Analysis of the Paper Curl Amount in the Fusing Process of Electrophotography by Calculation of Moisture Transport

Shunichi Oohara,[1] Yuko Hayama,[1] Hirofumi Tanigawa,[2] and Takaharu Tsuruta[2]; [1] Ricoh Company, Ltd. R&D Center, 16-1 Shinei-cho, Tsuzuki-ku, Yokohama-si 224-0035, Japan and [2] Department of Mechanical Engineering, Kyushu Institute of Technology, 1-1 Sensui-cho, Tobatake-ku, Kitakyusyu-si, Japan

Abstract

The mechanism of paper curl is examined using an experimental apparatus that presses a sheet of paper between two flat-heated plates. When both sides of the paper are heated at different temperatures, the moisture content of the low-temperature side becomes higher than that of the high-temperature side. A difference in the moisture content causes a shrinkage difference between both sides of the paper, generating paper curl. An analysis of the paper curl amount is then carried out by calculation of moisture transport that considers the capillary flow and water evaporation. The amount of paper curl is calculated as a function of heating time using a bi-metal model. The theoretical and experimental results are in good agreement.

Introduction

Paper curl generated by the fusing process of electrophotographic printers and copiers is a paper handling problem. A fuser consists of a heating roller that binds toner particles to a sheet of paper and a pressure roller that presses the paper against the heating roller. The temperature difference between these two rollers causes the paper to curl towards the low-temperature side. The objectives of this study are to investigate the mechanism of paper curl and to obtain a prediction method of the curl amount.

An experimental study on paper curl has been carried out [1], but the mechanism is still not well understood. This is because the apparatus used in the study is composed of two rollers to heat a sheet of paper, and these rollers cannot heat both sides of the paper accurately at the chosen temperatures. Furthermore, the shape of the nip region between the two rollers varies the shape of the paper.

In this study, an experimental apparatus consisting of two heated flat plates is used to press a sheet of paper at controlled temperature and heating time. It also allows the absolute humidity of both sides of the heated paper to be measured. The absolute humidity of the surface of the paper correlates with the moisture content. It is found that a temperature gradient within the paper leads to moisture transfer from the high-temperature side to the low-temperature side. After heating, the low-temperature side loses more moisture than the high-temperature side, and shrinks more in size. The paper subsequently curls toward the low-temperature side.

Next, a moisture transport calculation method that considers the capillary flow and water evaporation is proposed to predict the amount of paper curl. The calculation is a one-dimensional model of the direction of paper thickness, and it assumes a sheet of paper as a uniform porous medium. The moisture content distribution along the paper thickness is calculated when both sides of the paper are heated at different temperatures, and it shows moisture transport from the high-temperature side to the low-temperature side.

Another experiment is also carried out to measure the dependence of paper shrinkage on the moisture content and temperature. A sheet of paper is assumed to be composed of two layers, and the shrinkage of each layer is calculated from the results obtained from the analysis and experiment. The amount of paper curl is calculated as a function of heating time using a bi-metal model.

Curl Mechanism

Fig. 1 shows the experimental apparatus used to analyze paper curl. It has two heated flat plates with controlled temperature and pressing time. The test paper width is 20 mm and the heating length is 100 mm. In this apparatus, the paper is unaffected by the nip region and the bending of transportation guides, and thus the generated curl is caused by only heating. Two humidity sensors are arranged adjacent to the sides of the paper. After heating, the sensors move to the heated region to measure the absolute humidity of surfaces of the paper.

Curl amount

Fig. 2 shows the relationship between the temperature difference and curl curvature. One side of the paper is heated to 80 °C, and the heating temperature of the other side is varied from 60 to 180 °C at 20 °C intervals. Prior to the experiments, the paper is placed in two environments with different humidities.

The curl curvature increases with increasing temperature difference. In addition, it is found that the paper placed in the environment with high humidity generates a larger curvature than the one placed in the environment with low humidity. The experimental results correspond to observations of the paper curl amount in printers and copiers.

Humidity measurements of paper surfaces

Nonomura and co-workers showed that the curl curvatures correlate with the amount of evaporation. Accordingly, we measure the absolute humidity of the paper surface. The sensor was developed in-house and it can measure the humidity at a sampling frequency of approximately 100 Hz.

