

Steady State Curl Due To Ink Jet Printing

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Abstract

In thermal ink jet printing with aqueous based inks, paper fibers swell due to absorption of moisture from the pores of the paper, and internal or drying stresses are released in the paper. Two types of paper deformation in the form of curl occur. The first type of curl occurs as soon as moisture gradients are set up in the paper, and the second type of curl occurs due to long term stress relief of the paper. The first type of curl known as Al (away from image) curl occurs almost instantaneously, unless the paper is actively dried. The second type of curl, known as Tl (toward image) curl usually occurs in steady state conditions which could take several hours to develop. Steady state curl is most problematic from the viewpoint of paper handling and aesthetic appearance of the printed image.

This paper presents experimental data to explain the steady state curl phenomenon and simple analyses are postulated to explain the physics and mechanisms which drive the two types of curl.

Techniques and methods for controlling steady state curl are recommended. Data is also presented which relates printing and drying scenario which reduces steady state paper curl.

Introduction

Much attention has been paid in the literature to the dependence of ink jet printed image quality on ink/paper interactions and ink compositions, when the ink is aqueous based and the substrate is "plain paper".[1,2,3,4] Limited attention has been paid to paper deformation in the form of cockle and curl during ink jet printing.[5,6]

This paper presents analytical and experimental methods for understanding the development of steady state curl during ink jet printing. In typical ink jet printing, the mechanisms for curl production follow two phases. In the first phase, the curl is almost instantaneous, and occurs when moisture penetrates the paper and causes the fibers to swell. The fibers may swell by as much as 10 to 30 times in their thickness due to moisture intake. Because the printed side of the sheet expands more than the unprinted side of the sheet, hygroexpansion Al (away-from-image) curl occurs. This will be referred to as expansion curl.

When the sheet dries, the printed side experiences internal stress or drying stress relief and shrinks. The reason for the shrinkage is that the paper, when manufactured, was dried under restraint. Unrestrained drying therefore permits the paper to return to a condition of minimum energy, and Tl (toward-image) curl occurs. This will be referred to as shrinkage curl.

The amount of internal stress in a sheet of paper may be measured by stress relaxation techniques.[7] Since internal stress also forms part of the elastic modulus of paper, a sheet which shrinks during drying will have lower elastic modulus, and will require longer elongation before rupture than a constrained sheet of paper.

In addition to curling deformation, the sheet will also develop cockle, because of non uniform irreversible swelling in the thickness direction, which reduces the flatness of the sheet.

Data will be presented to show that methods exist for controlling the amount of steady state curl which is developed during ink jet printing. The methods rely on the mode of drying, mechanical decurling, ink formulation, and the mode of printing. Application of these methods could alter the curl formation scenario, which usually consists of hygroexpansion Al curl, followed by Tl shrinkage curl. While it is possible to bypass hygro-expansion Al curl steady state curl is almost always in the form of Tl shrinkage curl.

Physics of Steady State Curl

Steady State Curl in paper may occur due to (a) mechanical deformation in the form of irreversible or unrecoverable strain, or (b) irreversible strain due to the release of internal stresses or drying stresses in the paper. Internal stresses are produced in the paper because of the nature of the paper making process.

Experimental data indicates that the development of steady state irreversible curl during ink jet printing proceeds according to the mechanisms illustrated in Figure 1. Consider an unprinted sheet of paper to have the sides A and B (A will become the imaged side and B will become the non imaged side).

After printing side A with aqueous ink droplets, penetration of moisture into the paper creates hygroexpansion of side A, so that away-from-image (Al) curl develops almost instantaneously. After moisture is driven from the paper (after drying), side A experiences greater stress relief than side A. As a result of internal stress relief, side A shrinks more than side B. and the paper develops irreversible toward-image (Tl) curl.

