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Experimental Study of the Influence of Nozzle Defects on Drop-on-Demand Ink Jets

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Abstract. *The effects of nozzle defects on the behavior of drops ejected from drop-on-demand printheads were studied. Nozzles in two types of commercial printheads were modified with two different micromachining techniques: focused ion beam (FIB) milling and pulsed laser micromachining. Nozzles were modified by producing single or multiple notches on their edges. The studies focused on the volume, speed, and direction of travel of the drops. Fifteen different types of geometrical defects on nozzles were studied. Shadowgraph images were used to determine the drop size, speed, and trajectory from the same nozzles before and after modification. The results indicate that geometrical defects up to* ∼*100* μm^2 *at the front (exit) face of a 50* μ*m diameter tapered nozzle do not cause any significant variation in the behavior of these nozzles, but that defects at the back (entry) of the nozzle can have a major effect on the direction of jetting.* © *2011 Society for Imaging Science and Technology.*
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INTRODUCTION

The number of potential novel applications of ink jet technologies has increased in recent times.[1] Current proposals range from DNA arrays to printed electronics. Regardless of the application, several issues must be solved for these technologies to become a reality. Satellite droplets, the nozzle geometry and its size, the fluid properties and the driving waveform are all variables that affect the jetting of droplets and as such have to be controlled to optimize the printing process. As theoretical models and numerical simulations are often limited to symmetrical geometries, and to relatively simple (e.g., Newtonian) liquid properties, users are obliged to make trial-and-error tests to determine the best conditions for printhead operation.[2–7] It has been observed that individual nozzles within a printhead can behave in different ways as a result of factors such as nozzle imperfections, the presence of dried ink around the nozzles, inhomogeneities in the piezoelectric elements and in the nozzle plate material, and the presence of air bubbles in the printhead channels.[8] In this study, our efforts are concentrated on nozzle imperfections and their effects on jet and droplet directionality.

Defects in nozzles are common in many (if not all) commercially available printheads. It is generally accepted that these defects affect the function and reliability of printing. However, very few studies have been carried out to quantify these effects. The influence of nozzle properties on jet directionality has received little attention because the modification of small nozzles (typically tens of micrometers in diameter) is difficult: it would require precise micromachining in a way that should not affect the normal operation of the printhead. In practice, the modification of such small nozzles presents challenges, as it requires the use of precise techniques not only to machine the nozzles but also to characterize their geometry once they have been modified. In addition to this complication, a wide variety of nozzle plate designs exists and the geometrical tolerances can vary greatly depending on the manufacturing technique used to create the nozzles.

In this article, a technique based on shadowgraph imaging is used to observe changes in the jetting direction of printed droplets. Two methods are used to produce defects on two types of nozzles in a controllable way. A series of experiments is carried out to quantify the effects of these nozzle defects on the behavior of droplets jetted from commercial piezoelectric drop-on-demand printheads. The results are divided into four groups: (i) experiments using a focused ion beam (FIB) to make notches in the nozzle exit; (ii) experiments where single notches were created by laser pulses; (iii) experiments where the inside surfaces of nozzles are modified; and (iv) experiments involving more complex patterns of notches.

EXPERIMENTAL METHODS

Two techniques widely used for micromachining were used to produce rectangular defects (notches) on the nozzle plates of commercially available printheads. FIB milling is an accurate technique usually used in research and to fabricate features on metallic substrates and consequently was utilized on a printhead with a metallic nozzle plate. In contrast, laser micromachining is regularly used for the rapid drilling of metallic and nonmetallic substrates and was utilized to modify a printhead with a polyimide nozzle plate. These experimental techniques are described more fully below.

FIB Milling

The technique of FIB milling is used in materials science to machine materials on scales ranging from a few nanometer

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to micrometer. Scanning electron microscopy (SEM) is often used in conjunction with FIB to direct the probe and observe its effects. A FIB can be used to remove material from the edge of a metallic nozzle in a very accurate way by the action of focused high-energy ions. In this work, FIB milling was used to produce square notches in the edges of a set of nozzles. The aims of these experiments were to produce well-characterized defects in printhead nozzles in the form of notches, and to characterize the directionally of the droplets ejected from these nozzles. The milling was carried out with a Carl Zeiss 1540 XB CrossBeam FIB/SEM system.

