheet paper grade was specified and recognized by the industry. Continuous-forms printing has lacked a similar effort; one of of the ground rules during the development of the 3800 printer was that it should print on general-purpose, off-the-shelf, continuous forms. Machine performance was monitored continuously using paper from all over the world and across the spectrum of allowed weights and sizes. Therefore, the paper used has been that of the generally less expensive and more variable register bond grade adapted to the requirements of specific printing systems (e.g., as indicated in Ref. [4]). As can be seen from the examples described, both electrophotographic and paper-handling requirements should be considered for any system printer. Many considerations necessary for the 3800 were similar to those necessary for xerographic cut-sheet copiers and printers. This led to a paper path that did not require major modifications in the evolution to its Models 3 and 8 from its Models 1 and 2. Differences

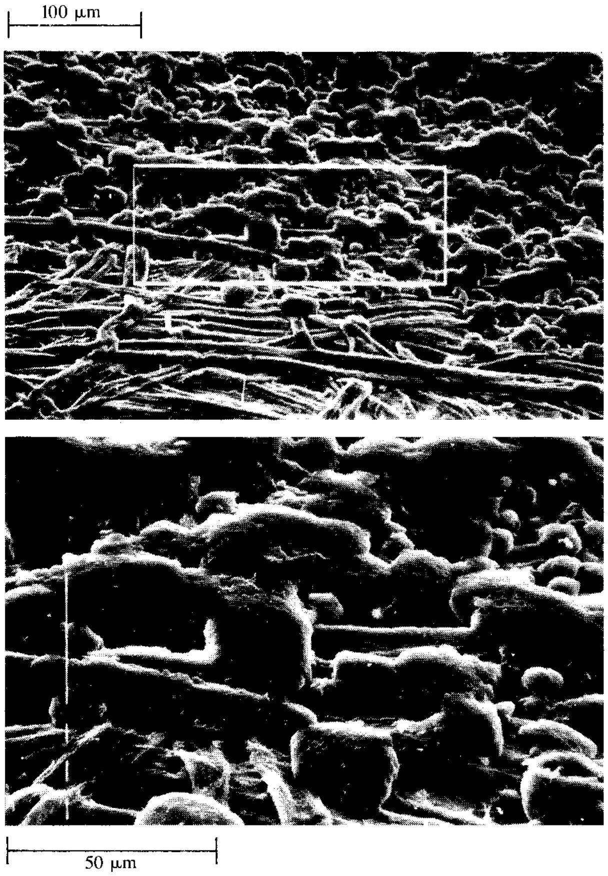

Figure 1 Portion of electrophotographic image illustrating toner particles on paper fiber surface. Lower photograph depicts framed area of upper photograph at increased magnification.

Table 1 Effect of paper properties on transfer and fuse grade. Arrows denote increasing or decreasing trends.

Paper property	*Transfer*	*Fuse grade*
Low or high resistivity	↓↓	—
High moisture content	↓↓	↓
Chemistry (hard sizing)	—	↓↓
High roughness	↓	↓
Low porosity	↑	↑
High substance or caliper (thickness)	↑	↓

between the former and the latter are covered in the introductory paper [5] to the series of papers in this issue which pertain to the 3800. Trends in the overall electrophotographic process are described elsewhere in this issue [6]. Here, it is our intention to examine aspects related to similarities and differences for cut-sheet vs. continuous-forms use.

Transfer

In electrophotographic non-impact printing, the image on the paper is created by charged toner particles that must be transferred from a photoconductor surface to a paper surface. Physically, the process is one in which polymer particles of micrometer size are transferred between two dielectric solids at different voltages. Transfer efficiency should depend on paper caliper (thickness) and dielectric constant, as described by Yang and Hartman [7].

Table 2 Effect of paper properties on handling characteristics.

Paper property	*Handling problem*	
	*Cut sheet**	*Continuous form***
Low stiffness	Jams	Misfolds
Low strength	—	Breakage
High curl	Jams, feeding failure, poor roll stripping	—
Low moisture content	Poor feeding, wrinkling, static electrification	—
High resistivity	Static electrification	Static electrification
High porosity	Vacuum feeding failure	—
Low friction	Friction feeding failure	Slippage
Low surface strength	Friction feeding failure	—

* Ref. [9].
** 3800 Printer experience.

