Correlation of Misdirected Satellite Drops and Resultant Print Quality Defects with Nozzle Face Geometries in Thermal Ink Jet Printheads

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Abstract

Satellite drops are a normal consequence of liquid ink drop ejection from the nozzle structures of ink jet printheads. Misdirected satellite drops can cause observable printing defects which significantly degrade printer performance.This is especially true when the misdirection is consistently along the process direction and the printhead is used, for example, in a bi-directional carriage printing application. When misdirected satellite drops fall outside the main ink spot on the print medium, the spot is no longer circular, but rather elongated. Collectively, the effectively larger and misshaped spots result in optical density shifts in fine-toned print patterns as well as ragged edges on printed text and lines. It has been determined experimentally that such misdirected satellite drops can be generated when the plane of the ink meniscus at the nozzle face deviates significantly from being perpendicular to the plane of the channels. The deviation is referred to as the effective meniscus tilt angle (θ_{TILT}), and is established by critical front face geometries. This paper describes the experiments and data analysis used to correlate q_{TILT} values in thermal ink jet printing devices with resulting misdirected satellite print quality defects. The results have been used to set printhead manufacturing tolerances such that satellite-related print quality defects can be avoided.

Introduction

Drop-on-demand ink jet printing is rapidly becoming the technology of choice for the low-end printer market. In particular, state-of-the-art thermal ink jet printheads have enabled this technology to produce low cost, high quality printers with relatively high speed and quiet operation. As competition rapidly drives the market to even higher levels of performance (greater resolution, higher speed, full color capability, etc.), the demands on print quality become more severe. Although the interaction between the ink and the print medium ultimately determines the level of print quality that can be achieved, print quality defects originating at the drop ejector itself must be controlled within acceptable limits. The more obvious of such defects include jet misdirectionality, drop size variation, and jet dropout, among others. Second order print quality defects however are often associated with the smaller satellite drops which typicallyaccompany the primary ink drop on its path to the print medium. The satellite drops arise from the breakup of the ligament or "tail" of ink which attaches the ejected drop to the ink in the printhead channels prior to separation. Under desirable drop ejection conditions, the ligament breaks off at or very near the center of the nozzle structure, and the satellites generated follow the same trajectory as the primary ink drop. For drop motion parameters, throw distances, and printing speeds typical of most ink jet printing applications, such satellite drops will fall within the ink spot area created by the primary drop on the print medium, and no print quality defects are observed. If, however, nozzle face conditions are such that the ligament breaks off at a location other than the center of the nozzle structure, "tail bending" will occur and the satellites formed follow a trajectory different from that of the primary drop, resulting in print quality defects. If the cause of this satellite misdirectionality affects all or a large number of jets, the effectively larger and misshaped spots result in optical density shifts in fine-toned print patterns as well as ragged edges on printed text and lines. Whether or not these satellite-related print quality defects are observed depends on the direction of relative motion between the printhead and the print medium, the process speed, and the throw distance from nozzle to medium. Print quality defects arising from misdirected satellites such as those described above are perhaps most noticeable when the printhead is used in bi-directional carriage printer applications. In such cases, when satellites are mis-

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directed along the process direction, print quality defects can appear when the printhead travels in one direction but not in the other. The result is a swath-to-swath "banding" problem caused by the enhanced optical density for the alternate swaths exhibiting the print quality defect.

