Simulation Technology to Predict Paper Curl Reformation by Visco-elasto-plastic Model

Ryosuke Takahashi, Tomoyuki Ito, Kiyoshi Hosoi, Takashi Ogino; Fuji Xerox Co., Ltd.; Ashigarakami-gun, Kanagawa/Japan

Abstract

The simulation technology for virtual design of a decurler device in electrophotography is developed. A paper curl is a phenomenon in which arc-like residual deformation occurs, and it degrades publishing quality and printing productivity. To reform the paper curl, decurler devices are installed in electrophotography products. In the decurler devices, paper is bent in large curvature against the direction of the curl to be reformed. Reformation amount of the curl is affected by decurler parameters including radius of rollers and nip load. In addition, amount of the curl to be reformed varies with paper brand, type of fusing system and image density. For these reasons, much effort and many resources are required for designing decurler parameters. To clarify the mechanism of the curl reformation, measurements of curl amount in various decurler conditions are carried out, and it becomes apparent that the paper curl is dependent on plastic and viscous characteristics of paper. By calculating history of stress-strain state during transportation through decurler devices with visco-elasto-plastic model which reflects characteristics of the paper, prediction of curl amount in high accuracy becomes possible. By utilizing this technology for virtual design of decurler devices, reduction of the development period to one fifth was accomplished.

Introduction

A paper curl is one of the chronic issues in copiers and printers with the electrophotography process. The paper curl occurs when paper is bent in the fusing nip and the paper path during transportation. Expansion and contraction on the paper by the variation of temperature and moisture content also affect the curl. By the occurrence of the curl, not only the printing quality turns worse, but also printing productivity largely falls because paper jam caused by the curled paper occurs.

A decurler is one of the devices to control the amount of the curl. The decurler is installed between the fuser and the machine exit to reform the curl that occurs in the fuser. Paper is bent in the direction opposite to the occurring curl in the decurler. There are various types of decurlers, and a roller type and a belt type which are shown in Figure 1 are used in common. Both of these types have equal function that is to bend a paper in arbitrary curvature and reform the curl of the paper while transporting it. To minimize the amount of the curl by the decurler, optimization of decurler parameters for various conditions including paper brand and type of fusing system is required. However, the paper brand diverges into many branches, and the amount of the curl varies depending on image density even if paper brand is the same. Hence, enormous resources are required for experimental optimization of the decurler parameters for all combinations of factors such as paper brand, image density and environmental condition. Therefore, development of a simulation technology to predict the amount of the paper curl reformation in the decurler device has been demanded.

In this study, the mechanism of the curl reformation effect in the decurler is clarified by preliminary experiments. Furthermore, the simulation technology to predict the amount of the paper curl reformation is developed by considering plastic and viscous characteristics of paper.

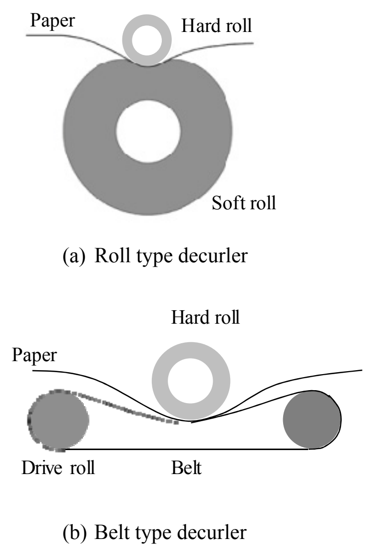


***Figure 1**. Decurler devices*

Study of curl reformation mechanism

Researches aiming to predict a paper curl by numerical simulation have been carried out previously. A method to calculate paper deformation by a linear visco-elastic model depending on the moisture content of paper was proposed by Uesaka [1]. By Ito, a method for prediction of curl amount considering variation of curvature, temperature and moisture content during transportation by expressing the paper characteristic with a double Maxwell model was established [2]. On the other hand, because deculrer devices are installed away from the fuser in most machines, temperature and moisture content of paper have little dependence on fusing conditions when the paper is transported through the decurler. Therefore, an assumption that the effect of curl reformation is unrelated to variation of temperature and moisture content is made in the present study.

To clarify the mechanism of the curl reformation in the decurler, preliminary experiments were carried out to understand effects of key factors. As the key factors, (a)bending curvature, (b)deformation time, (c)compression acting in the thickness direction of the paper, (d)tension acting in the in-plane direction of the paper, and (e)friction acting on the paper surface, were chosen. To quantify the effects of each factor independently, a measurement device shown in Figure 2 was built and amount of the curl was measured under the conditions shown in Table 1.

