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Ultrafast laser-enabled 3D metal printing: A solution to fabricate arbitrary submicron metal structures☆

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ABSTRACT

3D metal printing has become one of the critical manufacturing methods in recent years that enables a variety of applications across different disciplines, e.g. aerospace and medicine. In this work, we present a high-throughput 3D metal printing method based on a programmable femtosecond light sheet and electrodeposition, achieving submicron resolution in both lateral and axial directions. The light sheet, for parallel material removal, is generated by spatially and temporally focusing the ultrafast laser in the processing plane, which is in conjugation with a digital micromirror device (DMD), thereby allowing fast pattern generation in synchronization with laser pulses. High quality metal layers are formed successively via electrodeposition processes. Accordingly, 3D metal printing is realized by repeating the steps of (1) forming structural/sacrificial layers; and (2) laser micromachining. In the experiments, we demonstrate fast metal printing of various complex 3D structures within tens of laser pulses over an area of 100 × 60 μm^2. Compared with the existing sequential metal printing techniques, the new method has substantially improved both the throughput and resolution by a factor of ∼100 times.

1. Introduction

3D printing, i.e., additive manufacturing, is a disruptive technology that generates profound impact from personal to industrial level. This technology enables rapid prototyping and customization as well as the fabrication of complex structures that cannot be produced via conventional methods etc. Recent advancements in 3D printing technology further improve the printing resolution, scale and material choices, e.g., printing composite materials. In terms of resolution, nanometer scaled structures have been printed on photopolymers via femtosecond lasers and commercialized, e.g., Nanoscribe Gmbh, extending the application of 3D printing to the area of photonics [1–3]. However, these results are mostly not applicable to metals, which is an equally or more important material for engineering applications. Compared to polymers, metals have better mechanical strength, heat resistance, and electrical and magnetic properties. State-of-the-art commercially available metal printing methods include selective laser sintering (SLS) [4], selective laser melting (SLM) [5], and laser engineered net shaping (LENS) [6], which are all based on sintering or melting metal powders. Much effort has been made to improve the resolution, speed, and yield by adjusting the laser parameters and powder properties. However, the resolution of such systems is limited to tens of microns scale owing to their operating principles, i.e., the melting/sintering and resolidification processes of metal powders prevent them to form nanoscale structures. In addition, the temperature induced residual stresses may negatively affect the quality, e.g., deformation, of the printed microstructures. New applications in metamaterials [7–9], medical devices [10], electronic devices [11,12], and microrobotics [13], may emerge if one can additively print metal structures of submicron resolution with good throughput.

To improve the resolution micropipette-based methods have been developed, e.g., filament-based direct ink writing, inkjet printing, and electrohydrodynamic inkjet printing [14–17]. Although some methods have demonstrated nanometer level resolution, their throughput and practicality are limited by the slow mechanical scanning of nozzles. Recently, the laser-induced forward transfer (LIFT) method is introduced to address the issue of throughput [18–20], where a picosecond laser is focused onto a thin metal donor layer to melt and transfer the metal droplets to a receiver substrate at 200 Hz; in addition, the throughput may be further increased when the laser is split into multiple beams via a lens array. Comparing with the micropipette-based methods, the LIFT achieves higher throughput at the expense of print resolution (∼5 μm). One issue associated with the LIFT method is that the printed metal parts lacks mechanical strength due to the weak connection between metal drops. Electrodeposition of metals is an

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attractive method to grow dense and high-quality metal films and structures. As an old art, the fabrication cost is relatively low. Accordingly, some new 3D metal printing methods have adopted electrodeposition. For example, the force-controlled nanopipette 3D printing technique [21], where localized electrodepositions is used to print complex structures of submicron resolution. In this method, the throughput is limited by the serial mechanical scanning process and the deposition rate. A related method uses stereolithography and electrodeposition to achieve high-resolution metal printing [22], where metal structures are formed by electrochemical deposition in polymer masks prepared by direct laser writing. Although achieving high-resolution (500 nm), this method cannot print complex structures, e.g., woodpile structures, due to the lack of metal ions in the polymer mask. Electrochemical Fabrication (EFAB) is a commercially available metal microprinting technique that exploits electrodeposition and has a resolution of ~5 μm [23]. As a large number of custom-designed masks are required to print each part, EFAB is more suitable for volume production instead of rapid prototyping.

2. Experiment

2.1. Working principle

In this work, we present a new metal 3D printing method that realizes high-resolution (800 nm), high-throughput fabrication based on a programmable femtosecond light sheet and electrodeposition. The high-energy light sheet realizes parallel laser micromachining and simultaneously preserves the advantages of femtosecond lasers, i.e., high precision, large material removal rate, minimal thermal damage, and ability to process nearly any material. To ensure the quality of printed structures, electrochemical deposition with custom-developed formulations on various metals, which serve as structural and sacrificial layers, is used to grow fully dense metal structures at submicron scales. Fig. 1(A) presents the process flow of the new metal printing method, where sacrificial or structural layers are deposited alternately, followed by material removal and flattening steps via patterned femtosecond light sheets. In the experiments, nickel and copper are used as the structural and sacrificial materials respectively to demonstrate how the new process works. To release the printed nickel structures, an etchant of high copper selectivity (i.e., Copper Etch BTP, Transene) is used with an etch rate of 150 Å/sec. Typical etching processes are performed at room temperature and completed within several minutes. Fig. 1(B) visually illustrates step (2) in Fig. 1(A), where the pattern on the femtosecond light sheet is directly controlled by a digital micromirror device (DMD) to perform parallel laser machining. Note that as the femtosecond light sheet can process nearly any material, the selection of structural and sacrificial materials is only restricted by the electrodeposition and etching processes, i.e., different metals can be arbitrarily combined as long as a selective etchant is available.

