Prediction Technology of Paper Curl in Fusing System

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Abstract

A high accuracy model to predict the amount of paper curl, which varies depending on the design parameters of fusing systems, is developed. To predict the curl, a visco-elasto-plasticity deformation model considering material properties under high temperature and moisture conditions in a fusing nip, and a dehumidification model considering the influence of decreasing drying were investigated. Proposed models were verified with two-roll fusing system and free belt nip fuser, and the models could predict the curl of different types of fusing systems under several conditions varying fusing temperature, moisture content of paper, paper type and amount of toner with high accuracy. This technology enables specification study of fusing and decurler systems without constructing many prototypes and, design man-hours needed for the development of a new system are reduced.

Introduction

Paper curl that causes paper transportation failures and deteriorations of printed media is one of the chronic problems in electrophotography system. The major problems of the curl occur after machine layout decision, and they lead to a significant reduction in development efficiency. Therefore, to predict the curl by simulation and to take measures in the early stages of development are important. The curl formed by a fusing nip is a complicated phenomenon induced by time transient mechanical deformation and dehumidification. Previously, a model assuming visco-elastic properties of the media to predict the paper curl caused by curved geometry of the paper path [1], and a model assuming visco-elasto-plasticity to predict the curl formed by decurler system [2] have been proposed. Furthermore, a technique for prediction of the curl formed by the fusing nip by treating moisture migration and stress relaxation due to thicknesswise temperature difference has been reported [3]. However, a model that predicts accurately and with general applicability the changes that occur with layout and fuser construction (not dependent on environment or type of paper), which is necessary for the application of the simulation in design, has not been constructed.

In this study, an integrated model of paper curl was constructed to deal with the complex phenomena in fusing systems. First, a technology to measure mechanical properties of paper under conditions of high temperature and high moisture content was constructed. Second, a simulation technology to predict the paper curl affected by paper visco-elasto-plasticity and changes in paper moisture content was developed. With these technologies, the dependence of curl on the design parameters of fusing systems could be accurately predicted.

Mechanism of Paper Curl

The mechanism of curl can be classified into two types: mechanical deformation and moisture shrinkage. The mechanical deformation is a phenomenon of visco-elasto-plasticity deformation by an external force such as paper path bending. The visco-elasto-plasticity properties depend on the temperature and moisture content and, the residual deformation increases with a rise in temperature and moisture content.

The deformation due to moisture shrinkage is caused by a phenomenon that the paper shrinks in proportion to the amount of moisture content which reduces via dehumidification of fibers in the paper. Particularly in the fusing nip, where the temperature of the paper differs in the thickness direction a large strain difference occurs as shown in Figure 1. Generated vapor in a high temperature side moves through the void of the paper causing the vapor to be absorbed into the fibers of the low-temperature side.

In the fusing nip, the curl is generated as a result of the interaction of these two phenomena. In order to predict the amount of curl accurately, those two physical phenomena were modeled separately, and an integrated simulation technique was constructed.

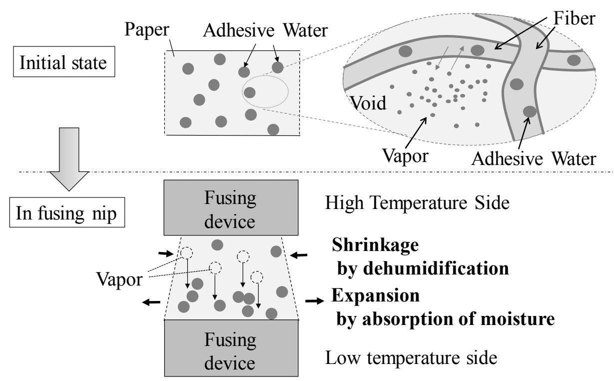

Figure 1. *Curl Mechanism in Fusing Nip*

Modeling

Simulation of Mechanical Deformation

Mechanical Model

The visco-elasto-plasticity properties and shrinkage properties due to change in moisture content of paper are modeled. In the fusing nip, the positive and negative bending moment is repeatedly applied to the paper. Therefore, it is necessary to construct a mechanical deformation model that can consider visco-elasto-plasticity properties dependent on the temperature and moisture content, and repetition responses. The stress-strain relationship was expressed by adding viscosity and moisture shrinkage to Ramberg-Osgood model [4] that can represent the history of repetitive strain [5] and elasto-plasticity properties of the paper. The mechanical behavior is classified into those due to initial loading and after unloading, and corresponding stress-strain relationship for each is represented by a skeleton curve and a history curve. The stress-strain curve in consideration of the history is shown in Figure 2. The skeleton curve is expressed as Equation (1) and the history curve is expressed as Equation (2).

