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Considerations on the Level of Heat and Work Energy in the Nip Region for Toner Fusing*

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Abstract. *In 2000, the author and his team reported the effect of the energy from the heat and nip pressure supplied to the toner. They found that, in typical roll fusers, the fuse grade changes very little when the width of the nip is enlarged by reducing the hardness of the pressure roll's elastic layer without increasing the pressing load. This observation yielded a fuse grade contour in coordinates of heat supply and pressure from which the author could derive design concepts and procedures for basic specifications of roll fusers. This prior study, however, had some outstanding issues: especially in regard to fusing phenomena, the supplied heat is assumed to be equal to the thermal energy used for fusing. However, the absorbed or latent heat should be examined, and rheology should be taken into consideration when this heat is to be compared with the work due to the nip pressure. This article reviews and reconsiders the situation presented in the prior study. It provides a solution describing the roles and effects of thermal energy and work due to nip pressure during toner fusing.* ©*2012 Society for Imaging Science and Technology.*
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INTRODUCTION

Fusing in electrophotography involves supplying energy to the toner by applying heat and work to the nip region. This work is referred to as "work due to nip pressure" in this article. Knowledge of its quantitative effects is important for designing electrophotographic fusers. That is, clarifying the phenomena involved will be very important for making progress in fusing technology.

A few reports have discussed toner fusing from the viewpoint of energy supply.[1–7] In particular, one of the previous studies determined a relationship between the supplied heat and the nip pressure[1], and applied it to the design of a heat roll fuser. However, the physical phenomena involved in melting and fixing the toner are seldom mentioned in the cited references. Previous studies assumed that the total energy of heat and work due to nip pressure in the nip region determines the fuse grade. A coefficient for converting from supplied heat to net heat, k, was defined in order to derive an effective thermal energy for melting and fixing the toner, since the energy level of the heat supply is very high compared with the work due to nip pressure. However, the value of this energy is quite small, and its definition has yet to be justified. That is, in the absence of a precise physical model for toner melting and fixing, we do not actually know the thermal absorption process in the toner. Fortunately, other literature[2] provides data, from which thermal absorption during toner melting can be derived.

In this study, we review the first study[1] and use the second study[2] to derive a thermal absorption model. After that, we calculate the work due to nip pressure and arrive at a precise physical interpretation of these energy consumption mechanisms.

Providing a complete solution for the energy consumption mechanisms during toner melting and fixing is hard. However, the considerations presented in this study should be of value because the author has placed a premium on an order estimation, instead of rigorous quantitative results and fittings, as the main principle for resolving these issues.

Fuser system

The fuser system fixes the toner on the paper in an electrophotographic process. There are mainly two types of fuser system. One is non-contact fusing, in which heat is supplied to the toner by radiation or other non-contact energy. The other is contact fusing, in which heat and pressure are supplied to the toner. Flash fusing with xenon flashlights is a typical non-contact fusing system, and heat roll fusing is a typical contact fusing system. Although the two may have different energy consumption mechanisms, we shall consider only the heat roll fuser in this study.

Figure 1 shows a schematic diagram of a typical heat roll fuser. The most important feature is obtaining a sufficient fuse grade while satisfying several important requirements. The system is mainly composed of heat and pressure rolls. The heat roll and the pressure roll are pressed against each other and rotated. A nip region is formed between the two rolls. The nip region is formed by elastic deformation of the pressure roll by using a pressing load. Toner is heated and pressed in the nip region along with the paper and then fixed on the paper. The circumferential length, transit time, and pressure of the nip region are called the nip width, dwell time, and nip pressure, respectively. The dwell time is normally several milliseconds to several tens of milliseconds in order to obtain a sufficient thermal energy supply to the toner

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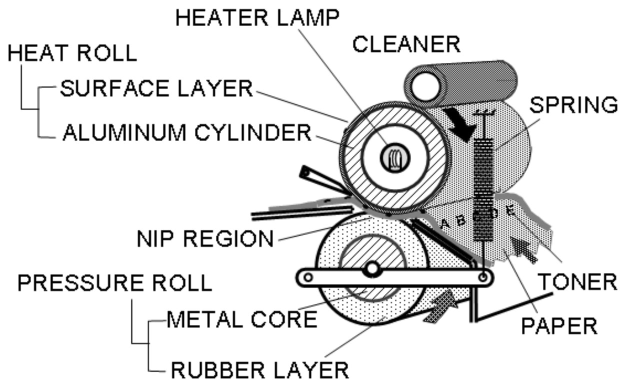

Figure 1. Heat roll fuser.