Fig. 3 shows the changes in absolute humidity of the paper surface. Prior to the experiment, a sheet of paper with a 0.24 mm thickness is placed in an environment with a humidity of 75% RH for approximately a day. The heating time is from 2.9 s to 4.9 s, and the sensor moving time is from 5.0 s to 5.2 s. The two solid lines shown in Fig. 3 are cases when the paper surfaces are heated at different temperatures. The absolute humidity of the low-temperature side heated at 80 °C is higher than that of the high-temperature side heated to 160 °C. The two dotted lines are cases when the paper surfaces are heated at the same temperature of 160 °C. The absolute humidity of the same temperature heating is higher than the case of high temperature heating and is lower than the case of low temperature heating when the paper is heated at different temperatures. This result suggests that the moisture content of the low-temperature side increases, that is, the moisture content of the high-temperature side is transferred to the low-temperature side within the paper, since moisture is not supplied to the paper during and after heating.

Paper shrinkage after heating

If a high moisture content causes a high shrinkage ratio, it will be clear that an increase in the moisture content causes the paper to curl towards the low-temperature side. Thus, we measure the relationship between the moisture content and the shrinkage after heating. Fig. 4 shows the equipment used to measure the paper shrinkage after heating. A slide guide and a displacement sensor are added to the apparatus shown in Fig. 1. The lower side of the paper is held by the slide guide which can move freely depending on the paper length. The slide guide has a target for measuring the displacement sensor.

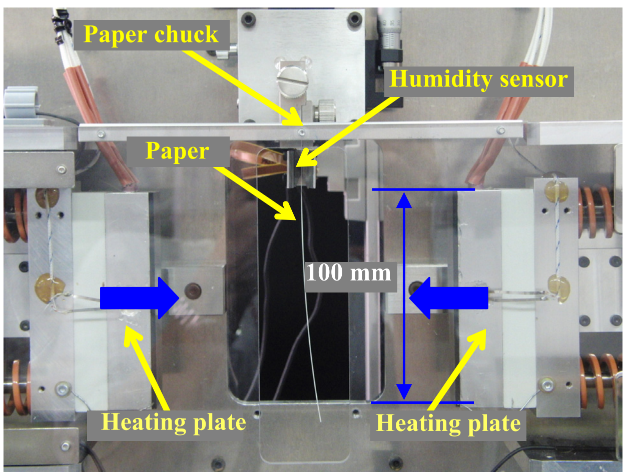

Figure 1. *Experimental apparatus for analyzing paper curl*

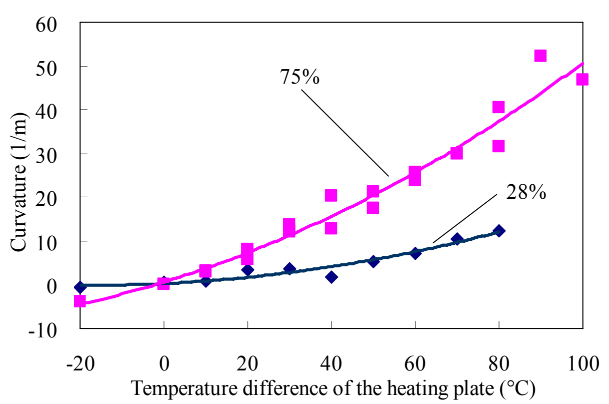

Figure 2. *Relationship between the temperature difference of the heating plates and the curl curvature at two humidity levels.*