$$\frac{d\varepsilon}{dt}=\frac{1}{E}\frac{d\sigma}{dt}+\frac{\sigma}{\mu}+\frac{3}{7}\frac{n}{E}\left(\frac{\sigma}{\sigma_y}\right)^{n-1}\frac{d\sigma}{dt}+\alpha_W\frac{dW}{dt} \quad (1)$$

$$\frac{d\varepsilon}{dt}=\frac{1}{E}\frac{d\sigma}{dt}+\frac{\sigma}{\mu}+\frac{3}{7}\frac{n}{E}\left(\frac{\sigma-\sigma_M}{2\sigma_y}\right)^{n-1}\frac{d\sigma}{dt}+\alpha_W\frac{dW}{dt} \quad (2)$$

where t is a time, ε is a strain, σ is a stress, σ_y is an yield stress, E is a modulus of elasticity, n is a hardening coefficient, μ is a viscosity coefficient, and α_W is a shrinkage rate. Even after unloading, if the stress on the history curve exceeds the stress on the skeleton curve, the stress of paper is returned on the skeleton curve. To consider the mechanical properties depend on the temperature and moisture content, the property values are expressed in the following exponential functions.

$$E=E_0\exp\left(-\frac{T}{\tau_{ET}}\right)\exp\left(-\frac{W}{\tau_{EW}}\right) \quad (3)$$

$$\mu=\mu_0\exp\left(-\frac{T}{\tau_{\mu T}}\right)\exp\left(-\frac{W}{\tau_{\mu W}}\right) \quad (4)$$

$$n=n_0\exp\left(-\frac{T}{\tau_{nT}}\right)\exp\left(-\frac{W}{\tau_{nW}}\right) \quad (5)$$

$$\sigma_y=\sigma_{y0}\exp\left(-\frac{T}{\tau_{\sigma_y T}}\right)\exp\left(-\frac{W}{\tau_{\sigma_y W}}\right) \quad (6)$$

where T is a temperature. Further, E_0, μ_0, n_0, σ_{y0} and τ are constants for expressing the dependence on temperature and moisture content of the properties. They are identified from the experimental results using curve fitting, as will be described later.

Measurement of Mechanical Properties

In the fusing nip, the paper is heated to a temperature above 100□ in a sealed condition. A measurement apparatus capable of measuring the stress-strain relationship of the paper under the conditions of high temperature and high humidity as the fusing nip was developed. The measurement results of the stress-strain relationship of paper using the apparatus are shown in Figure 3. The slopes of the curves representing stiffness of the paper decrease with increasing temperature and moisture content. Young's modulus obtained from the measurement results is shown in Figure 4. Constants representing dependency of mechanical properties on the temperature and moisture content are identified by fitting curves expressed by Equation (3-6) to the measured results.

