WATER PENETRATION DYNAMICS AND FLEXO PRINTABILITY OF LINERBOARD

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ABSTRACT: It is extremely important for the corrugated box industry to increase and predict flexo print quality of linerboard. There is a lack of tools able to predict flexo print quality on the basis of measurement of physical or physico-chemical properties of linerboard. For example, the roughness of the substrate does not always correlate with the print quality. The reason for this may be different sheet formation with different paper machines, resulting in different ink penetration behavior. One of the best predictors of print quality up to now seems to be the dynamic contact angle measurement that has already proven itself to be a useful tool for predicting bar code readability. The work presented herein demonstrates a correlation between water penetration characteristics as measured by ultrasonic device EMTEC-PDA and printability of flexo printed linerboard using water-based ink.

INTRODUCTION

Whether print quality is judged by experts or by non-experts, print mottle is the most important factor affecting print quality. If the effect of all the factors that affect printability were taken as 100, the effect of mottle is approximately 50. This figures does not change substantially if the judges are scientists, technologists, technicians involved in printability research, professional printers, or members of a secretarial pool [Vanya,1989].

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Mottle, the irregular and unwanted variation in density (density mottle), gloss (gloss mottle), or color (color mottle) occurs in all printing processes. Mottle can also be defined as a spotty, non-uniform, or galvanized appearance of solids. There are many factors, and their combinations, causing mottle. Probably the most frequently occurring type in flexographic printability with water based ink is the absorptive mottle. Absorptive mottle is caused by an imbalance between the ink and substrate. Substrate that has non-uniform absorptivity, or ink exhibiting non-uniformly penetrating, causes visible mottling. More mottling occurs in board than in paper [Aspler, 1991].

Specular gloss of the print depends on surface roughness. Therefore, any increase of surface roughness lowers the gloss. The interactions of water based ink with paper increases sheet microroughness through fiber swelling, bond breakage, and stress relaxation [Skowronski, 1985]. Gloss mottling becomes severe especially in the multicolor printing.

As the demand for print quality increases, corrugated board producers have recognized that printing of boxes has become one of the primary challenges in the manufacture of high quality corrugated board [Shulman, 1994]. Clearly printed bar codes are needed to facilitate inventory control and product management; major retail chains in the U.S. have stated that suppliers will be rejected solely on the basis of having unreadable bar codes. While there are well-accepted test methods for measuring the strength properties of linerboard, corrugated medium, and combined board [DiDominicis, 1983], there are currently no commonly accepted testing methods for printability. Much remains poorly quantified concerning how to improve and test linerboard for surface quality. Also, as printing speed increases and flexo ink becomes more viscous, other factors such as pH, wettability, and surface strength may play an important role in determining printability.

Wetting is a surface phenomenon; therefore, it is unsatisfactory to view uncoated board as simply being composed of cellulose, hemicelluloses, and lignin, since the chemical composition of surface layers down to monomolecular thicknesses determine the wetting characteristics. Surface morphology also plays a role in wetting. Drops of nonwetting liquids tend to exhibit higher contact angles on rough surfaces and tend to extend more readily along grooves or fibers than across them [Oliver, 1976]. The penetration of aqueous liquids into lignocellulosic substrates such as linerboard is further complicated by absorption into fiber walls, and the consequent increase in fiber wall thickness. Swelling appears to be proportional to the amount of liquid absorbed [Chatterjee, 1971; Hoyland, 1977] and tends to close the voids in the fiber surfaces while enlarging interfiber voids in the fiber network.

Print quality depends on linerboard surface properties, dynamic water absorption, its surface smoothness, and surface formation [Aspler, 1998; Zangh, 1995]. Solids print density and ink holdout decrease as linerboard becomes rougher and more hydrophobic, but only when considered across the whole commercial range from brown top to white top to solid bleach linerboard. Within any single grade, roughness and water absorbency do not have any influence [Aspler, 1998]. On the other hand, the subjective quality of half-tone photograph increases as the board becomes smoother and brighter.

