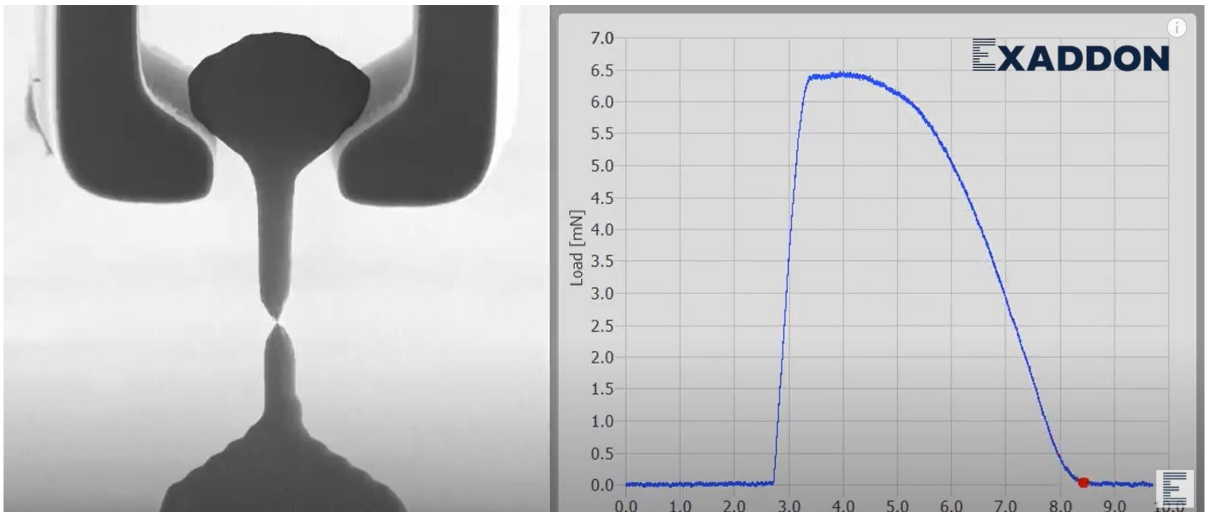
WHITE PAPER

MATERIAL PROPERTIES of µAM OBJECTS

TESTING MATERIAL CHARACTERISTICS OF METAL OBJECTS PRINTED WITH EXADDON MICRO 3D PRINTING TECHNOLOGY



COPPER µAM. Microscale copper test pieces behaved just like their macroscale counterparts.

MICROSCALE VS MACROSCALE

Micro- and nanoscale objects can exhibit different behavior to their macroscale counterparts. Material characteristics such as conductivity, tensile strength, and density, are crucial data points to researchers in industry and academia – one cannot assume the same values as bulk metals, and this is perhaps especially true of new approaches in additive micromanufacturing (µAM).

In partnership with the Swiss Federal Laboratories for Materials Science and Technology (EMPA) and Alemnis AG, we have analyzed the material properties of our printed structures.

TENSILE STRENGTH TESTING WITH THE ALEMNIS ASA

Tensile strength is the strength of a material under tension, whilst the yield strength denotes the point at which elastic behavior ends and plastic behavior begins; this provides further insight into how a material will act under tension.

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Scientists at EMPA conducted tensile strength and yield tests using the ASA system from Alemnis. This equipment is unique in its ability to grip and test microscale parts; the jaws of the gripper in the image are less than 20 μm apart.

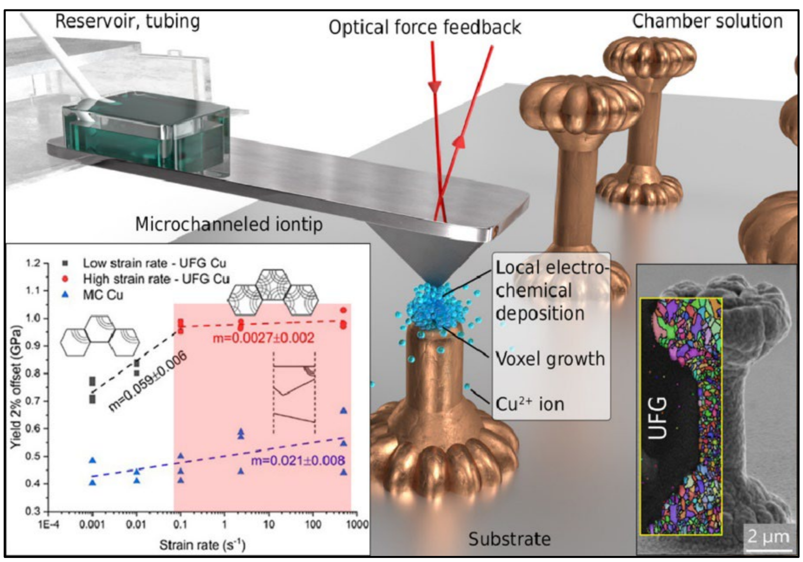
A 5 μm diameter copper dogbone printed with our CERES system was used as the test piece within the ASA system. This copper dogbone was subjected to slow and constant elongation with a standardized speed, as per standard tensile test protocol. As the piece was strained uniformly along its length, material behavior was plotted in real-time on a force elongation diagram. This diagram maps force (x axis) vs the elongation delta (y axis).