The first series of experiments used a Spectra Dimatix SE-128 printhead. This printhead typically produces drops with a volume of ∼30 pl at 8–12 m/s and has a gold-coated nickel nozzle plate, with 128 nozzles, 35 μm in diameter, spaced at a pitch of 508 μm. All the working nozzles of an unused printhead were initially inspected by SEM to look for preexisting defects. Although remnants of dried ink (used in testing) are usually observed on the surface of the nozzle plate, some other defects which intruded into the nozzle outlet, apparently on the surface of the nozzle plate, were also occasionally observed. As these features showed a similar contrast and luminosity in the SEM images, it was concluded that they were probably composed of the same material as the nozzle plate and quite possibly produced during the nozzle manufacturing process. An example of these features is shown in Figure 1(b).

The FIB system was then used with an ion current of 50 pA to machine square notches on the sides of nozzles. Three notch sizes were machined: 1×1, 2×2, and 3×3 μm^2. At this current and with this substrate (gold-plated nickel), a machining tolerance of ∼50 nm was achieved. The FIB technique has the advantage of being very precise, but the disadvantages of being applicable only to metallic materials and being slow (e.g., drilling a 3×3 μm^2 notch through the nozzle plate took ∼1.5 h). In addition, the method is not very flexible, as samples are subject to high vacuum and the size of the instrument chamber limits the size of printhead which can be modified. All the notches were machined completely through the nozzle plate as shown in Fig. 1(c).

After the nozzles had been modified, the printhead was used to carry out jetting experiments to quantify the effect on the droplet directionality caused by the machining of notches. All the jetting experiments were performed with a commercial black UV-curable ink.

Pulsed Laser Machining

The aim of these experiments was to extend the studies carried out with the FIB to a scale where the size of the defects machined on the sides of nozzles was considerably larger, observable and quantified.

For these experiments, a Xaar XJ126 printhead was used, with a polyimide nozzle plate, and these larger defects were formed by pulsed laser micromachining. This technique is much more rapid than FIB milling and readily applicable to polymeric materials; it is not as precise as FIB but much more flexible as it does not require the printhead to be machined in a vacuum or even to be dried, and is not restricted to metallic materials. All the working nozzles on the printhead were inspected by optical microscopy. Some examples are shown in Figure 2(a). After inspection, some nozzles were then modified with the introduction of edge notches ranging in size from 4×4 to 25×19 μm^2, as shown in Figs. 2(b)–2(d).

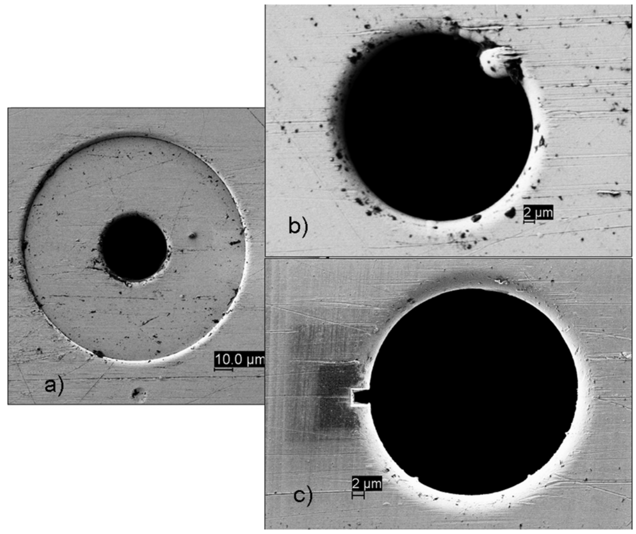

Figure 1. SEM images showing: (a) a Spectra Dimatix nozzle (with a nickel nozzle plate; (b) an example of a typical naturally occurring defect on this printhead; (c) a notch on the side of a nozzle, produced by focused ion beam milling.

The Xaar XJ126 printhead has 126 active nozzles, with an outlet diameter of 50 μm and a pitch of 137 μm. Machining was performed with a Nd:YAG pulsed laser (New Wave Quicklaze 50ST2) mounted on a three-dimensional stage support. To machine the notches, a focused train of ultraviolet laser pulses (wavelength 355 nm), 4 ns in duration and with energy of 2 mJ per pulse, was used. The number of pulses was varied to control the size of the notch. In contrast to the FIB, the machining of a square notch 25×25 μm^2 was carried out in ∼500 ms. However, the optical and mechanical elements used limited the machining quality to tolerances of the order of 3–5 μm. Notches were cut on the sides of nozzles into the nozzle plate with the following dimensions: 4×4, 12×7, 16.5×15, 19×17, and 25×19 μm^2.

Thirty nozzles were modified for these experiments: they were machined in sets of three with the same size of defect. Sets of three nozzles were machined with the same notch size located to one side and another set of three was machined with the notches located on the other side. The behavior of this printhead was tested before and after its notches were machined by jetting droplets of diethyl phthalate at 5 m/s.

