

Supplementary information

Enhanced aerosol-jet printing using annular acoustic field for high resolution and minimal overspray

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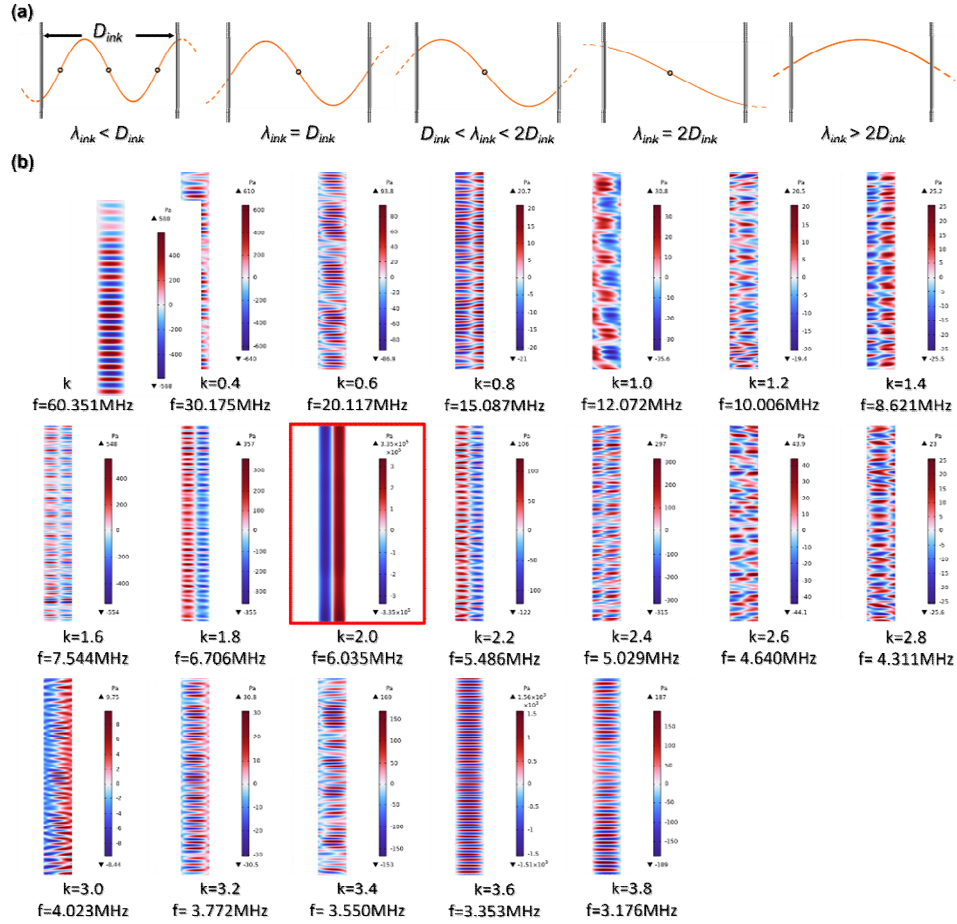
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1 Acoustic pressure node and field distribution



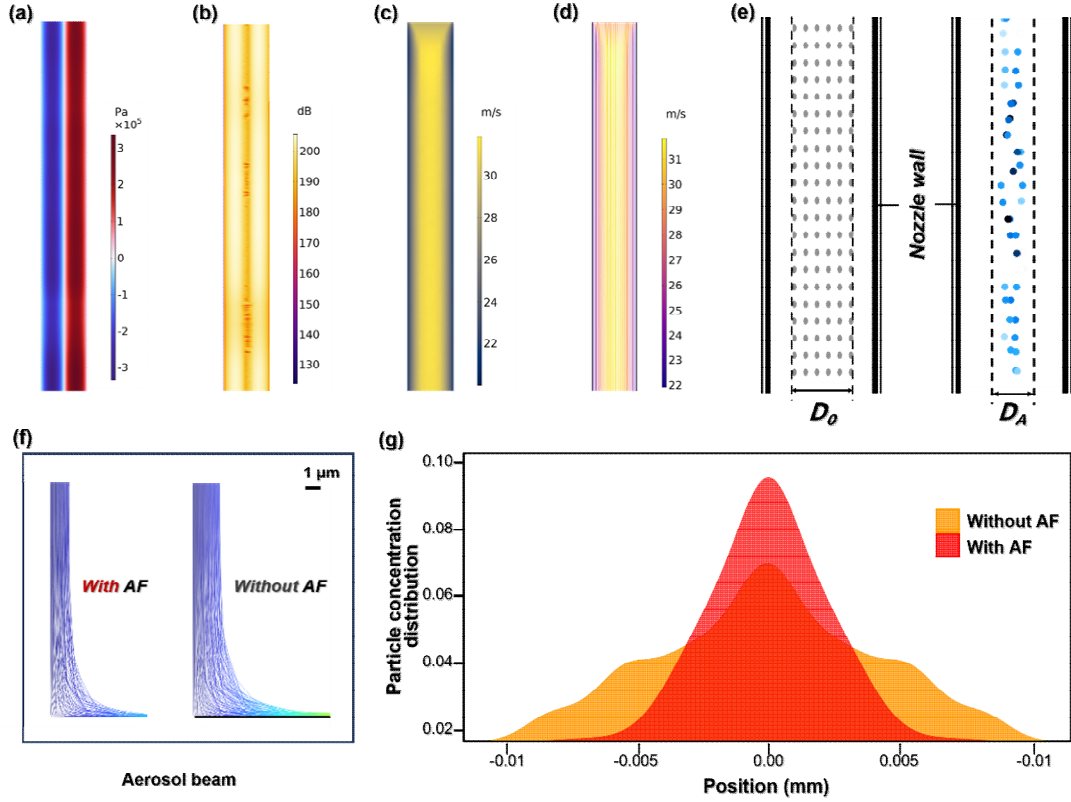
Supplementary Fig. 1 Acoustic pressure node and field distribution. **a** Schematic diagram of the relationship between acoustic pressure node distribution and wavelength in ink flow. D_{ink} is the diameter of the ink flow, and λ_{ink} is the acoustic wavelength. **b** Parameterized scanning acoustic frequency search for the optimal acoustic field distribution for focusing aerosol particles