Figure 3 shows the results of the curl measurements. The curl height is defined as the height of the edge of the arc-shape under the effect of no gravity. The result shows that bending curvature (factor (a)) and deformation time (factor (b)) mainly affect the amount of the curl and other factors have little or no influence. The result that the amount of the curl increases linearly with bending curvature can be explained by the relationship between yield stress and bending stress of the paper. Furthermore, the result that the amount of the curl increases exponentially with deformation time is explained by stress relaxation. From the result described above, it was concluded that the paper curl occurs by plastic and viscous deformation when large and prolonged bending is exerted on paper.

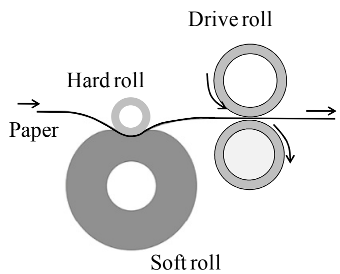
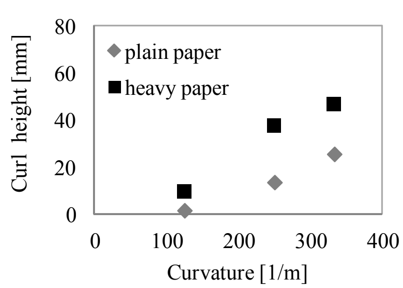


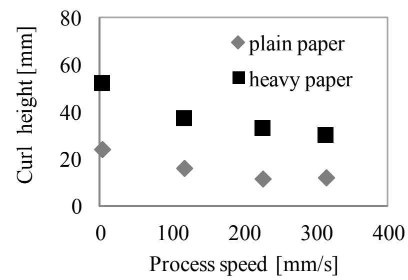
***Figure 2.** Paper curl measurement device*

Table1 Experimental condition

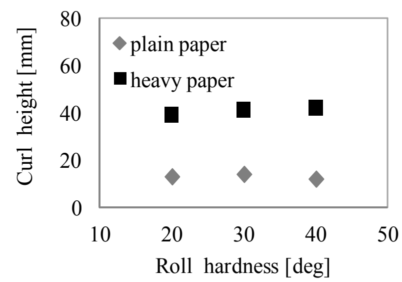
Factors	Experimental parameters		
(a) Bending curvature	Hard roll curvature	125, 250, 333	[1/m]
(b) Deformation time	Process speed	3, 117, 226, 314	[mm/s]
(c) Compression	Soft roll hardness	20, 30, 40	[degree]
(d) Tension	Drive roll tension	0.71, 0.96	[N]
(e) Friction	Roll-paper frictional coefficient	A:hard:0.2 soft:1.0 B:hard:0.2 soft:0.2 C:hard:1.1 soft:0.2	[-]



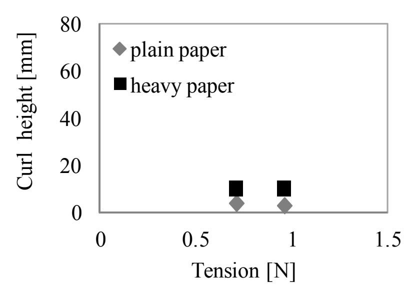
(a) Influence of bending curvature



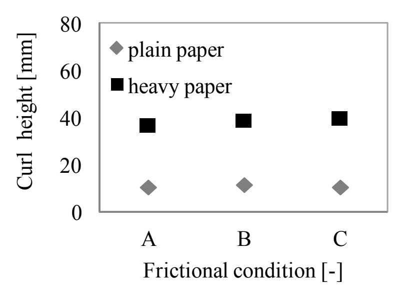
(b) Influence of deformation time



(c) Influence of compression



(d) Influence of tension



(e) Influence of friction

***Figure 3.** Results of paper curl measurements for clarification of the curl reformation mechanism.*

Visco-elasto-plastic model

Based on the mechanism described above, a mathematical model to express the plastic and viscous characteristics of paper was built. A base element consists of a spring, a slider and a dashpot. A multiple visco-elasto-plastic (hereafter denoted as "v-e-p") element is formed by linking a number of the base elements and single spring in a parallel manner as shown in Figure 4 [3][4]. In the figure, E is the elastic coefficient, μ is the viscous coefficient and σ_Y is the yield stress, and subscripts indicate the number of base elements. The distribution of the internal stress within the paper under the bending is calculated by assuming a finite number of the in-plane multiple v-e-p elements distributed in the thickness direction. Relationship between the stress and the strain of the multiple v-e-p elements is described by equations (1) to (3).

