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New designs and manufacturing possibilities for inkjet print head nozzle plates

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Abstract

The design of today's inkjet printheads is often limited by the micromanufacturing methods used. Furthermore, today's inkjet technology suffers from several limitations in term of ink viscosity, particle size and jetting distance. Yet, new micromanufacturing technologies have been recently developed. In this work, we explore the potential of using femtosecond laser glass micromanufacturing to fabricate inkjet printheads parts. The performance of such modified printheads is compared to their commercial counterparts.

Introduction

Nowadays, a new era for inkjet printing is coming. In the context of the Industry 4.0, the inkjet printing technology has the unmatched advantage of being digital by its nature and serving as a digital construction kit in three dimensions. Hence, if instead of the usual inks employed for graphical printing, more and more new functional inks will be available and used, the inkjet printing technology will clearly open the door to a plethora of new fabrication pathways for customizable products in a multi material and multi functionality dimension. Not only inkjet allows the fabrication of personalized products, but it also dramatically reduces material waste, stock levels and shipping across the whole world. Products will be manufactured on demand and on site directly close to the customer [1], decreasing the environmental footprint of today's society.

Inkjet print heads have been successfully optimized in the last decades for the graphical industry and are now working sufficiently reliable in industrial applications at 24 h / 7-day production scale. Yet, most of the functional inks suitable for additive manufacturing clearly differ from the ones currently used in graphical printing. In particular, inks with a high viscosity or a very high particle load cannot be digitally printed by inkjet technology today. So far, in industrial environments, mostly only low-viscosity fluids (with viscosity below 20 mPa*s) containing only small particles ($< 3.5\mu$m) and low solid contents can be printed by commercially available multi-nozzle inkjet print heads. This is particularly an issue in additive manufacturing, where the speed of fabrication strongly depends on the functional material load of the ink and thus on its dynamic viscosity. The main hurdle for this digital inkjet revolution to happen are the limitations of today's inkjet print heads in terms of viscosity, particle size and concentration, and jetting distance [2]. Furthermore, current industrial inkjet print heads do not allow for in depth analysis of the inner process during operation, which is mainly limited to X-Ray imaging or IR microscopy (for silicon nozzle plates).

The low-viscosity limitation has driven the attention of several main print head manufacturers. Recently, Quantica developed a new print head employing a novel operation mode for the fluid ejection [3]. With this new technology, Quantica has been able to print fluids at 250 mPa*s with big drops and high frequencies. Currently, the price to pay is the very low resolution. As a conclusion, industrial print heads for larger viscosity are slowly coming to the market, but there is still room for improvements and new concepts.

One limitation preventing new print heads to be developed consist of the constraints imposed by the available micromanufacturing methods and employed materials. Stacks of 2D simple polymeric or metallic layers, assembled with different adhesives, form current inkjet print heads. Complex 3D channel geometries are not possible and the chemical incompatibility between the print head materials, including the adhesives, and the inks often result in short lifetimes of the device or even make it impossible to inkjet print such inks.

Interestingly, even though the original and first successful commercial application of microfluidics was indeed for the development of inkjet print heads, microfluidics has then evolved along a completely different path. Nowadays, very sophisticated microfluidic circuits have been designed for biomedical and biotech applications, while the microfluidic circuits of current inkjet print heads still rely on very old and basic designs, mainly because of the limitations imposed by microfabrication methods for the materials suitable for inkjet print heads. Inkjet print head nozzle plates are nowadays manufactured by laser drilling, micro punching, electrical discharging machining or electro erosion.

In the same time, new micromanufacturing technologies have emerged. For example, fused silica processing with femto second laser [4] perfectly fits the stringent requirements for inkjet print heads and gives unmatched design freedom. Beside the micromanufacturing of the different parts composing a print head, the adhesives used for their assembly play a key role. New formulations have been develop that can simplify the assembly process.

In this work, an industrial piezoelectric drop-on-demand print head has been modified, assembled and characterized to overcome above-mentioned limitations, both in terms of print head designs as well as micromanufacturing and assembly methods.