Ink transfer and mileage is of particular concern in flexography because of its high production volumes and the environmental concerns with flexo inks. No exact models are accepted for ink transfer in flexography [Aspler, 1993b]. In a flexo press, the ink is dried after each unit; thus, the second ink is transferred to a dry ink film or to the unprinted paper. In the second and subsequent units of a multi-color press, ink is transferred to both inked and uninked areas. Dry trapping (i.e., the transfer of ink on already printed and dried area) is generally not a problem, unless there are surface energy problems in wetting the dried ink. Ideally, the same amount of ink is transferred to the ink film as would be transferred to an unprinted paper surface. Generally, the ink absorption into the paper substrates is a function of both porosity and average pore radius. In addition, while porosity is important for ink adsorption, there are many other factors that influence capillary action, as described by the modified Lucas-Washburn equation [Zangh, 1995; Lepoutre, 1978]. Liquid penetration is affected by the local geometry of a pore system, hence grooved structures and convergent pore geometries accelerate the flow rate, while retardation occurs in divergent discontinuities in the coating layer structure. Also, the properties of the ink system determine the post-nip penetration characteristic [Kent, 1989].

Simple models describing ink transport, capillary action, diffusion, and setting or absorption have been reported [Nordstrom, 1995]. However, the interrelationships between these processes are poorly understood and much remains unknown, especially regarding the mechanism of ink transfer and setting [Nordstrom, 1995]. Ink spreading and penetration are not easy to predict because of varying ink viscosity and contact angle, i.e., the surface tension properties of the ink are not constant during the setting process. The reason is related also to the heterogeneity of the paper surface [Aspler, 1993b].

The functional principle of penetration dynamics analysis lies in transmitting ultrasonic signals through the sample which are reflected, scattered, or absorbed during the process of liquid penetration. As penetration proceeds, the ultrasonic receiver records any change in the signal. Depending on the pattern of liquid penetration into the sample, a typical curve is obtained that describes the parameters of wetting, saturation, or sample swelling. A better understanding of ink penetration dynamics as well as a better understanding of the paper properties most affecting ink penetration dynamics can help to understand and decrease mottling patterns and improve print quality. Our work aims to elucidate the effect of wettability on linerboard printability. To achieve this goal, a new type of analytical technique allowing quantification under controlled conditions of such factors such as wettability, ability to absorb liquids, and sizing is employed to correlate the water penetration dynamic with print quality of commercial linerboards.

EXPERIMENTAL

Printing

Commercially available white- top (W) and brown (B) linerboards were printed using water based Ultra Gloss Rubine (UGL026625) or Ultra Gloss Plus Jet Black ink (UGL 041201) from Water Ink Technologies. The viscosity of ink was measured as "efflux time" using a Zahn #2 cup. Ink efflux time was 24 s, which is 40 cP according to the conversion chart (Dietzgen Co., U.S.A.). Ink pH was maintained at a constant value of 9.0. Samples 11"x 17" were printed on a GMS single sheet drum flexo proofing press at 280 lpi. A 4 BCM anilox roll was doctored by a 0.008" steel doctor blade.

Analysis

Water Penetration Dynamics

Once the liquid makes initial wetting contact with the specimen, the ultrasound signal travels through both the liquid and the specimen. The power of the ultrasound signal received by the sensor changes with the time based upon the wetting characteristics of the specimen. The detected changes in ultrasound power are due to a combination of reflection, absorption, and scattering phenomena. Ultrasound reflectivity is described as:

$$\rho_1 = [(Z_1-Z_2)/(Z_1+Z_2)]^2 \quad (1)$$

Where ρ_1 = the reflectivity of an interface for ultrasonic radiation,
Z_1 = the ultrasonic impedance of the liquid involved [g/cm^2 .s], and
Z_2 = the ultrasonic impedance of the dry surface of the sample involved [g/cm^2 .s].

Absorption of ultrasound is described as:

$$I = I_o \, . \, e - \exp(4\pi v^2 \eta / \rho_o . c_o^3) . \, x \quad (2)$$

Where I = the intensity of a beam of ultrasound radiation after traveling a distance x through a medium [W/cm^2],
I_o= the intensity of a beam at x = 0 [W/cm^2],
v = the frequency of the beam of ultrasonic radiation [Hz],
η = viscosity of the medium in which the beam propagates [10^{-3} Pa.s],
ρ_o = the mass density of that medium [g/cm^3] and
c_o = the speed of the sound in the medium [m/s].

