Theory of Ink Transfer in HP-Indigo Digital Press Machines

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Abstract

In the digital press machines developed and manufactured by HP Indigo Division the world leader in the field, the ink is transferred from roller to roller and finally from roller to the substrate. A fundamental demand to digital printing is that each page can be different from the previous one. This requires 100% transfer efficiency, i.e. no ink should be left behind.

In the previous NIP conference a model for the electrically driven transfer from the photoconductor roller to the intermediate transfer member roller (ITM drum) was presented [1]. This year we treat the transfer from the ITM drum to the substrate. Rather than providing an exact model, the aim here has been delivering a simple theory that is capable of pointing out general trends and the main parameters leading to perfect transfer.

It will be shown that only ink possessing elastic properties can lead to 100% transfer. Based on this, the ink sandwiched between the ITM drum and the substrate is approximated as real elastic solid having rough surface. The model leads to the conclusions that the main factors governing transfer efficiency are the elastic modulus of the ink and the surfaces of the ITM drum and the substrate. The ink will adhere to that surface where the composite modulus of the surface and the ink is substantially larger. Other parameters influencing transfer are surface energy and roughness. Since elastic modulus varies from material to material by several orders of magnitude and strongly depends on temperature while the range of surface energy and roughness is much more limited, it is natural to control ink transfer through properly selecting the surface modulus of the ITM drum and the temperature dependence of the modulus of the ink.

Finally, it will be shown that HP Indigo's unique ElectroInk and ITM drum ideally fulfill the requirements pinpointed by the theory and ensure 100% ink transfer to the substrate.

Introduction

In press processes ink is permanently being transferred from cylinder to cylinder. Figure 1 schematically shows the ink transfers in HP Indigo Division Digital Press. The cylinders themselves are covered by various materials, e.g. metal, rubbers, photoconductor, substrates etc.

Problem statement:

The questions that naturally arise are:

- What is the reason(s) that ink gets separated from one of the cylinders and attaches to the other?
- When does the ink split between the two cylinders; what is the ratio of the amount of the ink following each cylinder?
- What are the physical parameters that govern this process? Which of these parameters are the dominant ones?

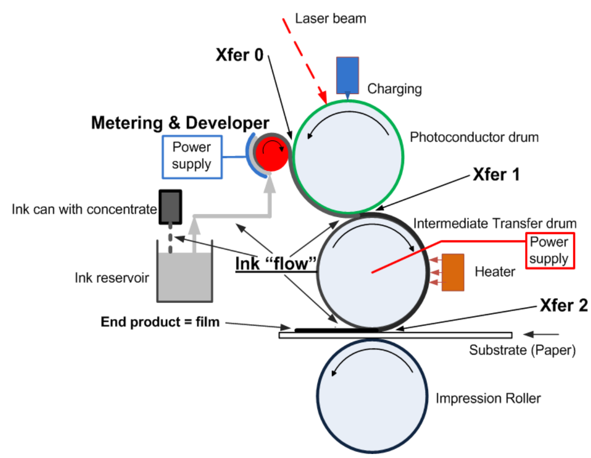

Figure 1: Ink transfer in HP Indigo Division Digital Press (Schematic).

The purpose of this paper is to answer the above questions. The problem of ink transfer has been addressed by many investigators [2, 3, 4]. These papers however do not exactly fit to the case of Indigo technology where the requirement to 100% transfer is essential. In the previous NIP conference a model for the electrically driven transfer from the photoconductor roller to the intermediate transfer member roller (ITM drum – Xfer 1) was presented [1]. In the present paper the transfer from the ITM drum to the substrate (Xfer 2) will be dealt with. Rather than providing an exact model, the aim here has been delivering a simple theory that is capable of pointing out general trends and the main parameters leading to perfect transfer.

Theory

Transfer scenarios

Transfer from cylinder to cylinder while having common elements is also somewhat different from the usual coating scenarios. Before the nip the to-be-transferred material has already been adhered to one of the cylinders and entering the nip adhesion is made to the second cylinder. Inside the nip the physical properties of the to-be-transferred material are going to be modified, as will be shown here, the most important change being made to the mechanical modulus across the to-be-transferred material perpendicular to the process direction. After the nip the distance between the cylinders surfaces increases. The to-be-transferred material having been adhered to both surfaces will be subjected to a gradually increasing extension force perpendicular to the direction of main movement. When this force exceeds the cohesive strength of the to-be-transferred material the material will be divided into two or, alternatively, if one of the adhesive strengths acting at the contact sides is less than the cohesive strength of the material detachment will occur from that cylinder's surface where the adhesive strength proved to be smaller.

