Prediction Model of Paper Curl Formed by Transportation Path

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Abstract

In an electrophotographic process without a decurler device, the amount of paper curl depends on the geometry of its transportation path. However, since the paper path affects the whole layout of the machine, it may not be modified even if the paper curl turns out to be out of acceptable range. To overcome the difficulty, a simulation model to predict the paper curl formed by the transportation path geometry is developed so that the paper path can be designed considering the paper curl at the early stage of product development. The mechanical characteristics is measured by a thermo-mechanical analyzer, and expressed as the double Maxwell model. Given fuser device and paper condition, the paper curl is calculated using the time variation of paper deflection during transportation. With three different types of paper, it is verified that the present simulation model is able to predict the amount of paper curl accurately.

Introduction

In the development process of electrophotographic copiers and printers, paper curl could be a serious impediment. The amount of paper curl depends on several factors including not only operation parameters of the fuser or characteristics of paper, but also the geometry of the transportation path, process speed, and the ambient conditions. Therefore, the actual amount of the paper curl cannot be recognized until the whole system is assembled and paper is fed. In the system that has multiple exits of paper, the paper curl also varies depending on which exit to choose. If the paper curl turns out to be out of acceptable range at the final stage of the development process, it could result in redesign of the paper path and it may impact the whole layout of the machine. This problem is serious especially in low cost machines that are not equipped with decurler devices. In previous paper handling studies, curl is taken as fixed input in general [1]. Therefore, prediction technology of paper curl under effect of transportation geometry is valuable.

Through preliminary studies, we clarified that the paper curl is determined by combination of three effects, which we call (1) fuser nip curl, (2) contraction curl, and (3) paper path curl. The fuser nip curl is formed by heat and strain when a sheet passes through a fuser nip. It therefore depends on configuration of the fuser and fusing parameters in addition to characteristics of the paper. The contraction curl occurs due to the in-plane contraction of the sheet that is nonuniform in the thickness direction [2]. Since the cause of the contraction is primarily dehumidification of the paper fabric and solidification of toner layer thereon, the contraction curl generally increases with an elapsed time after the fusing process, and stabilizes gradually. The paper path curl arises as the sheet is hardened by decrease in moisture and temperature while it is deflected by the transportation path. The hardening of the sheet is a result of formation of new bonds in the material, and newly formed structure has a tendency to maintain its deflected shape. This is why the transportation path geometry affects the paper curl significantly even though strain due to the deflection is well below the yield limit.

Since the same fuser configuration is used for several products, the fuser nip curl is measurable at the early stage of product development in general. Even when a new fuser technology is applied, basic configuration is already fixed when the product development starts. In the model constructed in the present work, therefore, the fuser nip curl is treated as the initial condition, and gradient of internal in-plane stress is calculated taking time-dependent variation of mechanical properties of paper, contraction curl, and deflection curvature due to the transportation path as inputs. The paper curl is evaluated using the converged value of the stress gradient after paper exits the machine.

Viscoelastic Model of Paper

It is widely recognized that paper possesses viscoelastic properties [3][4]. Since measurement by DMA (Dynamic Mechanical Analyzer) was not successful because paper was not tough enough for oscillating stress especially under high moisture condition, a measurement procedure of the viscoelastic mechanical response of paper by TMA (Thermo-Mechanical Analyzer) was developed. In Figure 1, a tensile stress pattern applied to paper is shown as a dotted line. The corresponding measured strain is shown as a thin solid line, which represents a typical viscoelastic behavior such as a delay in response and residual strain. Even though ordinary Maxwell model that consists of an elastic element and a viscous element connected in series did not fully capture the

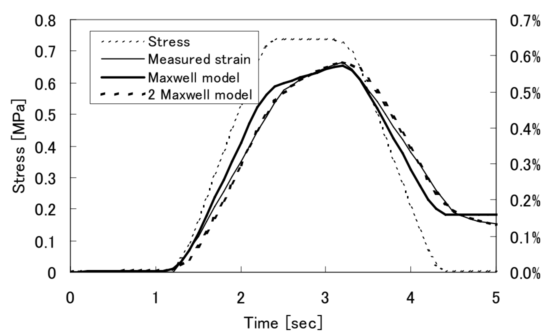

***Figure1**. Measurement of mechanical properties of paper*

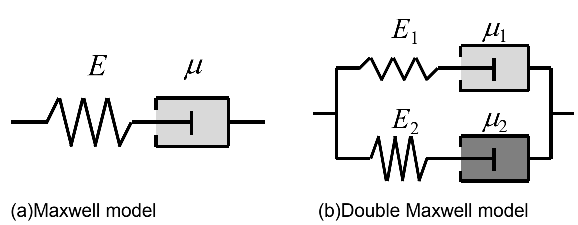

***Figure 2**. Viscoelastic model of paper*

feature of the strain response (shown as a thick solid line), it was found that a double Maxwell model connected in parallel manner (Figure 2) was able to reproduce the behavior in detail (thick dotted line) for most paper types under the examination.

