Transfuse Mechanisms

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Abstract

The transfuse process combines transfer and fusing of toner images to the final substrate into a single step. This paper studies interfacial separation and cohesive failure based on: thermodynamic work of adhesion, filament detachment and crack propagation. It provides an understanding of the transfuse process and guidelines for choosing proper material properties for transfuse. A good transfuse process needs a high transfer efficiency of toned images from the donor surface to the receiver surface and a high fix level of transferred images onto the receiver. Criteria for good transfuse are derived to relate surface energies, interaction parameters and surface contact factors. Other criteria based on filament detachment and crack propagation are also presented. The derived transfuse criteria compare favorably with observation in practical applications. The mechanisms studied here are also applicable to the roll fusing process and offset printing.

Introduction

There are increasing interests in transfuse process for both dry powder and liquid toner imaging systems. In these systems, it is known to heat the toner images on the intermediate transfer members before transfuse to the final receiver substrate. The goal is to completely transfer the toned images from the donor surface to the receiver surface (typically paper) and fuse the images onto it, Figure 1. Both image transfer efficiency and fix level depend on materials properties, temperature, pressure and strain energy.

If the donor surface has high release properties, the transfer efficiency will normally be high. The surface with low surface energy usually possesses high release properties. To ensure good transfuse, it also needs good contact between the toner and the receiver. A good contact is typically achieved by heat, pressure and having proper materials properties. Once toners and the paper are in good contact, higher temperature will enhance the toner flowing onto paper fibers and solidified with multiple interlocks as it cools down. Adhesion of a polymer to a solid is profoundly influenced by the thermodynamic properties of the polymer and solid at the interface, rheological properties of polymer, operating conditions, and surface contact. But just how these properties are coupled has not been clear. Historically, the surface separation has been analyzed in terms of the free energy of adhesion. Good and Gupta[1] remarked on the mechanical model for the analysis of local peeling of a filament base. Andrews and Kinloch[2] found that the work of bond fracture across the interface for clean interfacial failure is equal to the thermodynamic work of adhesion.

This paper discusses some theoretical considerations of interfacial separation and cohesive failure. It provides some understanding and guidelines for choosing proper materials properties for transfuse. The objective is to study total transfer of images to the paper (separation at donor/toner interface) without offset (cohesive failure) problems.

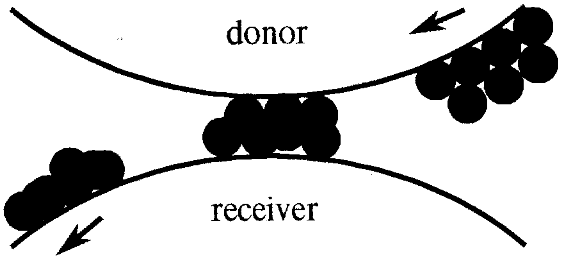

Figure 1. Sketch of Toner Transfer at Transfuse.

Theory

Thermodynamic Work of Adhesion and Energy of Cohesion

In classical terms, the thermodynamic work of cohesion is defined as work associated with the mechanical separation of a primarily monolithic material and further adiabatic displacement of a separated part to infinity. When the two phases are dissimilar, the work required for separation is known as the work of adhesion.[3]

$$W_A = \gamma_1 + \gamma_2 - \gamma_{12} \qquad (1)$$

where γ_1, γ_2= surface energy or surface tension of substrates 1 and 2, γ_{12} = interfacial surface energy or tension.

Combining Equation 1 and Young's equation[4]:

$$\gamma_1 = \gamma_{12} + \gamma_2 \cos\theta \qquad (2)$$

one obtains

$$W_A = \gamma_2 (1 + \cos\theta) \qquad (3)$$

where θ is the contact angle. The cohesive energy is (i.e. when $\theta = 0$)

$$E_c = 2\gamma_2 \qquad (4)$$

The intermolecular interactions at interfaces have been correlated by Girifalco and Good[5] with an equation relating the interfacial tension to the two surface tensions:

$$\gamma_{12} = \gamma_1 + \gamma_2 - 2\Phi (\gamma_1 \gamma_2)^{1/2} \qquad (5)$$

where Φ is the interaction parameter and can be approximated.[6,7] It was shown[6] that for van der Waals interactions in vacuum, the value of Φ varies between 0.98 and 1. Wu[7] calculated values of Φ between polymers from the interfacial and surface tension data with Equation 5 and found it to be in the range of 0.8 to 1.0.

