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Discrete element modeling of the transient heat transfer and toner fusing process in the Xerographic printing of coated papers

Pooya Azadi[a], Ning Yan[b], Ramin Farnood[a,*]

[a] Department of Chemical Engineering and Applied Chemistry, University of Toronto, Toronto, Ontario, Canada
[b] Faculty of Forestry, University of Toronto, Toronto, Ontario, Canada

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ABSTRACT

In this study, a computer model based on discrete element method is employed to simulate the unsteady state heat transfer from the fuser roll to the toner and coating layer during the Xerography printing of coated papers. 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, toner thermal conductivity, coating layer thermal conductivity, and fuser roll temperature and pressure were investigated. Iso-thermal contours of fusing time were generated to demonstrate the relative importance of different fusing conditions and toner properties. Simulation results showed that temperature variation highly depended on the toner size, toner melting energy and the fuser roll temperature. Moreover, simultaneous coupling of the compressive stress and heat transfer indicated that the pressure exerted by the fuser roll did not significantly affect the rate of heat transfer.

1. Introduction

In recent years, with the emergence of high-speed Xerography printing presses for large volume commercial applications, a better understanding of heat transfer in the fuser nip has become increasingly important. Modern Xerographic presses are expected to produce hundreds of pages of high quality prints per minute on a large variety of substrates. In such applications, toner particles have to be fixed within milliseconds onto the paper substrates that could vary greatly in terms of grammage, thickness, and surface treatment. Therefore, improving our knowledge of the fusing process would help to improve printer design and print quality.

In Xerographic printing, toner particles are bonded to the substrate through the fusing process. The fuser is a key sub-system that strongly affects the print quality and the energy consumption of a Xerographic printer. In a hot roll fusing configuration, due to heating and pressure in the fuser nip, thermoplastic toner particles undergo a series of phase changes including softening, coalescence, melting and sintering, and thereby become fixed onto the paper (Schein, 1992).

Since the measurement of transient heat transfer in the fuser nip is rather challenging, theoretical modeling has often been used to study this process (Al-Rubaiey, Hartus, & Oittinen, 2002; Gane, Ridgway, Schoelkopf, & Bousfield, 2007; Hartus, 2001; Mitsuya & Hijikata, 1997; Mitsuya, Kumasaka, Fujiwara, & Nishino, 1991; Samei, Shimokawa, Takenouchi, & Kawakita, 1998; Samei, Takenouchi, Shimokawa, & Kawakita, 1998; Takenouchi, Samei, Shimokawa, & Kawakita, 1998). However, a review of literature shows that the existing models are either limited to uncoated papers or treat the coating layer as a continuum material. In reality, the porous and heterogeneous structure of paper coating is expected to have a significant influence on heat transfer and ultimately on the fusing process. Additionally, although coating layer deformation in the fuser nip is expected to be small (Azadi, Farnood, & Yan, 2008a,b), deformation of toner particles and surface rearrangements of the coating components may increase the contact area between the coating layer and toner particles and hence increase the rate of heat transfer. However, the effect of nip pressure on the transient heat transfer during the fusing process has not been investigated.

Discrete element method (DEM) is a numerical approach to simulate the behavior of systems that consist of a large number of particles. This method is computationally intensive; however, with advances in computer hardware in recent years, DEM is finding a wider application.

In Xerographic printing of coated papers, both the toner layer and the coating structure could be considered as many-particle systems, and therefore may be best studied using DEM. Paper coating is a porous structure composed of a large number of pigment particles. These particles are about 0.1–1.5 μm in size and glued

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* Corresponding author.
E-mail address: ramin.farnood@utoronto.ca (R. Farnood).

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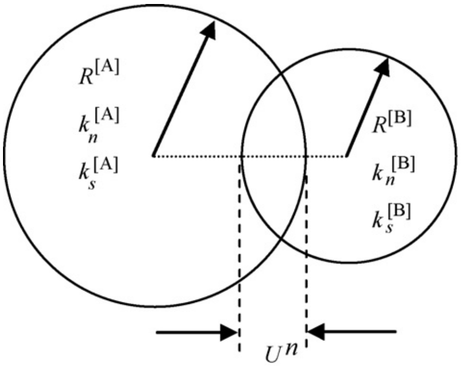

Fig. 1. Schematic illustration of soft contact between two particles with radii $R^{[A]}$ and $R^{[B]}$.

together and to the base paper by a polymeric material that is known as a binder. A typical binder that is widely used in the paper coating is latex. Latex is usually supplied as an aqueous emulsion of submicron particles (~0.1–0.3 μm) that during the drying process coalesce and bond pigment particles to each other and to the base paper. In addition, toner material used Xerographic printing is in the form of a powder with the average particle size of about 5–10 μm.