Materials and methods

Modified inkjet print head design Piezoelectric drop-on-demand inkjet print heads are composed by piezoelectric actuators that induces acoustic waves in the resonant chambers eventually resulting in the fluid motion through the nozzle and the ejection of a droplet [5]. Hundreds or even thousands of actuators, resonators and nozzles are stacked one next to each other to form a print head.

In this study, a Fujifilm DIMATIX StarFire SG1024/MA-2C has been employed. This print head is composed by four modules, each having two nozzles rows with 128 nozzles each. The native resolution of the print head is 400 dpi, meaning that the pitch between two nearby nozzles of the same row is 508μm.

The recommended ink viscosity is in the range 10 – 14 mPa*s and the firing frequency can go up to 35 kHz, with a native drop size of 30 pL.

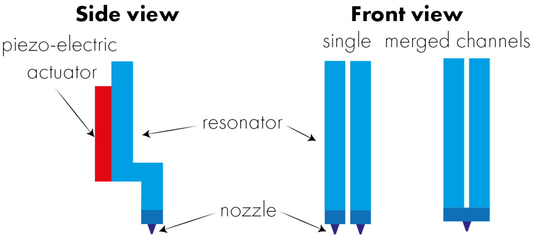


Figure 1. Sketch of the modified print head.

The print head has been unmounted and only the separate modules consisting of the piezoelectric actuators and resonators have been kept. Two different nozzle plates have been designed and glued underneath the module (see Figure 1 to Figure 3). The first one consists of trumpet-shaped nozzles that are connected to each single resonator (see Figure 2(a)). In the second nozzle plate design, on the other hand, two nearby resonators are merged into a single nozzle (see Figure 2(b)). The geometry of the latter is identical as for the single-nozzle configuration for the sake of comparison. With the employed micromanufacturing technique, totally new nozzles geometries can be investigated. This is the subject of ongoing and future studies.

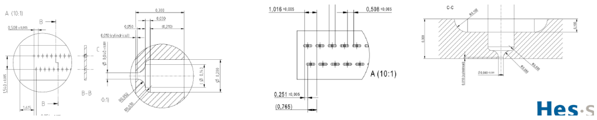


Figure 2. Designs of the (a, left) single nozzle and (b, right) merged nozzles configurations for the nozzles plate.

Micromanufacturing and assembly of modified inkjet print head Micromanufacturing methods for inkjet print heads have to fulfill stringent requirement. For example, the precision for the microchannel geometry and in particular the nozzle plate has to be below 1μm, and this over the entire length of the print head. Nozzle plates are nowadays manufactured by laser drilling, micro punching, electrical discharging machining or electroforming. In this work, however, we employed the FEMTOPRINT® technology to manufacture fused silica nozzle plates (see Figure 3). This technology combines femto second laser and chemical etching, allowing for a sub-micron resolution and sub-micron repeatability and alignment precision. 3D free-form monolithic glass microfluidic chips can be manufactured, including adhesive-free glass-to-glass bonding. Not only the device is transparent, which is clearly an advantage for failure diagnostics and design optimization, but it is chemically inert.

The fuse silica nozzle plate have been assembled to the module of the StarFire. Several different adhesives and processes have been tested.

The developed process has been found to be very simple, yet very robust. The assembled nozzle plate has been verified by visual inspection with a Keyence microscope, before performing jetting tests. Only less than 5% of the nozzle have been found not to work properly after assembly, for the very preliminary modified print head. Furthermore, since the time for polymerization at room temperature is 72h, there is sufficient time to eventually correct the alignment between nozzle plate and module. The polymerization time is reduced to 3h hours at 80°C.