Experience with the 3800 has shown that transfer efficiency increases with substance (weight) and/or paper density (low porosity and high caliper in Table 1). This is contrary to the Yang-Hartman model predictions, where high dielectric thickness (thickness-to-dielectric-constant ratio) created by high paper caliper should impede transfer. It demonstrates the necessity for considering physical contact between the paper and the toner in the transfer zone. Physical contact is a prerequisite for transfer to occur (e.g., the detrimental effect of wrinkles and folds). Both increased smoothness (Table 1) and pressure may affect toner-paper contact. The rationale for the pressure effect is that increased thickness and decreased porosity lead to more effective "trapping" of corona ions in the paper, thereby creating better electrostatic attraction between the paper and the photoconductor surface. As indicated in Table 1, the predominant transfer-degradation effect is the variation in paper resistivity beyond that normally encountered for bond papers without excessive moisture or antistatic additives (**Figure 2**) [8, 9]. The lower line in Fig. 2 shows surface resistivity at 10^{11}–10^{13} ohms for 3.7%–5.7% moisture content, the latter being the moisture-specification range for xerographic cut-sized office papers (ASTM D3460). For cut sheets, both paper handling and transfer characteristics are strongly affected at high resistivity levels [9].

Since continuous forms rather than cut sheets are used in the 3800, paper-handling problems are less severe at high resistivity levels. However, because printing is achieved by electrophotographic imaging, print problems may occur outside the resistivity range applicable to the cut-sheet xerographic paper grade (Fig. 2). For example, it was found that toner transfer, as measured by print reflectance, decreased because of high humidity when measured on similar paper sheets conditioned at various humidity levels and used for printing in a humid environment (>70% RH) (**Figure 3**). The evaluation of print quality parameters of the 3800 is addressed elsewhere in this issue [10]. Thus far, no detailed study of toner transfer to paper has been carried out that takes into account the variation in physical and chemical paper characteristics. It has been shown [11] that pulp type, chemical additives, and fiber orientation affect paper conductivity in addition to humidity. It appears reasonable to assume that similar considerations are in order when assessing efficiency in the toner-transfer process.

Fusing

The physics of fusing is that of melting, sintering, and spreading of polymer particles on paper fibers, as described by Lee [12] and Prime [13]. Individual toner droplets are seen adhering to paper fibers in Fig. 1. Good fusing, and, in particular, adequate spreading during the spreading phase of the fusing process, should depend on toner viscosity and the physical size of the sintered particles [13]. Initially, only paper moisture content and substance or caliper were considered to affect fuse grade through their effect on heat transfer in the fusing process. High moisture content, substance, or caliper were perceived to lower the fuse grade (Table 1).

The 3800 has been used in the printing of an increasingly variable range of paper substrates that have not traditionally been used for electrophotographic printing. These have included preprinted forms, papers used for utility forms (meter reader forms), paper containing quantities of ground wood or recycled pulp, etc. Rapidly, it became clear that print results were dependent on the chemical composition of the paper. In particular, the fusing grade was sometimes appreciably lower than that obtained for papers similar to the grade used for manufacturing xerographic cut sheets. A laboratory procedure developed specifically to assess fusing grade independent of machine testing [3] confirmed that the paper's chemical composition was instrumental in creating good fusing. **Figure 4** shows a comparison between different paper brands. The average adhesion force correlated with the fusing degree in the 3800.