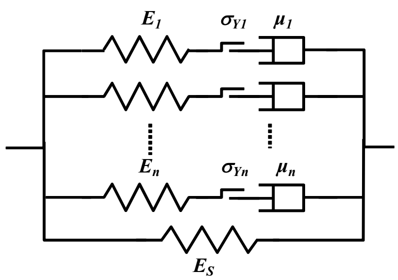


***Figure 4.** The multiple visco-elasto-plastic element*

$$\dot{\varepsilon} = \frac{\dot{\sigma}_i}{E_i} \qquad (-\sigma_{Yi} \le \sigma_i \le \sigma_{Yi}) \tag{1}$$

$$\dot{\varepsilon} = \frac{\dot{\sigma}_i}{E_i} + \frac{\sigma_i - \sigma_{Yi}}{\mu_i} \qquad (\sigma_i < -\sigma_{Yi},\, \sigma_{Yi} < \sigma_i)) \tag{2}$$

$$\sigma = \sum_{i=1}^{n} \sigma_i \tag{3}$$

Flow of the analysis is shown in Figure 5. The history of the paper curvature is computed by a general purpose FEM simulator, Abaqus. Characteristics of the paper are estimated from the strain-stress curve measured by a uniaxial tensile tester. In the present analysis, an initial curl is defined as the amount of the curl after the fusing that is to be reformed, and it depends on various conditions including paper brand, image density and type of the fusing system. The in-plane compression rate of toner is estimated from experimental relationships between the amounts of the curl after the fusing and an image density. The in-plane compression rate depends on the paper brand because variation of the temperature after fusing differs according to the thickness and the thermal characteristics of the paper. To predict the amount of the paper curl, relationships between history of the curvature and that of the internal stress distributions in paper are calculated by equations (1) to (3).

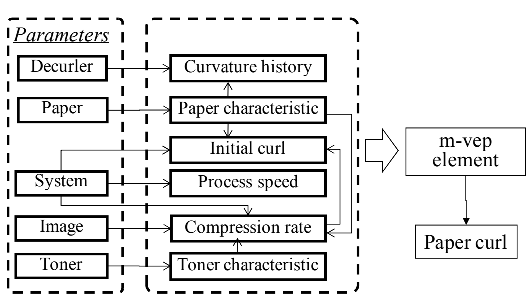


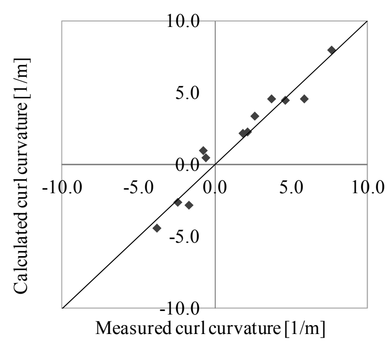
***Figure 5.** Flow of the analysis*

Result

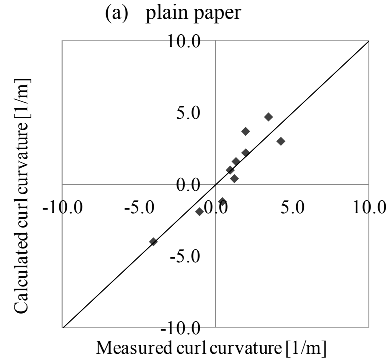
Comparison between the amount of the curl obtained by an experiment and a simulation was conducted for verification of the v-e-p model. Conditions of the verification and the results are shown in Table 2 and Figure 6 respectively. As shown in Table 2, the amount of the curl was measured and calculated under various conditions of decurler parameters, paper brand and image density. According to Figure 6, the calculated curl curvature has a good correlation with the measured curl curvature. The results above indicate that the v-e-p model is capable of predicting the amount of the curl with high accuracy that is sufficient for practical use. In addition, to verify reliability of the v-e-p model for parameter design, variation of calculation errors, which is the difference between the numerical and the experimental results, are investigated in Figure 7. In the figure, dashed lines indicate a triple standard deviation of the calculation errors evaluated assuming that the calculation errors are distributed normally. From the result, the triple standard deviation is smaller than the acceptable value of the curl. This result indicates that v-e-p model is able to determine whether the amount of the curl falls within the range of curl acceptable range with more than 99% probability.