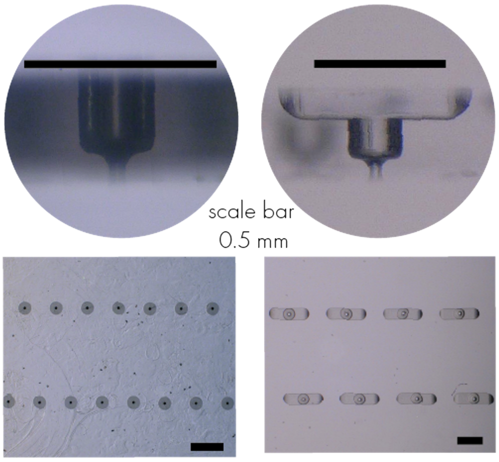


Figure 3. Images of the manufactured nozzle plate.

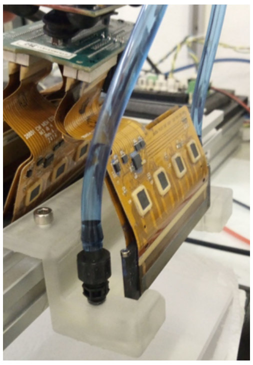


Figure 4. Image of modified print head module mounted on the holder.

The holders for the StarFire module that are supplying the ink have been 3D printed with a Formlabs 2 SLA-printer. To avoid as much as possible leakages between the print head module and its holder, the 3D printed part has been polished and a sealing has been used.

Platform and fluids for assessment of modified inkjet print head To assess the performance of the modified print head, a simple drop watching platform has been developed (see Figure 5). It consists of the modified print head on its holder, the ink supply system, the drop watching system and the driving electronics. The meniscus pressure is regulated simply through the hydrostatic pressure given by the height of the ink reservoir. The drop watching system is composed by a flashing LED, a camera and optics. An internally developed software for image acquisition and treatment has been used to obtain the droplet speed and volume. A typical image obtained by drop watching is shown in Figure 6.

For the results presented in this article, ethylene glycol (16.1mPas at 25°C) or glycerol-water mixture with viscosity ranging from 30mPas to 60mPas at 32°C have been used. The temperature indicated corresponds to the ink temperature during the tests.

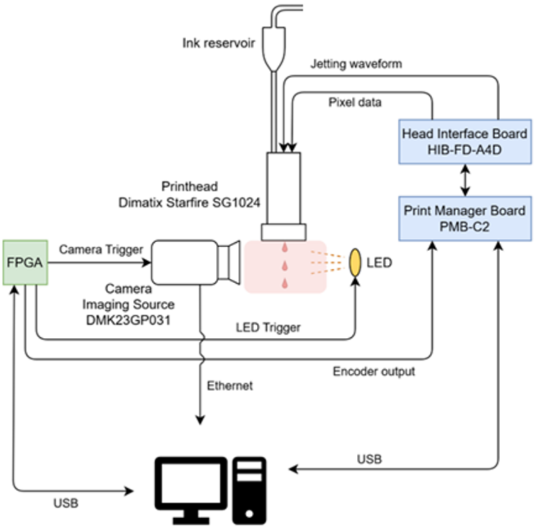


Figure 5. Schematics of the drop watching platform developed to assess the modified print heads.

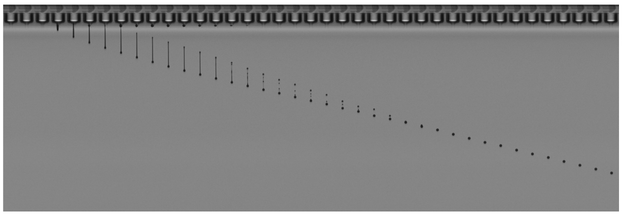
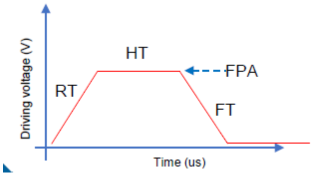


Figure 6. Typical drop watching result where the different stages of the ligament ejection and droplet ejection are visible.