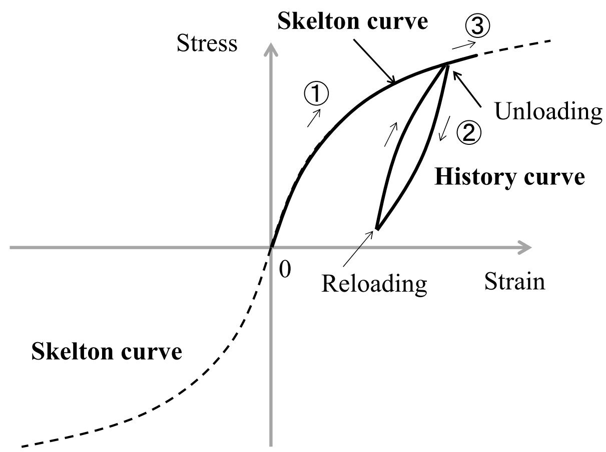

Figure 2. *Stress–Strain Curve*

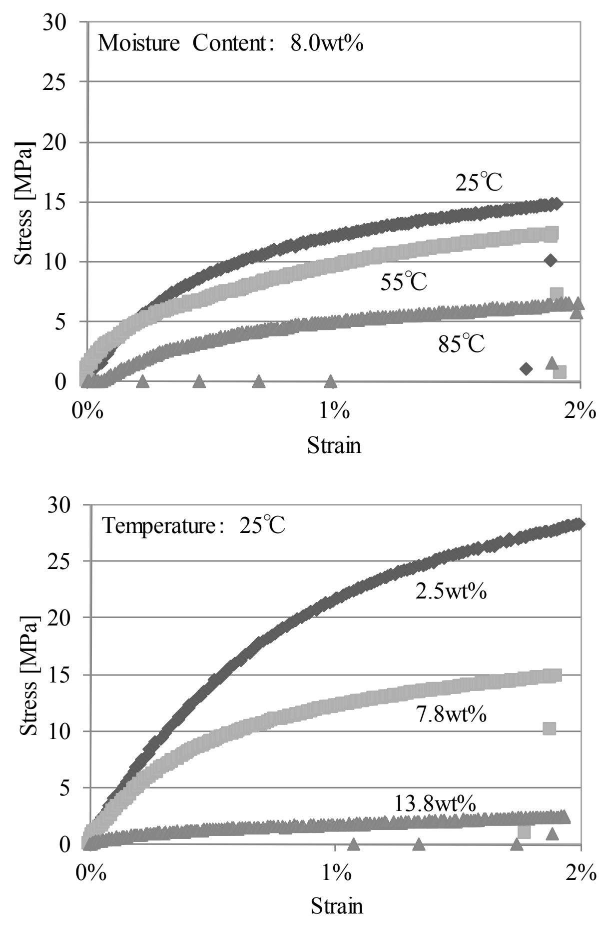

Figure 3. *Measurement Results*

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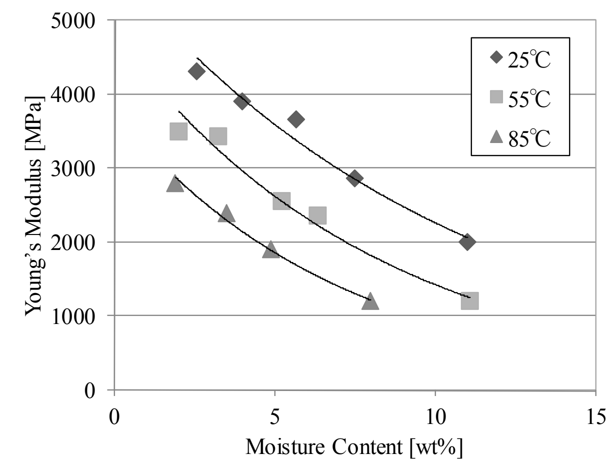

Figure 4. Young's Modulus in Various Conditions

Verification of Curl Simulation with Mechanical Model

To verify the mechanical model, calculation results and experimental results were compared. A 2-roll fusing bench was used in the verification. Investigated factors were fusing temperature and moisture content of paper that greatly affect the mechanical deformation.

In the beginning, the curvature history and the stress of paper in the fusing nip were quantified by a structural analysis with Abaqus [6], which is a general purpose FEM simulator. The amount of curl was calculated with a mechanical model constructed using the products of the structural analysis.

The result of comparing the factorial effect of the curl amount of the experimental and calculated values is shown in Figure 5. The value of the vertical axis is curvature of the paper. The mechanical model could accurately predict the effect of each factor.

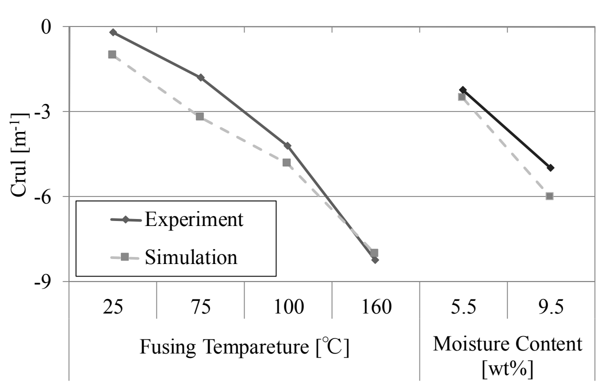

Figure 5. Verification Results of Mechanical Model

Simulation of Moisture Content Variation Model

The moisture content variation is modeled in this section. Paper is porous media composed of fiber and air void, and therefore, the major transportation paths of the moisture are those through the void and the fiber-void interface. The moisture movement between fiber and void is modeled by drying, and the moisture movement in void is modeled by vapor transportation.