Substituting Equation 5 into 1, the work of adhesion becomes

$$W_A = 2\,\Phi\,(\gamma_1\,\gamma_2)\;0.5 \tag{6}$$

The surface tension is a function of temperature and molecular weight.

In adhesive bonding, bond failure occurs in one of following modes: cohesive, adhesive, or mixed. A cohesive locus of failure within the adhesive indicates that the ultimate performance has been reached for a given adhesive; improved performance can only be achieved by redesigning the adhesive. Huntsberger[8] and Gutowski[9,10] presented some theoretical considerations and experimental evidence for interfacial separation based on thermodynamic work of adhesion.

The work of adhesion has been shown in Equation 3 or 6. For interfacial failure, the energy of adhesion must be less than the energy of cohesion $2\gamma_2$ of the adhesive.

$$2\Phi\,(\gamma_1\,\gamma_2)^{0.5} < 2\gamma_2 \tag{7}$$

or

$$\Phi\,(\gamma_1/\gamma_2)^{0.5} < 1$$

in a dimensionless form.

Criteria of Surface Energies for Transfuse

In the transfuse process, the donor substrate with images and the receiver are generally sandwiched between two rollers under pressure and at an elevated temperature. Under the pressure and at an elevated temperature, the toner polymer can penetrate into the paper fibers. It prefers the adhesive failure along the toner/donor interface, not the cohesive failure. So that on the separation of the paper from the donor substrate, no toner residue remains on the surface of donor substrate. To avoid toner offset, it is necessary to have high cohesive energy of toner polymer. The energy needed to break this bond is $2\gamma_2$ per surface area as shown in Equation 4. Representing the surface energy of the donor as γ_D and the surface energy of the toner as γ_T, the criterion of this interfacial separation becomes

$$F_{DT}\,\Phi_{DT}\,(\gamma_D/\gamma_T\,)^{0.5} < 1 \tag{8}$$

where F_{DT} is the donor/toner surface contact factor, Φ_{DT} is the interaction parameter between the donor and toner. The best method for obtaining Φ_{DT} is using Equation 5, so that all interaction factors at the interface can be taken into account. It is typically less than one. From Equation 8, it is evident that it is desired to have the surface energy of the donor substrate to be a small value.

At the toner and the receiver interface, we don't want the interfacial separation, Figure 1. The toners should stick to the receiver. This criterion is, therefore,

$$F_{TR}\,\Phi_{TR}\,(\gamma_R/\gamma_T)^{0.5} > 1 \tag{9}$$

where F_{TR} is the toner/receiver surface contact factor. For the paper, it could be at least[11] 1.5 to 3. Φ_{TR} is the interaction parameter between toner and receiver, and γ_R is the surface energy of the receiver.The surface contact factor is given by

$$F = \frac{S}{P} \tag{10}$$

where S is the actual contact area of interface and P the projected area.

Equations 8 and 9 can be combined to become criteria for transfuse.

$$F_{TR}\Phi_{TR}\left(\frac{\gamma_R}{\gamma_T}\right)^{\frac{1}{2}} > 1 > F_{DT}\Phi_{DT}\left(\frac{\gamma_D}{\gamma_T}\right)^{\frac{1}{2}} \tag{11}$$

or

$$F_{TR}\Phi_{TR}(\gamma_R)0.5 > (\gamma_T)0.5 > F_{DT}\Phi_{DT}(\gamma_D)0.5 \tag{12}$$

Table 1. Surface Tension of Various Materials at 20°C

Materials	Surface Tension (dyne/cm)
Polydimethyl siloxane	16-20
Silicone Oil	20
Si Rubber	22
Teflon, TFE (tetra Fluoroethylene)	21.5-23.9
Kynar, PVF2 (polyvinylidene fluoride)	25
Tedlar, (PVF) (polyvinyl fluoride)	28
Polypropylene	29
Polyethylene	31, 35
Nylon 12 (polyamides)	35.8
Kapton (polyimides)	37.7-41
Polycarbonate	43
Mylar (polyethllene terephthalate)	43, 44.6
Bond Papers	25.8-64.2
Epoxy	45-47

From Equation 11 or 12, we observe that if F_{TR}, F_{DT}, Φ_{TR} and Φ_{DT} are all equal to one, we have

$$\gamma_R > \gamma_T > \gamma_D \tag{13}$$

to achieve a high transfer efficiency for the transfuse.

