Measurement and Improvement of Automatic Document Feed Performance of Solid Ink Prints

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Abstract

Automatic Document Feed, or ADF, is defined in this paper as the ability to feed printed matter in large amounts through the paper-handling equipment of copiers. The desire to perform this operation on any kind of printer output without annoying interruptions or jams is widespread among customers. This is particularly true for prints from color printers. Until now it could be reliably achieved only by prints from xerographic and ink jet color printers. The output from solid-ink color printers on the other hand - despite excelling in many areas - was not competitive in this point. The reason for this has to be seen in a high Coefficient of Friction (COF) of ink-covered parts of documents against the glass surfaces present in the imaging systems of copiers.

Great efforts have been made, and several solutions were proposed, to find a remedy for this problem. In this context, it is an important task to measure the progress in product performance. Clearly, the Coefficient of Friction under the above mentioned conditions fulfills this demand from the point of view of the engineer or physicist. But how can this easy to determine number be translated into meaningful information about the most likely performance in the field? To find an answer to this question, this paper addresses the problem of setting control limits for the Coefficient of Friction of solid-ink color prints, introduces the "ADF-Index" for measurement of customer satisfaction, and attempts to give a correlation between COF and ADF-Index.

Introduction

Easy operation, low price, and improvements in speed of printing are among many features, which make solid-ink office color printers attractive to the user. Through continuing research and development efforts in system design and ink formulation, these printers have established themselves comparable or superior to xerographic or electro-photographic (EP) color printers in all aspects. The endpoint of this development has not been reached yet, and a number of technical problems have still to be solved until the technology becomes fully superior to xerographic printing.

One of these technical problems is the inability of prints from solid ink color printers to be fed through the paper handling machinery of copiers. However, using models of viscoelasticity and friction in polymers,[1-3] significant progress has been made in the recent past. This paper presents a brief overview of the tools, which were used to measure this progress.

Coefficient of Friction (COF)

Definition

Friction always arises when two solid bodies, which are in surface contact, move tangentially relative to each other. It is a resisting force that strives to suppress this translational motion, and effectively transforms the kinetic energy of the two moving bodies into heat. Since the beginning of the systematic investigation of the phenomenon, several empirical laws of friction have been found.[4] Also, the differentiation into internal friction and surface friction is well established[5]. In this picture, internal friction is an essential part in cyclic processes like rolling friction, where mechanical damping together with delayed recovery causes dissipation of energy. Surface friction, on the other hand, is present when two solid surfaces slide past each other. It is seen to be a composite of a shearing and a ploughing term, with a significant influence of adhesion. In this case, it is generally assumed that due to sub-microscopic roughness - sometimes discussed as surface asperities[3] - contacting surfaces touch each other only on very few points. At these points, large forces are produced during sliding, which are observed as friction in a macroscopic scale. The coefficient of friction μ is then defined to be the ratio of the resultant of these forces F_T, acting tangentially to the surface of contact, to the normal force F_N, acting perpendicularly to the surface of contact:

$$\mu = \frac{F_T}{F_N} \tag{1}$$

For practical purposes, a distinction is made between a static coefficient of friction μ_{static}, and a kinetic coefficient of friction $\mu_{kinetic}$[6,7,8].

The static coefficient of friction characterizes the resistance against the initiation of motion. It should be noted, that if stiction, or adhesion, is discussed, this view is somewhat problematic.[9] However, since we want to be in accordance with standard methods, we have kept this definition for the static coefficient of friction.

The kinetic coefficient of friction is defined to be equal to the ratio of the tangential force required to sustain the relative movement of the surfaces to the normal force. For the purpose of the present discussion, only surface friction is considered.