Drying Model

Paper has a decreasing drying property that the drying speed is changed by the moisture content. The drying speed of paper can be expressed by the following equation, which is proportional with the difference in partial pressure of water vapor (P) and drying pressure (P_s).

$$\frac{dW}{dt} = k\left(P - P_s\right) \tag{7}$$

where k is a coefficient of mass transfer. The partial pressure of water vapor is expressed as the following equation by Boyle's law.

$$P = H_{VH} R_W T \tag{8}$$

where R_W is a gas constant of vapor and H_{VH} is an absolute humidity.

Next, the drying pressure is modeled. To clarify the relationship between the drying pressure, the temperature and moisture content, the moisture content of the paper was measured under given temperature and humidity. The measurement state was assumed to be in the equilibrium state and the following formula is established.

$$P = P_s \tag{9}$$

Figure 6 shows results of measuring the relationship between the temperature, the relative humidity and the moisture content. The relative humidity (H_{RH}) is a value normalized by saturated water vapor (P^*) as the following equation.

$$H_{RH} = \frac{P}{P^*} \tag{10}$$

Then, the relationship between the moisture content and humidity and temperature was represented by the following equation, and constants T_0, H_0, W_{T0H0} are determined by curve fitting.

$$P_s = P^* H_0 \ln\left(\frac{W}{W_{T0H0}\exp\left(-\frac{T}{T_0}\right)}\right) \tag{11}$$

The fitting results are shown by solid lines in Figure 6.

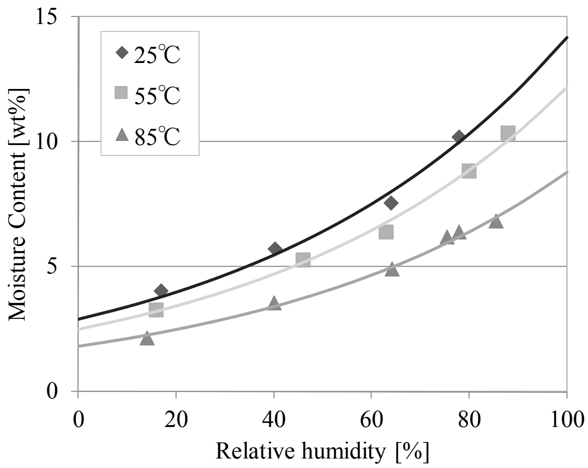

Figure 6. *Relationship between Moisture Content, Relative humidity and Temperature*

Vapor Transportation Model

Vapor transportation in void of paper is modeled. A transportation diffusion model that can handle both of the pressure gradient and humidity gradient was adopted.

$$\frac{\partial H_{VH}}{\partial t} = \frac{\partial}{\partial x}\left(K_D \frac{\partial H_{VH}}{\partial x}\right) + \frac{\partial}{\partial x}\left(K_P \frac{\partial P}{\partial x}\right) + \frac{\rho_P}{e}\frac{dW}{dt} \tag{12}$$

where K_D is a diffusion coefficient, K_P is a transportation coefficient, ρ_P is a density of paper and e is a void ratio of paper.

Moisture Content Variation Model

A moisture content variation model combining the drying model and the vapor transportation model was verified. The calculated time history of the paper moisture content after the discharge from fusing nip was compared with experimental values. To calculate the temperature of paper, the heat equation in consideration of heat radiation and evaporation latent heat as shown below was used.

$$C_V \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda \frac{\partial T}{\partial x}\right) - L\rho_W e \frac{dW}{dt} \tag{13}$$

$$-\lambda \frac{\partial T}{\partial x} = \alpha\left(T_\infty - T\right) \quad (Boundary) \tag{14}$$

where C_V is a heat capacity, λ is a heat conductivity, L is a latent heat, α is a heat transfer coefficient and T_∞ is an ambient temperature.

The verification results are shown in Figure 7. Drying speed is high when moisture content is high, and decreasing of drying speed due to the reduction of the moisture content represents property of decreasing drying. This result reproduced the experimental results accurately.