2 Coupling multi-physical field simulation

Supplementary Table 1 Material properties used in the simulation

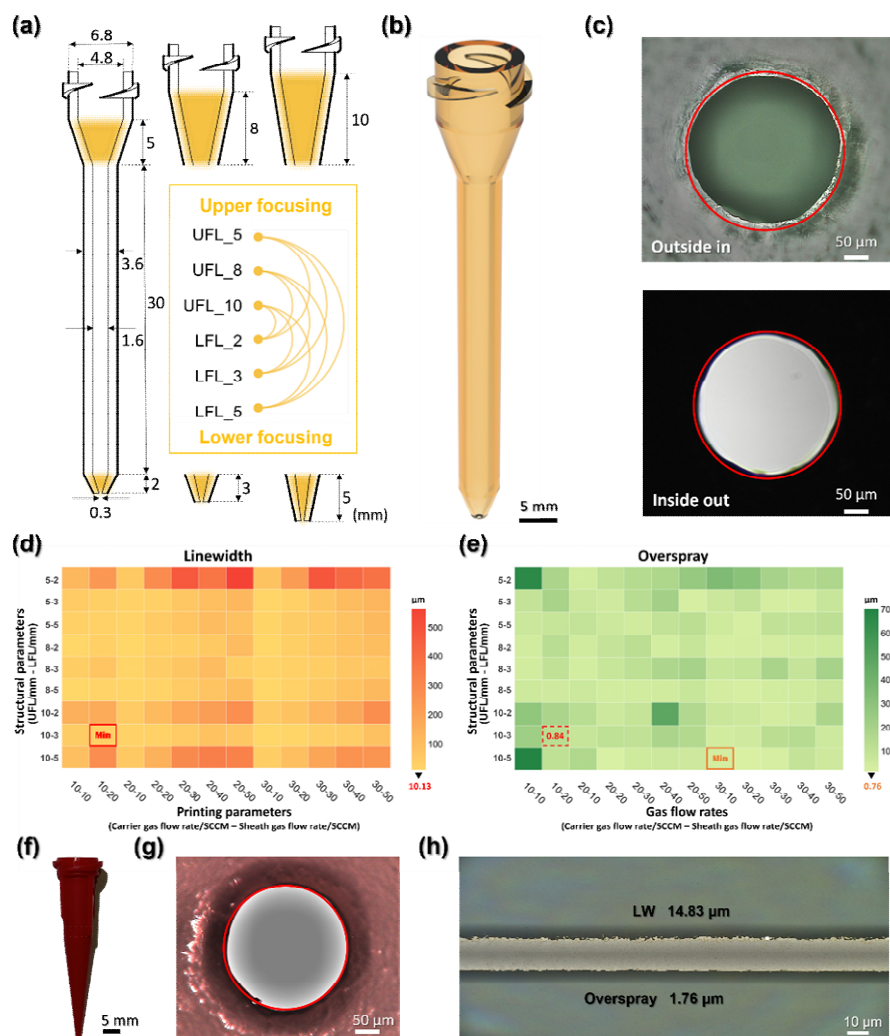
Domain	Material properties		
	Parameter	Definition	Value
Ink	μ_{ink}	Viscosity of ink (cP)	15
	ρ_{ink}	Density of ink (kg/m ³)	789.9
	C_{ink}	Heat capacity of ink (J/kg/K)	1280
	k_{ink}	Thermal conductivity of ink (W/m/K)	1.9762
	c_{ink}	Speed of sound of ink (m/s)	1207
	γ_{ink}	Ratio of specific heats of ink	1.1928
Gas	μ_{gas}	Viscosity of gas (cP)	0.0183
	ρ_{gas}	Density of gas (kg/m ³)	1.25
	C_{gas}	Heat capacity of gas (J/kg/K)	1038
	k_{gas}	Thermal conductivity of gas (W/m/K)	0.02583
	c_{gas}	Speed of sound of gas (m/s)	343
	γ_{gas}	Ratio of specific heats of gas	1.407

Nozzle	c_{nozzle}	Speed of sound of nozzle (m/s)	2760
	μ_{nozzle}	Density of nozzle (kg/m ³)	1120
Piezoelectric tube	μ_{piezo}	Density of piezoelectric tube (kg/m ³)	7750
	E_c	Elasticity matrix of piezoelectric tube	COMSOL database
	E_{se}	Coupling matrix of piezoelectric tube	COMSOL database
	E_ϵ	Relative permittivity of piezoelectric tube	COMSOL database



Supplementary Fig. 2 Simulated process of AJ printing with/without acoustic focusing (AF) of the optimal frequency (6.035 MHz). **a** Acoustic pressure distribution. **b** Acoustic intensity distribution. **c** Flow field distribution. **d** Particle trajectories and their velocities. **e** Particle motion distribution in aerosol ink flow before and after AF. D_0 and D_A are the original and focused diameter of the ink flow, respectively. **f** Simulated particle trajectories with/without AF. **g** Particle concentration distribution of the AJ printed trace with/without AF. Source data are provided as a Source Data file.