Further experiments with the Xaar printhead were carried out with symmetrically placed notches cut by laser

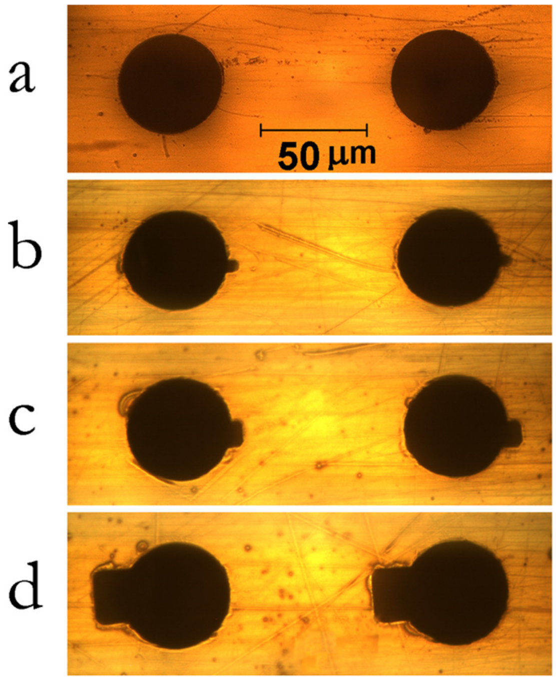

Figure 2. Optical images of nozzles in a Xaar XJ126 DoD nozzle plate: (a) unmodified nozzles; (b) nozzles with notches of $4 \times 4\ \mu m^2$; (c) nozzles with notch sizes of $12 \times 7\ \mu m^2$; and (d) nozzles with notches of $25 \times 19\ \mu m^2$.

micromachining as shown in Figures 3 and 4. All these notches were perpendicular to the nozzle plate (which was $\sim$50 μm thick) and penetrated fully through the material as shown at the bottom of Fig. 4.

The aim of these experiments was to study the behavior of droplets formed by differently modified nozzle geometries. The directionality, speed and volume of the main droplets produced from these nozzles were studied and compared with the values for unmodified nozzles in the same printhead. Five different patterns of notches were created on a Xaar 126 printhead by laser machining. These geometries were: two opposed notches each $7 \times 7\ \mu m^2$ in size across the axis of the nozzle; two opposed notches each $7 \times 11\ \mu m^2$ in size across the axis of the nozzle; four notches each $7 \times 7\ \mu m^2$ in size placed on the vertical and horizontal axes (bottom left image in Fig. 3); four notches each $7 \times 7\ \mu m^2$ in size placed at diagonal positions on the nozzle (bottom right image in Fig. 3); four L-shape notches each located on the vertical and horizontal axes (top right image of Fig. 3).

Identical defects were machined in groups of three nozzles surrounded by neighboring unmodified nozzles used as control references. The jetting of both printheads was analyzed by an imaging system described in the section Shadowgraph Imaging and Droplet Directionality Analysis.

Shadowgraph Imaging and Droplet Directionality Analysis

A shadowgraph technique was used to visualize the jetting of droplets from the printheads described above. The experimental setup is shown in Figure 5 and was a conventional

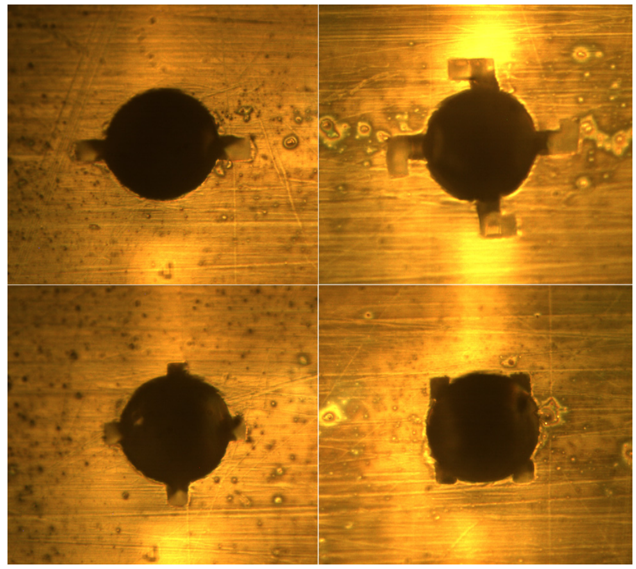

Figure 3. Examples of symmetrical patterns machined on the nozzles of a Xaar XJ 126 printhead by UV laser micromachining (optical images). In these optical images, some residues of the jetting fluid are present in the notches.