Further work demonstrated that the amount and nature of the paper sizing have significant effect on the fusing. Papers that traditionally have been used for electrophotographic printing are relatively slack-sized, i.e., treated with low amounts of rosin-type additives. Papers that were treated with higher size amounts or more effective synthetic sizes (e.g., alkyl ketene dimer) often showed low fusing grade. As seen in **Table 3**, the size level had to be reduced to create sufficient fusing grade, as measured by a scratch test device for fuse

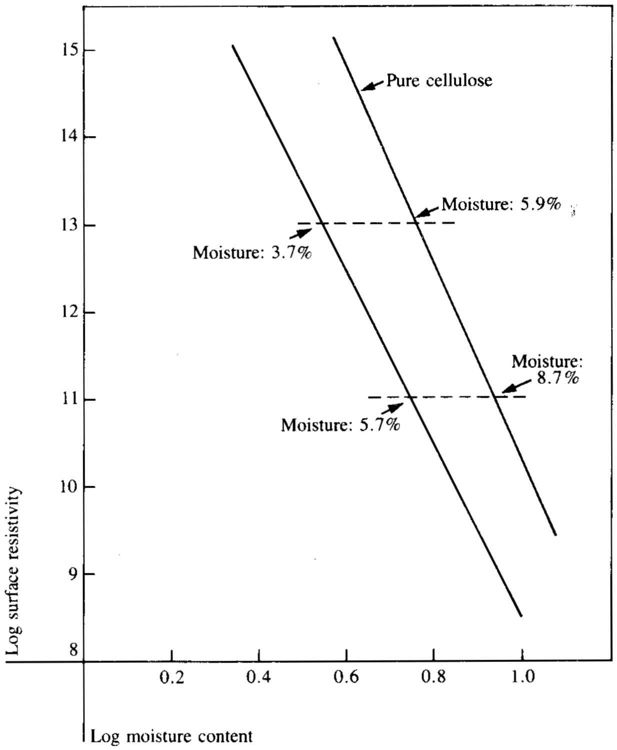

Figure 2 Moisture and resistivity properties of bond papers used in the electrophotographic process, as indicated for example in [8] and [9].

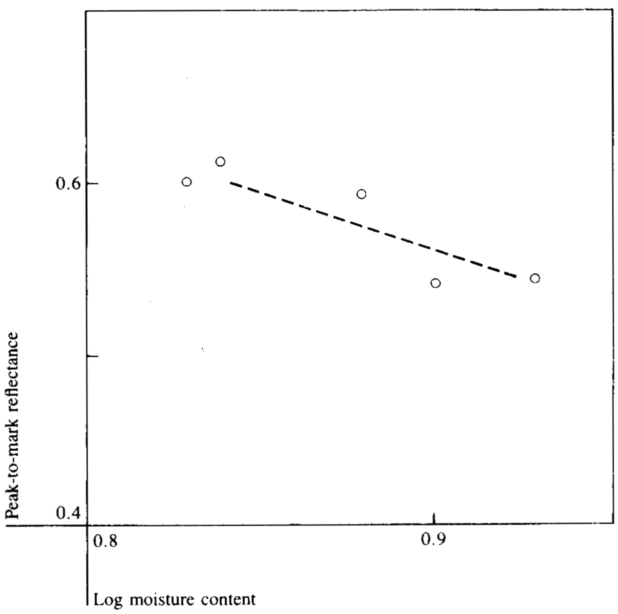

Figure 3 Moisture-induced decrease in toner transfer for the 3800 printing process. The vertical scale is a measure of toner transfer.

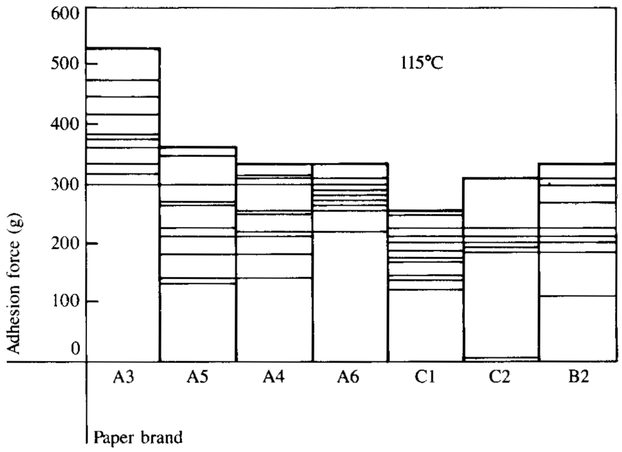

Figure 4 Adhesive characteristics of different paper brands. High adhesive force (ten measurements for each brand) indicates the tendency for good fusing. (From [3], reproduced with permission.)