The ultrasound scattering is described by the Raleigh equation:

$$I_{sca} = I_0 . (\omega_0^4 R^6 / 9c^4 r^2) \{ 1 + 3/2 \cos \Xi \}^2 \qquad (3)$$

Where: I_{sca} = scattered intensity [W/cm^2],
I_0 = the intensity of incident beam [W/cm^2],
ω_0 = the angular frequency of the ultrasonic radiation [2πHz],
R = radius of the scattering centers [μm],
c = the speed of sound in the surrounding medium [m/s],
r = the distance between receiver and scattering centers [mm], and
Ξ = the scattering angle, i.e. the angle between a line extending from the scattering centers to the receiver and the incident beam [°].

Conditions for Raleigh scattering:

$R << \lambda$ where R = radius of scattering center; λ = wavelength

The experimental conditions were as follows: Water Penetration Dynamics was measured using EMTEC PDA 4.0 Penetration Dynamics Analyzer at 2 MHz frequency, 35 mm sample diameter, using deionized water at a temperature of 22°C as the penetration medium, falling level 70 mm, no insert was used.

Porosity, roughness and compressibility

A Parker Print-Surf Model ME 90 (Messmer Instruments Ltd., U.K) was used for both porosity and roughness measurements. Porosity was measured using a clamping pressure of 1000 kPa; roughness was measured at 500 and 1000 kPa. The compressibility was calculated as the ratio of roughness at 500 kPa and 1000 kPa clamping pressure.

Contact angle

Contact angles of linerboards were measured using a Fibro 1121/1122 DAT - Dynamic Contact Angle and Absorption Tester (FIBRO System AB, Stockholm, Sweden). Contact angles were taken at 0.1, 0.5 and 1.0 second. Deionized water was used for contact angle determination.

Image analysis

Area, perimeter, and roundness of magenta or black dots were recorded at a tone scale of 10 % by means of a Hitachi HV-C10 camera (Hitachi Denshi, Ltd., Japan). Image analysis was performed by means of computer software Image–Pro Plus, Version 3.0.

RESULTS AND DISCUSSION

The water penetration dynamics of linerboard from a variety of machines, geographic regions, and fiber furnishes were measured and compared to their respective printability. An Emtec PDA Penetration Dynamics Analyzer was used for the study. The dynamics of water penetration can give a rough estimate of wettability, ability to absorb liquid, and porosity. All of these characteristics correlate with print quality to some extent. Three parameters, w, Max, and A, are calculated from the penetration curves illustrated as a function of the time. Two of them, w and Max, represent surface qualities, and A represents fluid absorption over a defined period of time. The parameters w (non-dimensional value calculated with an empirical algorithm) and max (sec) are measures of the surface porosity and surface sizing. A, a non-dimensional empirical value, correlates to the Cobb value. However, little or no useful information about flexo printability has been obtained from the Cobb test so far [Steadman, 1993].
The water penetration curves for white and brown linerboards are illustrated in **Fig. 1** and **Fig. 2**.

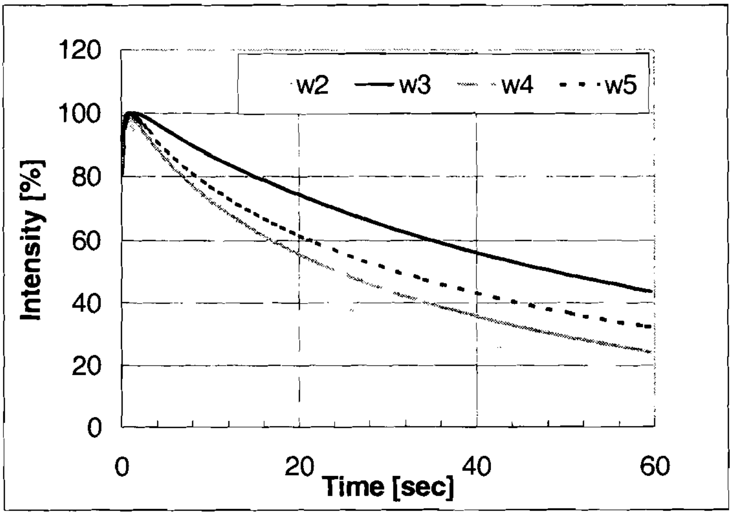

Figure 1: Water penetration dynamics curves for white linerboard

To better understand and utilize all of those parameters for characterization of linerboard interaction with printing ink, regression analysis between w and max, as well as w and A60 (fluid absorption over 60 seconds) was done.