At the very beginning it has to be noted that transfer occurs not in the nip between two cylinders involved in the process but after the ink leaves the nip where the distance between the surfaces increases. This is a consequence of the fact that in the nip the ink moves between two more or less parallel walls therefore the question of where to go simply does not arise.

It also has to be realized that material possessing zero viscosity cannot be transferred from one cylinder to a contacting other one. The liquid will simply be held back in the nip by capillary forces.

For "pulling" out the liquid from the nip the liquid has to have finite viscosity. Moderately viscous liquids however will not provide full (100%) transfer. These fluids adhering to both of the bounding walls (in this case to the surfaces of the cylinders) will go in both directions with the cylinders i.e. will split after leaving the nip.

In case of high viscosity the shear stress on the walls may be so high that detachment will take place, i.e. the fluid will slip on the wall. This is however not a stable process; upon slipping the shear stress falls to zero and the liquid adheres again to the walls.

In Indigo technology (Figure 1) the transfer should be stable and, in most cases, E.g. Xfer1 and Xfer2, 100% to the second cylinder (in other words zero percent of ink is allowed to stay behind on the first cylinder). In a previous paper Xfer1 was treated [1]. Here we concentrate on Xfer2. 100% transfer requires that the ink has to have large enough cohesive forces for avoiding splitting and achieving separation from the first cylinder. For this to occur the necessary condition is that the ink has to able to develop elastic forces when being pulled in direction perpendicular to the direction of rotation of the cylinders. In other words the ink has to behave as viscoelastic body. Indeed, rheological measurements have been demonstrated that ElectroInk behaves as a viscoelastic solid body rather than viscous fluid [1]. Consequently, it is a better way to describe the transfer as a process in which three (viscoelastic) solids are involved than the way usually employed by theories dealing with coating processes that treat the media being transferred (i.e. the coating material) as viscous liquid.

The transfer is modeled in the following way: A body (1, the ink) is sandwiched between two other bodies (2 & 3, the cylinders surfaces). Bodies 2 & 3 start being pulled away from each other. The question is: Where does body 1 go?

When bodies 2 and 3 are departing from each other a force common across all three bodies arises. Depending on where is the weakest bond and supposing that it is not inside bodies 2 and 3, the following cases are possible:

A. Rupture inside body 1 – cohesive failure and splitting of body 1
B. Detachment between body 1 and 2 – adhesive failure between body 1 and 2
C. Detachment between body 1 and 3 – adhesive failure between body 1 and 3

If prior to the separation of bodies 2 and 3 body 1 was attached only to body 2 and body 3 came only later into contact with body 1, case B relates to transfer of body 1 from body 2 to body 3. The realization of this case is of interest for Indigo technology. Case 1 can be avoided if body 1 has large enough elasticity [4]. Thus for solving the problem of transfer the process of adhesion and separation of solid bodies has to be analyzed. An approximate mathematical treatment of this problem will be given here. From this analysis it will follow that the separation force will be smaller i.e. the sandwiched body will go the direction where the composite modulus of the contacting bodies is smaller.

Adhesion and separation of solid bodies

Solid bodies never have perfectly smooth surfaces; they have asperities on the surface. Solid bodies will therefore contact each other through asperities. Since surface energy usually decreases when a surface faces condensed matter rather than air, the asperities will deform creating contact area between the contacting bodies. The decrease of surface energy ensures the adhesion.

Upon separation the contact area on top of the asperities has to be reduced to zero. This will involve the deformation of the asperities back to their original shape. If the asperities have the same modulus that they had during adhesion the force necessary for separation will be just the force of work increasing the surface energy back to the state of solid surface – air contacts.

If, however, the modulus of the asperities for some reason is higher than it was during the adhesion process a higher force will be needed to deform the asperities back to their original shape. Consequently the force necessary for separation will be larger.

The tip of the asperities will be approximated as elastic spheres. According to Hertz analysis [5] the force necessary to create contact area of radius **a** between two elastic spheres is

$$\mathbf{F = (4/3)\, E^*\, a^3 / r^*_{mean}} \qquad \text{Eq. 1}$$

Where **E*** refers to as the composite modulus defined as

$$\mathbf{1/E^* = (1 - \nu_1)/E_1 + (1 - \nu_2)/E_2} \qquad \text{Eq. 2}$$

The indices 1 and 2 refer to the two spheres and ν denotes Poisson's ratio. It is important to note that the composite modulus is always smaller than the smallest of $\mathbf{E_1}$ and $\mathbf{E_2}$.

$\mathbf{r^*_{mean}}$ refers to as the composite radius of the spheres and is defined as

$$\mathbf{1/ r^*_{mean} = 1/r_1 + 1/r_2} \qquad \text{Eq. 3}$$

$\mathbf{r_1}$ and $\mathbf{r_2}$ being the radii of the spheres.