Constitutive equations of the double Maxwell model are as folllows:

$$\sigma_1 + \frac{\mu_1}{E_1}\frac{d\sigma_1}{dt} = \mu_1 \frac{d\varepsilon}{dt} \tag{1}$$

$$\sigma_2 + \frac{\mu_2}{E_2}\frac{d\sigma_2}{dt} = \mu_2 \frac{d\varepsilon}{dt} \tag{2}$$

$$\sigma = \sigma_1 + \sigma_2 \tag{3}$$

where σ is stress, ε is strain, and μ and E represent viscous and elastic constant respectively. Hereafter, subscripts 1 and 2 indicate variables related to each Maxwell element. Based on a beam assumption considering the paper as a media that consists of uniform material and therefore shows linear distribution of tensile in-plane stress and strain under bending, (1) and (2) are differentiated in thickness direction to obtain the curl equations.

$$\sigma_1' + \frac{\mu_1}{E_1}\frac{d\sigma_1'}{dt} = \mu_1 \frac{d\gamma}{dt} \tag{4}$$

$$\sigma_2' + \frac{\mu_2}{E_2}\frac{d\sigma_2'}{dt} = \mu_2 \frac{d\gamma}{dt} \tag{5}$$

$$\sigma' = \sigma_1' + \sigma_2' \tag{6}$$

Here, σ' represents the in-plane stress gradient and γ is curvature of paper deflection. Taking the fuser nip curl as the initial curvature, and time variation in the curvature of paper deflection by the transportation path as an input, equations (4) and (5) can be solved to trace the time variation of the stress gradient. After the paper exits the machine, constraint to the shape of the sheet disappears and deflection curvature of the sheet is determined so that the stress gradient is maintained to be zero assuming stress free condition. The paper curl continues to vary even under the stress free condition not only because temperature and moisture content keeps changing but also stress relaxation continues to occur in each Maxwell element. In order to solve the equations numerically, equations (4) and (5) are integrated with respect to time assuming, the time step Δt, constant curvature increment $\Delta\gamma_p$ is given. The resulting equations may be organized as follows:

$$\sigma_1'^{n+1} = A_1 \sigma_1'^{n} + B_1 \Delta\gamma_p \tag{7}$$

$$\sigma_2'^{n+1} = A_2 \sigma_2'^{n} + B_2 \Delta\gamma_p \tag{8}$$

$$\sigma'^{n+1} = \sigma_1'^{n+1} + \sigma_2'^{n+1} \tag{9}$$

A represents ratio of stress relaxation over the time step Δt. B is ratio of stress gradient increment and the curvature increment. The contraction curl is taken into account by subtracting its curvature increment from $\Delta\gamma_p$.

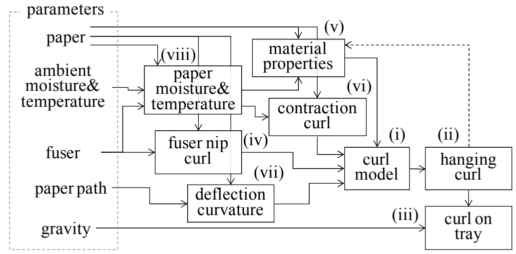

***Figure 3**. Calculation flow*

The flow of curl estimation is schematically shown in Figure 3. In order to solve the curl models (7) to (9), to obtain the stress gradients (i) that result in the hanging curl (ii) and curl on tray (iii), the fuser nip curl (iv) is needed as the initial condition of the paper deflection. Time history of variables describing paper status such as mechanical properties (v), curvature of deflection due to transportation path (vi), and curvature of the contraction curl (vii) are taken as inputs. Among them, mechanical properties and contraction curl depend on temperature and moisture content of paper (viii). Although the real paper curl has an in-plain variation in curvature especially under the effect gravity, a characteristic value representing degree of curl is focused on in the present work, and therefore, only a hanging curl was evaluated at the center of a sheet. In the following chapter, methods to evaluate functions and parameters used in the flow are described.