YIELD STRENGTH AND TENSILE STRENGTH

In a standard tensile test, the expected behavior is as follows; the force rises rapidly at first, and the initial linear curve shows the elastic behavior of the material. At the point of maximum force, a neck (narrower section) begins to form; all subsequent plastic deformation is confined to this neck, until fracture finally occurs there. This is exactly what happened in our testing.

The calculated yield stress was 320 MPa and the tensile strength 342.5 MPa, values in line with cold drawn copper. Failure of the sample occurred within the central gauge section, at a few percent of inelastic strain. When analyzing the yield stress using the Hall-Petch relationship for grain boundary strengthening, the copper grains in our μAM test piece are likely of a diameter of around 160nm.

UNPRECENDENTED YIELD STRENGTH RESULTS WITH EMPA & MPIE



Rigorous testing of the dynamic strain properties of 3D printed copper micropillars was conducted with EMPA and MPIE (Max Planck Institute).

The study shows *unprecedented* experimental yield strength results across certain strain rates.

Yield strength ranged from **0.4 to 1.0 GPa**; the highest strain-rate dependent yield-strength in literature - not only additive manufacturing literature.

UNPRECEDENTED VALUES. Graphic abstract from [1]. Image courtesy of S Kalácska.

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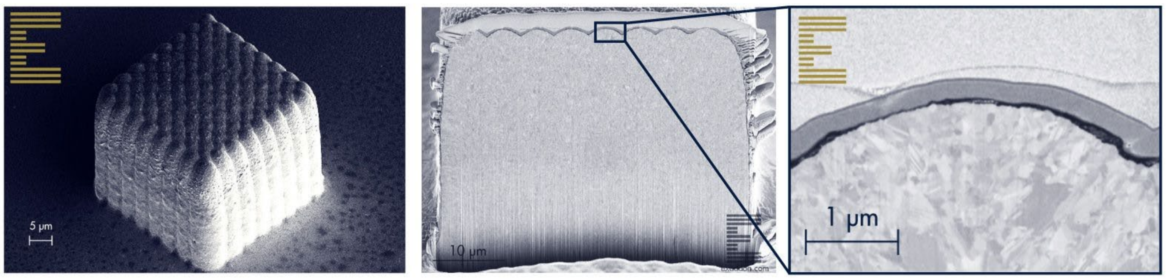
MATERIAL DENSITY

As part of a voxel spacing/merging test, we printed an array of copper micropillars in close proximity, such that they merged into an approximate cube (~50 µm diameter). We then sliced it with a Focused Ion Beam (FIB) to assess the homogeneity of the grain structure.

Whilst the left image shows the relief of the individual pillars, the cross-section SEM on the right shows the deposited material to be uniform and homogeneous; there are no visible traces of the individual voxels.