3 New nozzle design

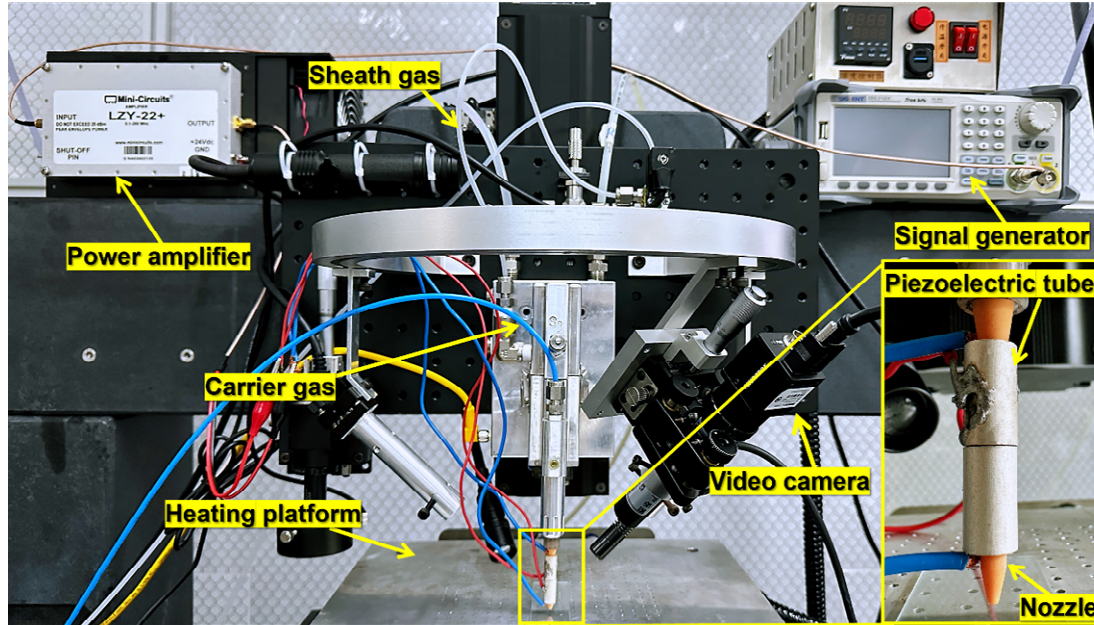


Supplementary Fig. 3 Design of the nozzle used in this study. **a** Geometric structure and design parameters of the new nozzle. **b** Optical image of the new nozzle. **c** Outlet of the stereolithography printed new nozzle. **d, e** Quantitative comparisons of the printed linewidth (**d**) and overspray width (**e**) under different printing parameters for the new nozzles with different structural parameters. UFL and LFL are the upper and focusing length, respectively. SCCM means standard cubic centimeters per minute. Source data are provided as a Source Data file. **f** Optical image of the commercial nozzle. **g** Outlet of the available nozzle. **h** Geometric morphology of the available nozzle printed line.

Supplementary Table 2 Structural parameters of the new nozzle

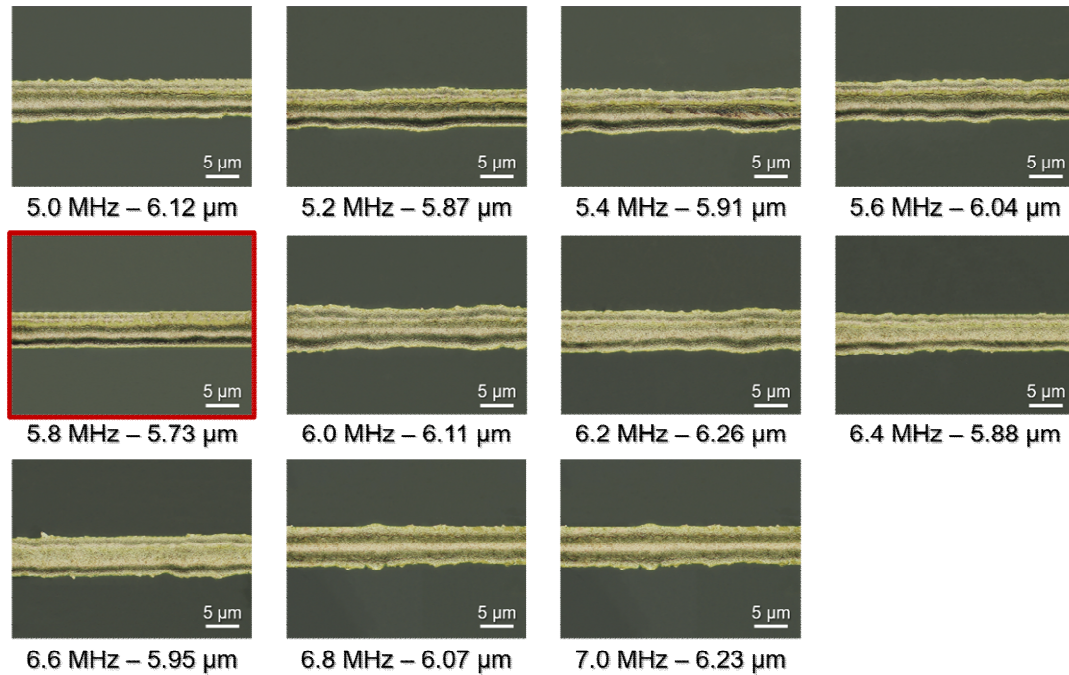
Upper focusing length (mm)	Lower focusing length (mm)	Acoustic channel inner diameter (mm)	Acoustic channel outer diameter (mm)	Outlet diameter (mm)	Inlet diameter (mm)
10	3	1.3	3.5	0.3	4.8

