Full Length Article

Jetting dynamics of Newtonian and non-Newtonian fluids via laser-induced forward transfer: Experimental and simulation studies

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A R T I C L E  I N F O

Keywords:
Laser-induced forward transfer
Nanoparticle inks
Newtonian fluids
Non-Newtonian fluids
Jetting
Simulation

A B S T R A C T

Current technological trends in the field of microelectronics have highlighted the requirement to use cost-effective techniques for the precise deposition of highly resolved features. Laser-induced forward transfer (LIFT) meets these requirements and has already been applied for the direct printing of devices and components. However, in order to improve the process’ reproducibility and printing resolution, further research has to be conducted, regarding the rheological characteristics of the printable fluids and their jetting dynamics. In this work, we employ both pump-probe and high-speed imaging in order to investigate the formation and expansion of the liquid bubble, as well as the liquid jet’s propagation. Newtonian as well as non-Newtonian fluids are studied and compared, over a wide range of viscosities. Furthermore, a computational model is utilized in order to gain more insight on the transfer mechanisms of the process. The simulation predictions are validated against experimental results, and found to be in good agreement, even in the case of non-Newtonian fluids. The results indicate that such accurate modelling can be developed as a new cost- and time-effective tool for the technique’s optimization.

1. Introduction

Over the past few years, the demand to incorporate a rapid prototyping, cost effective deposition technique for functional interconnects in electronic circuitry has prompted many research groups to study a wide variety of deposition techniques. In general, the conventional approach for the fabrication of fine electrodes usually involves complex time consuming and expensive methods. For example, electrodeposition of copper is a widely adopted technique for production of printed circuit boards, however most electrodeposition techniques use toxic precursors and therefore health, safety, and environment related hazards would have to be considered \cite{1}. More and more in recent years, non-contact and “direct-write” printing techniques have been investigated for the formation of interconnect structures. Among these printing techniques, inkjet printing has been widely investigated \cite{2,3} and is a relatively fast, environmentally friendly technique. However, since inkjet is a nozzle-based technology, it typically handles low viscosity inks (1–15 mPa·s) \cite{4} as an alternative printing technique, laser-induced forward transfer (LIFT), is a nozzle-free technique and therefore is capable of printing a wide variety of materials ranging from low (i.e. water), to medium and high viscous solutions (i.e. Ag pastes). It consists of a laser source irradiating the so-called donor substrate, which comprises of a thin film of the printable fluid coated on a transparent carrier. Consequent to the irradiation, a liquid jet is formed, propagating towards the printing surface, called receiver substrate, which is placed in parallel to the donor substrate in a distance of several microns. The technique has attracted attention as a tool for printing low viscosity fluids \cite{5} and biological inks \cite{6} with applications in biomedicine, low viscosity metallic nanoparticle (NP) inks, such as silver ink \cite{7-10}, as well as high viscosity NP pastes \cite{11} with viscosity > 100 Pa·s \cite{12,13} for the fabrication of metallic interconnections and wire-bonding.

Printed micro-electrodes are made of conductive materials which can usually be processed in the form of a liquid solution and printed onto a substrate. The transferred conductive inks usually contain suspensions of nanoparticles (NPs) of up to 100 nm in diameter. The most common ones typically consist of silver, gold or copper NPs due to their high conductivity and easy handling. While LIFT has been adequately studied over the past, the same cannot be said for the inks used for printing. Most groups use commercial inks which are not specifically
designed for the LIFT process. To our experience, we believe, this is one of the main reasons responsible for low quality printing or the non-reproducibility of results. Hence, optimizing the printing parameters in order to control and reproduce the size and morphology of the printed metallic micro-patterns has become an issue of major importance. Some reports have progressed further the study of the printing behavior of fluids (silver NP ink and organic solvents) by observing the jet-jet interactions for specific inter-beam separations where the jets were generated with high repetition rate lasers or by two different laser sources [14,15], as well as by imaging the liquid ejection during CW-LIFT [16]. Additionally, solid phase LIFT for 3D metal printing has also been studied. More specifically, in the latter case stress relaxation and/or partial vaporization of the donor metallic layer upon irradiation, subsequently leads to the ejection of a liquid metal micro-droplet. Influence of experimental parameters and material’s properties on the mechanism of transfer behavior for 3D metal printing has been discussed in the case of gold [17], and copper [18,19].