Measurement and Control of Measurement Process

A large variety of instruments exist for the experimental determination of coefficients of friction.[8] With respect to friction testing in the Plastics, Ink and Coatings Industry, Figure 1 gives the basic principles of the most popular methods. The Inclined Plane Method, sketched in Figure 1a, determines the static coefficient of friction only. Here, the Sample S is placed on a planar surface, which gradually gets inclined towards the horizontal by an angle α. It is important to determine a particular value of α - the friction angle, or constant angle of repose α_F – at the moment when S starts to slide down. The static coefficient of friction is then determined by Equation (2)[10],

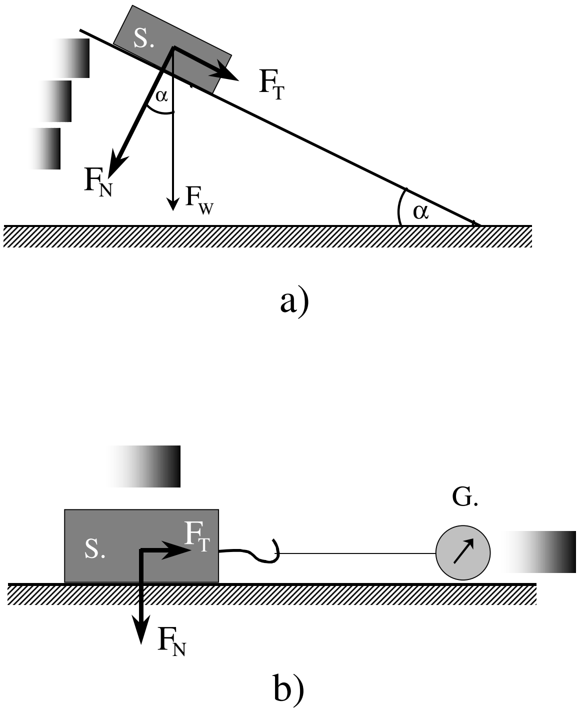

Figure 1. Measurement principles for the determination of COF. A) Inclined Plane Method, b) Horizontal Plane Method. Symbols are explained in the text.

$$\mu_{static} = \tan\alpha_F \qquad (2)$$

The Horizontal Plane Method, sketched in Figure 1b, determines the static, as well as the kinetic COF. In this case, the Sample S is dragged with a defined speed over a horizontal surface. For this purpose, it is connected with a force gauge G, which itself is attached to the drive. The normal force F_N is equal to the known weight of S. The gauge measures the tangential force F_T, and both forces are inserted into Equation (1) to yield the COF as a function of time, or displacement. Alternatively, the method is performed using a moving plane and a stationary sample S. – This is our preferred method to compare frictional properties – and ultimately ADF performance – of phase change inks.

Table 1. Capability Test of Friction Tester. Sample mass 200 grams. Speed 2 inches/min. Measurement time 10 s.

Friction Pair	μ_{static}	$\mu_{kinetic}$
Kapton Tape/ Kapton Tape	0.298 std. deviation: 0.019	0.284 std. deviation: 0.023
HDPE/HDPE	0.253 std. deviation: 0.020	0.240 std. deviation: 0.022
Kapton Tape/HDPE	0.209 std. deviation: 0.026	0.170 std. deviation: 0.027

During this work, all measurements were done with a Friction/Peel Tester, Model 225 from Thwing-Albert Instrument Company. Using 10s measurement period, μ_{static} is calculated as the maximum COF during the first 0.102 inches of displacement. The kinetic COF is the average of all measured COF data points.

To demonstrate capability of the instrument in the product development process, it would be desirable to regularly run control charts of COF with certified solid standard materials. Unfortunately, such certified standards do not exist to our best knowledge. Since the demonstration of instrument capability – not necessarily the determination of absolute values of friction coefficients – is one goal of this work, cheap and simple “internal” standard materials are desired. There would be three requirements for these solids. First, they should be relatively robust against wear – e.g. they should not transfer films when sled over a surface, and change their profile significantly after a few tests[3]. Second, they should not attract large amounts of atmospheric moisture over a time period, which would form films on their surfaces, and alter their frictional properties. And third, they should chemically resemble somewhat the materials that are used in solid inks.

Encouraged by the fact that the friction behavior of paper is a topic of published experimental investigations,[11-14] this material was first tried as a “standard”. Examples for friction profiles of Hammermill Paper are given in Figure 2. However, it soon became clear that this would be a bad choice. Due to its hygroscopic nature, and possibly also due to variations in surface structure, it is difficult to keep frictional properties of paper within narrow limits. A more favorable choice would be hydrophobic plastics. In this respect it was encouraging to find COF for some polymers tabulated in the literature.[15] Unfortunately, with a few exceptions, no explicit information is given in the tables about the nature of the surfaces against which the named plastics were tested. But according to theoretical models of friction, this is an important detail[16]. Molecular adhesion is one of the intrinsic properties, which determine friction. The COF increases with stronger adhesion. All other conditions being constant, friction of a material against itself is then usually higher as measured against a chemically different material. The validity of this statement is illustrated by the data presented in Table 1 and Figure 2.