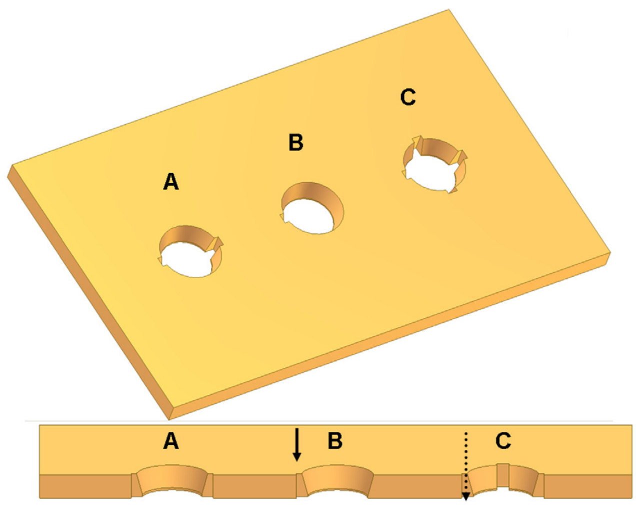

Figure 4. Examples of symmetrical patterns machined on the nozzles of a Xaar XJ 126 printhead by UV laser pulses. In (a), a nozzle with opposed notches across the nozzle axis is shown. (b) A single notch on a side of the nozzle. (c) shows a nozzle where opposed notches have been machined on both the vertical and horizontal axes. Notches were machined perpendicular to the nozzle plate, as indicated by the arrows.

shadowgraph system in which the droplets are illuminated from behind so that the droplet shadows are recorded.[9] A double spark flash was used as a light source to freeze the motion of the droplets at two different times.

Droplet images were captured with an optical system consisting of a microscope lens array (Navitar 12X Ultra zoom), a Nikon D80 DSLR camera and a double-flash spark light source (Nanolite). The flash duration was 20 ns, and both printheads were driven to produce droplet speeds of approximately 5 m/s.

The direction of motion of the drops ejected from individual nozzles was determined from analysis of the

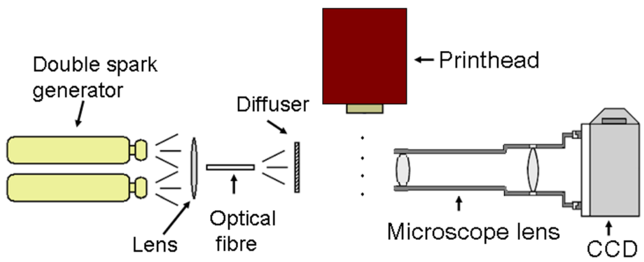

Figure 5. Double-flash shadowgraph system. A Nikon D80 DSLR was used to record the images at a resolution of 10.2 megapixels.

double-flash images, by calculating the vectors joining the drop positions at the two different times, as shown in Figures 6 and 7. The method used to identify the position of the center of mass of the droplets from such images is described elsewhere.[10]

The direction of the jetted droplets was determined for all the working nozzles of both printheads in batches of images each covering ten jets. Each image overlapped its neighboring images to the extent of five jets. With the same optical system, images of a precision square grid (microscope graticule) were also captured to determine a correction factor for the optical distortion of the lens. A third-order polynomial function was computed and applied to the droplet position data to compensate for this small but significant distortion.

The direction of drop travel from each nozzle was taken as the mean value derived from five separate images. All the nozzles in printheads were characterized in terms of the jet direction before and after modifications to identify any differences.

RESULTS

Figure 8 shows results of jet directionality from the Spectra Dimatix printhead before and after the modifications by the focused ion beam technique. In brief, they indicate that notches with sizes 3×3 μm^2 and even smaller did produce some change in the jet direction, but that these effects are difficult to quantify and reproduce because they are superimposed on the intrinsic variability in directionality of the jets, which is observed when the printhead is emptied of ink, studied by SEM, and then remounted and refilled with ink. Those processes alone produced directionality changes as large as 0.7° and may be associated with ink deposits around the nozzle inlets. In brief, two important conclusions can be drawn from the experiments with FIB: (i) the double-flash imaging results confirmed the intrinsic jet straightness variability claimed by the printhead manufacturer (<1°); and (ii) very small notches do affect the directionality of jets, but the deviation is of the same order of magnitude as the natural variability observed between the nozzles in an array.

As mentioned above, all the nozzles of the Spectra printhead were inspected optically and by SEM, and thus the effect on the jet directionality could also be determined for those nozzles with "additions" (i.e., intrusive features as shown in Fig. 1(b)). Our observations indicate that the direction of deflection of the jet caused by a defect cut into the edge of the nozzle (i.e., a notch) is always in the direction of the defect, while if the defect consists of additional material, then the direction of deflection is away from the defect, as illustrated in Figure 9.