Earlier studies on the printing of Newtonian fluids attempted to unveil the mechanism of LIFT technique and provided valuable information for optimizing the process parameters of the technique. In addition, to avoid direct irradiation of the fluid of interest or due to the fact that some of the fluids are transparent to the laser radiation, an absorbing layer, also known as dynamic release layer (DRL), is usually placed between the transparent container and the printable fluid. On the one hand, in the case of metallic DRL (gold [20], Ti [21,22]), upon irradiation local vaporization of the metallic layer and part of the printable fluid takes place and leads to the creation of a vapor bubble which expands driving the fluid towards the free area. When the vapor bubble reaches a maximum size it begins to collapse, while the fluid maintains its progression in the form of a jet. On the other hand, in the case of polyimide DRL (BA-LIFT) [23,24,21], upon irradiation the laser energy is absorbed within a small part of the polyimide near the interface with the transparent carrier causing vaporization of the film and resulting in a confined pocket that encloses these vaporized products. The rapidly expanding blister leads to the deformation of the remaining intact polyimide film. In this case, rapid blister expansion, confined within the polyimide layer, is responsible for the ejection of the printable ink in the form of a jet. Boutopoulos et al. [25] imaged the transfer behavior of silver NP ink (0.012 Pa·s) from donors with and without Ti-DRL. In that work, it was found that jet formation was initiated by a bubble expansion for both donor configurations. However, due to different mechanisms involved in the generation of the bubble’s expansion, a significantly faster dynamic behavior was observed in the case of DRL-free LIFT technique, and therefore only a narrow processing window enabled controllable jetting behavior. Computational models have also been employed in previous studies of BA-LIFT (blister actuated-LIFT), investigating both the blister (bubble) formation [26] and liquid ejection and deposition of Newtonian fluids [27].

In recent years, the ejection behavior of non-Newtonian fluids, such as conductive NP pastes, have also been investigated. In a study by Mathews et al. [28], a high speed imaging setup was employed to visualize the ejection behavior of silver NP pastes, with viscosities higher than 100 Pa·s, from donors without DRL. It was observed that the examined pastes did not exhibit jetting behavior. In particular, for pastes with viscosities > 500 Pas the transfer mechanism is similar to that of solid-phase LIFT for ceramic layers where the paste that detaches from the donor fragments during transfer. Time-resolved imaging has also been used to identify ejection mechanisms of silver NP paste, with viscosity ~250 Pas, from donors without using any DRL [29]. It was observed that for laser fluences above the transfer threshold, a high-pressure, high-temperature bubble is formed that expands and contains clusters of paste. When the bubble starts to decelerate these clusters accumulate in the pole of the bubble. As laser fluence increases the bubble’s expansion is more violent resulting to an explosive transfer. Finally, if the donor thickness is large enough relative to the donor/receiver gap, then a liquid bridge is formed wetting both donor and receiver substrate, preventing fragmentation during transfer. In all of the above described transfer mechanisms no jet formation is observed as opposed to that of Newtonian fluids. In a more recent study [30], time-resolved imaging was used to observe the transfer mechanism of non-Newtonian fluids similar to that of silver NP pastes, by means of BA-LIFT. In this case, above a certain laser fluence, jet formation is initiated and according to the experimental conditions the jet breaks in one or multiple drops. The behavior of non-Newtonian jets will therefore depend on the experimental conditions as well as the ink’s inherent properties. For example, breakup mechanism of jets formed from inks that are viscoelastic in nature, usually exhibits a beads-on-a-string phenomenon where the jet breaks up into multiple droplets interconnected by a thinning jet/thread [31]. LIFT printing of viscoelastic alginate solutions was investigated by Zhang et al. [32,33], and in particular in their more recent study three main break-up mechanisms were identified: jet break-up into multiple droplets before it reaches the receiver substrate, jet break-up into a single droplet after it reaches the substrate, jet break-up into multiple droplets and formation of beads-on-a-string structure after it reaches the substrate.

