Hot Offset Simulation in Fuser Process

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Abstract

The toner deformation simulation based on the finite element method and Arbitrary Lagrangian-Eulerian (ALE) method has been used to calculate the hot offset in the fuser process. The viscoelasticity of toner, the adhesion force between toner and the material contacting the toner, and the fuser condition are taken into account. The method is able to calculate the toner deformation in the process of pressurization and strain in fusers, and the simulation results have reproduced the hot offset in fusers. When the method is used to estimate the hot offset level, the dependency of image density on the hot offset level matches experimental results.

Introduction

In the fusing process of electrophotography, toner is deformed by heat and pressure to be fixed onto paper. In designing the fusing process, it is necessary to determine the conditions under which the fixed toner image obtains sufficient strength without the occurrence of poor imaging or paper jamming, among a variety of design factors.

Weak fixed image strength is a problem at low temperature. The authors reported the results of viscoelastic fluid simulation on the toner deformation process in a fuser, and quantitatively estimated the fixed image strength [1]. Another problem of poor imaging is hot offset at high temperature. Hot offset is considered to be caused by toner separation due to the cohesive force of toner becoming less than the adhesion force between toner and fuser material when toner is excessively heated [2]. A part of the separated toner adheres to the fuser material and then is transferred to paper by rotation of the fuser material, causing poor imaging. Accordingly, like weak fixed image strength, hot offset is a serious design problem but has not been examined by simulation.

In this study, the process of toner separation from fuser material was calculated by applying the adhesion force between toner and fuser material to the results of the toner deformation simulation [1]. In addition, the method was used to simulate the hot offset phenomenon in an actual machine, and the validity of the simulation was examined.

Simulation method

The governing equations for an incompressible fluid are the mass conservation law, the momentum conservation law, and a constitutive equation:

$$\nabla \cdot \boldsymbol{v} = 0 \tag{1}$$

$$\nabla \cdot \boldsymbol{\sigma} + \boldsymbol{f} = \rho \boldsymbol{a} \tag{2}$$

$$\boldsymbol{\sigma} = -p\mathbf{I} + \boldsymbol{\sigma}' \tag{3}$$

The symbols $\boldsymbol{v}$, $\boldsymbol{\sigma}$, $\boldsymbol{f}$, $\boldsymbol{\rho}$, $\boldsymbol{a}$, $\boldsymbol{p}$, $\boldsymbol{\sigma}'$ respectively represent velocity, stress, body force, density, acceleration, pressure and extra stress. These governing equations are calculated using the finite element method for a two-dimensional field. The Giesekus viscoelastic model [3] is used as the constitutive equation for the extra stress in Eq. (3):

$$\left[\mathbf{I} + \frac{\alpha_i \lambda_i}{\eta_i} \sigma_i'\right] \cdot \sigma_i' + \lambda_i \overset{\Delta}{\sigma_i'} = 2\eta_i \boldsymbol{D} \tag{4}$$

where $\boldsymbol{D}$ represents deformation velocity. The subscript i represents the number of modes, which is obtained by fitting the coefficients (η_i, λ_i, α_i) of each mode to the frequency characteristics of dynamic viscoelasticity. Assuming that a shift function $H(T)$, which indicates the temperature dependency of viscoelasticity, acts on the viscosity and shear velocity, the shift function $H(T)$ is obtained by fitting C_1 and C_2 to the measured data of the dynamic viscoelasticity using the following Williams Landel Ferry (WLF) law [4]:

$$\ln H(T) = -\frac{C_1 (T - T_a)}{C_2 + T - T_a} \tag{5}$$

where T represents temperature, and T_a reference temperature.

The Arbitrary Lagrangian-Eulerian (ALE) method [5] is used to solve the free surface of toner. In the process of toner particles making contact and bonding with each other, it is determined whether contact between toner particles occurs, and if interference between the interfaces exists, the elements are redivided to take the interference into account. Physical quantities at the newly added nodes in the redivision are given by coordinate interpolation to the quantities at the original nodes.