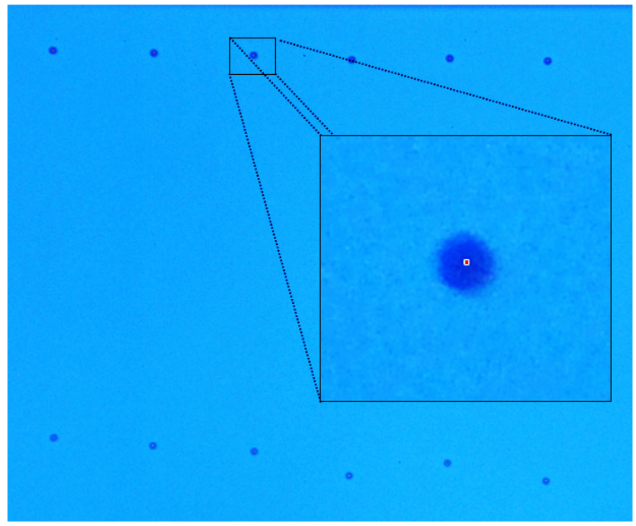

Figure 6. Double-flash shadowgraph image showing a set of six droplets jetted from the Spectra Dimatix SE-128 printhead. Six droplets are observed in the top row and the same six droplets are imaged at the bottom 700 μs later.

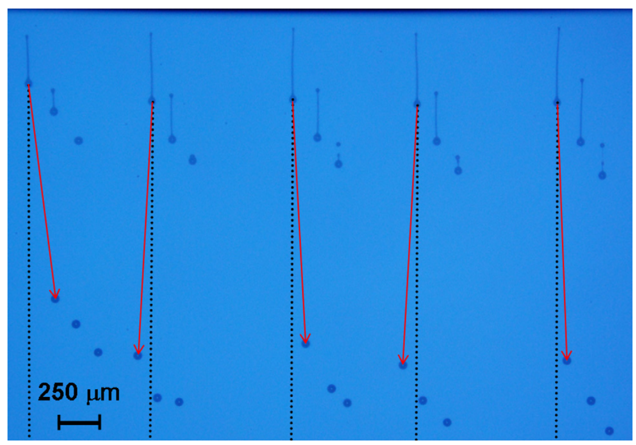

Figure 7. Double-flash shadowgraph images showing the direction of jetting. This image shows 12 jets produced by a Xaar 126 XJ printhead.

The results obtained with the Xaar printhead, which was modified by laser micromachining were consistent with those from the FIB experiments. The results are shown in Figure 10, where the variation of jet direction with notch length is presented. In brief, notches smaller than 7×9 μm^2 did not produce significant changes in the jetting behavior. The inherent variability of jet direction in this printhead was ~1°.

The droplets jetted from symmetrically modified nozzles were observed with the shadowgraph system and the images analyzed as described above. The results are shown in Figure 11 (marked "symmetrically modified") and

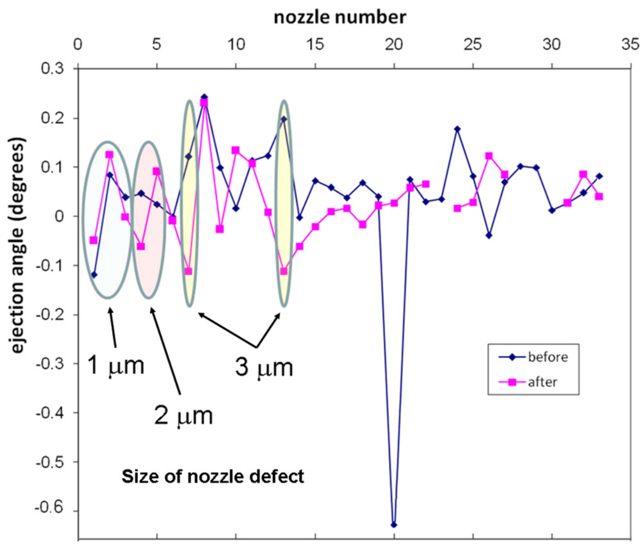

Figure 8. Angles of droplet travel (relative to the nozzle plane normal) before and after nozzle modification by FIB milling. The effect of the changes is noticeable but of similar magnitude to the effect produced by cleaning and refilling of the printhead.

indicate that the directionality of the main drops remained unchanged for all the symmetrically modified nozzles. None of the nozzles observed on this printhead contained remnant material around the nozzle outlet.

