euspen's 18th International Conference & Exhibition, Venice, IT, June 2018
www.euspen.eu

Pinpoint additive manufacturing of complex 3D microstructures of pure metal

Wabe W. Koelmans, Thibaut Merle, Giorgio Ercolano, Michael Gabi and Edgar Hepp

Cytosurge AG, Sägereistrasse 25, Glattbrugg, Switzerland

wabe.koelmans@cytosurge.com

Abstract
Direct 3D printing of metals with submicron resolution is a promising additive manufacturing (AM) technique in a wide range of sectors. Here we present the FluidFM µ3Dprinter, the world's first 3D printer capable of delivering such resolution, while offering scalability and good prospects in both production cost and speed. The FluidFM µ3Dprinter is an elegant combination of fluidic scanning probe microscopy and 3D printing. Pinpoint-accurate 3D printing revolutionizes micromanufacturing by combining AM with traditional microfabrication methods. The 3D objects are aligned with previously manufactured structures using high-resolution cameras. We demonstrate a fully integrated system that prints high-quality metal microstructures in one processing step, at room temperature. This technology has the potential to drive AM well beyond current technological boundaries.

3d printing, metal, localized electroplating, additive manufacturing, FluidFM

1. Introduction

The relentless drives to miniaturize components, customize mass production and shorten development and production cycles set a welcoming stage for additive manufacturing (AM) of pure metal microstructures. Despite the need, no established technology is available to print 3D structures at a submicrometer resolution [1]. The reasons for that are manifold, as there are many technologies for the AM of metals [1-3]. The use of high temperatures, vacuum environments, low material quality and a limited set of geometries printable are amongst the most important reasons. A room-temperature, template-free process without post-processing that delivers complex, high-quality 3d metal structures is required.

Here we present the most mature 3d printing technology capable of meeting these requirements. The metal is produced by standard, but localized, electroplating and are therefore of a high quality, as electroplating is well established. This work is building on studies carried out by Hirt et al. [4]. We report a fully integrated system in section 2.1, the printing routine in 2.2, an optimized electrochemical process in 2.3 and then in section 3 we show state-of-the-art printing results.

2. The FluidFM µ3Dprinter

2.1. Integrated system

The FluidFM µ3Dprinter is a combination of scanning probe microscopy (SPM), femtoliter-precise liquid dispensing, and electrodeposition. The system uses Atomic Force Microscopy (AFM) cantilevers with a microfluidic channel and a hollow tip, called FluidFM iontip [5]. The FluidFM probe dispenses an electrolyte solution in 3D space. A microfluidics control system applies a pressure to a reservoir containing the electrolyte solution to push it through the cantilever and out of the tip. The FluidFM iontip is part of the printing head that is moved in z-direction by a linear motor at a 1 nm resolution, see Figure 1. The use of linear motors overcomes the limited range of piezo motors that are typically employed in SPM. The range in z is 60 mm. The linear motor ranges in x and y are 240 mm and

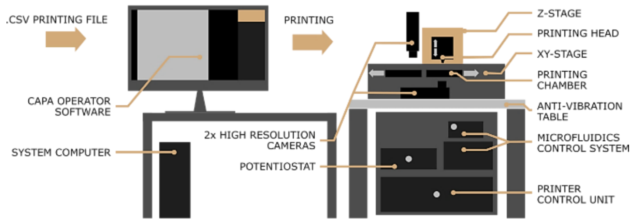

Figure 1. Schematic of the complete system, now available as a product. The FluidFM µ3Dprinter sits atop an anti-vibration table to achieve high printing accuracy.

76 mm, respectively. Both the x and y stage have a 5 nm resolution.

Two high-resolution cameras (top and bottom view) enable the automated iontip loading and visualization of the printed structures. Computer-assisted alignment is built-in for pinpoint-accurate printing on, e.g., integrated electrodes that are pre-defined on a chip surface.