Origins of Misdirected Satellites

Random front face wetting, which tends to destroy the physical symmetry of the nozzle structure can cause the drop ligament to break off at locations other than the nozzle center and cause misdirected drops as well as satellite-related print quality defects. In the present case, however, it has been found that when the plane defined by the nozzle face deviates from being perpendicular to the direction of drop ejection, the ligament break-off location moves from the center of the nozzle toward the site on the nozzle face with the most advanced position. A nonperpendicular nozzle face can result from various processing steps in the fabrication of the die print module. The Xerox thermal ink jet printhead design makes extensive use of silicon integrated circuit fabrication technologies in order to manufacture the printing devices (die). A heater wafer is fabricated using silicon IC fabrication technology to produce arrays of heater transducers which are coupled to integrated electronics (logic and driver circuitry).[1] The top surface of the heater wafer is patterned with a relatively thick (~10-50 microns) organic material (e.g., polyimide) which passivates the underlying electronic circuitry and also places the heater surface at the bottom of a pit structure to improve jetting characteristics.[2] A corresponding channel wafer is processed using silicon orientation dependent etching (ODE) techniques to form the ink jet channels (with triangular cross section), ink reservoir structures, and ink inlet openings.[3] The two wafers are then aligned and bonded together to form a sandwiched pair, which is then precision diced to produce individual printing device die modules. It is during this dicing operation that the nozzle face is formed. The final step before the devices are packaged into printheads is to coat the front face with a hydrophobic thin film to improve jet directionality and print quality.[4] Part of the coating process is a plasma etching step prior to the thin film deposition which removes dicing debris and organic residue from the front face, promoting adhesion of the hydrophobic coating. Since the polyimide pit layer is an organic material, an amount of material is also removed from the front face at the base of the nozzles. The plane of the nozzle face is therefore determined by the dicing angle (θ_{DICE}) and the amount of polyimide which is removed from the base of the channels during the plasma etching step (X_{PE}). The resulting situation is shown schematically in Figure l(A), where the plane of the nozzle face is shown as deviating by some angle from being perpendicular to the ink channel. Referred to as the effective meniscus tilt angle, θ_{TILT} can be defined relative to a line perpendicular to the planes of the heater/channel plates by an imaginary line joining the channel apex to the polyimide edge. [Note: We will adopt the convention that angles are positive when measured counterclockwise from the perpendicular (as shown), and negative when measured clockwise from the perpendicular.] Simple trigonometric relationships lead to the following expression for θ_{TILT}:

$$\theta_{TILT} = \tan^{-1}\{[(X_{HP} — X_{CP}) + X_{PE}]/H\}, \qquad (1)$$

or,

$$\theta_{TILT} = \tan^{-1}\{\tan q_{DICE} + X_{PE}/H\} \qquad (2)$$

where: X_{CP} = channel plate offset (+ for protruding apex, -for recessed apex),
X_{HP} = heater plate offset (+ for protruding apex, - for recessed apex),
X_{PE} = polyimide undercut distance (due to plasma etching),
θ_{DICE} = dicing angle (+ for protruding apex, - for recessed apex),
and H = channel height (from polyimide surface to channel apex).

The equation is also valid for negative tilt angles which occur, for example, when there is negligible polyimide undercut ($X_{PE} \rightarrow 0$); under such conditions, X_{HP} is redefined as the distance to the leading edge of the polyimide layer, as shown in the diagram of Figure l(B). Assuming a hydrophobic front face condition, the relative positions of the channel apex and the edge of the polyimide layer will determine the effective meniscus tilt angle (EMTA) of the column of ink in each channel. For either situation, the result is an effective tilt of the meniscus for the ink in the channel, and this is the parameter which must be controlled if the satellite problem is to be controlled.

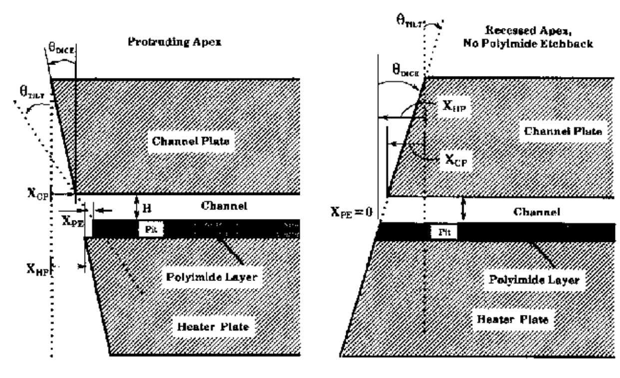

Figure 1. Schematic definition of the effective meniscus tilt angle, θ_{TILT} , for (A) positive and (B) negative values