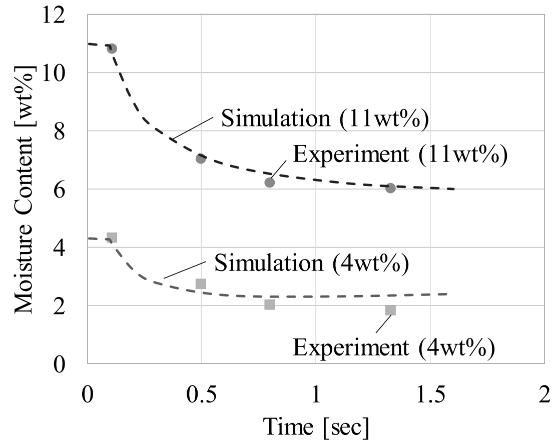

Figure 7. *Verification Results of Moisture Content Variation Model*

Verification of Curl Simulation with Moisture Content Variation Model

To verify the integrated model with the moisture content variation model and the mechanical model for curl prediction, calculated and experimental results were compared. A 2-roll flat nip bench was used in the verification. Investigated factors were fusing temperature difference, moisture content and shrinkage rate of paper those greatly affect the moisture content variation. The example of calculation results are shown in Figure 8 and the verification results are shown in Figure 9. As shown in Figure 8, the fusing temperature difference results in a temperature gradient in paper and, the gradients of humidity, moisture content and stress occur by the temperature gradient. Eventually, the stress gradient causes the curl of the paper. A factorial effect for the moisture content, shrinkage rate and fusing temperature of the calculated results using this curl model coincide with that of the experimental results.

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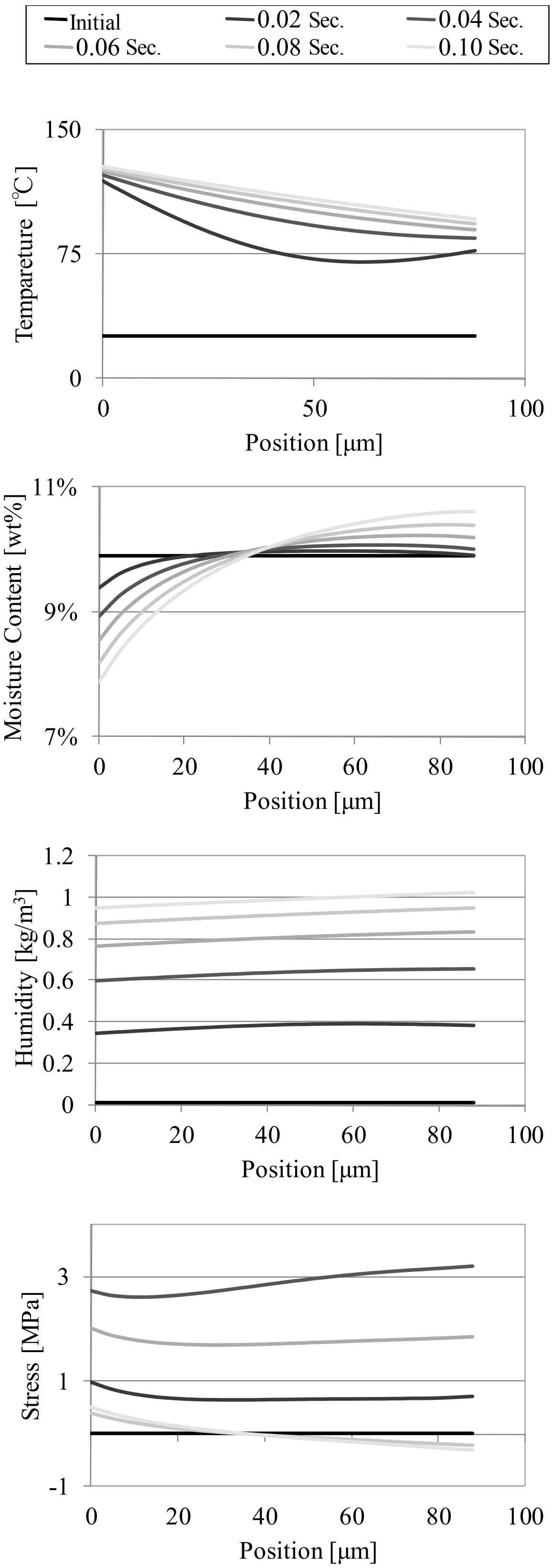