In this study, both commercial and research grade (manufactured especially for LIFT) inks are used, containing metallic loading of either copper (Cu) or silver (Ag) NPs, in order to examine their jetting dynamics. Manufacturers’ data provide us with crucial information about their rheological characteristics and behavior, helping us better understand the impact that laser irradiation has on their properties (i.e. viscosity) and, subsequently, on their ejection behavior. Firstly, two side-view imaging setups were designed: (i) a time-resolved imaging setup, in order to capture the initial growth and expansion of the ink bubble (t < 1 μs) before its collapse and (ii) a LIFT setup coupled with a high speed camera for the complete visualization of the ejection process with one laser pulse on the donor. In addition, in order to further investigate the process, a computational model is employed using ANSYS Fluent; a well-established software for simulating computational fluid dynamics (CFD) problems. Instances from the aforementioned experiments are used as initial conditions for our model, as well as means of validation of the simulations’ results. Correlation between experimental and simulation results would help in the evaluation and extraction of operating parameters in terms of the reliability of the jetting quality for inks exhibiting both Newtonian and non-Newtonian behavior.

2. Materials and methods

2.1. Materials

In this study two different types of metallic inks are investigated. Copper NP ink (CI-004), is commercially purchased by Intrinsiq Materials Ltd. Silver NP ink (I75T-H53 (E14)) is research grade, manufactured from PV Nano Cell Ltd. and specifically designed for LIFT printing. Ink properties are summarized in Table 1. Experimental results of viscosity as a function of shear rate were provided by the manufacturers and reveal that copper NP ink exhibits a Newtonian behavior, as shear stress has a linear dependence on shear rate (Fig. 1a),

<table>
<thead>
<tr>
<th>Type of ink</th>
<th>Solvent</th>
<th>NP-Size (nm)</th>
<th>Metallic loading (%)</th>
<th>Viscosity (Pa·s) @ shear rate 1 s⁻¹</th>
<th>Surface tension (mN/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silver NP</td>
<td>TPM</td>
<td>&lt; 200</td>
<td>75</td>
<td>54</td>
<td>28</td>
</tr>
<tr>
<td>Copper NP</td>
<td>1-Methoxy 2-Propanol, Dipropylene glycol, Glycerin</td>
<td>&lt; 100</td>
<td>20</td>
<td>0.5</td>
<td>31</td>
</tr>
</tbody>
</table>
while silver NP ink is a non-Newtonian, shear-thinning fluid (Fig. 1b).

Before each experiment the donor substrates are prepared by coating a thin film of the printable fluid via an adjustable micrometer film applicator (SH1117/100, Sheen Instruments) onto a 1-mm thick circular quartz substrate (25 mm in diameter) purchased from UQG Optics.

2.2. Time-resolved imaging setup

The time-resolved imaging setup is designed in order to accurately capture the initial formation and expansion of the ink bubble, caused by the laser irradiation, resulting in local heating and partial ink vaporization. It comprises two lasers; a diode pumped solid state STANDA STA-01 ($\lambda = 532$ nm, $\tau = 600$ ps) laser, used for LIFT and a ND:YAG laser ($\lambda = 532$ nm, $\tau = 10$ ns) used for illumination. The first laser is used for the printing process, focused through a plano-convex lens (f = 50 mm) to the interface of the donor-ink layer, while the pulse of the second laser irradiates a rhodamine 6G fluorescent solution placed in the camera axis, producing incoherent light. The still image is captured by a CCD camera coupled with a 50× objective lens, placed 13 mm away from the donor holder. The time delay between the two laser pulses is controlled via LabVIEW software and verified by directing part of the laser beams into two photodiodes (DE11O/M-Si Detector, 200–1100 nm, Thorlabs), measuring the time delay of the produced signals. Laser fluence is controlled via an attenuator plate and the laser spot size on the interface is 50 $\mu$m.

2.3. High speed camera setup

The second setup, utilizing a high speed camera (Mini AX-100, Photron), is shown in Fig. 2. The same laser as before (STANDA STA-01) is used for printing, with its laser fluence regulated by an attenuating system placed before the plano-convex lens. To illuminate the process, we use a standard LED (Thorlabs LEDD1B) placed opposite of the high speed camera, which is focused on the liquid jet's formation plane, perpendicularly to the donor-receiver substrates. The gap between the two substrates is set at 600 $\mu$m. Furthermore, the camera is coupled with a magnifying system, resulting in a total optical magnification of 3×. Lastly, the synchronization of the laser-camera triggering, is achieved with a custom program on LabVIEW.