4 Experimental setup



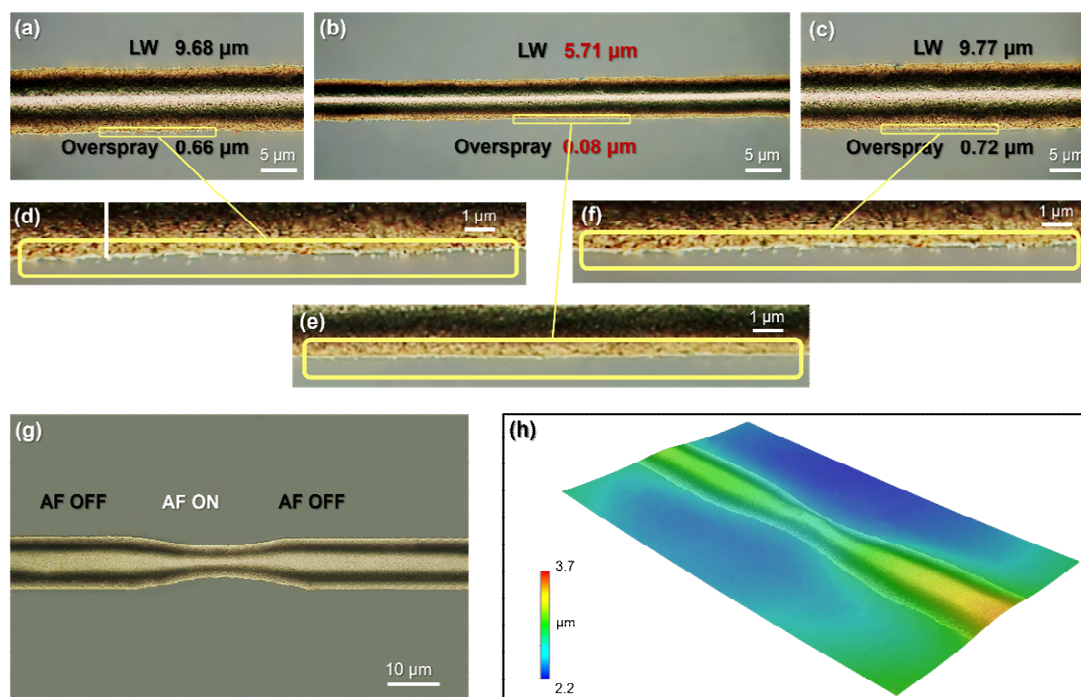
Supplementary Fig. 4 The AJ printing system integrated with the annular piezoelectric tube.

5 Optimal AF frequency search experiment



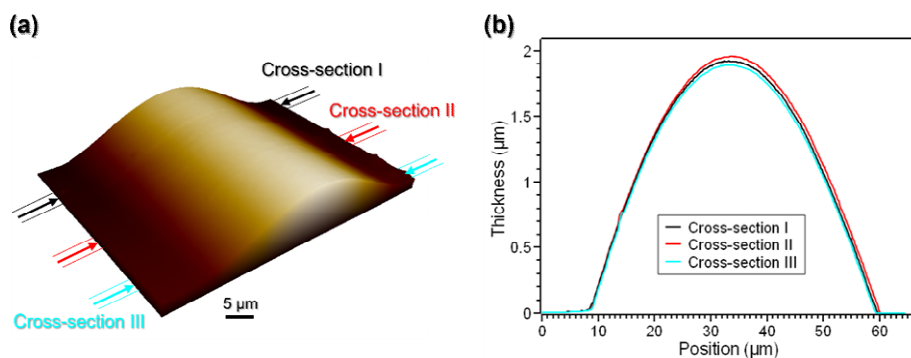
Supplementary Fig. 5 AF-assisted AJ printed trace images with a step size of 0.2 MHz in the acoustic frequency range of 5-7 MHz.