Figure 8. Examples of Simulation Results

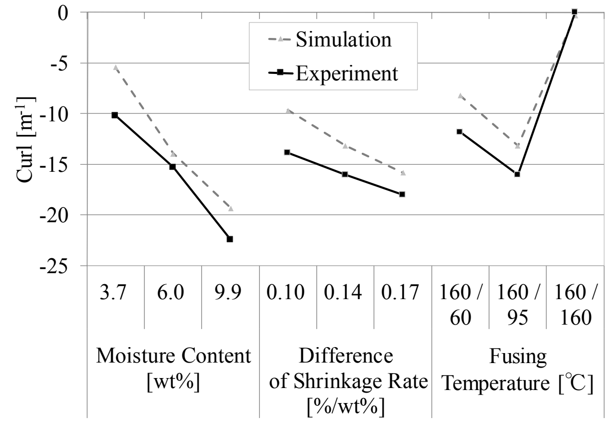

Figure 9. Verification Results of Curl Simulation with Moisture Content Variation Model

Prediction Result for Fusing Systems

To apply the curl prediction model to real machines, the amount of curl was calculated varying multiple factors: type of fusing system, fusing temperature, type of paper, moisture content of the paper and amount of toner. The values of each factor are shown in Table 1. Two fusing systems were selected. One of them consists of 2 rolls, and the other consists of a belt and a roll. Furthermore, the paper types are decided from the upper and lower limit of the stiffness and air permeability. To predict a deformation of toner, a model that connects an elasticity spring, a viscosity damper and a heat shrinking element in series was used [2].

The calculated results and the experimental results of paper curl after the fusing nip are shown in Figure 10. The calculated and experimental value matched with high accuracy and the correlation coefficient 0.98 was obtained. The prediction accuracy of the model is high enough to be utilized for design of the system.

Table 1: Factors and Values of Verification

Fusing Temperature	2-roll (160℃/160℃-95℃) Free Belt Nip Fuser [7] (95℃-170℃)
Paper (Thickness)	Plain Paper (88μm-251μm) Coat Paper (90μm)
Moisture Content	3.7wt% - 9.9wt%
Amount of Toner	0% - 200%

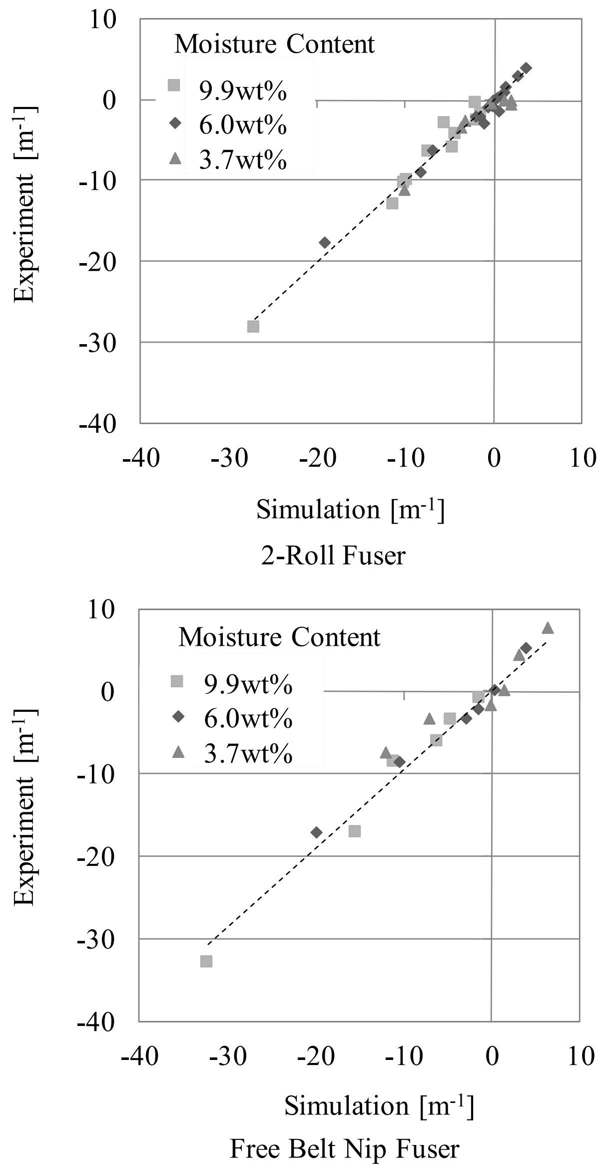

Figure 10. *Verification Results of Curl Simulation with 2-roll and Free Belt Nip Fuser*