Experimental Details

The objective of the experiment was to establish a quantitative relationship between the magnitude of the satellite-related print quality defect and the effective meniscus tilt angle, θ_{TILT}. In order to characterize the magnitude of the satellite related print quality defect as a function of the changes in front face geometries, a metric referred to as the spot aspect ratio (SAR) was used. This metric is simply the ratio of the length of the spot in the process direction to the width of the spot in the channel-to-channel direction. Thus, perfectly round spots would have SAR values of unity, while spots elongated in the process direction by misdirected satellite drops would have SAR values greater than unity. Fortunately, this ratio can be quickly and easily measured for large numbers of test pattern spots through the use of computer automated vision systems (and appropriate software) such as the Cognex®- based system described in a previous publication.[5]

The remaining task was to be able to systematically vary the two major factors affecting the front face EMTA (i.e., dicing angle and polyimide undercut), and then assess the impact on print quality by measuring the resultant SAR. It was possible to alter the front face dicing angle on an individual die module by using a precision front face "shaving" process on the dicing saw after it had already been diced from the sandwiched wafer pair. The degree of polyimide undercut (etchback) was varied by changing the duration of the plasma etch portion of the front face coating process.

A total of seventeen 128-jet die modules were included in the study. All of these devices had nominal (triangular) channel dimensions of 66 microns width at the base and 45 microns height to the channel apex. After standard wafer pair dicing, individual devices were then precision shaved to provide a range of both positive and negative dicing angles (θ_{DICE}). These values were then coupled with various levels of polyimide undercut produced during the hydrophobic front face coating process. The combined effects of the two processes produced θ_{TILT} angles ranging from about -5.0° to + 10.0° as determined by an optical microscope and depth of focus measurements (accuracy ~ ±0.5µm at 500X magnification). Die-level print quality tests and measurements of spot aspect ratio (SAR) in both "forward" and "reverse" paper motion directions were made under typical print conditions (4.5kHz, 0.035" throw distance) for each device using the die probe print test station[5] and Cognex® system. For these tests, the "forward" direction is arbitrarily defined as that in which the print medium moves from the channel apex toward the channel base, and vice versa for the "reverse" direction.

Results

The resultant data is presented as a plot of SAR vs. the effective meniscus tilt angle (θ_{TILT}) in the graph of Figure 2 for both forward and reverse paper motion directions. In order to show the data as a continually varying function, the deviation from an aspect ratio of unity, ±(SAR-1), is plotted along the ordinate axis. A positive value for this function means that the satellite drops emerge from the main spot on the apex side of the channel, while a negative value means that the satellites emerge from the channel floor side of the main spot, regardless of paper motion direction. The cross-hatched band on the plot (SAR values between 1.1 and -1.1) shows the approximate range of SAR deviation which is qualitatively (and conservatively) regarded as being acceptable with respect to the satellite-related print quality defect. More quantitative boundaries can be established by using optical density measurements, if desired. It can be seen from the data that for positive values of θ_{TILT}, SAR values do not exceed the limit until effective meniscus tilt angles ~4.5°-5.0° are reached. At this point, SAR values increase rapidly for the forward direction of paper motion. For negative values of θ_{TILT}, SAR values do not exceed the lower limit until effective meniscus tilt angles of approximately -2.5° or more are reached. At this θ_{TILT} value the SAR increases rapidly for the reverse direction of paper motion. Thus, a window which is free of significant satellite-related print quality defects exists for effective meniscus tilt angle values ranging from approximately -2° to + 4°.

As further confirmation that our understanding of the origins of these misdirected satellites was correct, we were able to take die modules which did not exhibit a satellite-related print quality defect and convert them into devices with the defect by shaving the front face at a more extreme angle. Similarly, die modules having the satellite-related print quality defect were converted to non-defective devices by shaving the front face to produce a more nearly perpendicular EMTA.

