Influence of Nozzle Defects on Drop-on-demand Ink-jets

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Abstract

The effects of nozzle defects on the behaviour of drops ejected from drop-on-demand print-heads were studied. Nozzles in two types of commercial print-heads 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 128 nozzles were studied. Shadowgraph images captured with short high time resolution 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 μm diameter nozzle do not cause any significant variation on the behaviour of these nozzles but that defects at the back (entry) of the nozzle can have a major effect on the direction of jetting.

Introduction

A series of experiments was carried out to quantify the effects of nozzle defects on the behavior of droplets jetted from a commercial piezoelectric drop-on-demand printhead. These experiments are of interest as most applications require the directionality of droplets, and their speeds, to be as uniform and predictable as possible. The behavior of droplets is determined by several variables such as the liquid properties, the drive pressure history and the dimensions and shape of the nozzles [1]. As theoretical models and numerical simulations are often limited to symmetrical geometries and to relatively simple liquid properties (e.g. Newtonian) users are obliged to make trial-and-error tests to determine the best conditions for printhead operation [2-4]. 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 on the nozzle plate material, and the presence of air bubbles in the printhead channels [5]. In this study our efforts were concentrated on nozzle imperfections and their effects on jet and droplet directionality.

The influence of nozzle properties on jet directionality has received little attention because the modification of very small nozzles (typically tens of micrometers in size) is difficult: it requires precise micromachining by techniques which do not affect the normal operation of the printhead. In our experiments, several methods were considered to create artificial imperfections in nozzles but only a few techniques were identified with the necessary tolerances (a few micrometers) which were also compatible with common nozzle plate materials. This paper describes a series of experiments that were carried out to characterize the directionality of jets through the shadowgraph imagining of droplets produced by micro-modified nozzles [6]. The work is described in four sections: *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 were modified and *iv)* experiments involving more complex patterns of notches.

Notches produced by focused ion beam (FIB) milling

The technique of focused ion beam (FIB) milling is used in materials science to remove materials on scales from a few nm to μm. It is often used in conjunction of a scanning electron microscope (SEM) to direct the FIB probe and observe its effects. For this work, FIB milling was used to produce square notches on the edges of a set of nozzles. The aim of these experiments was to produce well-characterized defects in the form of notches on printhead nozzles and to characterize the directionally of droplets produced by such nozzles. The milling was carried out with a Carl Zeiss 1540 XB CrossBeam FIB/SEM system. Briefly, the FIB was used to remove material from the surroundings of a metallic nozzle in a very accurate way by the action of focused high-energy ions. With an ion current of 50 pA a machining tolerance of ~50 nm was achieved. This technique has the advantage of being very precise but the disadvantages of being applicable only to metallic materials and slow (drilling a 3 × 3 μm 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.

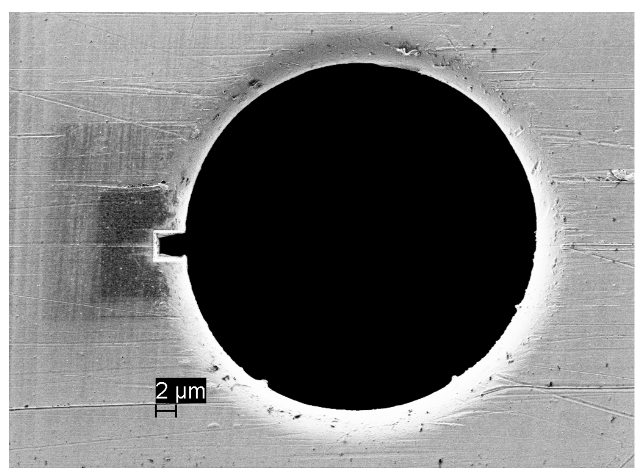

***Figure 1** SEM image of a notch on a Spectra nozzle (in a nickel nozzle plate) produced by focused ion beam (FIB) milling.*

Nozzle modification experiments were carried out on a Spectra Dimatix SE-128 AA printhead which has a gold-coated nickel nozzle plate, with 128 nozzles, 35 µm in diameter, at a pitch of 508 µm,. This printhead typically produces drops with a volume of ~30 pL at 5 m/s. An example of a modified nozzle is shown in Fig. 1. Three notch sizes were milled in these nozzles: 1 × 1 µm, 2 × 2 µm and 3 × 3µm. In each case the notch penetrated through the whole nozzle plate. Jetting experiments were performed with a generic UV curable black ink.

