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# Using a Computer-Controlled Hot-Roll Fusing Test System


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***Paper presented at the 3rd International Conference on Imaging Science and Hardcopy***

***Organized by Reprographic Scientists and Engineers Society, China***
***The Society of Electrophotography, Japan***
***The Society for Imaging Science and Technology, USA***
***UK Chinese Opto-Electronic Association***

***May 26-29, 1998, Chongqing, China***

# Optimization of Toner Fusing Using a Computer-Controlled Hot-Roll Fusing Test System


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## Abstract

A fundamental objective in the development of hot-roll fusing sub-systems in electrophotography is to optimize fusing latitude. A broad fusing latitude, defined by the temperature range between which cold and hot offset occurs, is a critical factor in achieving a robust printing process and ensuring the highest print quality. With the recent introduction of a stand-alone, computer-controlled hot-roll fusing test apparatus, developers of toners, toner resins, print media, fuser rollers, fusing sub-systems, and related products now have available to them a highly flexible tool that greatly enhances both objectivity and productivity in optimizing and characterizing the hot-roll fusing process. The system allows the user to control the process speed, the contact load between the rollers, the temperature range, and the lubrication. In addition to the flexibility it affords in controlling the process variables, the modular design of the system enables the user to change the fuser rollers with ease and to control heating of the fusing and pressure rollers independently. System design considerations and a range of practical application examples are discussed.


## Introduction

In dry toner electrophotography hot-roll fusing technology is most commonly used to fix the toner to the media. The process of hot-roll fusing involves melting of the toner, coalescence, spreading, penetration into capillaries, and resolidification[1-3]. The combined effects of time, temperature and pressure determine the quality of fixing. Acceptable fusing quality can only be achieved when these parameters are within the fusing latitude, or "fusing window." The fusing window is bounded below by cold offset due to adhesive failure between the toner and the media, as manifested by the transfer of unfused toner to the hot roll. It is bounded above by hot offset due to cohesive failure within the molten toner layer, as manifested by adhesion of the toner to the hot-roll surface.

Fusing system designers and toner developers aim to maximize the fusing latitude so that acceptable fixing can be achieved consistently despite uncontrollable disturbances to the system. Because the hot-roll fusing process is so complex and its outcome is usually difficult if not impossible to predict analytically, an experimental approach to studying and optimizing the fusing process is often adopted for fusing research and development. What has been missing until now was the right tool for studying system interactions, including interactions between roller design, toner, media, and lubrication under the full range of process conditions. With the increasing trends toward color and high speed in electrophotograpic printing systems, the need to understand the complexity of the hot-roll-fusing process defines the need for a reliable and flexible test apparatus — the subject matter of this paper.

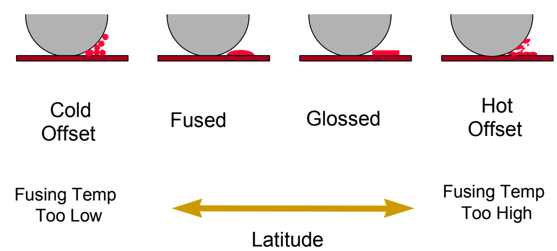


Figure 1 Fusing latitude in hot-roll fusing

**Factors considered in the design of a computer-controlled hot-roll fusing test system**

The fusing latitude and the quality of fix depend on many variables, including the following.

The design of the fusing system:

- Soft vs. hard rollers
- Heating of one vs. heating of both rollers
- Heater characteristics
- Heating control algorithm

Material variables:

- Roller hardness and surface energy
- Toner resin rheology and thermal properties
- Toner particle size

- Toner mass per unit area
- Lubrication (internal vs. external lubrication)
- Media roughness and surface energy
- Media thickness and thermal properties

Process variables:

- Fusing speed
- Paper feed speed
- Roller temperature
- Nip pressure
- Fusing sequence

Given a process as complex as hot-roll fusing, an apparatus designed to study it must allow the user easy, reliable control over a host of variables. The system now commercially available[4] closely simulates the operating environment of a printer but permits parametric fusing experiments to be performed quickly, under controlled conditions, and the results to be used to quantify the effects of each variable on the degree and quality of fusing. The system is suitable for testing a wide variety of toners and media. It accommodates a broad range of fuser roller types and sizes. In a typical session, the user loads unfused images (typically generated by a printer with its fusing system disabled) into a paper cassette, sets the process parameters, and launches the fusing cycle with the control software. The test process fuses the images under the conditions specified, monitors media temperature, computes temperature statistics during the fusing process, and delivers the fused images to an output tray for subsequent analysis of the fix level using abrasion, crease or tape adhesion tests.