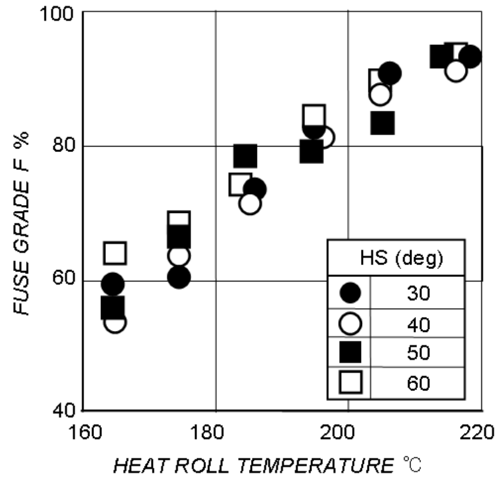

Figure 2. Fuse grade with rubber hardness.

with a high-temperature (130°C or higher) heat roll. The nip pressure for applying work to the toner is normally set at 5–50 N/cm^2. The heat roll has a thin surface layer made of fluoride resin on the outer surface of an aluminum cylinder for preventing toner offset. Offset is displacement of the toner from the paper to the heat roll surface during the dwell time. This causes print quality and reliability problems. The surface layer behaves as a thermal resistance in the nip region. Therefore, the surface layer thickness is often set to be around 20–40 μm. The pressure roll has an elastic layer, normally made of silicone rubber, on the outer surface of a metal core for forming the nip region. A small amount of offset toner is generated even though a fluoride surface layer is formed on the heat roll. Therefore, an offset toner cleaner is often installed on the heat roll.

REVIEW OF THE PREVIOUS STUDY

Mitsuya et al.[1] presented a remarkable report on this subject. Their report discusses the energy distribution between heat and work due to nip pressure.

Figure 2 shows the tested relationships between fuse grade, F, and heat roll temperature with the hardness of the pressure roll elastic layer. The fuse grade, F, is measured with an adhesive tape peeling test. The loads for pressing the heat and the pressure rolls are the same for all conditions. The heat and pressure balance varies with the elastic layer hardness. The thermal energy supply becomes smaller, and the work due to nip pressure increases under high pressure roll conditions, since a harder pressure roll makes the nip width narrower; thus, the heating period (the dwell time) becomes shorter and the pressure (force per unit area) becomes higher. However, the fuse grade does not change when the elastic layer hardness is varied. Therefore, the previous study considered that the total energy imparted to the toner by heat and pressing must be constant.

The net heat for melting a unit area, Q, is

$$Q = k \int_0^T \dot{q}\,\mathrm{d}t. \tag{1}$$

Here, the heat flux to toner, the dwell time, the transit time after the nip region inlet, and the coefficient for converting from the heat supplied to the net heat for melting are denoted as $\dot{q}$, T, t, and k, respectively. The heat for melting can be represented as the heat supply, Q/k, assuming that the coefficient, k, is constant.

The work due to nip pressure per unit area for a toner deformation, W, is

$$W = P \cdot \delta L. \tag{2}$$

Here, toner deformation and nip pressure are denoted as δL and P. The work due to nip pressure can be represented by the nip pressure, P, since the toner deformation, δL, within the same fuse grade level is considered to be constant.

Figure 3 plots the relationship between the heat supply, Q/k, which represents the heat for melting, and the nip pressure, P, which represents the work due to nip pressure. The curve satisfies the relationship shown in Fig. 2, which means that the total energy of heat and work due to nip pressure is constant even when the balance between heat and work changes. The plotted values are calculated from the conditions in which the elastic layer hardness varies. The fuse grade is the same at any point on the curve.