A list of surface tensions for various materials[12-14] of interest is tabulated in Table 1.

Surface tensions of materials of interest along with Φ and F need to be measured. Equation 11 or 12 offers one method for choosing proper materials and parameter for obtaining a good transfuse process.

Other Mechanisms and Criteria in Polymer Adhesion Failures

With the transfuse process under pressure and at an elevated temperature, the viscoelastic properties of the toner polymer also need to be considered. Applying pressure on the heated toner is to produce better toner flow and contact which increases the surface contact factor.

Filament Detachment

It is well established that filaments or fibers exist in crazes in thermoplastic polymers and in the peeling of pressure sensitive tapes off solids. Good and Gupta[1] have proposed a model and examine the questions of how a filament deforms, and whether separation will occur at the interface between the base of the filament and the solid, or if rupture will occur somewhere along the body of the filament.

In principle, the separation at the interface between filament base and solid might start by a lift off mechanism. The thermodynamics of this process is described by Equation 1 for the work of adhesion. As an extreme alternative, the separation might start out with a large degree of plastic deformation of the base, in the region near the interface, so that the base region retained its general shape but shrank overall. For a change in base area (dA), the surface work required will be[1]

$$dW_c' = \Delta G\, dA \qquad (14)$$

where ΔG is the free energy requirement. The flow field corresponding to the deformation of the filament is complex. Good and Gupta[1] proposed this deformational work to be

$$d\,W_c = \sigma_y A dl \qquad (15)$$

where σ_y = effective yield strength, A = the mean area of the filament base and dl=the net increase in length due to the flow of polymer from the base. The differential work associated with the change in polymer/solid area is

$$d\,W_c = d\,W_c' + d\,W_c' \qquad (16)$$

The work against the work of filament stretching is

$$d\,W_e = \mu_E s \bullet Adl \qquad (17)$$

where μ_E is the elongational viscosity and s is the stretch rate. Based on a "least energy" principle, the filament begins to detach from solid surface if

$$d\,W_e > d\,W_c \qquad (18)$$

and filament elongates continuously if

$$d\,W_e < d\,W_c \qquad (19)$$

The detachment criterion Equation 18 is similar to Equation 7 based on surface energies.

Based on this theory of filament detachment, the criteria for transfuse mechanism become

$$dW_{TR} > dW_T > dW_{DT} \qquad (20)$$

where dW_{TR} is the differential work associated with the change in toner/receiver interface, dW_T the work against the work of toner polymer stretching, and dW_{DT} the differential work associated with the change in donor/toner interface.

Crack Propagation

Andrews[15] provides a summary of the generalized fracture mechanics (GFM) approach to express the adhesive failure parameters in terms of the interfacial energy and the mechanical hysteresis properties of the bulk phases. This permits the surface and bulk contributions to adhesive failure energy to be separate, allowing an analysis of the fracture process and the way it is controlled by rate, temperature, and other environmental factors. Adhesive failure is regarded as a fracture process involving the propagation of an existing crack along the interface between the adhering phases.