Since this calculation is carried out only for the mesh inside the toner region, toner deforms without being affected by the surrounding air even if an incompressible two-dimensional field is assumed. Meanwhile, the temperature distribution in toner is affected by the surrounding air, which is not taken into account in the deformation calculation. In order to estimate the heat transfer field, the following heat transfer equation is calculated by creating an orthogonal mesh space other than that for deformation estimation:

$$\frac{\partial T}{\partial t} = \nabla \cdot \alpha \nabla T \tag{6}$$

where T represents temperature, and α thermal diffusivity. The values of α are assigned by mapping the positional relationship of toner, paper and the like in a fluid calculation mesh onto the respective elements in a heat transfer field mesh. The fluid calculation and heat transfer calculation are carried out in order in each of the time steps.

The influence of the moving state of a fuser material that applies pressure to toner is taken into account by applying the normal stress represented by the following equation to the contact region between toner and fuser material (pressing material):

$$f_{s,n} = -k(\boldsymbol{v}_s - \boldsymbol{v}_w) \cdot \mathbf{n} \tag{7}$$

where $\boldsymbol{v}_w$ represents the moving velocity of the fuser material, and $\boldsymbol{v}_s$ the velocity of toner in the contact region. k represents a penalty coefficient, to which a large value (= 10^{13}) is set so as to make the toner interface follow the movement of the fuser material. In order to take account of adhesion between toner and fuser material in the contact region, the nodes at which the tensile stress exceeds the adhesion threshold value are not taken as the contact region, and therefore the nodes are not given the boundary condition represented by Eq. (7). In Fig. 1, which shows this processing schematically, when the tensile stress at the end node P of the contact surface of toner (Fig. 1 (a)) exceeds the adhesion threshold value, the node P is not taken as the contact region and thus separates from the fuser material with the elapse of time (Fig. 1 (b)).

The adhesion threshold value means the adhesion force per unit area between toner and fuser material, and is obtained by measuring the force between toner and fuser material when they separate from each other. Figure 2 shows the measurement results of the adhesion force between toner and paper, and toner and the surface of the fuser material (fluororesin, PFA) respectively. The contact area may change depending on the toner temperature in the measurement, however, it is clear that the adhesion force linearly increases with increase of contact area. Since the gradients in Fig. 2 represent the adhesion force per unit area, the adhesion threshold value between toner and PFA is smaller than that between toner and paper. With respect to the conditions in the tangential directions between toner and fuser material, and between toner and paper, the following equation applies to the toner surface in the contact region:

$$f_{s,s} = -\mu P_s \tag{8}$$

where μ and P_s respectively represent the coefficient of dynamic friction and the normal stress at an arbitrary position in the contact region between toner and contact material. The value of μ depends on the contact material, and was set to be 0.2 for paper to toner and 0 for the fuser material surface (PFA) to toner [1]. Thus, on the fuser material side, there is no friction force of a tangential component and so the toner tends to expand, that is, the stress is less prone to concentrating than on the paper side, which is disadvantageous regarding separation and shows a different aspect from the adhesion threshold value. In this calculation, both effects and the balance between them can be taken into account to simulate the separation process between toner and contact material.