Some fuser specifications can be derived from this fuse grade contour line. Table I shows two examples of fuser. A is for high-speed fusing, and B is for low-speed fusing. The energy balances of fusers A and B correspond to points A and B in Fig. 3, respectively.

CONSIDERATIONS ON THE ENERGY SUPPLIED TO THE TONER

The previous study derived a relationship between the supplied heat and the nip pressure for the fuse grade to be constant.[1] It also applied its findings to a heat roll fuser design. However, the physical phenomena involved in toner melting and fixing are not well known. To make progress from the previous study, the following issues should be examined.

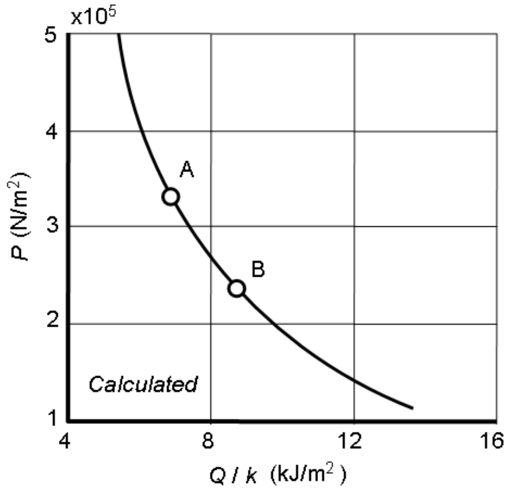

Figure 3. Contour diagrams of fusing energy.

Table I. Specifications of fuser. (Note: HR: Heat roll; BR: Back-up roll (pressure roll); SL: Surface layer; HS: Rubber hardness; *t*: Thickness.)

	Point A	Point B
Nip width	10 mm	7 mm
Nip period	14 ms	25 ms
HR/BR load	3.3 N/mm	1.8 N/mm
HR/BR diameter	86 mm	46 mm
HR temperature	190°C	170°C
HR SL	*t* 20 mm	*t* 40 mm
BR hardness	HS 50 Degree	30 Degree
BR rubber	*t* 10 mm	*t* 6 mm

1. The previous study assumed that the total energy of heat and work due to nip pressure in the nip region determines the fuse grade. However, toner fusing was not physically modeled.
2. The coefficient converting from supplied heat to net heat for toner melting, k, is defined for the purpose of deriving an effective thermal energy for toner melting and fixing since the energy of the heat supply is much higher than the work due to nip pressure. Moreover, the coefficient, k, is assumed to be constant and quite small. The definition lacks a solid ground because the previous study did not do a precise physical modeling of thermal absorption in the toner or of melting and fixing.

Providing a complete solution to these problems is hard. Our attempt to address them in this study places a premium on the order estimation rather than on rigorous quantitative results and fittings.

PHYSICAL MODEL OF TONER FUSING

It is well known that melt toner shows viscoelastic behavior. Figure 4 shows a fusing model, which is from a four-element model describing viscoelastic deformation in the rheology field. The Maxwell and Voigt models are basic models of viscoelastic deformation. The four-element model combines the Maxwell and Voigt models and is applicable to viscoelastic deformation.

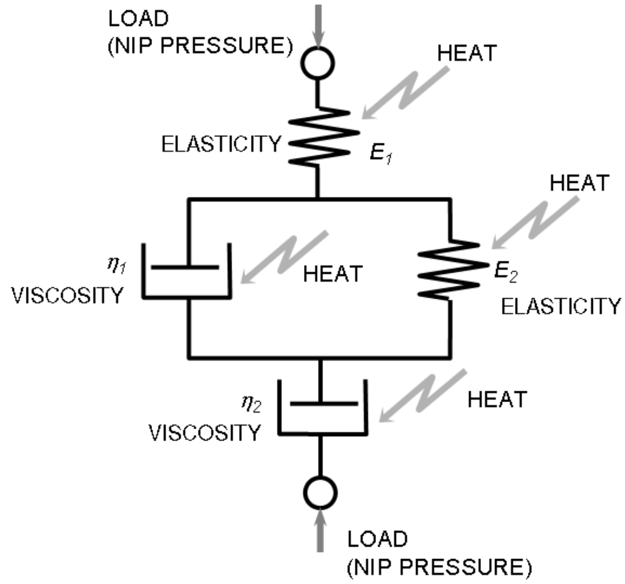

Figure 4. Toner fusing model.