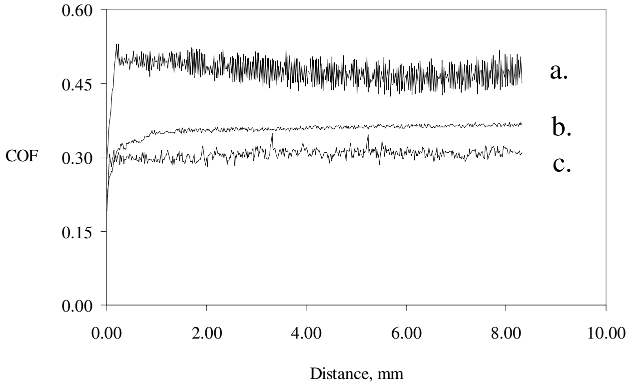

Figure 2. COF of Hammermill Paper at a velocity of 2 in./min, and a sample mass of 200g. a. Against itself (μ_{static}=0.53, $\mu_{kinetic}$= 0.47), b. Against Glass (μ_{static}=0.36, $\mu_{kinetic}$=0.36), c. Against Steel (μ_{static}=0.32, $\mu_{kinetic}$=0.30).

The data in Table 1 represent control chart limits for the "standard" plastics of choice – Kapton® Tape, and High-Density Polyethylene (HDPE).

Factors Which Influence COF

The following discussion focuses exclusively on the COF. It is not considered, whether proposed measures have a positive or negative impact on other properties of the inks or prints.

A more detailed analysis in the context of the adhesion theory of friction leads to the following expression for the coefficient of friction[16,17]:

$$\mu = \frac{\tau}{p_y} \tag{3}$$

In this equation, τ represents the shear strength, or resistance against plastic flow in shear, of a junction between the two surfaces. This value is equal to or somewhat smaller than the bulk shear strength of the softer material. The denominator p_y is the yield pressure, or resistance against plastic flow in compression, of the softer material.

A further discussion in terms of the theory of elasticity sets p_y equal to the hardness of the softer material, and relates it to Young's modulus E[16]:

$$p_y \propto E^n \tag{4}$$

For the current problem, a low COF is desirable. Equations (3) and (4) allow drawing some practical conclusions about controlling and lowering COF:

- An increase of hardness in the softer material (here this would be the solid ink) – hence, an increase in p_y – will decrease the COF.
- For this increase in hardness, materials (inks) with higher Young's modulus would be preferred (e.g. in Electrophotography, toner materials have such a high value of E at room temperature, because they are in the sub-T_g region).
- The resistance against plastic flow in shear τ needs to be decreased for a decrease in COF. This involves lubrication by liquid or solid agents,[3,18] which form thin layers of low shear strength.

A further aspect would be the surface roughness of the frictional area.[17] In contrast to the statements of the adhesion theory of friction, experience shows that an increase in roughness – within certain limits – decreases the COF due to a decrease in the real area of contact, A_r. This seems to be particularly true if roughness is combined with hardness, as seen from curves a. and c. in Figure 2. This will be illustrated again in one example in the following paragraph.

COF and its Relation to our Product Development, Examples

Until now, color prints which were made with solid inks could cause jams when fed through the paper handling equipment of copiers. This means in terms of tribology, that the COF of these prints versus glass is very high. Curve b in Figure 3 illustrates this statement. In fact, the depicted pattern of oscillation indicates a strong stick-slip behavior. It is always observed when the static COF is significantly bigger than the kinetic COF[16]. Furthermore, in terms of Equation (3), it means that the shear strength τ is very big. Figure 3 also shows the significance of the surface roughness on the COF pattern of the same sample: exchanging the relatively smooth glass surface against the much rougher steel plate lowers and stabilizes the COF, as Curve a. indicates.