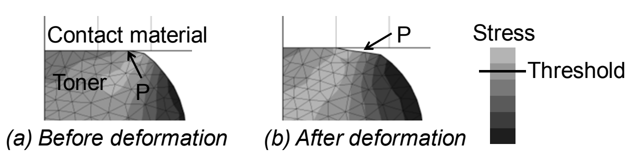


Figure 1. *Calculation method of peeling process.*

Simulation in consideration of adhesion force

Figure 3 shows the calculation model for verifying the effect of adhesion force. The entire structure and the toner region are respectively illustrated as (a) and (b). The toner on paper is pressed by a fuser material (film), and it is assumed that the toner consists of three layers. A boundary condition is given at both ends of the analysis region so that the velocity in the x direction is zero. Figure 4 (a) and (b) respectively show the load and temperature applied to the back surfaces of the film and paper. The load was obtained by calculating the contact pressure between the fuser material and paper by structural analysis considering the constitution and mechanical characteristics of the fuser. The temperature condition was determined otherwise by heat transfer calculation in a two-dimensional cross section perpendicular to the axial direction on the basis of the shape obtained by the structural analysis. The method for applying the load and temperature was the same as in the literature [1]. Figure 5 shows the calculation results of toner deformation for (a) pressing and (b) separation, not taking account of the adhesion threshold (adhesion threshold = 0), and (c) separation taking account of the measured adhesion threshold. Under these calculation conditions, offset does not occur for any value of adhesion force, which is due to the large amount of toner as explained later. However, it is clear that the shape of the toner surface in the steady state is quite different between (b) and (c). These results suggest that adhesion force must be taken into account in order to precisely examine the surface shape after deformation.

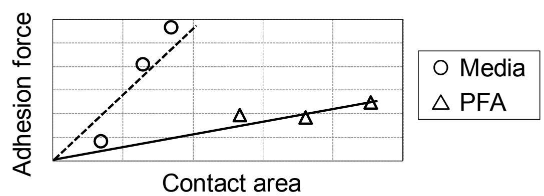


Figure 2. *Measurement results of adhesion force.*

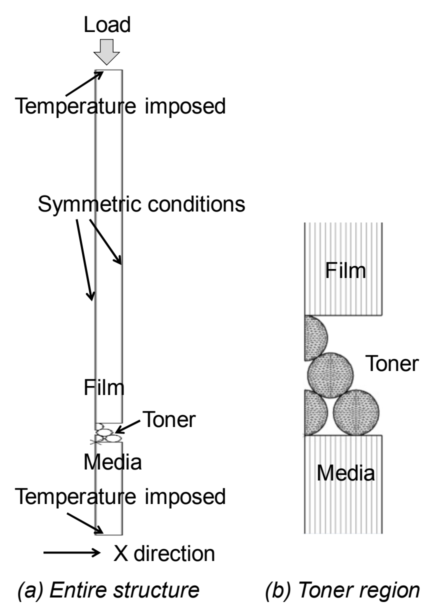
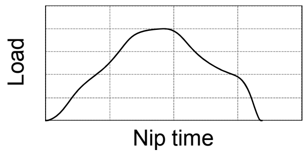
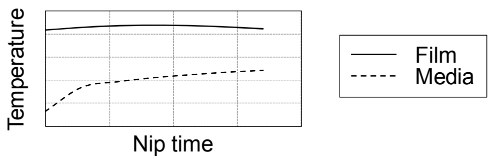