The heat supply, which affects the dashpots and springs, is included in this model. The dashpots correspond to viscosity, and the springs to elasticity. This means that the thermal energy affects the toner melt properties and makes it soften. Note that the thermal energy is not the supplied heat, but the heat absorbed in the toner. Problem No. 2 listed above is that the supplied heat was used in evaluating thermal energy for fusing in the previous study.[1] The absorbed heat and the work due to nip pressure are examined in the next section.

A load for pressing is applied to the top and bottom terminals. The work due to nip pressure is derived from the product of the force per unit area (P) and the deformed distance (δL).

From this model, it is clear that fusing consists of two functions. One is property softening by thermal absorption. The other is deformation by the pressing force. In this article, the former function is called melting, and the latter function is called deformation. If only thermal absorption occurs, the fusing is not complete, because the work due to nip pressure is necessary for its deformation at the same time, even though the toner can melt from the thermal absorption.

ENERGY LEVELS OF SUPPLIED HEAT, NET THERMAL ABSORPTION FOR MELTING, AND WORK DUE TO NIP PRESSURE FOR DEFORMATION

In this section, the energy levels at point A in Fig. 3, which is for higher-speed fusing, are estimated as an example.

From point A in Fig. 3, the heat supplied per unit area, Q_{sa}, is 6.8×10^3 (J/m^2). Figure 5 shows the change in enthalpy with temperature of the toner, as published

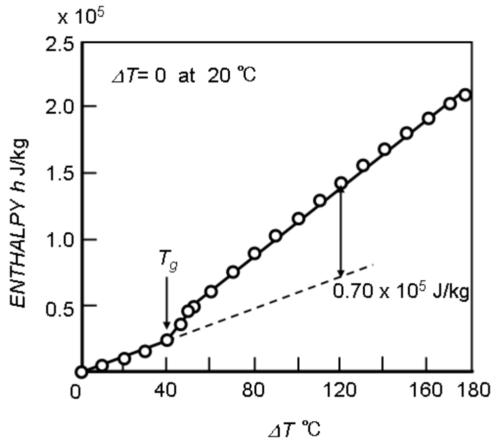

Figure 5. Data for toner enthalpy change.

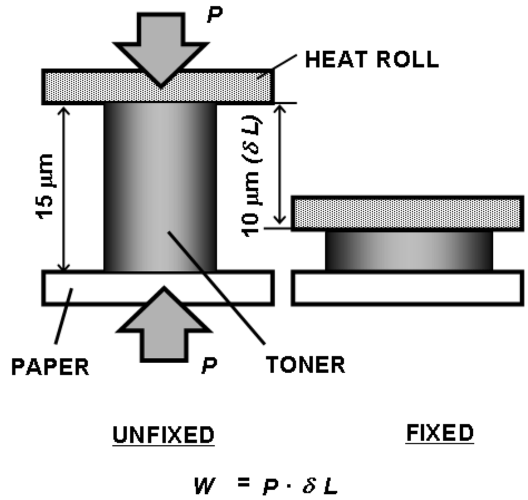

Figure 6. Model for estimation of work by nip pressure.