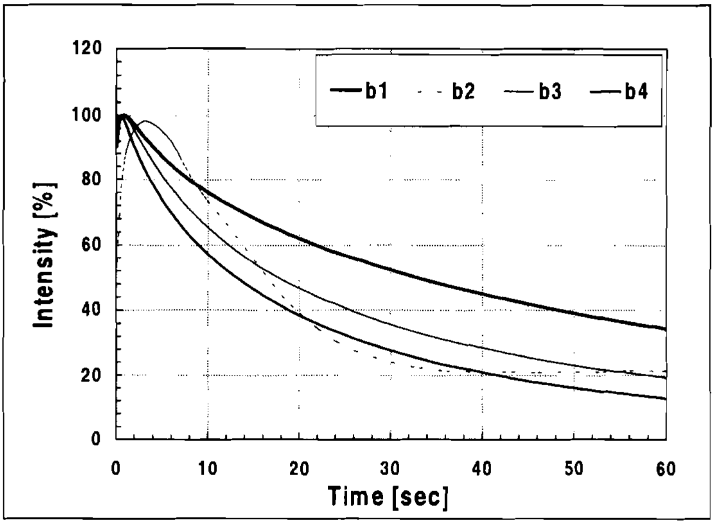

Figure 2: Water penetration dynamics curves for brown linerboard

An almost linear relationship was found for Max and w values, with a R-squared value R^2 = 0.99 for white liner [**Fig.** 3], and a logarithmic function with a value R^2 = 0.96 for brown liner [**Fig. 4**]. Those two parameters are in excellent accord. It means that it is sufficient to study one of these parameters, either w or Max, and its relationship to the printed substrate. This will provide maximum obtainable information and analysis of second parameter and its relationship with substrate printability will only duplicate previously found relationships. The correlation of w vs A60 resulted in a quadratic function with R-squared value R^2 = 0.50 for white liner. Correlation for brown liner was much worse (data not shown). Because of a lesser degree of w vs. A correlation, it is necessary to study separately A60 versus printability characteristics of linerboard.

The next step was to analyze surface properties of linerboards such as contact angle, roughness, porosity and their relationship with w and A60, respectively. The contact angle of linerboards correlated better with A60 values than with w or Max. A60 decreased with increasing contact angle following a quadratic function with the value R^2 = 0.69 with a local minimum at 97 degrees contact angle **[Fig. 5]**. A60 decreased slightly with increasing PPS roughness **[Fig. 6]**, having a R-squared value R^2 = 0.70 for the white liner, and for brown liner only R^2 = 0.25. PPS porosity correlated better with factor w than with A60 **[Fig. 7]**. Factor w decreased with increasing porosity. A quadratic function was found for the relationship of porosity vs. w with R^2 =0.75 for white liner and R^2 =0.40 for brown liner.