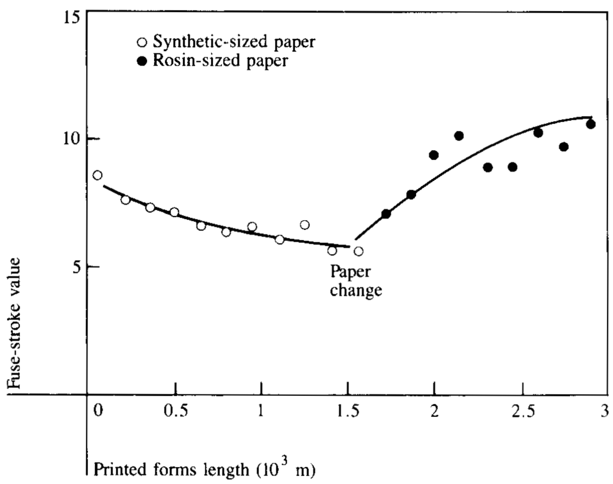

Figure 5 Fusing variation for synthetic- and rosin-sized papers.

stroke grading [13]. This variability in fusing grade is increasing because current trends in the making of fine papers are to develop more process variability (alkaline papermaking) [3, 14].

The variation in fusing grade which depends on paper chemistry can be understood as poor toner-to-paper adhesion caused by low surface energy of the paper substrate (Table 3, Column 2) [3]. The spreading process on the paper fiber surfaces is incomplete, and character break-out is facilitated through reduced contact between the toner and the paper. The selection of papers suitable for high-quality fusing grade has been stressed in recent updates of the document that specifies paper recommendations for the 3800 [4].

Table 3 Alkyl-ketene dimer treated paper.

Size level (%)	*Surface energy** (mN/m)	*3800 Fuse stroke*
0.10	20	1–2
0.05	28	6
<0.05	33	20

*Comparative value only (Ref. [3]).

Heat stability

Temperatures in high-speed fuser assemblies typically range from 180° to 200°C (350° to 400° F). For plain paper, the main effects of this temperature "shock" are to dry the paper (moisture content reduction) and to affect the paper-handling properties described below. The dwell time is too short to discolor the paper or to affect its other characteristics in a permanent manner. Nevertheless, it is imperative that all components used in the papermaking process be heat-stable and not create heat-unstable reaction products (e.g., hydrolysis of synthetic size additives). Because of the high printer speeds, even minute thermally unstable impurities will build up on the rolls in the fuser assembly or even be expelled into the printer environment. **Figure 5** shows fusing grade variation for the 3800 when plain paper was processed and when organic constituents in a synthetic sized paper type were not heat-stable. Fuse-stroke values decreased from 9 to nearly 5 when approximately 1500 m (two cartons) of paper was processed in the printer. As indicated in the figure, a change to rosin-sized paper at 1500 m gradually restored fusing grade because the new paper cleaned the roll surface. The difference in fusing grade between the two papers fused by a clean fuser roll (at 0 m and at 3000 m) was caused by surface energetics differences between rosin- and synthetic-sized papers, as described above.

Potentially less damaging problems during the processing of plain papers in the 3800 are dust and rosin or moisture buildup on printer covers and other surfaces in the fuser environment. Loose fiber, filler, rosin, and other paper particles also are capable of buildup on transfer coronas, as well as on components where they may be cleaned off more readily. Though moisture generation in itself generally is harmless, vaporization (steam distillation) can remove other possibly harmful components.

Present trends are to apply electrophotographic printing to specialized substrates that may not be heat-stable. Forms and cut sheets with lithographic preprint are now routinely processed in high-speed printers. The continuous-forms printer is particularly versatile for this application because of the freedom in forms design afforded by the multiple forms sizes that the printer will accept. For the 3800 and other similar hot-fusing printers, it is necessary to eliminate the transfer to the fuser roll of heat-unstable ink components which may create a fusing grade variation similar to that indicated in Fig. 5 for synthetic-sized paper. However, ink contamination generally occurs more rapidly, sometimes with complete fusing failure and at unpredictable intervals during the printing run, possibly caused by variations in the curing (drying) stage of the preprinted substance. Usually the fuser roll is visibly contaminated as a result of the color of pigments and dyes in the inks. Heat-stability requirements for lithographic printing inks have led to the recommendation of specific ink types for laser printers [15]. Although these polymerizing and oxidative types do not contaminate the fuser-roll system after proper printing and curing procedures, they tend to generate trace levels of air contamination during the curing process [16]. Therefore, it is necessary to ensure that lithographic printing conditions and forms handling after the preprinting process do not compromise electrophotographic printing because of either machine or air contamination.