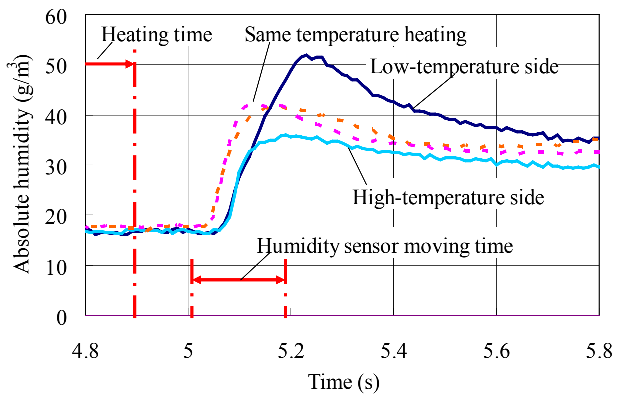

Figure 3. *Absolute humidity of the paper surfaces after heating*

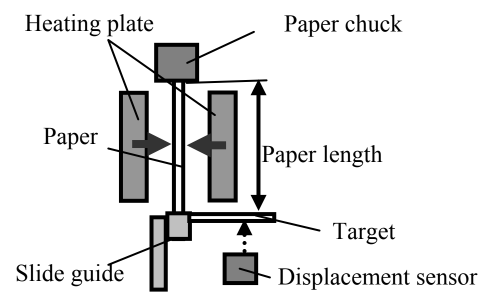

Figure 4. *Equipment for measuring paper shrinkage*

Fig. 5 shows the measured paper shrinkage as a function of time after heating. The paper thickness is 0.24 mm, the heating temperature is 160 °C, and the heating time is 2.0 s. Three sheets of papers with different moisture contents are used.

The amount of paper shrinkage increases with time after heating, and it is clear that a high moisture content causes a high shrinkage ratio.

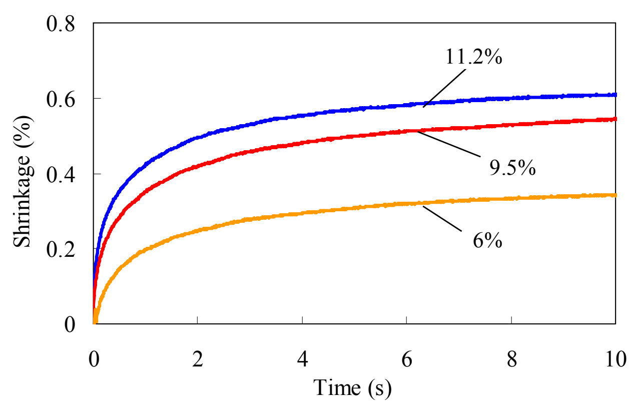

Figure 5. *Paper shrinkage at various moisture contents after heating*

As a result, we can conclude that the mechanism of the paper curl is as follows. Firstly, the moisture within the paper transfers from the high-temperature side to the low-temperature side during heating, resulting in increasing moisture content of the low-temperature side. Secondly, much of the moisture evaporates from the low-temperature side, and thus its shrinkage ratio is higher than that of the high-temperature side. This causes the paper to curl towards the low-temperature side.

Prediction of Curl Amount

Moisture transfer within the paper causes paper curl when the paper is heated at different temperatures. We can predict the amount of paper curl by calculating the distribution of moisture content within the paper. Accordingly, we attempt to develop a curl prediction method.

Analysis of moisture transport within paper

A numerical simulation that calculates the moisture transfer within the paper has already been investigated by Bandyopadhyay et al. [2]. The simulation considers the moisture transfer as water vapor transfer, and the moisture is calculated from the moisture isotherm. In this study, we proposed a calculation method that the moisture transfers as liquid water through the thickness direction. The calculation also considers water evaporation during heating. Equations are solved using the finite volume method.

The uniformity of the water flow can be expressed as:

$$\rho_l \varepsilon \frac{\partial S}{\partial t} = -\frac{\partial F_l}{\partial x} \quad (1)$$

where,
ρ_l : Density [kg/m^3] (Water)
ε: Porosity
S : Moisture content
t : Transfer time [s]
F_l : Flow [kg/m^{2}s] (Water)
x : Distance [m]

The energy within the paper can be expressed as:

$$\frac{\partial}{\partial t}\left(c_{pT}\rho_T T\right) = \frac{\partial}{\partial x}\left[\lambda_T\left(\frac{\partial T}{\partial x}\right)\right] - \frac{\partial\left(c_{pl}F_l T\right)}{\partial x} - L\cdot\rho_l\cdot\varepsilon\cdot\frac{\partial S}{\partial t} \quad (2)$$

where,
c_{pT} : Specific heat at a constant pressure [J/(kgK)] (Paper)
c_{pl} : Specific heat at a constant pressure [J/(kgK)] (Water)
T : Temperature [°C]
λ_T : Thermal conductivity [W/(mK)] (Paper)
L : Latent heat of vaporization [J/kg]
ρ_T : Density [kg/m^3] (Paper)

When the control volume reaches 100 °C, it is assumed that the moisture of the control volume evaporates and the paper loses latent heat, resulting in 0% moisture content.