DISCUSSION

Experimental results obtained from printheads with metallic and plastic nozzle plates are summarized in Figs. 8 and 11, and indicate that notches less than 9 μm long do not produce a significant change of the directionality of jetted droplets. The geometry of these nozzles suggests that only defects large enough to reach the back of the tapered nozzle produce a change of the directionality. A notch length of $\sim$9 μm was required for the defect to reach the rear surface of the nozzle plate (approximately 50 μm thick) in this geometry as shown in Figure 12; this figure illustrates how the back of the nozzle is modified only when the notch is large enough to penetrate all the way through the thickness of the nozzle plate.

This result therefore suggests that the jetting direction becomes significantly affected only when the defect affects the back face of the nozzle plate, at the entry to the nozzle. These experiments suggest that superficial scratches on the surface of the nozzle plate do not affect the behavior or directionality of jetted droplets and only relatively large defects penetrating right through the nozzle affect the directionality of the printed droplets. In contrast, a very large defect affecting the back of the nozzle produces a significant change of directionality; a notch size of 25×19 μm^2 produced a change on the jetting angle of 6°. For both printheads, the native jetting angle variability was estimated to be less than 1°.

To extend this thesis, further experiments were conducted to determine the effect on the droplet directionality of defects lying parallel to the conical surface of the nozzle,

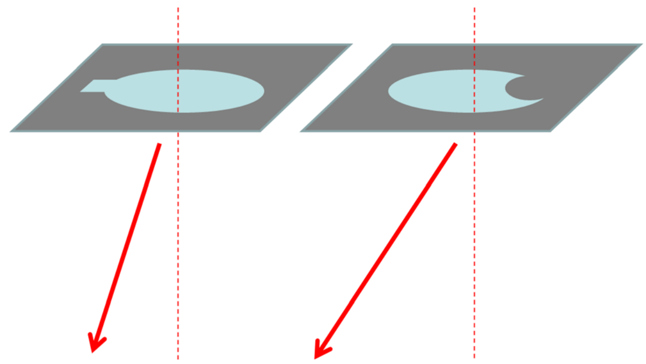

Figure 9. Schematic diagram showing the effects on the directionality of jets caused by the two types of defects on the nozzle plate of a Spectra Dimatix head.

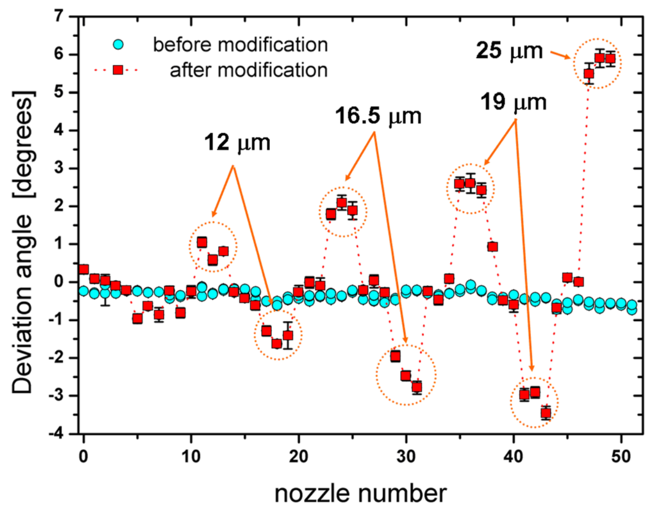

Figure 10. Results from the image analysis of double-flash shadowgraph images for jetting from nozzles with notch defects cut by laser machining. The circular points show, the jetting angle of droplets from unmodified nozzles; the squares indicate the jetting angle of droplets from the same printhead but after some of its nozzles were modified. The jets produced by the nozzles with the two largest notches were analyzed manually as the droplets had been deviated by more than the nozzle pitch under these conditions of field of view and flash separation.

as shown in Figure 13. In these experiments, 7×7 μm^2 square notches were created in five nozzles of a Xaar XJ126 printhead with trains of UV laser pulses using the techniques described above. During the machining of the notches, the printhead was inclined in such a way that the laser beam entered parallel to the nozzle inlet. Given the geometry and materials used in the construction of this printhead, these defects could not be observed directly. These modified nozzles were used to eject droplets, and their directionality was determined by the methods described above. Fig. 11 shows the results (marked as "notches parallel to the nozzle entry"), which demonstrate a significant effect on the directionality of the droplets and support the suggestion that damage at the rear of the nozzle has more effect than the same amount of damage at the front.

