Modeling of the Transient Heat Transfer in Xerographic Fusing Using a Discrete Element Approach

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Abstract

In This study, a computer model, based on discrete element method, is used to simulate unsteady state heat transfer at the fuser/toner and toner/coating layer interfaces during the Xerography fusing process. The model coating layers consisted of randomly arranged spherical pigment and latex particles with commercially relevant size distributions. Effects of coating characteristics, toner size, multiple toner layers, toner melting energy and toner thermal conductivity on the unsteady state heat transfer in the fusing process were investigated. Results showed that temperature variation highly depended on the toner size, toner melting energy and the fuser roll temperature. Moreover, simultaneous coupling of the stress and heat transfer indicated that the pressure exerted by fuser roll cannot significantly affect the rate of heat transfer to the toner particles.

Introduction

Fusing process strongly affects the print quality as well as the energy demand of a Xerographic printer. Therefore, improving our fundamental knowledge of factors that affect the fusing process will help to advance the performance of such printers. In particular, with the emergence of high speed Xerography processes, a better understanding of heat transfer in the fuser nip has become increasingly important. Since the measurement of transient heat transfer in paper during the fusing process is a challenging task, theoretical modeling of this process has been often used. Several researchers have investigated the heat transfer from a hot fuser roll or a flash fusing lamp to a stack of toner layer, base paper and the pressure roll [1-7]. However, firstly these models are limited to uncoated papers and the porous structure of paper coating layers has not been taken into account and secondly the effect of different line loads during fusing process has not been addressed. Although coating layer deformation under fusing nip load (~1 MPa] is expected to be small [8], surface re-arrangements of coating components may provide a higher heat transfer area between toner and coating layer, as a result, a soft layer absorbs higher amount of heat from the toner than a stiffer layer does.

Therefore, in this study, a computer model based on discrete element method (DEM) is employed to simulate the simultaneous effects of pressure and heat transfer during fusing. In particular, effects of toner size, toner arrangement, toner conductivity, toner melting energy, fuser roll temperature and paper coating layer characteristics on the fusing process will be discussed.

Theory

Discrete element is a deterministic approach to simulate the behavior of the systems built up by particles of arbitrary size and size distribution. In recent years, with advances in the computational processing, DEM is finding a wider application for the modeling of systems that consist of a large number of particles.

In the present study, toner, pigment and latex particles are modeled as circular objects and are randomly deposited with a prescribed area. Although these particles are spherical in their free states; adjacent particles may overlap under compressive force. The extent of overlap is proportional to the amount of force and the stiffness of particles (Fig 1).

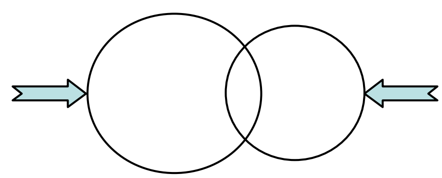

Figure1. Illustration of soft contact

In order to introduce the tensile forces that may arise between bonded materials such as a film forming latex or a coalesced layer of toners, a finite amount of a hypothetical glue is considered to act between the bonded particles; As a result, bonded particles cannot move independently (Fig. 2). The degree of bonding can be adjusted by changing the stiffness of this “glue”.

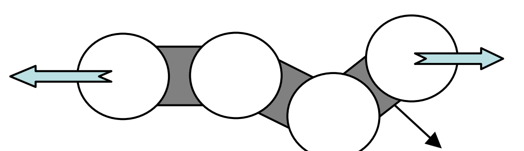

Figure 2. Illustration of cement-like bonds among particles

The existence of a bond between two particles can also facilitate the rate of energy exchange between them. Further information regarding the governing equations of bonded particles may be found in [9].

Using the above concepts, forces acting on each particle as well as particle position, velocity, momentum, and temperature could be calculated during the simulation process based on the laws of motion and linear contact theory [8].

The transient temperature profiles in the toner and coating layers are calculated based on the one dimensional unsteady state Fourier's equation:

$$\frac{\partial^2 T}{\partial x^2} + \overset{\circ}{q} = \rho\, C_p \frac{\partial T}{\partial t} \qquad (1)$$

In above equation, $\overset{\circ}{q}$ is the volumetric rate of heat generation and x is the direction of heat flow which is assumed to be the same as the direction of the center to center line of the two particles.