**Optimizing fusing conditions – an experimental study**

In a previous study[4], the efficacy of the fusing test system was demonstrated by determining the fusing windows for several toner types under a broad range of fusing temperatures and roller speeds. In the current study, the investigation aims to develop insight into the interactions between media characteristics such as type and thickness and important process variables including:

- ***Time***, i.e., residence time, of the media in the nip region. Residence time is controlled by the roller's rotational speed and the nip width. Nip width, in turn, is determined by the applied pressure and roller elasticity.
- ***Temperature***, i.e. the roller temperature. Temperature is set by the user via the control software and monitored by means of a non-contact infrared thermometer.
- ***Pressure,*** i.e., the nip pressure. Pressure is determined by the contact force between the rollers and the nip area.

A commercial desktop color laser printer is used to generate the unfused images by disabling its fusing subsystem. The toner mass per unit area is controlled by the gray level of the test print and is determined by weighing the media before and after printing. The fuser and pressure rollers are commercial rollers with a release coating and a medium hardness. Both the fuser and pressure rollers are equipped with tungsten-halogen heater lamps at their cores. Most experiments in this study were conducted with both heater lamps on, but the test system does allow the user to turn the heaters on and off independently. Unfused pages were loaded into a computer-controlled paper cassette. It should be noted that the paper cassette gives the user control over the fusing sequence, including the option of using blank paper (for cleaning and/or conditioning) between samples.

**Materials – media and toner**

To explore the effects of media characteristics on fusing quality, 22 different paper samples were tested. The media used represent a spectrum of variables including basis weight (75g/m², 90g/m² and 120g/m²), recycled or cotton fiber content, smoothness, whiteness, and opacity. The retail cost of the media sampled ranges from under US$0.01 per sheet to US$1 per sheet.

The toner used for all tests is the CMYK toner set obtained from the OEM supplier of the desktop color laser printer used in this study. The toner used evidently has lubricant built into its composition and therefore does not require additional external lubrication.

**Fixing ratio evaluation and quantification**

A crease test was used to evaluate the fusing quality of the fused images. The paper was folded across a solid fill area of the image, and controlled pressure was applied to form a crease. The paper was then unfolded, and a clean cotton swab was used to wipe away loose toner along the crease. The optical density in an area centered on the crease ($D_{crease}$) was measured using a densitometer. Finally, the optical density of an area away from the creased area ($D_{field}$) was also measured. The ratio of these two densities, $R = D_{crease}/D_{field}$, is the fixing ratio. Fixing ratio (R) is a direct quantitative measure of fusing quality, with a maximum value of 1.

Another phase of this study evaluated image quality in terms of fundamental quality parameters such as dot gain, line width, modulation, tone reproduction, image noise, color reproduction, etc., using an automated image quality analysis system. The results of this phase are reported in another publication.

**Fusing window determination**

The fixing ratio, or fusing quality, of several media types was obtained throughout a range of fusing temperatures to determine the fusing window. The results of one of these experiments are shown in Figure 2.

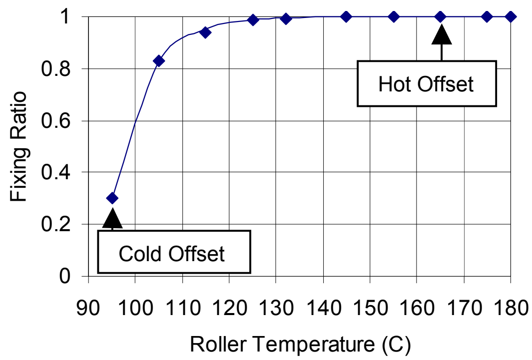


Figure 2 Fixing quality as a function of fusing roller temperature

As the figure shows, at a surface speed of 10 pages per minute (ppm), an average nip pressure of 0.58 MPa, and a nip residence time of 170 msec, the minimum fix temperature for the toner under study is about 100 °C and the hot offset temperature is about 165 °C.