6 The edge morphology of continuous AJ printed line with/without AF



Supplementary Fig. 6 The edge morphology of continuous AJ printed line with/without AF. **a** Original geometric morphology of an AJ printed line before AF. **b** Geometric morphology of the line printed continuously under AF ON. **c** Geometric morphology of the line printed continuously with (b) after turning off AF. LW is linewidth. **d**, **e**, **f** Enlarged images of the edge morphology of the AJ printed line without/with/without AF of (a), (b) and (c) respectively. **g** 2D and **h** 3D whole track geometry of the AJ printed trace before, during and after a short-term AF.

7 Measuring the cross-sectional profile of AJ-printed traces



Supplementary Fig. 7 Measuring the cross-sectional profile of AJ-printed traces. **a** 3D model of the AJ-printed trace scanned by AFM. **b** Three randomly selected parts of the trace were chosen as the cross-sections (I, II, III). Source data are provided as a Source Data file.

8 Printing parameters

Supplementary Table 3 Printing parameters of the experiments

Line width (μm)	Nozzle diameter (μm)	Carrier gas flow rate	Sheath gas flow rate	Printing speed (mm/s)	Standoff distance (mm)	Platen temperature ($^{\circ}\text{C}$)	Substrate material
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		(sccm)	(sccm)				
10	300	8	21	9	2.5	80	Glass
30	300	15	33	9	2.5	80	Glass
50	300	22	47	9	2.5	80	Glass
80	300	36	78	9	2.5	80	Glass

9 Quantification and comparison of the geometric and electrical characteristics of AJ printing before and after focusing

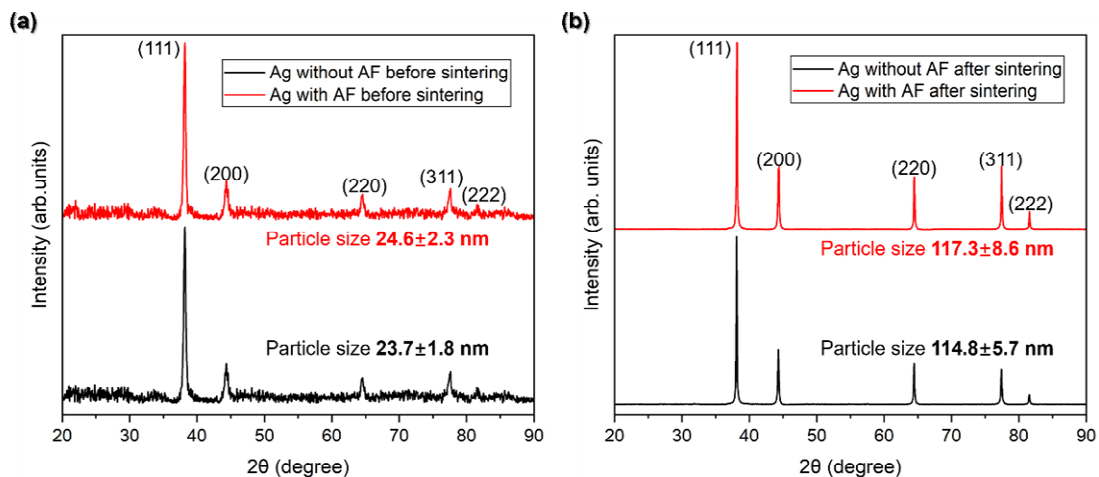
Supplementary Table 4 Geometric characteristics of the AJ printed lines with/without AF

Group	AF	Line width		Thickness		Cross-sectional area	
		μm	Change rate (%)	μm	Change rate (%)	μm^2	Change rate (%)
A	OFF1	9.64		1.29		9.33	
	ON	5.72	58.9	1.54	118.6	8.07	84.1
	OFF2	9.79		1.32		9.88	
B	OFF1	32.37		1.69		38.16	
	ON	19.97	62.3	1.88	110.7	31.79	78.2
	OFF2	31.72		1.70		37.99	
C	OFF1	48.36		1.92		59.79	
	ON	29.76	61.1	2.27	116.8	48.78	82.3
	OFF2	49.13		1.97		58.87	
D	OFF1	83.67		2.11		115.68	
	ON	49.87	59.9	2.44	115.8	87.84	75.8
	OFF2	82.94		2.09		116.13	

Supplementary Table 5 Electrical characteristics of the AJ printed lines with/without AF