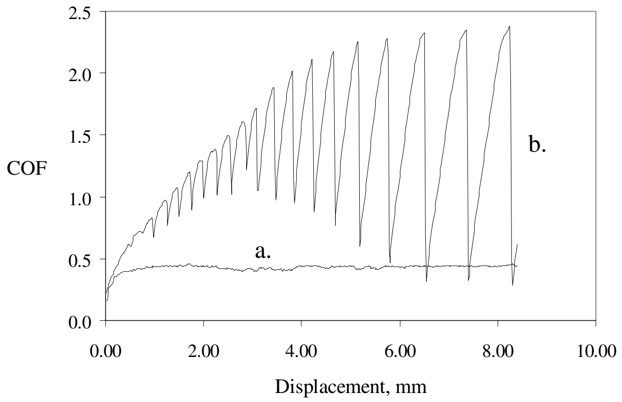

Figure 3. Friction Test Profiles for Cyan Phaser 850 Ink: a. Sample slides over abraded steel(μ_{static}=0.46, $\mu_{kinetic}$=0.43), b. Sample slides over tempered glass (no distinct COF available).

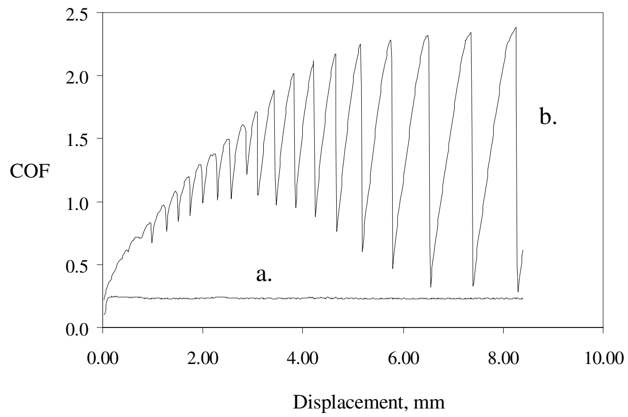

Figure 4. Friction Test Profiles for samples sliding over tempered glass: a) Cyan EP Toner (μ_{static}=0.24, $\mu_{kinetic}$=0.23), b) Cyan Phaser 850 Ink (same as in Figure 3).

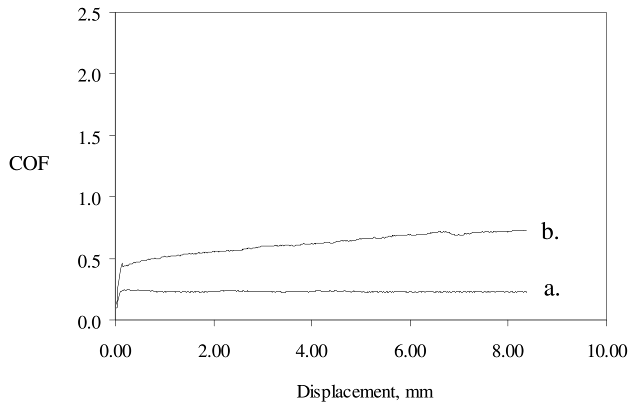

Figure 5. Friction Test Profiles for Samples sliding over tempered glass: a) Cyan EP Toner (same as in Figure 4), b) Prototype Solid Phase Change Ink (μ_{static}=0.58, $\mu_{kinetic}$=0.62). Same scaling as in Figures 3 and 4.

To set the performance of solid ink prints vs. glass surfaces into perspective, Figure 4 compares the friction profile of a cyan solid fill Phaser 850 print with that of an EP print of the same color. The low COF of the Laser Print correlates with the capability to feed in copiers without problems.

It would therefore be desirable, to change the oscillatory stick-slip friction profile in Figure 4 in such a way that it comes closer to the flat profile of an EP print. This was indeed accomplished by a set of measures, details of which are not the topic of this paper. However, the effects of the research and development work for the COF of solid ink prints vs. glass are illustrated in Figure 5.

In Figure 5, the COF of the EP print from Figure 4 (Curve a) is compared with the COF of a prototype solid ink (Curve b). Clearly, the stick-slip behavior has been eliminated. Although the static and kinetic COF have been significantly lowered, they still remain higher than the COF for the EP print, and they show a tendency to slightly increase during testing. This latter observation is related to the inherent softness of the ink. During the sliding process, the true area of contact between ink and glass increases, which in turn increases the COF.