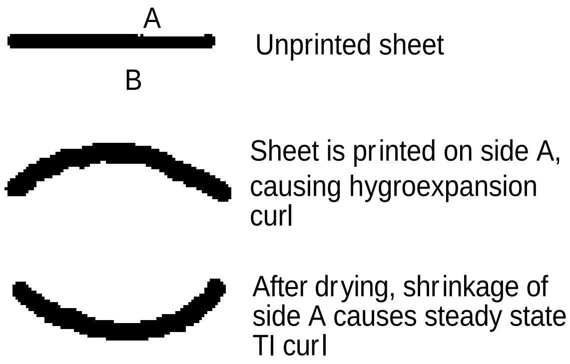

Figure 1.

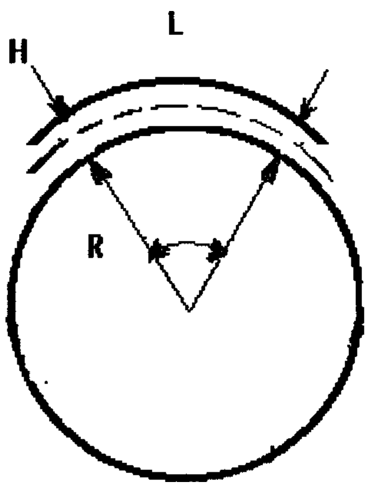

Figure 2.

The scenario described is typical of most plain papers printed by aqueous based inks, but the situation can be altered or delayed by treating the paper with different types of coating, sizing the paper, or designing inks with special properties.

The following discussion presents the reasons why steady state curl is permanent or irreversible.

Figure 2 illustrates the bending deformation of an elastic deformable material about its neutral plane. If the initial length of the material is L, its thickness is H. and it subtends the angle θ, then the extension of its top fiber is

$$\delta = (R + H)\,\theta - (R + H/2)\,\theta = (H\theta)/2 \qquad (1)$$

Since, along the neutral plane,

$$L = (R + H/2)\,\theta \qquad (2)$$

therefore

$$\delta = (H/L)/(2R + H) \qquad (3)$$

and the total strain is

$$\varepsilon_T = H/(2R + H) \qquad (4)$$

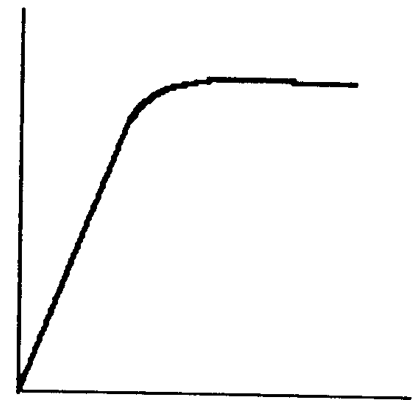

Figure 3.

In order for permanent or irreversible curl to occur, the total strain should exceed the recoverable (or elastic) strain, ε_E. In Figure 3, the elastic strain is determined from the linear portion of the stress-strain curve (aa) for paper, at the required straining rate. Beyond the elastic region (bb), the stress-strain curve is non linear until rupture occurs.

Note that the elastic modulus, which is the slope of the straight line in region aa, is a function of straining rate, and of the type of paper. Typically, for plain papers, the elastic strain falls within these limits

$$10^{-3} < \varepsilon_E < 5 \times 10^{-3}$$

Permanent or irreversible strain occurs when $\varepsilon_E > \varepsilon_T$, that is, the minimum radius of curvature at which irreversible strain begins in the paper is

$$R_{min} = H(1 - \varepsilon_E)/2\varepsilon_E \qquad (5)$$

If the radius of curvature is less than, then the plastic or irreversible strain, eP, developed is

$$\varepsilon_P = \varepsilon_T - \varepsilon_E = H(2R + H) - \varepsilon_E \qquad (6)$$