The water flow given by Darcy's law and Fick's law is as follows.

$$F_l = -\rho_l\left[\frac{KK_{rl}}{\mu_l}\left(\frac{\partial p_l}{\partial x}\right)\right] - \rho_l\left[D\left(\frac{\partial S}{\partial x}\right)\right] \quad (3)$$

where,
K : Permeability [m^2]
K_{rl} : Relative permeability (Water)
D : Moisture diffusion coefficient [m^2/s]
μ_l : Viscosity coefficient [sPa] (Water)
p_l : Saturation vapor pressure [Pa]

Fig. 6 shows the relationship between the distance from the surface of the high-temperature side and the moisture content for various heating times. The initial moisture content of the paper is 10%, and the paper thickness is 0.24 mm. Meanwhile, the heating temperatures are 80 and 160 °C and the heating time is 2.0 s.

As the heating time increases, the peak region of the moisture content moves from the high-temperature side to the low-temperature side. The result of the calculation clearly indicates occurrence of moisture transport within paper. The moisture content of the high temperature-side becomes 0% based on our assumption that the moisture content becomes 0% when the paper temperature reaches 100 °C.

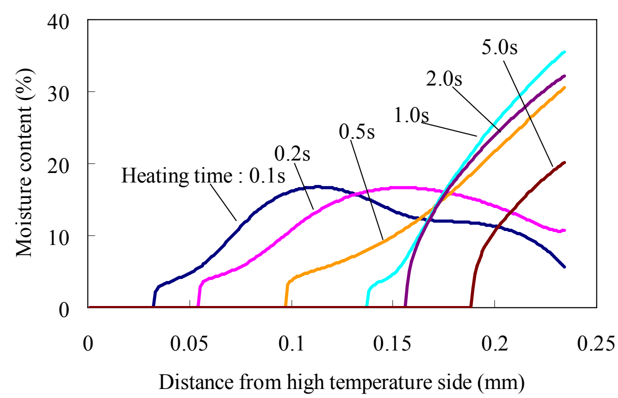

Figure 6. Moisture content distribution within the paper for various heating times.

Paper shrinkage at various heating temperatures

Paper shrinkage is affected by the moisture content and heating temperature. Thus, it is necessary to obtain the relationship between the amount of paper shrinkage and heating temperature. We measured the amount of paper shrinkage at various heating temperatures using the apparatus shown in Fig. 4.

Fig. 7 shows the relationship between the amount of paper shrinkage and moisture content at several heating temperatures. A sheet of paper with 0.24 mm thickness is placed in three environments with different humidities for about a day prior to the experiment, and thus the three papers have different moisture contents. Both sides of the paper are heated at the same temperature for 2.0 s. The amount of shrinkage is measured immediately after heating is done, which is also the time at which the curl growth stops.

The amount of paper shrinkage is in proportional to the moisture content, and increases with the heating temperature.

Calculation of curl amount

The curl curvature is calculated by the bi-metal model [3]. A sheet of paper is assumed to have a high-temperature side and a low-temperature side. The average moisture contents and the average temperatures of the sides are calculated.

Fig. 8 shows the relationship between the heating time and moisture content of each side. As the heating time become longer, the moisture content increases in the low-temperature side and decreases in the high-temperature side. The heating time of the paper with a high moisture content becomes longer as it thickness increases.

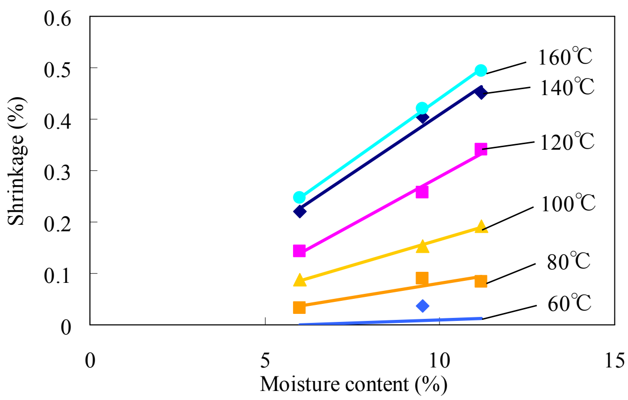

Figure 7. *Relationship between the amount of paper shrinkage and moisture content at various heating temperatures*