In an investigation by Andrews and Kinloch[16], it was shown that the adhesive failure energy, ε, of joints involving a rubber adhesive, could be expressed as a function of an intrinsic failure energy, ε_0, and a "loss function", K, as the product

$$\varepsilon = \varepsilon_0 K \qquad (21)$$

where K is a function of temperature, crack rate, and strain intensity. The values of ε_0 were determined for a range of joints and the results fell into two categories; in one category were joints where $\varepsilon_0 \approx W_A$, the thermodynamic work of adhesion and, in the other, those for which $\varepsilon_0 > W_A$. By the use of a variety of microscopical and spectroscopical techniques, it was shown that when $\varepsilon_0 \approx W_A$, joint failure was wholly interfacial, but when $\varepsilon_0 > W_A$, it was always partially cohesive failure. Andrews[15] showed good agreement between the ε_0 values obtained directly from the mechanical debonding experiments and the calculated W_A values obtained by surface chemical methods. This represents a vindication of the GFM theory of adhesion, since for interfaces bonded only by secondary interatomic bond ε_0 and W_A are, by definition, the same quantity, namely, the energy required per unit area to break the interfacial atomic bonds.

Based on this theory of crack propagation, the criteria for toner transfuse mechanism can be written as

$$\varepsilon_{TR} K_{TR} > \varepsilon_T K_T > \varepsilon_{DT} K_{DT} \qquad (22)$$

where ε_{TR} = intrinsic failure energy of toner and receiver interface, K_{TR} = loss function of toner and receiver interface, ε_T = intrinsic failure energy of toner polymer, K_T = loss function of toner polymer, ε_{DT} = intrinsic failure energy of donor/toner interface, K_{DT} = loss function of donor/toner interface.

Practical Examples in Transfuse

The transfuse process has been used in office and offset printing industries by Oce, Tektronix, Indigo, Delphax, and printing presses etc. Si rubber or low surface energy material is commonly used as a release (donor) layer. Surface tension of polymer is a function of temperature, molecular weight and others. Figure 2 shows examples[17] of surface tension as a function of temperature for some polymers. The surface tensions decrease almost linearly with the increase of temperature. The surface tensions of Si rubber and paper at elevated temperatures are not available. Figure 3 shows examples of transfuse criteria as a function of paper surface tension. It shows that the results satisfy the transfuse criteria, Equation 11. Since slopes of surface tensions as a function of temperatures, shown in Figure 2, remain almost a constant, the criteria should also remain almost constant at higher temperatures if the interaction parameters and surface contact factors remain the same.

For good transfuse, it is better to have the criterion at the receiver interface as high as possible and the criterion at the donor interface as low as possible. Using Equation 11, it is possible to quickly examine the transfuse criteria. For example, if we use Si rubber release layer, polyester toner and low surface tension paper, then $F_{DT}\ \Phi_{DT} < 1.40$ and $F_{TR}\ \Phi_{TR} > 1.29$ are the conditions required to satisfy the transfuse criteria. Since the interaction parameter Φ is typically between 0.8 and 1, it may have transfuse problem if the surface contact factor between the receiver and the toner is too low.

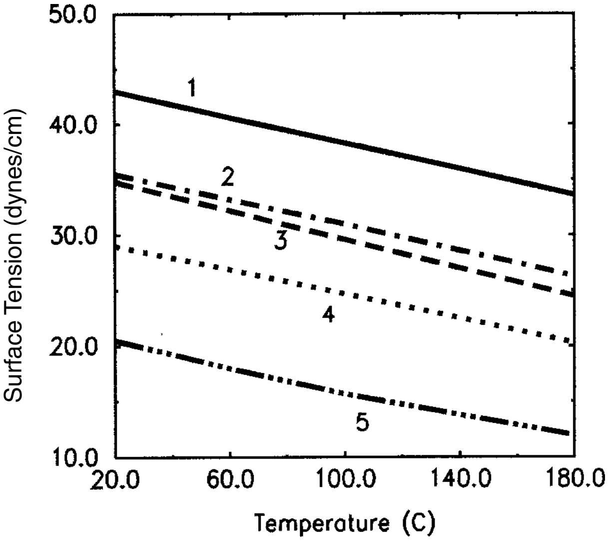

Figure 2. Surface Tensions of Polymers as a Function of Temperatures, 1=Polyester, 2=Linear Polyethylene, 3=Branched Polyethylene, 4=Polypropylene, 5=Polydimethylsiloxane.