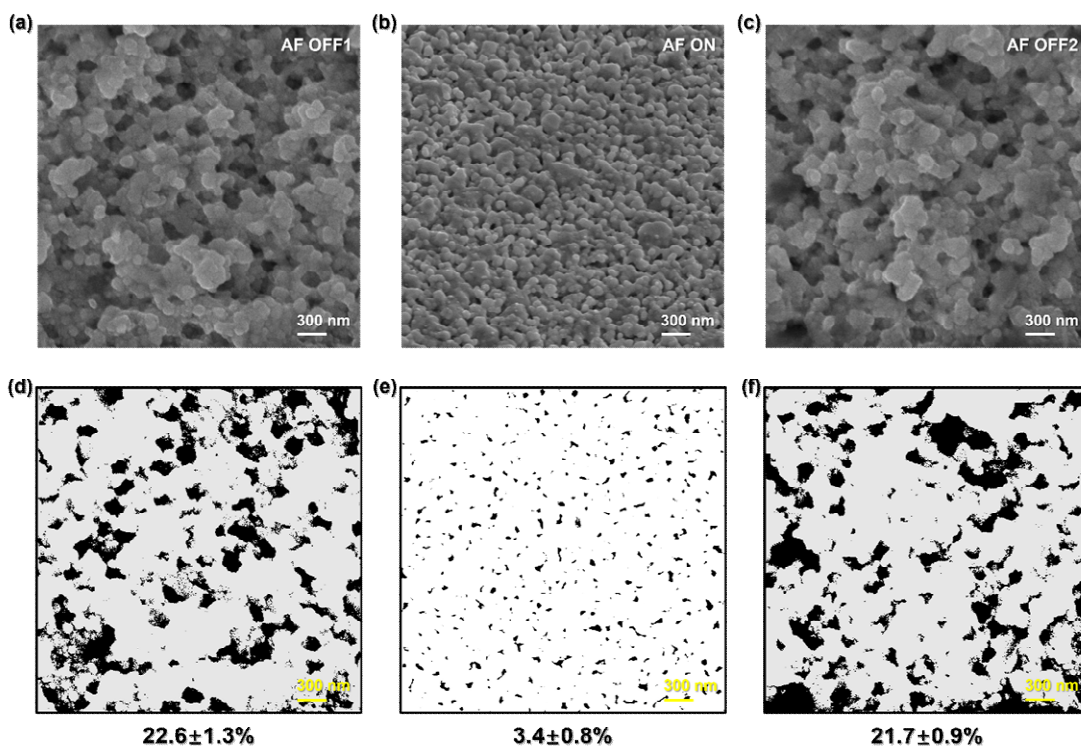
Line width (μm)	AF	Resistance		Conductivity	
		Ω	Change rate (%)	10^6 S/m	Change rate (%)
10	OFF	26.42		5.12	
	ON	16.79	63.6	9.59	187.1
30	OFF	6.46		5.28	
	ON	4.25	65.8	9.62	182.1
50	OFF	4.14		5.29	
	ON	2.73	65.9	9.78	184.8
80	OFF	2.74		5.32	
	ON	1.68	61.3	9.91	186.2

10 XRD spectra



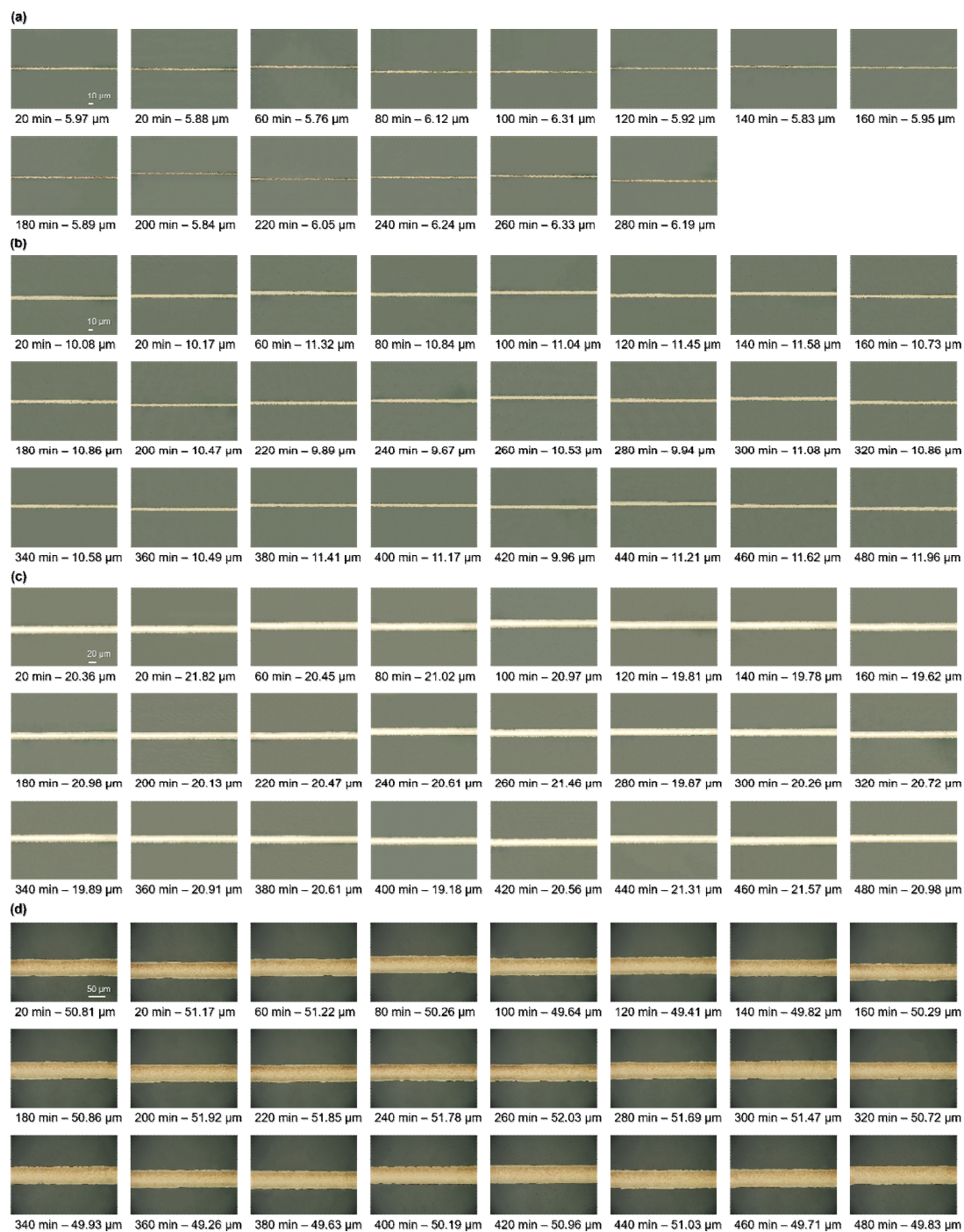
Supplementary Fig. 8 XRD spectra of Ag printed without and with acoustic focusing (AF) **a** before and **b** after sintering respectively. Source data are provided as a Source Data file.