Table 2 Verification conditions

Factors	Values	
Paper type	plain, heavy	
Decurler type	roll-type, belt-type	
Nip depth	0.5 - 3.0	[mm]
Process speed	200, 400	[mm/s]
Image density	0 - 400	[%]



(a) plain paper



(b) heavy paper

***Figure** 6.Verification result of visco-elasto-plastic model*

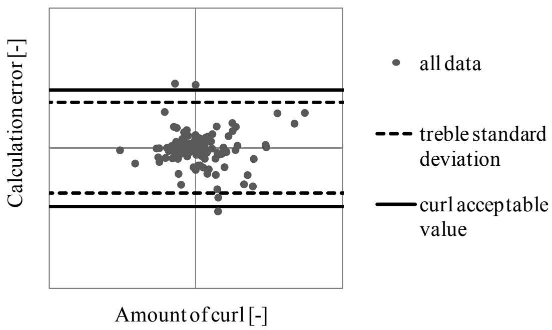


Figure 7. *Comparison of analytical error and curl acceptable value*

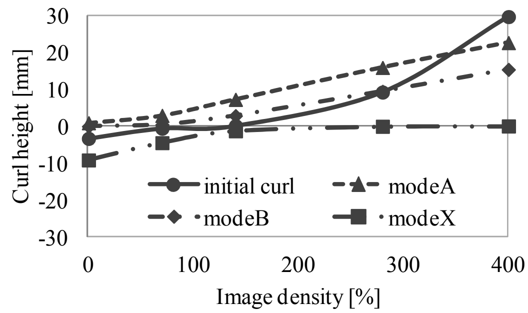


Figure 9. *Relationships between curl amount and image density in each decurler parameters.*

As the quantitative accuracy and reliability for parameter design of the v-e-p model is confirmed, virtual design of decurler parameters was carried out. The decurler device is controlled in accordance with an operation table shown in Figure 8. In the figure, alphabets indicated in the table correspond to operating modes of the decurler. For instance, when the paper brand is "PaperA" and the image density is 400, mode "X" will be selected and the decurler will be operated with a parameter set assigned to the mode "X". Determination of the specification of the operation table accounts for the large portion of design process of the decurler device. Relationships between curl amount of plain paper and the image density for several operating modes are shown in Figure 9. The result indicates that the optimum mode changes with variation of the image density. In the plain paper considered in Figure 9, a mode "B" is the optimum mode for the image density of less than 120%, and mode "X" is optimum in other range of the image density. The same analyses were carried out for all target paper brands, and the operation table was determined. Evaluation of the performance was conducted with a copier with the operation table determined by v-e-p model, and it was confirmed that no problem caused by paper curl occurred. By utilizing this technology, the period required for the design of decurler parameters was reduced by one fifth or less.

		Paper brand		
		PaperA	⋯	PaperZ
Image density	10	A	D	A
	20	A	E	A
	30	B	E	A
	40	B	E	A
	·	·	·	·
	·	·	·	·
	·	·	·	·
	380	X	X	B
	390	X	X	B
	400	X	Y	B

Figure 8. *Decurler operation table*

Conclusions

In this study, a simulation technology to predict the amount of paper curl reformation by a decurler was developed. By the preliminary experiments to clarify the mechanism of the curl reformation effect, it became clear that bending curvature and deformation time affected the curl largely. To express plastic and viscous characteristics of paper, the visco-elasto-plastic model consisting of springs, sliders and dashpots was built. Quantitative accuracy sufficient for parameter design of a decurler was confirmed. By utilizing this technology, virtual design of decurler parameters was accomplished and period required for experimental design was reduced by one fifth or less.

References

[1] J T. Uesaka, T. Ishizawa, I. Kodaka, and S. Okushima "Curl in paper (3) Numerical Simulation of History-Dependent Curl", Japan Tappi Journal, 43, pp.689-696 (1989).
[2] T. Ito, K. Hosoi, and T. Ogino "Simulation Model of Paper Curl Formed by Transportation Path" , Imaging Conference Japan 2011 Ronbun-Syu, The Imaging Society of Japan, pp.249-255.
[3] Л.М.Качанов, and Y. Ohashi, "Basic of plastic theory ", Yokendo (1978), pp.28-42
[4] S. Onogi, "Rheology Youron", Maki-Syoten (1957), pp.51-95

Author Biography

Ryosuke Takahashi holds a BS degree in chemical engineering from Doshisha Univ.(2006). In 2006, he joined Fuji Xerox Co., Ltd., where he engages in a research on electrophotography process simulation. He is member of Imaging Society of Japan and Japan Society of Mechanical Engineers.