In this study, a computer model based on the discrete element method is employed to simulate the simultaneous effects of pressure and heat transfer in the fuser nip for the Xerographic printing of coated papers. The simulated coating layers consist of randomly arranged spherical pigment and latex particles with commercially relevant size distributions. Effects of toner size, toner arrangement, toner thermal conductivity, toner melting energy, fuser roll temperature and paper coating layer characteristics on the heat transfer will be discussed.

2. Theory

In the present study, a commercial 2D discrete element modeling software (PFC2D, Itasca) is used to study the heat transfer in the fusing process. This software is capable of modeling "the movement and interaction of assemblies of rigid circular particles" (Anonymous, 2004).

In this approach, toner, pigment and latex particles are modeled as circular objects that are randomly deposited within a prescribed two dimensional domain, representing the cross section of the toner and coating layers. Compared to 3D models, such a 2D model is less computationally demanding, allowing for a larger simulation domain. Moreover, although this 2D model provides an overly simplistic picture of particle–particle connectivity, assuming that coating layer is an ergodic stochastic structure, the toner heating time obtained from this model would be a good approximation for the 3D case.

Here, movements of toner, pigment and latex particles during compression in the fuser nip are simulated based on the linear contact theory and laws of motion. Details of the governing equations used in the simulation program may be found elsewhere (Anonymous, 2004); however, a brief description of some basic relationships is provided here.

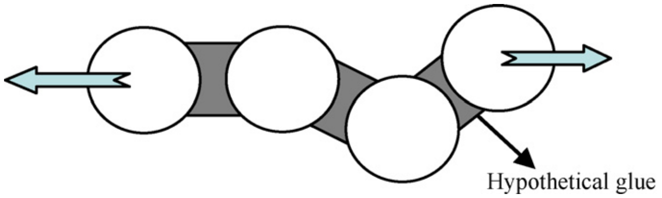

Fig. 2. Schematic illustration of particle–particle bonds.

Contact force arising between two particles can be decomposed into normal (F^n) and shear (F^s) components. Although these particles are considered to be rigid in their free states; adjacent particles are allowed to overlap at contact under a compressive force (soft contact), and the extent of overlap is related to the amount of force (Fig. 1). Based on the linear contact model, the normal contact force can be calculated from the extent of the particle–particle overlap, U^n:

$$F^n = K^n U^n \tag{1}$$

Here, K^n is the normal secant stiffness at the contact that may be found from:

$$K^n = \frac{k_A^n k_B^n}{k_A^n + k_B^n} \tag{2}$$

where k_A^n and k_B^n are the normal stiffness of particles A and B, respectively (Fig. 1).

As for the particle–particle shear forces during the compression of coating layer, the exact mechanism of this process is rather complex. In this study, a simplified approach is adopted where the shear contact force is assumed to increase proportional to the relative shear displacement at contact. Based on this assumption, the incremental increase in the shear contact force, ΔF^s, due to the shear displacement over a time step of Δt is calculated from (3):

$$\Delta F^s = -K^s V_s \, \Delta t \tag{3}$$

where V_s is the shear contact velocity, and K^s is shear tangent stiffness at contact that is determined from:

$$K^s = \frac{k_A^s k_B^s}{k_A^s + k_B^s} \tag{4}$$

where k_A^s and k_B^s are the shear stiffness of particles A and B, respectively. Therefore, the total shear contact force at time $t + \Delta t$ could be calculated from:

$$F^s(t + \Delta t) = F^s(t) + \Delta F^s \tag{5}$$

In order to introduce the tensile forces that may arise between the 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". The existence of a bond between two particles can also facilitate the rate of energy exchange between them. To model the bonding between latex–latex and latex–pigment particles, the "parallel bond" model is used (Anonymous, 2004).

The total force associated with a parallel bond (F_b) is resolved into normal and shear components with respect to the contact plane; i.e. F_b^n and F_b^s, and the incremental changes in the elastic normal and shear forces after time interval Δt are determined from:

$$\Delta F_b^n = -k_b^n A_b V_b^n \Delta t \tag{6}$$

$$\Delta F_b^s = -k_b^s A_b V_b^s \Delta t \tag{7}$$

where A_b is the parallel bond cross section, k_b^n and k_b^s the normal and shear stiffness of parallel bond, and V_b^n and V_b^s are the normal and shear components of the contact velocity. Further information regarding the governing equations of bonded particles may be found in Anonymous (2004).