11 Porosity analysis



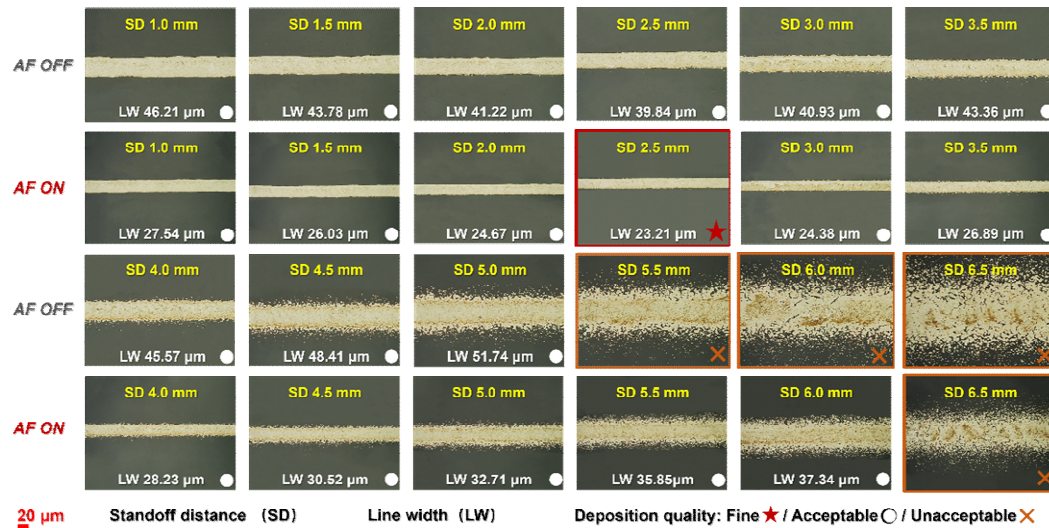
Supplementary Fig. 9 SEM images of the cross-sectional area of AJ printed trace **a** Acoustic focusing (AF) OFF1, **b** AF ON, **c** AF OFF2. **d**, **e**, **f** the calculated corresponding porosity.

12 Printing stability test



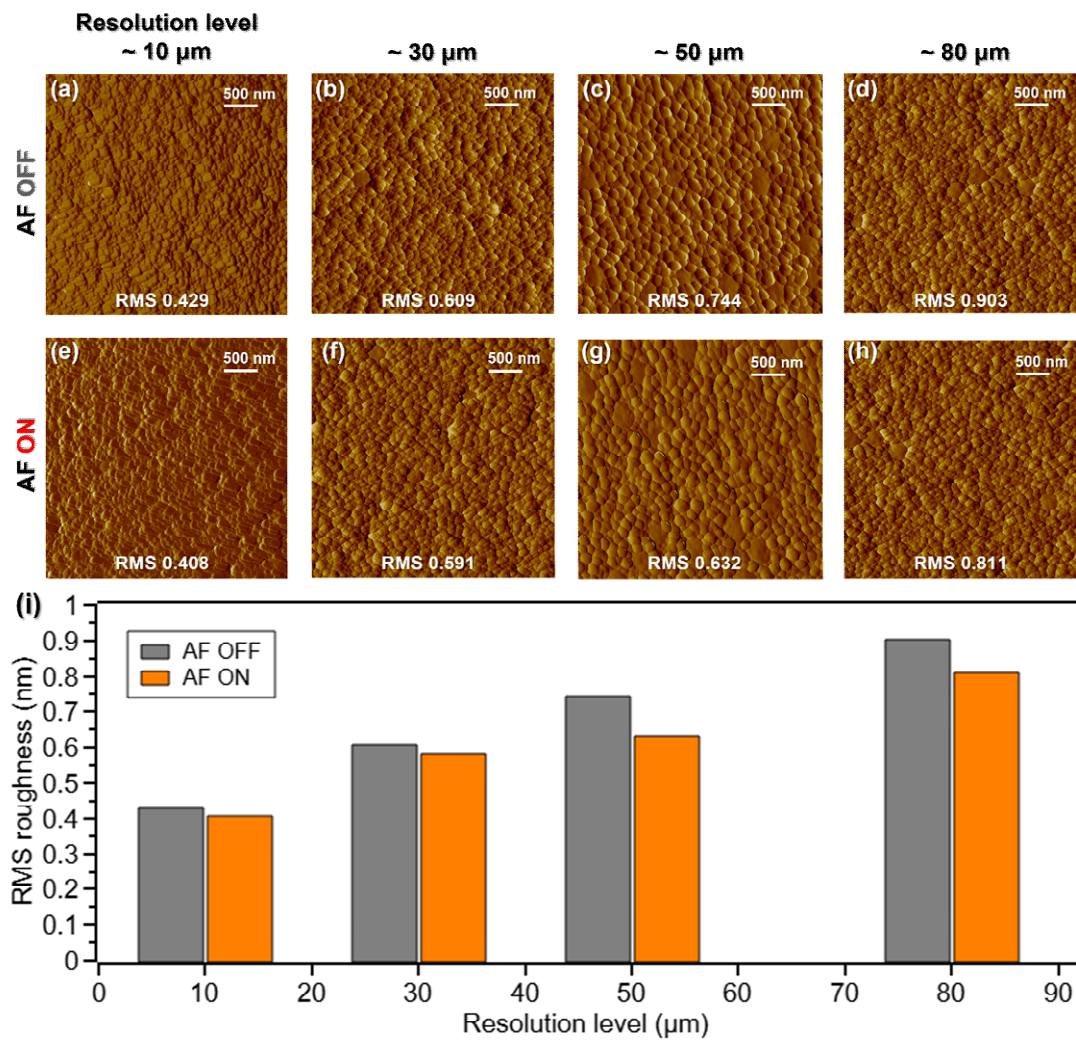
Supplementary Fig. 10 Continuous AJ printing assisted with AF, during which the morphology and geometric values of the printed line were measured in steps of 20 minutes. a LW ~6 μm for 4.5 hours. b LW ~ 10 μm for 8 hours. c LW ~ 20 μm for 8 hours. d LW ~ 50 μm for 8 hours.