Paper handling

Both cut-sheet and continuous-forms paper handling are affected by dimensional changes caused by the temperature and pressure of the fuser assembly. Typically, printing and writing papers show higher humidity expansivity in the cross direction than in the paper travel or machine direction [CD/MD expansivity ratio in **Figure 6(a)**] [17]. Fiber orientation, sheet two-sidedness (difference in physical characteristics between the two sheet surfaces), and built-in stresses caused by paper formulation and drying conditions determine how the paper responds to the temperature and pressure profiles in the fuser assembly. **Figure 6(b)** shows nonreversible shrinkage as functions of moisture contents and dwell times typical for cut-sheet papers used in electrophotographic high-speed copiers and printers [17]. This figure illustrates that the paper will not return to its original shape after passage through the fuser, even when moisture and temperature are allowed to adjust to original values. Paper-handling characteristics of high-speed, cut-sheet printers are mainly affected by paper curl (unequal expansivity on the felt and wire side), jams, and roll stripping, as indicated in Table 2. In continuous-forms printing, proper handling requires that the fuser assembly not create paper deformation that impacts printer throughput.

The design of the 3800 fusing system has been described by Brooms [2]. As an overview, and referring to **Figure 7**, paper is pulled across a heated convex aluminum plate called a preheat platen, by a pair of rubber-coated rolls. The top roll, which is coated with a thin layer of silicone rubber, is heated internally. The lower back-up roll is coated with a thick, soft layer. The rolls are loaded against each other to cause a nip in which the fusing process is completed. The heating process is initiated on the preheat platen. The platen contains vacuum slots to maintain good thermal contact between the paper and