From this data, it is apparent that the optimum operating temperature is above 135 °C and below 165 °C. To highlight the sensitivity of the fixing ratio to media and process variables, a roller temperature of 130 °C at the fringe of the optimum range was used in the remainder of this study.

**Fusing quality on commercial media**

The fusing conditions for this experiment were: a roller temperature of 130°C, an average nip pressure of 0.58 MPa, and a surface speed of 10 ppm. Under these conditions, no obvious correlation was found between the fixing ratio and the visible whiteness and brightness of the paper. Similarly, the relationship between fixing ratio and advertised smoothness was not apparent. The most noticeable correlation found was between fixing ratio and the basis weight of the paper (Table 1).

Table 1 Average fixing ratio for different basis weight media

| **Basis Weight (g/m²)** | **Average Fixing Ratio** |
|---|---|
| 75 | 1 |
| 90 | 0.94 |
| 120 | 0.82 |

As the table shows, the fixing ratio (R) decreases as the basis weight or thickness of the media increases. This observation raises some interesting questions:

1. If fixing quality decreases with basis weight, why are consumers willing to pay more for heavier paper?
2. What mechanisms account for the observed correlation between fixing ratio and basis weight?

The first question is really a business consideration and can most likely be accounted for by two factors:

1. Consumers presumably measure quality by the look and feel of the sheet – its weight, whiteness, apparent smoothness, etc.
2. The experimental conditions used in our study may not have been exactly the same as normal operating conditions for the printer used and may not have been optimal for producing the best fixing ratio.

The second question is of significant practical value. The answer offers insight into the mechanisms at work in hot-roll fusing and provides useful information for the design and optimization of fusing subsystems and processes. The balance of this paper will focus on the factors that account for our observations.

**Fixing ratio and media thickness**

Our experiment used 75 g/m². media, the basis weight group with the highest fixing ratio. The average nip pressure was 0.58 MPa, and the fusing temperature was 130 °C. The controlled variable in this experiment was the thickness of the media. Both thick and thin sheets were used. Thick sheets were obtained by stacking several thin sheets together and feeding the stack through the fusing test system. Since paper jamming is not a problem in this system, up to ten 75 g/m². sheets could be fed through at the same time.

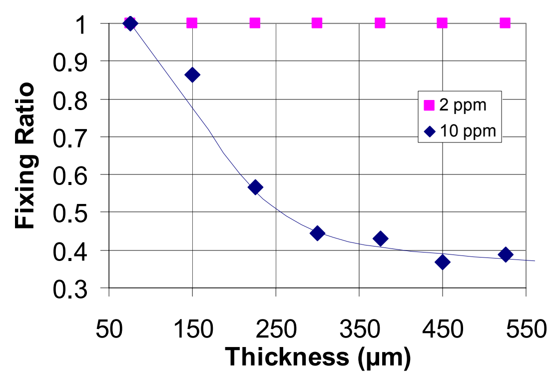


Figure 3 Fixing ratio as a function of media thickness at 130°C and different speeds.

As shown in Figure 3, at a fusing speed of 10 ppm, the fixing ratio decreases substantially from — R=1 to R=0.4 — as the media thickness increases from 75 µm (single sheet) to 300 µm (4 sheets). Beyond 300 µm, however, the fixing ratio remains quite constant. On the other hand, at 2 ppm the fixing ratio remains high — at R=1 — throughout the whole range of media thicknesses studied. In other words, at a low fusing speed, fusing quality is independent of media thickness.