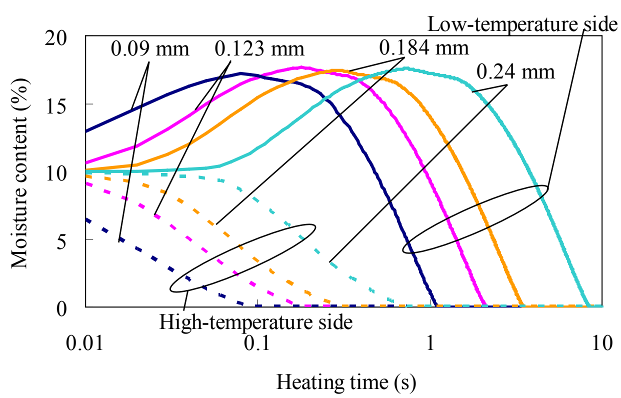

Figure 8. *Relationship between the heating time and moisture content at various thicknesses.*

The amount of shrinkage of the two sides is calculated by the first-order approximation obtained from Fig. 7. When the temperature lies between two examined temperatures, the formula is found by collinear approximation of two experimental formulas. The shrinkage of each side is calculated by the formula.

The strain of the heated paper, ε_p, can be calculated as follows.

$$\varepsilon_p = \frac{S_h - S_l}{L_h} \tag{4}$$

where,

S_h : Shrinkage (high-temperature side)

S_l : Shrinkage (low-temperature side)

L_h : Heating length (Paper).

The curl curvature R can be expressed as follows.

$$R = \frac{3\varepsilon_p}{2t_p} \tag{5}$$

where,

t_p : Thickness (Paper)

Fig. 9 shows the curvature transition of the heated paper. The solid and dotted lines are results obtained by calculations and the symbols are those obtained experimentally.

An increase in heating time causes an increase in curl curvature, but long heating time decreases the curl curvature. This is because long heating time causes evaporation of moisture, and thus less shrinkage after heating. The curvature of a sheet of thin paper is larger than that of thick paper. This is predictable from eq. (5). In the region of short heating time, the curvatures obtained by calculations are larger than those obtained experimentally, particularly for the thin paper. However, the maximum curl curvature obtained by calculations corresponds with that obtained experimentally, and the tendency of the curl curvature transition influenced by the heating time and paper thickness is in good agreement.

The error in the region of short heating time is due to heating resistance which exists between the heating plates and the paper surfaces.

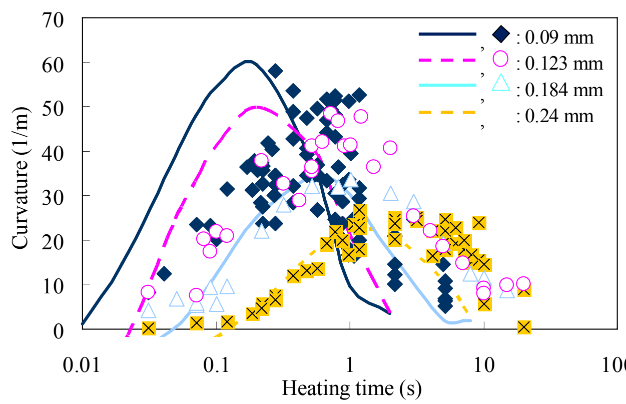

Figure 9. *Curvature transition of heated papers with various thicknesses*

Conclusions

Paper curl is observed when both sides of a sheet of paper are heated at different temperatures. This is because the moisture content of the low-temperature side becomes higher than that of the high-temperature side due to moisture transport from the high-temperature side to the low-temperature side. To predict the curl amount, a moisture transport calculation method that considers the capillary flow and water evaporation is carried out, and the amount of paper curl is calculated as a function of heating time using a bi-metal model. The theoretical and experimental results are in good agreement.

References

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Author Biography

Shunichi Oohara received his B.E. in mechanical engineering from the University of Tohoku, Sendai, Japan in 1985. He has been researching and developing mechanical structures of machineries in the Mechanical R&D Laboratory of Hitachi, Ltd. since 1985 and in the Core Technology R&D Center of Ricoh, Ltd. since 2008. He is currently investigating the mechanism of paper deformation in printing processes. He is a member of ISJ and JSME.