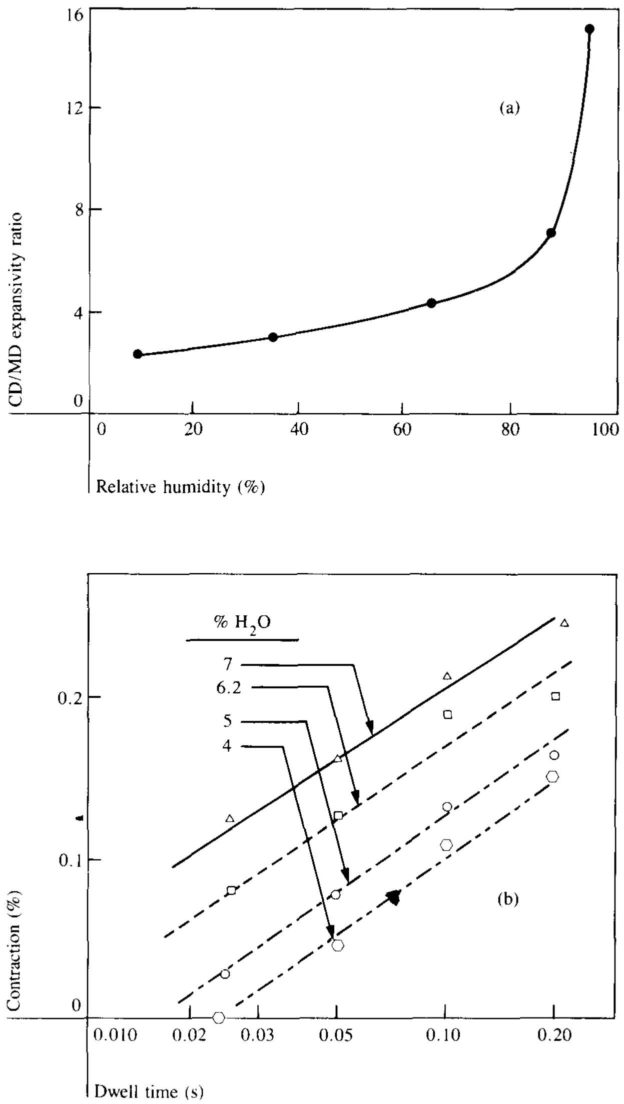

Figure 6 Humidity effects on dimensional characteristics: (a) Effect of relative humidity on cross-to-machine direction (CD/MD) expansivity ratio; (b) Effect of moisture content and dwell time on nonreversible shrinkage at 200°C. (From [19], reproduced with permission.)

its heated aluminum surface. These slots extend nearly to the carrier strip holes in the widest form that can be processed in the printer.

In the 3800, paper-handling problems have been encountered which were caused by paper wrinkling. The resulting wrinkles were near the paper carrier-strip edges and were only observed on the widest processable forms. Once the paper began to wrinkle, it became worse until new rolls were installed. Printed data in or adjacent to the wrinkles were often lost because of poor fusing. It was found that the problem was connected with paper contractions on the preheat platen; more shrinkage occurred in the vicinity of the vertical centerline

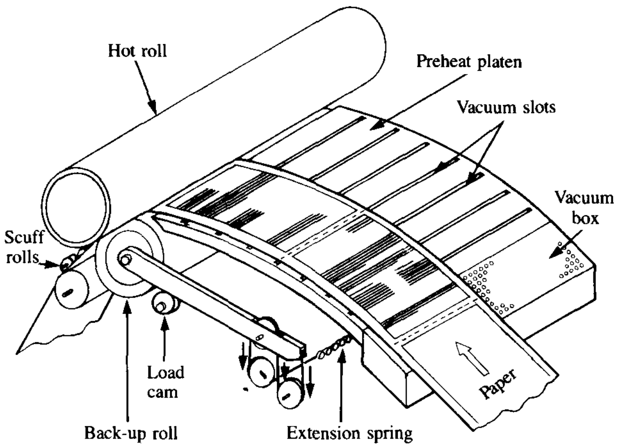

Figure 7 The 3800 fuser assembly. (From [2], reproduced with permission.)

than near the edges. The edges of the paper were not held tightly enough against the preheat platen as the paper approached the fuser nip. Only some types of paper would actually wrinkle; "normal" paper displayed the same characteristics, but to a lesser and tolerable extent. It was decided to offset the nonuniform shrinkage on the preheat platen by modifying the footprint of the pressure-creating backup roll in the fusing assembly (Fig. 7). Rolls were obtained with flares to increase the footprint (contact area) at their ends. This shape not only eliminated the wrinkling but proved to be more cost-effective due to longer roll life; the slippage at the ends had caused accelerated roll wear.

Future perspective

In spite of significant advances in the understanding of paper requirements in the electrophotographic process [3, 9], it is obvious that several aspects of paper performance need more attention. The process of toner transfer to paper is not completely understood. Models must be established that define the nature and importance of paper characteristics. The fusing process covers the interdisciplinary sciences of polymer rheology, wetting, and adhesion, and a better physical understanding of each aspect is needed. The effects of the components in the chemically complex paper surface have not yet been fully appreciated, and present papermaking trends (e.g., alkaline papermaking) threaten to further decrease paper latitude of existing printer products. Paper variability that is difficult to control (e.g., the heat deformation described above) should be considered early in the development stage of the printer.

Summary

Aspects of the printing process related to paper interactions (transfer, fusing, and paper handling) have been examined for the electrophotographic imaging process used in system printers. The transfer of toner particles to the paper surface requires electrical paper characteristics similar to those of xerographic cut sheets intended for copies and printers. Hot-pressure fusing requires adequate paper-fiber wettability by the hot molten toner and, therefore, is affected by the chemistry of the papermaking process (in particular, the sizing treatment). Paper-handling capability in the IBM 3800 Printing Subsystem was improved by use of a fuser roll design that would allow for nonuniform paper shrinkage without creating unacceptable paper wrinkling.

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