Figure 3. *Simulation model.*

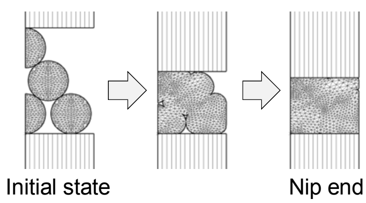


(a) Nip load

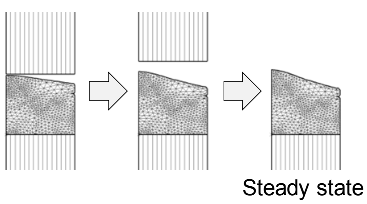


(b) Temperature

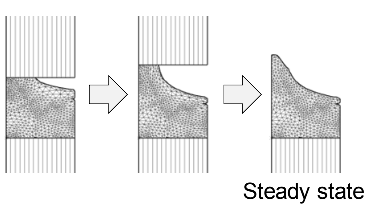
Figure 4. *Boundary conditions.*



(a) Deformation in nip region



(b) Deformation after nip without adhesion



(c) Deformation after nip with adhesion

Figure 5. *Comparison of toner deformation processes.*

Figure 6 presents an example of the calculation results under the condition that the toner amount is so small that offset occurs. Toner cannot be separated from the fuser material, and thus is strongly drawn. As a result, the tensile stress inside the toner, especially at the portion indicated by a circle, becomes large. In actuality, it is considered that when the stress reaches a certain level the toner itself suffers cohesive failure. Simulation of cohesive failure is complicated in modeling the failure conditions and also in processing the calculation mesh after the failure. Therefore, a failure model is not constructed in this case, but whether hot offset occurs or not is judged according to the change of the tensile stress. Figure 7 shows the calculated maximum value change of the tensile stress at the interface between toner and fuser

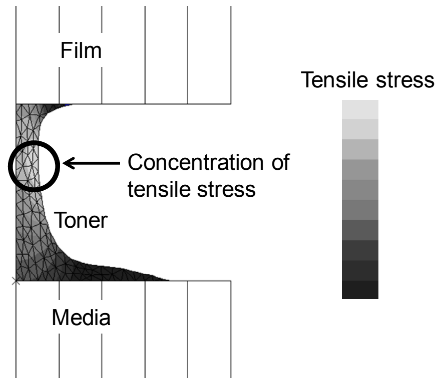


Figure 6. *Tensile stress distribution of toner.*

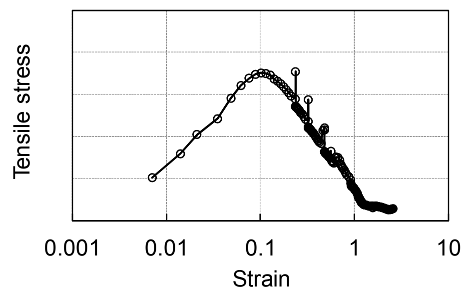


Figure 7. *Tensile stress variation.*

material, plotted with respect to strain on the basis of the toner height at the fuser nip exit. The tensile stress increases after exiting through the nip, and then starts to decrease after reaching a certain level as shown in Fig. 6. In other words, when the tensile stress is the maximum, if the stress at the interface does not exceed the adhesion threshold value, toner cannot be separated from the fuser material and so the strain increases until the toner inevitably suffers cohesive failure, which is considered to be the occurrence of hot offset.

Effect of toner amount on hot offset

The relationship between toner amount (toner mass per unit area) and hot offset is examined. The grade of hot offset in the experiment is defined by a hot offset level *Lh* represented by:

$$Lh = \frac{D_{hot} - D_{media}}{MS} \tag{9}$$

D_{hot}, D_{media}, and *MS* represent respectively the reflection density of an offset image, the reflection density of paper, and toner amount. The reflection density is represented by the reflectivity measured by a reflection densitometer. The higher *Lh* is, the greater the hot offset that occurs, and vice versa. Figure 8 shows the measurement results of the relationship between toner amount and hot offset level at a controlled temperature of 225°C. As the figure shows, *Lh* decreases as the toner amount increases. Since hot offset can be visually observed when *Lh* is larger than the value indicated by the broken line, hot offset becomes a significant problem when the toner amount is less than 0.14 mg/cm^2.

A simulation of toner deformation was carried out for the toner amounts of 0.08 mg/cm^2 (Case A), 0.15 mg/cm^2 (Case B), and 0.39 mg/cm^2 (Case C), which are the process conditions also used in the experiment above. Figure 9 illustrates the calculation models around the toner region. The toner is assumed to consist of one layer, and the width of the model is altered in accordance with the toner amount. The simulation results at the nip end (t = 0), and at 2 msec and 4 msec after the nip end, are shown in Fig. 10. In Case B and Case C, toner is separated from the fuser film respectively at 4 msec and 2 msec after the nip end. Meanwhile, in Case A, toner cannot be separated from the fuser film and causes hot offset. These results agree with the experimental results of hot offset shown in Fig. 8.