These results immediately suggest the importance of the thermal diffusivity of the media in hot-roll fusing. Thermal diffusivity is the ratio of thermal conductivity to specific heat. If the thermal diffusivity of the media is known, a characteristic time constant for thermal diffusion can be computed for a given thickness. Once the thermal diffusion time constant is known, it can be used as a benchmark for determining "sufficient" heat transfer. Qualitatively, the results in Figure 3 can be explained on the basis that as total media thickness increases, the thermal diffusion time constant also increases. The thermal diffusion time most likely exceeds the residence time at a thickness of about 300 µm and a fusing speed of 10 ppm, and never exceeds the residence time at 2 ppm for the range of media thicknesses studied. Hence the observed thickness dependence at 10 ppm but not at 2 ppm. This observation will be explored more quantitatively in the next section.

**Importance of thermal diffusion in hot-roll fusing**

To evaluate the role of thermal diffusion in hot-roll fusing, the thermal diffusion time constant was computed using the following relationship:

$$\tau = \frac{d^2}{\alpha} \qquad [1]$$

where:

$\tau$ = Diffusion time constant
$d$ = thickness
$\alpha$ = thermal diffusivity

The thermal diffusivity for paper is estimated to be 600 µm²/msec based on values reported in the literature[5]. Based on Equation 1, the relationship between the thermal diffusion time constant and paper thickness is computed as shown in Figure 4.

For most office applications, 75 and 90 g/m² papers are typically used, and the approximate thicknesses are 75 and 90 µm. The corresponding thermal diffusion time constants are 9 and 14 msec.

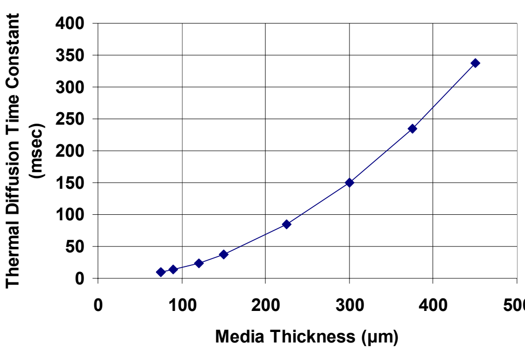


Figure 4 Thermal diffusion time constant as a function of media thickness

The residence time of the media in the nip is governed by the fusing speed and the nip width. The nip width can be experimentally determined as a function of the applied pressure. With the nip width data, the residence time can be computed as shown in Figure 5.

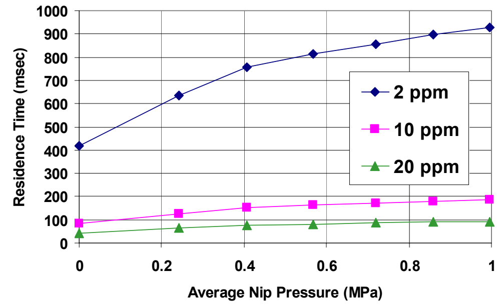


Figure 5 Residence time as a function of nip pressure.

The relationships shown in Figures 4 and 5 and their influence on fixing ratio can be described as follows: if the residence time is significantly longer than the thermal diffusion time, there is practically no media-thickness effect on fixing ratio. On the other hand, if the residence time is comparable to or shorter than the thermal diffusion time, the thickness effect on fixing ratio is quite noticeable. Applying this principle, the residence time at 10 ppm and 0.58 MPa is about 160 msec (Figure 4), and thermal diffusion time increases from about 10 to 160 msec when the media thickness increases from 75 to 310 µm (Figure 5). Given a residence time of 160 msec, we can now understand in terms of increasing thermal diffusion time why the fixing ratio decreases from R=1 to 0.4 as the paper thickness increases from 75 to 310 µm. Similarly, at 2 ppm and 0.58 MPa, the residence time is about 810 msec, significantly longer than the thermal diffusion time for a thickness below 500 µm. No degradation of fixing ratio is observed in this range of media thicknesses.

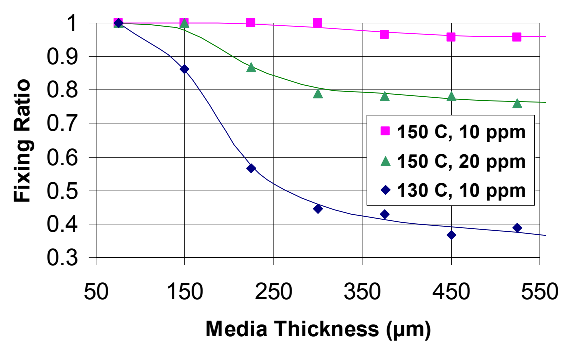


Figure 6 Fixing ratio as a function of media thickness at different temperatures and speeds.