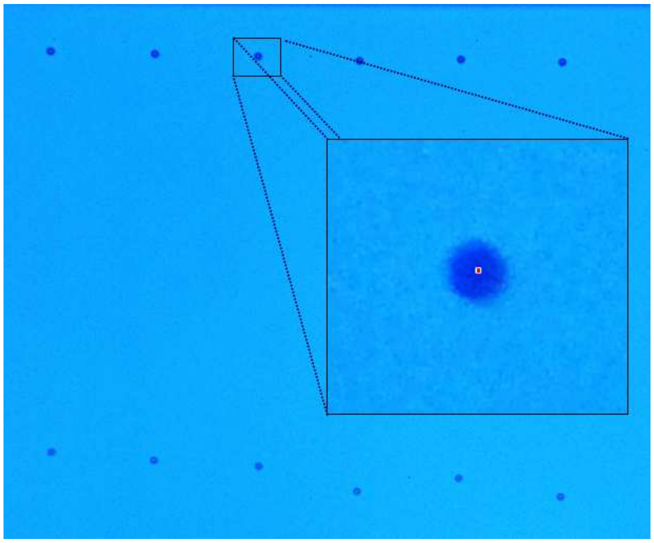

***Figure 2** Double flash shadowgraph image showing a set of six droplets jetted from the Spectra SE-128 printhead. Six droplets are observed on the top and the same six droplets are observed at the bottom 700 µs later.*

The direction of motion of the drops ejected from individual nozzles was determined from analysis of double-flash images by calculating the vectors joining the drop positions at the two different times, as shown in Fig. 2. The method used to identify the position of the center of mass of the droplets from such images is described in [7]. Droplet images were captured with a shadowgraph 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 direction of the jetted droplets was determined for all the 128 nozzles of the printhead in batches of images covering 10 jets each. Each image overlapped its neighboring images to the extent of five jets in order to assess and quantify the pincushion distortion caused by the optical system. With the same optical system, images of a precision square grid (microscope graticule) were also captured to determine a correction factor for this distortion, as shown in Fig. 3. A third order polynomial function was computed and applied to the droplet position data to compensate for this small but significant distortion. All the nozzles in the printhead were characterized in terms of the jet direction before and after the FIB modifications to identify any differences. The direction of drop travel from each nozzle was taken as the mean value derived from five separate images.

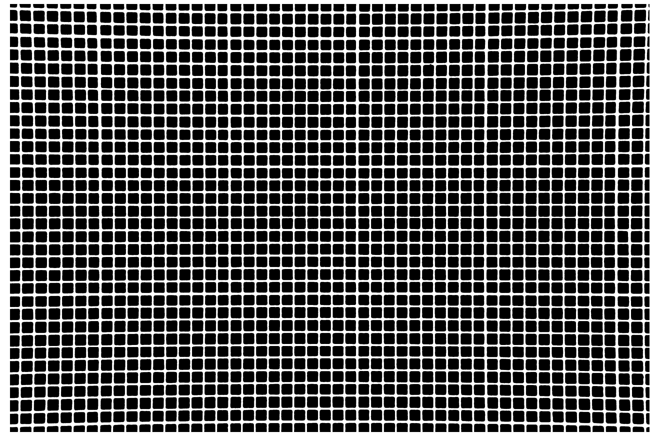

***Figure 3** Image of a square grid showing pincushion distortion; the effect is most noticeable at the image borders and negligible at the center. The size of each square is 100 µm.*

Figure 4 shows results which indicate that notches of sizes 3 × 3 µm 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, 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. However, two important conclusion can be drawn from this work: (i) the double-flash imaging results confirmed the intrinsic jet straightness variability claimed by the head manufacturer (< 1°) and (ii) very small notches can produce 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.

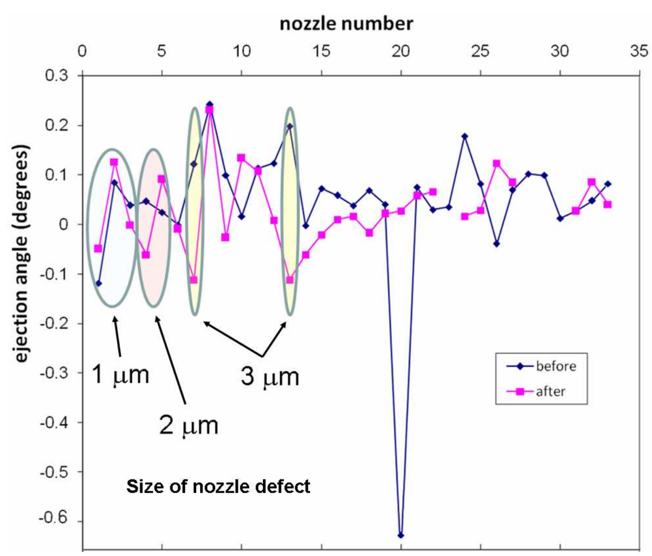

***Figure 4** Angles of droplet travel (relative to the nozzle plane normal) before and after modification by FIB milling. The effect of the changes is noticeable but of similar magnitude to the effect produced by cleaning and refilling of the printhead.*

