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[INVITED] Laser-induced forward transfer: A high resolution additive manufacturing technology

Philippe Delaporte *, Anne-Patricia Alloncle

Aix-Marseille University, CNRS, LP3 laboratory, UMR 7341, 13288 Marseille, France

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ABSTRACT

Among the additive manufacturing techniques, laser-induced forward transfer addresses the challenges of printing thin films in solid phase or small volume droplets in liquid phase with very high resolution. This paper reviews the physics of this process and explores the pros and cons of this technology versus other digital printing technologies. The main field of applications are printed electronics, organic electronics and tissue engineering, and the most promising short terms ones concern digital laser printing of sensors and conductive tracks. Future directions and emerging areas of interest are discussed such as printing solid from a liquid phase and 3D digital nanomanufacturing.

1. Introduction

Laser-induced forward transfer (LIFT) is a printing process allowing the deposition of a small amount of material in solid or liquid phase with high resolution. It was suggested and demonstrated for the first time almost 30 years ago by Bohandy et al. [1]. Since then many LIFT-based approaches have been developed to adapt this process to the printing material properties and to the targeted application.

Several presentations of this technique [2–4] are available in the literature and the following description of the LIFT principle is limited to the basic characteristics of the process. As shown in Fig. 1, the transfer of pixels in solid phase consists in irradiating with a pulsed laser a thin layer of an absorbing material (the donor) previously deposited onto a transparent substrate. The layer is irradiated through the substrate and the light-matter interaction which takes place at the interface generates a strong increase of the local pressure. As a result, a small pixel of the thin film is ejected from the donor and deposited onto a target substrate (the receiver) which is placed close to the donor substrate. The transfer of transparent layers is also possible with this technique using an absorbing layer, called a dynamic release layer (DRL), between the substrate and the film to be transferred [5]. Size and shape of the ejected material are controlled by the size and shape of the incident laser spot. LIFT enables the deposition of a large range of materials with typical size of a few micrometers. When printing droplets in liquid phase, the donor film consists in a liquid layer with a thickness of a few micrometers. The laser interacts with a DRL or directly with the liquid layer if it is absorbing enough, which generates the formation of a vapor bubble expanding towards the surface of the liquid. This process drags the liquid around the bubble to form a very thin and stable jet which reaches the surface and form a droplet [6].

Successfully LIFT-printed materials include deoxyribonucleic acid (DNA) [7], active optical structure [8,9], polymers [10,11], biomaterials [12,13], nanotubes [14], graphene [15], metals [16,17], particles [18,19] and inks [20–23]. This process is a single-step direct printing technique that offers the ability to perform surface micro patterning and localized deposition of almost any material. It can be used to print sensitive materials without altering their properties but it also allows to direct-write multilayer systems in a solvent-free, single-step process, without requiring any shadowing mask or high vacuum setup [24,25].This process appears as an alternative technique for various applications like electronic components fabrication [26], such as organic thin film transistors [27–29] or organic light emitting diode [30–32], microelectromechanical systems (MEMS) [33,34], sensors [35–38] and also for medical applications such as tissue engineering [39,40]. However, like most laser processes, LIFT has some advantages and disadvantages and the successful development of a laser printing application requires a good knowledge of the physical mechanisms driving the ejection and deposition of the material.

This paper presents first the physics of the LIFT process as a function of the properties of the material to be printed and the characteristics of the laser irradiation. Fast imaging techniques have been used by many groups to study the dynamics of the ejection mechanisms in both solid [41–43] and liquid phase [44–47]. Based on this LIFT physics knowledge, the second part of the

* Corresponding author.
E-mail address: philippe.delaporte@univ-amu.fr (P. Delaporte).

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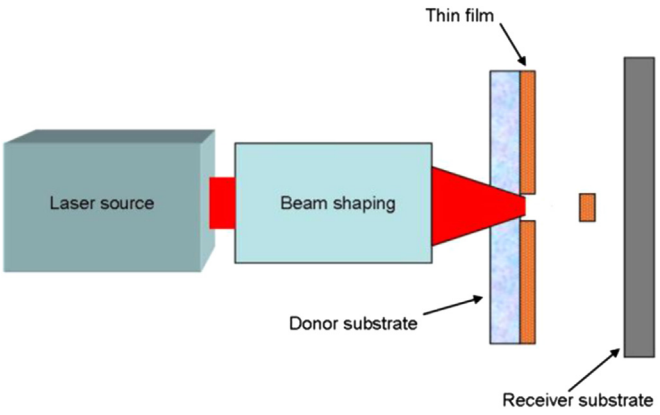

Fig. 1. scheme of LIFT process in solid phase.

article discusses the pros and cons of this process to address its major potential applications.

2. Physics of LIFT

2.1. LIFT of solid materials

The transfer of a solid pixel is induced by mechanical forces resulting from the absorption of the laser energy at the interface between the transparent donor substrate and the thin film. A fast increase of the temperature and pressure occurs in this confined volume which breaks the film around the irradiated zone and pushes this pixel away from the donor towards the receiver. A shock wave is also generated during the process, propagating in front of the pixel. This is clearly visible in the images of the Fig. 2.