In this study, it is assumed that each particle has a uniform temperature that changes with time. Particles that are bonded or are simply in contact are allowed to exchange heat by means of a conceptual thermal route referred to as a "heat pipe" [9]. A heat pipe is defined by two parameters: pipe length and thermal resistance per unit length. Pipe length is considered to be equal to the distance between the centers of the particles and thermal resistance of each pipe is obtained according to the thermal conductivity of the particles in contact. In order to perform a thermal analysis in a discrete system, there are two other micro-properties that should be assigned to each particle prior to the simulation: density and specific heat of particles.

DEM Model

A schematic illustration of the fusing process for a coated paper is given in Fig 3. In the fuser nip, toner particles come in contact with the hot fuser roll cover for several milliseconds. Typical values for fusing conditions and toner characteristics are listed in Table 1. In order to simulate heat and stress transfer in the fusing nip, three layers of particles have been placed on each other to model the fuser roll cover, the toner layer, and the paper coating layer. Fig. 4 illustrates one of the models which have been used in this investigation. In this model, paper coating layer consists of spherical pigments and a large number of bonded latex particles that are located within a 50 × 10 µm^2 box. Pigment particles are generated according to the particle size distribution of HydroCarb 60 (Omya) while latex is modeled as mono-dispersed particles with a diameter of 0.2 µm.

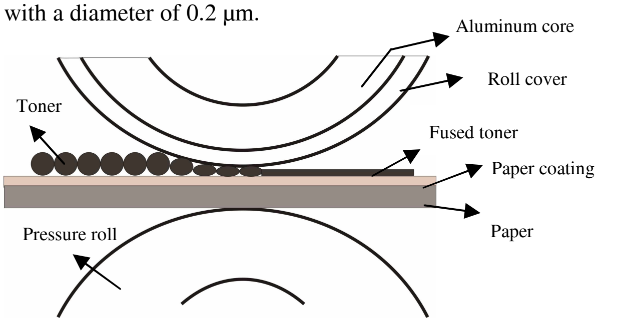

Figure3. *Schematic illustration of the fusing process for a coated paper.*

After obtaining a proper structure for the paper coating layer (i.e. 10% cross-sectional porosity), toner particles are deposited on the coating layer. During this step, toners are only allowed to move downward and their horizontal velocity is set to zero. It was observed that a fairly smooth surface can be obtained by this approach. Finally, a thin layer is placed on the top of the toner particles to represent fuser roll cover. Tables 1 and 2 provide the physical properties of model components, and the fusing conditions used in this study. It should be noted that due to the porous structure of coating layers, density and thermal conductivity of coating layers are much smaller than those of pigment particles.

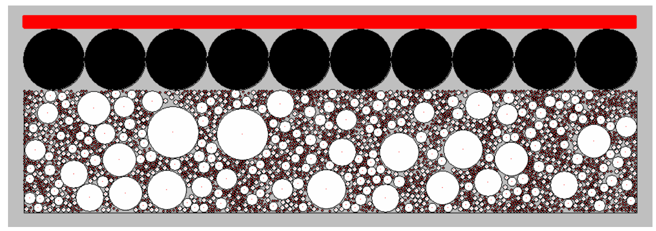

Figure 4. Demonstration of the discrete element model illustrating the fuser roll cover, toner particles and coating layer

Table 1 Model characteristics and fusing conditions.

Fusing roll temp.	160 - 180˚C
Ambient temp.	25˚C
Dwell time	20 ms
Fuser pressure	0.5 – 2 MPa
Aluminum thickness	1.5 mm
Roll coating thickness	40 µm
Small toner size	5 µm
Big toner size	10 µm
Toner glass trans. temp.	65˚C
Toner melting energy	12 -20 J/g
Paper coating thickness	10 µm
paper thickness	80 µm
pressure roll thickness	100 µm

Table 2 Physical properties of model components

	ρ, kg/m^3	k , W/ m K	Cp , J / g K
Pigment	2700	2.6	0.86
Latex	1050	0.2	1.1
Paper coating	1400	0.25	0.88
Toner	1200	0.15	1.4
Paper	1060	0.12	3.0

Xerographic fusing rolls are usually heated using a constant power heat source which is located at the center of the fuser cylinder. Considering the thermal conductivity and thickness of the aluminum core and the fuser roll coating, the corresponding temperature drop across these two layers could be obtained for a given heat flux. For instance, if the equivalent heat flux in a fuser roll is 40 kW/m^2, the corresponding temperature drop for aluminum core and fuser roll coating would be 0.3 and 8.9 ˚C respectively. Therefore, the temperature at roll coating/toner interface is 160.8˚C.

Results and Discussion

There are four distinguishable states during the fixing process. The approximate range of each step are listed below.