2.4. Simulation

In order to further investigate the LIFT process, a computational model is employed. Given the fact that the jet's propagation direction serves as a symmetry axis, we can significantly reduce computational time by solving a 2-D axisymmetric model in ANSYS Fluent R18.0. Gravity is neglected in the study as it is observed both experimentally and based on simulation results that it does not affect the process. Calculation of the Bond number, $Bo = \frac{\Delta \rho g L^2}{\sigma}$, where $\Delta \rho$ is the density difference between two phases, $g$ is the gravitational acceleration, $L$ is the characteristic length and $\sigma$ the surface tension of the fluid, results in a very low value, meaning that surface tension dominates over gravitational forces, validating our observations. The inks are simulated as homogeneous fluids with their properties previously shown in Table 1 and, in the case of the silver NP ink, its non-Newtonian behavior is taken into consideration by setting its viscosity variable, following the power law equation (derived from the mathematical fit on the log-log plot of Fig. 1b):

$$
\mu(\gamma) = a \gamma^n
$$

where $a$ is the consistency index, $\gamma$ the shear rate, and $n$ is a measure of the deviation of the fluid from Newtonian behavior [30].

The domain is discretized via a quadrilateral face meshing and a uniform size function with the element size being 1 $\mu$m. An edge sizing is also applied along the symmetry axis (which coincides with the jet propagation axis) in order to further increase the quality and precision of the solution.

Our model is transient and in order to track the liquid-air interface, the explicit formulation of the Volume of Fluid (VOF) model is employed (Eq. (2)). The latter can model two or more immiscible fluids by solving a momentum equation (Eq. (3)) for an incompressible fluid. The jet propagation length within a time step and in our simulations is set at 0.25 $\mu$m. Courant (CFL) number determines the time step is set at 10 ns for the first 100 steps (in order to have increased solution accuracy) and then set to change automatically by the solver (up to 1 $\mu$s) as the jet propagates along the free surface and as long as the convergence criterion, Courant number, is met. Courant (CFL) number determines the jet propagation length within a time step and in our simulations is set at 0.25 [34].

$$
\frac{a_{q}^{n+1} - a_{q}^{n}}{\Delta t} V + \sum_{f} (\phi_{f} U f_{q} a_{q}^{n}) = \left[ \sum_{p=1}^{n} (m_{pq} - m_{qp}) + S_{nq} \right] V,
$$

where $n + 1$ = index of current time step, $n$ = index of previous time step, $a_{q}^{n}$ = face value of the qth volume fraction, $V$ = volume of cell, $U f_{q}$ = face value of the face, $m_{pq}$, $m_{qp}$ = the mass transfer from...
phase \( q \) to phase \( \bar{q} \) and vice versa, \( \rho = \text{density} \) and \( S_{aq} = \text{mass source term} \) which is set to zero.

\[
\frac{\partial}{\partial t} (\rho \vec{v}) + \nabla (\rho \vec{v} \cdot \vec{v}) = -\nabla p + \nabla \left[ \mu (\nabla \vec{v} + (\nabla \vec{v})^T) \right] + \rho \vec{g} + \vec{F},
\]

(3)

where the left-hand side expresses the inertial forces and the right-hand side the pressure, viscosity and external forces.

The computational model is axisymmetric, and does not take into consideration the thermal phenomena occurring at the early stages of the process, given the fact that the thermal diffusion length is of the order of nm, several orders of magnitude lower than the ink's thickness (15 \( \mu m \)). Alternatively, we assume that the fluid motion is induced by a deforming boundary [27], whose spatial and time-dependent profile is directly linked to the laser energy and spot size, as it is derived from the results of the pump-probe experiments (Fig. 3). To this end, the first frames of the pump-probe experiments (Fig. 3a) are processed to define the outer spatial profile of the ink bubble via a 4th degree polynomial fit by a custom Matlab program (Fig. 3b-d). Secondly, a temporal evolution function is derived after applying a fit on the normalized bubble height versus time plot. By multiplying these two functions we get a displacement equation:

\[
\delta(X, T) = X(x) \cdot T(t) = (p_1 x^3 + p_2 x^2 + p_3 x + p_4) \cdot (at^2 + bt + c)
\]

(4)

From that we can specify a time-dependent velocity, as shown in Eq. (5). Finally, we assume that this velocity is the deformation rate of the boundary, imported in the model via a User Defined Function (UDF),

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Fig. 2. Schematic illustration depicting the laser-induced forward transfer experimental setup.