Discussion and Analysis

If ink jet printing devices are to be free of misdirected satellite print quality defects, manufacturing specifications must be set which control the resultant geometry of the die module front face during its fabrication, i.e. the dicing angle (θ_{DICE}) and the amount of polyimide etchback during the front face coating process. Figure 3 shows the effective meniscus tilt angle (θ_{TILT}) as a function of front face dicing angle (θ_{DICE}) for polyimide etchback distances (X_{PE}) ranging from 0 to 5 µm. The relationships are calculated from the given expression for θ_{TILT}, where the channel height distance for these devices (45 µm) has been substituted for the parameter H. The acceptable range of values for θ_{TILT} with respect to the satellite problem (ref. Figure 2) is indicated by the cross-hatched region, thus giving the acceptable process latitude windows for dicing angle and polyimide etchback. In practice, minimum levels of polyimide undercut required for sufficient front face adhesion exist, as do limitations in dicing angle accuracy. Once these values are determined, the manufacturing engineer is able to use the data of Figure 3 to optimize the dicing and etching processes. For example, if the necessary (or typical) plasma etchback value is X_{PE} = 2.0 µm to enable sufficient front face coating adhesion, then θ_{DICE} is restricted to values between + 1.5° and -4.5°. The same analysis has also been applied to smaller channel devices, and experimental data have correlated well with analytical calculations.

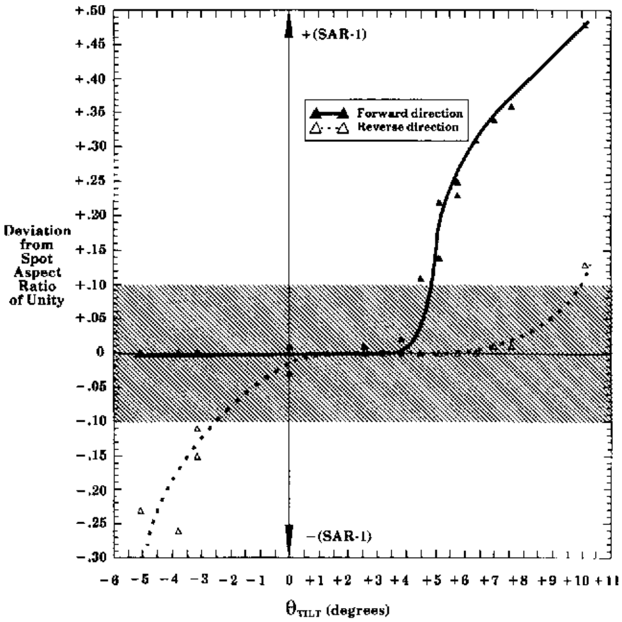

Figure 2. Spot Aspect Ratio (SAR) vs. Effective Meniscus Tilt Angle (θ_{TILT})

Conclusion

The causes and corrective measures required for control of misdirected satellite-related print quality defects are well understood in terms of the effective meniscus tilt angle and related front face topographical features. Engineering solutions to the problem can be achieved through appropriate control of front face dicing angle and/or total polyimide etchback within the “acceptable” process latitude ranges which have been identified for these parameters.

Acknowledgments

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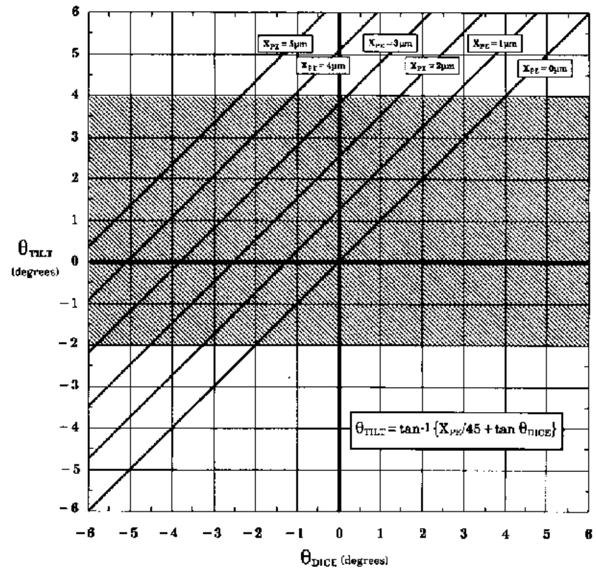

Figure 3. Effective Meniscus Tilt Angle (θ_{TILT}) *vs Dicing Angle* (θ_{DICE}) *and Polyimide Undercut* (X_{PE})

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