1. Warming: 25 - 65˚C
2. Softening: 65 - 90˚C
3. Melting: 90 - 130˚C
4. Liquid-like: >130˚C

In the present work, it is assumed that model components have constant properties during each of the above steps. For example, change in the specific heat of toner material between 25 to 65˚C is neglected, while changes of properties due to state change have been taken into account. The only exemption to this condition is the apparent specific heat of toners above 90˚C which increases with temperature.

As glass transition is a second order phase change, no latent heat is incorporated with it. On the other hand, melting of the toners occurs within a temperature range and it consumes a noticeable amount of heat. Hence, changes of toner's properties at glass transition temperature have been considered as a step change at 65˚C while melting energy of toners is assumed to be uniformly distributed within the melting temperature range.

In order to demonstrate the effect of each parameter, only one parameter is changed per simulation run. The default values of the model's parameters used in this study are listed below.

Table 2 Toner and fusing roll default characteristics

Fusing roll temp.	170˚C
Fuser pressure	1 MPa
Toner size	5 µm
Toner thermal conductivity	0.15 W/mK
Toner melting energy	12 J/g

Effect of toner size

In order to investigate the effect of toner size on the transient heat transfer during fixing, two different toner sizes with 5 and 10 µm have been used. Coating layer was covered with a single layer of toner particles and the resulting structure was analyzed using the method described earlier. As expected, simulation results (Fig. 5) indicate that a layer of toner made by large toner particles requires a longer time to reach the liquid-like state. Although the effective heat transfer area between fuser roll and large toners is slightly greater than the heat transfer area formed between a small toner and the fuser roll, it does not compensate the difference in the melting time of the toner particle.

Based on Fig.5, the thermal time constant for toner layer with 5 µm toner particles is about 6 times less than that of 10 µm toners. Therefore, for larger toners, a greater fraction of the dwell time in fusing nip has to be dedicated to the toner melting process. This is undesirable for the effective operation of high speed electrophtographic printers.

It should be emphasized that the heating of toner particles is a nonlinear process. This nonlinearity stems from a) variation of the thermal properties of toners in the fusing operating conditions, and b) exchange of heat between adjacent toner particles and between toner and paper coating layer

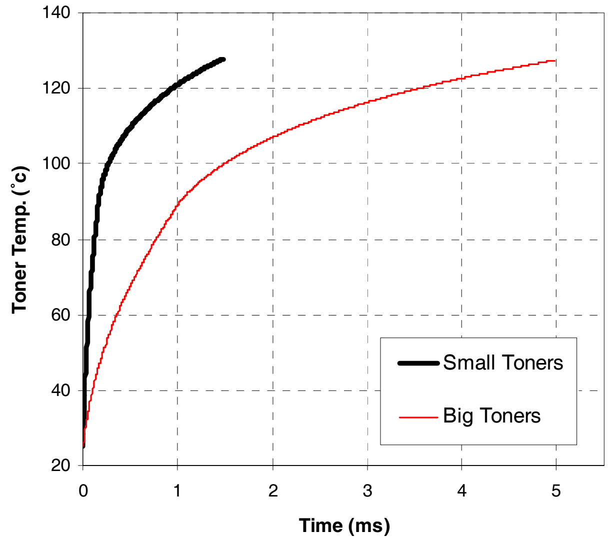

Figure 5. *Transient toner temperature in the fuser nip for 5µm toner particles (small toners) and 10 µm toner particles (large toners)*

To illustrate the significance of the above nonlinearities on the toner heating process, consider the temperature variation of a single toner particle subjected to a constant temperature source. For small Biot numbers, toner temperature may be approximated by a linear first order system:

$$T = T_c - (T_c - T_0) e^{-t/\tau} \qquad (2)$$

Here T_0 and T_c are the initial temperature of toner particle and the source temperature; respectively. τ is the time constant of toner that is proportional to its diameter, therefore the time constant for the heating of 5 µm toner particles is 2 times less than that of 10µm toners. This factor is much smaller than the result obtained by DEM model (i.e. 6). Hence, nonlinear effects play a major role in the toner heating process.

Multiple toner layers

Fig. 6 shows temperature variation of a single layer of toner versus double layers of toner with a hexagonal packed arrangement (Fig. 7).

Simulation results show that both top and bottom toner layers need a longer time to reach the melting temperature. Specially, the bottom toner layer requires twice higher time than the time required for the heating of a single toner layer.