Now, a first question is, whether this increase of COF can be prevented? An answer is attempted in the last paragraph of the last section. Here, it is only noted that certain compromises have to be made with other performance properties, which in high likeliness pose a difficulty to further lower the COF – although it still may be possible. A second question is, in how far the COF profile in Figure 5b does already guarantee a flawless ADF performance? This problem is addressed in the next two sections.

ADF Index

Definition

It is probably safe to state that any industrial R&D Process has accomplished its mission when its results are implemented in a product, which better satisfies the needs of the customer. But once the product is in the hand of the customer, it is difficult for the product developer to access information about its performance. Consequently, the question arises, how a product development engineer would measure and quantify – in a short term, *anticipate* – "customer satisfaction" of the product, before it actually comes into contact with the customer? For this specific case, the question would be: How low has the COF at least to be to feed in the customer's copier, to the customer's satisfaction?

For purposes of quantification, one can think about ADF as a process, which is repeated thousands of times per day in a rather large variety of copiers with a variety of prints. In this picture, customer satisfaction is achieved, when the relative amount of failure events per day – the probability of failure – is low. Hence, customer satisfaction is a statistical property, related to statistical process control.

Therefore, we define the "Customer Satisfaction Index", or ADF Index, as the composite probability – a number between 0 and 1 (or 0% and 100%) – which is calculated from the probability of success, determined in two experiments:

- Feed a particular type of print through the paper handling equipment of a defined number of copiers of different makes.
- Feed a defined number of different prints with different amounts of ink coverage through the paper handling equipment of a copier of a particular make.

Measurement

In the procedure, which was used to determine the ADF index, these two experiments were performed simultaneously. Five different prints (P1 to P5) were printed in standard resolution. In qualitative terms, the ink coverage in these prints varied from "picture, fully covered" (P1 and P2) via “mostly pictures and graphics” (P3), and “pictures and graphics with mostly text” (P4) to “text only” (P5). Four replicates of each print (R1 to R4) were printed. The test itself involved individual feeds of these prints in five copiers of different brands and duty cycles. Only successful feeds were counted, and related to the total amount of feeding attempts.

An example is given in Figure 6. It demonstrates how data in this test were recorded. In the schematic, bullets indicate successful feeds, empty cells symbolize failures. For simplicity, the example involves only two copiers, named C1 and C2. As Figure 6 indicates, there are a total of 20 feed attempts per copier. To calculate the total success per printer, the number of successful feeds is divided by 20, which yields 80%, and 70% for copiers C1, and C2, respectively. Furthermore, an over-all-copier success *per replicate*, and *per print* can be estimated. The example in Figure 6 shows the former to be 90%, 80%, 80%, and 50% for R1, R2, R3, and R4, respectively. Here, the number of successes in a column was divided by 10. For a calculation of the over-all-copier success rate per print, the number of successes per particular print in the two copiers is divided by 8. This yields 62.5%, 37.5%, 87.5%, 87.5%, and 100% success for P1, P2, P3, P4, and P5, respectively.

The ADF Index can then be calculated as a composite from the two probability values for total success by just averaging them. In the example, this yields an ADF Index of 75% customer satisfaction, with a standard deviation of 7.1%. To check for consistency, one can also calculate the composite success probability from the over-all-copier success per replicate, and from the over-all-copier success per print. Both yield 75%, with higher standard deviations – 17.3%, and 25%, respectively.

		R1	R2	R3	R4	**Total success per printer**
C1	P1	●	●		●	**0.8** **80%**
	P2	●		●		
	P3	●	●	●	●	
	P4	●	●	●		
	P5	●	●	●	●	
C2	P1	●		●		**0.7** **70%**
	P2		●			
	P3	●	●	●		
	P4	●	●	●	●	
	P5	●	●	●	●	
Over-all success per replicate		**0.9** **90%**	**0.8** **80%**	**0.8** **80%**	**0.5** **50%**	

Figure 6. Example of an ADF score sheet. For detailed explanations, see text.