In order to calculate the curl reducer $_c$, of a sheet of paper of length, L, refer to Figure 2. If the plastic extension is δ_P, then the deformed length is $L + \delta_P$, so that the plastic strain is $\varepsilon_P + \ _P/L$. From simple geometry,

$$\sin(\theta/2) = L/2R_c \qquad (7)$$

Since we are dealing with small strains,

$$L + \delta_P = \theta\, Rc \qquad (8)$$

The plastic extension, $\delta_P = \varepsilon_P L$, therefore

$$(L/2\,R_c)\,(1 + \varepsilon_P) = \sin^{-1}(L/2R_c) \qquad (9)$$

and the curl radius, R_c, is obtained by solving the transcendental equation

$$F(\eta) = (1 + \varepsilon_P)\,\eta - \sin^{-1}\eta = 0 \qquad (10)$$

with $\quad \eta = L/2R_c. \qquad (11)$

The theoretical model presented may be utilized for assessing permanent curl radius (a) when a sheet of paper is deformed mechanically, and (b) when shrinkage occurs due to the release of internal stresses during ink jet printing. It should be noted that the model may not be adequate for ink-paper interactions in which the paper deformation scenario does not follow the assumptions of the model.

A more exhaustive treatment of paper curl by Holmes[8] is based on the Halsey, White and Eyring nonlinear viscoelastic model.[9] In this study, curl is measured as either hanging curl radius or lying curl height, known as flat curl. In some cases, hanging curl is plotted as the reciprocal. Lying curl is the height of a curled sheet when placed on a flat surface.

Experimental Data

Although the theoretical model is useful for understanding the physics of steady state irreversible curl, steady state curl behavior of ink jet printed papers is best studied with regard to ink-paper interactions and the mode of drying utilized.

A sheet of paper printed with aqueous ink formulation should develop Al (away-from-image) curl in the short term, and Tl (toward-image) curl in the long term under typical conditions. However, if the sheet is over dried (very rapid drying), shrinkage curl may overshadow hygroexpansion curl, so that Tl curl develops both in the short and long term.

It is possible, by varying controllable parameters which govern ink-paper interactions, to determine the rate and the path of progression of steady state curl. Some of the controllable parameters are choice of paper fibers, paper coating and sizing, drying rates, printing modes, backside heating, tensioning the sheet during printing and drying, moisturizing the backside, varying the ink chemistry so as to hasten or delay the penetration of moisture into the paper fibers.

Figure 4 presents measured data which illustrates the progressive development of steady state curl under different printing and drying conditions. The data indicates that under uncontrolled drying conditions, many printed papers will exhibit steady state Tl curl curvature exceeding 0.1 in^{-1}, which falls outside an arbitrarily defined acceptable zone of $\pm$ 0.1 in^{-1} of steady state curl. Tl curl is defined as positive, and Al curl as negative. The data is explained as follows:

From state 1 - 2: Unprinted sheet is rapidly dried (Per cent moisture in the sheet drops from 5% to 4%, but the steady state curl of about 0.05 in-1 is unchanged).

From state 1 - 3: Sheet is printed at about 100% area coverage, no drying.% Moisture increases to about 30% and Al curl reaches about -0.25 in^{-1}.

From state 1 - 4: Printed sheet is rapidly dried, so that virtually all moisture is removed before significant penetration into the sheet occurs.% Moisture drops to 3.9%, and steady state curl reaches 0.09 in^{-1}.

From state 3 - 5: The sheet dries under ambient conditions and reaches shrinkage curl of about 0.15 in^{-1} after a long time.

From state 4 - 6: The sheet equilibrates in high relative humidity environment to about 9% moisture and steady state curl of 0.25 in^{-1}.

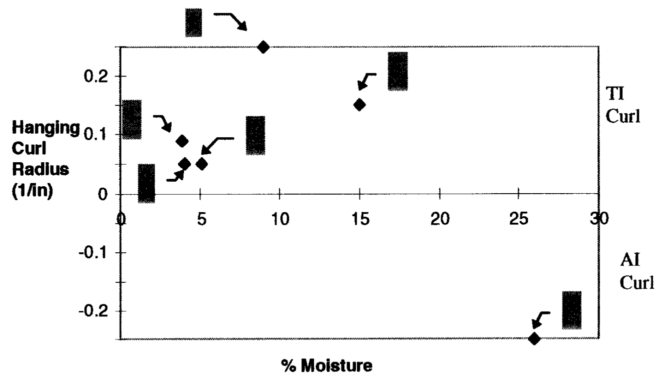

Figure 4. Progressive Development of Steady State Curl.