Side notches produced by laser machining

The aim of these experiments was to extend the studies carried out with the FIB to a scale where the effects of side-notches on nozzles were easily observable and quantified. The technique of pulsed laser micromachining can be applied to non-metallic materials such as silicon and polymers. The method is not so 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. In our experiments, we modified certain nozzles in the polyimide nozzle plate of a Xaar XJ126 printhead. This printhead has 126 active nozzles, with a 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. In contrast to the FIB, the machining of a square notch 25 × 25 µm was carried out in >500 ms. However, the optical and mechanical elements used in this technique limit the machining quality to tolerances of the order of 3-5 µm. Both inspection and machining involved optical microscopy. The laser pulses were used to create defects on the sides of nozzles, in order to study the effect of the notch size on the jet direction and speed. Notches were cut completely through the nozzle plate (approximately 50 µm thick) with the following dimensions: 4 (width) × 4 (length) µm, 12 × 7 µm, 16.5 × 15 µm, 19 × 17 µm, and 25 × 19 µm. All the defects were produced by trains of UV laser pulses (355 nm wavelength) with 4 ns duration and 2 mJ pulse energy. The number of pulses was varied according to the size of the notch. Thirty nozzles were modified for these experiments: they were machined in sets of three with the same size of defect. Figure 5 shows an example of a modified nozzle. Jet direction was measured for each nozzle before and after the defects were created. Double-flash images of the drops were analyzed to identify the drop center positions, angle of travel and speed. As in the FIB experiments, optical distortion was corrected during the analysis. The results are shown in Figure 6 (marked 'side notches'), and Figure 7 shows the variation of jet direction with notch length.

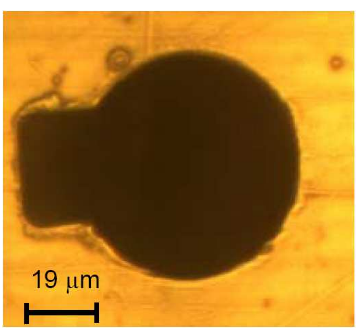

Figure 5 *Optical image of a machined notch (25 × 19 µm) on the side of a nozzle in a polyimide nozzle plate, produced by pulsed laser micromachining.*

The results obtained with this technique were consistent with those from the FIB experiments. Notches smaller than 7 × 9 µm did not produce significant changes in the jetting behavior. The inherent variability of jet direction in this print-head was ~1°. A notch length of ~9 µm is required for the defect to reach the back surface of the nozzle plate in this geometry. This 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 ruled out the assumption that superficial scratches on the surface of the nozzle plate may affect the behavior or directionality of jetted droplets, as only relatively large defects penetrating right through the nozzle plate were found to affect the directionality of the printed droplets.

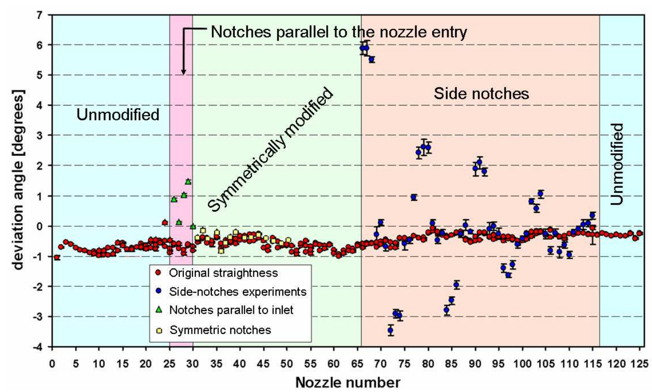

Figure 6 *Results of experiments with the nozzles of a commercial print-head modified by laser-machining, as described in the text.*

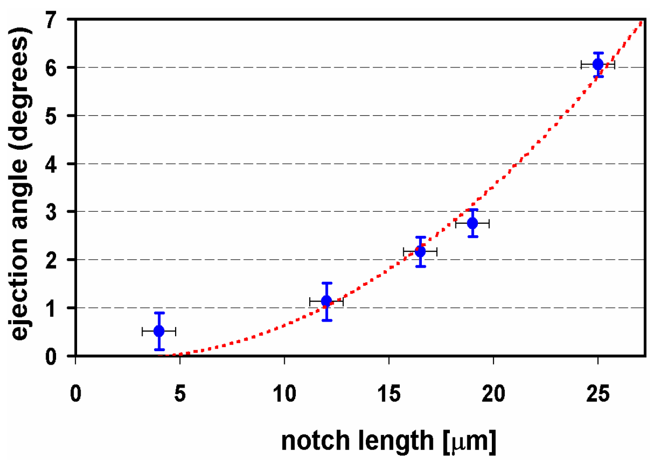

Figure 7 *Jet direction (expressed as angle of travel) plotted against notch length for single side-notches. Changes in the jet angle were significant only for notches longer than ~4 µm.*