13 Standoff distance test



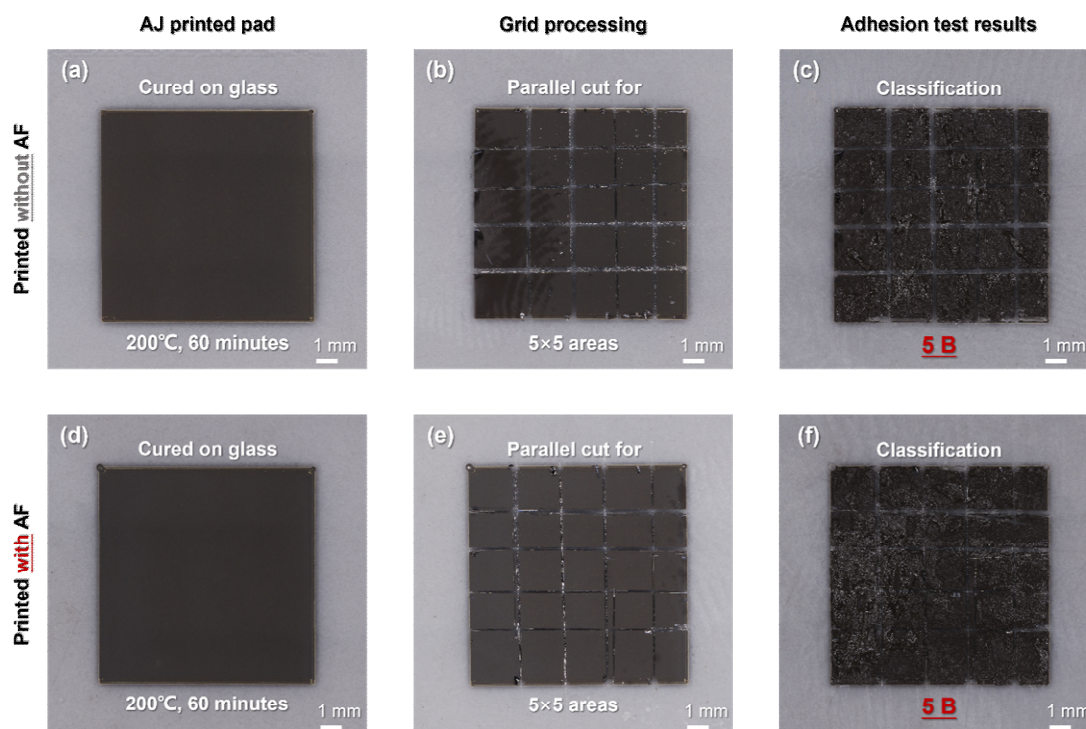
Supplementary Fig. 11 Images of acoustic focusing (AF)-assisted AJ printed traces with different standoff distance (ranging from 1.0 mm to 6.5 mm). SD means standoff distance, and LW means linewidth.

14 RMS roughness analysis



Supplementary Fig. 12 RMS roughness analysis. a-h Surface morphology with corresponding RMS roughness of the AJ printed deposition at different printing resolutions (~ 10 , ~ 30 , ~ 50 , ~ 80 μm) before (a, b, c, d) and after (e, f, g, h) acoustic focusing (AF) measured by AFM. i Analysis of the change in RMS roughness before and after AF. Source data are provided as a Source Data file.

15 Adhesion test



Supplementary Fig. 13 Adhesion test. a, d Aerosol-jet (AJ) printed pads cured on glass at 200°C for 60 minutes without acoustic focusing (AF) (a) / with AF (d). b, e 5 × 5 areas obtained by parallel cutting of the pad printed without AF (b) / with AF (e). c, f Adhesion test results with classification of AJ printed pads without AF (c) / with AF (f)