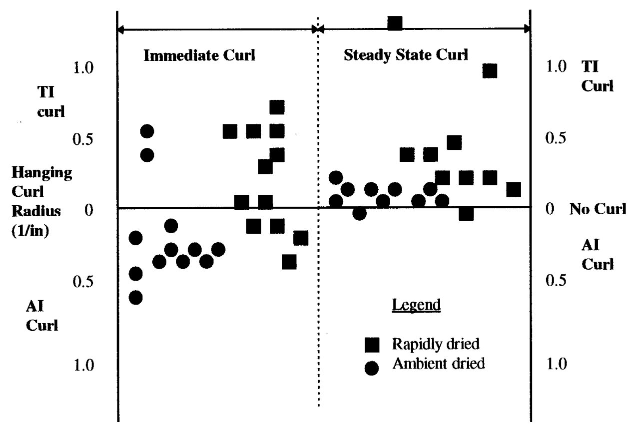

Figure 5. Curl development as function of drying rate.

Further understanding of the development of curl as function of drying rate is provided by the data in Figure 5. Data plotted as circles denote ambient dried sheets, while data plotted as squares denote rapidly dried sheets.

Important points to recognize about the plotted data are:

(a) Ink-paper interactions which exhibit immediate Tl curl when hygroexpansion curl is overshadowed by shrink age curl. This is the case when rapid drying removes most of the moisture before it penetrates the paper. Applica0 tion of intense heat to the printed surface of the sheet removes moisture and simultaneously stress relieves the printed surface of sheet, causing Tl shrinkage curl.

(b) Solvents in the ink may accelerate ink penetration and stress relief, causing both hygroexpansion curl as well as rapid differential shrinkage. In these situations, short term curl may not be predictable.

(c) Long term or steady state curl is due to shrinkage curl. In rapidly dried sheets, the amount of shrinkage curl is diminished. In ambient dried sheets, the Tl shrinkage curl is usually large. If the ink formulation contains solvents which delay fiber shrinkage (such as ethylene glycol), shrinkage curl may be delayed and large Tl curls may take several hours to develop.

Based on experimentally measured data, it is postulated that, in the absence of curl controlling mechanisms, curl formation scenario during ink jet printing follows the sketch shown in Figure 6.

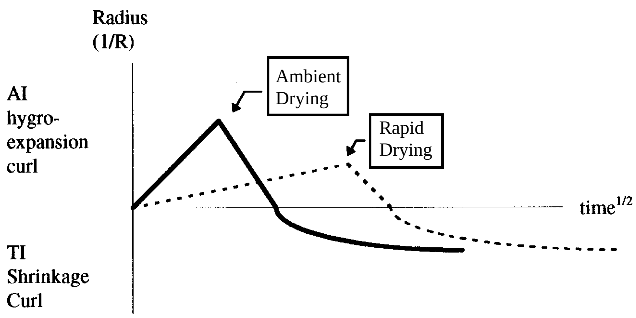

Figure 6. Curl Development Scenario

Steady State Curl Control

Three methods for controlling steady state curl formation are presented. The first relies on the method of printing, the second on mechanical decurling, and the third on rapid drying. A fourth method, not discussed, relies on ink formulation.

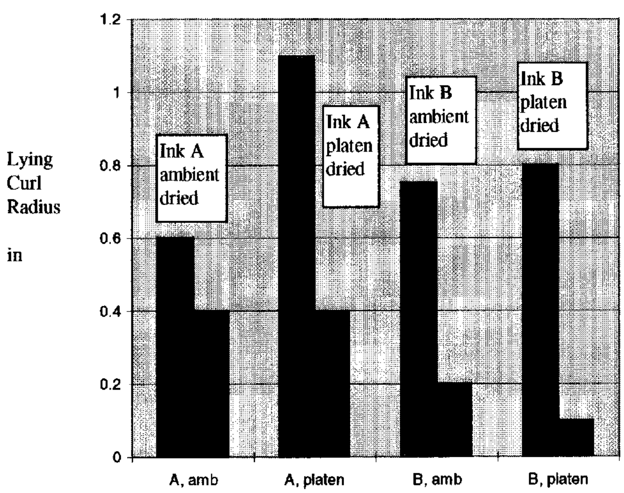

Figure 7. The use of checkerboard printing in minimizing steady state curl. The higher value refers to no checkerboard printing, the lower value to checkerboard printing.