Case Example

To narrow down a design from plurality of candidates, the curl of paper transported through the fusing nip was calculated by the proposed simulation technique. The configuration of the fusing device is shown in Figure 11. The shape of the pad in Figure 11 needs to be determined in this study. The simulation results of two representative structures are shown in Figure 12. Case 1 with high curvature on the paper path, is shown by dotted line, and Case 2 with relatively low curvature on the paper path, is shown by solid line, and the results with three representative paper (A, B, C) are shown. The limitation of curl that the paper can be transported is shown as a dark solid line in Figure 12. As shown in Figure 12, a configuration of Case 2 that all three types of paper can be transported, was selected by the curl simulation. Design of the fusing system with fewer prototypes are possible by this analysis technology and, front-loading development has been achieved. Design man-hours needed for the development of a new fusing system were reduced with this technology.

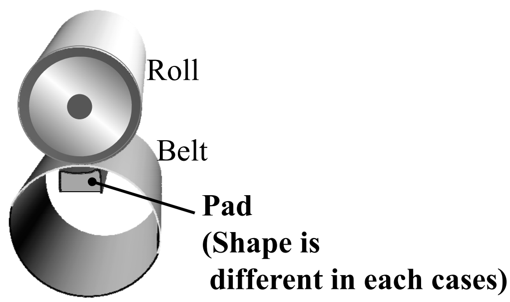

Figure 11. *New Fusing Device*

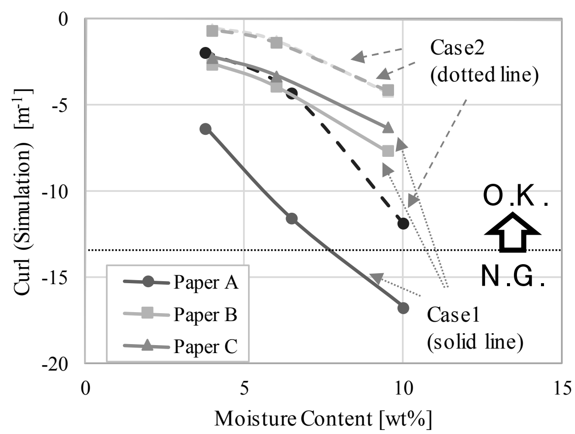

Figure 12. *Simulation Results for New Fusing Device*

Conclusion

A high accuracy model to predict the amount of paper curl that depends on the design parameters of fusing systems was developed. First, a mechanical deformation model considering stress history of paper path and mechanical properties under high temperature and high humidity in the fusing nip was developed. Furthermore, a moisture content change model with the drying model reflecting the decreasing drying property of paper and the vapor transportation model could predict moisture content of paper with high accuracy. The integrated model of mechanical and moisture could predict the amount of curl accurately (correlation coefficient is 0.98) under various environments and types of paper in various fusing systems. Additionally, the technology was adapted for a development of a new fusing system, and designs of the new system with fewer prototypes were possible by this technology.

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References

[1] T.Ito, “Simulation Model of Paper Curl Formed by Transportation Path”, Journal of the Imaging Society of Japan Vol.51, No.3, pp.248-254, (2012) [in Japanese]

[2] R.Takahashi, “Simulation Model to Predict Paper Curl Reformation in a Decurler Device”, Journal of the Imaging Society of Japan Vol.52, No.6, pp.523-529, (2013)

[3] S.Oohara, “Prediction of Paper Curl Generated by Fusing Process”, Journal of the Imaging Society of Japan Vol.52, No.6, pp.567-574, (2013)

[4] P.Wellmar，“Fracture toughness of paper – development of a test method”, Nordic Pulp Paper Res. J., Vol.12, No.3, pp.189-195, (1997)

[5] Jennings, “Periodic Response of a General Yielding Structure”, Proc. ASCE, EM2, pp.131-163, (1964)

[6] https://www.3ds.com/products-services/simulia/products/abaqus/ [Abaqus Product Information]

[7] Yasuhiro Uehara, “Free Belt Nip Fuser technology”, Fuji Xerox Tech. Rep. No.14, pp.82-88, (2002) [in Japanese]

Author Biography

Masato Ando obtained his masters in mechanical engineering at Doshisha University in Japan in 2010. He then joined Fuji Xerox Co., Ltd., where he engages in a research on electrophotography process simulation. He is a member of Imaging Society of Japan.