2.2. Printing routine

The printing process is voxel-based. Voxels are defined as elementary 3D blocks. Stacked in a layer-by-layer sequence at defined coordinates, the voxels form the desired 3D geometry, see Figure 2. Free-standing structures and 90° overhanging angles are feasible without support structures, bringing true design freedom.

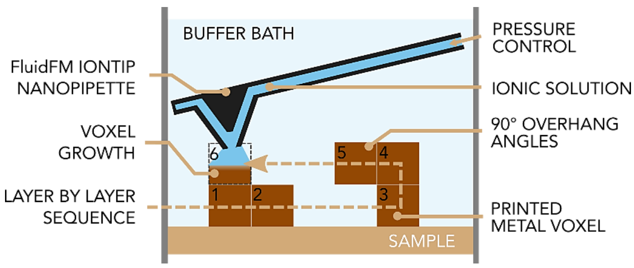

Figure 2. The printing process is executed voxel-by-voxel and layer-by-layer. The process allows 90° overhanging structures.

The printing process is automated by real-time feedback of the deflection of the FluidFM iontip. As a voxel reaches completion, the top side of the voxel interacts with the tip, exerting a few nanonewton of force that deflects the cantilever by a few nanometer. When a, user-defined, deflection threshold is reached, the voxel is considered as printed. The tip is then quickly retracted to a safe traveling height and is moved to the next voxel. The voxel coordinates, the printing pressure and the deflection threshold of the cantilever are specified in a .csv file. The file is loaded into the printer's controller software.

2.3. Electrochemical process

The voxels are built from an electrolyte solution that is pumped out of the iontip by a microfluidic pressure controller. The controller regulates the pressure applied with a precision of < 0.2 mbar. This precision combined with a 300-nm-wide tip aperture allows for a liquid dispensing precision on the order of 100 fl/s. When an appropriate potential is applied to the substrate the metallic ions are reduced to metallic ions.

In Figure 3 a process to print copper is shown. The

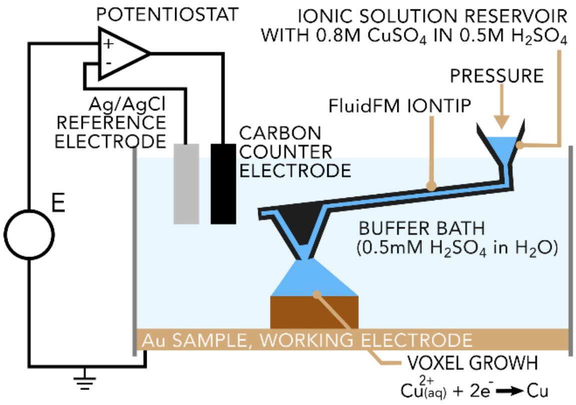

Figure 3. Schematic of the printing cell. The iontip dispenses the electrolyte into a buffer bath. At the working electrode, Cu^{2+} ions are deposited as solid copper.

potentiostat-controlled electrochemical cell has a three-electrode configuration with a quasi-reference electrode. The buffer bath does not contain metal ions and serves as a conductive medium for the charge transfer essential to the reduction reaction. The electrolyte is a metal salt solution ($CuSO_4$) in sulfuric acid (H_2SO_4). The reaction that takes place at the working electrode is $Cu^{2+}(aq) + 2e^- \rightarrow Cu\ (s)$.

The plating process has been optimized for surface smoothness by optimizing the printing parameters (pressure, voxel pitch, etc.) and by using copper plating additives.

A conductive surface is required for the working electrode on which the local electrodeposition process takes place. With a 300-nm-wide tip aperture diameter the volume of a voxel is about 0.5 to 2 μm^3. The printing time is between 0.25 s and 2.5 s for 1 voxel. The maximum volumetric printing rate of high-quality, solid copper is above 3 μm^3/s. and the average deposition current is estimated to be on the order of 100 pA.