The controlled temperature dependence of hot offset was also calculated for the toner amount of 0.08 mg/cm^2 (Case A). Figure 11 shows the simulation results for the controlled temperature of 180°C and 225°C, and indicates that hot offset occurs at 225°C, but not at 180°C.

Conclusions

Calculation methods for the toner deformation process and process of toner separation from fuser material in consideration of the adhesion force between toner and fuser material were derived. The hot offset levels in a fuser were measured, and the results were compared with simulation results. The simulation results reproduced the phenomenon of improvement in hot offset as the toner amount increases. This simulation will be useful for predicting hot offset in the fusing process.

References

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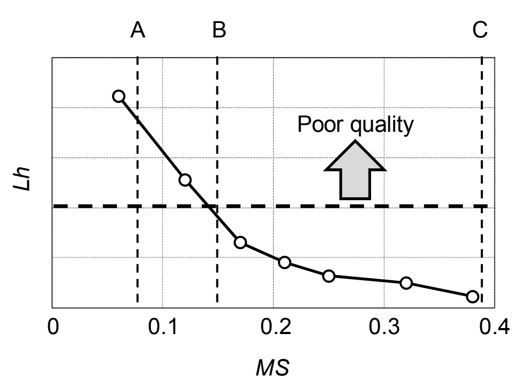

Figure 8. *Experimental results of hot offset level.*

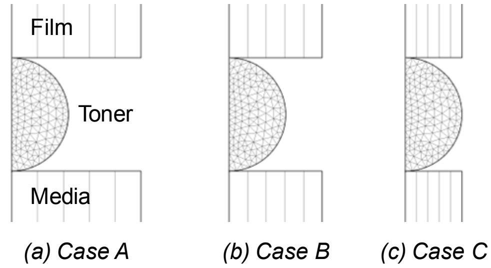

Figure 9. *Simulation models of hot offset simulation.*

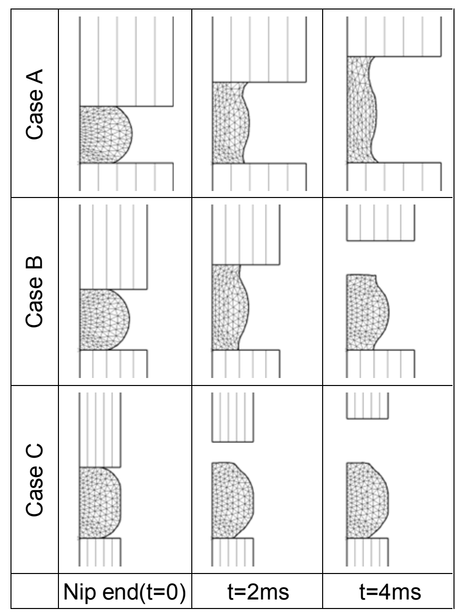

Figure 10. *Calculation results of hot offset simulation.*

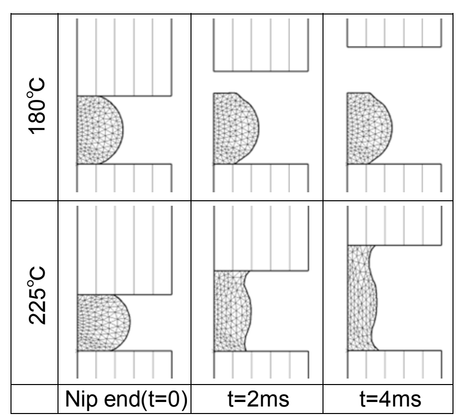

Figure 11. *Temperature dependency of hot offset.*

Author Biography

Kyohei Kato received his B.E. and M.E. degrees in Applied Physics and Physico-Informatics from Keio University, Japan in 2004 and 2006, respectively. He joined Canon Inc. in 2006 and has been engaged in the development of electrophotography by using numerical simulation.