As Figure 6 shows, at 130°C the fixing ratio does not decrease continuously, but instead levels off at a fixing ratio of R=0.4. A likely explanation is that since both the fuser and pressure rollers are heated in this experiment, both heat sources contribute to toner fusing depending on media thickness. While the heat contribution of the pressure roller is nearly shut off by the presence of a thick media layer (i.e., when there is a long diffusion time constant relative to residence time), the fuser roller continues to add thermal energy to the fusing process, contributing to some degree of fixing. Figure 6 shows additional data obtained at a roller temperature of 150°C and a fusing speed of 10 and 20ppm. Comparing the 10 ppm data in Figures 3 and 6, it seems clear that at the higher roller temperature, fusing quality becomes significantly less dependent on media thickness; the minimum fixing ratio of 0.95 at 150°C contrasts with 0.4 at 130°C. When the fusing speed is doubled from 10 to 20 ppm, however, the minimum fixing ratio drops to approximately 0.75. These observations substantiate our original observation of the correlation between fixing ratio and basis weight and demonstrate the mediating effects of residence time and temperature.

In the 150°C data shown in Figure 6, we can estimate that the minimum fixing ratio is reached at thicknesses of about 300 and 400 μm at 20 and 10 ppm, respectively. From an analytical point of view, Figures 4 and 5 suggest that, assuming the minimum fixing ratio is reached when the residence time is equal to the thermal diffusion time, the predicted thicknesses at the minimum fixing ratio will be 220 and 320 μm, respectively. Although these predicted thicknesses do not exactly match those obtained experimentally, they are close enough to lend further credence to the theory that thermal diffusion is an important controlling mechanism in the hot-roll fusing process.

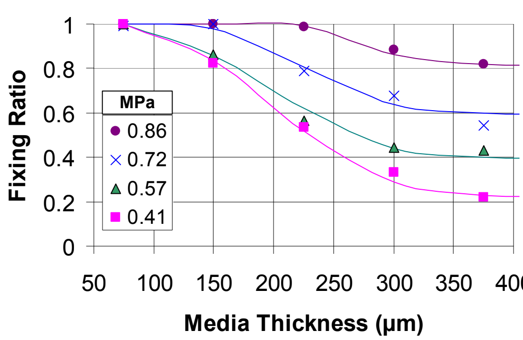


Figure 7 Fixing ratio as a function of media thickness at different pressures.

### Effect of applied pressure on fusing quality

Figure 7 shows the effect of applied pressure on fusing quality for a range of media thicknesses. The results show that for a given thickness, as the applied pressure increases, the fixing ratio also improves. Furthermore, at a high enough applied pressure (say, greater than 0.72 MPa), the fixing ratio is independent of media thickness in the range of interest for most office applications (i.e., less than 150 μm), even at the relatively low fusing temperature of 130°C. It should be noted that significant improvement in fusing quality can be achieved by increasing the applied pressure. In this example, at 10 ppm, with an increase from 0.41 to 0.86 MPa, the residence time increases from 150 to 180 msec. A mere 20% increase can produce a substantial increase in the fixing ratio, particularly for thick media (Figure 7). The role of applied pressure is twofold: a) increasing nip pressure increases the nip width and hence the residence time; and b) increasing nip pressure increases the contact area between the fuser roller and the media, thereby reducing thermal contact resistance and enhancing heat transfer between the heat source and the media.

### Further confirmation of the correlation between fusing quality and media thickness

Figure 8 shows the average fixing ratios of the original set of 22 commercial media samples superimposed on a portion of Figure 3, which contains data from a single sample. The agreement between the two sets of data is reasonable, further substantiating the importance of media thickness and thermal diffusion in hot-roll fusing.