Characterization of modified inkjet print head The quantities that have been monitored to compare the performance of the modified print heads compared to the original one are the acoustic times, the droplet speed and volume and the jetting stability. The employed waveform is shown in Figure 7, where the relevant parameters are highlighted. For the sake of clarity, the same waveform has been used throughout the work and only the hold time has been varied to find the acoustic optima or the fire pulse amplitudes to see performance of the print heads. The applied voltage induces a deformation of the piezo-electric element such that the volume of the resonant chamber is slightly increased and a negative pressure wave is generated. The voltage is returned to its reference value after the so-called acoustic time. This time is choses such that the positive pressure wave resulting from the reflection of the negative pressure wave at the open end of the resonant chamber is synchronized with the generation of a second positive pressure wave induced by the motion of the piezo-electric element when the voltage is returned to its reference value. A large positive pressure peak is induced at the nozzle, allowing for the droplet ejection [5]. This gives the highest jetting efficiency.

Results

Acoustic optima To better understand the acoustic behavior of the different print heads, an acoustic optima study has been performed. The droplet speed has been measured while increasing the hold time. It has been found that the first acoustic optimum is nearly identical for all print heads. The rationale is that the first acoustic optimum is directly related to the geometry of the resonant chamber, which is given by the StarFire print head module and is therefore identical in all print heads. On the other hand, the second and third acoustic times differ between the different print heads due to their different geometries close to the nozzle.



RT : Rise Time
HT : Hold Time
FT : Fall Time
RT+HT = AT : Acoustic Time
FPA : Fire Pulse Amplitude

Figure 7. Sketch of the used waveform with the relevant parameters.

The first acoustic optima has then be employed to define the acoustic time of the standard waveform for the results presented in Section .

Jetting properties The performance of the different print heads has been compared based on the droplet speed, droplet volume and jetting frequency stability as a function of the fire pulse amplitude. It has been found that the droplet speed of the merged channel print head is approximatively the double of the single channel print head (see Figure 8). Hence, losses in the merged channel are negligible and the double electrical energy provided by the two piezo-electric elements in the two connected resonant chambers is transformed into a double kinetic energy of the ejected droplet. Strikingly, it has been possible to jet at very high speed ($>$ 20m/s) while having a very good ligament breakup and droplet formation. It has however to be noted that the jetting from the original print head has not been optimized in details.

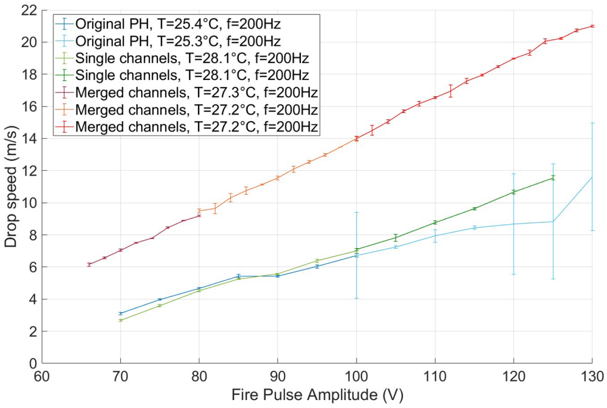


Figure 8. Droplet speed for the different print heads and fire pulse amplitudes.

The stability of the jetting process over the entire frequency range has been compared. It has been confirmed that the droplet formation process remains stable up to at least 30 kHz for all considered print heads.

Finally, leveraging on the combined actuators of the merged channel print head, fluids with a viscosity much higher than the recommended one for the original StarFire print head have been successfully printed. The droplet formation process for an ink having a viscosity of 60mPa*s can be seen in Figure 9. The droplet speed is rather small (3 m/s), but the same waveform as the one for the lower viscosity fluid has been used. Further improving the waveform would allow for jetting fluids of even higher viscosities.

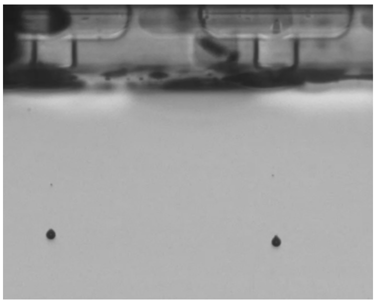


Figure 9. *Droplet formation process for an ink of viscosity of 60mPa*s jetted with the merged channel print head.*

Finally, thanks to the transparency of glass, detection of jetting issues is because of issues in the microchannels or nozzle is possible (see Figure 10).