The shadowgraph images obtained during jetting of droplets from the Xaar printhead were also used to study the behavior of the ligament produced at the early stages of

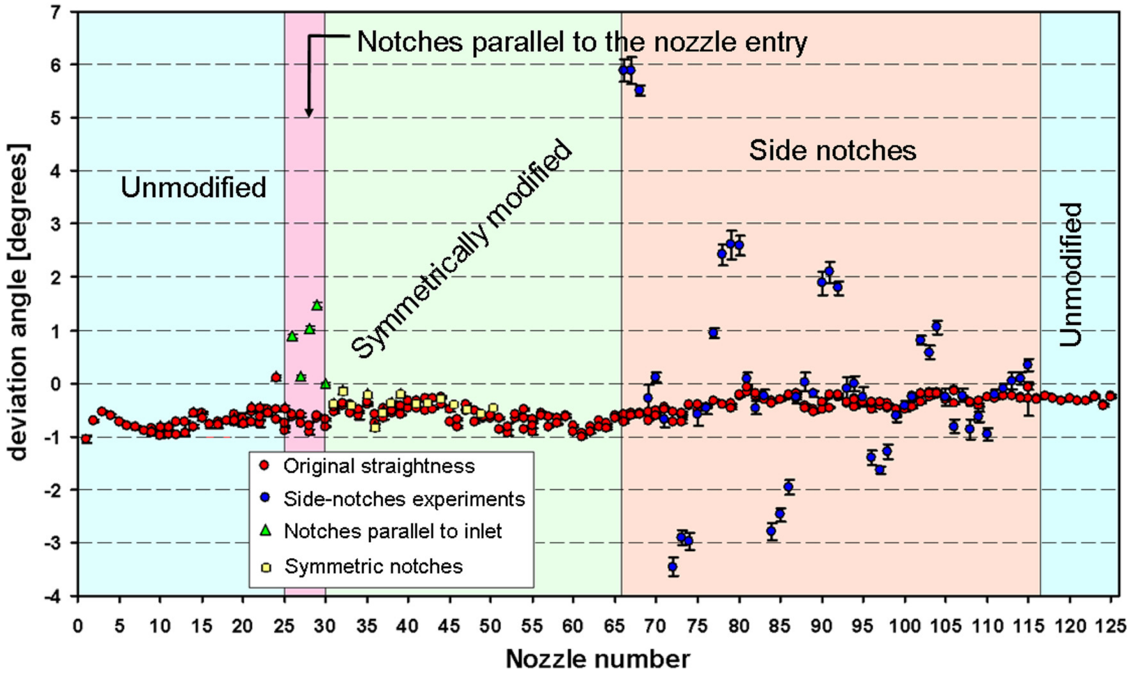

Figure 11. Results of experiments with the nozzles of a commercial printhead modified by laser machining, as described in the text.

drop formation, to diagnose any change in the satellite drop formation due to the change of nozzle geometry. The results are shown in Figure 14. Image analysis was performed to identify and record the length of the ligament attached to the back of droplets.[9] According to these results, with the exception of the nozzles with $25 \times 19\ \mu\text{m}^2$ notches, the length of the ligament was not significantly changed, and the formation of satellite droplets was not affected by the presence of the notches. The change observed in the jetting from nozzles with the largest notches can be attributed to the change in the effective nozzle area, which led to the production of larger, slower droplets.

Image analysis was also used to study the number of satellite droplets created by unmodified and modified nozzles. Results are shown in Figure 15. Satellite droplet sizes and speeds also remained constant within the precision of our measurements. The large error bars presented in these results are an indication of the randomness of the breakup process; this natural variability of the breakup process sets a limit to the level of change which can be detected. The size and speed of the main drops also remained the same for both modified and unmodified nozzles.

CONCLUSIONS

We have performed a series of experiments to explore the influence of nozzle defects on the directionality and other properties of droplets printed from commercial piezoelectric DoD printheads. Two techniques to modify nozzles were tested. Metallic nozzles were modified using the technology of FIB milling, which was used to introduce defects with high precision. Polymeric nozzle plates were modified by laser micromachining at much higher speeds. Laser micromachining and FIB milling were used to produce square notches on the sides of nozzles in various patterns, ranging from a single notch on one side to several notches distributed around the nozzle exit.