Fig. 3. (a) Time-resolved image, (b) image converted to binary, (c) image with bubble boundaries detected and (d) polynomial 4th degree fit on ink bubble's spatial profile.
serving as an initial condition for our simulation.

\[
\frac{\partial \phi(X, T)}{\partial t} = \frac{\partial \phi(X(t), T)}{\partial T} = (p_1 x^4 + p_2 x^3 + p_3 x^2 + p_4 x + p_6)(2at + b)
\]

(5)

3. Results and discussion

To gain insight into the transfer mechanisms of both Cu and Ag NPs inks, side-view images of the inks’ ejection, during the first few microseconds by means of DRL-free LIFT technique, are recorded with a time-resolved imaging setup. All experiments are conducted in three laser fluences (110, 200, and 280 mJ/cm²), for 15 μm ink layer thickness on donor and laser spot diameter fixed at 50 μm on the transparent carrier/ink interface.

3.1. Comparison between Newtonian and non-Newtonian ink’s ejection behavior

Firstly, a low viscosity copper NP ink is tested as the printable fluid which exhibits a Newtonian behavior, according to rheology measurements provided by the manufacturer (Fig. 1a). In the low fluence case (Fig. 4a), the bubble’s momentum is not sufficient to overcome the friction forces, so after reaching a maximum height, the bubble collapses back to the donor layer. Since no jet is formed, 110 mJ/cm² is regarded as the threshold fluence of our process. For higher laser fluences though, when the external pressure and surface tension become larger than the bubble’s internal pressure, the bubble again collapses, this time into a jet propagating towards the free surface (Fig. 4b and c).

For a laser fluence near the threshold fluence, the bubble expands slowly with a mean velocity of 80.7 ± 5.3 m/s and reaches a maximum height of 90 μm at 1.2 μs after laser irradiation. Jet formation is initiated at 2.3 μs where the bubble takes a more conical shape (Fig. 4b). As one can observe, bubble height depends on laser fluence, with the expansion velocity reaching up to 150.4 ± 6.5 m/s and a maximum height of 178.2 μm for a laser fluence of 280 mJ/cm² (Fig. 4c), where a jet starts to form in the pole of the bubble. In addition, a laser fluence of 280 mJ/cm² yields the most stable jet in the range of donor-receiver gaps most commonly used and is further examined.

Secondly, a high viscosity silver NP ink, specifically designed for LIFT printing, is chosen as the printable fluid to investigate its ejection behavior. This ink has a high NP loading, very high initial viscosity (Table 1), and exhibits a shear thinning behavior (Fig. 1b). Results are shown in Fig. 4d-f, which correspond to bubble profiles of the silver NP ink. More specifically, 110 mJ/cm² is regarded as the threshold fluence also in this case, where a bubble expands very slowly with a mean velocity of 5.8 ± 0.7 m/s, as observed in Fig. 4d. At 200 mJ/cm² the bubble expansion velocity is high enough (11.4 ± 1.1 m/s) to generate a jet that progresses with a jet width of 24.2 μm (Fig. 4e). As the laser fluence increases (280 mJ/cm²) the bubble expands considerably slower (13.6 ± 1.5 m/s) than the one for the copper ink at the same fluence and the jet width (41.9 μm) is thicker than the lower tested fluence (Fig. 4f).

3.2. Comparison of modelling with experimental results

The ejection mechanism observed for the two inks, led us to the conclusion that the laser pulse induces a significant amount of shear stress to the ink, resulting in high shear rate that causes the viscosity’s value to change and eventually become very low, comparable to that of the copper NP ink. For the confirmation of this assumption, a high-speed imaging setup is employed, in order to compare the recorded images with simulation results.

On the one hand, Cu NP ink is a Newtonian fluid; hence its viscosity remains constant during our transient simulation model. Fig. 5 illustrates the size, shape and temporal evolution of both simulated and experimental jets at a laser fluence of 280 mJ/cm². Results of the simulation are shown in Fig. 5b and are compared against still images (Fig. 5a) acquired from videos recorded (at 170.000 fps) by using the high speed camera visualization setup. It is observed that for a gap distance between donor and receiver substrate of 600 μm, the jet impacts with the receiver substrate at approximately 11 μs after irradiation. A liquid bridge is thus formed between donor and receiver substrate which persists for at least up to 24 μs. Finally, at a later stage the jet has thinned from 23 μm jet width at 23.4 μs to 9.8 μm at 60 μs and the jet breaks into smaller parts. As one can notice, there is a close correlation between simulation and experimental results as the jet propagates simultaneously towards the receiver substrate.