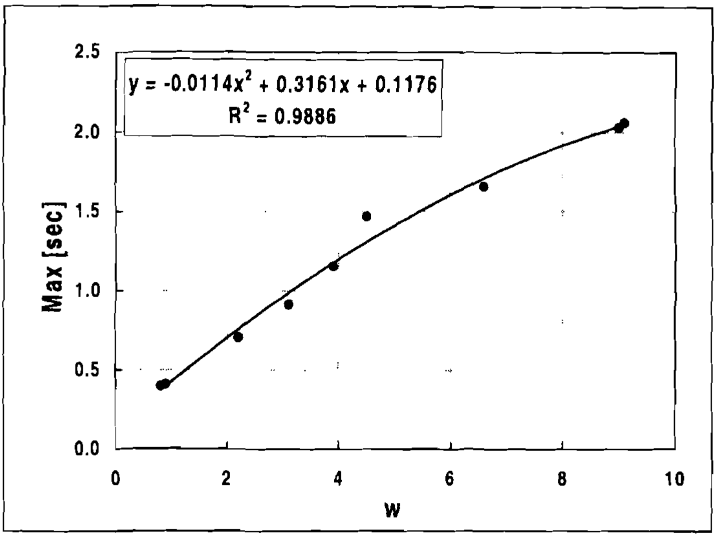

Figure 3: Max values versus w for white linerboard

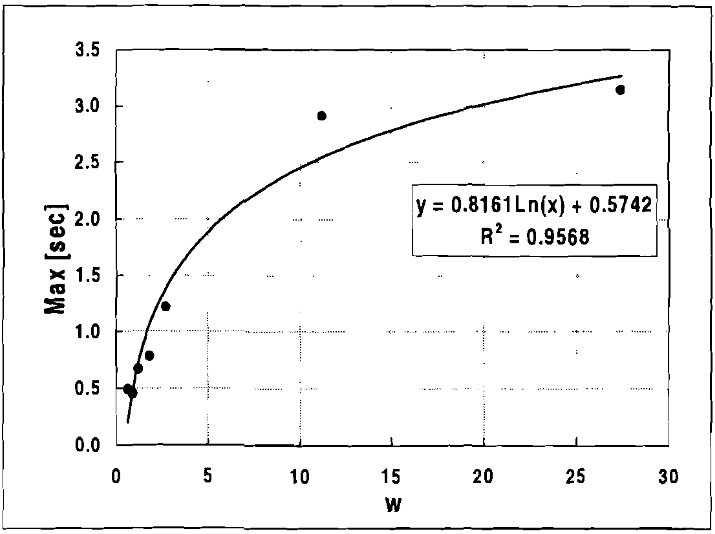

Figure 4: Max values versus w for brown linerboard

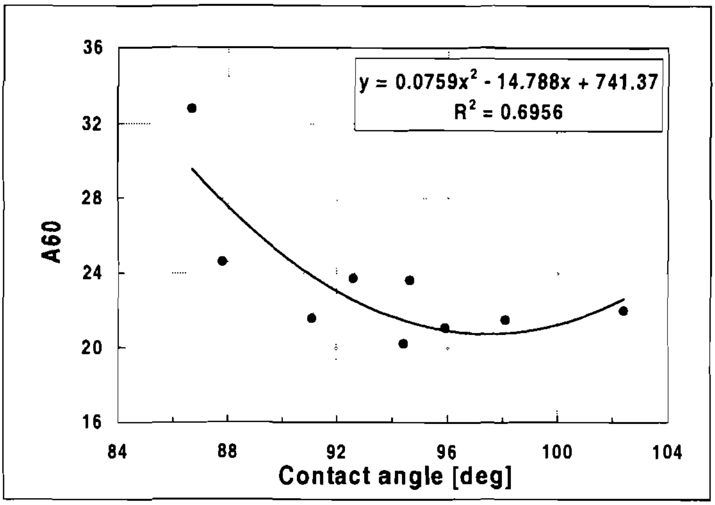

Figure 5: A60 versus contact angle for white linerboard

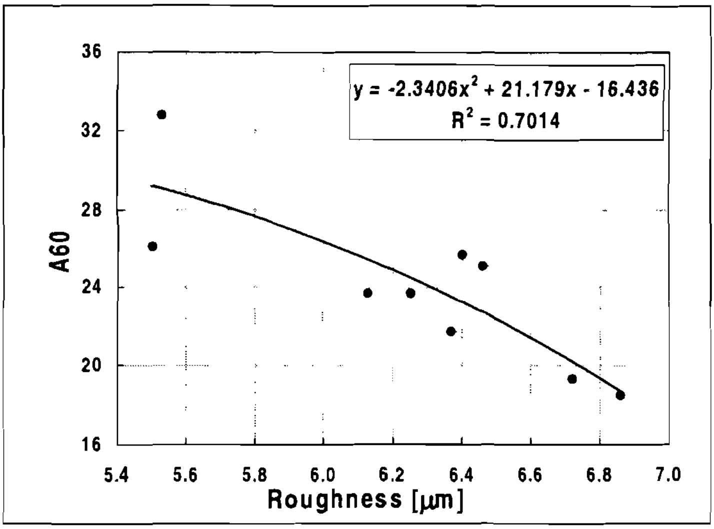

Figure 6: A60 versus roughness for white linerboard

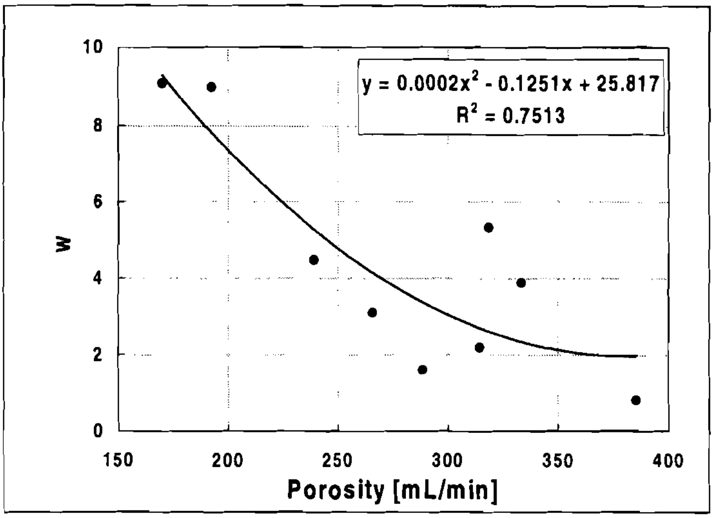

Figure 7: w versus porosity for white linerboard