Evaluation of Functions and Parameters

The fuser nip curl (iv) is governed by the fuser system and it's parameters. Even though measuring curvature of the hanging curl after fusing is a trivial matter, the measured curvature is that of the fuser nip curl and the contraction curl superposed. Let γ_n and γ_c represent curvature of the fuser nip curl and the contraction curl respectively. Suppose that the measured curvature of hanging curl after fusing is $\gamma_1 = \gamma_n + \gamma_c$. When paper is set upside down and the same experiment is carried out, the measured curl has to be $\gamma_2 = \gamma_n - \gamma_c$. With both results, the fuser nip curl is determined by

$$\gamma_n = \frac{\gamma_1 + \gamma_2}{2}\,. \tag{10}$$

Dependency of mechanical properties on temperature and moisture content (v) was measured by TMA controlling ambient temperature and humidity. As shown in equations (1) and (2), viscoelastic property of paper is represented by four parameters, μ_1, μ_2 , E_1 and E_2 . Even though the dependencies of the four parameters differ from each other, they are generally expressed as functions converging to a certain value as temperature and moisture content increase. As an example, μ_2 is expressed as

$$\mu_2(T,W) = \mu_{R2} \exp\left(-\frac{T}{T_{\mu 2}}\right) \exp\left(-\frac{W}{W_{\mu 2}}\right) \tag{11}$$

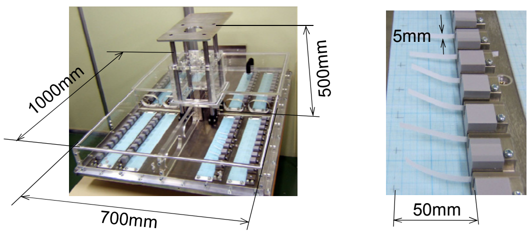

Figure 4 Measurement apparatus of contraction curl

Table 1 Evaluation conditions

factors	conditions		
paper type	plain	recycled	heavy
decor shaft	no shaft	with shaft	-
upside	felt side	wire side	-
moisture	fresh	conditioned	-
exit path	face down	face up	-
temperature & moisture	high	mid	low

where T and W represent temperature and moisture content of paper respectively, μ_{R2} is the reference value of μ_2 which is the value when T=$T_{\mu 2}$, W=$W_{\mu 2}$. Compensation for nonlinear effect such as stiffening by strain is required for some types of paper.

Contraction curl (vi) was measured in a humidity-controlled chamber shown in Figure 4. Physically, contraction curl should be modeled considering thickness-wise distribution of contraction ratio that occurs during its production process. In the present work, however, only macroscopic curl is needed and a contraction curl ratio C_c, which is a ratio of increment in moisture content and resulting curl curvature increment, was measured as a property of paper.

$$d\gamma = C_c \, dW \tag{12}$$

Temperature and moisture content of a paper (vii) were measured in the target machine on-line, using noncontact sensors. Assuming that paper may be treated as a lumped system whose solution is approximated by an exponential function, parameters were determined by a curve fitting.

$$T(t) = T_{cnv} + \left(T_{ini} - T_{cnv}\right)\exp\left[-\frac{t}{\tau_T}\right] \tag{13}$$

$$W(t) = W_{cnv} + \left(W_{ini} - W_{cnv}\right)\exp\left[-\frac{t}{\tau_W}\right] \tag{14}$$

Measurement of deflection curvature of a sheet under transportation in a machine (viii) is troublesome. However, paper paths are designed by numerical simulation tools recently and detailed information of paper deflection during transportation is available. In a two-dimensional simulator, the shape of paper is expressed as nodes connected by links, in general. From coordinates of adjacent three nodes, a radius of curvature which is a reciprocal of curvature is determined, as schematically shown in Figure 5. An example of time history of paper deflection curvature under transportation is given in Figure 6.

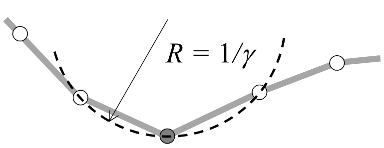

***Figure 5**. Evaluation of deflection curvature*

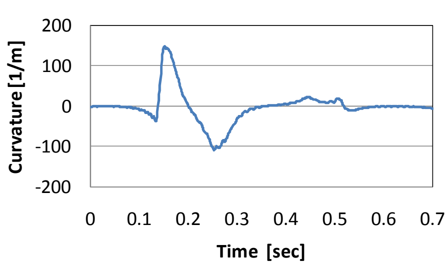

***Figure 6**. Example of deflection curvature history*

Result of Curl Estimation

For a verification of the prediction method described above, a commercially available electrophotographic machine was prepared and, simulations and experiments were carried out under all