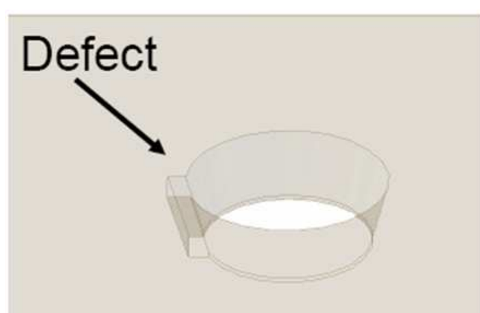

Figure 8 *Schematic diagram of a notch parallel to the nozzle surface.*

Notches machined parallel to the nozzle inlet by pulsed UV laser

The objective of these experiments was to determine the effect on the directionally of droplets of defects lying parallel to the conical surface of the nozzle, as shown in Figure 8. In these experiments, 7 × 7 µm square notches were created in five nozzles of a Xaar XJ126 printhead with trains of UV laser pulses using the technology 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. Unfortunately, given the geometry and materials used in the construction of this printhead, the defects could not be directly observed. These modified nozzles were used to eject droplets and their directionality determined by the methods described above. Figure 6 shows the results (marked as 'notches parallel to the nozzle entry') which demonstrate a clearly significant effect on the directionality of the droplets and confirm that damage at the rear of the nozzle has more effect than the same amount of damage at the front.

Symmetrical notches machined by pulsed UV laser

The aim of these experiments was to study the behavior of droplets formed by different 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 print-head. Five different patterns of notches were created on a Xaar 126 printhead by laser machining. These geometries were: two opposed notches each 7 × 7 µm in size across the axis of the nozzle; two opposed notches each 7 × 11 µm in size across the axis of the nozzle; four notches each 7 × 7 µm in size placed on the vertical and horizontal axes (bottom left image in Figure 8); four notches each 7 × 7 µm in size placed at diagonal positions on the nozzle (bottom right image in Figure 8); four L-shape notches each located on the vertical and horizontal axes (top right image of Figure 8). Identical defects were machined in neighboring groups of three nozzles.

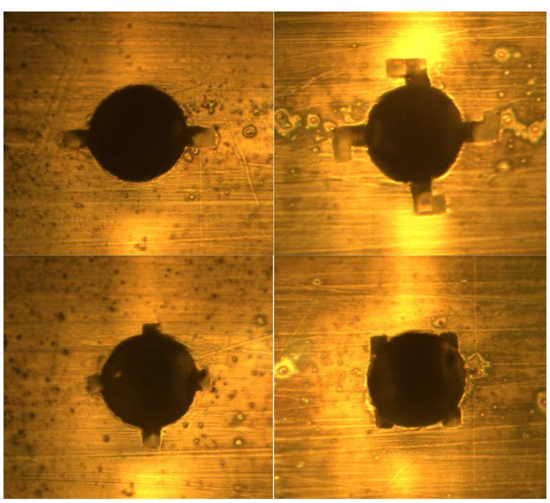

Figure 8 *Examples of symmetrical patterns machined on the nozzles of a Xaar XJ 126 print-head by UV laser micromachining (optical images).*

The droplets jetted from modified nozzles were observed using the shadowgraph system and analyzed as described above. The results are shown in Figure 6 (marked 'symmetrically modified'). The directionality of the main drops remained unchanged for all the symmetrically-modified nozzles. Droplet sizes and speeds also remained constant within the precision of measurement.

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 print-heads. Laser micromachining and focused ion beam (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. Our results show that only defects that affect the shape of the back of the nozzle (i.e the entry region) affect the jet directionality in a significant way. For a print-head with a 50 µm nozzle diameter in a 50 µm thick nozzle plate, defects smaller than 19 × 17 µm did not alter the volume or the speed of the main droplets. These studies suggest that scratches on the front surface of a nozzle plate should not affect the directionality of printed droplets as they are superficial and usually smaller than the defects introduced in this work.

This work was supported by the UK Engineering and Physical Sciences Research Council in the 'Next-generation inkjet technology' project.

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Author Biography

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