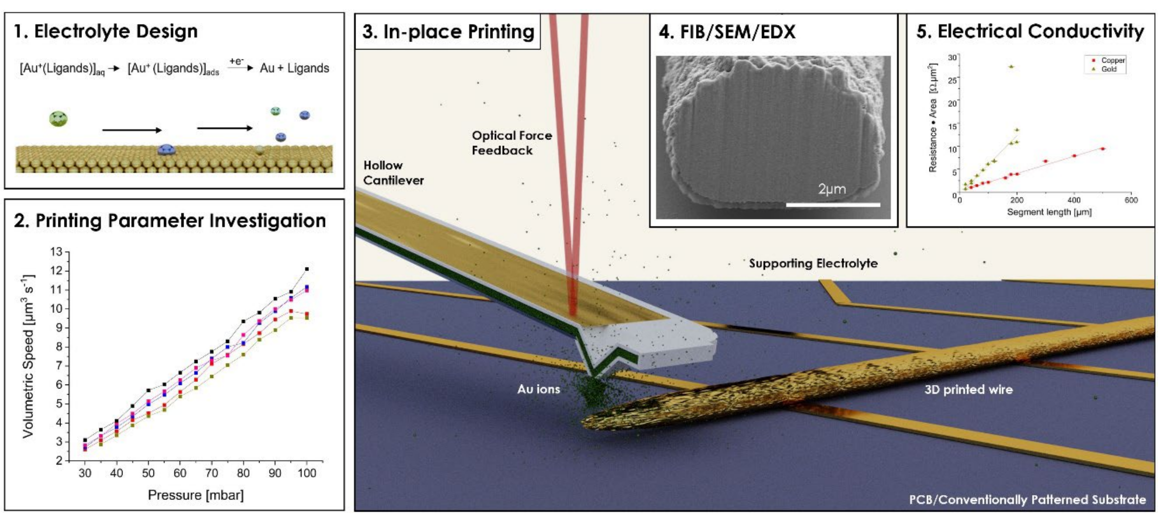


This homogeneity of grain structure is essential in many use cases, such as heat-sensitive applications. Low porosity is also crucial in microelectronic applications where conductivity is paramount.

- Our printed microcrystalline copper has > 99% density

MATERIAL CONDUCTIVITY

Research from Exaddon and EMPA [2] details how highly conductive microstructures can be 3D printed directly on pre-patterned microchips, thus combining micro 3D printing with traditional photolithographic processes.



RESISTIVITY TESTING. 4-point probe measurements of Exaddon 3D printed microwires. Graphic abstract from [2].

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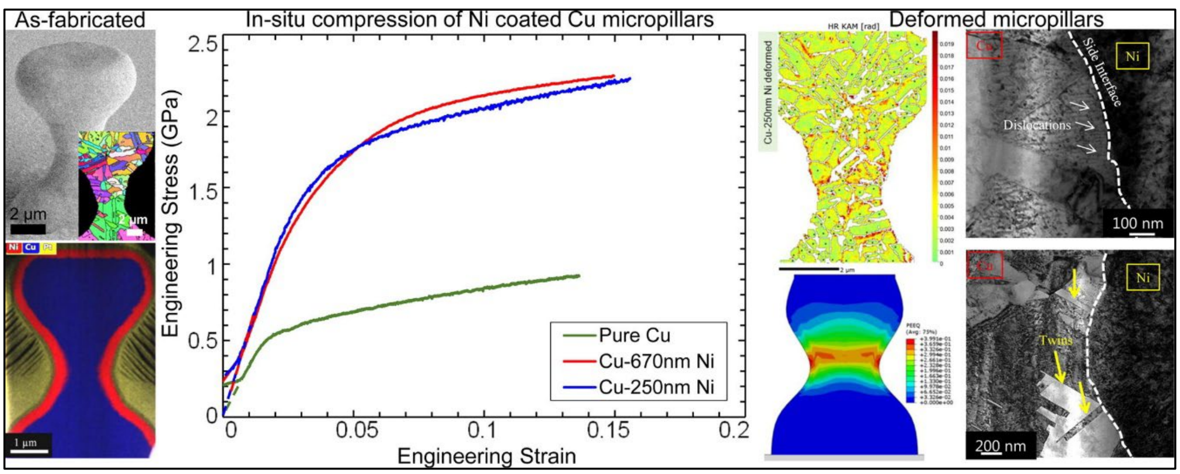
Four-point probe measurements were performed on copper and gold microwires 3D printed orthogonally across eight parallel electrodes.

- Resistivity of copper structures: **19 ± 2 nΩ·m**
- This is around 87% of the conductivity of bulk copper
- Resistivity of gold structures: **65 ± 6 nΩ·m**
- This is excellent in the context of gold electrodeposition.

NICKEL COATING OF COPPER CORES

Further research with EMPA [3] analyzed the strength increase gained from coating Exaddon copper structures with nickel shells. The study found an exceptional **~3-fold increase in strength** after coating the Cu microstructures with a Ni shell just 250 nm thick (compared to pure Cu).

The study demonstrated that the shape and dimension of the 3D-printed objects can be retained whilst drastically increasing their strength. This opens an exciting route toward creating strong microscale metal structures for future research and real-world application.



NICKEL SHELLS. Coating Cu objects with 250 nm Ni shells gave ~3x strength increases. Graphic abstract from [3].

References

[1] Ramachandramoorthy R., Kalácska S., Poras G., et al. Anomalous high strain rate compressive behavior of additively manufactured copper micropillars. Applied Materials Today. Volume 27, 2022. 101415, ISSN 2352-9407. https://doi.org/10.1016/j.apmt.2022.101415.

[2] Schürch P, Osenberg D, Testa P, et al. Direct 3D microprinting of highly conductive gold structures via localized electrodeposition. Materials & Design 2023, 111780. https://doi.org/10.1016/j.matdes.2023.111780.

[3] Jain M, Sharma A, Schürch P, et al. Strengthening of 3D printed Cu micropillar in Cu-Ni core-shell structure. Materials & Design. Volume 227,2023, 111717. https://doi.org/10.1016/j.matdes.2023.111717.

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