It should be noted that the foregoing represents a hypothetical example. The actual experiments were done on more than two copiers. Hence, a slight increase in the number of prints and replicates would add more confidence to the result. However, this depends on the amount of time, the experimenter is willing to invest into this procedure. Also note, that the distribution of the ADF index is confined to the interval between 0 and 1. Consequently, as it approaches 1, it should more and more deviate from the symmetric Gaussian type of distribution.

Correlation between COF and ADF Index

The Intuitive Picture

The foregoing section related many successful “ADF events” to high customer satisfaction, and a high ADF Index. A necessary condition for this desired state of matters is a low COF between prints and glass surfaces of the copiers. Therefore, the two quantities, COF and ADF Index, must be related to each other. Specifically, they should show inverse proportionality. The experimentally determined shape of this function is given in the next paragraph.

Results

Figure 7 gives a quick overview of the correlation between the kinetic COF and the ADF Index. Although the data do scatter, it is possible to discern the falling tendency of the ADF Index with increasing COF. Interestingly, the data distribution indicates the existence of a maximum kinetic COF, above which the customer satisfaction starts to decrease, and below which it is close to 100%. According to Figure 7, this threshold COF is estimated to be approximately 0.58.

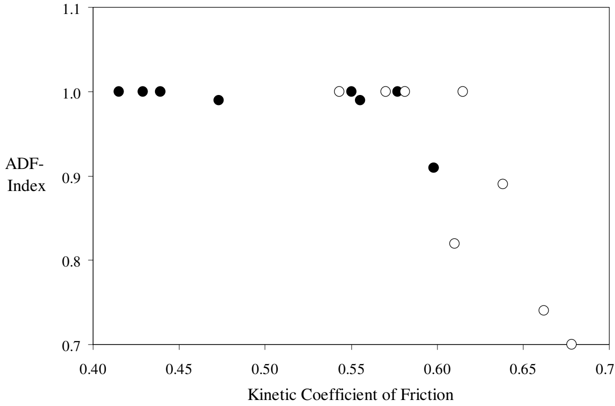

Figure 7. Correlation between ADF Index and Kinetic Coefficient of Friction. Filled circles represent measurements shortly after printing. Open symbols represent measurements 3 days after printing.

ADF Performance and its Relation to other Ink Performance Properties

High flexibility and toughness, and good adherence to media, are among the performance properties of solid ink, which are appreciated by the customer. To add complexity to the picture, they are also directly connected with ADF behavior. This connection is mediated by thermo-mechanical properties, measurable by DMA, like Young’s Modulus E (or E’ and E”, from dynamic measurements), Glass Transition Temperature T_g, and Loss-Angle Tangent ($\tan\delta$) in the glass transition region. Equations (3) and (4) indicate, that a high value of E would be most favorable for ADF, since it lowers the COF. Also, a high T_g is favored for the purpose of increasing the ink hardness. Unfortunately, actions to increase E and T_g – while keeping the viscosity of the molten ink reasonably low – decrease the area under the $\tan\delta$-curve in the glass transition region, and hence the amount of mechanical energy which can be dissipated. This means an enhancement of brittleness of the solid ink layer in a print. As a consequence, one has to expect drawbacks in ink flexibility and toughness, when only a decrease of COF is attempted by means of ink formulation. The same holds true for other thermo-mechanical based performance properties, like gouge resistance and foldability. Blocking in many cases was improved by measures focussing on low COF. To answer the question at the end of the second section, it must be concluded that there is only limited room for further lowering the COF. Any such attempt by solely focussing on ink formulation has to be carefully weighted against negative influences on other properties within the framework of a set of design of experiments (DOE).

Conclusion

The preceding discussion has shown that Coefficient of Friction (COF) and ADF Index, as defined here, are useful tools for measurement and improvement of Automatic Document Feed performance of solid ink prints in copiers. The advantage of the COF measurement has to be seen in its short measurement time, and its ease. Although in comparison, ADF Index determination requires more time for measurement and data evaluation, it adds information about the very important detail of long-term reliability. It was found that both quantities do reasonably correlate. Therefore, by using this correlation, a quick ADF Index determination via COF measurement is possible in future research, and product quality control.

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Biography

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