2.2. Optical configuration

Fig. 2 presents the configuration of the new 3D metal printing system, which consists of an optical unit and an electrodeposition unit. The optical subsystem generates patterned femtosecond light sheet for material removal [24]. The laser source is a Ti-Sapphire regenerative amplifier (Spitfire Pro, Spectra-Physics) with a central wavelength of 800 nm, pulse width of 100 fs, and repetition rate of 1 kHz. A half wave plate and a polarized beam splitter together control the laser power. A beam homogenizer (piShaper_TisHP, AdlOptica GmbH) is used to flatten the Gaussian beam profile. Next, a high reflectance mirror guides the laser beam to a DMD (DLP4500, Texas Instruments), which simultaneously disperses the laser beam and generates 2D patterns. (The DMD can be considered as a programmable blazed grating as it is a two dimensional array of micromirrors with a pitch of 10.8 μm. Each micromirror has two stable states at ± 12° and a bandwidth of 4.2 kHz.) After the concave mirror, an objective lens (S Plan Fluor ELWD 40x, NA = 0.60, Nikon) recombines the dispersed spectral components. Accordingly, the laser beam is spatially and temporally focused at the focal plane, forming a thin light sheet (3–10 μm thick) with DMD patterns, i.e., the laser pulse widths are of 100 fs only at the focal plane and widened everywhere else due to dispersion. Once the laser power goes above the ablation threshold, patterns on the DMD will be fabricated on the structural layer. During the 3D printing process, the DMD receives external streaming 2D cross-sectional patterns of the designed 3D structure. As metals are opaque, a reflectance microscope is built in conjunction with the optical module to observe the fabrication progress in situ. An epi-illumination light source is coupled into the optical path

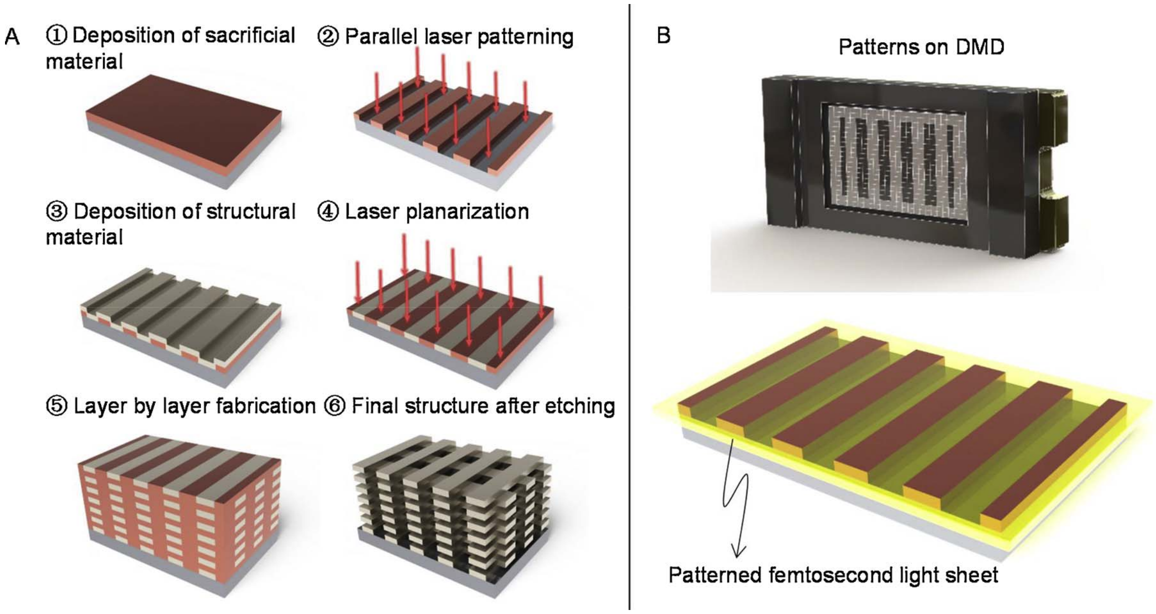

Fig. 1. (A) Process flow of the high-resolution 3-D metal printing technique: (1) deposition of sacrificial materials; (2) removal of redundant materials via a patterned femtosecond light sheet; (3) deposition of structural materials; (4) planarization of metal structures via a plane femtosecond light sheet; (5) repeat of steps (1) to (4) to create 3-D metal structures layer by layer; and (6) removal of the sacrificial materials (layers) via wet etching; (B) illustration of step (2), where a patterned femtosecond light sheet performs parallel laser micromachining.