On the other hand, in the case of Ag NP ink, the viscosity’s dependency on shear rate can be expressed by the power law equation described above (Eq. (1)). The same model is used for simulating this ink, with the main difference being that its viscosity is not constant, but varying according to Eq. (1), with \( n = -0.76 \), which was calculated by fitting a log-log plot of viscosity versus shear rate (Fig. 1b). Having previously tried to simulate this ink as a Newtonian fluid, it led to an ink bubble reaching a steady shape, never forming a jet or collapsing back to the donor layer due to their high viscosity value. This was the initial stimulus that impelled the authors to further investigate its properties and realize its non-Newtonian character. Results of the simulated jet are shown in Fig. 5d (Fig. 5c corresponds to still images extracted from experimental video recorded at 340.000 fps). It can be observed that the Ag jet impacts the receiver at a later stage (at 53 μs as illustrated in Fig. 5c and d) than the Cu ink (at 11 μs as illustrated in...
Fig. 5. (a, b) Comparison of experimental and simulation results of copper NP ink irradiated at 280 mJ/cm². (c, d) Comparison of experimental and simulation results of silver NP ink irradiated at 280 mJ/cm².

Fig. 6. Experimental vs simulation jet front velocity of (a) Cu NP ink and (b) Ag NP ink. (c) Velocity magnitude contours of Ag NP ink irradiated at 280 mJ/cm².
Fig. 5a and b) and at 147 μs the jet has thinned but has not broken into smaller droplets (Fig. 5c). Qualitative juxtaposition between simulated and experimental jetting of Ag NP ink validates the accuracy of our model with the only small deviation at late stages after irradiation where in the simulation results the jet starts to break from 147 μs (Fig. 5d).

Furthermore, an analysis of the jets’ velocities verifies the fidelity of the results. As it can be observed, the velocity is not constant, not only in time (Fig. 6a and b) but also across the length of the jet (Fig. 6c). More specifically, the temporal evolution of the velocity can be divided into two regimes. The first is that of a rapid growth during the first μs of the ejection process, as a result of the bubble’s collapse which imparts momentum to the liquid jet, followed by an exponential decay, until the jet reaches the receiver substrate. In the case of the silver NP ink, as time elapses, the effect of the laser irradiation and the shear stress induced to the ink substrates, leading to an increasing viscosity value which in conjunction with the surface tension forces cause the jet’s velocity to decline abruptly. For the copper NP ink this variation is more gradual, due to its Newtonian behavior. Furthermore, simulation results show that the velocity is not constant across the length of the jet. In each instance, the velocity’s maximum appears at the jet front, decreasing gradually towards its “tail” (Fig. 6c). Experimental velocity is calculated via a custom Matlab program by measuring the propagation length of the jet front between two consequent frames and dividing it with the elapsed time, while simulation velocity values derive from the contours of velocity magnitude. The simulation values on the graphs of Fig. 6a and b correspond to the jet front velocity at each time step and as one can observe, the computational model is able to correctly predict its temporal evolution.

4. Conclusion

In this work, a DRL-free (in order to conform with semi-industrial requirements) LIFT printing is conducted, employing inks of both Newtonian and non-Newtonian character. It is shown that the laser pulse induces a great amount of shear stress, affecting and altering the viscosity of the non-Newtonian ink in such an extent that its effective viscosity becomes several orders of magnitude lower than its nominal value. The ejection mechanism of both inks is recorded via a pump-probe imaging system and is observed to be similar. More specifically, a vapor bubble is formed which in the case of the copper NP ink expands more rapidly due to its lower viscosity. A computational model based on experimental data is also introduced, able to accurately predict the liquid jet’s formation and evolution, even in the case of the non-Newtonian ink. An analysis of the jet’s velocity indicates that its propagation rate is not constant which is also confirmed by our simulation results. Building from the results presented here, future work could explore (a) including viscoelastic properties of the inks into the computational model, and validating jetting evolution such as the formation of beads-on-a-string structures (b) investigating simulation and experimental results of the printed droplet with regards to the printed volume and/or the printed droplet size. Overall, the presented work may serve as a cost- and time-effective tool that, in our belief, can contribute towards the industrialization of the process.

Acknowledgments

This work has been funded by “HiperLAM” Project, an initiative of the Photonics and Factories of the Future Public Private Partnerships and received funding from the European Union’s Horizon 2020 Research and Innovation Programme under Grant Agreement No. 723879.

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