Summary

Three adhesion theories have been presented. Based on these theories, three criteria were derived for toner release and binding in transfuse process. A low surface energy substrate, such as Si rubber, is commonly used as the intermediate substrate for transfuse. The Si rubber is tacky and provides attraction to the cold toner at the first transfer, but after heating the surface, it permits high release to the paper. The low surface energy substrate eases the release of images from the donor surface and the heating of the images partially dries the images and also promotes the toner polymer flowing onto the paper. The penetration of toners onto the porous surface of the paper gives an ideal situation for strong bonding between the two.

The roughness and contact area of the paper, which increase the bonding between the toner and the paper, need to be optimized for the desired image quality. With small toner particle sizes, paper should not be too porous or rough at the surface.

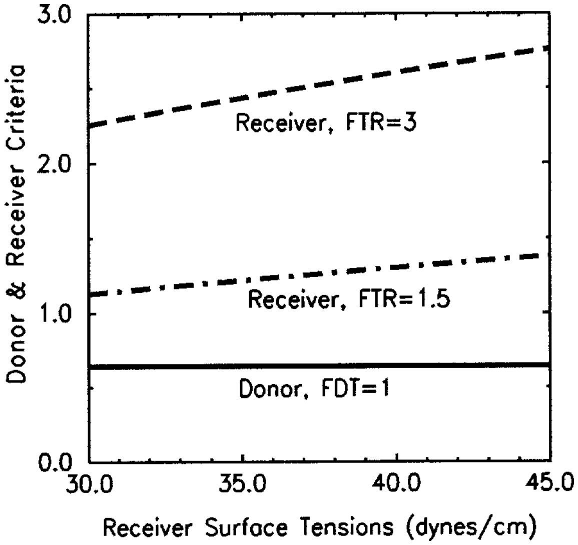

Figure 3. Transfuse Criteria as a Function of Receiver Surface Tension using Polyester Toner (43 dynes/cm), Si Rubber Donor (22 dynes/cm) and assuming Interaction Parameters = 0.9.

As a general consideration to obtain substantially complete or non-offsetting transfuse, it is clear that the cohesive force of the toner and the adhesive force between the toner and the receiver must exceed the force of adhesion exerted by the donor surface on the toner.

References

1. R. Good and R. Gupta, *Adhesive Bonding* edited by L. H. Lee, Plenum Press, New York, pp. 47-73, 1991.
2. E. Andrews and A. Kinloch, *J. Polymer Science*, No. **46**, pp. 1-14, 1974.
3. A. Dupre, *Gauthier-Villars*, Paris, p. 369, 1869.
4. T. Young, *Phil. Trans. Roy. Soc. London*, **95**, p. 65, 1805.
5. L. Girifalco and R. Good, *J. Phys. Chem.*, **61**, p. 904, 1957.
6. C. van Oss, R. Good, and M. Chaudhury, *J. of Colloid and Interface Science*, v.**111**, n2, pp. 378-390, 1986.
7. S. Wu, *J. Colloid Interface Sci.*, v. **31**, p. 153, 1969.
8. J. Huntsberger, *J. Polymer Sci.: Part A*, V**1**, pp. 1339 - 1344, 1963.
9. W. Gutowski, *J. Adhesion*, v**19**, pp. 29-49, 1985.
10. W. Gutowski, *J. Adhesion*, v**19**, pp. 51-70, 1985.
11. W. Zisman, *Contact Angle* edited by R. Gould, ACS, 1964.
12. S. Wu, *Polymer Handbook* edited by J. Brandrup & E. Immergut, John Wiley & Sons, New York, pp. vI/411-434, 1989.
13. E. Shafrin, *Handbook of Adhesives*, edited by I. Skeist, Van Nostrand, pp. 67-71, 1977.
14. L. Agbezuge and F. Wieloch, *J. Appl. Polym. Sci.*, **27**, pp. 271-275, 1982.
15. E. H. Andrews, *Adhesive Bonding* edited by L. H. Lee, Plenum Press, New York, pp. 337-358, 1991.
16. E. H. Andrews and A. J. Kinloch, *Proc. R. Soc. London Ser. A* **332**, pp. 385-414, 1973.
17. G. Gaines, *Polym. Eng. & Sci.*, v**12**, N1, pp. 1-11, 1972.