The ejection velocity of the pixels is determined from the analysis of the shadowgraphs. This velocity depends mainly on the laser fluence and film properties (thickness, Young's modulus…). When varying the pulse duration between a few tens of picoseconds to a few tens of microsecond no significant velocity change is observed. Typically, the solid pixels are ejected with velocities ranging from 200 m/s to 1200 m/s, which corresponds to more than three times the speed of sound in air. However, it is also possible to eject pixels at low velocity, down to 34 m/s, without any evidence of shock wave generation, when transferring PZT material with a 100 fs laser [42]. A part of the laser energy is absorbed by the material and heats the thin film, another part is used to break the film and the remaining part propels the film away from the donor substrate. The ideal condition would be first to limit the heat diffusion into the film to avoid its damage and the generation of melted debris on the receiver, then to use most of the energy to break the film and keep the pixel velocity low enough to ensure a smooth landing of this pixel on the receiver substrate. The use of femtosecond laser allows, for some materials, to optimize this energy distribution.

This shock wave generation is the major drawback of the LIFT process in solid phase. Indeed, R. Fardel et al. [48] have demonstrated that when the shock wave reaches the receiver substrate, it is reflected back and interacts with the pixel. This interaction stops the pixel motion and often destroys it. Laser printing at atmospheric pressure can be performed using a gap between the receiver and donor substrates of a few micrometers, or without any gap, and for a narrow process window of fluence. Printing experiments have been performed under vacuum to avoid this shock wave, but the velocity of the flyer was so high that it broke when reaching the receiver substrate [48]. It is necessary to reach a compromise between the shock wave intensity and the pixel velocity by controlling the surrounding gas pressure and the laser fluence [49]. For most materials, working at pressures between 10 mbar and 100 mbar allows a safe transfer of the pixels with a gap smaller than 50 μm.

As the LIFT process is based on the generation of a mechanical force to break the thin film, the printing of brittle materials or thick layers (more than a few micrometers) is very challenging. Two approaches have been developed to address these points. Kaur et al. [50] have used a focused ion beam to thin the 1 μm thick zinc oxide (ZnO) films down to 0.8 μm. A smaller laser energy is then required to break the remaining part of the film compared to a non-patterned film, and this reduction of the overall deposited energy allowed a smoother transfer and the deposition of undamaged ZnO pixels. With the same motivation L. Rapp et al. [51] have used a specific laser beam shaping to independently control the energy used to break the film, which is concentrated at the edge of the beam, and the energy used to propel the pixel. As shown in Fig. 3, by merging two beams with different energy profiles, they can increase the laser fluence at the edges of the beam while keeping a low fluence in the central part of the beam. This approach allowed printing polymer films thicker than 1 μm with a very good resolution [51,52].

The purpose of all these studies and efforts is to find the best conditions to transfer these pixels while minimizing the risk of material damage and then of modification of the material properties. As previously mentioned, dynamic release layers have been developed to print transparent materials. The most currently used DRL is based on a UV-sensitive aryltriazene polymer (TP) which has the particularity of decomposing into volatile fragments upon laser irradiation at very low fluences [5,53–55]. This approach prevents any direct interaction of the laser beam with the material

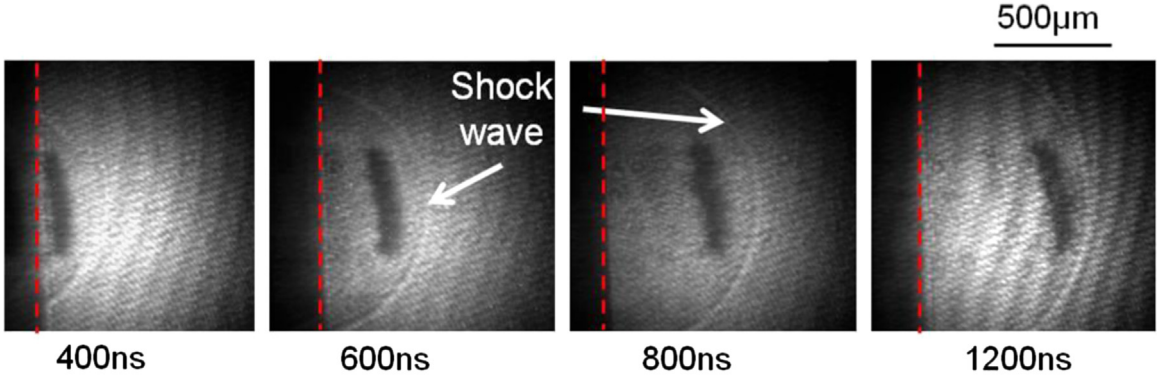

Fig. 2. Shadowgraph images of the laser-induced forward transfer of a 300 nm thick PEDOT:PSS film with a KrF laser (20 ns; 248 nm). The donor substrate is represented by the red dashed line, the laser comes from the left hand side and the delay from the laser irradiation is indicated below each image. One can see a spherical shock wave propagating in front of the pixel. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article)