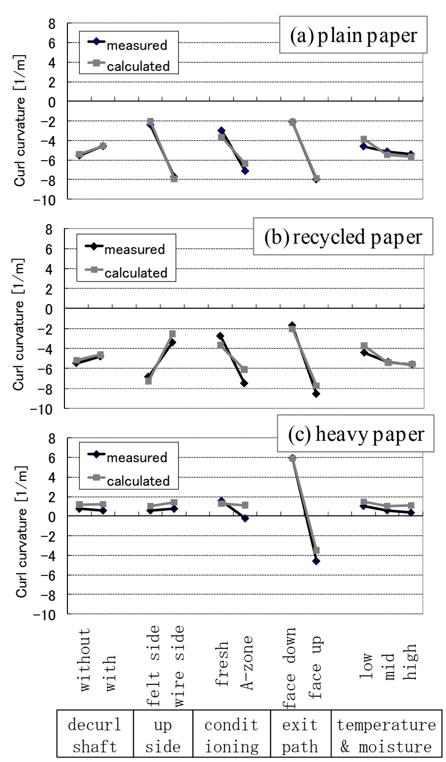

***Figure 7**. Comparison of measured and calculated curls*

combinations of the conditions given in Table 1. Three types of paper, plain, recycled and heavy were chosen. The target machine has a decurl shaft immediately after fuser that gives a deflection to a transported sheet. Under the "no shaft" condition, the decurl shaft was removed to change the deflection history. In order to capture the effect of the contraction curl, paper was set felt side up and wire side up. Moisture content was varied using fresh paper whose package is just unsealed and paper conditioned under high temperature and humid condition. The target machine is equipped with two exit paths after the fuser. The face down path leads the sheet to the top of the machine, and the face up path leads to a tray at the side of the machine. The ambient temperature and humidity were controlled in environmental chambers. For calculation of deflection curvature history, the commercial multibody dynamic analysis program, RECURDYN® was used.

Result of the verification is summarized in Figure 7. It represents factor effects of all conditions for each paper. As the measured and calculated results are compared, it is understood that they quantitatively agree quite well and they show accuracy of the prediction model. Coefficient of correlation between all measured and calculated results for each paper type was 0.90, 0.94 and 0.96 for plain, recycled and heavy paper respectively.

Figures 8 and 9 show a case example of an application of the present model. When a new machine started to be developed, risk of paper curl was argued. The machine was determined to be developed by modifying an existing machine that has a paper path from fuser to exit represented as (a) in Figure 8. Since the new machine was small sized, its paper path was that shown as (b), and because of the difference, paper curl became a concern. Using the above presented model, paper curl was predicted for both paper path varying environmental condition, paper conditioning and upside faces of paper, and it gave the results shown in Figure 9. Since there were not much difference in predicted curl, it was concluded that paper curl is not going to be a serious problem, and unnecessary devotion of development resources was avoided.

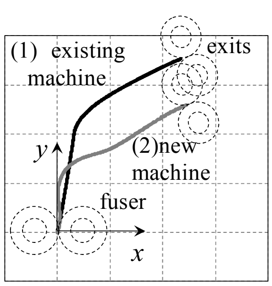

***Figure 8**. Transportation path*

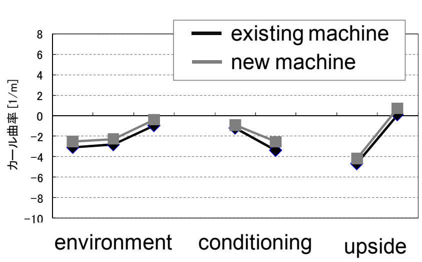

***Figure 9**. Result of curl evaluation*

Summary

Paper curl could be a serious problem because it depends on paper path geometry of the electrophotographic machine and the problem emerges after internal layout of the machine is fixed and the system is assembled. In order to counteract the problem, prediction model of paper curl due to the transportation path was developed.

Based on measured stress-strain response by TMA, viscoelastic properties of paper was expressed as a double Maxwell model, and assuming uniform material properties and thickness-wise linear distribution of stress and strain, the paper path curl equations relating the deflection curvature of the sheet and the in-plain tensile stress gradient were derived and discretized with respect to time. The model takes temperature and moisture dependent viscoelastic properties and curl caused by differential contraction as well as time history of the deflection curvature as inputs. Since paper curl caused by the fuser system is measureable in advance, it was taken as initial condition of curvature of the sheet.

As a verification of the model, corresponding measurements and calculations were carried out for combination of conditions including paper types, paper paths, upside faces of paper, and environmental conditions. Factor effects of acquired curl curvature for all conditions matched quite well and coefficient of correlation between all measured and calculated results for each paper type ranging from 0.90 to 0.96 were achieved.

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