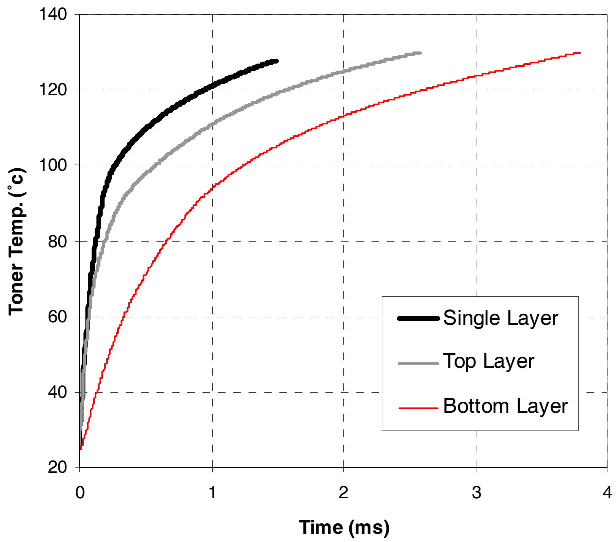

Figure 6. *Temperature variation of toner layers: single layer vs. double layer.*

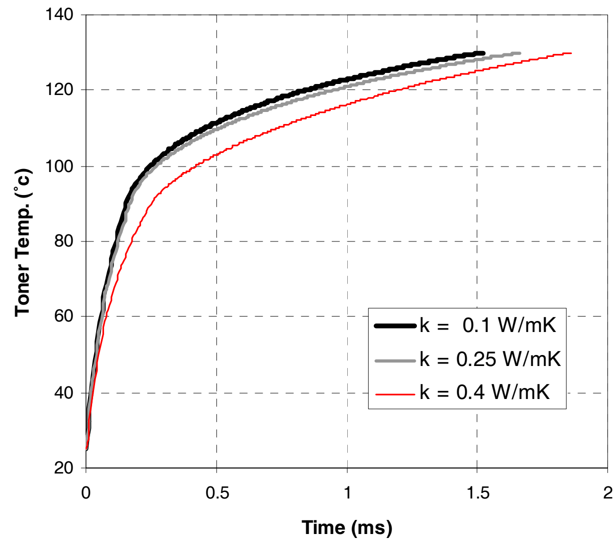

Figure 8 *Effect of thermal conductivity of paper coating layer.*

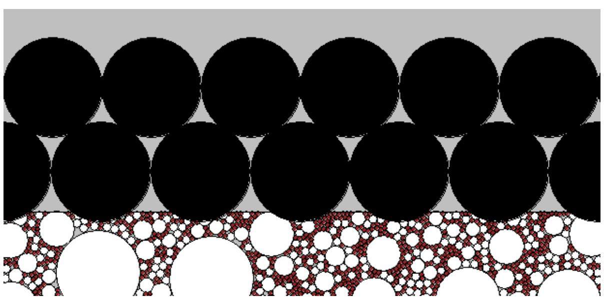

Figure 7. Illustration of a double toner layer.

Coating thermal properties

Thermal diffusivity of coating layer can affect the rate of heat absorption form the toner particles. The larger the thermal diffusivity, the lower the toner/coating interface temperature. Fig. 8 shows the temperature variation of toners for three different thermal conductivities.

Thermal conductivity of coating layer decreases with porosity and increases with latex content. Moreover, stiffness of coating layers below the critical latex concentration increases with latex content. As a result, the effective heat transfer area between a toner particle and the coating layer decreases by increasing the latex content of coatings. On the other hand, latex content of coating layer is likely to undergo a phase change which implies that the apparent specific heat of coating layer may dramatically increases at higher temperatures. Further study is needed to quantify the influence of latex content of paper coatings on the toner-coating interface temperature.

Toner melting energy

Toners require a significant amount of heat to reach liquid-like state. Almost 90% of the effective heat transfer time is used to melt the toners and only 10% of that is consumed to increase the toners temperature from 25 to 90˚C. As a result, toner melting energy has a noticeable effect on the performance of the fusing process. This effect is much greater for the larger toners; for instance, melting of toner (B) needs 8 times higher amount of energy than toner (A) does. Consequently, its melting time is much higher than toner A. The corresponding melting time of the two toners with three different melting energies are listed in table 3.

Table 3 Effect of melting energy on the required melting time

Melting energy	Toner A	Toner B
12 J/g	1.7 ms	5.6 ms
15 J/g	1.9 ms	6.3 ms
20 J/g	2.2 ms	7.8 ms

Fuser roll temperature

It is observed that the remaining heat transfer driving force at the upper limit of toner melting temperature (~ 120 - 130˚C) plays a significant roll on the toner melting time. Therefore, even with a 20˚C increase in the fusing temperature from 160 to 180 liquid-like phase can be obtained within a half amount of time that is required for fusing at 160˚C (Fig 9).