Thus the actual force depends on the moduli and radii of both spheres.

The displacement of the top of the spheres (the deformation) equals

$$\delta = a^2 / r^*_{mean} \qquad \text{Eq. 4}$$

The energy of elastic deformation stored in the deformation of contacting spheres will be

$$U_{el} = (8/15)\, E^*\, r^{*\,1/2}_{mean}\, \delta^{5/2} \qquad \text{Eq. 5}$$

Upon the asperities contacting each other the decrease of the surface energy will be accompanied by the increase of the elastic energy stored in deformation of the asperities. The two bodies will approach each other until the sum of these two energies reaches minimum. The loss in free surface energy U_s is given by [6]

$$U_s = -\pi a^2 \Delta\gamma \qquad \text{Eq. 6}$$

$\Delta\gamma$ is the energy of adhesion per unit area defined as

$$\Delta\gamma = \gamma_1 + \gamma_2 - \gamma_{12} \qquad \text{Eq. 7}$$

Where γ_1 and γ_2 are the surface energies of bodies 1 and 2 respectively when they face air and γ_{12} is the surface energy per unit area when bodies 1 and 2 are in infinitely intimate contact.

The total energy of the contact per asperity couple is

$$U_{tot} = U_s + U_{el}$$

$$= -\pi\, r^*_{mean}\, \Delta\gamma\, \delta + (8/15)\, E^*\, r^{*\,1/2}_{mean}\, \delta^{5/2} \qquad \text{Eq. 8}$$

Derivation by δ gives the force acting between the spheres

$$F = -U_{tot}/d\delta = \pi\, r^*_{mean}\, \Delta\gamma - (4/3)\, E^*\, r^{*\,1/2}_{mean}\, \delta^{3/2} \qquad \text{Eq. 9}$$

The maximum force equals to [6]

$$F_{ad} = \pi\, r^*_{mean}\, \Delta\gamma_{ad} \qquad \text{Eq. 10}$$

Here the subscript $_{ad}$ stands for adhesion and the formula gives the force necessary to pull apart the asperities.

Note: Johnson et al [7] (JKR analysis) introduced a coefficient of 1.5 in the above formula while Derjaguin et al [8] (DMT analysis) gave the formula with a coefficient of 2. For our purpose, however, namely searching trends, the exact value of the coefficient is not important. We deliberate therefore ourselves from the tedious task of chasing exact mathematical analysis of deformation.

The maximum deformation can be obtained from the minimum of the total energy

$$\delta = [(3/4)\, \pi\, r^{*\,1/2}_{mean}\, \Delta\gamma_{ad} / E^*_{ad}]^{2/3} \qquad \text{Eq. 11}$$

Upon separating the spheres δ and a have to be reduced to zero. The work that has to be done for this is

$$W = \pi\, r^*_{mean}\, \Delta\gamma_{sep}\, \delta - (8/15)\, E^*_{ad}\, r^{*\,1/2}_{mean}\, \delta^{5/2}$$

$$+ (8/15)\, E^*_{sep}\, r^{*\,1/2}_{mean}\, \delta^{5/2} \qquad \text{Eq. 12}$$

Where the subscript "sep" relates to separation since both the surface energy and the modulus may differ from the values they had during adhesion (say because of change in temperature or as a result of chemical or other physical changes).

By derivation of Eq. 12 and taking use of Eq. 11 we get the force necessary for separating the two bodies:

$$F_{sep} = \pi\, r^*_{mean}\, [\Delta\gamma_{sep} + \Delta\gamma_{ad}\, (E^*_{sep} - E^*_{ad}) / E^*_{ad}] \qquad \text{Eq. 13}$$

Comparing with Eq. 10 one can see that the surface energy is quasi increased by the factor $\Delta\gamma_{ad}\, (E^*_{sep} - E^*_{ad}) / E^*_{ad}$. Thus the stress necessary for separation may be increased either by increasing the energy of surface interaction (say as a result of chemical reaction) or by increasing the composite modulus relative to the value it had during the adhesion process (e.g. because some hardening process).

Following Greenwood [9] we approximate the number of contacts in unit area as

$$n = [2^{3/2} / (\pi\, r^*_{mean}\, R_q^3)]^{1/2}\, p / E^*_{ad} \qquad \text{Eq. 14}$$

Where R_q is the r.m.s. composite roughness of the surfaces ($R_q^2 = R_{q1}^2 + R_{q2}^2$) and p is the contact pressure.