3. Printing results

Figure 4 and 5 display copper structures as-printed. There has been no post-processing or post-treatment of any kind. The surface of the structures is seen to be very smooth and free of cavities. Figure 4a shows a pillar of one voxel in diameter; the voxels are stacked in one dimension. Figure 4b is a wall structure with a wall thickness of 1 voxel, the voxels are stacked in 2 dimensions and have smoothly merged. Figure 4c is a cube where the voxels have been stacked in 3 dimensions.

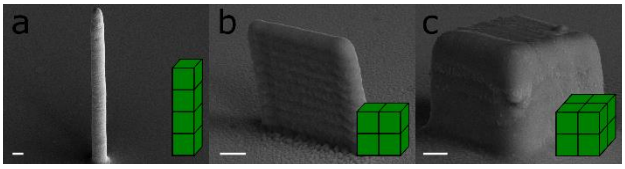

Figure 4. SEM images showing copper structures built out of voxels stacked in 1, 2 and 3 dimensions. Scale bars are 2 µm.

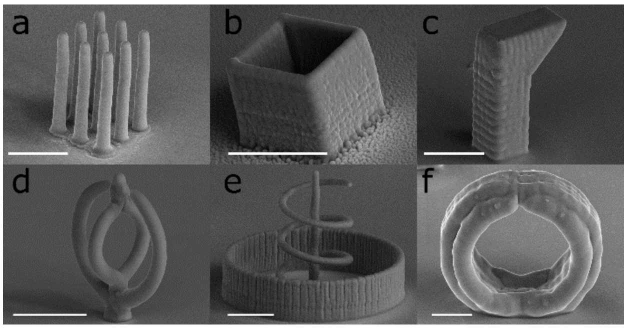

Figure 5. SEM images of 3d printed copper structures at the microscale. The structures were printed in one processing step. Scale bars are 10 µm.

The voxels merged in all directions with their direct neighbors to form a solid metal structure. In Figure 5 a range of structures is displayed. Figure 5a and b show an array of pillars and four connecting walls, respectively. In Figure 5c, a solid body with an overhang is shown. The top surface is flat and smooth, even though it consists out of 220 voxels. The complete structure is printed with 4'517 voxels in 1'219 seconds. At an estimated volume of 4'030 μm^3, the average printing rate is 3.3 μm^3/s. Figure 5d displays a double ring structure that has a 1 voxel wire diameter. The rings show that all deposition angles ranging from vertical to horizontal printing are possible. Figure 5e shows a combination of three structures, all printed in one print run: a cylinder, a helix and, in its center, a pillar. The structure shown in Figure 5f is a ring with two different outer diameters, the largest diameter one is 38 µm.

4. Conclusion

The AM of pure metal at the micrometer scale is a much-anticipated technology. We demonstrated a fully integrated system that prints high-quality metal microstructures in one processing step, at room temperature. The FluidFM µ3dprinter uses localized electrodeposition to generate a wide range of geometries. Freestanding structures with 1D, 2D and 3D voxel configurations have been shown in combination with overhangs up to 90° without the use of support structures. The printing rate is above 3 μm^3/s and, currently, up to 4 voxels per second can be printed. Future work targets higher speeds. The FluidFM µ3D printer is now commercially available and is well suited for rapid prototyping and process development of complex 3D metal structures for a wide variety of applications.

References

[1] Vyatka A, Delalande S, Kudo A, Zhang X, Portela C M, Greer J R 2018 *Nat. Commun.* **9** 593
[2] Frazier W E 2014 *Int. J. Adv. Manuf. Technol.* **67** 1721-1754
[3] Hirt L, Reiser A, Spolenak R, Zambelli T 2017 *Adv. Mater.* **29** 1604211
[4] Hirt L, Ihle S, Pan Z Dorwling-Carter L, Reiser A, Wheeler, J M, Spolenak R, Vörös J, Zambelli, T 2016 *Adv. Mater*. **28** 2311-2315
[5] Meister A, Gabi M, Behr P, Studer P, Vörös J, Niedermann P, Bitterli J, Polesel-Maris J, Liley M, Heinzelmann H, Zambelli T 2009 *Nanoletters* **9** 2501-2507