By using shadowgraph imaging and image analysis the jetting angles from metallic and polymeric nozzle plates were determined. Experiments carried out with a Spectra Dimatix printhead with a metallic nozzle plate indicate that the direction of droplet deflection by nozzles with cut-in notches is always in the direction of the defect, and away from the defect if the defect is an additive feature. Experiments performed with polymer Xaar nozzles with a conical entry show that only defects that affect the shape of the rear

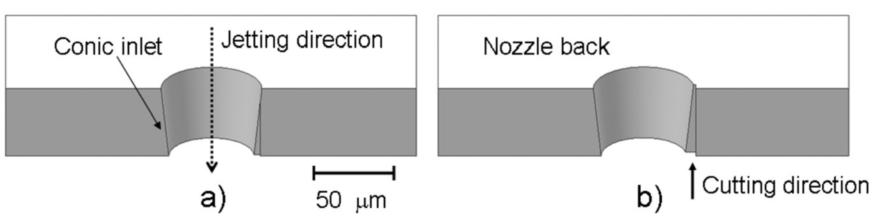

Figure 12. Diagram showing the nozzle geometry and the position and size of nozzle defects (square notches). In (a) a notch of $4 \times 4\ \mu\text{m}^2$ is shown. In (b) a notch size of $9 \times 12\ \mu\text{m}^2$ is shown and it is evident that for this size the defect just starts to affect the rear face of the conical nozzle inlet.

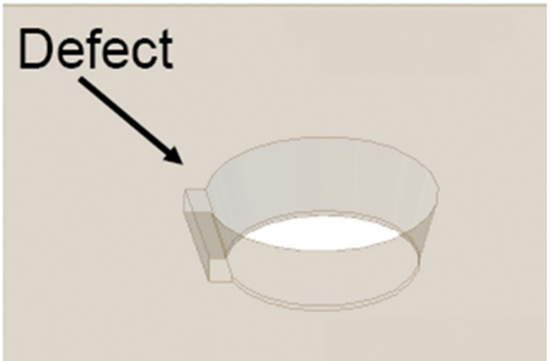

Figure 13. Schematic diagram of a notch parallel to the nozzle surface.

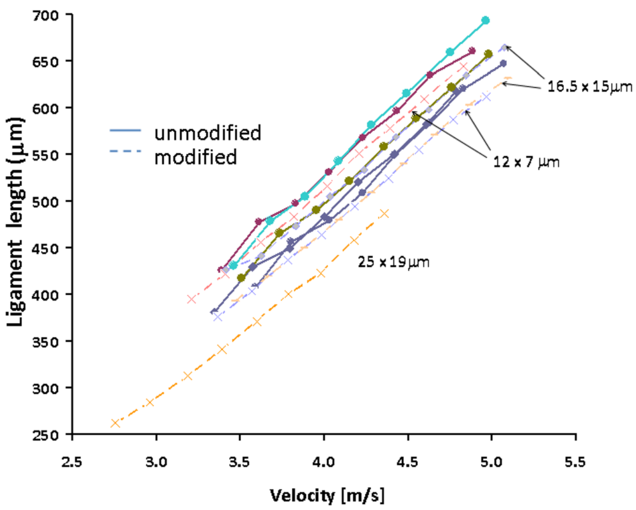

Figure 14. Ligament length plotted against droplet velocity for single side-notches.

of the nozzle (i.e., the entry region) affect the jet directionality in a significant way. For this printhead, notch-shaped defects smaller than 19×17 μm^2 did not alter the volume or the speed of the main droplets.

These studies suggest that scratches on the front surface of the nozzle plates should not affect the directionality of printed droplets provided that they are smaller than the defects introduced in this work, which did not show significant deflection. The results lead to the conclusion that if very small notches produce an effect on the directionality

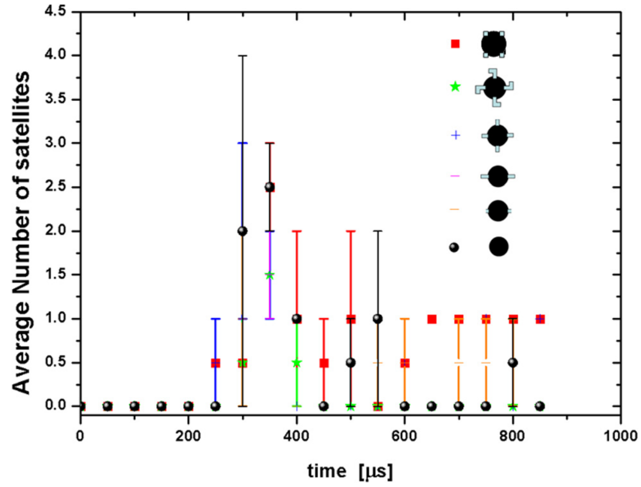

Figure 15. Number of satellites produced by symmetrically modified and unmodified nozzles. For these experiments, droplets were jetted at 3.5 m/s.

of jets then that deviation is masked by the intrinsic variability observed between the nozzles of a printhead. Only defects larger than about 10 μm, or about 1/5 of the nozzle diameter produced a detectable influence on the jet directionality.

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