Print gloss decreased with an increasing w value for both brown and white liner. The value $R^2 = 0.80$ was found for white liner **[Fig. 8]** and 0.41 for brown liner. Value A60 showed scattered relationship with print gloss.

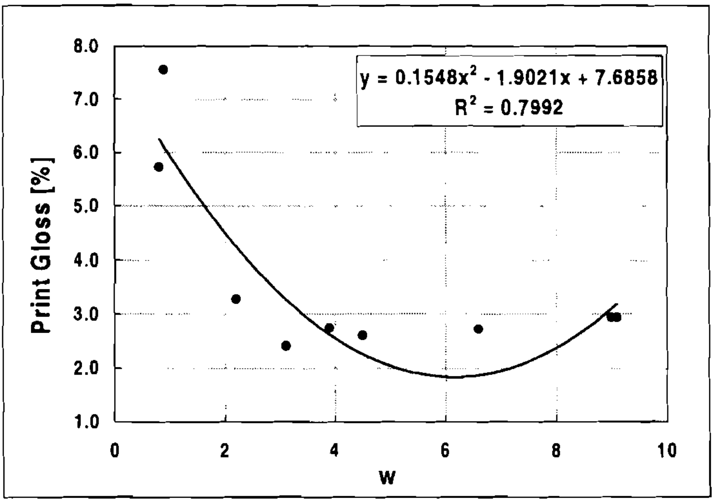

Figure 8: Specular gloss (60°) versus w value for white linerboard

The reflection density on solids decreased with an increasing w value with R-squared value R^2 = 0.85 for white liner **[Fig. 9]** and R^2 = 0.50 for brown liner. The reflection density correlated also with the A60 value. Reflection density decreased with increasing A60 or sample absorbency.