Finally the stress necessary for separating the two bodies can be obtained by multiplying equations. 13 and 14:

$$\sigma_{sep} = (2^{3/2}\, \pi\, r^*_{mean} / R_q^3)^{1/2}\, (p / E^*_{ad})$$

$$\times [\Delta\gamma_{sep} + \Delta\gamma_{ad}\, (E^*_{sep} - E^*_{ad}) / E^*_{ad}] \qquad \text{Eq. 15}$$

Discussion

According to Eq. 15, the stress necessary for separating the two bodies depends on the following parameters:

- The composite roughness of the contacting surfaces
- Radius of the asperities
- The load pushing the surfaces together during the adhesion step
- The change of surface energy during the adhesion step
- The change of surface energy during the separation step
- The composite modulus of the bodies during the adhesion step
- The composite modulus of the bodies during the separation step

The weights of the material parameters in controlling separation can be estimated as follows:

- Surface energy of organic substances varies in a relatively narrow range; the ratio of the maximum possible value to the minimum possible value does not exceed 5.
- The variation of surface roughness is estimated to range from 0.05 to 5 micrometer which because of the 3/2 power may change the stress by 3 order of magnitude.
- The moduli can easily be changed by as much as 3 or more orders of magnitude.

Therefore, the major parameters through which the separation stress can be controlled are the roughness and the composite modulus of the involved bodies. The roughness of the substrate is usually given. Actually the modulus is the most readily controllable parameter since it exponentially varies with temperature and solvent content. This way is employed in Indigo technology.

Application of the theory to Indigo process

Equation 15 shows that the adhesion increases with increasing composite modulus upon separation and decreasing modulus upon contacting (i.e. upon application of the adhesive material to the surface). Therefore the ink will adhere to that surface where the composite modulus of the surface and the ink is substantially larger. Accordingly, when exiting the nip the composite modulus of the ink and the substrate has to be larger than the composite modulus of the ink – ITM drum couple. This is achieved by

1) Covering the ITM drum with material of low elastic modulus which is independent of the temperature and

2) Heating the ITM drum while the substrate remains cool.

The ink arriving at the nip on the hot ITM is soft providing low $\mathbf{E^*_{cont}}$ with the substrate. In the nip the ink contacting the cold substrate cools down and its modulus increases leading after the nip to **E(ITM) < E(Ink) < E(Substrate).** Since the composite modulus is always less than the smaller between the two modulus, $\mathbf{E^*_{sep}}$ on the ITM side is less than on the substrate side. Rheological measurements have shown that during cooling from the ITM temperature to temperature of the substrate the modulus of the ink increases by three orders of magnitude (Figure 2). It is more than enough to compensate the possible influence of the surface roughness and surface energy that may be different on the ITM side and the substrate side, therefore the adhesion force between the ink and the substrate is larger than between the ink and the ITM and the ink will leave the nip with the substrate.

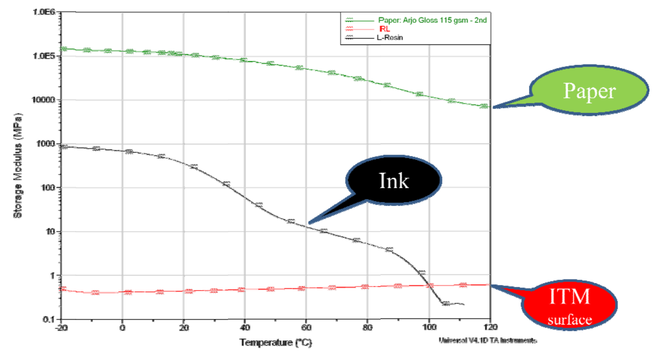

Figure 2: Variation of modulus with temperature. Measurements carried out with a TA Instruments Q-800 Dynamic Mechanical Analyzer.

Conclusions

It has been shown that for 100% ink transfer

- The ink has to possess the properties of an elastic solid body.
- The major parameters through which the separation stress can be controlled are the roughness and the composite modulus of the involved bodies.
- The necessary conditions for stable 100% second transfer are:
  - Good ink:
  - Small elastic modulus (high compliance) at high temperature and
  - Large elastic modulus (high cohesion) at low temperature,
- Good Intermediate Transfer Drum surface: Low elastic modulus both at high and low temperatures.

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Author Biography

Peter Forgacs (peter.forgacs@hp.com) has earned his PhD degree in physics from the Eotvos Science University, Budapest, Hungary in 1978 and undertook a post-doctoral training in the Polymer Research Institute at the University of Massachusetts in1982-1984. In 1989 he joined Hewlett-Packard Indigo Division, Israel, at that time Indigo Co., for managing the Laboratory of Physical Properties in the R&D Materials Science Section. His main topics of interest are rheology, adhesion, tribology, measuring techniques and surface characterization of solids.

5