The first method, checkerboard printing, relies on depositing minimal quantities of ink on the paper and letting it dry before another printing pass is made. This has the advantage of minimizing shrinkage curl, at the cost of reducing the throughput rate of printing Figure 7 shows reduction in lying curl which could be gained by checkerboard printing. Two types of ink are shown on plain paper, Ink A is a dye based ink and Ink B is a pigment based ink. The bar charts show greater curl for no checkerboard printing, compared with checkerboard printing. Ambient drying and platen drying methods were utilized in the experiment.

The second method, mechanical decurling, imposes mechanically induced Al irreversible curl on the paper in order to nullify the Tl shrinkage curl. This method requires that the shrinkage induced Tl curl be predictable in order to apply the correct amount of compensating Al irreversible curl. This method would therefore be more challenging to implement.

The third method, rapid drying, dries off the moisture quickly before significant ink penetration into the paper occurs. This has the effect of minimizing internal stress relief and Tl shrinkage curl which occurs afterwards. This method should be effective, provided that the ink does not contain solvents which are difficult to evaporate and which create internal stress relief in the long term. Figure 8 indicates that rapid drying is capable of producing acceptable steady state curl, while mechanical curl control is more difficult to implement. The unprinted sheet, state a, acquires (28% moisture, –4″ Al curl), state b, after printing. Rapid drying moves the sheet from state b to state c (4% moisture, 14" Tl curl). Printing with mechanical decurling moves the sheet from state b to state d (5% moisture, 3" Tl curl).

Assuming that acceptable steady state curl should have a hanging radius of more than 12.5", it is apparent that rapid drying is much more effective for minimizing shrinkage curl.

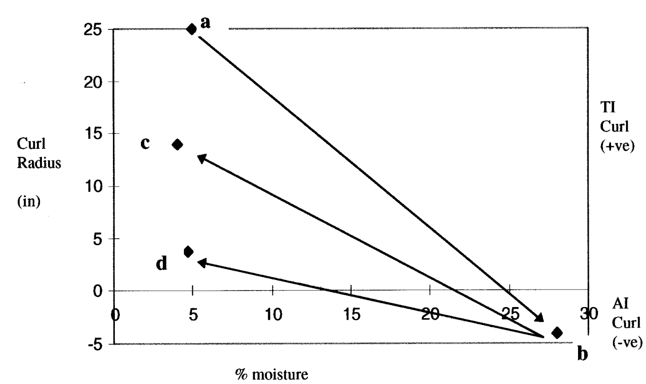

Figure 8. Steady State Curl Control

Conclusions

It has been shown that steady state curl which occurs during ink jet printing is due to shrinkage curl which produces Tl (toward image) curl. This curl is caused by the release of internal or drying stresses in the paper when moisture gradients and/or thermal gradients are introduced in the paper.

The severity of the steady state curl depends on paper properties, ink properties, the mode of printing and the mode of drying.

Rapid drying could be used to minimize the penetration of ink into the paper fibers, thereby minimizing internal stress relief in the paper, and the magnitude of steady state curl In the same way, because checkerboard printing minimizes the penetration of large quantities of ink into paper, steady state curl is minimized. Printing with reduced ink coverage and away from the edges of the paper also reduce the magnitude of steady state curl.

Mechanical decurling could also be utilized for eliminating steady state curl, but it requires that steady state curl be predictable.

Ink formulations with solvents which delay stress relief of paper fibers could cause steady state curl of large magnitudes to develop after several hours.

If no curl control is exercised during printing, the typical curl formation scenario consists of an almost immediate hygroexpansion Al (away-from-image) curl, followed by longer term Tl (toward-image) shrinkage curl.

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