in the Japanese literature.[2] In this article, this data will be used to make an order estimation of the toner's thermal absorbed energy level. T_g in Fig. 5 means the glass transition temperature of the toner. The toner melts at a higher temperature than T_g. A dashed line above T_g means an enthalpy without melting, because it is an extrapolation based on solid-state toner below T_g. Therefore, the difference between enthalpy with melting (solid line) and without melting (dashed line) above T_g, indicates the heat absorbed during melting. Another article[3] calculated the temperature of the interface between the toner and paper at the end of the nip region, and it is around 135°C, given a heat roll temperature of 190°C and dwell time of 15 ms. Deriving a rigorous average temperature in the toner layer during the dwell time is challenging, since the temperature distribution in the toner layer is complex, due to an unsteady and nonlinear temperature field. Moreover, a rigorously determined average temperature is not significant to this study. The above-mentioned results can be used to calculate the time and space averaged temperature during the dwell time in the toner layer as 140°C. In Fig. 5, assuming 20°C for room temperature, the ΔT value between it and the 140°C of the toner temperature is 120°C. From the data in the figure, the absorbed heat per unit mass of melting toner, Q_{am}, is 0.70×10^5 (J/kg) at a ΔT of 120°C. Assuming that the toner fused solid layer thickness on paper is 5 μm and that the toner density is 1.1 (g/cm^3), a unit mass of toner covers $A_t = 1.8 \times 10^2$ (m^2/kg). Therefore, the absorbed heat of a unit area of melting toner, Q_{aa}, can be derived as

$$Q_{aa} = Q_{am} \cdot A_t. \tag{3}$$

Substituting 0.70×10^5 (J/kg) and 1.8×10^2 (m^2/kg) into Q_{am} and A_t in Eq. (3), we get an absorbed heat of melting of $Q_{aa} = 3.9 \times 10^2$ (J/m^2).

There is quite a large difference between the absorbed heat of melting, Q_{aa}, and the heat supplied, Q_{sa}, and their ratio, i.e.,

$$R = Q_{aa}/Q_{sa} \tag{4}$$

is 5.7×10^{-2} for $Q_{aa} = 3.9 \times 10^2$ (J/m^2) and $Q_{sa} = 6.8 \times 10^3$ (J/m^2).

The absorbed heat of melting, Q_{aa}, is thus only 5.7(%) of the heat supplied, Q_{sa}. This means that most of the thermal energy supplied to the toner is not used for melting. The heat goes through the toner and into the paper.

Figure 6 shows a model for deriving the work due to nip pressure. Work can be derived from the applied force and deformed distance. The work due to nip pressure for fixing is the product of the force (P in unit area) and deformed distance (δL). The deformed distance can be estimated from the toner heights before and after fixing. Another article gives 15 μm for the unfixed toner height.[8] Assuming a fixed toner height of 5 μm, the deformed distance, i.e., the difference between the unfixed and fixed states, is 10 μm. Point A of Fig. 3 gives a nip pressure, P, of 3.3×10^5 (N/m^2). The nip pressure is a force per unit area. Thus, the work due to nip pressure, W, can be derived by multiplying the force, P ($=3.3 \times 10^5$ N/m^2), and deformed distance, δL ($=10 \times 10^{-6}$ m), as shown in Eq. (2). W turns out to be 3.3 Nm/m^2. The work due to nip pressure is thus only 0.85(%) of the absorbed heat (Q_{aa}: 3.9×10^2 (J/m^2)).

Compared with the absorbed heat of melting, the work due to nip pressure is quite small. This means that the functions of heating and pressing are different. In the prior study, the author supposed that the total energy of heat and work due to nip pressure determined the fusing[1]. However, this hypothesis should be revised; the two types of energy should be evaluated separately.

This study examined how the supplied heat, absorbed heat, and work due to nip pressure are involved in a typical case of toner fusing. It did not clarify how these quantities are related under extreme heat and pressure conditions. Moreover, the limitations of the clarified relationships are not known yet. These issues should be examined in the future.

CONCLUSIONS

The prior Japanese study[1] on energy in fusing was reviewed, and the thermal absorption and the work due to nip pressure were calculated. A model including the absorbed heat and work due to nip pressure was examined, and a precise physical interpretation for the two energy consumption mechanisms was given. The following findings were revealed.

(1) The energy order levels of the heat supply, thermal absorption, and work due to nip pressure were clarified. The heat absorbed by the melting toner is much smaller than the supplied heat, and the work due to nip pressure is much smaller than the absorbed heat.

(2) It is supposed that the heating and nip pressure do not contribute in the same way to toner melting and fixing. That is, the total energy of the heat and the work due to nip pressure cannot determine the dynamics of fusing. Therefore, these quantities should be evaluated separately.

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