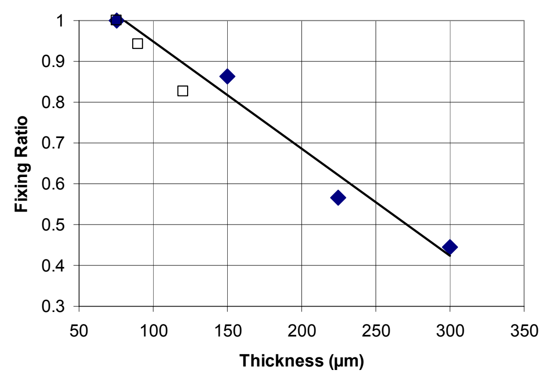


Figure 8 Fixing ratio as a function of media thickness.

## Discussion

With a computer-controlled toner fusing test system, a parametric study was conducted to elucidate the effects of process variables such as roller temperature, applied pressure, residence time and media characteristics on fusing quality. The most significant observation of this study is the importance of the combined influences of thermal diffusivity and media thickness on fusing quality. Most studies of the effects of media on fusing quality have emphasized surface characteristics such as roughness and surface energetics[6-11]. Very few have highlighted the importance of heat transfer in the hot-roll fusing process. Oliver[12-13] points out that "thermal conductivity and in particular thermal contact resistance may play a more important role in the mechanism of fusing than was previously considered," but he does not elaborate beyond identifying the issue in the referenced paper. In our study, with the fusing test system as a vehicle, the importance of heat transfer and the use of the thermal diffusion time constant as a tool for understanding and predicting fusing quality is explained and illustrated.

Thermal diffusion takes place in the bulk of the media, whereas toner fusing takes place at or near the surface. While this study highlights the importance of thermal diffusion as a controlling factor in toner fusing, the importance of the media's surface properties such as surface roughness and porosity is in no way minimized. Surface roughness is a source of thermal contact resistance, and porosity at the media surface provides the anchors for the toner. The role of surface roughness and porosity is the subject matter of an on-going study.

An important contribution noted in this paper is the development of the test apparatus itself. It is well known that fusing quality in hot-roll fusing depends on a myriad of variables including machine design, process variables, and material variables. While the fusing process can be analyzed theoretically using analytical or numerical techniques, the complexity of the process makes accurate prediction of fusing quality difficult, if not impossible, using such techniques. Therefore, to advance the technology of hot-roll toner fusing in electrophotography, an experimental approach is more practical. Fusing experiments were difficult to conduct in the past since most were performed in printers, in which process parameters are difficult to control. With the commercial availability of a computer-controlled toner fusing test system, experimental fusing studies can now be conducted easily, reliably, quantitatively, and quickly. This report demonstrates the application of such an apparatus. With this apparatus, the researcher's effort is now focussed on design of the experiments and analysis of the results, freeing up time previously wasted in setting up the equipment and in the drudgery of gathering and managing large volumes of test data.

## Conclusions

1. A computer-controlled hot-roll fusing test system is introduced in this paper. The design requirements are described. The value of the apparatus for experimental research in toner fusing is reported from the first-hand experience of the authors.
2. Using the apparatus, an experimental study was conducted to elucidate the effects on fusing quality of process variables such as time, temperature, and pressure. The fusing window for a given toner type can be obtained readily and quantitatively.
3. Twenty-two commercially available media samples were evaluated using the test apparatus. The objective was a better understanding of the relationship between media properties and fusing quality. The results suggest that one of the most important media variables is basis weight (thickness).
4. The results of the media thickness experiment clearly demonstrate the influence of thickness on fusing quality. The results also highlight the importance of heat transfer – an important part of the hot-roll fusing process not well understood in the past.
5. The dependence of fusing quality on media thickness can be reduced or eliminated by using a higher fusing temperature and increasing the applied pressure. The hot offset temperature limits the fusing temperature, and the applied pressure is limited by the rigidity of the printer structure.
6. The significance of the thermal diffusion time constant and the residence time of the media in the roller nip is demonstrated by the experimental results. Thermal diffusion is an important rate-controlling factor in achieving good fusing quality.

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