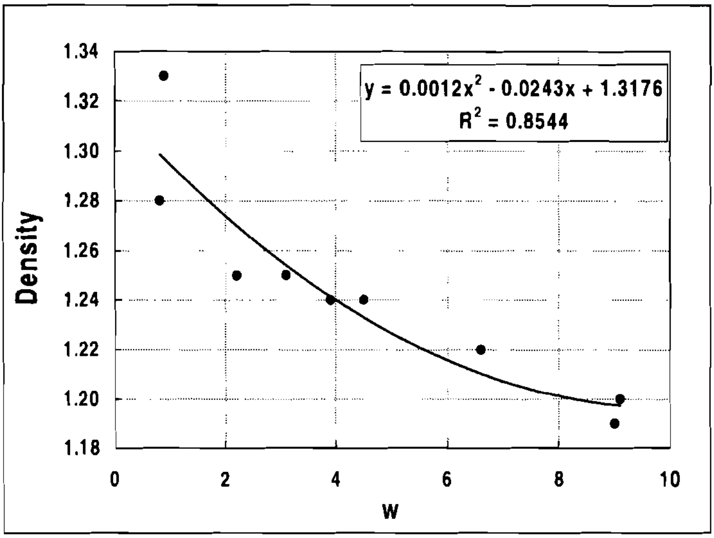

Figure 9: Reflection density on solids versus w for white linerboard

According to Aspler [1993], ink transfer increases with water absorbency. More ink is transferred to the more absorbent samples. However, greater ink penetration occurs into more absorbent boards; thus, print density is not necessarily higher. The "printing efficiency" or effective print density per gram of ink is lower on highly absorbent substrate [Mangin, 1984]. This is in good accord with our findings.

The print contrast decreased with an increasing w value, but the R-squared value was only 0.42 for white liner, and the relation was scattered for the brown liner. Dot gain increased with increasing w value, having a value R^2 =0.92 for the white liner **[Fig. 10]**. Density mottle also increased with increasing w value. The R-squared value was 0.45 for the white liner for mottle vs. w value. Mottle, as opposed to print uniformity, is an important factor in print quality. Wetting problems are a known cause of mottle in printing coated boards with water based flexo inks [Jensen, 1989; Bassemir, 1991]. Observers react strongly toward print mottling [Wågberg, 1992]. Image analysis, dot area, perimeter, and roundness, was performed in relation to w and A 60 values, and no strong relationship was found.

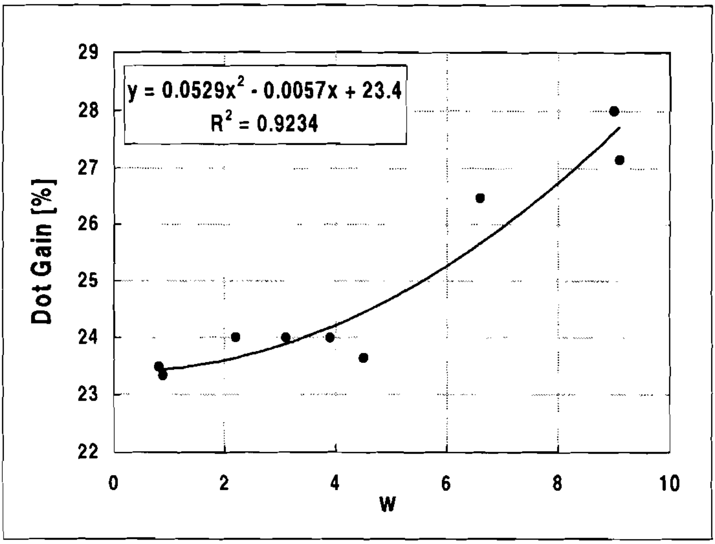

Figure 10: Dot gain versus w value for white linerboard

A regression analysis of print density, print contrast, dot gain, and specular gloss with penetration dynamics characteristics confirm that the w value is the most useful parameter for linerboard print quality prediction. It was found that an increasing w value decreases linerboard print quality. Furthermore, A60 has less influence on print quality than does the w value. Better R-squared values were found for white liners than brown ones. This may be connected with the fact that higher variation of sample quality (roughness, porosity, sizing, contact angle, linerboard fiber type) was observed for brown liners.

CONCLUSION

The Emtec PDA penetration dynamic analyzer was used for linerboard water penetration dynamics characterization. The study was done by correlating parameters w, max, and A with the linerboards' flexo printability characteristics (reflective density, specular gloss, print contrast, dot gain, image analysis). It was found that w closely correlates with the Max value. Therefore, for characterization or prediction of printability, it is sufficient that only one of the parameters w or Max be used. The parameter A60 correlated better with the linerboards' contact angle and roughness than the w value did. On the other hand, it was found that specular gloss, reflective density, dot gain, and print contrast correlated better with the w value than with the A60 value. Print quality measured by using the above characteristics (gloss, density, dot gain and print contrast) decreases with an increasing w value. Also, the correlation was better when done in a narrower spectrum of samples.

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