Toner thermal conductivity

Toner thermal conductivity is often between 0.1 and 0.25 W/m.K and along with the toner melting energy, it is considered to be the dominant parameter in the fusing process. Although higher toner conductivity leads to a higher heat loss to the coating layer, it can facilitate the overall rate of heat transfer, and therefore improve the rate of heating of toner particles (Fig. 10).

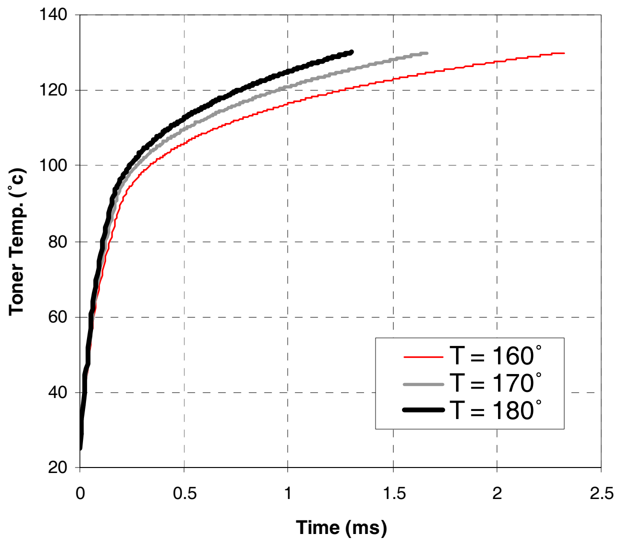

Figure 9. *Effect of fuser roll internal temperature*

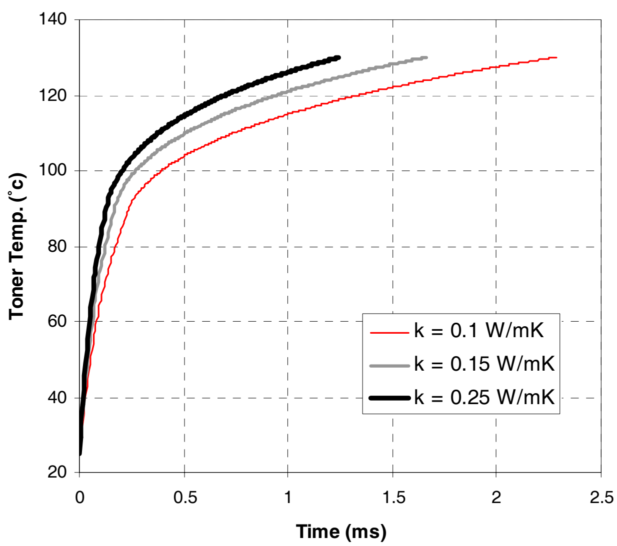

Figure 10. *Effect of toner conductivity on heat transfer to toners*

Conclusions

DEM is an effective tool for the modeling of the heat transfer process in the fusing process. Using this method, physical characteristics of toner, pigment and latex particles can be investigated. In addition, the effect of the structure of coating and toner layers, particularly the presence of void (i.e. air) among the toner and pigment particles is automatically taken into account. Simulation results show that toner size, toner melting energy and fusing roll temperature strongly affect the heat transfer rate while fusing pressure does not have any significant effect on the heat transfer process. Furthermore, it is observed that in contrast with toner conductivity, thermal conductivity of coating layer is inversely related to toner temperature elevation.

In fusing process, it is desirable to have a melted toner at the nip's pressure peak that occurs at the middle of the paper dwell time. Therefore, using large toners with a high melting energy may lead to some unfused area; particularly when toners are deposited on a rough surface, some of them only receive energy from the adjacent toners or the base paper and this issue causes some temperature non-uniformity in the toner film. Thus, the actual melting time of the toner film is likely to be slightly higher than the simulation results showed in this study.

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Author Biography

Pooya Azadi was born in Tehran, Iran, in 1983. He received his BS in Chemical Engineering from the University of Tehran in 2005 and since 2006, he has joined Pulp & Paper Centre at the University of Toronto. Currently, he is a master student working under the supervision of Prof. R. Farnood and Prof. N. Yan and his focus is on modeling of the micro-structures of paper coating layers, particularly their behaviors during Xerographic fusing and hot nip calendering.