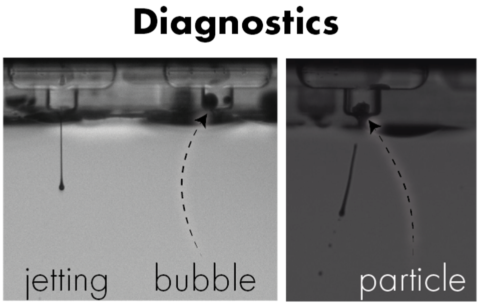


Figure 10. *Examples of printing diagnostics possible with the glass nozzle plate.*

Conclusions

This work presents a possible way that can be pursued, by combining new micromanufacturing, assembly methods and new microfluidic designs, to develop new inkjet print heads and therefore overcome today's inkjet limitations and allow for a better adoption of this technology in the future digital additive manufacturing.

The original and modified print heads have been characterized by drop watching analysis in terms of acoustic periods, droplet speed, frequency stability and jettable viscosity. The 1st acoustic optimum has been confirmed to be the same for all print heads. The modified single channel print head features comparable jetting performance to the original print head. With the merged nozzles, where two actuators and resonators are connected to the same nozzle, the maximum drop speed can be doubled compared to the original design, thus allowing for a significant increase of viscosity. The consistent increase of drop speed was confirmed with ethylene glycol (15 mPa*s) as well as with a water-glycerol mixture (60 mPa*s). Furthermore, jetting was stable until the full specification of the original printhead of 30 kHz, and this in spite of the high droplet speed or fluid viscosity.

To further improve the jetting process both in terms of jettable ink viscosity and droplet speed, new waveforms are currently investigated. Additionally, new nozzle hole geometries can be now easily manufactured and optimized for specific purposes.

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Author Biography

Jonas Maturo has a Bachelor's degree in Mechanical Engineering and a Master's degree in Biomedical Engineering. In 2018, he started working at iPrint, where he worked on various lab projects like designing and testing microfluidics on print heads, studying droplet aerodynamics, developing printed electronics, and investigating the transport of drop-encapsulated objects. Since 2023, Jonas has been actively involved in the family-owned business, focusing on tailored solutions in mechanical development.

Johannes Renner studied mechatronics with specialization in automation technology at the Secondary Federal College of Engineering in Vienna, and mechanical engineering as well as mechatronics at the Bern University of Applied Sciences, where he worked after graduation in 2007 as scientific assistant and later on as scientific officer for the Institute of Print Technology. In 2013 he joined the iPrint institute. Johannes has gained over 15 years of experience in applied research with the focus on inkjet technology and is contributing to many of iPrint's inkjet-related projects.

Jérémy Vuilleumier holds a EPFL Master and a Phd in molecular and biological chemistry obtained in 2015 and 2019, respectively. Jérémy's activities at iPrint have been focused on the development of microfluidic chips for biomedical applications as well as for new inkjet printheads.

Yoshinori Domae studied Mechanical engineering and joined Seiko Instruments Inc. in 2006. Working in Seiko I Infotech division, he was in charge of design and development of wide format inkjet printers. After moving to SII Printek division in 2011, he was the Project Leader and Chief Designer of printhead R&D. Then he invented and designed RC1536 inkjet printhead which was disruptive new recirculation printhead for some industrial inkjet applications. After that, he moved to France where he had worked as the Technical Manager for all industrial inkjet applications in EMEA, since 2014. In 2019 he joined iPrint in Switzerland, and started his activities especially for inkjet technology and innovation.

Gioele Balestra holds a Master degree in Mechanical Engineering from ETH Zurich and a PhD from EPFL. He joined iPrint in 2019 to develop new digital deposition techniques and since July 2020 he is in charge of the applied research and educational activities of the institute and competence center.